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Geomorphology 50 (2003) 181–202
GEOMORPHOLOGY
www.elsevier.com/locate/geomorph

Differential features of alluvial fans controlled by tectonic or eustatic accommodation space. Examples from the Betic Cordillera, Spain

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Received 1 September 2000; received in revised form 1 June 2001; accepted 15 July 2002

Abstract

The creation of accommodation space in subaerial sedimentary environments is closely linked to uplift the source area (along basin–margin faults) or to a rise in base level. Depending (amongst others) on the relative importance of these two factors, the margins of terrestrial sedimentary basins (where alluvial fans develop) produce aggradational, progradational or retrogradational stratigraphic architecture.

We studied a total of 43 Quaternary alluvial fans in the Granada and Bajo Segura basins (Betic Cordillera, Spain). The analysis of their stratigraphic architecture and sedimentary facies has revealed the existence of three groups characterised by distinct stratal stacking patterns, which is the result of differences in eustasy and tectonics. The qualitative and quantitative analysis of these alluvial fans and their drainage basins has allowed us to define certain characteristic geomorphological patterns related, in each case, to the main mechanism operative in the creation of accommodation space. These patterns are described as follows.

(1) Alluvial aggradation is the main result of high tectonic subsidence with the development of quite open, but small fans with a constant steep slope lacking incised channels and headward-eroding gullies.

(2) In contrast, when the principal mechanism in creating accommodation space is low tectonic subsidence, progradation occurs and the fans are narrower and larger. Moreover, the slopes of such fans are less steep in relation to the drainage area than in the above case, being constant or even concave in longitudinal profile. They also have short, deep incised channels, culminating downfan in a depositional lobe. In inactive zones, long, deep headward-eroding gullies develop.

(3) Areas of extremely low tectonic subsidence and base level rise produce very open fans in the sedimentary basin, although with a pronounced mountain embayment, which gives them a characteristic “mushroom” shape in plan view. In the latter case, retrogradation is the typical stratigraphic stacking pattern and the fans are quite extensive with respect to their drainage areas, usually showing a segmented longitudinal profile with a low gradient. The feeder channels do not surpass stream order 3, and various extremely long and shallow incised channels can appear.

(4) Contrary to the case of fans developing under a regime of subsidence, when the accommodation is due to base level rise, the fan slopes bear no relation to the extent of the catchment basins. In such a case, the overall fan slope is strongly influenced

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PII: S0169-555X(02)00214-3

by the extent of the mountain embayment because it determines the distributions of debris and sheet-flows over the alluvial surface.

Keywords: Alluvial fans; Morphometry; Stratigraphic stacking pattern; Accommodation space; Betic Cordillera

1. Introduction

The basic form of an alluvial fan is a depositional response to the expansion of a confined channel flow as it leaves the rockhead valley to emerge onto the fan surface (Leeder, 1999). For sediment accumulation to occur, there must be accommodation space for the material carried by the current to be deposited and preserved where the channel flow expands. The concept of accommodation was defined for marine sedimentation as the space made available for potential sediment accumulation in order for sediments to be preserved, for which there must be space available below base level (Jervey, 1988). Obviously, this definition is not valid for subaerial sedimentary environments. Thus, Posamentier and Vail (1988) define subaerial accommodation as the space available for sediment to fill between the old stream profile and a new higher stream profile. According to Miall (1996), rivers and fans adjust to a new profile in response to changes in base level, tectonic movements or hydraulic conditions (discharge or sediment supply). Sediment accumulation occurs when the accommodation space is positive, which happens among other cases, when the graded profile moves upwards in response to a rise in base level or to uplift the source area, for example, along a basin–margin fault (Harvey, 1984, 1987).

Nonetheless, the latter theory also entails problems in its use. Indeed, some authors have reported significant difficulties in identifying equilibrium profiles from existing landforms and from the stratigraphic record. They question the usefulness of the equilibrium profile and of the geomorphic base level concept to identify accommodation, particularly in subaerial environments (Muto and Steel, 1997, 2000). An alternative criterion has therefore been proposed: the stratigraphic base level (Wheeler, 1964) is the equilibrium surface that describes the direction in which a stratigraphic system is likely to move towards sedimentation and stratigraphic preservation or sediment bypass and erosion (Shanley and McCabe, 1994). Under this concept, subaerial accommodation is regarded as the space developed between successive depositional surfaces of different ages and most commonly driven by changing subsidence, uplift or eustatic sea level. Thus, we arrive at a new definition of accommodation in terms of a resultant sedimentation, which is the thickness, measured at a specified site and time of a space that becomes filled with sediments during a specified time interval (Muto and Steel, 2000). This last concept of accommodation is applied in this study, wherein, we treat the mechanisms involved in alluvial aggradation, progradation and retrogradation, as well as the surface expression of these stratigraphic stacking patterns in terms of morphometric and morphological variables. This approach is very close to that of "realized accommodation" of Cross (1988).

The relative role played by tectonics, climate and eustasy on alluvial sequence stratigraphy has been widely treated in the literature (Marzo et al., 1988; Anadón et al., 1986; Ouchi, 1985; Van Wagoner et al., 1990; Wright and Marriot, 1993; Shanley and McCabe, 1994; DeCelles et al., 1991; Alonso Zarza et al., 1992; Fraser and DeCelles, 1992; Blair, 2000; Stokes and Mather, 2000, amongst others), in addition to their role in the cyclicity in sedimentation at different scales (Heward, 1978; Rust, 1978; Sneh, 1979; Crews and Ethridge, 1993; Wright and Alonso Zarza, 1990; Sambrook Smith, 2000). In addition, there has been a certain amount of research on the influence of these allogenic factors on the morphology and morphometry of Quaternary alluvial fans and the morphometric relationships with their source areas (Harvey, 1984, 1987, 1988, 1997; Muto, 1987; Ferrill et al., 1996; Calvache et al., 1997; Harvey et al., 1999a,b; Sorriso-Valvo et al., 1998).

Southeastern Spain was the site of excellent conditions for the development of alluvial fans during the Quaternary. In addition to a semiarid precipitation regime, the tectonic activity of the Betic Cordillera has produced recent extreme vertical movement with highly different uplift rates from one sector to another.

Thus, active tectonics, combined with other geological and environmental processes, produced a wide variety of allogenic control mechanisms on alluvial sedimentation. Spectacular phenomena of basin inversion, for example, have been produced in relation to this recent tectonic activity, involving piracy and drastic changes in the drainage patterns of some basins and in the transfer pathways of sediment from certain sectors of the cordillera to others (Viseras and Fernández, 1992; Mather, 1993, 2000a,b; Calvache and Viseras, 1997). Furthermore, the easternmost basins are connected to the Mediterranean; hence, eustatic cycles together with different rates of subsidence or of uplift contribute to form a complicated pattern of allogenic control on the stratigraphic architecture and the distribution of sedimentary facies in alluvial fan systems (Harvey, 1988, 1990; Silva et al., 1992; Harvey et al., 1999b).

For this study, we selected three groups of Quaternary alluvial fans located in similar geological contexts (the Internal Zone of the Betic Cordillera) that developed during the same interval (late Pleistocene–Holocene) and under similar climatic conditions (currently the mean annual precipitation in the Granada Basin is 450 mm and about 350 mm in the Bajo Segura Basin). However, these three groups differ in relation to the mechanisms for the creation of accommodation space. As shown below, these mechanisms acted in entirely different ways during the Quaternary, which allows us to distinguish the role of the two main allogenic controls (tectonics and eustasy) on the morphology and morphometry of alluvial fans, as well as on the morphometric relationships between fans and their catchments.

2. Methodology and survey

This research (of 43 alluvial fans, 21 in the Granada Basin and 22 in the Bajo Segura Basin) is based on quantitative and qualitative data taken in the field and from aerial photographs at a scale of 1:20,000. The groups of fans were chosen so as to include three different contexts regarding the creation mechanisms of accommodation space for alluvial accretion during the Quaternary. All the information has been transferred to topographic maps with a scale of 1:10,000 with 10-m contour lines, from which we obtained the morphometric data and the profiles of the fans and their catchments.

The analysis focused on the morphology and morphometry of fans and their catchments, on sedimentary facies and on a comparison of the distinct parameters characteristic of the fans and their catchments. The parameters providing the most interesting results are given below (Tables 1 and 2):

- Fan area (Fa), the total planimetric area of each fan.
- Drainage basin area (Da), the total planimetric area of each basin.

Table 1
Parameters used in the morphometric analysis of the alluvial fans and their drainage basins

Symbol	Parameter	Unit	Meaning
Fa	Fan area	km^2	Total planimetric area of each fan
Da	Drainage basin area	km^2	Total planimetric area of each basin
Fs	Fan slope	nondimensional	Gradient measured along the axis of each fan or along the axis of the active depositional lobe
Ds	Basin slope	nondimensional	$Ds = eL/A$, where e is the equidistance between contour lines, L is the total length of contour lines and A is the basin area
Cs	Feeder channel slope	nondimensional	Gradient measured along sectors of the feeder channel
WLF	Ratio width/length of the fan	nondimensional	Expresses the elongation of the fan
WLD	Ratio width/length of the drainage basin	nondimensional	Expresses the plan-view morphology of the catchments
As	Sweep angle	degrees	Angle between the two outermost positions of the channels of a fan
ICP	Incised channel percentage	%	Percentage of fan radius occupied by an incised channel

Table 2
Data set of fans and drainage basins population

Fan	Fa	Da	Fs	Ds	WLF	WLD	As	ICP
Group 1								
1	0.011	0.118	0.14	0.36	1.200	0.59	55	–
2	0.012	0.051	0.21	0.39	1.500	0.26	83	–
3	0.016	0.045	0.22	0.48	1.125	0.23	62	–
4	0.014	0.038	0.24	0.47	0.750	0.39	30	–
5	0.019	0.028	0.22	0.45	0.636	0.37	27	–
6	0.091	0.192	0.17	0.57	1.444	0.33	60	–
7	0.630	1.762	0.14	0.55	1.325	1.07	118	–
8	0.062	0.307	0.15	0.51	1.000	0.38	74	–
9	0.020	0.055	0.08	0.51	0.818	0.39	55	–
10	0.108	0.554	0.14	0.52	1.500	0.41	113	–
11	0.035	0.285	0.19	0.45	1.300	0.26	69	–
12	0.125	0.519	0.12	0.58	2.166	0.51	104	–
Group 2								
1	–	–	–	–	0.600	0.53	–	16.21
2	3.059	1.663	0.10	0.50	0.946	0.32	88	8.00
3	0.503	0.286	0.18	0.62	0.666	0.23	53	17.39
4	1.395	0.785	0.17	0.67	1.135	0.45	86	17.60
5	0.115	0.159	0.20	0.70	0.437	0.26	45	40.00
6	0.087	0.126	0.21	0.49	0.312	0.28	18	33.00
7	0.075	0.144	0.21	0.77	0.363	0.21	25	–
8	0.058	0.108		0.80	0.444	0.23	39	–
9	0.048	0.074			0.722	0.19	50	–
Group 3								
1	0.273	0.378	0.10	0.79	0.388	0.52	85	47.90
2	1.866	2.126	0.08	0.56	0.694	1.08	95	–
3	0.267	0.413	0.08	0.57	0.500	0.38	64	27.27
4	0.275	0.217	0.07	0.60	0.750	0.50	68	52.30
5	1.875	1.577	0.05	0.61	0.820	0.85	76	20.00
6	0.238	0.394	0.11	0.60	1.200	0.34	132	43.47
7	0.734	0.818	0.08	0.60	0.978	0.93	63	45.65
8	0.235	0.490	0.05	0.58	0.765	0.50	110	34.28
9	0.125	0.380	0.06	0.47	0.475	0.30	71	64.44
10	0.554	0.377	0.08	0.57	0.660	0.40	125	68.00
11	0.199	0.273		0.62	0.595	0.79	103	44.73
12	0.144	0.385	0.07	0.72	0.880	0.63	80	48.07
13	0.567	1.193	0.08	0.59	0.717	1.03	68	80.35
14	0.348	0.400	0.10	0.64	0.596	0.47	44	–
15	0.384	0.390	0.10	0.57	0.581	0.47	37	–
16	0.275	0.516	0.09	0.64	0.967	0.75	129	32.25
17	0.297	0.288	0.07	0.70	1.025	0.93	132	38.88
18	0.540	0.642	0.07	0.72	0.563	0.75	66	22.35
19	0.126	0.351	0.12	0.88	0.700	0.46	58	41.66
20	0.886	1.097	0.10	0.77	0.632	0.52	173	–
21	0.363	0.765	0.12	0.80	0.627	0.74	90	–
22	0.798	1.046	0.06		1.000	0.64	178	51.28

- Fan slope (Fs), the gradient measured along the axis of each fan or along the axis of the active depositional lobe, where present.
- Basin slope (Ds), obtained following Roche (1963) using the equation: eL/A, where e = equidistance, L = total length of contour lines and A = basin area.
- Feeder channel slope (Cs), the gradient measured along sectors of the feeder channel in the drainage area.
- Ratio width/length of the fan (WLF), which expresses the elongation of the fan (termed WLR by Sorriso-Valvo et al., 1998).
- Ratio width/length of the drainage basin (WLD), used in this work as an estimate of the plan-view morphology of the catchments.
- Sweep angle (As), the angle between the two outermost positions of the channels of a fan (Viseras and Fernández, 1994).
- Incised channel percentage (ICP), defined in this paper as the percentage of fan radius occupied by an incised channel.

3. Geological background

The Betic Cordillera basically consists of two structural domains: the Internal Zones to the south, also called the Alboran Micro-Plate (Andrieux et al., 1971), Meso-Mediterranean Micro-Plate (Martín Algarra et al., 1992) or South-Sardinian Block (Sanz de Galdeano and Vera, 1992) and to the north the External Zones or the Southern Iberian Palaeomargin (initially forming part of the Iberian Plate; Vera, 2001) (Fig. 1).

Until the early Miocene, both domains underwent convergence and collision, leading to significant thickening of the crust. This compressive phase was followed by an extensional phase dominated by detachment movements, which played a decisive role in the development and evolution of the sedimentary basins (García Dueñas et al., 1992; Jabaloy et al., 1992). Once the continental collision had ended, postorogenic basins formed during the late Miocene and Pliocene (Vera, 2000). Some of these basins developed as intramontane depressions over the old contact between the two converging domains, which is the case of the Granada and Bajo Segura Basins (Fig. 1). The late Pleistocene–Holocene fill of these two basins is the subject of this study.

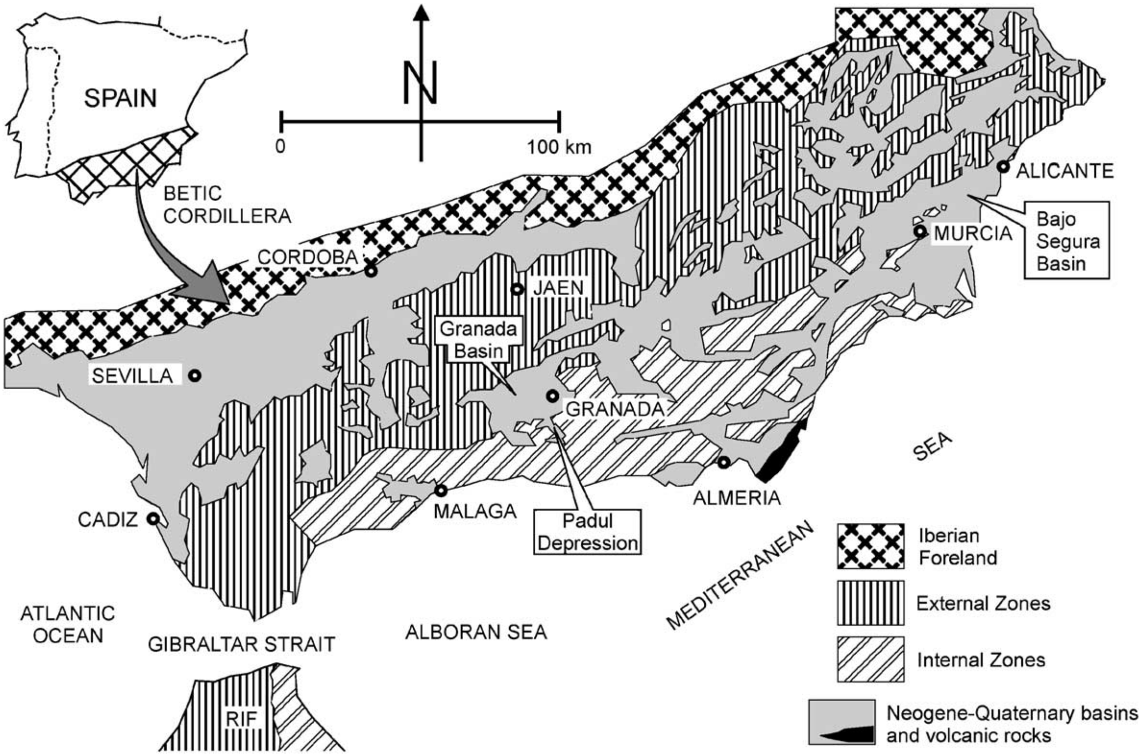

Fig. 1. Location of the Granada and Bajo Segura basins in the geological context of the Betic Cordillera.

3.1. The Granada Basin

The Granada Basin is located in the central Betic Cordillera. Its stratigraphic record comprises six units dating from the late Tortonian to the present (Fernández et al., 1996).

During the Pliocene, a small tectonic depression (referred to as the Padul Depression: Sanz de Galdeano, 1996; Calvache et al., 1997; Sanz de Galdeano and López Garrido, 1999) in the extreme SW of Sierra Nevada (Internal Zones) was differentiated from the rest of the Granada Basin. It is bounded by a series of NNW-SSE striking faults crosscut by others striking WSW–ENE (Fig. 2), thus, dividing this small depression into a series of blocks subjected to different subsidence rates (Lhenaff, 1965; Santanach et al., 1980; Domingo et al., 1983; Alfaro et al., 2001).

During the late Pleistocene–Holocene, a set of alluvial fans developed abutting onto the NE margin of this depression (Calvache et al., 1997) extending laterally to a set of sands and peaty clays deposited in a lake towards the centre of the depression (Fig. 2). These fine-grained materials have been well dated both by ^{14}C dating and by their palynological succession (Florschütz et al., 1971; Nestares and Torres, 1998). The alluvial deposits here reached a thickness of nearly 115 m, with three main cycles separated by unconformities. Their stratigraphic relations, as well as the syn-sedimentary faulting provide evidence for significant tectonic control on the sedimentation patterns (Calvache et al., 1997). These fans are fed almost exclusively by limestone–dolomite detritus from the relief in the extreme SW Sierra Nevada (Internal Zones).

The fans studied form a coalescent system (bajada) abutting a fault striking approximately NNW–SSE that marks the boundary of the Sierra Nevada in this sector. This discontinuous fault, known as the Padul Fault (Alfaro et al., 2001), has been divided and displaced by another fault striking approximately WSW–ENE. As a consequence of this crosscutting relationship, the two fragments of the Padul Fault act

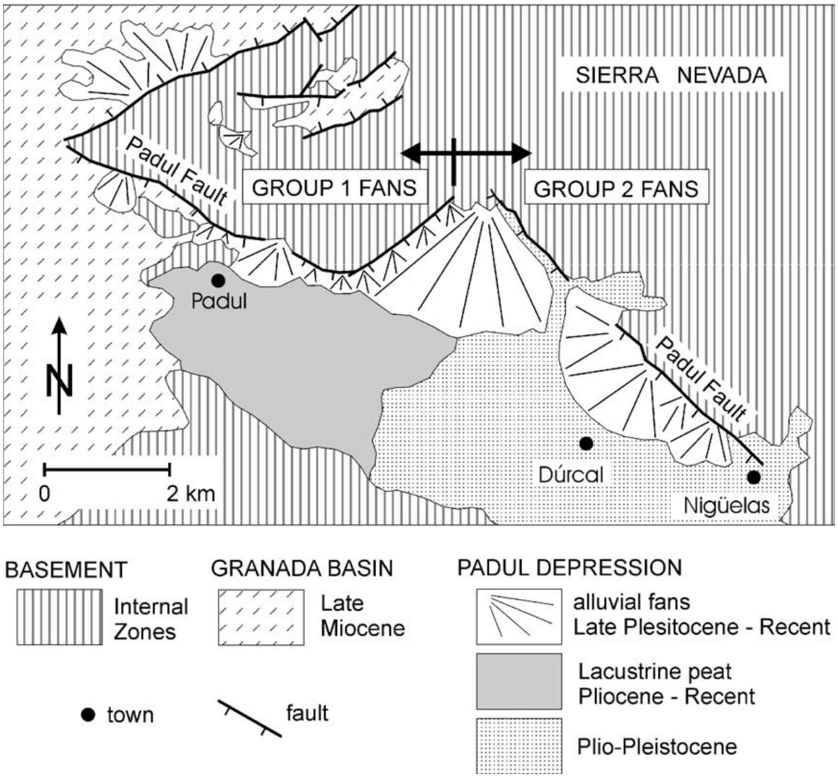

Fig. 2. Geological setting of the fans of Groups 1 and 2 (after Sanz de Galdeano, 1996, simplified). See Fig. 1 for location of the Padul Depression in the Granada Basin.

independently, delimiting two sectors: (1) a northern sector with very marked tectonic subsidence, with periods in which the vertical movement can be estimated at several millimeters per year (Sanz de Galdeano, 1996; Sanz de Galdeano and López Garrido, 1999) and (2) a southern sector with much more moderate subsidence, as deduced from gravimetric studies (Alfaro et al., 2001). Likewise, the alluvial set can be divided into two groups of fans, termed 1 (or North Granada Basin) and 2 (or South Granada Basin) here (Fig. 3). They are characterised by a different series of geomorphological and facies architecture features (Calvache et al., 1997).

3.2. The Bajo Segura Basin

The Bajo Segura Basin is located at the eastern end of the Betic Cordillera, and like the Granada Basin, it lies over the contact between the Internal and External Zones (Fig. 1). It is tectonically limited by two main structures: the Crevillente Fault to the north and the Bajo Segura Fault to the south (Fig. 4). The Bajo Segura Basin, currently connected eastwards with the Mediterranean, is filled by marine and continental sediments of late Miocene–Quaternary age. The sedimentary record has been divided into six stratigraphic units bounded by unconformities and their correlative conformities (Soria et al., 2001).

The alluvial fans in this study border the Sierras of Orihuela and Callosa (Fig. 4) and belong to the most recent stratigraphic unit filling the basin dated by ^{14}C at late Pleistocene–Holocene (Soria et al., 1999). The thickness of this unit is 30–60 m, the oldest absolute age determined is 14,570 ± 310 year B.P. (at a depth of 19.50 m) and the youngest age is 710 ± 80 year B.P. (at a depth of 1.25 m) (Fig. 5). In contrast with the Granada Basin, which is connected with an endorheic palustrine environment, this fan system

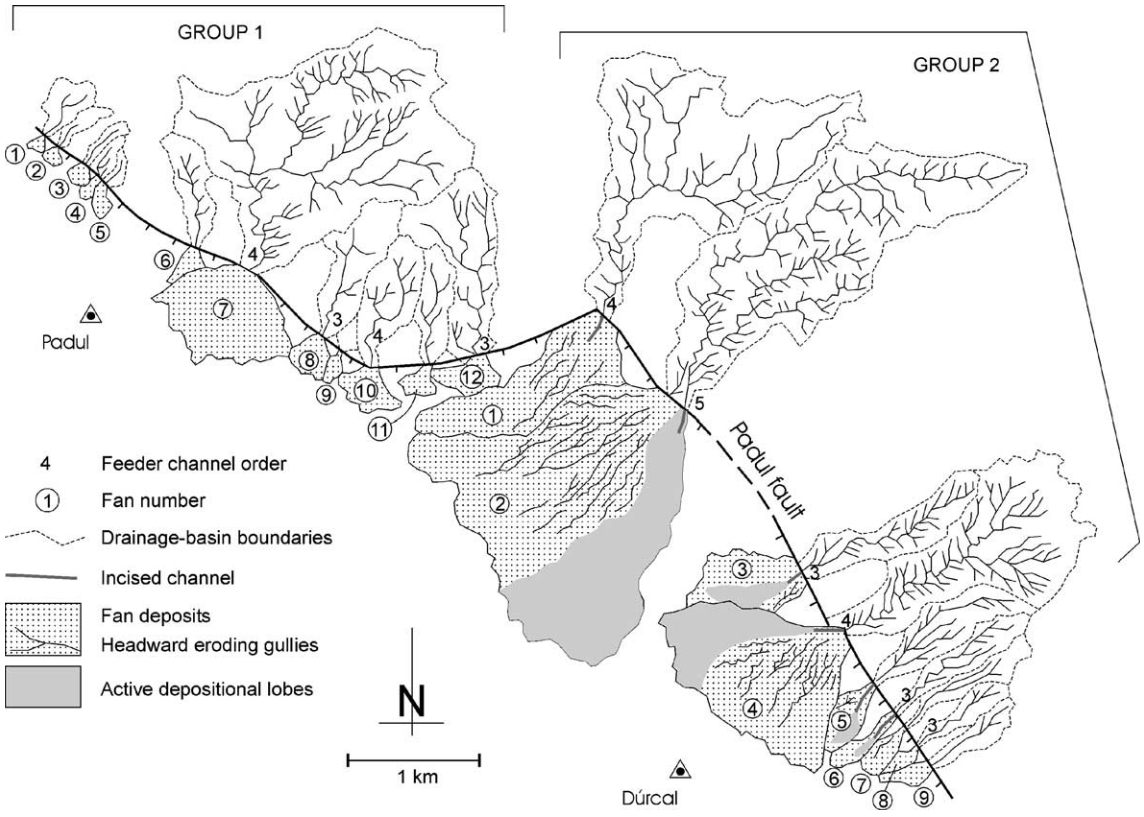

Fig. 3. Fans of Groups 1 and 2 and their drainage basins. See Figs. 1 and 2 for location.

interfingers with coastal-plain and lagoonal sediments, which in turn are connected with well-defined beach sediments that developed during the Quaternary in this marginal sector of the Mediterranean (Soria et al., 1999). The alluvial fans have a retrograde stacking pattern, as deduced from the vertical facies succession of the Callosa borehole (Fig. 5). This borehole reveals a fining and thinning-upward sequence beginning with alluvial fan gravels. These gravels pass upwards to fan-fringe coarse sands alternating with dark-grey lutites containing layers of coal and of bivalves and gastropods. The layers indicate coastal-plain and lagoonal environments, respectively. The beach deposits interfinger with the coastal plain in a retrograde stacking pattern, as well as it can be seen from the Guardamar borehole (Fig. 5). This overall pattern indicates a general transgressive sequence related to an eustatic rise of the Mediterranean during the Holocene, estimated at about 60 m (Hernández Molina et al., 1994). Quaternary tectonic activity is very low in this basin, with vertical movements of 0.1–0.5 mm/year (Alfaro, 1995).

All these data indicate that the creation of accommodation space in this basin is fundamentally due to a rise in base level (Holocene eustatic rise). These alluvial fans are both close to the coastline (30–40 km) and at a low altitude (15–70 m asl in the medial fans). These circumstances mean that their retrogade stacking pattern affects even the most proximal sectors of the fans, causing basement onlap. Thus, the rise in base level caused an upward migration of deposition throughout the alluvial system (see Schumm, 1993).

Another feature these fans have in common with those of the Granada Basin is the lithology of the source area (the Callosa and Orihuela Sierras), where once again locally metamorphosed carbonates from the Triassic of the Betic Internal Zones dom-

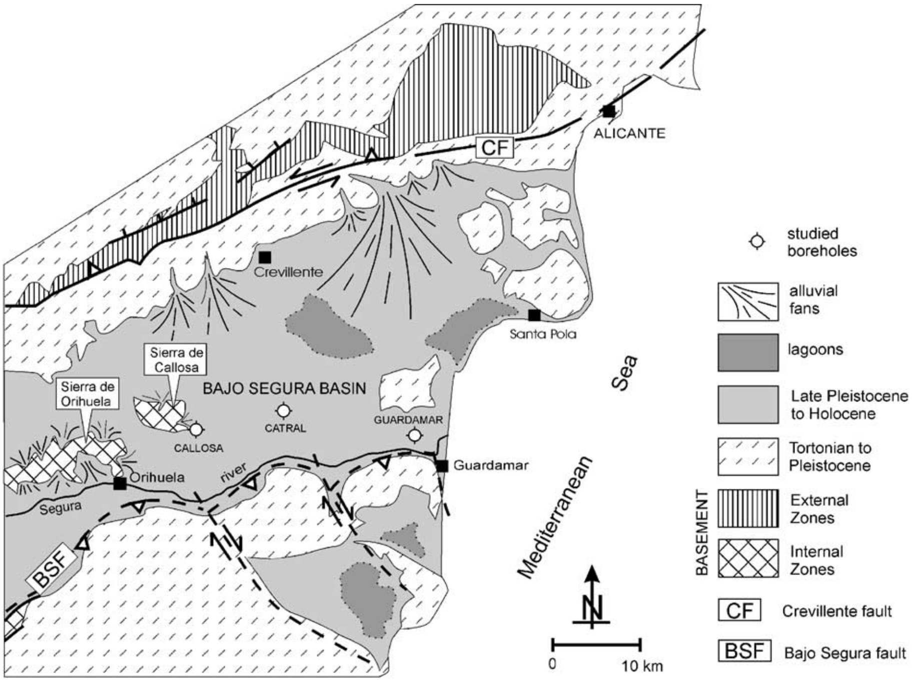

Fig. 4. Geological setting of the fans of Group 3, abutting onto the Sierra de Orihuela and Sierra de Callosa reliefs.

inate. Locally, these carbonates are intercalated with slates.

4. Morphology, morphometry and sedimentary facies of the fans

In order to describe the morphological and morphometric features of the fans and their catchments, we will refer to the three groups. Group 1 includes the 12 fans lying against the NW section of the Padul Fault in the Granada Basin. Group 2 corresponds to nine fans studied in the least active sector of the Padul Fault (SE of the above ones) and Group 3 comprises 22 fans in the Bajo Segura Basin (Figs. 3 and 6). Below is a description of the most characteristic features of each group of fans.

4.1. Plan-view morphology

Two parameters have been chosen to quantify the plan-view morphology of the fans, the ratio width/length of the fans (WLF) and sweep angle (As). Group 1 fans are relatively open, with a WLF ranging between 0.64 and 2.17 with an average of 1.23 (Table 3). It is worthy to note that 9 of the 12 fans surpass the value of 1, that is, their radius is lower than their width (radial fans; Moreno and Romero-Segura, 1997). The sweep angle of 10 of the 12 fans is over As 50° ranging from 27° to 118° with an average value of 71°.

Group 2 fans are more elongated, with a lower WLF (0.31–1.14, average 0.63). The value of WLF 1 seems to be critical, since in this case only one of the nine fans surpasses it. The mean As is 51° only surpassed by three of the nine fans with values ranging from 18° to 88°.

Many of the Group 3 fans have a distinctive morphological feature consisting of marked development of the alluvial facies within the source area (mountain embayment; Blair and McPherson, 1994). Therefore, although these fans have a large sweep angle (As from 37° to 178° with an average of 93°, and 19 of the 22 fans surpassing 60°), the WLF parameters are similar to those of Group 2 (0.39–1.20, mean 0.73, with a value of 1 surpassed only by 3

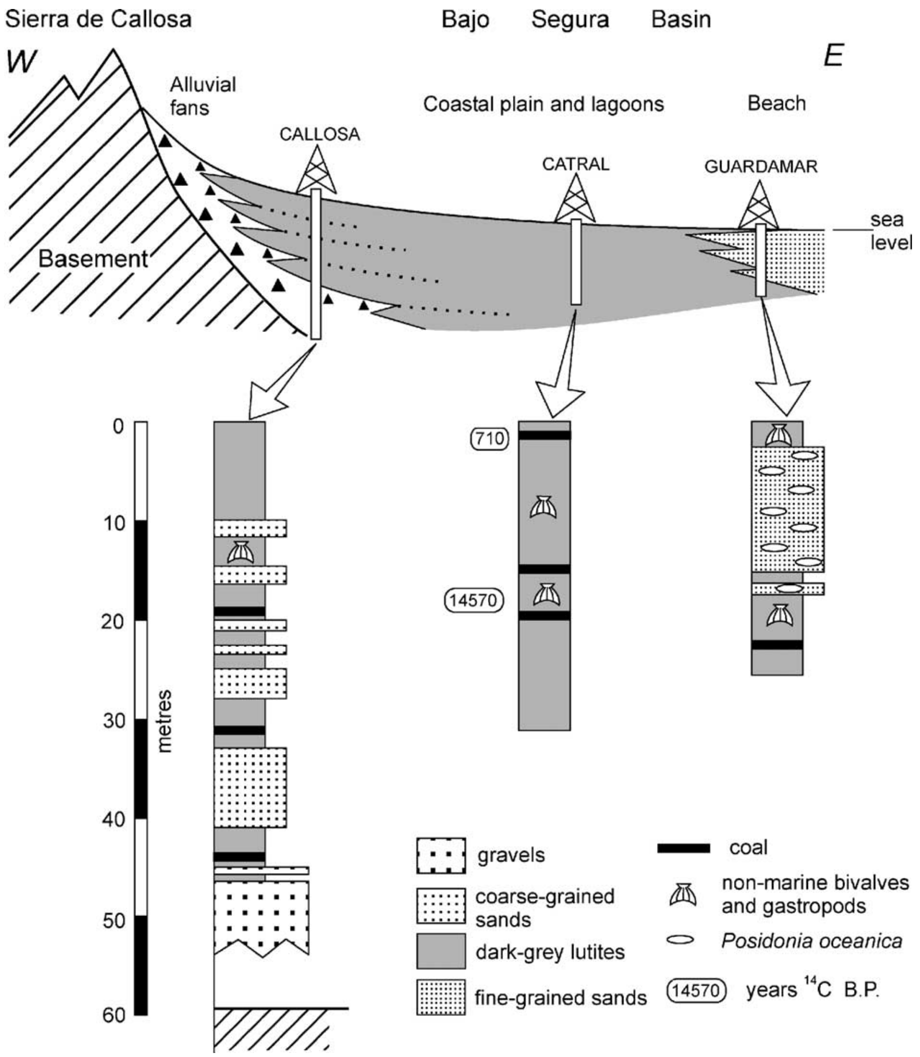

Fig. 5. Stratigraphic relationships of the fans of Group 3 and the flood-plain, lagoonal and coastal deposits of the Bajo Segura Basin. See Fig. 4 for location of the studied boreholes.

of the 22 fans). As indicated by these values, the fans in this group often have a "mushroom" plan-view morphology, with a narrow, elongated proximal area (mountain embayment) and a semicircular distal area (Fig. 6B, fans 20 and 22).

4.2. Longitudinal profiles

The highest average slope values of the longitudinal profiles of the fans are found in Group 1 (N Granada Basin), where four fans surpass the value of 0.20, even reaching 0.24 in the case of fan number 4. Group 2 fans (S Granada Basin) also have a steep slope, although the maximum is only 0.21 and only three of the fans surpass 0.20. Group 3 fans (Bajo Segura Basin) have considerably lower slopes; the highest is 0.12 and only 5 of the 22 fans surpass a slope of 0.10. The Granada Basin fans of Groups 1 and 2 have a longitudinal profile with a constant slope, with the sole exception of Fan 2 in Group 2, which has a concave profile (Fig. 7). In contrast, the Group 3 fans commonly have a profile that is clearly

Table 3
Maximum, minimum and mean values of the characteristic parameters for the three groups of fans and drainage basins

	Fa	Da	Fs	Ds	WLF	WLD	As	ICP
Group 1								
Maximum	0.630	1.762	0.24	0.58	2.17	1.07	118	–
Minimum	0.011	0.028	0.08	0.36	0.64	0.23	27	–
Mean	0.095	0.330	0.17	0.49	1.23	0.43	71	–
Group 2								
Maximum	3.059	1.663	0.21	0.80	1.14	0.53	88	40.0
Minimum	0.048	0.074	0.10	0.49	0.31	0.19	18	8.0
Mean	0.668	0.418	0.18	0.65	0.63	0.30	51	22.0
Group 3								
Maximum	1.875	2.126	0.12	0.88	1.20	1.08	178	80.4
Minimum	0.125	0.217	0.05	0.47	0.39	0.30	37	20.0
Mean	0.517	0.660	0.08	0.65	0.73	0.64	93	44.9

divisible into two segments, a proximal segment with a steeper slope and a distal segment with a much more gradual slope (Fig. 7).

4.3. Development of incised channels and depositional lobes

The development of incised channels in the fan apex, and consequently active depositional lobes, is another clear differential feature of the three groups of fans. For instance, whereas no fans from Group 1 have an incised channel, this feature is a very characteristic of the fans from the other two groups. Indeed, six of the nine fans from Group 2 have incised channels, with ICP mean value (incised channel percentage) of 22% (Table 3). In these cases, the maximum depth of the incised channels tends to be about 4 m.

In Group 3 fans, 17 of the 22 fans have incised channels, and in most cases, the ICP is near 50% (mean of 44%). Moreover, in this group, there is frequently more than one incised channel per fan (two or even three, which may or may not converge downfan) (Fig. 6). However, these channels are shallower, rarely exceeding 2 m in depth.

4.4. Development of headward-eroding gullies

Headward-eroding gullies are lacking in Group 1 fans, but do appear in medial parts of the fans of the other two groups, albeit with different characteristics (Figs. 3 and 6). Thus, such gullies are very well developed in the Group 2 fans, with the occurrence of channels incised up to 2 m deep in the alluvial sediments and a long trajectory over the fan surface. In Group 3 fans, however, the headward-eroding gullies are more incipient. Although they appear in 10 of the 22 fans of this group, they are short and rarely exceed 1 m in depth.

4.5. Sedimentary facies

Although the aim of this work is not to exhaustively analyse facies development (amply reported in the literature and the subject of ongoing research, Calvache et al., 1997; Soria et al., 1999; Viseras et al., 1999), we nevertheless wish to present certain data that confirm some of the great similarities among the three groups of fans.

Both the Granada Basin fans (Groups 1 and 2) and the Bajo Segura Basin fans (Group 3) show a clear evolution from debris-flow to sheet-flow dominated fans. This tendency seems to be a common feature in other alluvial systems in SE Spain (Harvey, 1984, 1990) and it has been explained as due to the combined effect of several factors, particularly of: (a) climate, initially more humid (during the Pleistocene), implying greater hillslope soil development, leading to slope failure and hillslope debris-flow activity and (b) aging of the catchments involving the progressive removal of soils (Harvey, 1984, 1990; Calvache et al., 1997; Viseras et al., 1999).

It is worth noting that, although in the three groups, the most recent alluvial sedimentation corresponds to sheet-flow dominated fans, the proportion of debris-flow in the sedimentation is much higher in the Bajo Segura Basin system than in the Granada Basin groups.

5. Morphology and morphometry of the drainage areas

5.1. Size, shape and drainage patterns

The size of the drainage areas is similar in the three systems, although slightly larger in Group 3 (maximum value of 2.13 km^2 compared to 1.76 and 1.66

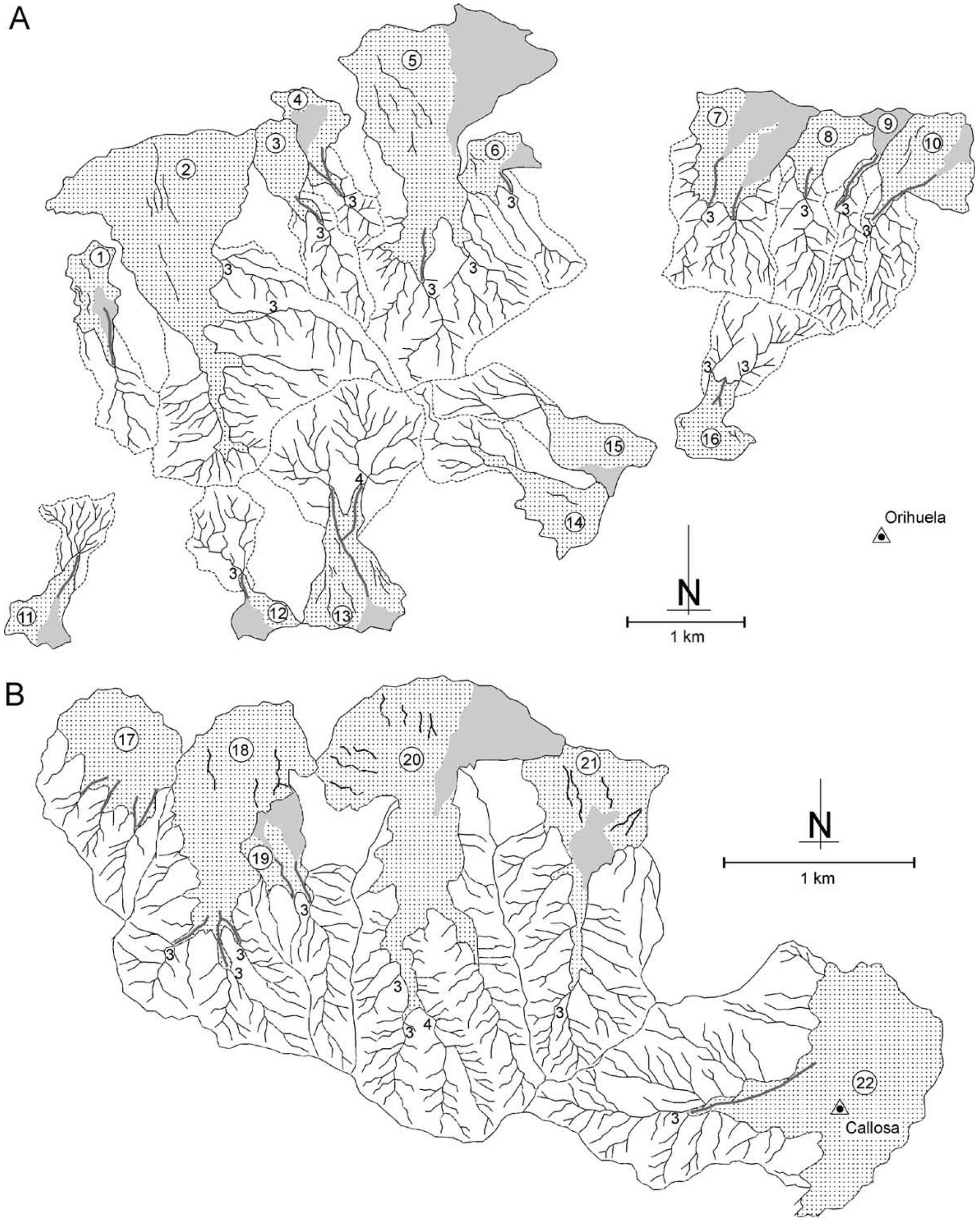

Fig. 6. Group 3 fans and their drainage basins. (A) Sierra de Orihuela and (B) Sierra de Callosa. See Fig. 4 for location and Fig. 3 for legend.

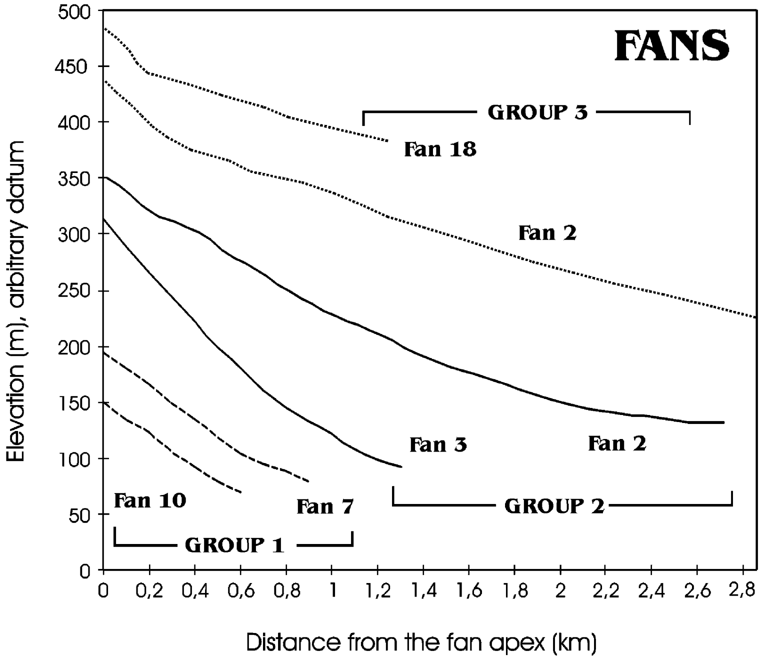

Fig. 7. Fan longitudinal profiles. Vertical exaggeration is 5.

km^2 for Groups 1 and 2, respectively, and minimum values of 0.22 km^2 compared to 0.03 and 0.07 km^2) (Table 3).

To quantify the shape of the catchments, we introduce the WLD parameter, which compares the width and length of the drainage basins, and thus provides us with certain useful characteristic patterns. A value of 1 corresponds to basins with equal width and length, whereas, values under 1 characterise basins that are more elongated than wide. The catchments of Groups

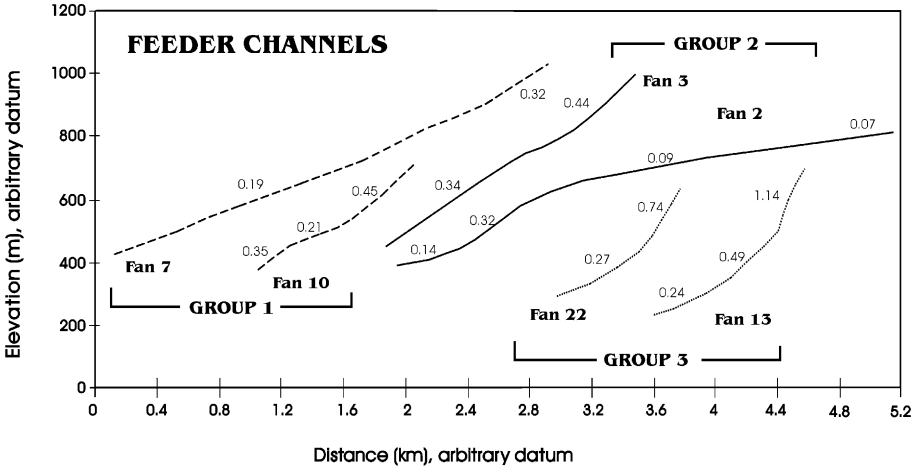

Fig. 8. Feeder channel long profiles above some of the fans. The slopes of the feeder segment are labeled. Vertical exaggeration is 5.

1 and 2 have relatively low WLD values (mean of 0.43 and 0.3, respectively) while the Group 3 basins are quite rounded (mean WLD of 0.64).

Backfilling of the fans into the drainage areas in Group 3 also alters the drainage pattern, producing feeder channels with a maximum of stream order 3 (according to the methodology of Strahler, 1957), and in many cases, no greater than order 2 (Fig. 6). Notwithstanding, the fans of the other two groups, with little invasion onto the basement rocks, show better-structured drainage networks. So, they reach order 4 in Group 1 (fan 7) and order 5 in Group 2 (fan 2) (Fig. 3).

5.2. Relief

The average slopes of the catchments are lowest in Group 1 (from 0.36 to 0.58), somewhat higher in Group 2 (up to 0.80) and highest in Group 3 (up to 0.88, Table 3), where escarpments are a common feature in the Orihuela and Callosa Sierras.

Fig. 8 presents the profiles of the feeder channels for some of the fans from the three groups. Groups 1 and 2 show stepped slopes, resulting from faults whose recent activity has modified the feeder-channel profiles. Fan 13 in Group 3 also shows slope discontinuities, although due, in this case, to a lithological contact between two carbonate sets with different degrees of compaction.

The slope of the feeder channels of the fans in Group 3 is steeper than in the other two groups. Particularly, noteworthy is the feeder-channel to Fan 13, which reaches a slope gradient of 1.14, quite outstanding in comparison to those of the feeder channels of Groups 1 and 2, which range from 0.07 to 0.45 (Fig. 8).

6. Alluvial fan–drainage basin relations

6.1. Drainage area (Da) versus fan area (Fa)

There is a high correlation between the drainage area (Da) and the fan area (Fa) in the three groups analysed, as evidenced by the high correlation coefficients (R) obtained (0.98, 0.91 and 0.84 for Groups 1, 2 and 3, respectively). As shown in Fig. 9, each group of fans fits a potential function whose equation is given in the graph ($Fa = xDa^{e}$). The Da exponent is interesting because its values range from 0.7 to 1.1,

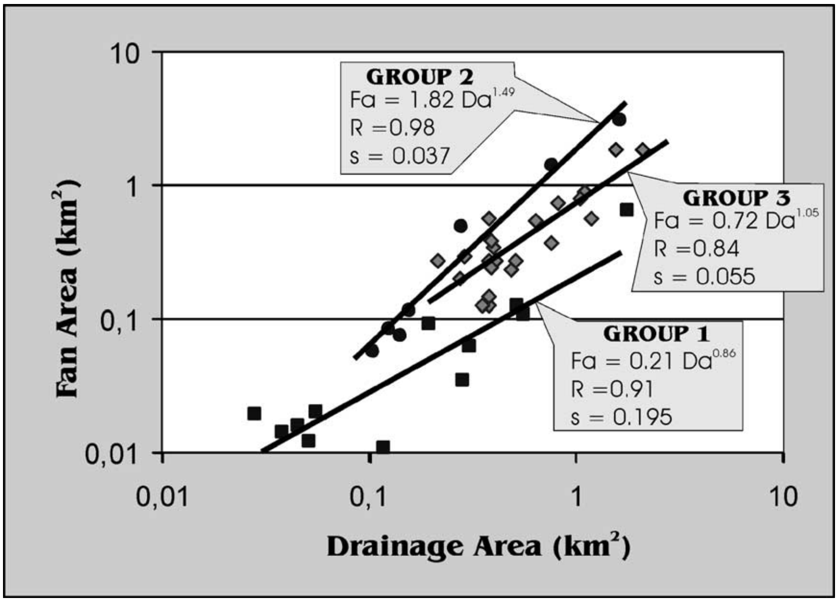

Fig. 9. Drainage basin area (Da) versus fan area (Fa) log–log plot for the three groups of fans. s—Standard error.

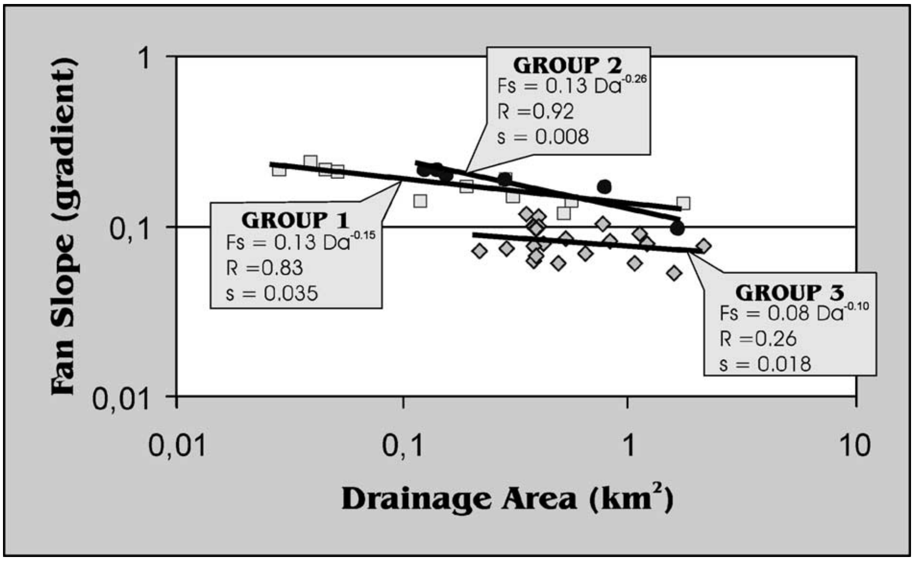

Fig. 10. Drainage basin area versus average fan slope log–log plot for the three groups of fans. Note the low coefficient correlation in the regression line corresponding to Group 3. *s*—Standard error.

depending on the particular conditions of each group of fans described in the literature. The Group 1 fans have an exponent of 0.86, which is close to the lower limit of the examples described by Harvey (1990). That is, these fans increase little in extension when the drainage area increases. At the other extreme, the Group 2 fans have an exponent of 1.49, which surpasses the upper limit reported in previous works (Harvey, 1990), meaning that these fans undergo a unusually high increase in fan area when their drainage area increases. In the Group 3 fans, the Da exponent is intermediate (1.06), although this is still steep compared to other examples described in the literature (Harvey, 1990).

As with the Da exponent, the intercept values (x) are also at minimum in Group 1 (0.21), at maximum in Group 2 (1.82) and intermediate in Group 3 (0.72). These values indicate that the Group 1 fans are smaller in relation to their drainage basins than the Group 3 fans and much smaller than the Group 2 fans. These differences in fan size among the three groups become more marked as the catchment sizes increase.

6.2. Drainage area (Da) versus fan slope (Fs)

In the drainage area (Da) versus the fan slope (Fs) relationship, the most noteworthy result is that, while the Groups 1 and 2 fans have a high correlation between these two parameters according the potential function $\mathrm{Fs}=m\mathrm{Da}^{e}$ (correlation coefficients of 0.83 and 0.94, respectively), the Group 3 fans show a complete lack of relation between these two parameters (correlation coefficient of 0.27) (Fig. 10). In Group 1, the exponent is quite high (-0.15), at the upper limit of the exponents reported by other authors (-0.15 to -0.35; Bull, 1962; Hooke, 1967; Harvey, 1988; Silva et al., 1992). This value indicates that the slope of these fans decreases little in relation to an increase in their catchment areas. The Group 2 fans, however, have an intermediate exponent value (-0.26) compared to the examples described in the literature.

7. Discussion: mechanisms of accommodation and characterisation of fans

The three groups of fans chosen have a series of common features, such as their age (late Pleistocene–Holocene), the lithology of the drainage areas (partially metamorphosed Triassic carbonates, and in the case of Groups 1 and 2, locally intensely fractured) and climate (identical for Groups 1 and 2, which are adjacent and somewhat more arid for Group 3).

Nonetheless, there is a substantial difference in the geological context of the three groups, that is, the role of eustasy and tectonics in the creation of accommodation space. So, as for the other examples in SE Spain, morphometric differences between fans reflect differing tectonic contexts (Silva et al,. 1992) or base level conditions (Harvey et al., 1999a).

The Group 1 fans developed in a context of high tectonic subsidence due to the intense active tectonics of this sector of the Padul Fault, which registers vertical movement rates of several millimeters per year (Sanz de Galdeano and López Garrido, 1999). This tectonism is related to uplift the Sierra Nevada during the Quaternary, which caused marked relative displacements in this area, as deduced by both digital elevation models (Riley and Moore, 1993) and two-dimensional gravity models (Alfaro et al., 2001). This high tectonic subsidence is also responsible for the record of high sedimentation rates in the peat bog distally interfingered with the fans (sometimes exceeding 5 mm/year in the last 30,000 years, according to the data of Domingo et al., 1983).

Geological field data (Santanach et al., 1980; Sanz de Galdeano, 1996; Calvache et al., 1997) and gravimetric studies (Alfaro et al., 2001) show evidence that the Group 2 fans abut a sector of the Padul Fault that has undergone less vertical throw during the development of the fans, even though this so-called "moderate" tectonic subsidence is the fundamental mechanism for the creation of accommodation space allowing alluvial aggradation.

In contrast, tectonic subsidence is very weak in Group 3 fans, with vertical movement rates of 0.1–0.5 mm/year during the Quaternary (Alfaro, 1995). However, this alluvial system is directly connected with a coastal-plain and lagoonal system in contact with the Mediterranean, which underwent a significant sea-level rise during the Holocene (Dubar and Anthony, 1995; Hernández Molina et al., 1994; Weaver and Pujol, 1988). Soria et al. (1999) have carried out a detailed calculation of the sedimentation rates during the Holocene on the flood-plain material distally related with the fans of this group, concluding that in the last 8000 years, the rates have ranged from 3.7 to 1.9 mm/year. Therefore, the weak tectonic subsidence, the demonstrated sea-level rise, the high sedimentation rate and the retrograding stacking pattern of the alluvial deposits in relation with the coastal-plain and lagoonal deposits lead to the conclusion that the rise of the marine base level is the main mechanism influencing the creation of accommodation for the Quaternary alluvial sedimentation in the Bajo Segura Basin. As mentioned above, these fans are low altitude, close to the sea and have undergone a recent sharp eustatic rise. Therefore, the generation of accommodation space affects not only the beach, lagoonal and coastal-plain environments, but also the most proximal parts of the alluvial fans. As a consequence, the fans onlap a tectonically inactive basement.

In short, the dynamics of the creation of accommodation space is different for each of the three groups analysed, which implies a distinct stratigraphic base level in each case during the late Pleistocene–Holocene which in turn, affects the surface morphology of the fans. Therefore, below we lay out a series of characteristic patterns in the parametric and non-parametric data of the fans and their drainage areas accountable, at least in part, to the specific accommodation dynamics of each (Table 4, Fig. 11).

The plan-view morphology is one of the features that is most clearly controlled by the accommodation dynamics. In a context of high tectonic subsidence, for instance, aggradation is favoured. At the same time that the topographic changes produced in the basin margin by alluvial accumulation (filling the slope between the mountain front and the sedimentary basin) are compensated by marginward tilting (Fig. 11A). Thus, aggradation is favoured, as well as the lateral migration of the channels descending the fans (Viseras and Fernández, 1994, 1995), giving rise to the development of shorter fans, with a high sweep angle and a high width/length ratio. Moreover, the fan apex undergoes no upward or downward movement.

When the tectonic subsidence is lower, the areal distribution of the sediment is favoured. The change in slope at the bottom of the basin generated by the alluvial sedimentation is not replaced as quickly as in the above case. Therefore, sedimentation on the fan margins (where the slope is very steep and lateral migration of the channels is more difficult) happens more rarely. The result is longer fans with a low sweep angle and a low WLF.

Finally, in the absence of tectonic subsidence and the creation of accommodation by a rise in the base level, the fan apex is not forced to remain in the same position (the tectonic margin of the basin), but can

Table 4
Differential features of alluvial fans when accommodation is created by high tectonic subsidence, low tectonic subsidence or base level rise

Fans	Accom. Dynamics	WLF	As	Plan-view Morph.	IC		Headward Eroding Gullies	Longitudinal Profiles		Feeder Channel Order	Cs	Da *vs* Fa			Da *vs* Fs			Debris Flows/Sheet Flows	Stratigraphic Stacking Pattern
					ICP	Depth		Geometry	Grad.			R	e	x	R	e	x		
GROUP 1	**High Tectonic Subsidence**	> 1	> 50°	Open Fans	Non-existent		Non-existent	Constant Slope	0.17	≤ 4	Low 0.19-0.45	Very high 0.98	0.86 Small fans	0.21	High 0.83	-0.15 Very steep fans	0.13	1 : 4	Aggradation
GROUP 2	**Low Tectonic Subsidence**	< 1	≤ 50°	Closed Fans	Frequent 15-25%	≤ 4 m	Common Long and deep (≤ 2 m)	Constant Slope or Concave	0.18	≤ 5	Low 0.07-0.51	Very high 0.91	1.49 Very large fans	1.82	Very high 0.94	-0.26 Interm. gradient	0.13	1 : 4	Progradation (+ Aggradation)
GROUP 3	**Base Level Rise**	< 1	> 60°	Mushroom	Very frequent 35-65%	≤ 2 m	Occasional Short and shallow (≤ 1 m)	Segmented	0.08	≤ 3	High 0.24-1.14	High 0.84	1.05 Large fans	0.72	Low 0.26	-0.10 Gently sloping fans	0.08	2 : 3	Retrogradation

See text and Fig. 11.

WLF, ratio width/length of the fan. As, sweep angle. IC, incised channel. ICP, incised channel percentage. Cs, feeder channel slope. Da, drainage basin area. Fa, fan area. Fs, fan slope.

move towards the source area producing a mountain embayment (Blair and McPherson, 1994). This circumstance generates a low WLF; however, contrary to the above cases, when the fan enters the sedimentary basin, it expands producing high As values and the peculiar "mushroom" fan shape.

The presence of an incised channel or fan-head trench is considered by other authors to be a sign of maturity (Blair and McPherson, 1994; Blair, 1999). In our case, however, we have noted an almost perfect inverse relation with the rate of tectonic subsidence. That is, fans abutting a constantly rising margin (such as the Group 1 fans, N Granada Basin) maintain for a prolonged time the typical characteristics of early development stages, such as the absence of an incised channel. This feature is more frequent in fans subjected to less subsidence (Group 2, S Granada Basin), which might be considered more mature, and is a very characteristic feature of systems completely lacking in tectonic subsidence (Group 3, Bajo Segura Basin). In the latter case, the topographic differences between the fan and the source area are constantly been leveled, developing incised channels that can be even longer than half the radius of the fan. Once again, the backfilling of the Group 3 fans causes the present alluvial sedimentation to occur over positions formerly belonging to the source area. Thus, these fans often have more than one feeder channel, and consequently, more than one incised channel.

Another effect directly derived from mountain front backfilling is the decreasing order of the feeder channels. The reason is very simple: the old, higher order feeder channel has been occupied by alluvial aggradation and the fan is now directly connected with lower order channels. The concentration of sedimentation in lobes developing distally from the intersection point is a direct consequence of the presence of the incised channel. This type of sedimentation is concentrated in small sections of the fan and implies the existence of prolonged periods with no sedimentation over a wide sector of the alluvial surface. Headward-eroding gullies develop in this sector which is something that occurs extremely rare in systems with high tectonic subsidence. A rising base level hinders the vertical entrenchment both of the incised channel and of the eroding gullies of the Group 3 fans, where these features are characteristically shallower than in fans with low subsidence (Group 2).

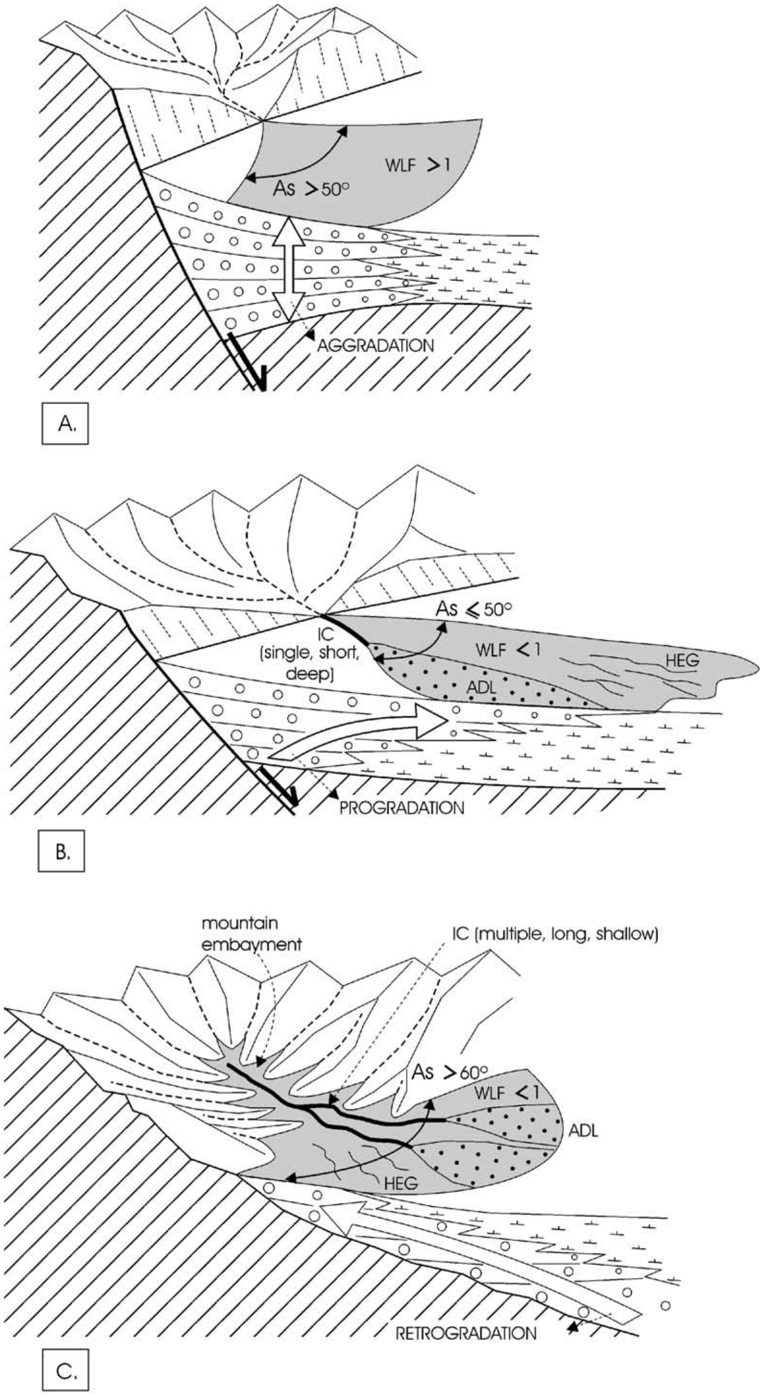

Fig. 11. Stratigraphic stacking patterns, fan morphologies and morphometries of alluvial sediments when accommodation is created by (A) high tectonic subsidence, (B) low tectonic subsidence and (C) base level rise. IC, incised channel. ADL, active depositional lobe. HEG, headward-eroding gullies. As, Sweep angle. WLF, ratio width/length of the fan.

Analysis of the relation between the areas of the fans and their catchments (Da versus Fa) yields some significant considerations in that the three cases have a high correlation and different functions. Comparing the two groups of fans controlled by tectonics (1 and 2), it can be seen that those in a context of higher subsidence are comparatively smaller in relation to their drainage areas than those with low subsidence. We therefore agree with Ferrill et al. (1996), who concluded that in tectonically active mountain fronts where the mountains are rising with respect to the adjacent basin, alluvial fans tend to aggradate vertically, resulting in fans of relatively small area (but greater thickness) with respect to their drainage area. In our examples, another factor favouring the development of extraordinarily large fans in the Granada Basin is the intense fracturing of the dolostone in some sectors of the source area (Calvache et al., 1997). This circumstance, absent in the Bajo Segura Basin, results in huge volumes of sediment supply in the Group 2 fans (S Granada Basin), which become (compared to their drainage areas) even larger than the Group 3 fans (Bajo Segura Basin), where tectonic subsidence is very weak (always less than 0.5 mm/year and in certain periods closer to 0.1 mm/year).

In systems controlled primarily by tectonics (Groups 1 and 2), the longitudinal fan profiles have a constant or even concave slope. In the case of Group 1, the rapid uplift of the mountain front may have contributed to the steep slope of the fans as compared to the extent of their catchments. A constant sinking of the depositional surface would occur, maintaining a sharp topographic relief on the basin margin that would be occupied by steeply sloping sediments (Calvache et al., 1997). The segmented profile characteristic of the fans in Group 3 can be explained by the constant change that the rising base level produces in the stratigraphic base level, which is progressively transmitted from the most distal area of the fans (which has a lower gradient) up to the apex (with a steeper gradient). We therefore agree with Bull (1964) in attributing this type of profile to changes in the base level of the fans. The absence of a relationship between the slope of the fans and their corresponding drainage areas in Group 3 is due, once again, to the development of the mountain embayment characteristic of these fans. Thus, in fans with this feature, the entire embayment comprises a proximal fan sub-environment. Primarily, debris-flows are deposited in this sub-environment, thus, producing an extensive steep slope in the embayment. Therefore, the extent of the embayment is obviously an important factor affecting the total fan slope.

Finally, the greater proportion of debris-flow as compared to sheet-flow deposits in the Group 3 fans believe to be related to the higher average slope of the catchments in this group, to the presence of small outcrops of slates intercalated with the basement carbonates and to the existence of sectors with a gradual slope within the feeder channels of the fans in Groups 1 and 2. Moreover, as we have shown, the latter act as traps for high-density flows which, thus, have greater difficulty in reaching the fans. These “steps” in the feeder channels are the result of a long history of mountain-front uplift (Riley and Moore, 1993; Sanz de Galdeano, 1996; Sanz de Galdeano and López Garrido, 1999; Alfaro et al., 2001), such that faults with recent activity crosscut and divide ancient profiles of the feeder channels.

8. Conclusions

The analysis of a total of 43 alluvial fans and their drainage basins has demonstrated the important role of creation mechanisms of accommodation space on alluvial fan development. We have been able to determine a series of characteristic patterns in quantitative and qualitative variables with respect to the morphology, morphometry, stratigraphic architecture and sedimentology of alluvial fans that are summarised below (Table 4, Fig. 11).

Fans that have developed at tectonically very active mountain fronts, where the mountains are rising with respect to the adjacent basin at a rate of several millimeters per year, tend to aggradate vertically. They develop plan-view morphologies of an open fan, with a width/length ratio of above 1 and a sweep angle of over 50°. The size of these fans increases little when their drainage areas increase (exponent of 0.86). Moreover, the fan slopes decrease little when the catchment area increases (exponent of -0.15). They have a longitudinal profile with a constant steep slope (mean of 0.17) and do not develop incised channels or headward-eroding gullies.

When the main creation mechanism of accommodation space is also tectonic subsidence, but the sinking of the basin with respect to the mountain front is much more moderate (on the order of 1 mm/year), the resulting fans are closed, with a sweep angle of $\leq 50°$ and a width/length ratio of < 1. In these circumstances, the dominant stratigraphic stacking pattern is progradation, with very extensive fans in relation to their drainage areas (intercept value of 1.82). The fans increase abnormally in area when their drainage areas increase (exponent of 1.49) and their slopes decrease more than in the above case (exponent of -0.26). They often develop a single, quite deep incised channel (up to 4 m), with a length around 22% of the fan radius with the sediment distributed, thence, in a depositional lobe. The temporarily inactive sectors of the fan are occupied by long, deep (up to 2 m) headward-eroding gullies.

In the case of fans created in a context of very weak tectonic subsidence and where the main creation mechanism of accommodation space is base level rise, the principal result is retrogradation of the alluvial system, which backfills into the catchments with a pronounced mountain embayment, developing a characteristic "mushroom-shaped" plan-view. That is, there is a low width/length ratio (< 1), yet the fans are very open in the sedimentary basin (sweep angle $>60°$). The backfilling of the mountain front triggers another series of circumstances, such as the reduction in size of the feeder channels (rarely surpassing order 3). Although the incised channel is a very characteristic feature of these fans, it differs from the previous case in that there are commonly several incised channels in the same fan. These channels are usually quite long (normally near 50% of the fan radius) and shallow (rarely surpassing 2 m). Occasionally, short and shallow (≤ 1 m) headward-eroding gullies occur as well. The fans increase considerably when their drainage areas increase (exponent of 1.05) and typically show a segmented longitudinal profile with a low slope (average of 0.08).

Acknowledgements

Financial support was provided by Research Projects PB 97-0808, REN2000-1377, BTE2000-0339 DGESIC, BTE2001-2872 and Research Groups RNM-163 and RNM-189. A.M. Harvey, M. Stokes and G. Nichols are thanked for their valuable suggestions that substantially improved the manuscript. Christine Laurin is responsible for the English translation of the text.

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