

Soil-landscape and climatic relationships in the middle Miocene of the Madrid Basin

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ABSTRACT

The Miocene alluvial-lacustrine sequences of the Madrid Basin, Spain, formed in highly varied landscapes. The presence of various types of palaeosols allows assessment of the effects of local and external factors on sedimentation, pedogenesis and geomorphological development. In the northern, more arid, tectonically active area, soils were weakly developed in aggrading alluvial fans, dominated by mass flows, reflecting high sedimentation rates. In more distal parts of the fans and in playa lakes calcretes and dolocretes developed; the former were associated with Mg-poor fan sediments while the latter formed on Mg-rich lake clays exposed during minor lake lowstands.

The non-east part of the basin had a less arid climate. Alluvial fans in this area were dominated by stream flood deposits, sourced by carbonate terrains. Floodplain and freshwater lake deposits formed in distal areas. The high local supply of calcium carbonate may have contributed to the preferential development of calcretes on the fans. Both the fan and flood plain palaeosols exhibit pedofacies relationships and more mature soils developed in settings more distant from the sediment sources. Palaeosols also developed on pond and lake margin carbonates, and led to the formation of palustrine limestones.

The spatial distributions and stratigraphies of palaeosols in the Madrid Basin alluvial fans suggest that soil formation was controlled by local factors. These palaeosols differ from those seen in Quaternary fans, which are characterized by climatically induced periods of stability and instability.

INTRODUCTION

Soils are integral parts of landscapes and are highly sensitive to changes in that landscape. Fossil soils (palaeosols) can provide information on palaeolandscapes and integrating analyses of palaeosols and facies can provide new insights into the geomorphology of ancient deposystems. Recently, several studies of palaeosols in alluvial and deltaic sequences have recognized specific geomorphologically controlled catenary (slope/drainage) and pedofacies relationships (e.g. Brown & Kraus, 1987; Besly & Fielding, 1989; Smith, 1990), and in this paper we attempt to look at palaeosol/palaeolandscapes relationships on a large scale.

The middle Miocene of the Madrid Basin, Spain, consists of a well-exposed alluvial and lacustrine

sequence which developed in varied landscapes of two distinct geomorphological regions, each with different bedrock geology, tectonic setting, topography and climate.

In this paper we relate the varied suite of palaeosols, especially their mineralogies and maturities, to their positions within the Miocene landscapes. In doing so it is possible to assess the relative roles of local factors versus extrinsic ones, such as climatic change, in controlling the broader-scale distributions and sequences of palaeosols in the fan deposits.

GEOLOGICAL FRAMEWORK

The Madrid Basin forms the major part of the Tajo Basin, one of three large continental basins which

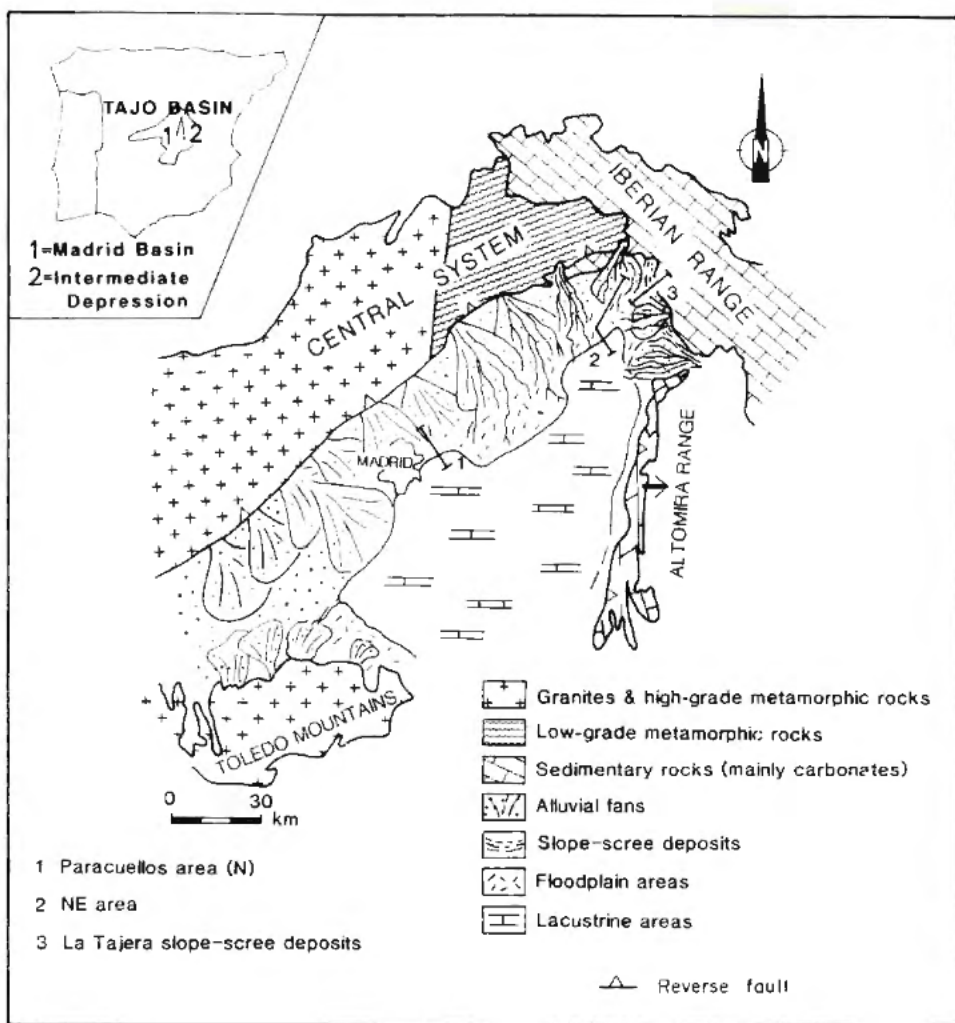


Fig. 1. Location of the Madrid Basin (inset) and schematic representation of depositional systems during the deposition of the Miocene Intermediate Unit. 1-3 are the study areas: 1=northern area; 2=alluvial fan floodplain area in the north east area; 3=slope deposits, north east area (La Tajera).

developed in the Iberian Peninsula during the Tertiary (Fig. 1). The basin is bounded by different types of fault systems which were active during compressive alpine movements. High-angle reverse faults were active from the Palaeogene to the middle Miocene at the northern margin of the basin; the southern and north eastern borders were, in general, characterized by Jessactive normal faulting; the faults on the eastern margin of the basin (Altomira Range) were only active during late Palaeogene and early Miocene times (Calvo *et al.*, 1989; De Vicente *et al.*, 1990).

These fault systems separated the basin from adjacent upland source areas, which were lithologically highly varied (Fig. 1). Granites and highgrade metamorphic rocks formed the area of high relief (the Central System, Sistema Central) in the north. Low-grade metamorphic rocks and sedimentary rocks formed lower relief margins in the easternmost part of the Central System (Somosierra) and the Iberian Range respectively. Sedimentary rocks (mainly Jurassic-Cretaceous carbonates) were exposed in the eastern part of the basin (Iberian and Altomira

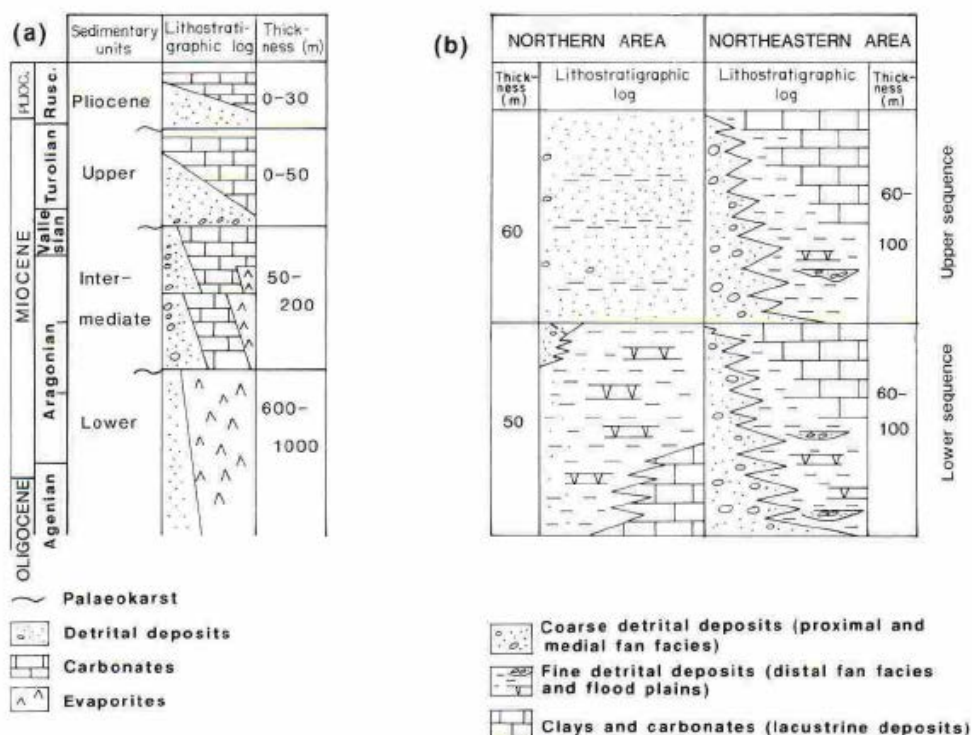


Fig. 2. (a) Stratigraphy of the Neogene sequence in the Madrid Basin. (b) Stratigraphy of the Intermediate Unit in the Madrid Basin contrasting the sequences in the north and north-eastern areas.

ranges). The Toledo Mountains to the south are composed mainly of granites and high-grade metamorphic rocks.

The Tertiary fill of the Madrid Basin comprises more than 3500 m of continental deposits which have been recognized from deep boreholes as well as from seismic profiles (Junco & Calvo, 1983; Megias *et al.*, 1983; Racero, 1988). In this continental sequence Neogene deposits include (Fig. 2):

(a) an early Miocene, mainly evaporite sequence (600-1000 m thick) with theardite, glauberite, halite, anhydrite and gypsum. These deposits have been assigned to the Miocene Lower Unit of the Madrid Basin (Garcia del Cura *et al.*, 1979, 1986). They range from Agenian to middle Aragonian in age (Aquitania-Burdigalian) (Fig. 2a);

(b) a middle Miocene unit consisting of clastic, carbonate and evaporite deposits, up to 200 m thick (Fig. 2b). These deposits are included in the Miocene Intermediate Unit (Junco & Calvo, 1983; Alberdi *et al.*, 1983) and are middle Aragonian to early Vallesian (Langhian to early Tortonian) in age (Fig. 2a);

(c) a late Miocene clastic and carbonate sequence overlying the Intermediate Unit, referred to as the Miocene Upper Unit. It is up to 50 m in thickness and has been considered to be of early Vallesian to late Turolian (Late Tortonian to Messinian) in age (Fig. 2a);

(d) the Pliocene sequence of continental clastics and carbonates forms the final fill of the basin.

These units have erosive and/or karstic boundaries

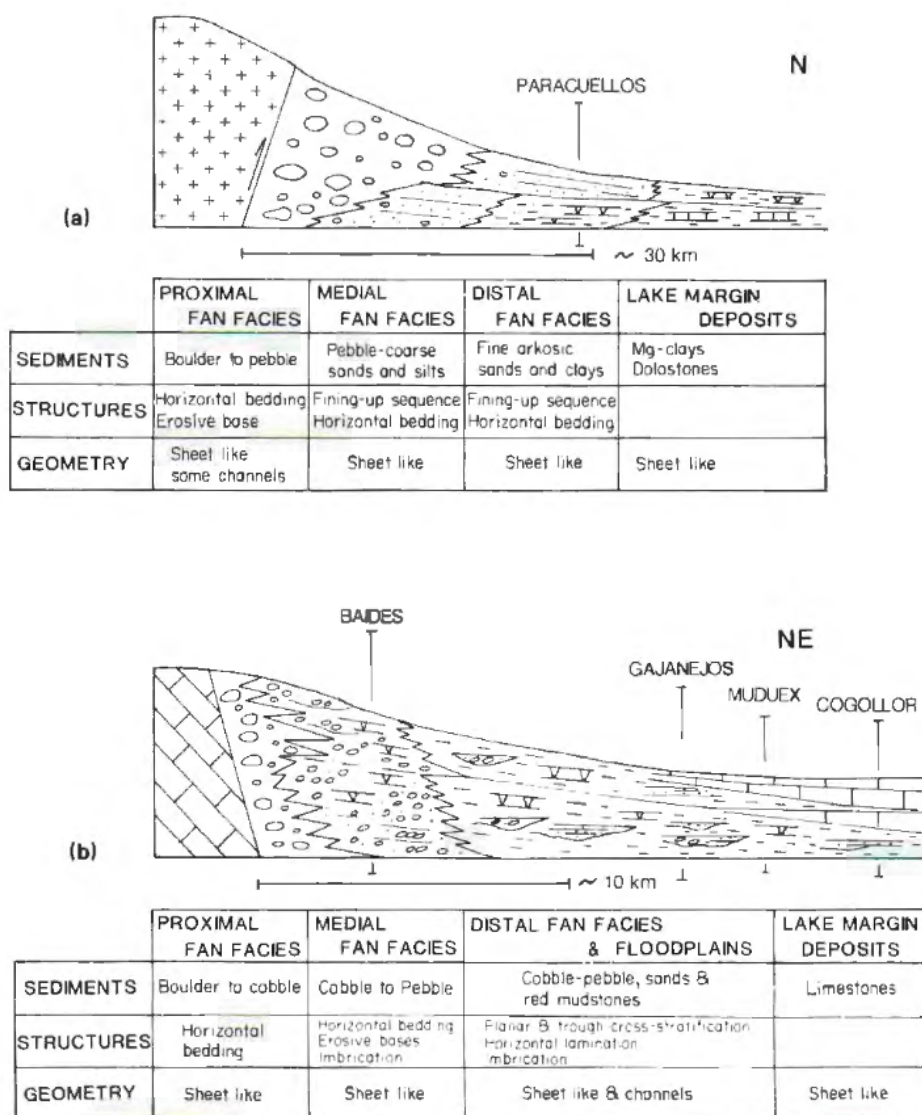


Fig. 3 Longitudinal schematic facies transects contrasting the north (a) and north-eastern (b) areas, illustrating the relationships between the alluvial fan and lacustrine deposits. Sedimentological logs from the marked localities are given in Fig. 4.

(Ordoñez *et al.*, 1985) and relate to tectonic activity in the basin (Megias, 1982).

The Miocene Intermediate Unit, which includes the palaeosols discussed in this paper, shows a great variety of lithofacies within the basin. Two contrasting areas are described in this paper, each displaying different assemblages of palaeosols. These areas are the northern part of the basin located around Madrid

(area 1 on Fig. 1) and the north-eastern area (areas 2 & 3 on Fig. 1).

Northern region

Miocene clastic deposits in the northern area extend south-west and north-west of Madrid (Fig. 1), and the thickness of the Intermediate Unit reaches 110 m.

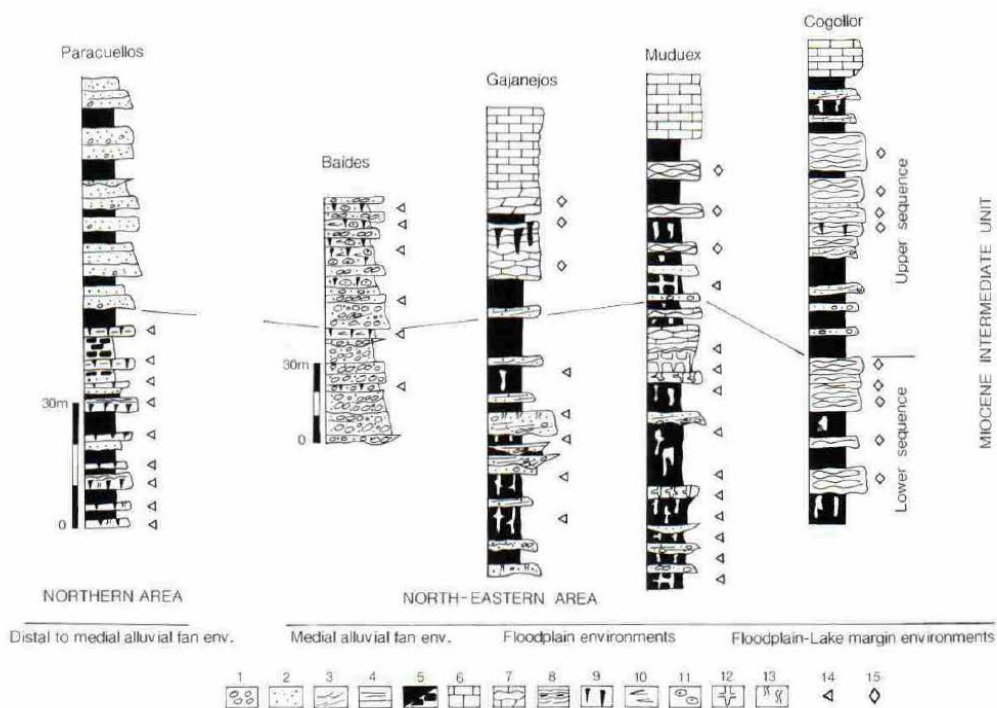


Fig. 4. Sedimentary logs of the Intermediate Unit showing general environmental interpretations and possible correlations: 1 = conglomerates, 2 = sandstones, 3 = crossstratification (planar & trough), 4 = planar lamination, 5 = clays including sepiolite, 6 = massive (lacustrine) limestones, 7 = nodular and mottled limestones, 8 = platy structure, 9 = prismatic structure, 10 = desiccation cracks, 11 = coated sands, 12 = red mottled clays & marls, 13 = bioturbation, 14 = calcrete-dolomite, 15 = palustrine limestone. The scale for Gajanejos, Muduej and Cogollor is the same as for the Bajades section.

They were sourced from granitic and high-grade metamorphic rocks of the Central System. Several reverse fault systems defined the boundary between the source areas and the basin (Calvo *et al.*, 1989). Well-developed alluvial fans spread from these fault-bounded uplands for more than 30 km into the basin. Although the fan systems have not been studied in detail, they are dominated by arkosic deposits showing a typical decrease in grain size towards more distal areas, ranging from granitoid and quartz boulders and pebbles at the apices, to coarse arkosic sands interbedded with silty clays in medial fan settings (Fig. 3a). The more proximal facies are dominated by mass flow deposits (Alonso *et al.*, 1986; I.G.M.E., 1989), extending, surprisingly, for many kilometres from the mountain front. Distal facies are well represented in the Paracuellos de Jarama area (Figs 1, 3 & 4) where

the lowest part of the sequence comprises brown clays (with trioctahedral and dioctahedral smectites and sepiolite), calcrete beds (locally silicified) and fine arkosic sands (Alonso *et al.*, 1986). This sequence grades laterally into lake margin deposits (Calvo *et al.*, 1989), here composed of green Mg-smectite-rich clays, palustrine nodular dolostones and, locally, sepiolite beds. However, coarse arkosic sands in the middle part of the Paracuellos sequence represent a phase of fan progradation (Figs 2b & 4). In contrast to the north-eastern area, no alluvial deposits have been recognized between the alluvial fan deposits and the lacustrine sequences. Calcretes apparently formed on a narrow fan fringe, about 1-1.5 km wide, between the fan and the nearby lake margin (Calvo *et al.*, 1989).

In general, the proximal fan deposits are much

more prominent than in the north-east, particularly near the faulted margin with the Central System. These proximal deposits Jack calcretes while the interbedded clays contain illite and dioctahedral smectites.

The general climate of the time was probably semi-arid or arid. In the lake deposits there is evidence of low lake levels, desiccation and moderately alkaline waters (Calvo *et al.*, 1989). The dominance of debris flow deposits in the fan sequences also supports the idea of low surface runoff with high sediment to water ratios.

Northern-eastern region

The architecture of the Miocene deposits along the north-eastern margin of the basin is rather different (Alonso-Zarza, 1989) (Fig. 3b). Small alluvial fans, which extended a maximum distance of 10 km into the basin, were derived from the uplands of the Iberian Range and locally from the eastern part of the Central System (Fig. 1). These were topographically confined, non-entrenched fans, which were fed mainly from carbonate and low-grade metamorphic terrains. In general, less active fault systems bounded the basins in this area (De Vicente *et al.*, 1990).

The relief was probably lower in this area as indicated by the fact that at present, the mountains of the Iberian ranges reach 1250 m, compared to 2400 m in the Central System. The climate was also different; the associated lake deposits in the north-east indicate a freshwater system, with fluctuating but non-evaporitic margins (Calvo *et al.*, 1989). This is in contrast to the saline-alkaline lake deposits of the northern area, where runoff must have been less than in the north-east.

Nearly 100 m of proximal and medial alluvial fan deposits crop out near the basin margins. These deposits consist of laterally extensive gravel sheets, with interbedded calcretes arranged in two fining-thinning upward sequences. The coarse conglomerates grade to red mudstones with interbedded sand and gravel-filled channels. These facies form the distal fan deposits and are crudely similar to the fluvial deposits formed on wide floodplains. Within the Intermediate Unit are two depositional sequences (Fig. 2b), each quite different in style to those seen in the northern area (Fig. 2). Both of these sedimentary sequences show clastic deposits at the base and lacustrine-lacustrine limestones, with a freshwater biota, at the top. The Intermediate Unit in these areas can reach 200 m in thickness. The clays in alluvial, fluvial and

lacustrine deposits are mainly illitic (Calvo *et al.*, 1989).

The north-eastern area is distinctly different from the northern area in several regards. The alluvial fans in the north extended much further downslope than those in the north-east. The latter fans occupied a small area, show more marked proximal-distal trends and were dominated by stream processes and not by debris flows (Alonso Zarza *et al.*, 1992).

In summary, the two areas clearly differed in source area geology, tectonics, relief and climate (and presumably sediment supply). Not unsurprisingly, the types of palaeosols to be found also differ and these differences reflect the contrasting geological and geomorphological settings.

PALAEOSOLS IN THE MADRID BASIN

Palaeosols in the northern area

Two palaeosol types can be recognized in the northern area: (i) reddened clays associated with alluvial fans, and (ii) calcretes associated with distal, sand-grade deposits and lacustrine clays. The former occur on the tops of arkosic sands, deposited in the medial fan deposits, and consist simply of reddened clays which show desiccation cracks and minor manganese oxide staining. These palaeosols, classified as entisols (Soil Survey Staff, 1975), are laterally very extensive, traceable for hundreds of metres and have an average thickness of about 0.5 m.

The calcretes are best developed at Paracuellos (3°31'46" W, 40°28'50" N), in the lower part of the Intermediate Unit (Fig. 4), where there is 10 m of stacked calcretes. Those in the lower part of the sequence (Figs 5 & 6, Paracuellos A) developed on bioturbated and rooted clays formed of smectites (tri- and dioctahedral), and minor illite and analcime. The individual, mainly carbonate profiles average 1.2 m in thickness and are mainly dolomite. They consist of a lower prismatic or nodular horizon, 0.2–0.8 m thick, and an upper platy horizon up to 0.4 m thick. The platy horizon is not always present. These carbonates (dolocretes in the sense of Netterberg, 1980) contain typical calcrete textures such as irregular spar-filled cracks (including circumgranular cracks), floating detrital grains, dense crystalline matrices and etched silicate grains (Alonso *et al.*, 1986). The platy horizons have a distinctive microfabric with thin contorted dolomicrite veins (up to 100 µm wide), coated by fine to medium crystalline

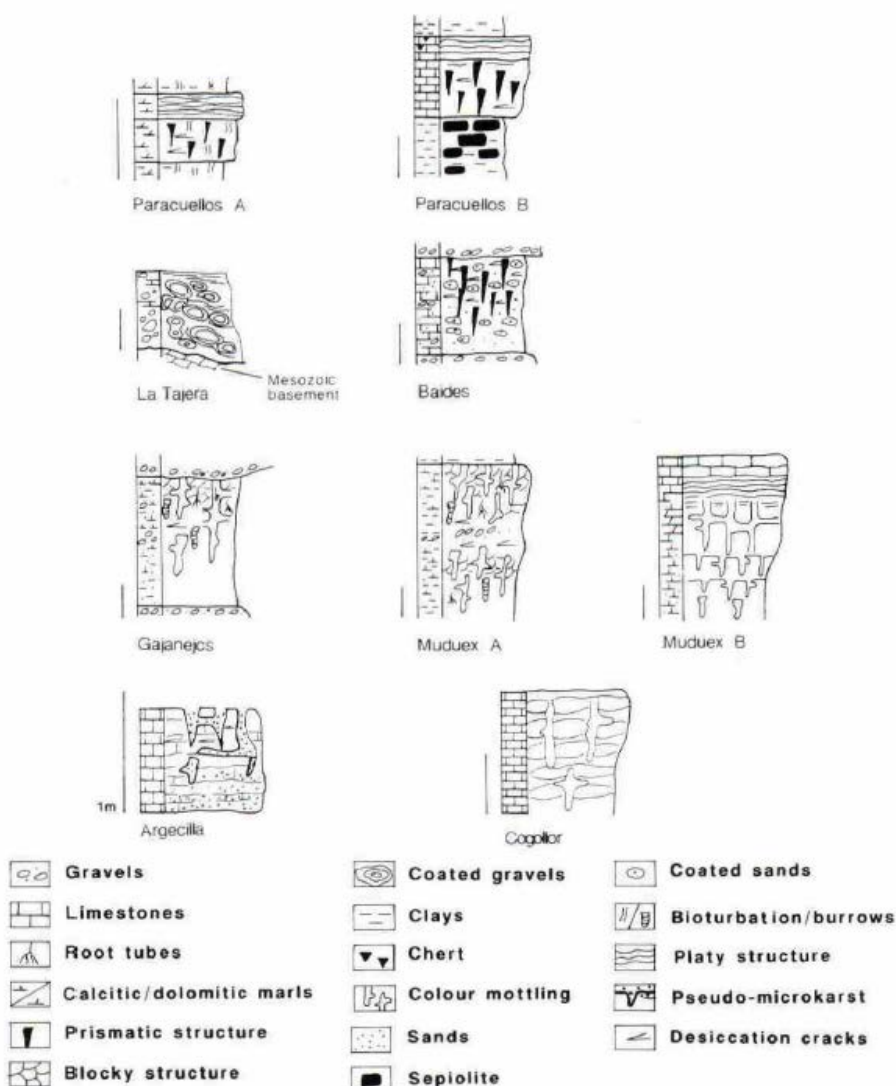


Fig. 5. Palaeosol profiles for complete caption see Fig. 4.

dolomite cement, separating areas of locally strongly orientated clays. Rhizocretions, fungal carbonates and faecal pellets are absent. The carbonate units correspond to maturity stages 2-3 of Machette's (1985) classification.

Towards the top of this lower sequence are more mature (stage 4) calcrete profiles (Figs 4 & 5) up to 2 m thick, interbedded with brown clays and fine

arkosic beds (Paracuellos B). These profiles, with a higher carbonate content than those below, are formed of calcite not dolomite. The clays consist of dioctahedral smectites, with minor illite and kaolinite. Sepiolite is commonly found with these calcretes, and also in the underlying clays (Calvo *et al.*, 1986). The profiles exhibit two parts, like the dolomitic ones below. The lower horizons are strongly prismatic (Fig. 5), with

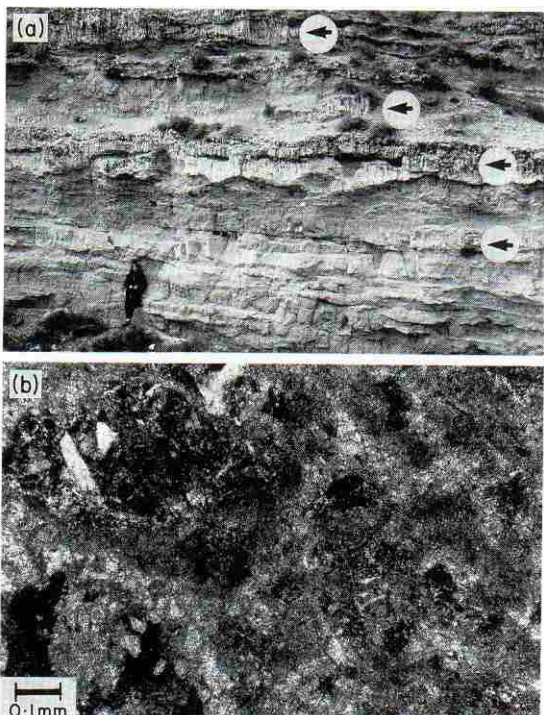


Fig. 6. (a) Mature calcrete profiles, Paracuel Jos. Carbonate horizons are arrowed. Figure in lower left corner for scale. (b) Photomicrograph of calcrete from Paracuel Jos section showing irregular micritic zones forming a network, separated by patches of microspar.

individual prisms up to 0.5 m long and 50–100 mm wide. The microfabric consists of dense micrites with minor irregular fractures and small patches of relict clays. The overlying platy units consist of a distinctive reticulate pattern of micrite and microspar with intervening millimetre-scale patches of clay (Fig. 6b). The calcretes are commonly silicified with micro-quartz-filled veins. The only clay in the upper, platy parts of these calcretes is sepiolite, suggesting a probable pedogenic origin (Calvo *et al.*, 1986). The calcretes are much more laterally extensive (traceable for up to 1.5 km) than the dolocretes, which can be traced laterally for only a few hundred metres.

Palaeosols in the north-eastern area

Palaeosols in this part of the basin developed in a variety of environmental settings including alluvial fan, floodplain and palustrine environments.

Proximal fan and colluvial deposits

Palaeosols in the most proximal parts of this depositional system occur on coarse, mainly carbonate, gravels. These gravels were deposited in the proximal areas of alluvial fans and as screes (colluvium), resting directly on Mesozoic carbonates (Alonso Zarza *et al.*, 1990). The most mature palaeosols (stages 4–5 of Machette's classification) are located on colluvium and small fans in the La Tajera area (2°27'30" N, 40°49'50" W) (Alonso Zarza *et al.*, 1990). The lateral extent of these calcretes is only a few hundred metres. They developed on coarse, very poorly sorted, matrix-supported carbonate conglomerate-breccias in which the clasts range from 0.7 m in diameter to sand sized (Fig. 5). Here the profiles vary in thickness from 0.4 to 3 m, and the thicker ones reach a maturity of Machette's stage 5. The thicker profiles have a twofold division with a lower horizon with coated clasts and an upper one of sheet-like laminar calcrete up to 0.1 m thick. The coatings on the clasts are locally up to 40 mm thick, and are continuous around the clasts but show microstalactitic thickenings. The submillimetre to millimetre thick laminae, present both coating the clasts and within the laminar horizons, consist of dense micrite-microspar layers. The thicker laminae consist of fine to coarse sand-grade peloids and coated grains (Fig. 7), cemented by spar and microspar. Detrital grains were incorporated into laminae. The coatings show none of the biogenic fabrics typical of some calcretes such as micritic outgrowths or needle-fibre calcite (Wright, 1989). The peloids are irregular in shape and poorly sorted, unlike faecal pellets in calcretes (Wright, 1983; Jones & Squirr, 1989). Peloids and coated grains are common in calcretes showing large void spaces (such as those

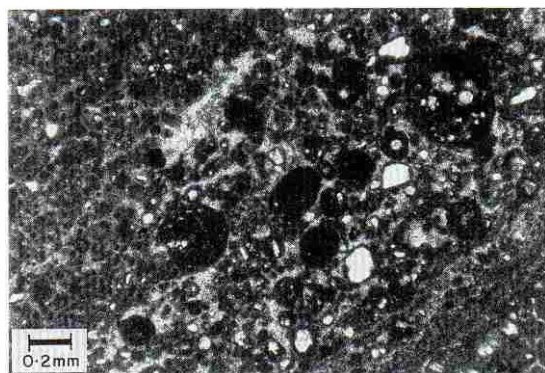


Fig. 7. Photomicrograph of peloidal fabrics of calcretes developed on colluvial deposits, north-eastern area.

developed on coarse-grained deposits or highly fractured mature calcretes: Hay & Wiggins, 1980). The peloids are disorthis to allorthis features (in the sense of Wieder & Yaalon, 1974). They have been translocated in the soil in many cases, and concentrated in the larger pore spaces.

Carbonate-coated clasts are a common feature of soils developed on Quaternary alluvial fans but there are few descriptions of their micromorphology. Fibrous calcite coatings, of the types noted by Chadwick *et al.* (1989), Blank & Fosberg (1990) and Reams (1990) from various carbonate-coated clasts in soils from the United States, were absent.

The laminar calcretes capping the profiles show dense micrite and peloid-rich laminae, appear to be abiogenic in origin and lack the typical features seen in microbial or rhizolite laminar calcretes (cf. Wright *et al.*, 1988; Wright, 1989).

In the proximal areas of the fans, soils developed on coarse conglomerates but they are not common and are spatially restricted. They correspond to stage 1-2 profiles of Machette (1985), and consist of 2-3 mm discontinuous carbonate coatings on clasts, thinner than those in the La Tajera colluvium. However, petrographically they are similar to the coatings in the scree deposits of La Tajera.

Medial fan areas

Near the village of Baidés ($2^{\circ}45'11''N$, $41^{\circ}00'40''W$) a discrete mappable fan, the Baidés Fan, was developed. Its medial fan facies, consisting of more than 100 m of stacked coarse gravel sheets with interbedded coarse sandstones (Figs 3b & 4), includes several calcretes (Alonso Zarza *et al.*, 1992). The calcrete profiles (Fig. 5) average 2 m in thickness and are discontinuous, being traceable for about 200–500 m along depositional strike. The calcrete profiles, which are at stage 3 maturity of Machette's (1985) classification, show a prismatic structure (Fig. 8a). Thin micritic coatings around the sand grains are the most typical petrographic features (Fig. 8b), and small carbonate nodules, rhizocretions and fine calcite spar-filled cracks are also present.

Distal areas and floodplains

Palaeosols in the distal fan facies are similar to those recognized in floodplain sequences. Two major sections, Gajanejos and Muduex, illustrate the variability in palaeosol development seen in these fluvial deposits. These two sections are 5 km apart and differ in the volume and style of associated channel deposits.

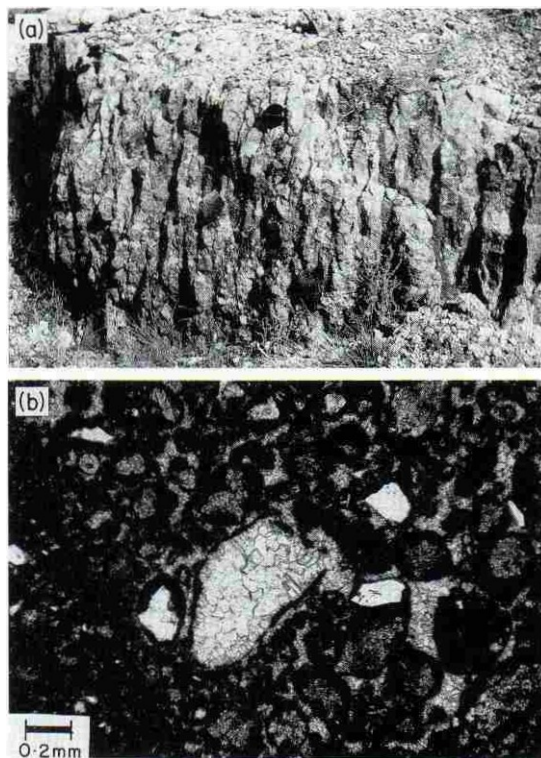


Fig. 8. (a) Prismatic calcrete, Baidés media fan facies. Lens cap for scale. (b) Photomicrograph of micritic coated grains and micritic-walled tubule (centre), from calcretes shown in (a).

In the Gajanejos area ($2^{\circ}56'06''N$, $40^{\circ}51'08''W$), the sequence contains a number of large channel sandstones up to 8 m thick (Fig. 4). The area appears to have been within a major channel belt and the associated floodplain deposits consist of coarse- to fine-grade sands, silts and clays. Individual units bearing pedogenic features can be up to 3 m thick. The red clays in these palaeosols are predominantly formed of illite and minor chlorite (less than 5%). Carbonate occurs as irregular, centimetre-sized, nodules and is commonly surrounded by green, vertically elongate, centimetre-sized mottles. The silts and clays have a subangular to blocky structure. Carbonate content, as well as mottling intensity, increase towards the top of each profile (Fig. 5) and root bioturbation effects are commonly seen. The maturity of these soils is up to stage 2 in the sense of Machette (1985). In the Muduex area ($2^{\circ}57'02''N$, $40^{\circ}50'12''W$) the lower part of the Intermediate Unit exhibits over 120 m of pedogenically modified floodplain deposits (Figs 3b & 4). Thick channel deposits are absent,



Fig. 9. Elongate carbonate nodules (arrowed) from a floodplain palaeosol, Muduex area.

small erosively based, fining upwards, sheet-like channels occur filled by imbricated gravels and planar cross-stratified sandstones. The associated floodplain deposits are finer grained than at Gajanejos and consist of silts and clays. The tops of the sandstones were pedogenically modified, and most of the floodplain deposits show evidence of modification including abundant, centimetre-sized carbonate nodules, root traces and burrow mottling (Muduex A, Fig. 5). Carbonate concretions commonly follow roots or burrows (Fig. 9). Reduced (green) mottling is particularly common around these roots, burrows and elongate carbonate nodules, forming 'drab-haloes' in the sense of Retallack (1990). These haloes probably represent areas of reduction associated with organic matter decomposition as the regional water table rose during floodplain accretion (accumulative hydromorphy phase of Brown & Kraus, 1987). The maturity stages seen in these carbonate profiles increases

but progressively up-sequence (Figs 4 & 5, Muduex A to B) from stage 3 to 4 of Machette (1985).

The Muduex B profile shown in Fig. 5 is located in the middle part of the lower sequence. It can be traced laterally for several kilometres and, towards the east (towards the Gajanejos area), its maturity progressively decreases until, close to the Gajanejos section shown in Fig. 4, it passes into sands and silts lacking obvious soil features. In the Muduex area this profile is developed on red silts and clays, the latter composed mainly of illites and minor interstratified illite-smectite. The profile contains some centimetre-thick gravel sheets, suggesting it is cumulative. The lowest part of the profile is a red silt with small, centimetre-sized carbonate nodules, passing progressively upwards into a continuous massive carbonate horizon. This upper unit locally contains ostracod valves, suggesting a possible palustrine origin.

Palustrine association

Palustrine carbonates are developed mainly at the top of each of the lower and upper sequences of the Intermediate Unit, and represent deposition in shallow lakes on the floodplains (Calvo *et al.*, 1989). Their wide extent and lack of interbedded clastic material suggests they developed when alluvial deposition from the fans or fluvial systems was reduced. Profiles analysed in this setting lie within the upper part of the Intermediate Unit. Lacustrine areas reached their maximum extent in the north-eastern area at this level. Thus, the deposits analysed here are younger (late Aragonian to early Vallesian age) than the palaeosols previously described (middle to late Aragonian) (Fig. 2).

In these settings the palaeosols developed on carbonate (limestone) substrates. It appears that soil processes did not contribute significantly to the accumulation of carbonate but modified the previously deposited palustrine carbonates (e.g. see also Platt, 1989). Two sections have been studied in detail: Cogollor and Argecilla (Figs 3 & 4). In general terms the Cogollor section is associated with alluvial facies while that at Argecilla is, stratigraphically, more closely related to lacustrine deposits (Alonso Zarza, 1989). In the Cogollor area palustrine deposits are represented by more than 20 m of mottled (yellow to brown) bioclastic limestone beds averaging 2 m in thickness (Fig. 5). The limestone beds are usually nodular and, in thin section, show strongly developed microfractures (Fig. 10). Root traces are common, as are ostracod and charophyte debris. Desiccation

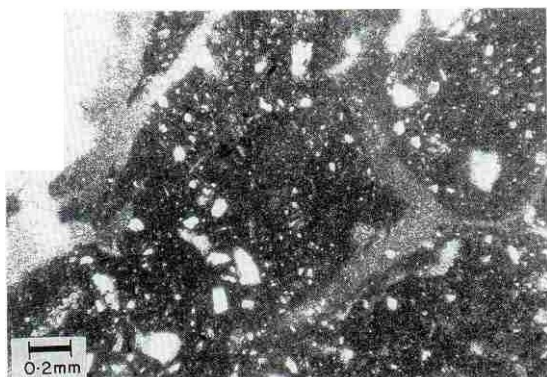


Fig. 10. Photomicrograph showing micritic calcareous limestone with microspar and spar-filled microfractures, Cogollor section.

features increase in abundance towards the top of many of the beds. Centimetre-sized cavities in the limestones are filled geopetally, with laminated vadose silts at the bottom and calcite spar cement at the top. Manganese oxide coatings are associated with the cavities. More extensive, connected cavities and solutional depressions (microkarst of Freydet & Plaziat, 1982) are rare.

The Argecilla sequence is different from that at Cogollor, showing well-developed pseudo-microkarst (Fig. 5). The thickness of the individual profiles averages 0.7 m. The lower parts of each profile are formed by graded units of gravel-sized carbonate intraclasts cemented by calcite spar, commonly showing micritic coatings. The middle part of each unit shows a micritic matrix with desiccation cracks but fewer intraclasts. At the top of each unit, large vertical and horizontal fractures cut the micritic limestone and are filled by intraclasts of sand to gravel grade. Open, vertical cavities, up to 0.7 m long (Fig. 11a)

occur which may represent root moulds. These are particularly common in limestones rich in lacustrine gastropods. Colour mottling is not well developed, but the most striking feature of these limestones are large (cm-dm), irregular cavities filled by peloids and larger intraclasts. The origin of the grains is seen in the surrounding bioclastic lime mudstones where desiccation has resulted in the formation of circumgranular cracking and peloids by 'grainification' (Mazzullo & Birdwell, 1989; Wright, 1990). Some of the peloids also represent small calccrete nodules (Fig. 11b). These cavities, and the peloids, correspond to the pseudo-microkarst and 'secondary pedogenetic grainstones' respectively of Freydet & Plaziat (1982), commonly seen in many ancient palustrine limestone sequences.

PALAEOSOL-PALAEOLANDSCAPE RELATIONSHIPS

It is clear that there are varied sets of palaeosols in the two areas, with marked differences, not only between the northern and north-eastern areas, but also within the north-eastern area alone. This is particularly true with regard to the maturities of the profiles described. Before offering possible explanations for these differences, some of the controls on soil development on alluvial fans and floodplains are briefly reviewed.

Alluvial fans

Soil-landscape relationships on alluvial fans are very complex, reflecting spatial and temporal variations in the geomorphological stability of fan surfaces. Stable surfaces, undergoing neither deposition nor erosion, undergo pedogenesis, and such surfaces develop on fans because of a number of factors. In non-entrenched fans, where the surface aggrades over a large part of the fan there is, typically, a contrast in depositional

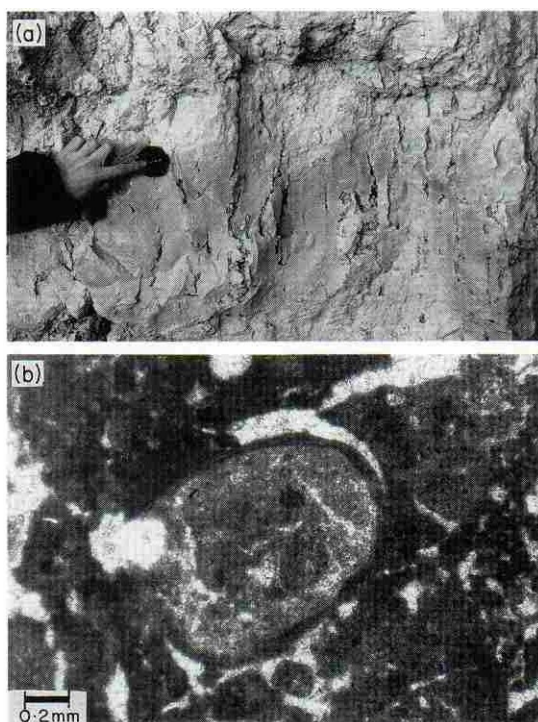


Fig. 11. (a) Palustrine limestone, Argecilla, showing prominent vertical cavities, interpreted as probable root moulds. Lens cap for scale. (b) Circumgranular spar-filled fractures in palustrine limestone, Argecilla.

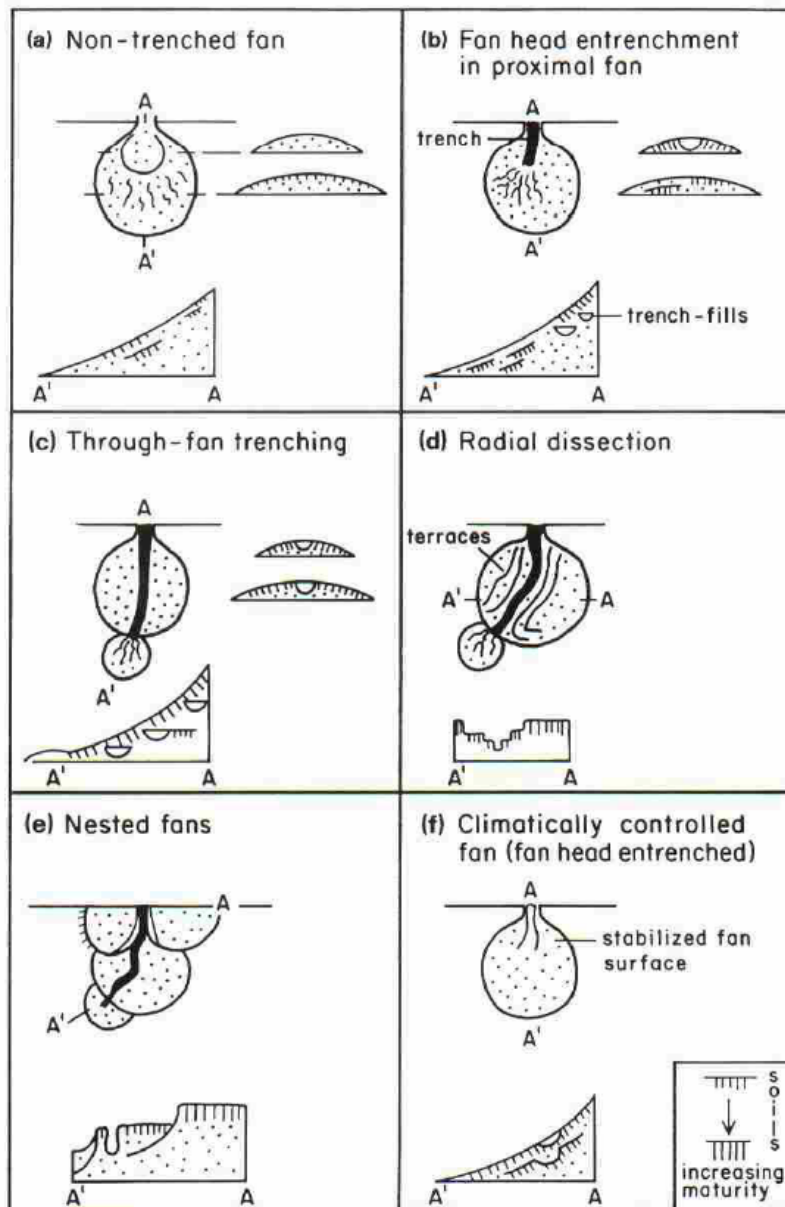


Fig. 12. Schematic pedostratigraphic models for alluvial fans (see text), modified from Wright (1991).

rate between proximal and more distal areas. The proximal areas have higher deposition rates and will have less developed soils than more distal areas receiving less sediment (McCraw, 1968) (Fig. 12a). This is a pedofacies relationship in the sense of Bown & Kraus (1987). In entrenched fans, the extent of the trench system affects soil development quite radically (McCraw, 1968; Wright & Alonso Zarza, 1990). If the trench is restricted to the upper part of the fan, the areas adjacent to this channel receive little or no

sediment, and the surface is subject to soil formation (Fig. 12b). As a consequence of trench switching, areas below the intersection points will experience alternating periods of deposition and pedogenesis, but in general the soils in these more distal areas will be less well developed than those adjacent to the trench channel. In situations where the stream has entrenched the full length of the fan ('through-trenches'), pedogenesis occurs over the whole fan surface (McCraw, 1968) (Fig. 12c). An additional factor is distal fan

trenching, typically associated with through-fan trenching (Harvey, 1987), where intersection point head-cuts or base-level-induced incision leads to the distal zone becoming trenched.

The fan deposits also reflect these differences in the degree of entrenchment. Non-entrenched fans consist of more sheet-like deposits with small-scale channelling, whilst entrenched fans exhibit larger channel and channel-fill features, with inset stratigraphies (Harvey, 1989).

Many fans are not just entrenched but are also dissected, either radially (Fig. 12d) or to produce nested surfaces (Fig. 12e). In such cases the fan has a complex topography with a variety of surfaces of different ages. The fan deposits also reflect this complexity with major channel/valley features and fills.

Geomorphological controls, as well as climate and tectonics, control the degree of fan entrenchment and dissection (Lecce, 1990). However, on Quaternary fans climate controls major phases of surface stability and pedogenesis, by switching off the whole depositional system (Talbot & Williams, 1979; Gile *et al.*, 1981; French, 1987; Harvey, 1990; Wright & Alonso Zarza, 1990) (Fig. 12f).

Not only is the distribution of soil surfaces on fans very complex, but local differences in fan behaviour make inter-regional comparison of soil stratigraphies very difficult. Areas relatively close to one another, with different geology, relief and microclimate, may not only display different depositional styles, but may also respond in different ways to changes in climate. For example, a change to a regime with increased effective precipitation can cause some areas to increase their sediment yield, increasing fan deposition, whilst nearby fans in a different microclimate, already at their peak sediment yield, may respond by an increase in the vegetation cover, causing fan stabilization (French, 1987). All these factors must be borne in mind when interpreting soil-landscape relationships in an area like the Madrid Basin, where marked regional variations in geology, relief and climate occurred.

Floodplain systems

Soil-landscape relationships in floodplain settings have been extensively documented from present-day systems and have also been interpreted in ancient sequences using palaeosols. The two main types of relationships are those related to catenas and to differential sedimentation rates (pedofacies). Topo-

graphic differences, affecting soil drainage, result in different soil types on a floodplain, caused by more and less poorly drained areas (Gerrard, 1981; Wright, 1991). Pedofacies relationships are seen where the maturity of a soil or palaeosol increases across a floodplain in response to the decreasing sedimentation rate away from the channel belt (Bown & Kraus, 1987). Near the channel belt higher rates of sedimentation result in numerous, stacked profiles with well-developed soils, whilst distant from the channel the soils receive much lower increments of sediment and are more mature (Kraus, 1991). This simple pattern is typically obscured in most floodplains where terracing disrupts the trend, with surfaces often in staircases, creating a complex set of soils of varied ages, typically in close vertical proximity to one another (Wright, 1991).

With these general principles in mind the differences in soil maturity and soil type in the Madrid Basin can be related to the geomorphological settings (shown schematically on Fig. 13).

Palaeosol relationships in the northern area

Alluvial fan settings

Debris flow deposits dominate these fans and extend considerable distances from the mountain front, suggesting high sediment to runoff ratios. High rates of sediment supply probably reflected continuing tectonic activity. The predominance of debris flow deposits also probably reflects high relief in the drainage basin, as is commonly seen in Quaternary fans (Harvey, 1990). The absence of extensive outcrops in the proximal fan deposits does not allow assessment of whether or not they were entrenched, but mature palaeosols were apparently absent (I.G.M.E., 1991).

Weakly developed palaeosols from the medial fan areas simply show reddening. The absence here of well-developed palaeosols suggests rapid fan aggradation without the development of long-term stable surfaces. Nevertheless, the weakly developed palaeosols are laterally extensive, indicating that short-term stability prevailed over large areas. Short periods of stability could have occurred on abandoned fan segments; certainly the lack of deep cut-and-fill sequences observed in the field argues against entrenchment and dissection in such areas. The high aggradation rates and Jack of extensive entrenchment suggest that the fans were never aged to a point where entrenchment occurred (cf. Harvey, 1989).

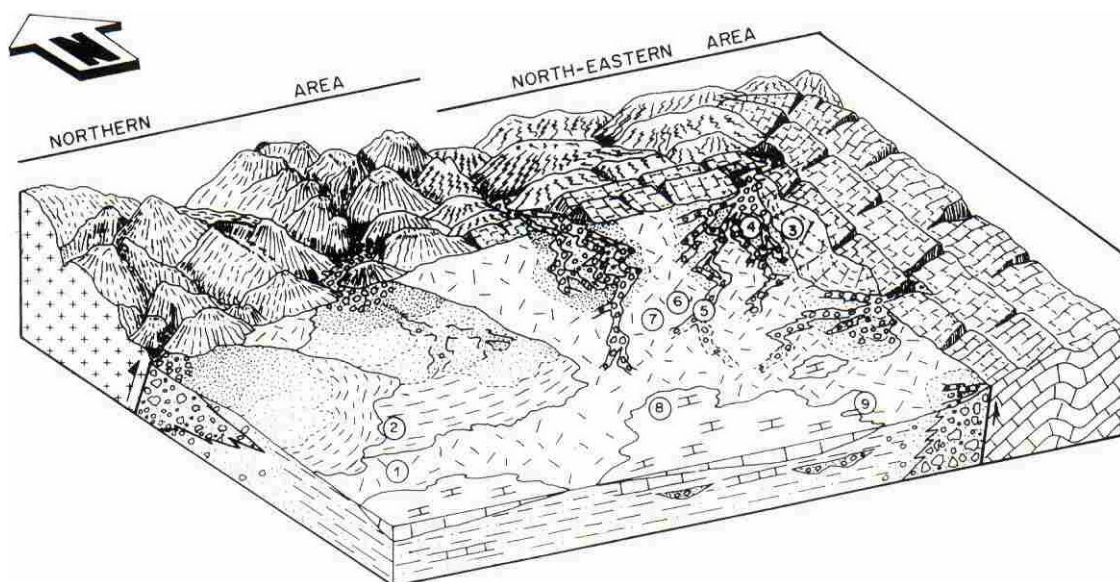


Fig. 13. Idealized reconstruction of middle Miocene landscapes of part of the Madrid Basin. Numbers refer to palaeosol profiles in Fig. 5: 1 = Paracuellos A, 2 = Paracuellos B, 3 = La Tajera, 4 = Baides, 5 = Gajanejos, 6 = Muduex A, 7 = Muduex B, 8 = Argecilla, 9 = Cogollor. For key see Fig. 1 and Fig. 5.

Lake margin settings

The mature palaeosols in the Paracuellos area may have formed in interfan or extreme fan toe settings, influenced by the nearby Jake but experiencing low aggradation rates for long periods. The proximity to a fluctuating endorheic Jake system would have resulted in frequent changes in the local base level. Drops in lake level would have caused trenching of the distal fans, creating more stable surfaces for soil development. However, there is no evidence of such dissection in the mid fan deposits suggesting that, if such falls occurred, they were very small. It seems likely that the mature calcretes developed during small-scale falls in Jake level, which exposed large areas of the low-gradient lake margin and caused local stabilization of the most distal fan areas. Miner falls in Jake levels are common in endorheic lakes and may reflect local and minor changes in the precipitation/runoff/evaporation budget, not great enough to have affected the adjacent fans themselves. In all these points, the limited outcrop of the northern fan deposits is a crucial factor to consider.

The stratigraphically lowest palaeosols contain dolocrete horizons lacking sepiolite but with analcime. An upward change from dolocrete to calcrete coincides with the coarsening upwards to more distal fan arkosic

sands. The clays on which the dolocrete developed are similar to clays in the adjacent Jake deposits, which have a high percentage of trioctahedral smectite (Calvo *et al.*, 1989). These clays were the probable source of Mg for dolomite formation. In contrast, the calcretes developed on clays mainly composed of dioctahedral smectite and illite, having a lower Mg content. Sepiolite is concentrated only in the most carbonate-rich layers in the calcretes, a feature also noted by Netterberg (1969) and Watts (1980) from Quaternary calcretes in southern Africa. To explain this inverse relationship between sepiolite concentration and the Mg content of the associated pedogenic carbonates, Watts (1980) suggested that Mg was released from high-Mg calcites in the soil carbonate following inversion to low-Mg calcite; the Mg enriched the soil waters and led to sepiolite neoformation. Alternatively, the preferential removal of CaCO_3 as low-Mg calcite might have led to locally high Mg levels in concentrated soil solutions (Calvo *et al.*, 1986; McGrath & Hawley, 1987). The occurrence of pedogenic sepiolite in the calcretes in this area and not in the north-eastern area is significant, and by analogy with Quaternary calcretes (McGrath & Hawley, 1987) suggests a difference in microclimate with the northern area being more arid than the north-

east. However, the availability of a source of Mg is a critical factor in influencing the distribution of sepiolite.

The calcrete and dolocrete profiles, while most closely resembling the discrete profiles found in pedogenic calcretes/dolocrete, may have been influenced by groundwaters (e.g. see examples discussed by Watts, 1980). No direct evidence has been noted for this, but analcime, which occurs in the calcretes, is commonly associated with high or perched water tables and high Na CO₃ concentrations (Nettleton & Peterson, 1983).

The availability of CaCO₃ may also have affected the distribution of calcretes in this area. The lack of carbonate in the fan palaeosols has been interpreted as reflecting high aggradation rates. However, in Quaternary fan sequences the distribution of calcretes is closely related to the nature of the substrate and proximity to playas (Lattman, 1973; Gile, 1977). Soils forming on Ca-poor substrates develop calcic horizons much more slowly (or not at all) compared to those with an abundant supply of Ca from limestone or dolomite clasts. Local supplies of Ca are usually not the main source of Ca in such soils, which comes from aeolian sources (Machette, 1985), but the local supply enhances the rate of accumulation. The Paracuellos calcretes and dolocrete had local sources of Ca and Mg from exposed Jake carbonates, whilst the fan deposits have a low Ca or Mg content and chemical weathering of the mainly granitic clasts may have been low under the prevailing 'arid-type' climate.

Palaeosol relationships in the north-eastern area

Exposure is much better in this area, where the depositional style and range of palaeosols is quite different, reflecting the different geology, relief, tectonics and climate.

Colluvial and fan settings

The calcretes which developed on the colluvial deposits are well developed and indicate stable slopes most probably stabilized by vegetation. Alonso-Zarza (1989) found no evidence of deep channelling and cut-and-fill sequences in any part of the fan deposits in this area, reflecting a lack of entrenchment or dissection. This is supported by the presence of only weakly developed palaeosols in the proximal fans suggesting that stable surfaces were not developed. This situation is typical of the proximal parts of non-entrenched fans (McCraw, 1968; Wright & Alonso

Zarza, 1990). The presence of more mature calcretes in the medial areas indicates more stable surfaces. On non-entrenched fans much of the sediment load is dumped near the fan apex so that areas lower down the fan experience less sediment input. This simple 'pedofacies' relationship is unlikely to explain the pattern seen in these Miocene fans, for the mature medial fan calcretes probably required long periods to form, perhaps thousands or tens of thousands of years. It is unlikely that preferential deposition in the apex could have continued for this length of time for the fan profile would have become very steep in the apex region and unstable. A second explanation is that the channels on the medial fan were less mobile than those on the proximal fan, allowing interchannel areas to develop more mature soils. Crusting of the fan surface by calcretes limits lateral erosion by channels on Quaternary fans (Harvey, 1989) favouring continued soil development. In addition, more permanent channels develop with time on Quaternary fans (Christenson & Purcell, 1985). We therefore favour the explanation that the absence of well-developed palaeosols in the proximal fan and their presence in the medial areas reflect the different activity of distributary channels in the two areas. The medial fan areas had more stable channels, the degree of soil development on the fans being as much a function of preservation potential than of aggradation rate. The distal fan deposits contain less mature calcretes which most likely reflects areas of more widespread and rapid deposition. However, the finer grain sizes of the sediments may have been an additional control because calcretes require longer periods to reach the mature stages in finer substrates (Gile *et al.*, 1966).

In summary the palaeosol distribution on the north-eastern area fans indicates that they were neither entrenched nor dissected. Relatively stable areas developed in the medial fan, perhaps as a consequence of the fixing of channels by fan crusting. There is no evidence from the palaeosols of fan-wide periods of stability which might have been caused by climatic changes.

Floodplain settings

The floodplain palaeosols exhibit lateral variations reflecting their positions on the floodplain relative to the main channel belt that drained the whole north-eastern area. The Gajanejos area, which was proximal to the channel belt, as indicated by abundant channel deposits, has thick floodplain deposits with weakly developed palaeosols (Fig. 4). In more distal areas,

such as Muduex, channel deposits are rarer and the palaeosols are better developed. This appears to represent a simple pedofacies relationship in the sense of Bown & Kraus (1987). This trend is supported by the fact that the grain size of the floodplain sediments decreases from Gajanejos to Muduex. The decreasing maturity and eventual disappearance of the palaeosol which was traced from Muduex to Gajanejos also supports this view. Calcrete maturity in the Muduex area increases up sequence, followed by lacustrine/palustrine deposits. This suggests reduced sediment input and rising lake levels, perhaps reflecting shifts to wetter conditions with increased stabilization of the fans by vegetation.

Lake margin settings

The palustrine deposits represent pond, marsh or lake margin sediments (Calvo *et al.*, 1989), and show contrasts between the two main sections, Argecilla and Cogollor. At Cogollor, the palustrine units occur in a floodplain sequence, where the carbonates are interbedded with clays. The presence of moulting, minor pseudo-microkarst and fracturing suggests some hydromorphism and also some short periods of exposure. These carbonates may have developed in small floodplain lakes or ponds.

The Argecilla palaeosols show extensive pseudo-microkarst development and ped (peloid) formation, indicating a longer exposure period, and a vegetation cover probably resulting in microkarst development (cf. Freytet & Plaziat, 1982). Argecilla is more proximal to the main lake area in the basin (Alonso Zárza, 1989) and these palustrine palaeosol profiles probably represent periods of lower lake levels exposing lake margin sediments.

Comparison of palaeosol development in the two areas

The differences in palaeosol development between these two areas reflect the interplay of several factors. The northern area, with its presumed higher topography (as today), more active faulting and more arid conditions, exhibits a thicker proximal fan sequence composed of mass flow deposits reflecting a high sediment to water ratio from a steep, mainly granitic catchment area. The arid climate may have favoured catastrophic floods. These fans were neither entrenched nor dissected, resulting in a lack of mature palaeosols. The probable high aggradation rates, coupled with the aridity and carbonate-poor substrates, resulted in a lack of calcrete development. The

playa margin palaeosols exhibit dolocrete horizons reflecting their Mg-rich substrates, whilst on the Mg-poor fan fringe deposits, calcretes formed.

In contrast, the north-east was wetter, as evidenced by permanent carbonate lakes (Calvo *et al.*, 1989). The resultant greater runoff resulted in fans dominated by braided stream deposits, reflecting a lower sediment to water ratio. The associated calcretes (and not dolocretes) reflect both the greater availability of CaCO_3 from carbonate source areas, and the lower levels of Mg in the substrate. The presence of floodplain deposits also reflects the greater runoff in this area. Calcrete-bearing palaeosols occur in these deposits, showing pedofacies relationships, with weakly developed profiles proximal to the channels, and more mature ones distal to the main channel belt. Small carbonate lakes (or ponds) also formed on these floodplains. Soils formed on the exposed lake, marsh and pond carbonates. Such contrasts in the two fan systems within one region are not unusual (see e.g. Harvey, 1990).

CONTRASTS WITH QUATERNARY ALLUVIAL FAN SEQUENCES

There are striking differences between these Miocene alluvial fan sequences and those seen in Quaternary fans. Many Quaternary fans are deeply entrenched, partly or fully, and/or dissected (French, 1987). The causes of trenching are diverse (Schumm *et al.*, 1987; French, 1987). Intrinsic factors tend to result in short-lived entrenchment (Harvey, 1989); extrinsically triggered entrenchment is typically more significant. External factors include tectonic activity (steepening the fan profile), climatic changes (leading to increases or decreases in stream power) and local changes in base level in adjacent basins caused by changed lake or sea levels.

Tectonic factors are important in affecting the long-term development of some fans (Harvey, 1989, 1990), acting to create the location and space for the fan. However, other factors such as climate and source area geology can control the short-term development and stratigraphy of the fan (Harvey, 1989). Fault movements are generally infrequent and their effects on the fans are overprinted by geomorphological and climatic factors. Indeed, even in fans where active uplift occurs in proximal areas, such as the Tapia fans of south-eastern Spain (Harvey, 1984), the mid and distal fan areas are not affected. Although the northern area was probably tectonically active during the

middle Miocene, this need not necessarily have been an important factor controlling the morphology or stratigraphy of the fans. Climatic change is regarded as critical in controlling Quaternary fan development (Talbot & Williams, 1979; Gile *et al.*, 1981; Lettis, 1985; Dom *et al.*, 1987; Blair *et al.*, 1990; Harvey, 1990). Climate is a particularly crucial influence on vegetation cover and is the main factor controlling fan stability. Quaternary climatic changes inducing stability have resulted in surfaces (and their associated soils) being regionally traceable (Gile *et al.*, 1981). As stated above, the range of maturity seen in the palaeosols on the Miocene fans argues against widespread periods of fan stability and suggests that climatically controlled phases of fan growth and stability did not occur. Evidence for possible climatic change does come from the associated lake deposits. The small-scale interfingering, in both areas, Jake deposits and alluvial fan or floodplain units (Calvo *et al.*, 1989) is clear evidence of both minor and major changes in the Jake level. These did not apparently affect the fan systems as a result of incision due to a change in the base level. Two larger-scale lake transgressions, recorded in the Intermediate Unit of the north-east area, reflect more significant climatic changes. However, no major palaeosols have been found which might correlate with these events. This could be explained by the fact that the fans did not directly feed into the lakes (Alonso Zarza *et al.*, 1992).

In summary, the major differences between these Miocene fan sequences and many Quaternary examples is the relatively regular fan growth exhibited throughout the middle Miocene in both regions of the Madrid Basin. Major climatically controlled alternations of aggradation, and stability/degradation, which have characterized Quaternary fan growth are not seen in the Miocene fan sequences. Changes in lake levels in the region do not seem to have been associated with changes in runoff sufficiently large to cause fan-wide shifts in stability.

CONCLUSIONS

The Miocene alluvial and lacustrine deposits of the Madrid Basin contain a variety of palaeosols developed in a range of landscapes.

The northern part of the basin had higher relief and was arid and tectonically active. Soils on the fans were weakly developed, reflecting aggrading fan surfaces. Local sources strongly influenced the composition of

the pedogenic carbonates which formed in the more distal settings. Calcretes formed on Mg-poor fan sediments whilst dolocretes developed on Mg-rich Jake clay. In contrast, the north-eastern part of the basin had lower relief, was less arid and tectonically active and was fed by stream-sourced by carbonate terrains. The fans were characterized by stream flood deposition, and extensive flood plains; freshwater lakes developed down-basin. Calcretes developed on the fans, perhaps partly reflecting the greater availability of carbonate. Unlike the fans in the northern area, pedofacies relationships, both on the fans and on the floodplains, are clearly seen. Palaeosols also developed on the exposed Jake margins, and floodplain pond carbonates. Local geological, climatic and geomorphological factors controlled the nature of the soilscape in the basin. The spatial distributions and stratigraphies of the palaeosols in the fans are different to those seen in many Quaternary fans where major climatic changes have led to discrete phases of stability (soil formation) and instability.

Soils are integral parts of landscapes. Palaeosols in ancient continental deposits can be used to assess the controls on the geomorphological evolution of an area, and the roles of local factors versus external ones such as climatic change.

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REFERENCES

- ALBERDI, M.T., Hovos, M., JUNCO, F., LOPEZ-MARTINEZ, N., MORALES, J., SESE, C. & SORIA, O. (1983) Biostratigraphie et évolution sédimentaire du Néogène continental de l'aire de Madrid. *Médit. Neog. Cont. Palaeoenvironm.*, Interim Coll., Montpellier, pp. 15-18.
- ALONSO ZARZA, A.M. (1989) *Estudio petrológico y sedimentológico de las Facies de abanicos aluviales del Neógeno en el sector NE de la Cuenca de Madrid y su relación con las Facies más centrales, provincia de Guadalajara*. Thesis, Uni. Complutense, Madrid, 473 pp.

- ALONSO, A.M., CALVO, J.P. & GARCIA DEL CURA, M.A. (1986) Sedimentología y petrología de los abanicos aluviales y facies adyacentes en el Neógeno de Paracuellos de Jarama (Madrid). *Estudios geol.*, 42, 79-101.
- ALONSO, ZARZA, A.M., CALVO, J.P. & GARCIA DEL CURA, M.A. (1992) Paleogeomorphological controls on the distribution and sedimentary styles of alluvial systems, Neogene of the northeast of the Madrid Basin (central Spain). *Spec. pubis int. Ass. Sediment.* (in press).
- ALONSO ZARZA, A.M., CALVO, J.P., GARCIA DEL CURA, M.A. & HOYOS, M. (1990) Los sistemas aluviales Miocenos del borde noreste de la Cuenca de Madrid; sector Cifuentes-Las Inviernas (Guadalajara). *Revta Soc. geol. Esp.*, 3, 213-229.
- ALONSO ZARZA, A.M., GARCIA DEL CURA, M.A. & CALVO, J.P. (1988) Significado paleogeográfico de las texturas y acumulaciones de carbonatos en perfiles edáficos de la Unidad Intermedia del Mioceno de la Cuenca de Madrid (prov. de Guadalajara). *Geocarta*, 5, 30-33.
- BESLY, B.M. & FIELDING, C.R. (1989) Palaeosols in Westphalian coal-bearing red-bed sequences, central and northern England. *Palaeogeogr. Palaeoclimatol. Palaeoecol.*, 70, 303-333.
- BROWN, T.M. & KRAUS, M.J. (1987) Integration of channel and floodplain suites in aggrading alluvial systems. I. Developmental sequences and Lateral relations of lower Eocene alluvial palaeosols, Willwood formation, Bighorn basin, Wyoming. *J. sedim. Petrol.*, 57, 589-601.
- BLAIR, T.C., CLARK, J.S. & WELLS, S.G. (1990) Quaternary continental stratigraphy, landscape evolution, and application to a rheology. Jarilla piedmont and Tularosagrabens floor, White Sands Missile Range, New Mexico. *Bull. geol. Soc. Am.*, 102, 749-759.
- BLANK, R.R. & FOSBERG, M.A. (1990) Micromorphology and classification of secondary calcium carbonate accumulations that surround or occur in the undersides of coarse fragments in Idaho (USA). In: *Soil Micromorphology: A Basic and Applied Science, Developments in Soil Science*, Vol. 19 (Ed. by L. A. Douglas), pp. 341-346. Elsevier, Amsterdam.
- CALVO, J.P., ALONSO, A.M. & GARCIA DEL CURA, M.A. (1986) Depositional sedimentary controls on sepiolite occurrence in Paracuellos de Jarama, Madrid Basin. *Geocarta*, 1, 25-28.
- CALVO, J.P., ALONSO ZARZA, A.M. & GARCIA DEL CURA, M.A. (1989) Models of Miocene marginal lacustrine sedimentation in response to varied depositional regimes and source areas in the Madrid Basin (central Spain). *Palaeogeogr. Palaeoclimatol. Palaeoecol.*, 70, 199-214.
- CHADWICK, O.A., SOWERS, J.M. & AMUNDSON, R.O. (1989) Morphology of calcite crystals in clast coalings from four soils in the Mojave Desert region. *Soil Sci. Soc. Am. J.*, 52, 211-219.
- CHRISTENSON, G.E. & PURCELL, C. (1985) Correlation and age of Quaternary alluvial-fan sequences, Basin and Range province, southwestern United States. *Spec. pap. geol. Soc. Am.*, 203, 115-122.
- DE VICENTE, G., CALVO, J.P. & ALONSO ZARZA, A.M. (1990) Main sedimentary units and related strain fields of the Madrid basin (central Spain) during the Neogene. *IX Congr. RCM NS, Abstracts. Inst. Paleont. M. Crusafont*, Barcelona, pp. 121-122.
- DORN, R.I., DENLRO, M.J. & AHE, H.O. (1987) Isotopic evidence of climatic influence on alluvial-fan development in Death Valley, California. *Geology*, 15, 108-110.
- FRENCH, R.H. (1987) *Hydraulic Processes on Alluvial Fans*. Elsevier, Amsterdam.
- FREYET, P. & PLAZIAT, J.C. (1982) Continental carbonate sedimentation and pedogenesis-Late Cretaceous and early Tertiary of southern France. *Contrib. Sedimentol.*, 12, 213 pp.
- GARCIA DEL CURA, M.A., ORDOÑEZ, S. & CALVO, J.P. (1986) La Unidad salina (Mioceno) en el arco de Madrid, características petrológicas y mineralógicas. *Bol. Soc. filol. Mineralogía*, 9, 329-338.
- GARCIA DEL CURA, M.A., ORDOÑEZ, S. & LOPEZ-AGUAYO, F. (1979) Estudio petrológico de la "Unidad Salina" de la Cuenca del Tajo. *Estudios geol.*, 35, 325-339.
- GERRARD, A.J. (1981) *Soils and landforms*. Allen & Unwin, London, 219 pp.
- GILE, L.H. (1977) Holocene soils and soil-geomorphic relations in a semi-arid region of Southern New Mexico. *Quat. Res.*, 7, 112-132.
- GILE, L.H., HAWLEY, J.W. & GROSSMAN, R.B. (1981) *Soils and Geomorphology in the Basin and Range area of southern New Mexico-Guidebook to the Desert Project*, Memoir 39. New Mexico Bureau of Mines & Mineral Resources.
- GILE, L.H., PETERSON, F.F. & GROSSMAN, R.B. (1966) Morphological and genetic sequences of carbonate accumulation in desert soils. *Soil Sci.*, 100, 347-360.
- HARVEY, A.M. (1984) Aggradation and dissection sequences on Spanish alluvial fans: influence on morphological development. *Catena*, 11, 289-304.
- HARVEY, A.M. (1987) Alluvial fan dissection: relationships between morphology and sedimentation. In: *Desert Sediments: Ancient and Modern* (Ed. by L. Frostick & Reid), *Spec. pubis geol. Soc. Lond.*, 35, 87-103.
- HARVEY, A.M. (1989) The occurrence and role of arid zone fans. In: *Arid Zone Geomorphology* (Ed. by D. S. G. Thomas), pp. 136-158. Belhaven Press.
- HARVEY, A.M. (1990) Factors influencing Quaternary alluvial fan development in southeast Spain. In: *Alluvial Fans: A Field Approach* (Ed. by A. H. Rachocki & M. Church), pp. 247-269. John Wiley & Sons, London.
- HAY, R.L. & WJGGINS, B. (1980) Pellets, ooids, sepiolite and silica in three calcretes of the southwestern United States. *Sedimentology*, 27, 559-576.
- LG.M.E. (1989) *Hoja Geológica de Madrid (559)*. Mapa Geológico de España 2ª serie, 71 pp.
- LG.M.E. (1991) *Hoja Geológica de Villaviciosa de Odón (558)*. Mapa Geológico de España 2ª serie (in press).
- JONES, B. & SQUAIR, C.A. (1989) Formation of peloids in plant rootlets, Grand Cayman, British West Indies. *J. sedim. Petrol.*, 59, 1002-1007.
- JUNCO, F. & CALVO, J.P. (1983) Cuenca de Madrid. In: *Geología de España*, Libro Jubilar J.M. Rios, IGME, 2, pp. 534-543.
- KRAUS, M.J. (1991) Tertiary paleosols. In: *Rocks and Soils* (Ed. by W. Chesworth & P. Martini). Elsevier, Amsterdam (in press).
- LATTMAN, L.H. (1973) Calcium carbonate cementation of alluvial fans in southern Nevada. *Bull. geol. Soc. Am.*, 84, 3013-3028.

- LECCE, S.A. (1990) The alluvial fan problem. In : *Alluvial Fans: A Field Approach* (Ed. by A. H. Rachocki & M. Church), pp. 3-24. John Wiley & Sons, London.
- LETTIS, W.R. (1985) Late Cenozoic stratigraphy and structure of the west margin of the central San Joaquin Valley, California. *Spec. pap. geol. Soc. Am.*, 203, 97-114.
- MACHETTE, M.N. (1985) Calcic soils of the southwestern United States. *Spec. pap. geol. Soc. Am.*, 203, 1-21.
- MAZZULLO, S.J. & BIRDWELL, B.A. (1989) Syngenetic formation of grainstones and pisolites from renestral carbonates in peritidal settings. *J. sedim. Petrol.*, 39, 605-611.
- McCRAW, J.O. (1968) The soil pauem of some new Zealand alluvial fans. 4 pp. 631-640.
- McGRATH, D.B. & HAWLEY, J.W. (1987) Geomorphic evolution and soil geomorphic relationships in the Socorro area, central new Mexico. In : *Guidebook 10 the Socorro Area of New Mexico* (Ed. by V. T. McLemore & M. R. Bowie), pp. 58-67. New Mexico Bureau of Mines & Mineral Resources.
- MEGIAS, A.G. (1982). Introduccion al análisis testosedimen- tario: Aplicacion al estudio dinámico de cuencas. In : *V Congreso La tillaamericano de Geología*. Buenos Aries, Actas, 1, pp. 385-402.
- MEGIAS, A.G., ORDÓÑEZ, S. & CALVO, J.P. (1983) Nuevas aportaciones a l conocimiento geológico de la Cuenca de Madrid. *Rev. Mat. Proc. Geol.*, 163-191.
- NETTERBERG, F. (1969) *The geology and engineering properties of So111/r Africa11 calcretes*. PhD thesis, University of Witwatersrand.
- NETTERBERG, F. (1980) Geology of Southern African calcretes: 1. Terminology, description, macrofeatures, and classification. *Trans. geol. Soc. S. Afr.*, 83, 255-283.
- NETILETON, W.O. & PETERSON, F.F. (1983) Aridisols. In : *Pedogel1esis a11d Soil Taxonomy li-Tire Soil Orders* (Ed. by L. P. Wilding, N. E. Smeck & G. F. Hall), pp. 165- 215. Elsevier, Amsterdam.
- ORDÓÑEZ, S., GARCIA DEL CURA, M.A., Hovas, M. & CALVO, J.P. (1985) Middle Miocene paleokarst in the Madrid Basin (Spain) a complex karstic system. In : 61/r *Eur. Reg. Mtg. Sedimemol. Im. Assoc. Sed., LJ eida. Abstr.* (Ed. by J. Rosell, E. Remacha & M. Zamorano), pp. 624- 627.
- PLAIT, N.H. (1989) Lacustrine carbonates and pedogenesis: sedimentology and origin of palustrine deposits of the Early Cretaceous Rupelo Formation, W. Cameros Basin, N. Spain. *Sedimentology*, 36, 665-684.
- RACERO, A. (1988) Consideraciones acerca de la evolución geológica del margen N W de la Cuenca del Tajo durante el Terciario a pa rt i r de los datos del subsuelo. In : *II Congreso Geológico de España* (Ed. by J. A. Vera), pp. 213- 222.
- REAMS, M.W. (1990) Stromatolitic humid-climate carbon- ates: a variety of calcrete? In : *Soif Micromorp/ 10/ogy : a Basic11d Applied Science Developmms in Soif Science*, Vol. 19 (Ed. by L. A. Douglas), pp. 395-400. Elsevier, Amsterdam.
- RETALLACK, G.J. (1990) *Soifs of the Past. An Introduction ta Paleopedology*. U nwin Hyman, London, 520 pp.
- SCHUMM, S.A., MOSLEY, M.P. & WEAVER, W.E. (1987) *Experimenial Fhwial Geomorphology*. Wiley, New York.
- SMITH, R.M.H. (1990) A lluvial paleosols and pedofacies sequences in the Permian Lower Beau fort of the south- western Karoo Basin, South Africa. *J. sedim. Petrol.*, 60, 258-276.
- SOIL SURVEY STAFF (1975) *Soif Taxo1lomy: a Basic System of Soil Classificatin for Making and Interpreting Soif Survey*. US Dept. of Agriculture Conservation Service, Agriculture Handbook No. 436. US Govt. Printing Office, Washing- ton, DC, 754 pp.
- TALBOT, M.R. & WILLIAMS, M.A. (1979) Cyclic allu vial fan sedimentation on the flanksof fited dunes, Janjari, Central N iger. *Catena*, 6, 43-62.
- WATTS, N.L. (1980) Quaternary pedoge nic calcretes from the Kalahari (southern A frica): petrology and regional sign ificance. *Sedimemology*, 27, 661-686.
- WJEDER, M. & YAALON, D.H. (1974) Elfect of matrix com position on carbonate nodule crystallization. *Geo- derma*, 11, 95- 121.
- WRIGHT, V.P. (1983) A rendzina from the Lower Carboni- ferous of South Wales. *Sedimentology*, 30, 83-94.
- WRIGHT, V.P. (1989) Terrestrial stromatolites and laminar calcretes: a review. *Sedime11t. Geol.*, 65, 1-13.
- WRIGHT, V.P. (1990) Syngenetic formation of gra instones and pisolites from rencstral carbonates in peritidal seuings: discussion. *J. sedim. Petrol.*, 60, 309-310.
- WRIGHT, V.P. (1991) Paleopedology: stratigraphic relation- ships and empirical models. In : *Rocks and Soifs* (Ed. by W. Cheswort h & I. P. Martini). Elsevier, Amsterdam (in press).
- WRIGHT, V.P. & ALOI'SO ZARZA, A.M. (1990) Pedostrati- graphic models for alluvial fan deposits: a tool for interpreting ancient sequences. *J. Geol. Soc. Lond.*, 147, 8- 10.
- WRIGHT, V.P., PLAIT, N.H. & WIMBLETON, W.A. (1988) Biogenic lam ina r calcretes: evidence of calcified root mat horizons in palcosols. *Sedimentology*, 35, 603-20.