ORIGIN AND DIAGENESIS OF CALCRETES IN UPPER MIOCENE LIMESTONES, SOUTHERN MADRID BASIN, SPAIN

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ABSTRACT

Different calcrete profiles are associated with lacustrine limestones in Upper Miocene formations on the south of the Madrid Basin. The limestones overlie mudstones which interfinger thin limestones beds and are also interbeded with sandy-filled channels. This set of underlying deposits represent a fluvial lacustrine complex which evolved to a large shallow lake system.

Two calcrete profiles, referred as ATS and MIR profiles, have been studied in detail. The profiles exhibit a typical zonation of diagenetic facies as follows: microsparite mosaics, massive calcrete with floating texture, horizons containing pisoliths with gravitational coatings and laminar crusts. These features have different development and vertical distribution in the studied profiles. Moreover, each profile shows particular features. Hollows and cavities filled by terrigenous and/or carbonate particles cemented by calcite are relevant in the ATS profile whereas in the MIR substrate platy cavities were developed. These variations would be indicative of the different paleomorphological position of the areas where the calcretes were developed.

Key words: Calcretes, Lacustrine limestones, Upper Miocene, Madrid Basin.

RESUMEN

En el sector sur de la Cuenca de Madrid, los últimos términos del Mioceno Superior están constituidos por calizas lacustres que presentan sobreimpuestos perfiles de calcreta. Las calizas se disponen sobre un conjunto sedimentario, predominantemente detrítico, formado por arcillas que se interdigitan con niveles poco continuos de calizas e intercalan canales arenosos de poca entidad. Este conjunto corresponde a un complejo fluviolacustre que evolucionó posteriormente hasta la implantación de un sistema lacustre extenso de carácter somero.

Se han estudiado detalladamente dos perfiles de calcreta (ATS,MIR) situados en un mismo nivel estratigráfico, distantes entre sí 1 km. Estos perfiles muestran sobreimpuestas al sustrato carbonático, entre otras, las siguientes facies de calcreta: masas de microesparita, micrita que engloba terrígenos dispuestos con textura ''floating'', horizontes de pisolitos con recubrimientos gravitacionales bien definidos y costras laminares. Estos rasgos, aunque comunes a ambos perfiles, se muestran con desigual desarrollo y reparto vertical en cada uno de ellos. Tales diferencias de distribución, así como otros rasgos específicos de cada perfil (conductos rellenos por terrígenos y cementados con micrita en el perfil ATS, huecos planares en el sustrato del perfil MIR), indican que los perfiles se desarrollaron en sustratos que ocupaban distintas posiciones paleomorfológicas.

Palabras clave: Perfiles de calcreta, Calizas lacustres, Mioceno Superior, Cuenca de Madrid.

1. INTRODUCTION

Calcretes, i.e., "terrestrial materials composed dominantly but not exclusively of calcium carbonate which occurs in states ranging from powdery to nodular to highly indurated and involve the cementation of, accumulation in and/or replacement of greater or lesser quantities of soil, rock or weathered material primarly in the vadose zone" (Goudie, 1983), are probably one of the most studied types of paleosols as they provide

useful information for sedimentological, palaeogeo-morphological and palaeoclimatic reconstructions as well as for the interpretation of ancient biological communities (Wright and Wilson, 1987; Retallack, 1988). Notwithstanding the wide attention paid to calcrete for at least three decades, other contributions to the understanding of processes of calcrete formation and interpretation of calcrete textures are still being offerred: distinction between pedogenically formed calcretes and those formed within the capillary-rise zone (Semeniuk and Meagher, 1981), origin of coated grains (Juliá and Calvet, 1983), significance of biogenic laminar facies in both ancient and recent calcrete profiles (Wright et al., 1988),.... The aforementioned examples provide evidence that our knowledge on calcrete profiles is increasingly improved throughout the study of new particular cases attempting to integrate a larger spectrum of geological situations: varied nature of the substratums in wich the calcrete is developed, control of position of the water table on primary and diagenètic features displayed by the calcrete profile, etcetera.

The objective of this paper is the description and interpretation of some calcrete profiles developed in lacustrine carbonate strata from Late Miocene successions of the southern Madrid Basin. The occurrence of the calcretes within the lacustrine carbonates would be indicative of stages of stabilization in the evolution of the lake system. Comparison between calcretes formed synchronously in different settings suggests that differences in the vertical arrangement of the calcrete features may be explained by paleogeomorphological controls. Particular textures within the calcretes, such as well developed gravitational pisoliths, are considered in detail. This study is included in a larger research program on telogenic processes affecting carbonate lacustrine sequences in central Spain.

2. GEOGRAPHIC AND GEOLOGIC SETTING

The study area is located in the southern part of the Madrid Basin, in the so-called "Mesa de Ocaña-Tarancón" (Fig. 1). This is a large, flat-topped outcrop of horizontally stratified Tertiary deposits limited north and south by the Tajo River and the Melgar Creek, respectively. The thickness of the succession of exposed Tertiary strata reaches up 120 m in thickness in the western side of the Mesa. There are three units in the Miocene recognized in the area, referred to as Lower, Intermediate and Upper Units (Junco and Calvo, 1983).

Fig. 1 shows a schematic map of the Tertiary deposits. The lowermost levels consist of gypsum and clays that belong to the Lower or Saline Unit. These evaporite beds contain glauberite and thenardite which are exploited in the northern slopes of the "Mesa de Ocaña-Tarancón", near Villarrubia de Santiago (García del Cura, 1979). In the southern part of the studied area the evaporites grade laterally into terrigenous deposits derived from the Toledo Mountains (Alía et al., 1973). The Intermediate Unit of the Miocene is composed of gypsi-

ferous sequences of marked detrital nature (gypsarenites and gypsolutites interbedded within cream, massive, autochthonous gypsum bed) (Megías et al., 1982) which intercalate with green and reddish mudstones in the sou thern part of the Mesa. The top of the Unit consists of a widely extended level of massive to roughly laminated dolostone. The age of these units spans the Lower and Middle Miocene (Junco and Calvo, 1983; Antunes et al., 1987).

The Intermediate Unit is discordantly overlain by terrigenous and lacustrine carbonate deposits that belong to the Upper Unit of the Miocene. Although direct paleontological evidence in the area to date these deposits has not been found, the age of the Upper Unit may be attributed, by stratigraphic correlation with other areas in the basin, to the Late Vallesian and Turolian (Antunes et al., 1987). The distribution of lithofacies is markedly heterogeneous. Both terrigenous and carbonate dominated sequences have been investigated in two large quarries (Asland and Iberia) located to the west of Yepes Village (Fig. 2). The sections measured in these quarries are representative of the lithostratigraphic characteristics of the Upper Unit of the Miocene in the western side of the "Mesa de Ocaña-Tarancón". The thickness of the Upper Miocene deposits does not exceed 10 m along this area. The calcrete profiles which are described here occur within this unit.

3. DEPOSITIONAL MODEL OF THE UPPER UNIT

Fig. 3 shows the correlation between eight lithostratigraphic logs measured in the Asland and Iberia quarries as well as in closely adjacent outcrops (Arroyo de las Cuevas del Oro section). Four different facies associations have been recognized from detailed sedimentological analysis of these logs:

a) *Sandstone/mudstone association.* Sandstones occur in isolated channels within the mudstones. The thickness of the channels rarely exceeds 1m. They are filled by cross-stratified (planar and trough cross-stratification) sands classified as subarkoses. Locally, the channels are filled by oncoliths and lime intraclasts. Mudstones associated to the channels are characteristically red to green, massive to roughly laminated silty clays. Locally the mudstones contain small amounts of cm sized lensoidal gypsum crystals.

b) *Mudstone/carbonate association.* This association has been only recognized in the Iberia quarry. Mudstones, consisting of finely laminated clays rich in palygorskite, alternate with thin carbonate beds displaying either a tufa texture or strong bioturbation by worms. The mudstones show dark brown to grey color due to richness in organic matter.

c) *Shallow lacustrine carbonate association.* It is the most widely distributed facies association in the
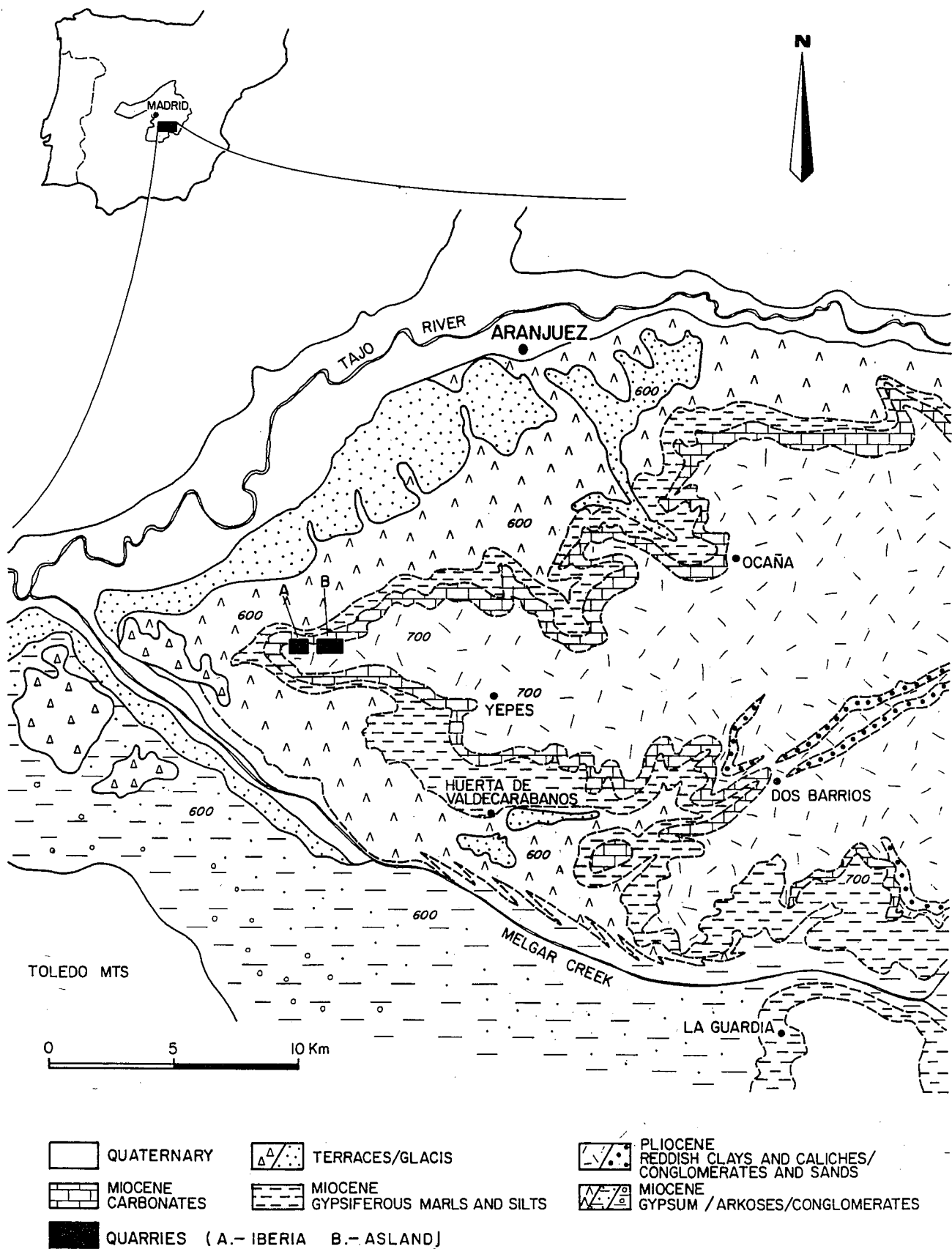
N

MADRID

TAJO RIVER ARANJUEZ
600

600

A B
600
700
OCAÑA

700
YEPES

HUERTA DE
VALDECARABANOS   DOS BARRIOS

600

600
700

MELGAR CREEK

TOLEDO MTS

LA GUARDIA

0   5   10 Km

QUATERNARY   TERRACES/GLACIS   PLIOCENE
                                             REDDISH CLAYS AND CALICHES/
                                             CONGLOMERATES AND SANDS
MIOCENE   MIOCENE   MIOCENE
CARBONATES   GYPSIFEROUS MARLS AND SILTS   GYPSUM /ARKOSES/CONGLOMERATES

QUARRIES (A.- IBERIA   B.- ASLAND)

Fig. 1.-Geologic sketch map and position of the studied outcrops (modified from Alía *et al.,* 1973).
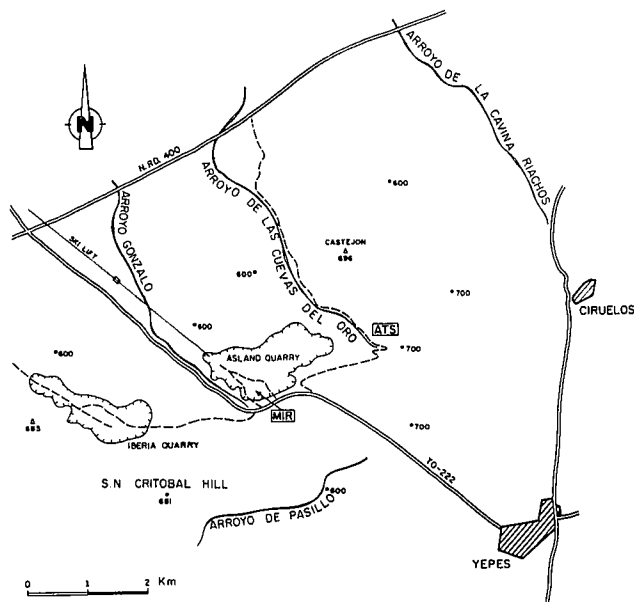Fig. 1.-Esquema geológico y situación de las canteras estudiadas (modificado de Alia *et al,* 1973).

Fig. 2.-Geographic setting and location of the studied outcrops.
Fig. 2.-Situación geográfica de los afloramientos y secciones estudiadas.

area. Several carbonate facies which interfinger laterally can be recognized: travertine (tufa) carbonates are dominant in the Iberia quarry but they are scarcely developed, even absent in the Asland quarry and northerly. In these latter zones the carbonates consist of micrites and biomicrites that contain small lenticular molds of gypsum, desiccation cracks, and fenestral fabrics. The calcrete profiles are commonly associated with these carbonate facies.

d) *Red mudstone/nodular to tabular carbonate association.* This association forms the uppermost levels exposed along the quarries. Mudstones include scattered gypsum crystals and carbonate nodules. They intercalate with irregular carbonate beds consisting of massive micrite.

Facies association (a) always occurs at the base of the sequence except for the eastern side of the Iberia quarry, where it interfingers the mudstones and carbonates of facies association (b). The shallow lacustrine carbonates of the association (c) are very continous laterally and overlie the deposits of the associations (a) and (b) all along the area. The thickness of the carbonate deposits shows small variations from one to other section.

Overall, the clastic and carbonate sediments of the Upper Miocene Unit in the studied area have been interpreted as fluvio-lacustrine deposits (Sanz, 1989). The four facies associations represent different depositional stages through the vertical evolution of the fluvio-lacustrine complex. In a first stage, sand filled fluvial channels and associated flood-plain mudstones were deposited over the gypsiferous beds of the Intermediate Unit. Small marsh areas (facies association b) coexisted with the fluvial sediments. In a second stage, a large shallow lake system was developed. The production

of carbonate, predominantly consisting of low magnesian calcite, was mainly contributed by plant photosynthesis as well as skeletal bioclasts. All the recognized features, such as presence of travertine tufas, abundance of desiccation cracks, gypsum moulds, and bioturbation features within the micrites are consistent with a shallow environment for the deposition of the carbonates. In addition, the superimposition of calcrete profiles in some carbonate beds clearly indicates that the lake environment was episodically subjected to drastic changes in lake level.

The final stage of the fluvio-lacustrine system is represented by facies association (d). These facies may be interpreted as muddy flood-plain deposits in which small ponds were developed leading to the formation of discontinuous carbonate beds, probably under some more arid conditions.

4. DESCRIPTION OF THE CALCRETE PROFILES.

Two calcrete profiles associated with the shallow lacustrine carbonate beds were selected for a detailed description and further interpretation. The first one (profile ATS) crops out in the Arroyo de las Cuevas del Oro (Fig. 2). The profile MIR was studied in a front located in the central part of the Asland quarry. Figures 4 and 8 correspond to the field sections of the calcrete profiles ATS and MIR respectively.

Extensive sampling of the two calcrete profiles was carried out in order to obtain detailed textural information from thin-sections, polished slabs and peels from the rock blocks. Mineralogy was identified by x-ray diffractometry of bulk powder samples rotated at 2.º/minute speed. The content of $MgCO_3$ in the calcite was determined by the method proposed by Goldsmith and Graf (1958). Cathodoluminiscence was used in some of the samples but results derived from this technique were not relevant for the present study provided the scarcity of luminiscent textures in our samples. CaO and MgO contents were determined in order to analyze vertical variations within the profiles. Also, K, Na,Sr, Mn, Zn and total Fe were analyzed in all the samples (K, Na by flame photometry; Sr, Mn, Zn, and total Fe by atomic absortion).

4.1. Profile ATS (Arroyo de las Cuevas del Oro)

A schematic representation of this profile is shown in Fig. 4. Total thickness of the measured section reaches up 4.40 m. Both field observation and recognition of textures in the laboratory reveal that the section is actually formed of two superimposed calcrete profiles, the lower one comprising 1.33 m at the base of the section. In general, the two superimposed profiles show similar evolutionary trends in vertical although the upper profile corresponds to a more mature calcrete.

The lower profile is composed from bottom to top of white-greyish nodular micrites containing scattered
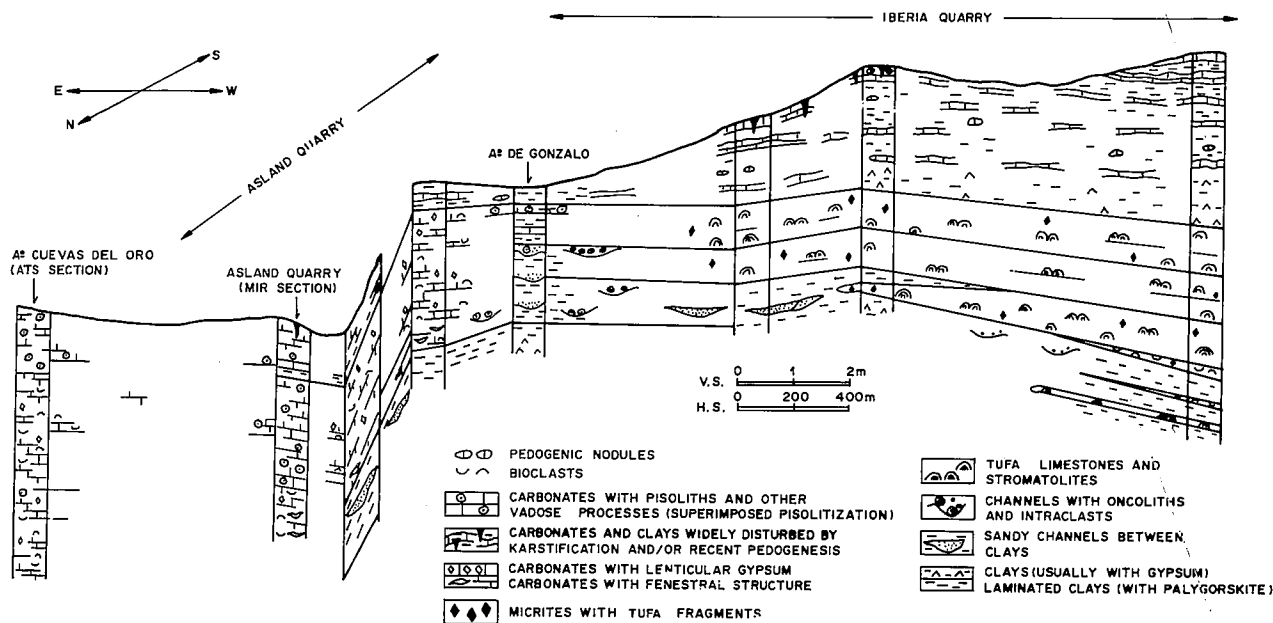
Fig. 3.-Sketch of correlation between lithostratigraphic logs.
Fig. 3.-Panel de correlación de facies entre las secciones estudiadas.

bioclasts and masses of lenticular gypsum; these micrites are penetrated by pink carbonates that petrographically consist of heterogeneous microsparite aggregates and small amounts of siliciclastic grains. Some fragments of the micrite substrate can be recognized within the microsparite aggregate. Both the micrite substrate and the microsparite are dissected by holes filled with 'peloids', limeclast and siliciclastic particles, and cemented by sparite calcite mosaics. The lime particles and the peloids are commonly contain by fragments detached from the substrate and the microsparite matrix.

The top of the described profile is sharply cut by a massive limestone bed (Fig. 4) which consists of micrite/whith variable amounts of molluscan fragments, charophyte stems and gyrogonites and some ostracods (Fig. 5a). The fabric varies from mudstone to packstone. The limestone is dissected by centimetre-scale cavities which give to the bed a slightly cracked appearance. These cavities, filled with siliciclastic and carbonate particles (Fig. 5e), extend and enlarge towards the top of the profile.

The micrites that form the substrate are replaced upwards by pink carbonates which consist of a mosaic of microsparite crystals with silt-sized siliciclastic grains (Fig. 5b). The limit between the microsparite masses and the micritic substrate is commonly diffuse. The amount of substrate fragments decreases upwards in the profile simultaneously to the progressive increase of the microsparite facies (Fig 6).

The upper horizon of the calcrete is formed of lithologies that differ from those described in lower positions of the profile, except for the clastic-bearing pink carbonates. Most of the volume of the upper horizon is occupied by dark red carbonate patches that are surrounded by the same material that fills the cavities in lower parts of the profile (Fig 6). Under the microscope, the dark red carbonate consists of dense micrite that

contain abundant sand-size clastic grains scattered in the micrite groundmass. This may be referred as "floating texture" (Esteban and Klappa, 1983). Several of the observed features are typical of this kind of texture, which has been frequently recognized in calcretes: abundance of corroded and fractured grains, disruption of the sediment matrix and clastic grains, coatings of micrite laminae and/or palissades of sparry calcite crystals (crystallaria) around the particles (Fig 5c). All these features are consistent with the displacive growth of calcite whithin the calcrete (Watts, 1978; Saigal and Walton, 1988; Braithwaite, 1989).

The dark red carbonate patches developed towards the upper part of the profile are typically bounded by a thin veneer of submillimetric thick laminae that consist of clay and fine grains included in a mosaic of calcite crystals. In the basal parts of the patches the laminae become thicker and form a well developed gravitational structure (Fig. 6). When developed at the base of small carbonate patches these structures look like asymmetric pisoids.

The top of the ATS profile is formed of a distinctive laminar calcrete which binds the carbonate patches with floating texture as well as the cavities filled with siliciclastic and carbonate particles. The latter lithology occupies a significant volume of the upper part of the profile (Fig. 6) and shows similar textural characteristics to that below. The laminar calcrete which is light reddish in colour, consists of an alternation of dense micritic laminae forming submillimetric rims and more porous layers showing micro-clotted texture and spheroidal to hemispheroidal aggregates of radial acicular calcite crystals (Fig. 5d). These aggregates are arranged in ribbons that are associated to the dense micrite laminae. Occassionally, the aggregates occur as clusters that give to the laminae a domed appareance. The diameter of the single radial aggregates ranges 30-40 μ. In
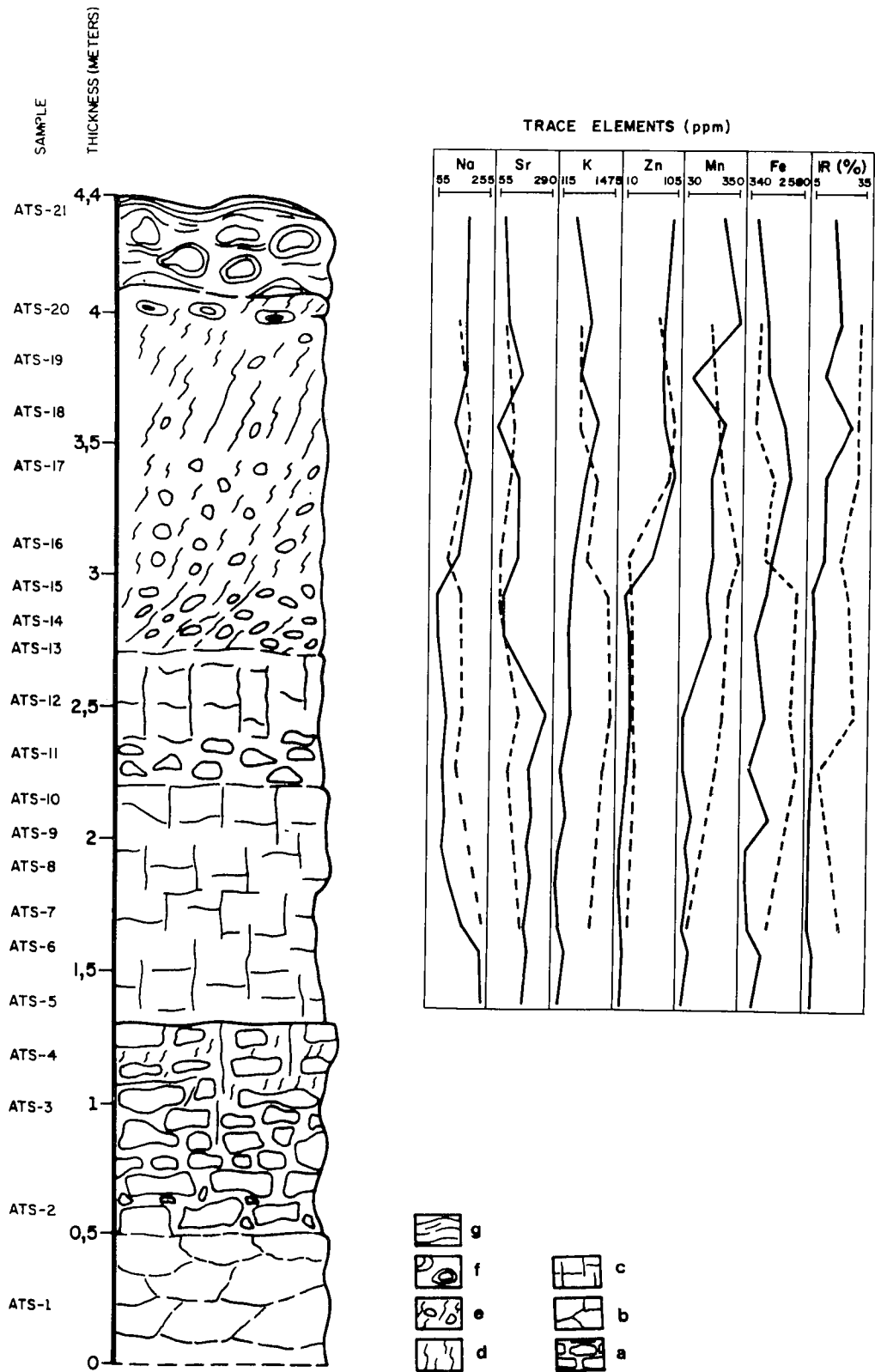
Fig. 4.-Schematic log of carbonate substratum and calcrete facies from the ATS section. a).- Brecciation, b).- nodular structure, c).- prismatic structure, d).- reddish carbonate, e).-calcareous nodules, f).- pisoliths, g).- laminations. Diagram of trace elements distribution along the uppermost profile. Discontinuos line represents the reddish carbonate lithology and the continous line represents the remainder lithologies.

Fig. 4.-Perfil esquemático de la seccion ATS mostrando la sobreimposición de sustratos carbonáticos y facies de calcretas. a).- Brechificación, b).- estructura nodular, c).- estructura prismática, d).- carbonatos de tono rojizo, e).- nódulos calcáreos, f).- pisolitos, g).- laminaciones. Gráfico de distribución de elementos traza en el perfil superior de la sección. El trazado discontinuo representa a la facies de carbonatos rojizos y el continuo a las facies restantes.

addition, small terrigenous grains are commonly found within the micro-clotted laminar fabric. In general, these features are similar to those described for laminar calcretes elsewhere (Harrison, 1977; Klappa, 1979; Semeniuk and Meagher, 1981; Esteban and Klappa,1983), though they correspond properly to the alpha type calcrete (Wright, 1990).

4.1.1. *Mineralogy and geochemistry*

The carbonate content in the Arroyo de la Cuevas del Oro section varies from 99% in the substrate limestones to 96.5% in the different calcrete horizons that form the profile. Carbonate mineralogy is characteristically low Mg calcite, as determined by the Goldsmith and Graf's method. Chemical analysis of the carbonates reveal that MgO contents do not exceed 2% in any case. CaO contents, ranging 39,5-44,5%, lie on the field indicated as normal for calcretes by several authors (Goudie, 1972; Aristarain, 1970).

The insoluble residues of the calcrete facies are usually composed of quartz, clays (illite predominant), and minor amounts of feldspars.

Trace element contents were determined by AAS and flame photometry for all the samples. The values that we have obtained for the upper profile of the section ATS are listed in table 1 and they are ploted in fig. 4.

Most significative trends of trace elements contents within the profile are represented, in our oppinion, by strontium, potassium, manganese and iron. Except for the former, the other elements show a progressive content increase from bottom to top which is in agreement with a process of gravitational percolation of meteoric water conducting to the creation of oxidant conditions. This could be clear for Fe and Mn whereas the increase of potassium appears closely related to calcrete facies (micrite with floating texture, voids filled with terrigenous) in which clastic grains and clays (mostly illite) are rather abundant. On the other hand, the strontium content decreases from average values of 220 ppm in the limestone substrate to contents below 200 ppm in the remainder facies. This is particularly evident in the laminar calcrete, where the really low Sr content suggests strong influence of meteoric water on its formation.

Mineralogical and chemical results obtained from the ATS section apparently support a "per descensum" model for the formation of the calcrete profile.

4.1.2. *Interpretation*

Facies analysis of the Arroyo de las Cuevas del Oro section indicates that two successive episodes of calcrete formation, separated by deposition of limestones in a freshwater shallow lake, were developed in the area. The profile that corresponds to the first episode of calcrete formation can be considered as a rather mature (Machette's Stage V) paleosol (Retallack, 1988). The top of the profile is sharply cut by shallow lacustrine deposits which provides evidence of a new period of lake expan-

sion in the area. Lacustrine sedimentation progressed until the area was newly desiccated and the exposed sediments were affected by pedologic processes leading to the development of the upper calcrete profile.

The interpretation of the calcretes is focused on the upper profile as it displays similar facies to the lower one and, besides, it seems representative of a more mature stage of soil development. The profile was formed throught successive stages which have been schematized in Fig. 7. The initial stage is marked by brecciation/cracking of the limestone substrate. The brecciation process could be related both to desiccation and and root penetration (stages 1,2, Fig. 7). The formed discontinuities favoured water circulation within the profile and created suitable conditions for diagenetic transformations of the host limestones. Differences of calcrete facies from bottom to top within the profile are indicative of distinct diagenetic conditions that, in turn, could be also related to different rates of carbonate accumulation. Thus, the calcrete facies in the lower part of profile consist of microesparite masses which resulted either by neomorphism (recrystallization) of the micrite substratum (James, 1972; Tandon and Narayan, 1981) or from alternanting phases of crystal growth and dissolution (Wright and Peeters, 1989). The process of microsparite formation should be more pervasive towards the middle part of the profile as indicated by the process upward decrease of micrite fragments. In the upper part of the profile, a generalised occurrence of carbonates showing floating texture is though to be indicative of the plugging of the soil profile owing to the precipitation of calcite under supersaturated conditions (stage 3, Fig. 7). The mechanism of formation of floating texture in calcretes has been recently revised by Braithwaite (1989). This author considers this texture as a product of progressive evaporation within the vadose zone, the process being favoured by reduction of permeability in the upper horizon of the calcrete profile.

A second phase for the development of the calcrete profile is indicated by the presence of hollows and cavities which deeply dissect the profile from bottom to top (stage 4, Fig. 7). The geometric relationships between the cavities, commonly filled by calcareous (peloids and fragments) and terrigenous grains in a microsparite to sparite crystalline matrix, and the previously mentioned calcrete facies (Fig. 7) suggests further reorganization of the soil profile. The dissection of the calcrete could be caused by disolution, in a similar way to that proposed by Netterberg (1980), or by the combined effect of plant penetration, desiccation and dissolution. Irrespective of the precise mechanism, there is good evidence that the cavities were the way for water circulation that plucked fragments from the walls and dragged them downwards. The detachment of the fragments could be favoured by cracking of the walls during periods of major desiccation and/or weak consolidation of the parent material.

The filling of cavities and hollows was terminated by the development of laminar veneers around the blocks. The larger development of the laminae at the
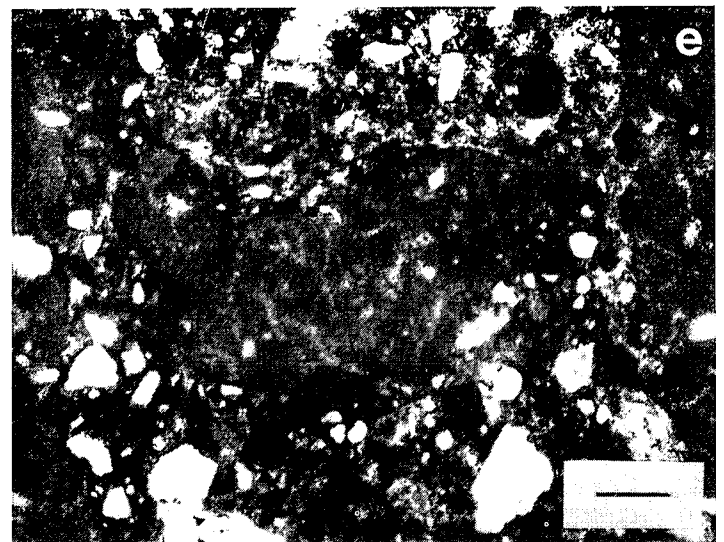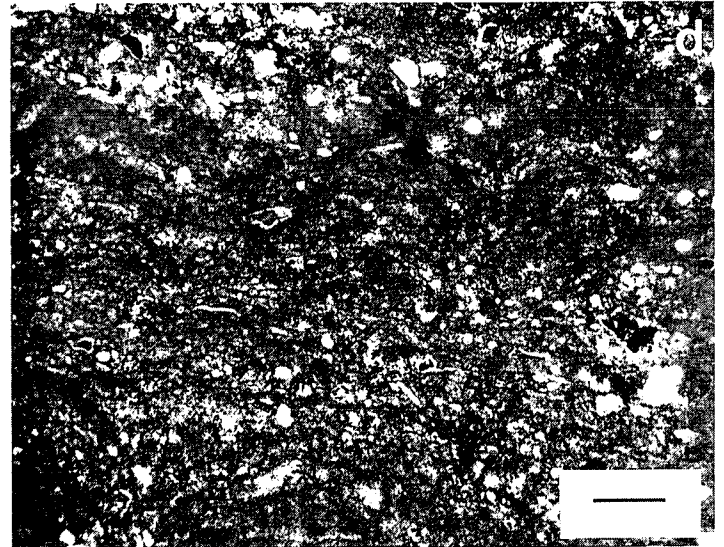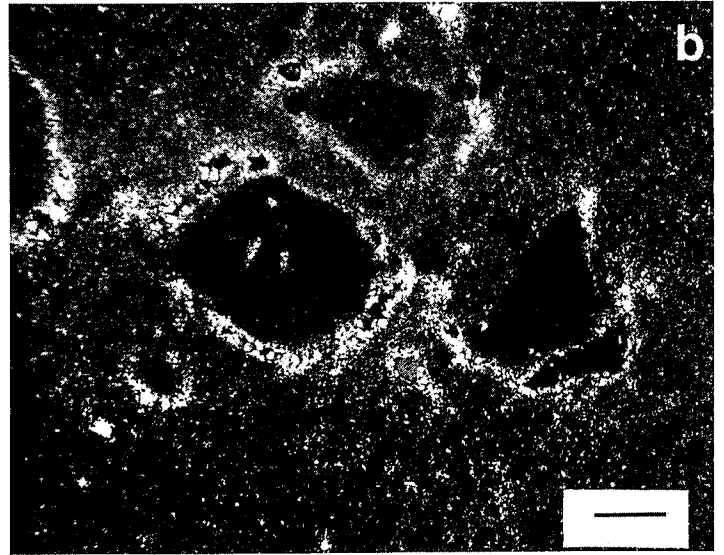
base of the blocks seems to corroborate that gravitational circulation of water was the main mechanism during the second phase of calcrete formation. On the other hand, the occurrence of a well developed laminar calcrete (stage 5, Fig. 7) at the top of the profile is related to plugging by carbonates of the underlying horizons. Laminar calcrete is interpreted as the result of successive periods of evaporation from $CaCO_3$ supersaturated water perched between the A and B horizons of the soil. In fact, the laminar calcrete is classified as an alpha-type calcrete (Wright, 1990), wich is in agreement with the proposed model of laminar calcrete formation. The role of organisms, probably represented by fibrorradiaxial microfabrics within the laminae, in the growth of the calcrete is not yet well understood.

4.2. Calcrete profile from the Asland quarry

The profile is located in the similar stratigraphic position that the Arroyo de las Cuevas del Oro profile. They can be correlated over a lateral distance of about 1 km (Fig. 3). In the Asland quarry, the calcrete profile was developed from the alteration of lacustrine limestones which are characterized by massive bedding and minor joints of clay material. The thickness of the studied profile reaches up 3 m and it is overlain by alternating red mudstones and carbonates (Fig. 8).

From bottom to top the profile is composed of the following horizons (Fig. 8):

1) hard, white, massive limestones which contain abundant planar voids arranged parallel to the bedding (Fig. 9). The length of the voids ranges 2-10 cm. The limestones themselves are fossiliferous micrites, and contain ostracods, charophyte gyrogonites, and gasteropods. They locally show tufa structures and calcitized pseudomorphs of lenticular gypsum.

2) white to pink, hard carbonates with pisoliths. The white carbonate material in this part of the profile corresponds to fragments of lacustrine limestones quite similar to the underlying horizon. The pink carbonate material is a matrix composed of microsparite which contains corroded silt and sand quartz grains. The amount of this matrix increases upwards within the level. The limit between the matrix and the fragments of lacustrine limestone is commonly sharp and is often occupied by blocky calcite cements. The pisoliths in this level are characteristically asymmetric exhibiting
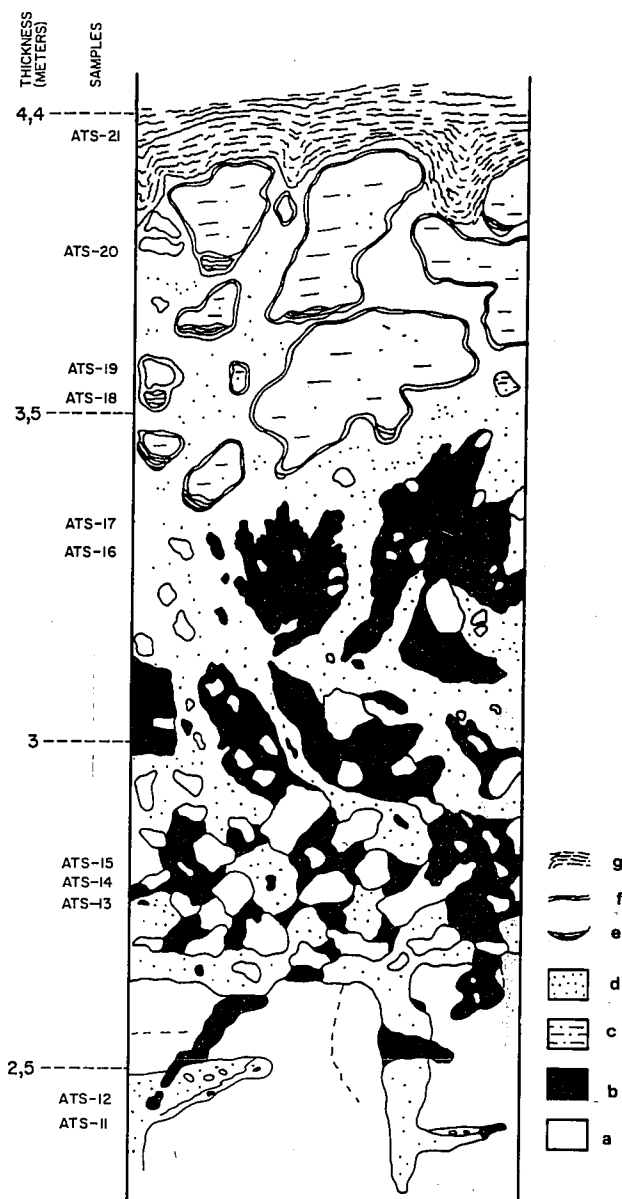

Fig. 6.-Vertical distribution of more relevant calcrete fabrics in the upper profile of the ATS section (Sketch obtained from the polished hand samples). a).- Limestone substrate, b).- microsparite masses, c).- micrite with floating texture, d).- holes filled with micrite and terrigenous, e).- gravitational lamination, f).- micrite coating, g).- laminar crust.

Fig. 6.-Esquema de distribución de facies en el perfil superior de la sección ATS (obtenido a partir de las secciones pulidas de muestras de mano). a).- Sustrato calizo, b).- masas de microesparita, c).- terrígenos insertos en micrita con textura "floating", d).- conductos rellenos con micrita y terrígenos, e).- laminaciones gravitacionales, f).- cubiertas micríticas, g).- costra laminar.

Fig. 5.-Photomicrographs of the different horizons of the ATS profile. a)- Fossiliferous limestone of the substrate. b).- Microsparite masses surrounding micrite nodules. c).- Micrite with "floating" detrital grains. d).- Dense micrite laminae forming layers in the laminar crust. e).- Detrital grains and fragments detached from the walls filling cavities. Scale bar represents 500μ in c) and 200μ in the remaining photomicrographs.

Fig. 5.-Microfotografías de los rasgos que caracterizan los horizontes diferenciados en el perfil ATS. a).- Sustrato biomicrítico. b).- Nódulos micríticos englobados por masas de microesparita. c).- Granos siliciclásticos "flotando" en la matriz micrítica. d).- Capas formadas por láminas de micrita densa en la costra laminar.e).- Siliciclastos y fragmentos micríticos rellenando cavidades. La barra representa 500μ en C) y 200μ en las fotografías restantes.
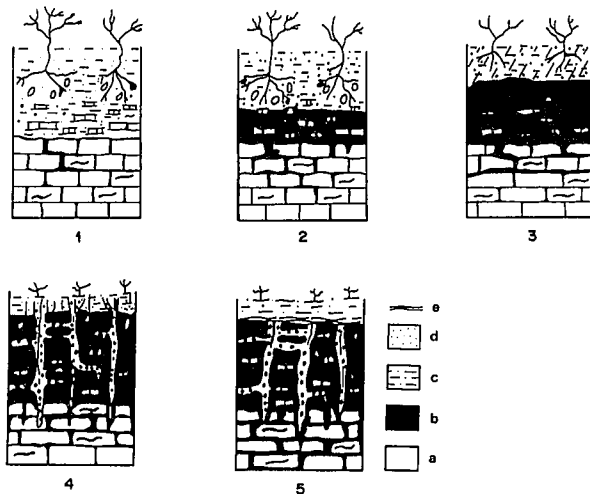
Fig. 7.-Evolutionary stages during the formation of the ATS profile. See text for explanation. a).- Limestone substrate, b).- microsparite masses, c).- soil surface, d).- holes, e).- laminar crust.

Fig. 7.-Etapas de formación del perfil ATS (explicación en el texto). a).- Sustrato calcáreo, b).- masas de microesparita, c).- Suelo superficial, d).- conductos, e).- costra laminar.

a marked gravitational growth (Fig. 10). The sizes of the pisoliths are varied, ranging from 0.3 to 3 cm.

The nucleus of the pisoliths typically consists of fragments of fossiliferous micrite. The thickness of the coatings is closely related to the size of the nucleus. Most developed coatings are 2.5 cm thick. The coatings are characteristically formed by two alternating types of laminae: a) dense micrite laminae with scarce silt grains and frequent polygonal cracks, and b) laminae consisting of peloids and other micrite aggregates, sand to silt-sized terrigenous grains, and calcite cement (Fig. 11). The latter laminae are usually thicker than the micrite laminae. As observed in Fig. 11 the mosaics of sparite may occur either as blocky cements in peloid rich laminae or as microstalactite rims with a pendant appearance. Similar sparite fabrics have been described by Chadwick *et al.* (1988).

3) the horizon is dominated by pink, hard carbonates which are similar to those described as microsparite matrix in the underlying level. This part of the profile is also characterized by a large development of pisoliths, though in this case the pisoliths show symetric coatings around the nucleus. The nucleus are usually formed of mosaics of microesparite, pseudosparite and other recrystallized textures. If not transformed, the fabric is seen to be formed of micrites with calcite seudomorphs after lenticular gypsum. Around the nucleus, the pisolith laminae consist of dense, reddish-pigmented micrite that contains fine-grained, corroded quartz grains as well as calcite prisms. The boundary between the laminae and the nucleus is irregular. Very often, the micrite laminae present alveolar textures as well as radially arranged calcite aggregates. Pisoliths with gravitational growth are rarely present in this horizon.

4) the level with symmetric pisoliths is capped by a thin laminar calcrete. Under the microscope, it consists of an alternation of mm thick dense micrite laminae, that characteristically exhibit micro fibrorradiaxial calcite aggregates, and laminae which are strongly pigmented by iron oxides and contain clays and fine silty particles.

4.2.1. Mineralogy and geochemistry

The carbonate content of the Asland quarry section varies from 98.5% in the substrate limestones to 96% in horizons that show evidence of pedologic transformation. As the ATS profile, all facies recognized here are characteristically composed of low Mg calcite, the values of $MgCO_3$ being systematically lesser than 4.5%. Average CaO contents of the substrate limestones and calcrete facies are 51% and 44.5%, respectively. MgO contents do not exceed 2% in any case.

The insoluble residues of the calcrete facies are usually composed of quartz, clays (illite predominant), and minor amounts of feldspars. Percentages of insoluble residues as well as trace element contents are listed in Table 2 and they are ploted in fig.8. In the MIR section the Fe content increases from bottom to top suggesting more oxidant conditions as well as higher contents of terrigenous particles upward in the profile. A similar, although no so clear, trend is observed for Mn. Strong increase of potassium from bottom to top is also thought to be indicative of progressive contamination by terrigenous (both sands and clays) particles. With regard to Sr contents, the obtained values do not show a clear tendency from higher contents in the substrate values to lesser amounts in all the calcrete facies. However, the relative lower Sr contents in the horizon 2 of the profile, dominated by microsparite matrix fits well with the supposed recrystallization processes that accounted for the formation of the microsparite facies.

4.2.2. Interpretation

In the Asland Quarry section only one well developed calcrete profile has been recognized. The profile, 3.30 m thick, records a complete vertical succession of calcrete horizons that were developed from a substrate made up of lacustrine limestones. The profile is capped by a thin laminar calcrete which is considered to correspond to the final stage of calcrete formation.

The initial stage of calcrete formation is thought to coincide with the complete exposure of the previously deposited shallow lake limestones. This is assumed in view of the morphology and distribution of voids in the bottom of the profile, the planar voids suggesting lateral circulation of water when the lake sediment was subaerially exposed. This effect should be combined with percolating water which mainly acccounted for accumulation of carbonate in the B horizon of the soil. The importance of gravitational movement of water within the profile would be corroborated by the common downward occurrence of strongly asymmetric pisoliths.
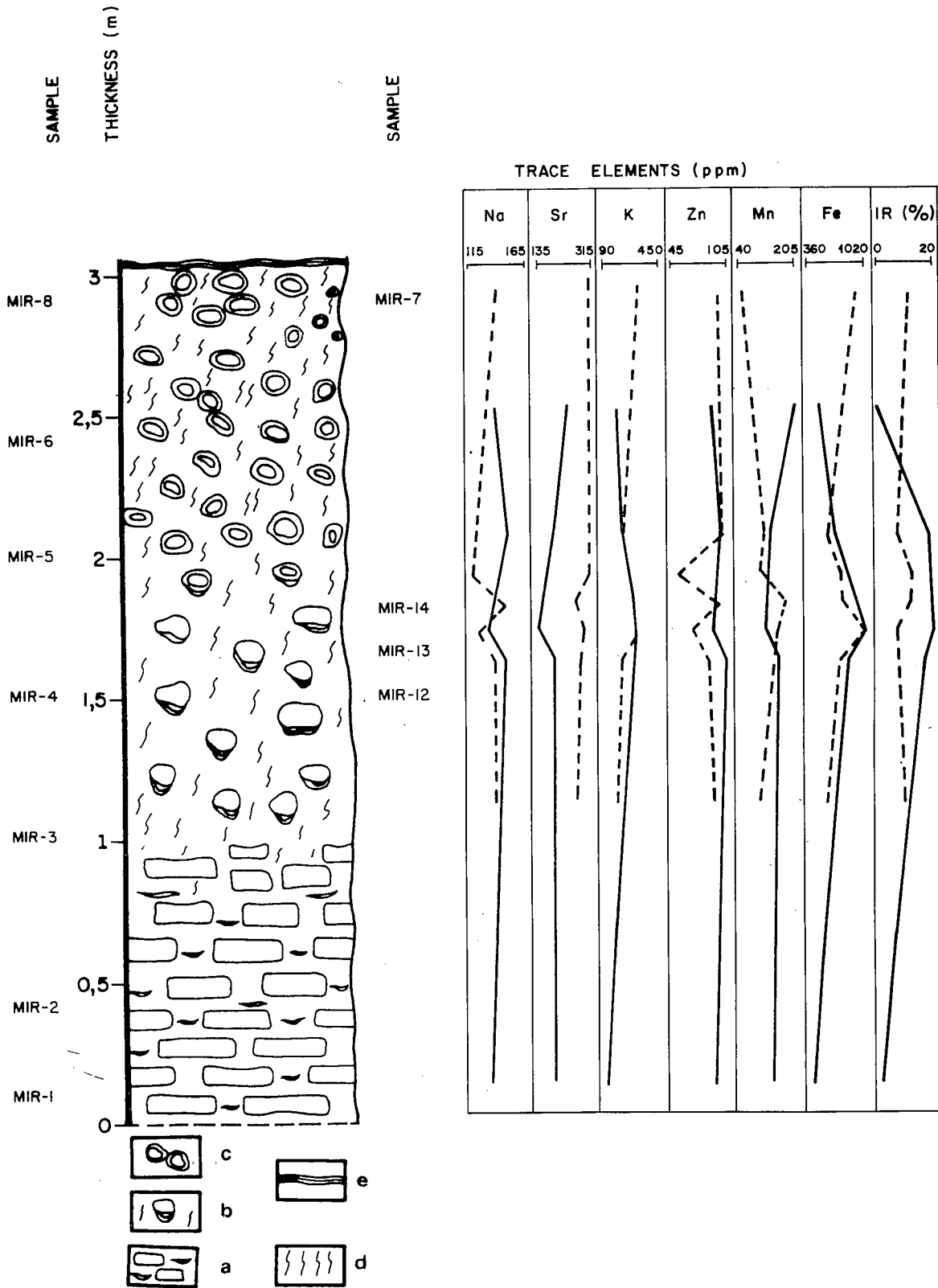
Fig. 8.-Schematic log of carbonate substratum and calcrete facies from the MIR section. a).- Limestones with subhorizontal porosity, b).-pisolith with gravitational laminations, c).- pisolith with continous coats, d).- pink carbonate, e).- laminar crust. Diagram of trace elements distribution along the profile. Discontinuos line represents the pisoliths lithology and the continuos line represents the remainder lithologies.

Fig. 8.-Perfil esquemático de la Sección MIR mostrando la sobreimposición del sustrato carbonático y facies de calcreta. a).- Calizas con porosidad subhorizontal, b).- pisolitos con laminaciones gravitacionales, c).- pisolitos con recubrimientos continuos, d).- carbonatos de tonos rosáceos, e).- costra laminar. Gráfico de distribución de elementos traza en el perfil. El trazado discontinuo representa a las facies pisolíticas y el continuo a las restantes.

Lithology	Sample	Na	Sr	K	Zn	Mn	Fe	% IR
Substrate	5	211	196	250	13	53	682	7
	6	206	214	317	18	71	924	8
	7	139	200	223	19	55	485	5
	8	103	225	118	16	75	349	5
	9	85	207	141	16	62	397	5
	10	92	229	287	18	71	982	5
	11	74	207	170	18	50	462	6
	12	93	288	268	21	34	912	5
Microsp. with subs fragments	14	58	113	221	23	86	586	7
	15	57	104	277	19	82	957	5
Microsp. with nodules	16	132	173	397	64	112	1208	12
	17	166	183	670	100	93	1941	13
Micrite with floating texture	18	133	55	1105	80	126	1803	23
	19	145	186	511	74	68	993	12
	20	149	127	884	74	351	993	19
Holes	7	252	208	900	20	68	1292	25
	11	115	133	1293	26	131	2581	9
	12	128	182	1476	25	151	2215	29
	15	119	83	1325	26	162	2473	27
	16	78	89	720	21	171	1107	21
	17	143	194	924	81	149	1447	33
	18	150	112	516	104	108	710	30
	20	116	118	582	70	136	679	32
L. Crust	21	132	70	288	87	132	378	12

Table 1.- Trace element contents of the upper profile of ATS section (contents are given in ppm).
Tabla 1.- Contenido en elementos traza del perfil superior de la Sección ATS (expresado en ppm).

Lithology	Sample	Na	Sr	K	Zn	Mn	Fe	% IR
Substrate	1	139	184	93	89	118	368	6
Pisoliths	3	148	245	168	94	78	531	11
	4	147	261	268	86	131	674	9
	12	122	266	394	66	133	1023	10
	13	159	247	383	96	157	763	13
	14	115	315	323	47	87	735	13
	5	165	294	235	97	97	559	9
	7	190	242	639	120	145	303	27
	8	152	301	437	97	43	895	13
Matrix	4	164	175	370	102	144	797	17
	12	136	136	443	90	103	986	14
	5	165	174	237	99	121	609	10
	6	155	229	167	90	203	430	4

Table 2.- Trace element contents of the MIR section (contents are given in ppm).
Tabla 2.- Contenido en elementos traza de la Sección MIR (expresado en ppm).

The development of the pisoliths is, however, envisaged as a rather late process during to the formation of the calcrete profile. Firstly, the lacustrine limestones were altered (recrystallized) to microsparite mosaics. The process of recrystallization became more developed from bottom to top in the profile. The resultant textures are quite similar to those observed in the Arroyo de las Cuevas profile and they are interpreted in a similar way.
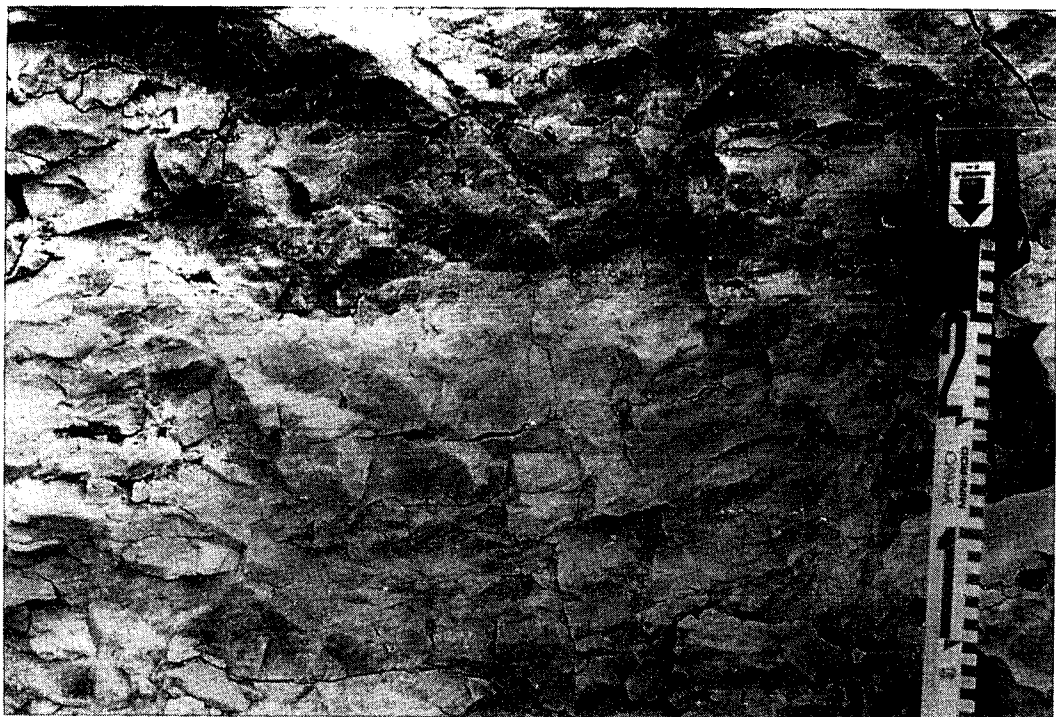

Fig. 9.-Development of planar voids in the substrate of the MIR profile.
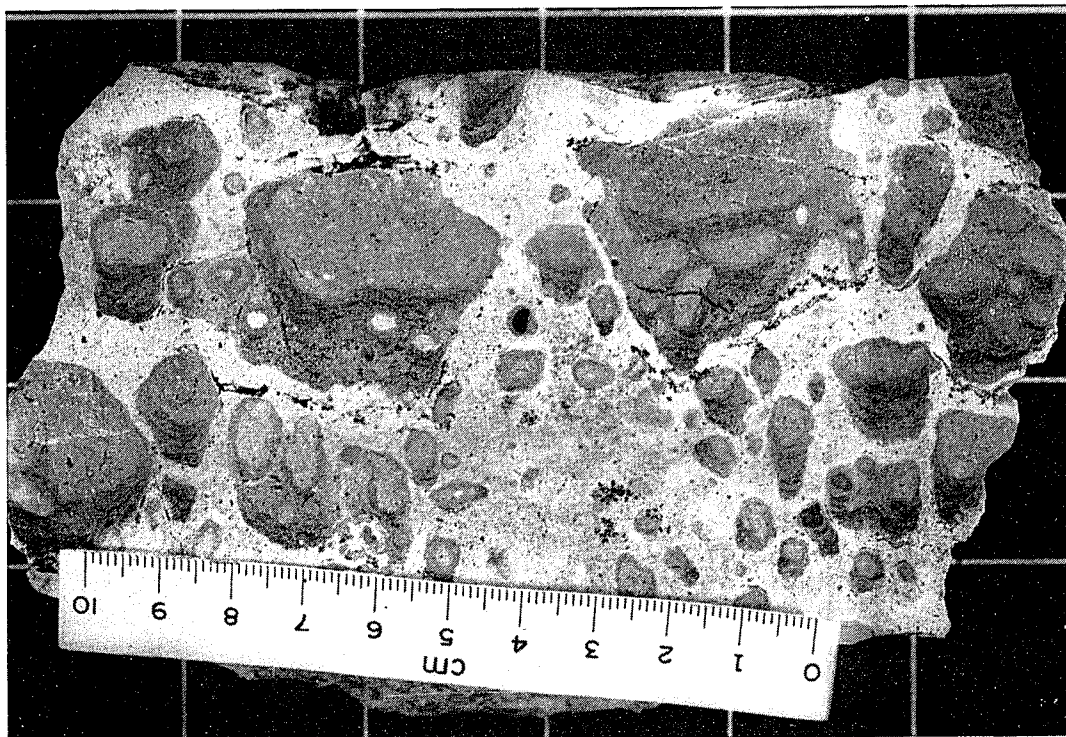Fig. 9.-Aspecto de los huecos planares desarrollados en el sustrato del perfil MIR.

Fig. 10.- Polished hand sample showing a marked development of gravitational pisoliths.
Fig. 10.- Muestra de mano pulida mostrando un marcado desarrollo gravitacional de los pisolitos.
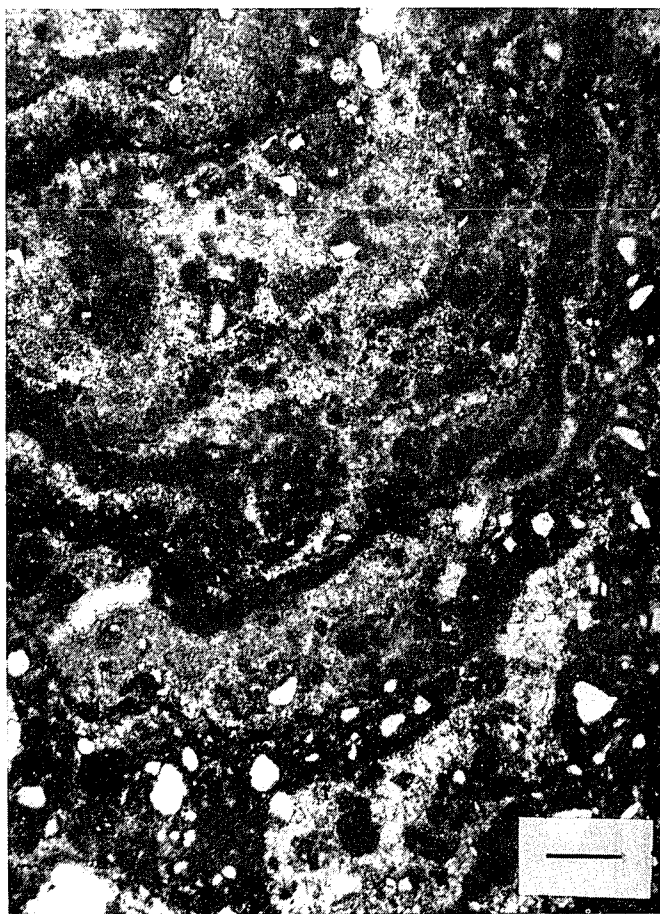

Fig. 11.- Photomicrograph of the layers of the pisolith coatings. Note the alternation of dark dense micrite whith scarce silt grains and clearer laminae formed of peloids, terrigenous grains and sparite mosaics. Scale bar represents 200μ.
Fig. 11.- Detalle de las capas que forman los recubrimientos gravitacionales de los pisolitos mostrando la alternancia de láminas oscuras de micrita y láminas más claras con peloides, granos terrígenos y mosaicos de esparita. La barra representa 200μ.

In constrast, the concentric (symmetric) pisoliths developed in the upper part of the calcrete profile are thought to have been due to root activity. The internal structure of the pisoids, formed of micrite with scattered lenticular gypsum moulds at the centre and concentric laminae of micrite displaying alveolar-septal texture (Calvet et al., 1975; Wright, 1986; Goldstein, 1988), is clearly indicative of the suggested organic influence on the formation of the pisoliths. The occurrence of the lenticular gypsum in the centre ("nucleus") of the pisoids could be related to the presence of organic matter derived from the decay of plants (Cody, 1979).

It is inferred that roots of plants should be progressively restricted to the upper parts of the profile as carbonate accumulated. Final deposition of carbonate is represented by the laminar calcrete which is considered to result from alternanting periods of more or less $CaCO_3$ saturated waters at the top of the profile.

5. DISCUSSION

The two described calcrete profiles show strong similarities concerning both the substrates over which the profiles were developed and the facies that can be observed in them. However, some differences arise when the distribution and textural characteristics of the calcretes are compared. The differences are thought to be related to the different topographic position of the areas where the two calcrete profiles were developed.

Limestones that form the substrate of the Arroyo de las Cuevas (ATS) and the Asland Quarry (MIR) are stratigraphically correlative and, in both cases, they show textures that are characteristic of a very shallow lake environment. The superimposition of two limestone-calcrete cycles in the ATS section suggests that the deposition of the limestones was rapidly followed by periods of subaerial exposure leading to the formation of the pedogenic profiles. The uppermost calcrete profile in the Arroyo de las Cuevas section is considerably more developed than the lower profile and shows features of a supermature stage of calcrete (Machette, 1985).

The host-rock of the calcrete profile of the Asland quarry is formed of limestones which exhibit both components and features indicative of extremely shallow and paludal conditions. Consequently, it is assumed that this area was located in a relatively higher topographic position than the Arroyo de las Cuevas del Oro location. The marginal lake area behaved as a higher landscape of moderate gradient that favoured better drainage than the central lake when the complete system became desiccated. Thus, when the general lake area was progressively desiccated the lacustrine sediments became exposed and affected by pedogenic processes which led to the formation of the calcretes. The process of pedogenic alteration might be somewhat diachronic in the Asland Quarry and the Arroyo de las Cuevas del Oro, the latter location remaining still ponded when the former was subaerially exposed. This situa-

tion could create a twofold gradient for water moving in the system. In the exposed areas the water could penetrate downward the lake sediments favouring the initiation of the calcretization of the carbonate substrates. This pattern was probably combined with lateral circulation of phreatic water at the base of the limestone beds as suggested by the occurrence of planar voids porosity observed in the lower part of the Asland Quarry profile.

The larger development of gravitational fabrics, particularly the assymetric pisoids, in the Asland Quarry profile seems to corroborate that vadose processes were somewhat more effective in this location Percolation of water is considered to be the main responsible mechanism for the origin of the pisoliths.

The intraclasts and peloids that form the laminae in the pisoids are interpreted as a product of the dissaggregation and further collapse of the walls of voids within the soil profile. The accumulation of these types of particles alternated with micrite laminae, which are thought to have been precipitated from $CaCO_3$ saturated water in periods of relative dryness. No clear evidence of organic contribution to the formation of this type of pisoliths has been found.

On the contrary, the symmetric pisolihs recognized in the upper part of the two studied profiles exhibit features (e.g., alveolar-septal textures) that can be considered characteristic of root activity. Likewise the spherulites or hemispherulites which occur within laminar calcretes are initially interpreted as related to biological activity. This type of microestructure has been seldom described in the literature on calcretes although our own experience indicates its rather common presence, at least in the examples provided by calcretes in many areas of Spain. No clear explanation has been given for these fan-like radiaxial sparite aggregates. Several types of spherules made up of aragonite needles, interpreted as related to organic activity, have been described in recent calcrete deposits by Ducloux and Butel (1983), and Nahon et al. (1980) but we lack examples of the diagenetic evolution of these microstuctures in older deposits. Our spherulites show, in some cases, similarities with the ribbon spars described by Goldstein (1988) but there are some differences regarding sizes, lateral continuity within the laminae, and they are generally less limpid than the Goldstein's examples.

6. CONCLUSIONS

Distinctive calcrete profiles were developed over lacustrine carbonates of Upper Miocene age in the southern part of the Madrid Basin. The calcrete profiles display features that are characteristic of a pedogenic super mature stage. The vertical succession of calcrete facies is as follows: 1) carbonate substrate made up of shallow lake and/or paludal limestones; 2) lower diagenetic facies, characterized by pervasive microsparite mosaics; 3) massive calcrete with floating texture; 4) hollows and cavities filled by terrigenous and/or carbonate particles cemented by low Mg calcite; and 5) la-

minar calcrete. This general trend is accompanied in the two studied profiles by a rather large development of pisoliths.

Differences between the calcrete profiles would be indicative of some variations of the regime of vadose processes leading to the formation of the profiles. These variations are thought to be related to the different topographic position of the areas where the calcretes were developed. In this way, when the lacustrine system became desiccated, the relatively higher marginal lake area, where the MIR section occurs associated, allowed better drainage conditions by comparison with the central lake placement of the ATS section.

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