Petrological and mineralogical characterization of lutitic deposits in a fluvial dominated depositional system. Upper Oligocene - Lower Miocene, Loranca Basin (Central Spain)

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Abstract: The study of the clay minerals in the Upper Unit (Upper Oligocene - Lower Miocene) in Loranca Basin shows a change from the bottom (subunit 1) to the top (subunit 2). Subunit 1 is characterized by the clay mineral association 1, when the great part of the clay minerals are detrital as illite and kaolinite. Subunit 2 is characterized by the clay mineral associations 2 and 3 which contain palygorskite. The great abundance in palygorskite along subunit 2 is related with a gradual diminution in the smectite content and with an important climate change. Clay mineral evolution reflects paleoenvironmental changes induced by tectonics and climate. Clay composition types cannot be associated to a clasification of flood-plain palaeoenvironments.

Key words: Clay sedimentology, Clay mineralogy, Palygorskite, Loranca Basin.

Resumen: El estudio de los minerales de la arcilla en la Unidad Superior (Oligoceno superior-Mioceno inferior) de la Cuenca de Loranca muestra un cambio desde la subunidad 1 a la subunidad 2. La subunidad 1 se caracteriza por la presencia de una asociación de minerales de la arcilla (asociación 1), donde la mayor parte de los minerales de la arcilla son de origen detrítico, como illita y caolinita. La subunidad 2 se caracteriza por las asociaciones 2 y 3 con paligorskita. La presencia de paligorskita a lo largo de la subunidad 2 se relaciona con una disminución gradual en el contenido de esmectita y con un importante cambio climático. La evolución de los minerales de la arcilla reflejan cambios paleoambientales inducidos por la tectónica y el clima. Los tipos composicionales de minerales de la arcilla no parecen estar asociados a los distintos paleoambientes dentro de la llanura fluvial.

Palabras clave: Sedimentología de arcillas, Mineralogía de arcillas, Paligorskita, Cuenca de Loranca.

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The Loranca Basin is located in the central part of Spain (Fig. 1, A). Three major stratigraphic units have been distinguished in the Tertiary succession of this area: the Lower Unit, the Upper Unit and the Terminal Unit (Garcia Abbad, 1975; Díaz-Molina and López-Martínez, 1979; Díaz-Molina *et al.*, 1985 and 1989; Gómez *et al.*, 1995). The Upper Unit is formed by two coalescing depositional systems (Fig.1, B): the Tórtola and Villalba de la Sierra systems (Díaz-Molina *et al.*, 1989). These filled the Loranca Basin from the late Oligocene to the Early Miocene. In the Early Miocene, at the top of the Upper Unit, gypsum deposits developed in the basin. The Tórtola and Villalba de la Sierra depositional systems of this Upper Unit were dominated by individual river channels. The deposits of these depositional systems overlie the earlier sediments of the basin with an onlapping relationship. Tectonic deformation also occurred during the deposition of this unit, as shown by progressive discordance on the flanks of the anticlinal folds and along the basin margins. The greatest exposed thickness of the Upper Unit is 900 m. Three subunits in the evolution of the depositional systems have been recognized (Díaz-Molina *et al.*, 1989) reflecting the rate of diastrophism and changes in the base level of the fluvial systems:

Subunit 1 corresponds to the most active period of the Tórtola fan. It consists mainly of channelized bodies composed of conglomerates and sandstones, together with silts, silty clays, thin sandstones or siltstones sheets and limestones layers.

Subunit 2 differs from the previous in several as-

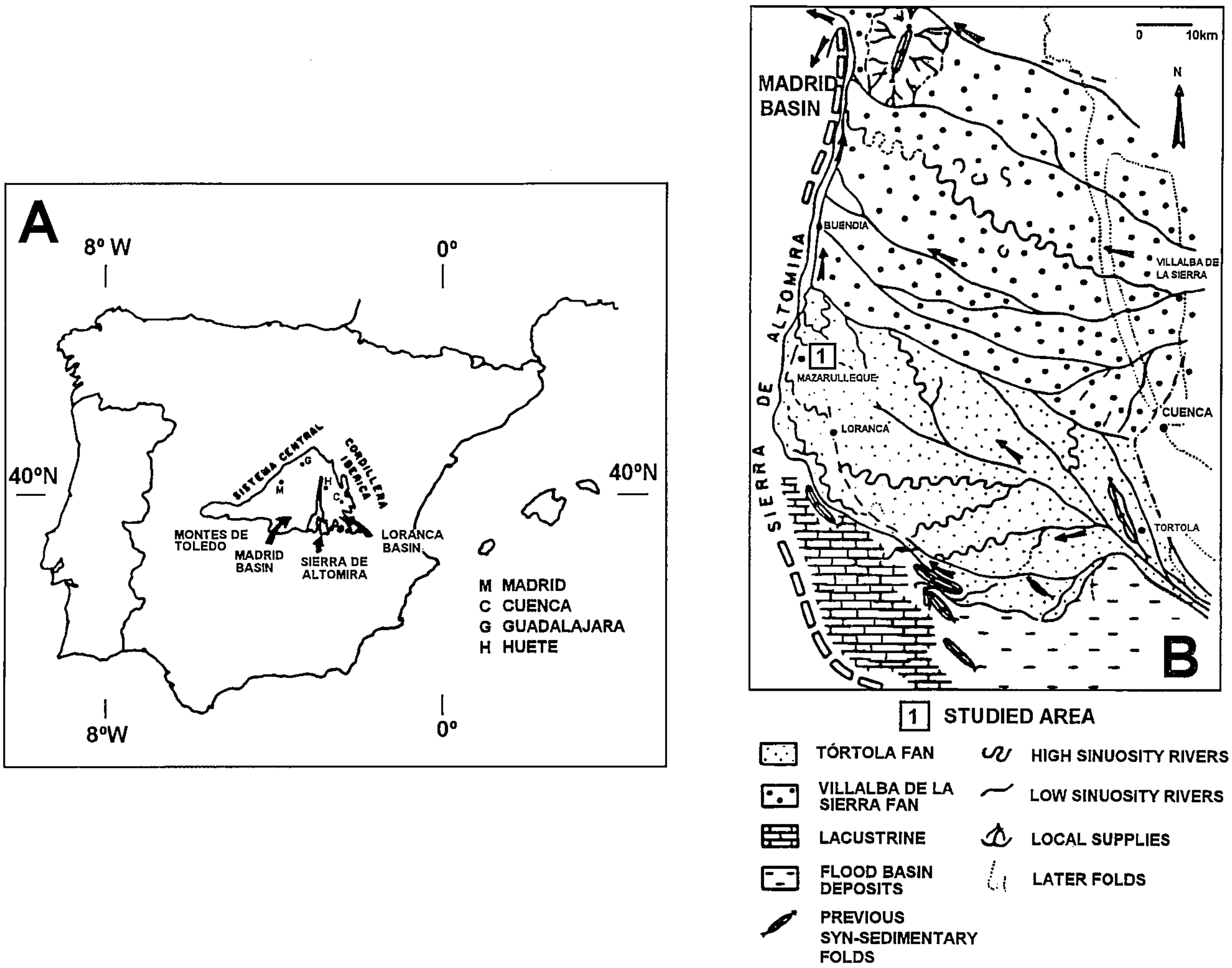

Figure 1.- A: Situation of the Loranca Basin; B: Reconstruction of the Tórtola and Villalba de la Sierra fans (Díaz-Molina *et al.*, 1989).

pects: the Tórtola fan became progressively inactive; other differences may be related to a reactivation of the Sierra de Altomira and sediments of local provenance developed around the western margin of the basin; also the Villalba de la Sierra fan reached its maximum extent, indicating a tectonic reactivation of the northern Serranía de Cuenca. Sediments are sandstones with gypsum cement, mudstones with gypsum crystals, gypsum, marls and limestones.

Subunit 3 is characterized by the dominance of gypsum deposits. The gypsum was clearly supplied from solution weathering of Late Cretaceous and Triassic rocks.

Several sedimentological and petrological studies of the Upper Unit have been carried out in the last years by Díaz-Molina (1978), Díaz-Molina and López-Martínez (1979), Díaz-Molina *et al.* (1985), (1989) and (1994), and Arribas & Díaz-Molina (1995). The majority of these are detailed studies about sandstone bodies. While there are few works in the lutitic sediments, being mudstones the most abundant sediments along subunit 1 and 2 of the Upper Unit. But it must be highlighted the study achieved by García Palacios (1977) about the clay mineral characterization of the Tertiary mudstones in this area.

The mudstone sediments studied in this paper correspond to the Upper Unit. The best exposures of these mudstones are located in the Mayor River Valley near of Huete locality (Fig. 2), where a cross-section was made (Fig. 3). The studied exposure is 800 m long. Its stratigraphic succession is 115 m thick and it comprises the upper part of subunit 1 and part of the subunit 2. Lithologies include sandstones, mudstones, limestones, gypsiferous silts and gypsum. The lower part of the section displays a greater abundance of sandstone bodies and gypsiferous layers are scarce. In the upper part, more reddish, gypsum layers and gypsum cement in the sandstones are conspicuous features. Correlations were mainly based on continous or partially continous distintive stratigraphic levels such as lacustrine carbonate and paleosols. Identified floodplain elements correspond to a landscape dominated by meandering rivers. They include meander loops, abandoned meandering channels, channel-fills, crevasse splays, levees and floodbasin. Abandoned meandering channels reveal a variety of facies and frequently show lacustrine condition upwards (ox-bow lake development). Channel fill deposit is used to indicate sandy fillings in non meandering channels; In this part of the Mayor River Valley exposure they are scarce and small, probably associated to crevassing. Overbank marginal deposits consist of sheet like sediments. They may show

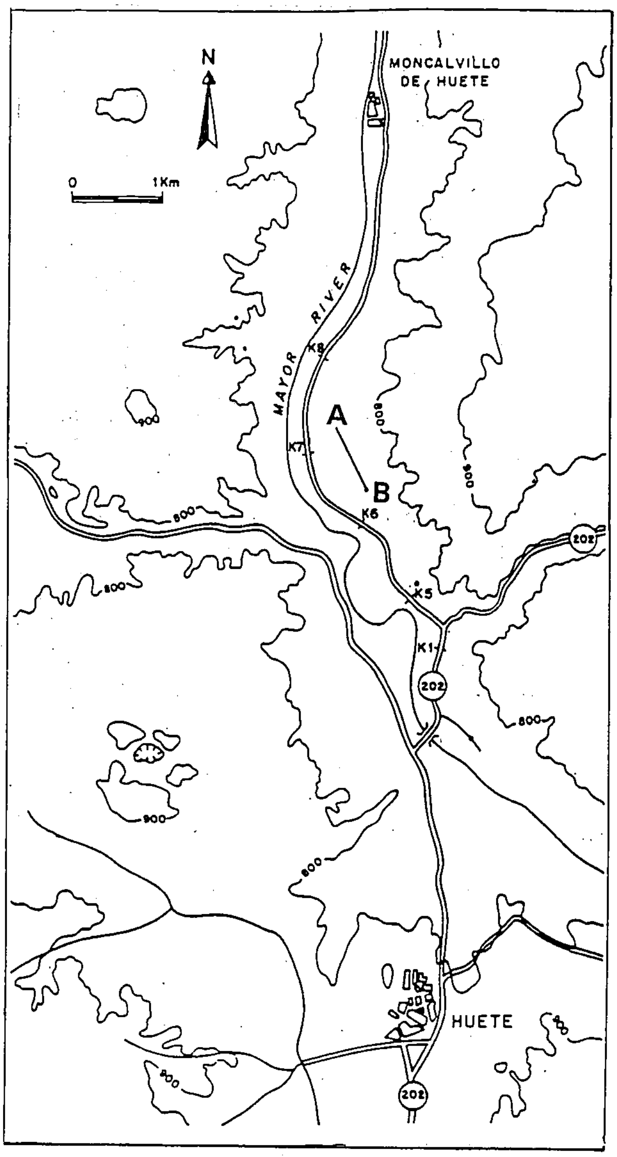

Figure 2.- Location of the cross-section (A-B).

an erosional basal surface indicating crevasse-splay nearness to the channel margin. The bulk of the floodbasin mainly consists of massive silty clays. They include lacustrine deposits consisting of marls and/or limestones. In the upper part of the stratigraphic succession silty clays contain lenticular gypsum crystals and were interpreted as playa-lake sediments (Díaz-Molina *et al.*, 1989; Arribas and Díaz-Molina, 1995). Meandering rivers eroded this substratum incorporating gypsum clasts to their bed load. Paleosols are entisols and calcretes, they mainly developed at the top of the abandoned channels, over marginal overbank deposits and in marginal lacustrine palaeoenvironments.

The aim of this paper is to characterize the clay mineralogy in a fluvial dominated depositional system and to decipher their significance in relation to the basin infill during subunit 1 and 2.

Analytical Methods

Along three stratigraphic logs and in some sedimentary facies corresponding to the Upper Unit 39 samples of mudstones were collected for mineralogical and petrological analysis. The mudstones sampled correspond to several sedimentary facies like: point-bar, flood basin, abandoned meandering channel, lacustrine and paleosol. In each sample mineralogical analysis have been undertaken to determine the bulk and the clay mineralogy (Figs. 4, 5 and 6). Besides a comparative study has also been made between the different clay mineral associations and their sedimentological facies.

Classical techniques were used to analyze the mineralogical composition of the whole and fine fractions (less than 20 and 2 μm) of the mudstones (claystones and siltstones), including microscopic techniques, X-ray diffraction and scanning electron microscopy. In each sample the sand and silt fraction has been separated and artificially cemented with blue epoxy resin. Then thin sections were obtained for petrographic observation. X-ray diffraction analysis have been carried out from the powder diagrams, using the reflectant powers method (Schultz, 1964) for the quantitative estimations of the minerals.

The fine fractions (<20 and <2 μm) was separated from the disaggregated samples by sedimentation and oriented slides were obtained. All the oriented slides were air dried, etylene-glycol treated and heated at 550°C. Quantitative estimations of the clay mineral components were obtained from the method of the reflectant powers (Schultz, 1964). The X-ray diffraction analysis were achieved using a Phillips PW 1130/90 X-ray diffractometer and Cu-Kα radiation. Scanning electron microscopy was performed on a JEOL-6400 equipment.

Mineralogical and Petrological features

The textural characteristic of the mudstones let their classification in siltstones and claystones. In general, siltstones and claystones have a massive structure and sometimes show parallel lamination. Although they appear in the Upper Unit without a clear order, normally siltstones are related to sand bodies (point-bars and crevasses). The mudstones in the subunit 2 contain gypsum crystals but not in the subunit 1.

Bulk Mineralogy

The bulk mineralogical composition of mudstones consists of calcite, dolomite, gypsum, quartz, potassium feldspar and clay minerals. These minerals have been quantified and the obtained results are summarized in a data base (Table I). Besides it has been recognized tourmaline and mica, but as mineral in trace (less than 1%).

Quartz (Figs. 4, 5 and 6). Appears in all lutitic sediments (claystones and siltstones), but decreases in claystones. The abundance in quartz varies between <5% and 50% (Table I). Also, a high proportion in quartz grains are present in lutites of the subunit 1, while in the subunit 2 are scarce. Monocrystalline (undulatory and nonundulatory) and policrystalline quartz grains (metaquart-

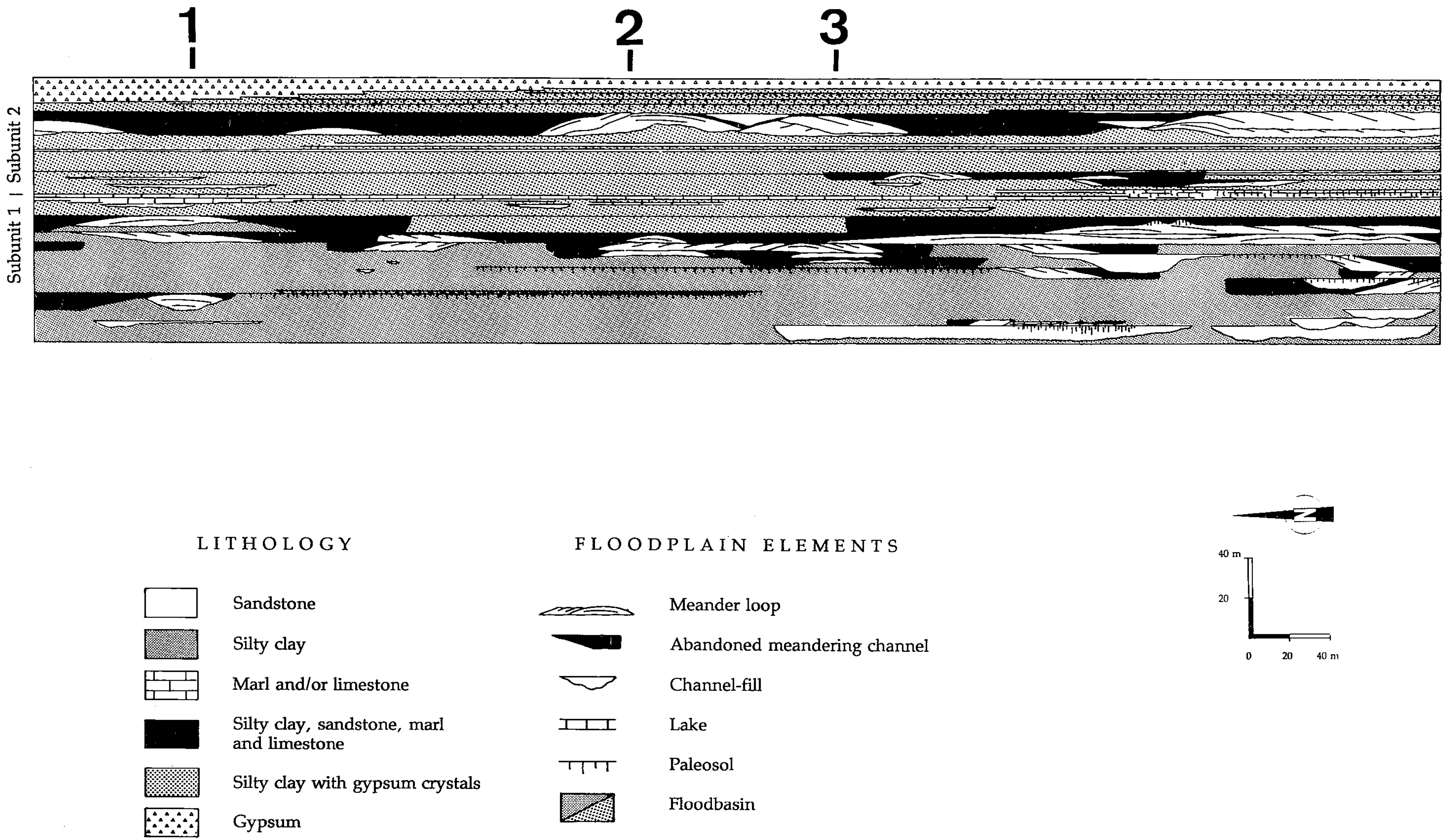

Figure 3.- Cross-section composition including identified floodplain elements and stratigraphic logs (After Díaz-Molina *et al.*, 1994).

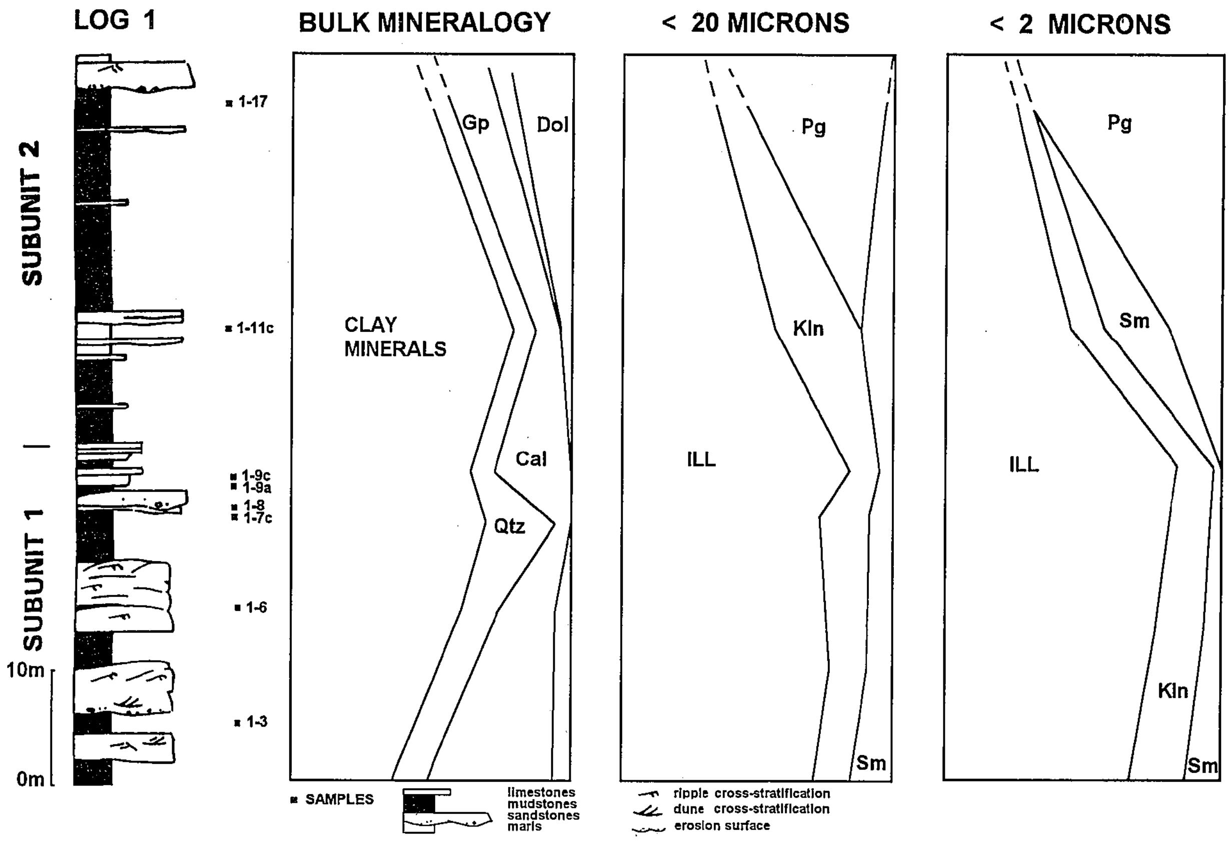

Figure 4.- Stratigraphic succession of log 1. Location in Figure 3. Abbreviations for minerals and clays: CM = Clay minerals; Qtz = Quartz; Cal = Calcite; Gp = Gypsum; Dol = Dolomite; Ill = Illite; Kln = Kaolinite; Sm = Smectite.

zite) has been observed. The petrographic study of the sand and silt fractions indicates a detrital origin for the quartz grains.

Calcite (Figs. 4, 5 and 6). is present in the subunit 1 and its proportion ranges from 10 to 65% (Table I). It appears with a micritic texture related with a quartz grains and clay minerals. Calcite disappears with the presence of gypsum crystals and dolomite in the subunit 2. Calcite is present as micritic aggregates, sometimes with a peloidal texture including quartz grains. Petrographic evidences show that carbonate grains reveal reworking from specific environments in the alluvial system as calcimorphic paleosols and lacustrine deposits.

Dolomite (Figs. 4, 5 and 6). Is present only in the subunit 2 as a major component constituted by dolomicrite aggregates. The abundance of this mineral ranges from <5% to 35% (Table I). In the subunit 1 dolomite is present as broken dedolomitized crystals but as mineral in trace (less 1%). Normally dolomicrite aggregates include gypsum euhedral crystals. This mineral has been interpreted as the result of a desplacive growth by evaporation processes in the flood basin areas joint other minerals as gypsum and palygorskite.

Gypsum (Figs. 4, 5 and 6). In the subunit 2 mudstones (claystones and siltstones) has an important amount of gypsum crystals, while in the subunit 1 gypsum is scarce. Its proportion varies from <5% to 60% (Table I). Gypsum crystals appear with several textures: lenticular crystals, rossetes-like aggregates and anhedral crystals. Generally, gypsum is related with dolomite. An early diagenetic origin was deduced for this mineral which formed inside lutitic sediments in flood basin and lacustrine areas. The presence of gypsum along the subunit 2 is in relation to an important change in the sedimentation, which evolves to evaporitic under arid conditions.

Clay minerals (Figs. 4, 5 and 6). These components are present in all samples along the Upper Unit, and the proportion varies between 15 to 85% (Table I). It has been differentiated: illite, kaolinite, smectite and palygorskite.

Clay Mineralogy

The main clay minerals identified in the fine fraction of the Upper Unit mudstones are: illite, kaolinite, smectite, palygorskite and illite-smectite and chlorite-smectite mixed layers (Table I). These clay minerals appear related in three types of clay mineral associations (Fig. 7).

Illite. Illite is the dominant clay mineral in the Upper Unit (Figs. 4, 5 and 6). The abundance of illite varies between 25 and 85% (Table I). Illite presents a light degree of interstratification Ill/Sm with the presence of open reflections. SEM observations reveal that illite grains emerge in thin flakes (laminar crystals) without a preferring orientation and the medium size is 2 µm (Fig. 8, A). Illite is associated with quartz, potassium feldspar and mica grains and inside the clay mineral group it is joined smectite and kaolinite. From the bottom to the top of the logs it is observed that illite decreases. The main

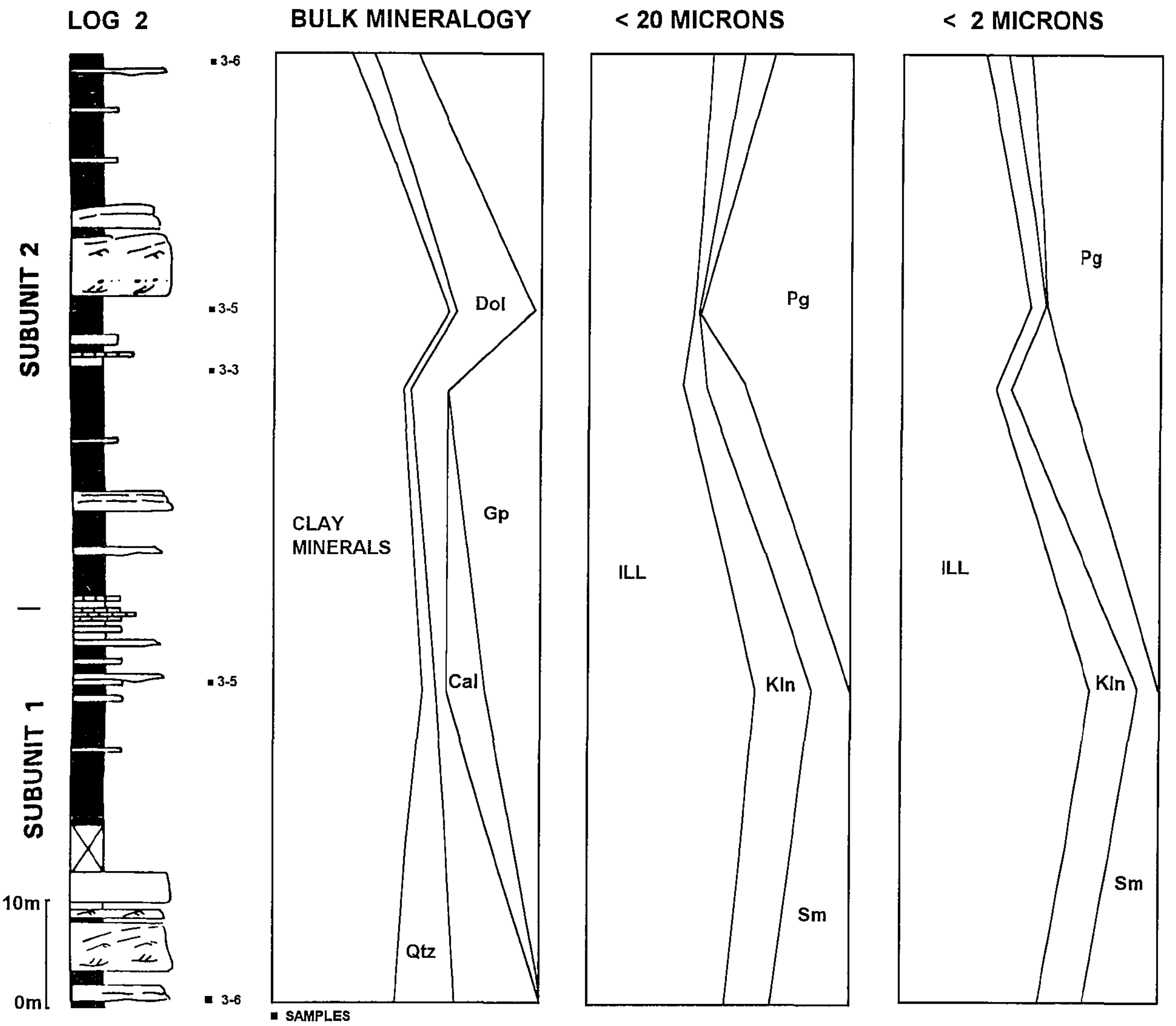

Figure 5.- Stratigraphic succession of log 2. Location in Figure 3. See Fig. 4 for minerals and clay abbreviations.

proportion of illite is located in the bottom of the stratigraphic succession, related with sand bodies (point bars and crevasses).

Smectite. The amount of this clay mineral varies between 5% and 50% (Table I). Smectite presents a light degree of interstratification Chl/Sm. SEM studies reveal that smectite is present as irregular flake-shaped particles of a medium size of 7 µm (Fig. 8, B). Smectite appears to be associated to illite and detrital components as quartz, potassium feldspar and mica. Smectite decreases at the top of the subunit 2, increasing the palygorskite proportion in this sense (Figs. 4, 5 and 6).

Kaolinite. It appears joint illite, smectite and other detrital components as quartz, potassium feldspar and mica. Kaolinite appears in all kinds of clay mineral associations. The kaolinite content ranges from <5% to 30% (Table I). SEM observations indicate that kaolinite crystals are sheet-shaped with alterated borders, but they conserve partially a characteristic pseudohexagonal habit. Kaolinite appears in all the mudstone levels and its proportion decreases upwards (Figs. 4, 5 and 6).

Palygorskite. This clay mineral appears only associated to gypsy mudstones in subunit 2 (Figs. 4, 5 and 6). Moreover, palygorskite proportion increases to the top. The abundance of this clay mineral ranges from 20 to 70% (Table I). Palygorskite appears in the associations 2 and 3 (Fig. 7). SEM studies reveal that palygorskite crystals consist of disordered fibers without a preferent orientation (Fig. 8, C). The medium size varies between 1 and 2 µm. Palygorskite fibers covered components impeded the observation of these, and in some cases it is possible to see palygorskite fibers formed from other laminar components as smectite (Fig. 8, D).

Evolution and distribution of clay minerals

The clay minerals of the mudstones of the Upper Unit in the Huete sector occur in several associations (Fig. 7). There is a clear differentiation between the clay mineral associations along the Upper Unit. In the subunit 1 clay mineral associations have not palygorskite while in the subunit 2 this clay mineral appears (Fig. 7). The presence of palygorskite point to an important change between both subunits 1 and 2.

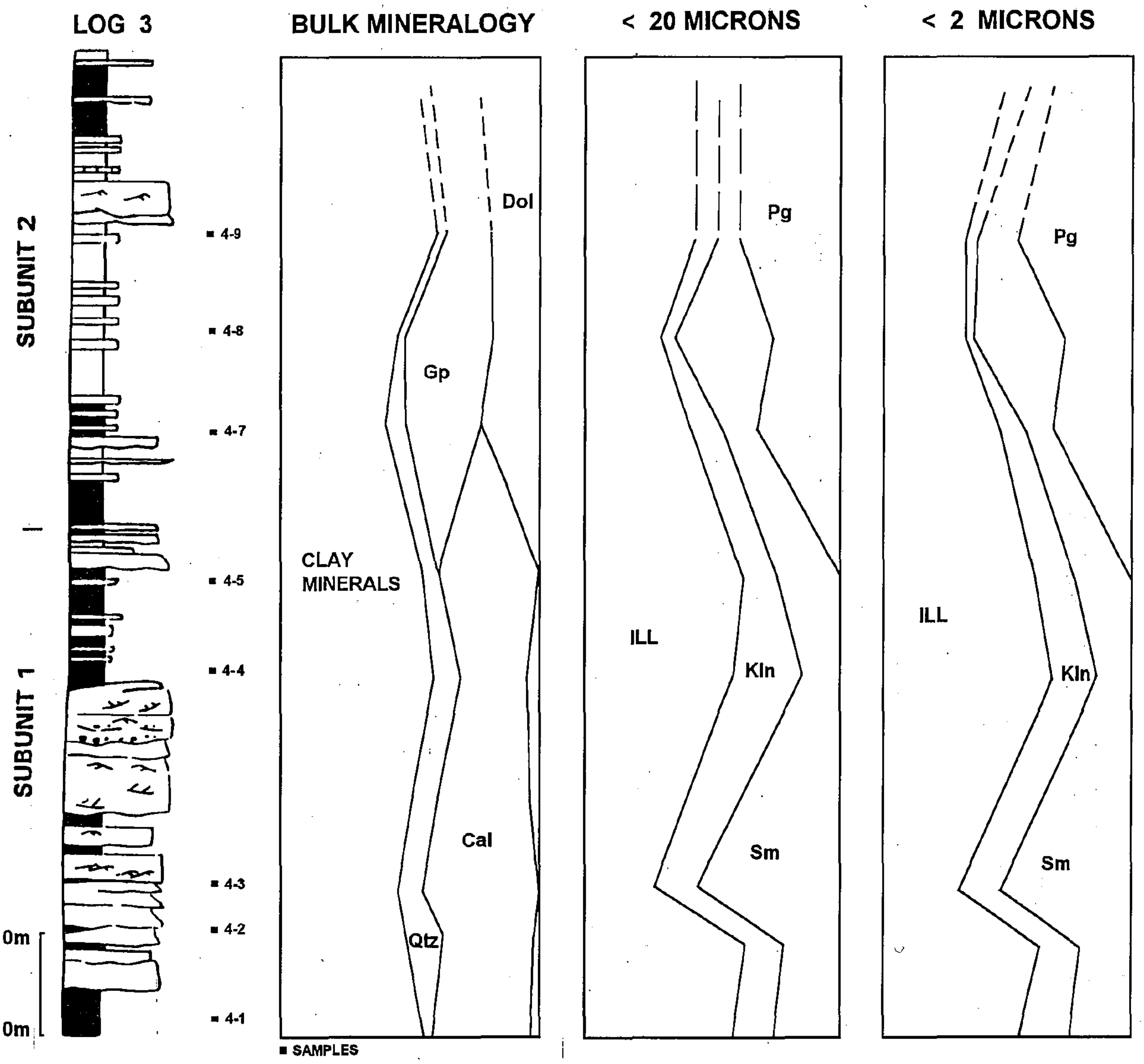

Figure 6.- Stratigraphic succession of log 3. Location in Figure 3. See Fig. 4 for minerals and clay abreviations.

Subunit 1: Clay mineral associations

The association 1 is characteristic along the subunit 1 (Fig. 7). The association 1 is represented by clay minerals as illite and kaolinite which has been interpreted like detrital clay minerals. The mineralogy of the detrital clay minerals agrees with the mineralogy of the Mesozoic materials that have constituted part of the source area (Caballero and Martín, 1974; Ruiz and Caballero, 1976; Garcia Palacios *et al.*, 1977; Fernández-Calvo, 1986). According to the main mineralogical characteristics of these materials that constituted the source area during the Miocene in this sector of the Loranca Basin, an assemblage of stable clay minerals (illite and kaolinite) which had been submitted to weathering and transport processes exists. In this case these clay minerals came from the source area as detrital minerals or partially transformed to clay minerals with open structures.

Subunit 2: Clay mineral associations

The subunit 2 is characterized by the clay mineral associations 2 and 3 which contain palygorskite. The palygorskite is the most characteristic clay mineral in this subunit. It appears suddenly at the beginning of the subunit 2. These associations are the result of the mineralogical transformations of the associations 1 along the subunit 2 (Fig. 7). The great abundance in palygorskite, along subunit 2, is related with a gradual diminution in the smectite content (Figs. 4, 5 and 6) and with an important climate change. The palygorskite was formed from the magnesian smectite transformation in arid conditions in the flood plain areas like a pedogenetic deposit (Singer, 1984; Chamley, 1989). The palygorskite is a typical clay of arid and semi-arid soils and one of the few useful paleoclimatic indicators among the clay minerals (Singer, 1980). The conditions of formation of palygorskite are remarked by Singer (1979) like: alkaline pH, high Si and Mg, and low Al activity. In these areas submitted to conditions of continuous evaporation it is possible to attain the required concentrations of Mg and Si for the palygorskite formation. In this sense, recent sedimentological studies of the Upper Unit point out that during the stage

Table I. - Mineralogical composition of the mudstone samples. **N** = Number of samples; **H** = High (m) in the cross-section; **L** = Lithofacies (S = silt without gypsum, SG = silt with gypsum, C = clay without gypsum, CG = clay with gypsum); **F** = Sedimentological facies (PB = point bar, FB = flood basin, MC = abandoned meandering channel, L = lacustrine, P = paleosol); **Cal** = % Calcite; **Dol** = % Dolomite; **Gp** = % Gypsum; **Qtz** = % Quartz; **CM** = % Clay minerals; **Kfs** = % Potasium feldspar; **SM** = % Smectite < 20 microns; **Ill** = % Illite < 20 microns; **Kln** = % Kaolinite < 20 microns; **P** = % Palygorskite < 20 microns; **sm** = % Smectite < 2 microns; **ill** = % Illite < 2 microns; **kln** = % Kaolinite < 2 microns; **p** = % Palygorskite < 2 microns.

N	H	L	F	Cal	Dol	Gp	Qtz	CM	Kfs	SM	Ill	Kln	P	sm	ill	kln	p
1	25.00	S	PB	45	5	0	10	40	0	15	65	20	0	15	65	20	0
2	30.00	C	PB	25	<5	0	10	60	<5	10	75	15	0	10	75	15	0
3	32.50	C	FB	25	0	0	5	70	0	10	70	20	0	5	80	15	0
4	33.50	S	PB	60	<5	0	25	15	0	15	65	20	0	30	60	10	0
5	34.25	C	L	30	0	0	15	55	0	20	60	20	0	20	60	20	0
6	35.25	C	L	30	0	0	5	65	0	5	85	10	0	5	85	10	0
7	35.25	C	L	30	0	0	<5	65	0	10	70	20	0	10	75	15	0
8	41.00	C	FB	10	<5	0	10	80	0	15	55	30	0	25	40	15	20
9	51.50	CG	FB	0	15	25	10	50	0	0	35	5	60	0	25	5	70
10	21.25	S	FB	0	35	0	20	45	0	30	50	20	0	30	50	20	0
11	32.00	CG	FB	10	<5	25	<5	55	0	15	65	20	0	10	70	20	0
12	48.50	SG	FB	0	15	35	<5	45	0	15	35	10	40	25	30	5	40
13	50.50	C	FB	0	30	<5	<5	65	0	0	40	<5	60	0	50	5	45
14	60.50	SG	FB	0	20	35	5	40	0	5	45	10	40	5	35	10	50
15	7.25	C	FB	30	5	0	5	60	0	20	65	15	0	20	60	20	0
16	18.25	C	FB	25	5	0	15	55	0	15	70	15	0	15	65	20	0
17	22.00	C	FB	40	0	0	10	50	0	55	30	15	0	50	35	15	0
18	29.50	C	FB	25	<5	0	10	65	0	10	60	30	0	10	70	20	0
19	34.50	C	FB	35	0	0	<5	65	0	20	65	15	0	20	65	15	0
20	43.75	SG	FB	0	20	30	10	40	0	15	45	10	30	10	50	10	30
21	48.00	SG	FB	0	15	35	5	45	0	40	30	5	25	40	35	<5	25
22	52.50	CG	FB	0	20	15	<5	65	0	10	45	10	35	15	35	5	45
23	59.50	SG	FB	0	25	45	10	20	0	10	45	5	40	10	45	5	40
24	37.00	S	FB	25	5	0	50	20	0	15	65	20	0	10	70	20	0
25	19.00	S	FB	35	5	0	30	35	0	20	55	25	0	25	50	25	0
26	19.50	S	FB	40	<5	0	30	25	<5	10	60	30	0	10	60	30	0
27	105.00	C	MC	0	20	0	5	75	0	5	80	15	0	5	85	10	0
28	52.50	CG	MC	0	10	5	5	80	0	10	50	10	30	10	60	10	20
29	56.00	C	MC	0	15	0	5	80	0	5	30	5	60	5	50	5	40
30	56.00	S	MC	50	10	0	10	30	0	15	70	15	0	10	70	20	0
31	16.50	C	MC	30	0	0	15	55	0	5	60	35	0	5	70	25	0
32	21.00	S	MC	50	5	0	15	30	0	25	50	25	0	20	55	25	0
33	18.00	S	MC	45	5	0	25	25	0	15	50	35	0	15	55	30	0
34	13.00	S	MC	45	0	0	30	25	<5	20	55	25	0	20	55	25	0
35	35.00	C	P	0	<5	0	10	85	<5	5	75	20	0	5	80	15	0
36	43.00	S	PB	65	5	0	10	20	<5	20	60	20	0	15	65	20	0
37	48.00	C	FB	15	10	0	10	65	0	15	65	20	0	10	75	15	0
38	58.00	S	PB	30	15	0	15	40	0	15	65	20	0	15	60	25	0
39	91.00	CG	L	0	5	60	5	30	0	20	60	20	0	10	50	10	30

2 contemporaneous playa-lakes were developed in the central part of the basin (Díaz-Molina *et al.*, 1989). On the other hand, in the Mesozoic source area there are magnesian minerals as dolomite and magnesite (Garcia Palacios *et al.*, 1977; Fernández-Calvo, 1986) able to provide into the basin an important amount of magnesium in solution necessary for the palygorskite formation. Also, the precipitation of Ca in the form of gypsum may be significant in raising the soluble Mg activity and favouring the palygorskite formation (Singer, 1984). This is very important due to the great amount of gypsum which appears joint palygorskite in the mudstones of subunit 2. Also, the palygorskite could be reworked in different subenvironments within the alluvial depositional system.

Fibrous clay minerals as palygorskite has been described by many authors in several spanish tertiary basins (García Palacios, 1977; Galán and Castillo, 1984; Leguey *et al.*, 1985; Rodas *et al.*, 1990; Fernández-García *et al.*, 1989; Pozo and Martín, 1989; Inglés and Anadón, 1991) associated with a restrictive chemical sedimentation in playa-lakes and poorly drained flood plains as Arribas and Díaz-Molina (1995) have described at the top of subunit 2. The kinds of clay minerals in association 2 are the result of the clay mineral transformation in the association 1 (Fig. 7). In the mineral evolution, from the association 1 to the association 2 smectite could be transformed into palygorskite. In general, association 2 characterizes the clay mineralogy of the subunit 2, but along this subunit it is possible to detect the association 3 constitued by kaolinite, illite and palygorskite (Fig. 7). This last association will represent the more evolved one of the mineral sequence, where there is no smectite due to the total transformation to palygorskite. The associa-

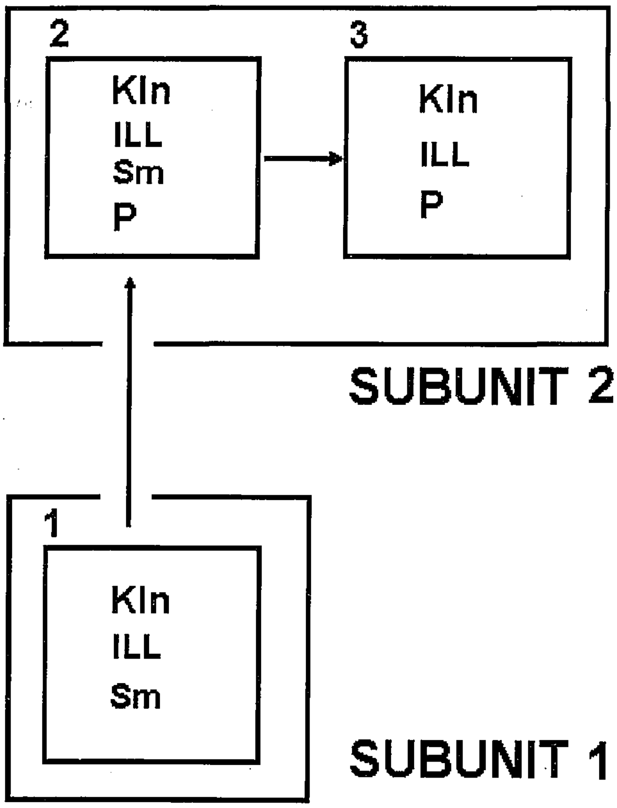

Figure 7.- Relation between clay mineral associations and evolution of clay minerals from subunit 1 to subunit 2.

tion 3 appears in the last levels of the subunit 2. Our sequence of palygorskite formation (Fig. 7) is similar to those described by Pozo and Martín (1989) and agrees with the theoretical magnesian sequence described by García Palacios (1977) where palygorskite could be formed from Mg-smectites under arid conditions.

Palaeoenvironmental evolution

On the whole it is possible to infer a detrital origin for the greater part of the clay minerals (illite and kaolinite). The palygorskite represent a clay mineral formed in the basin under arid conditions. The presence of palygorskite, gypsum and dolomite along the subunit 2 would indicate a climate change towards arid conditions in subunit 2.

Clay mineral evolution reflects paleoenvironmental changes induced by tectonics and climate. As the Loranca Basin became endorheic due to the tectonic shortening in the north area, saline lakes extended into the basin (Arribas and Díaz-Molina, 1995). In the marginal playa-lakes deposits palygorskite was formed under arid conditions. Paleoclimatic interpretation based on micromammal faunal successions found in the Spanish Tertiary Basins (Daams and van der Meulen, 1984), indicate a change to drier and colder environments from the Upper Oligocene to Lower Miocene, which seems to agree with the marine paleotemperature model (Muller, 1983).

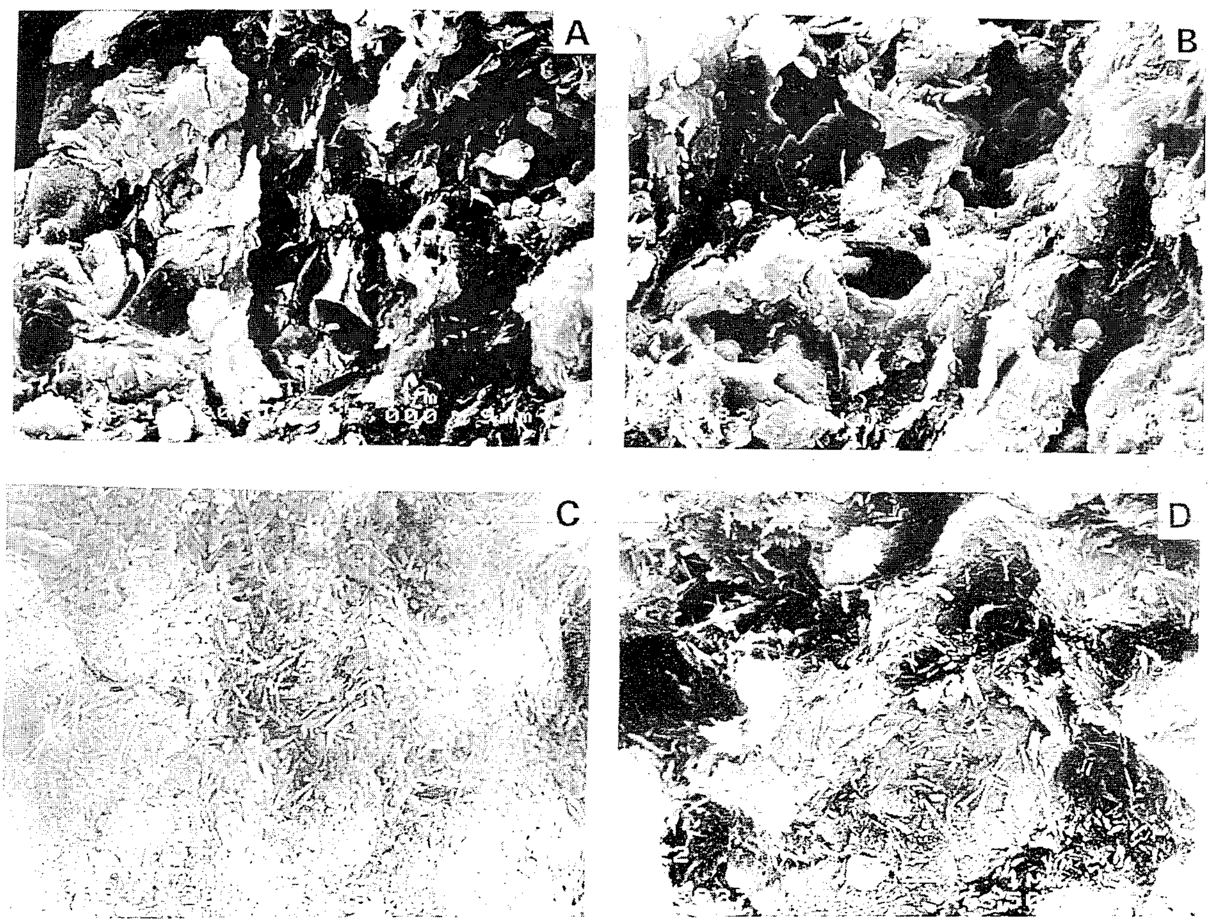

Figure 8.- A: Illite particules in thin flakes without orientation. B: Smectite particules with a flake-shaped morphology. C: Disordered palygorskite fibers without a preferent orientation. D: Transformation from laminar smectite to palygorskite fibers.

Daams and van der Meulen (1984) propose that the absolute temperature range might be tropical or subtropical in the whole period. The paleoclimatic change to drier climate can also be deduced from other sedimentological evidences. Between subunit 1 and 2 internal primary synclines were generated into the basin, however in spite of channel system concentration in more restricted areas, river size decreased indicating a relative rainfall decrease.

Sedimentary environments and clay minerals

Genesis of clay minerals deduced from mineralogical and petrological features can also be approached from a palaeoenvironmental classification. The following sedimentary facies have been differentiated: point bars, flood basin, abandoned meandering channels, lacustrine and paleosols. In these facies a study of the mineralogical composition of the clays has been undertaken.

Point-bars

It has been analyzed the mudstones interbedded in lateral acrection surfaces of the point-bars preserved in the upper part of these sandstone bodies (Fig. 9, A). They have a silty texture and the bulk mineralogy reveals a great proportion in calcite, quartz and feldspar. The petrographic study shows a great proportion of intraclasts which are the result of erosion of calcimophic paleosols, but also there are carbonate components with an extracuencal origin. Mudstones associated with point-bars show an homogeneous clay mineralogy characterized by the clay mineral association 1 which has a detrital character.

Flood basin

The mudstones which characterized flood basin areas present silty and clay textures. The bulk mineralogy of these deposits is variable, but it is possible to differentiate two principal mudstone groups: mudstones without gypsum crystals, in sediments of subunit 1 and mudstones with gypsum crystals in sediments of subunit 2. The first group is constituted by calcite, quartz and clay minerals, while the second one presents dolomite instead of calcite and gypsum. In these facies all clay mineral associations are present (Fig. 9, B). In flood basin areas, an important sedimentation of clay minerals due to the own dynamic of this environment is produced, and during great periods of subaerial exposure a transformation and neoformation of clay minerals take place. Along the subunit 1, in the flood basin facies, the clay mineralogy is very homogeneous with a detrital character, while in the subunit 2 the clay mineral associations content palygorskite. In these flood basin areas along subunit 2 playa lakes environments take place (Arribas and Díaz-Molina, 1995). As consequence, in the subunit 2 an important cli-

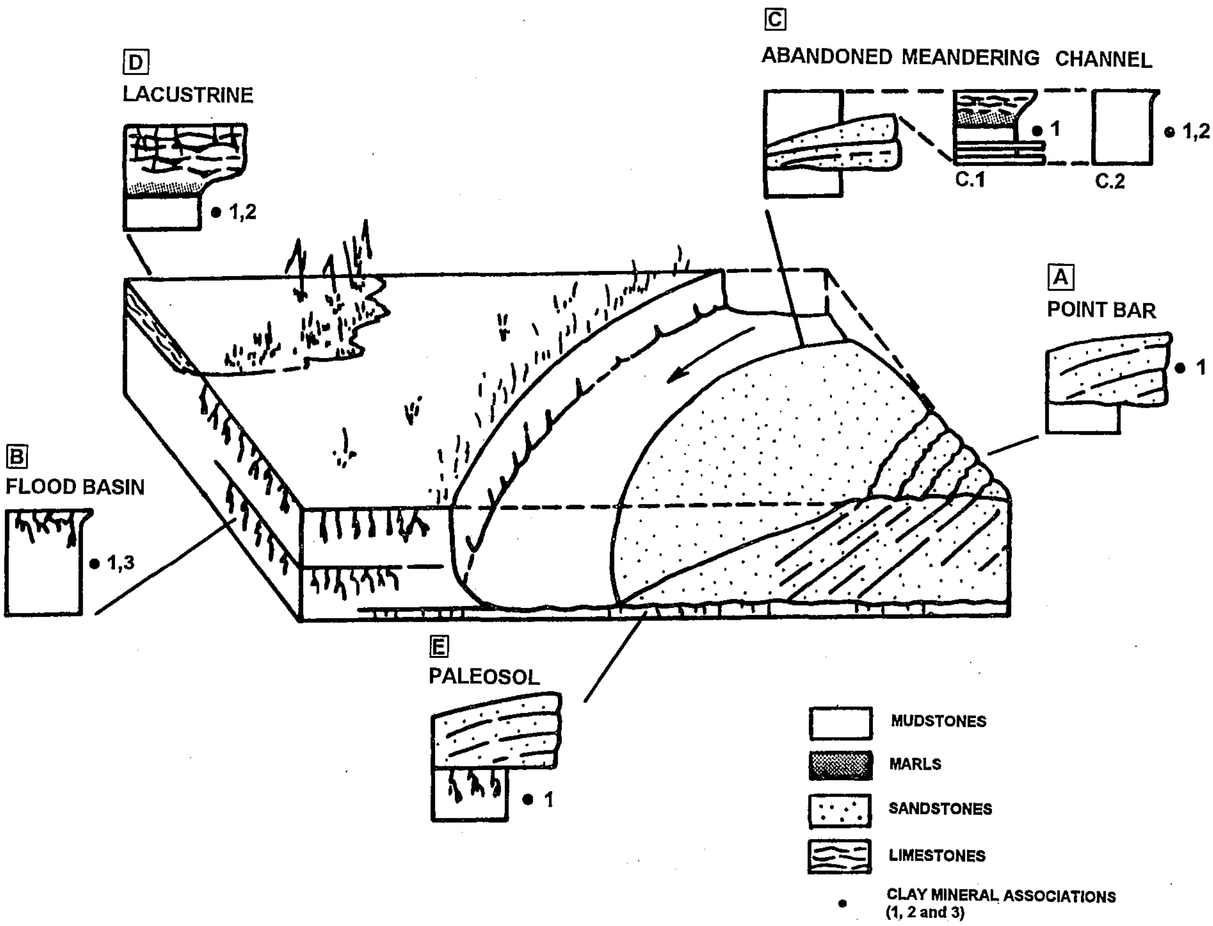

Figure 9.- Clay mineral associations (1, 2 and 3) and sedimentary environments. A = Point bar sequence; B = Flood basin deposits; C (C.1 and C.2) = Abandoned meandering channel sequences; D = Lacustrine sequence; E = Paleosol deposits.

matic change towards a main aridity is inferred, due to the presence of palygorskite. This clay mineral is neoformed in the flood basin as result of a continuous evaporation of residual water enriched in magnesium.

Abandoned meandering channels

These deposits are very different along the cross-section. In the subunit 1 these deposits are constituted by several lithologies as sandstones, marly clays and limestones and are ordered in two sedimentological sequences, C.1 and C.2 (Fig. 9, C). The mineralogical study reveals a high percentage in calcite (30-50%). The C.1 sequences finish with a thin layer of limestones (ox-bow lake development) with a great development of pedogenetic processes (Fig. 9, C). The characteristic clay mineral association of these facies in subunit 1 correspond to association 1 with a detrital character. Later a local carbonate sedimentation was favoured by a strong evaporation of residual water in the last phases of the channel filling. In this environment and along the subunit 1 clay mineralogy has a detrital character and only some clay mineral as illite and smectite show a light degree of interstratification (Ill/Sm) and (Chl/Sm) respectivelly, possibly favoured by wet climate conditions. Along subunit 2 abandoned meandering channels deposits are more homogeneous than in subunit 1, and are constituted fundamentally by clays with dolomite and gypsum, which occasionally show thin limestone layers at the top (Fig. 9, C.2). The characteristic clay mineral association in abandoned meandering channels deposits of subunit 2 correspond to association 2, but locally appears the association 1. In these sedimentary environments favourable conditions for palygorskite neoformation exist, due to a high magnesium content in the residual waters of the abandoned channel. In the fill of an abandoned meandering channel a quiet sedimentation and a continuous evaporation similar to those in a lacustrine sedimentation takes place. However, some of the palygorskite found in these facies can proceed from the erosion of substratum deposits corresponding to marginal playa-lake environment, where its formation took place.

Lacustrine deposits

These appear at the top and bottom of subunit 1 and 2 respectively. The lacustrine mudstones are associated to marls and limestones (Fig. 9, D), and constitute lowest levels of lacustrine sequences of somerization (Arribas *et al.*, 1992). In general they are marly clays without gypsum and with a percentage in calcite between 30-35%. Locally a level of gypsy silt with a lower proportion in clay minerals and calcite in the subunit 2 appears. The clay mineral associations are 1 and 2. The association 2 present palygorskite and is located in the subunit 2. The palygorskite can have a neoformed origin, as much in the flood plain area as in the little lacustrine basins associated, from a continuous evaporation in an arid climate. Also, palygorskite could be reworked in the lacustrine basin from the erosion of paleosols in the flood plain area. The clay mineral associations are the same as those found in abandoned meandering channel deposits, possibly due to the similar dynamic of sedimentation in both environments, abandoned channels and lacustrine basins.

Paleosols

They correspond to mudstone levels with edaphic structures and are interbedded with other alluvial facies inside the subunit 1 (Fig. 9, E). The clay minerals present in these facies are mainly inherited (association 1). The absence of palygorskite in this facies reflects a wet climate conditions, where the descendent lixiviation could take place favouring the washing of the soluble components as carbonates. Although major landscape changes along subunit 1 and 2 transition are associated to clay mineralogy variation. The genesis of clay minerals was not strongly controlled by floodplain paleoenvironments.

Conclusions

Substratum deposits of meandering rivers evolved from fluvial dominated flood-basin to playa-lake deposits, consisting of mudstones with gypsum crystals. In the upper part of the stratigraphic succession (subunit 2), channel incision on playa-lake deposits reflects base level oscillations.

Clay mineral evolution reflects the paleoenvironmental change induced by tectonics and climate. On the whole it is possible to infer a detrital origin for the greater part of the clay minerals (illite and kaolinite). As the Loranca Basin became endorreic due to the tectonic shortening in the north area saline lakes extended into the basin and palygorskite was neoformated under arid conditions. The presence of palygorskite, gypsum and dolomite along the subunit 2 would indicate an important climate change towards arid conditions in subunit 2. In subunit 1 sedimentation took place under a temperate-humid climate. Lacustrine sediments and abandoned meandering channel deposits show the same clay mineral associations as other fluvial facies (point-bars, flood-basin...) and calcite as the principal mineral formed from chemical precipitation processes. Clay minerals in paleosols indicate an important washing of the soluble components as carbonate. Palygorskite formation took place along subunit 2 in different environments as soils, lacustrine and abandoned meandering channels as the transformation from Mg-smectite. Also, palygorskite could be recycled in different environments in the fluvial depositional system (point-bars, floodbasin). Since fluvial plain palaeoenvironments are dominated by terrigenous sediments, clay mineralogy reflects the source area composition. Major changes in clay mineralogy are due to the palaeogeographic change, shown in the variation of substratum deposits of the meandering channels. Since meandering rivers eroded substratum deposits, during subunit 2 deposition, finer terrigenous associated to meandering channels may also contain detrital palygorskite.

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