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The microfauna assemblages as indicators of paleoenvironmental changes in the Miocene fluvial-lacustrine cycles (NE Duero Basin, Spain)

Las asociaciones de microfauna como indicadores de cambios paleoambientales en los ciclos fluvio-lacustres Miocenos (NE de la Cuenca del Duero, España)

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ABSTRACT

The siliclastic and carbonate deposits are interbedded in the Villadiego area (Miocene, NE Duero Basin). They have been subdivided into two high-rank depositional sequences: DDS and CDS. The sedimentary analysis of these units and the study of the microfauna content, mainly ostracods, led to the identification of lacustrine-fluvial interaction systems. The sedimentary characteristics reveal the existence of fluvial systems of gravel, flood plains and lacustrine systems that were interconnected and intimately related in north-south direction. In the sedimentological analysis, thirteen types of fluvial and lacustrine lithofacies and six genetic facies associations were recognized. The top of DDS is the result of lake level risings. The CDS shows a deepening-shallowing cycle. The ostracod micropaleontological analysis of the sediments have been studied, with the aim of reconstructing the palaeoenvironmental evolution of this area. These microfauna assemblages integrated with the analysis of the sedimentary facies allowed to conclude the existence of lakes with a water-bearing level of few tens of meters. A change in the chemical conditions of the waters, which evolved from oligohaline and carbonated to mesohaline and sulphated is concluded.

Keywords: fluvial system; lacustrine; ostracods, paleoecology; Upper Miocene; Duero Basin.

RESUMEN

Los depósitos siliciclásticos y carbonatados se encuentran intercalados en el área de Villadiego (Mioceno, NE cuenca del Duero). Se han subdividido en dos secuencias de depósito de alto rango: DDS y CDS. El análisis de estas unidades sedimentarias y el estudio del contenido de microfauna, principalmente ostrácodos, condujo a la identificación de sistemas de interacción lacustre-fluvial. Las características sedimentarias revelan la existencia de los sistemas fluviales de grava, llanuras de inundación y sistemas lacustres que estaban interconectados e

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íntimamente relacionados en dirección N-S. En el análisis sedimentológico se reconocieron trece tipos de litofacies fluviales y lacustres y seis asociaciones de facies genéticas. La parte superior del DDS es el resultado de levantamientos del nivel del lago. El CDS muestra un ciclo de profundización-somerización. Los sedimentos se han estudiado mediatne análisis micropaleontológico de ostrácodos, con el objetivo de reconstruir la evolución paleoambiental de esta zona. Estos conjuntos de microfauna integrados con el análisis de las facies sedimentarias permiten concluir la existencia de lagos con un nivel acuífero de pocas decenas de metros. Se concluye que existió un cambio en las condiciones químicas de las aguas, que evolucionaron a partir de oligohalinos y sin gas a mesohalino y sulfatadas.

Palabras clave: sistema fluvial; lacustre; ostrácodos, paleoecología; Mioceno superior; Cuenca del Duero.

Introduction

The sequence stratigraphy analysis was initially developed for nearshore marine sedimentary deposits affected by eustasy. The recognition in the sedimentary successions of surfaces such as marine flooding surfaces, transgressive surfaces of erosion and subaerial unconformities representing changes in accommodation space in response to eustatic, climatic and tectonic influences is an important factor (c.f. Posamentier *et al.*, 1988; Van Wagoner *et al.*, 1990; Shanley *et al.*, 1992; Shanley & McCabe, 1993). The geometries and stacking patterns of system tracks can be used to interpret a depositional history.

The continental basins are not affected by eustatic sea level fluctuations. The erosional unconformities and paleosoils can be used to divide the stratigraphic successions into sequences (e. g. Kraus & Middleton, 1987; Shanley & McCabe, 1994; Lemons & Chan, 1999). Also, the fluctuations in lake level may influence sedimentation, similar to sea level in marine environments (e. g. Legaretta *et al.*, 1993; Shanley & McCabe, 1994). The aggradation or incision of the fluvial systems are related to basin length, sediment supply, sediment size, discharge, and base level drive shifts in the fluvial profile (e. g. Blum and Tornqvist, 2000). In these basins, climatic variations and tectonics influences are the principal factors controlling the depositional evolution.

This study has focused on the study of mapping, stratigraphic and sedimentology of the deposits that outcrop in the northeastern boundary of the Duero basin, in the vicinity of the town of Villadiego (Burgos) (Fig. 1). The sector analysed forms part of the marginal Miocene rocks that are bounded to the north by the Mesozoic successions of the Basque-Cantabrian Mountains (Figs. 1 and 2). The sedimentary succession mainly comprises conglomerates, sands, lutites, limestones and marls, with a maximum thickness of 200 m (Herrero-Hernández, 1989).

One of the specific objectives of this paper is to report the analysis of the microfaunal composition of these Miocene sediments. Also, evaluate its distribution along the sedimentary record to characterize the evolution of the different types of aquatic ecosystems. This work focuses on the description, interpretation and correlation of the sedimentary facies. The analysis of the sedimentary processes helps to address the first interpretation and paleogeographic reconstruction of an alluvial fan, and fluvial distal-lacustrine depositional systems and their lateral relationships. The paleoenvironmental and paleogeographic interpretations led to the development of a sedimentary model for the Miocene deposits of the northeastern boundary of the Duero basin. The main allocyclic factor affecting the filling of the basin and their evolution is seasonal fluctuation in climate. It offers an excellent occasion for assessing the role of lake level changes on the morphology and sedimentary architecture of these sedimentary systems deposited in areas of tectonic activity basin edge.

Methodology

Field work consisted in detailed mapping and cross correlation of sixteen stratigraphic measured sections, at the most representative points in order to monitoring the lateral and vertical Miocene deposits. Fluvial and lacustrine rocks integrate these stratigraphic sections. Despite the paucity of outcrops, significant sections were reconstructed in which the Miocene geological framework of the Villadiego area could be established. Lithological and sedimentological

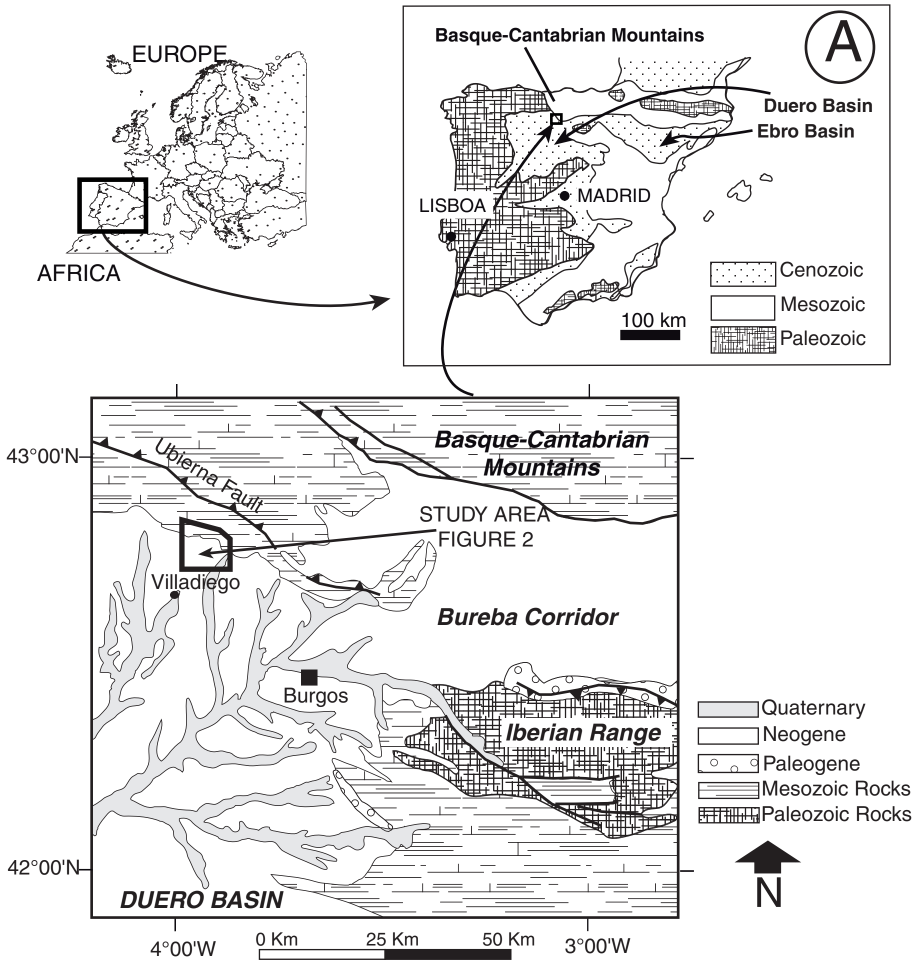


Fig. 1.—Geographic location of the study area. A: in the context of the Iberian Peninsula.

analyses, provenance of conglomerates and sandstones, as well as preliminary micropaleontological data (paleocological and biostratigraphic analysis) were acquired, in order to reconstruct the evolution and the stratigraphic setting of the Miocene succession. The sediments were sampled also for biostratigraphic, palynological and paleoecological analyses.

The sand bodies' shapes and their lateral extensions were identified. Sampling was directed to fossil content, carbonate facies analysis and petrology provenance of sandstones and conglomerates. Detailed sedimentological analyses of outcropping sections showed a wide spectrum of facies and facies associations related to different depositional systems. The microfaunal composition is based on ostracods, foraminifers, gastropods and charophytes from the lacustrine carbonates. These allow reconstruction of the depositional environment, but no value for dating.

Geological setting

Around the Hesperian Massif are located several sedimentary basins: Duero, Ebro, Tajo, etc., that were filled and deformed during Cenozoic period (Fig. 1). The Duero and the Ebro basins are considered as an intraplate basin and a foreland basin respectively (cf. Alonso-Zarza *et al*., 2002).

The Duero basin covers approximately 50,000 km^2 and was formed during the Alpine Orogeny. In the Cenozoic, the Duero Basin had an asymmetric tectonostratigraphic behavior in all its boundaries. This is the reason because it is difficult to assign a particular sedimentary basin model. However, the northwestern boundary of the Duero Basin has

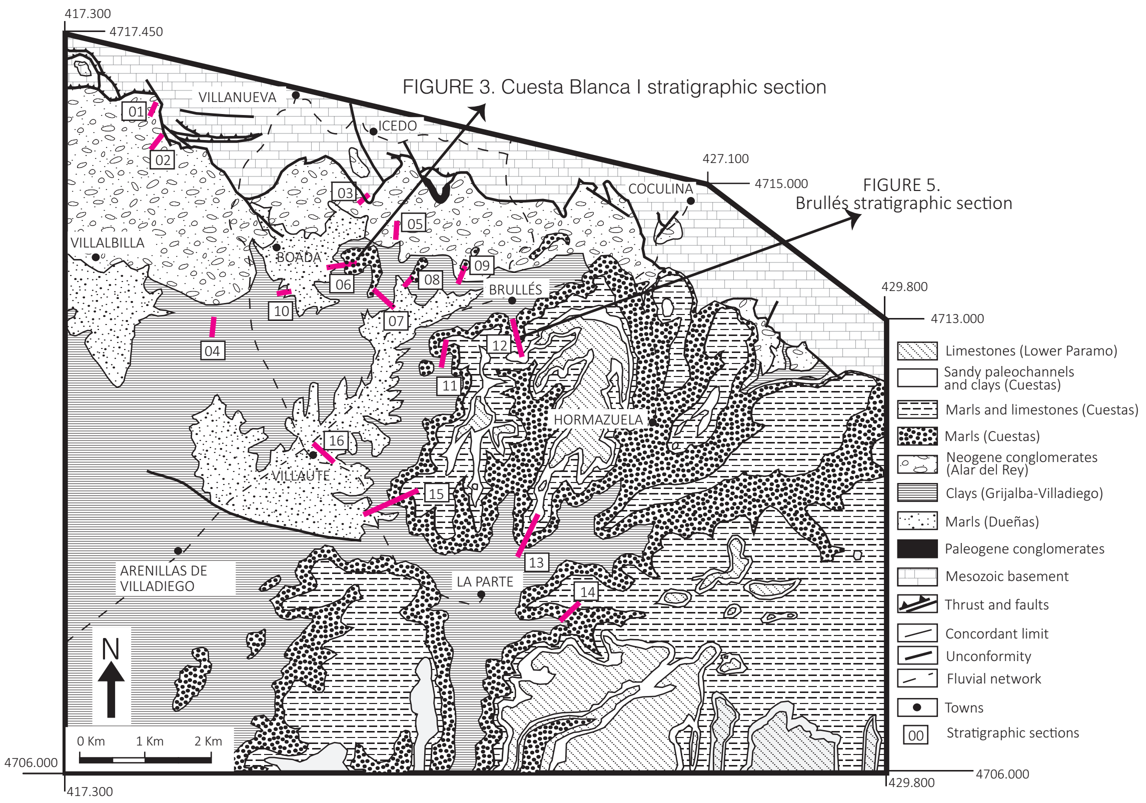


Fig. 2.—Geological map of the study area and its relationship to the Mesozoic substratum, with stratigraphic units and geographic location of the columns (modified from Herrero-Hernández, 1989 and Pineda, 1997).

been considered as a foreland basin by Mabesoone (1959 and 1961), Jong (1971); Alonso *et al*. (1996), Gallastegui (2000), Herrero-Hernández (2001) and, more recently, by Herrero-Hernández *et al*. (2004, 2010).

The study area are located between these two foreland basins: Pyrenean Chain (Ebro Basin) and northwestern boundary of the Duero Basin. It is likely that this area also develop a foreland basin in lateral continuity with those mentioned above. The compression in Basque-Cantabrian Mountains took place in a NE-SW direction approximately and their activity ceased in the Late Miocene. This activity produced mainly thrusts and associated folds (Herrero-Hernández, 1989), which gave rise to the more distinctive features of the present regional relief with a general northwestern-southeastern trend. Some of the main elevations were produced by a series of folds developed over the thrust ramps.

The sector analysed in the present work is located in the Villadiego Area, at northeastern domain of this basin. This sector is located next to the southern margins of pre-Cenozoic deposits of the Duero basin (Figs. 1 and 2).

In the study area the Neogene successions are constituted by conglomerates, sands, clays, marls and limestones, with a visible thickness of 200 m. These materials are grouped in a set of informal stratigraphic units to 1: 50,000 scale (e. g. Herrero-Hernández, 1989, Alonso Gavilán *et al.*, 1990 y Pineda, 1997) that, following the classic regional lithostratigraphy have been denominated: Alar del Rey Facies, Grijalba-Villadiego Facies, Dueñas Facies, Las Cuestas Facies and Los Páramos Facies (Hernández Pacheco 1912, 1915 and 1932, Royo Gómez, 1926; San Miguel de la Cámara, 1952, Aeroservice, 1967, García Abad & Rey Salgado, 1973; García del Cura, 1974 and 1975; Ordóñez *et al.*, 1976; Ordóñez & García del Cura, 1976; Mediavilla & Dabrio, 1986 and 1989; Mediavilla *et al.*, 1996; Armenteros *et al.*, 1997, Alonso Gavilán *et al.*, 1997, Armenteros *et al*., 2002 and Alonso Gavilán *et al*., 2004). According to textural and sedimentological features and extensive field mapping those facies were assigned to different stratigraphic units (Fig. 2) and were used as a base to interpret depositional environments (e. g., Herrero-Hernández, 1989; Pineda, 1997).

From north to south an evolution of the grain size of the deposits from conglomerates to marls and limestones was observed in the field, together with a change from red to white in the colour of the sediments. These lateral relations of the sedimentary bodies made it possible to establish an interdigitation of the Miocene units.

Taking into account lithostratigraphic and mapping criteria the red conglomerates are included within the so-called Alar del Rey Facies. Laterally towards the south (Fig. 3) this unit change to the Dueñas Facies (marls and white limestones) and to the Grijalba-Villadiego Facies (red sands and clays) (Fig. 4). To the south these units are intercalated with the marl and white limestone of the Las Cuestas Facies.

The lower and middle parts of the Las Cuestas Facies are characterized by a high volume of marls and limestones of white colour, and abundant fossil remains of ostracods, foraminifers, charophytes, gastropods and fishes. On the other hand, the upper part of this unit consists of clays and conglomerates (Pineda, 1997). The Miocene succession culminates in the region with the carbonate deposits of the Los Páramos Facies.

Facies model of the fluvio-lacustrine system

Two groups of facies are established by the lithology: siliciclastic alluvial-fluvial and carbonated lacustrine-palustrine facies. The fluvio-lacustrine depositional model comprises three main facies associations: alluvial fan-fluvial, transitional and palustrine/lacustrine. The main characteristics and interpretations of these facies and associations are summarized in Tables 1 and 2, respectively.

Alluvial fan and fluvial facies associations (AFA and FA)

These facies associations dominate in the north of the study area, and they are in direct contact with the Mesozoic substratum. These facies associations are not relevant for the work and here are summarized its most important features.

In the AFA the gravel facies (Gm and Gt) predominate over sands facies (St, Sm) (Table 2). They form a fining upward sequence with 2 to 8 m thickness. Internally, materials are disorganized, massive to weakly bedded and normal graded.

Interpretation. AFA association represents the filling of very proximal active channels, forming bars on the inside with very energetic tractive currents.

The FA association is predominant towards the south and is closely related to AFA association. It comprises Gt, St, Sm and Fm/P facies (Table 2) in fining- and thinning-upwards sequences. The conglomerates (basically carbonated) are well sorted and clast-supported with a sandy matrix. They contain imbrications and sedimentary structures including small to medium-scale cross-bedding. The sand are very sorted with matrix very fine, and present cross-bedding (St) or massive stratification (Sm). The mud presents abundant pedogenic modifications, such as carbonate root traces and clay and carbonate migrations, it make up calcretes.

Interpretation. This association can be interpreted as a product of longitudinal and transverse gravel and sand bars in braided fluvial channels, and overbank deposits. To the top represent abandoned channel fill and floodplain deposits with development of paleosoils.

Transitional facies association (BFA and DFA)

The transitional (BFA and DFA) facies associations consist of sands, lutites and and pebble-sized gravels. It is characterized by its paleogeographic position between palustrine-lacustrine and alluvial fan-fluvial facies associations.

DFA association is an association of lutites (Fm), sands (Sgm) and conglomerates (Gh). It is organized in thickening and coarsening-upward sequences from 2 to 6 m thickness (Table 2). The lutites facies are red, massive and they develop bioturbation. The sandy facies are fine to coarse grained, with beds of 0.8–1 m thick. They undeveloped internal tractive structures. The conglomerate beds are 0.3 to 1 m thick. They are clast supported, but fairly sand-rich, with horizontally stratified.

Interpretation. The upward decrease in clay and muddy matrix, not channelized basal surface and

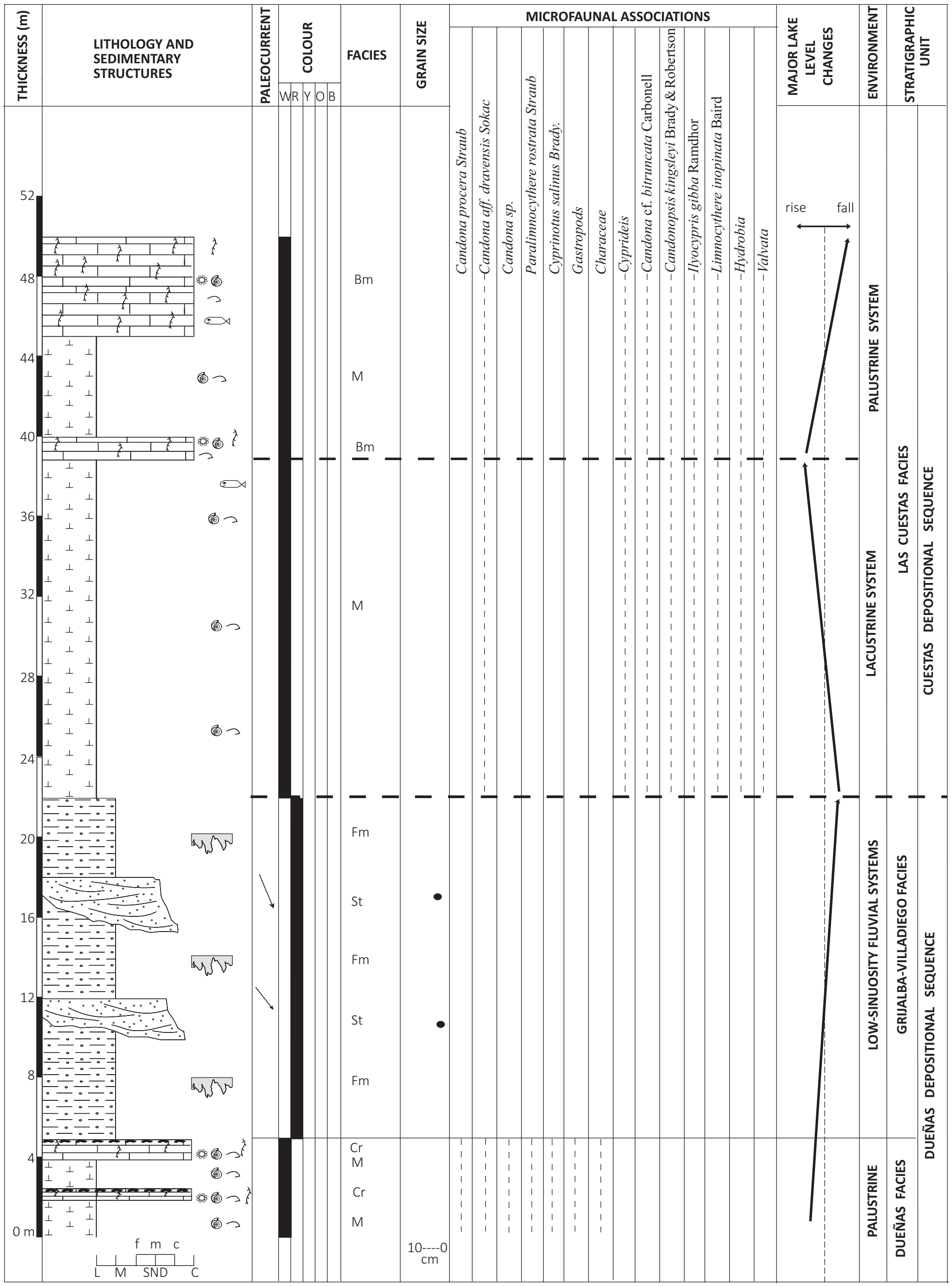


Fig. 3.—Lithological characteristics, and interpretation of the stratigraphic section of Cuesta Blanca I, location in Fig. 2.

upward-coarsening trend explain the two possible fluvial scenarios for the origin of the DFA association. In the first scenario this association is interpreted as the progradation of small channels of crevasse splays over the floodplain. In the second case, DFA represents the arrival of river channels to shallow water deltas dominated by fluvial processes, and interpret this association as the mouth bar progradation. Both explanations indicate an increase of energy towards the top, which is

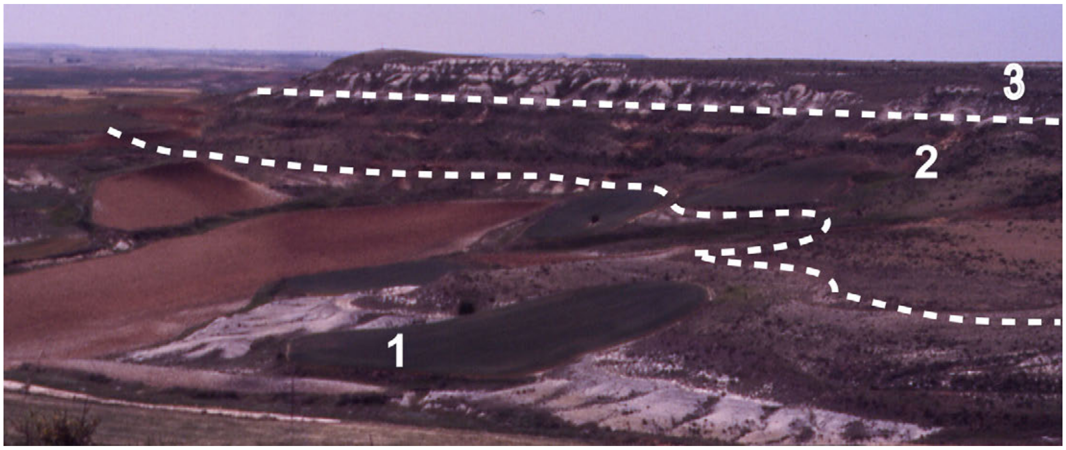


Fig. 4.—Field view showing the superposition of units: Dueñas Facies (1), Grijalba-Villadiego Facies (2) and Cuestas Facies (3).

reflected in the sedimentary structures. The upper part of sequence is constituted by conglomerates which allows to interpret a feeder channel preserved at the top.

The delta Postma's classification (1990) is based on feeder systems and water depth at river mouth. This last parameter allow to define two main typologies of deltas: Gilbert-type delta, with a steep front (25°–35°) and shallow-water type delta, with a gently inclined front (5°–15°). The latter case would be represented in the study area.

The DFA type develops into middle study area and it is related to the other facies associations.

The BFA association shows an abundant percentage of conglomerates and a smaller proportion of sands (Table 2). The base of this association is very similar to that of AFA type, conglomerates with cross-bedding (Gt), sometimes massive (Gm facies) with imbricate clasts, being differentiated by the occurrence of Sgo facies. The conglomerate bodies are amalgamated from 2.5 to 4 m thick. On the whole, the sequence is fining upward with an erosive base and a thickness that varies from 1.5 to 5 m. The paleocurrents make a direction preferentially towards S and SSE.

The Sgo facies are are sand-sized, oolithic grainstone with good sorting and sparite cement. They contain well sorted clasts of quartz and ooids (high percentage above 70%) and abundant remains of gastropods and algae. The ooids are sub-spherical, they have a size of up to 700 µm, these consist of a sand-sized nucleus of quartz, limestone or some skeletal remains, around which several micritic coatings develop. The nuclei, occasionally dissolved, are simple or compound. They are well graded and rounded underneath. Fragments of molluscs (gastropods), algae, geopetal fillings and traces of bioturbation were also found. The interparticle porosity was filled with sparite. It has lensoid cavities, millimetre- to centimetre-long (fenestrae) and as vadose meniscate calcite cement. Its internal structure has been, to a large extent, erased due to the effects of carbonate cementation.

Interpretation. This association is complex since the different facies reveal that the processes which took place at the base were are very different from those that were developing at the top, and the products of some processes were modified by posterior processes. At the base, the coarse sediments are interpreted as the filling of active channels with the development of longitudinal and traverse conglomerate bars.

The top of the sequences are formed by the Sgo facies, and it shows ooids and remains of gastropods. Armenteros (1986) interprets similar sandstones with an origin fluvio-lacustrine sequences and it pass upward to lacustrine-palustrine facies. The presence of ooids of variable sizes and shapes and the remains of organisms that are associated with microbial and algal activity suggests shallow-water conditions and/or even subaerial exposed environments. Fenestrae support formation close to the vadose zone. The marginal lake facies association was recognized by the abundance of sedimentary features attributed to subaerial and/or meteoric

Table 1.—**Description and interpretation of the siliciclastic and carbonated facies (Herrero-Hernández, 1989)**

	Code	Description	Interpretation	Stratigraphic Unit
SILICICLASTIC FACIES	Gm	Poorly sorted massive. Polymodal and imperfectly classified clast-supported conglomerates of normal gradation. Massive. Imbrications	Channel fill to channel bar representing sedimentation in a stream-dominated alluvial fan and fluvial environments	Alar del Rey Facies Grijalba-Villadiego Facies
	Gh	Polymodal clast-supported conglomerates. Normal gradation. Horizontal stratification. Imbrications	Fluvial gravel bars representing sedimentation in a stream-dominated alluvial fan and fluvial environments	Alar del Rey Facies Grijalba-Villadiego Facies
	Gt	Poorly sorted, moderately to well rounded, cross-bedded conglomerates, polymodal and clast-supported. Fining upward with erosive base	Fluvial gravel bars representing sedimentation in a stream-dominated alluvial fan and fluvial environments	Alar del Rey Facies Grijalba-Villadiego Facies
	St	Medium to coarse-grained sandstone. Trough cross-bedding	Fluvial sands. Migration of megaripples	Grijalba-Villadiego Facies
	Sgo	Well-graded microconglomeratic calcarenites. Ooids and fragments of organisms	Shallow lacustrine. Waves? Beach?	Grijalba-Villadiego Facies
	Sgm	Coarse grained, massive sandstone, pebbly. Well graded. High carbonatation. Arranged in thickening upward sequences.	Deltaic. River mouth bars	Grijalba-Villadiego Facies
	Sm	Medium to fine sands. Well graded. Massive. Non- erosive to erosive base	Channels fill. Sand dominated hyperconcentrated fow	Alar del Rey Facies Grijalba-Villadiego Facies
	Fm	Massive lutites. Traces of hydromorphism	Flood plain deposits. Low energy, and suspension fallout	Grijalba-Villadiego Facies
	L	White sandy muds. Microfauna	Shallow lacustrine. Carbonate precipitation	Dueñas Facies
CARBONATE FACIES	P	Edaphogenetic structures. Nodular caliche	Low energy, overbank deposit. Paleosoil	Grijalba-Villadiego Facies
	M	Green marls rich in fossils	Deep lacustrine. Carbonate precipitation	Dueñas Facies Cuestas facies
	Bm	Biomicrites. Massive. Banks of slight thickness. Scarce roots structures	Shallow lacustrine and palustrine deposits. Carbonate precipitation	Dueñas Facies Cuestas facies
	Cr	Grey limestones. 1 m thick banks. Bioturbation to roots	Shallow lacustrine and palustrine deposits. Vegetated mudflat.	Dueñas Facies Cuestas facies

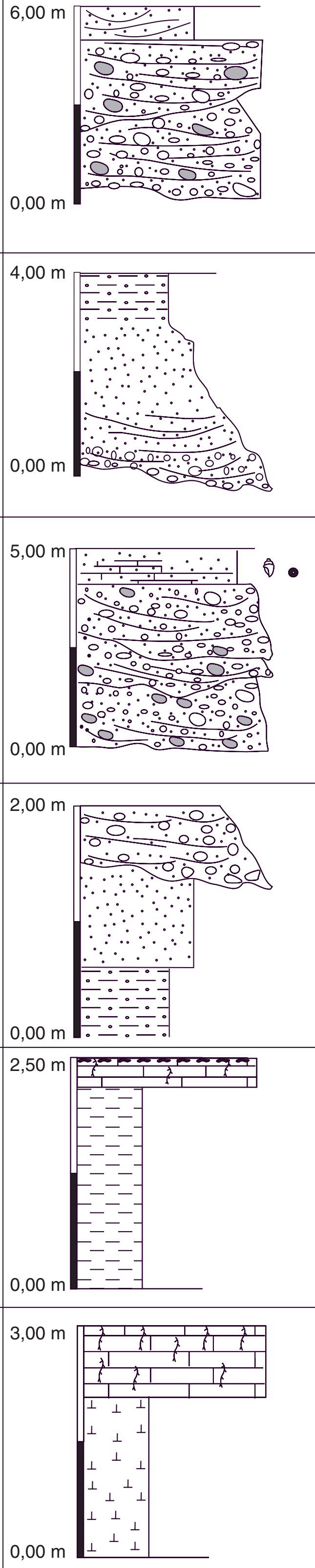
exposure, such as paleosoil, and fenestrae and meteoric cement.

Palustrine and lacustrine facies associations (PFA and LFA)

Remains fossils of ostracods, gastropods and charophytes are present. These provide the paleoecological and paleoenvironmental interpretations.

The PFA facies association is made up of facies L and Bm. Lithologically show lutites and white biomicrites in banks of thickness up to 1 m (Table 2). The clayey minerals are smectites, palygorskite, illite and chlorite. Bm facies under a microscope are mainly grainstone to packstone with bioclasts (biomicrite), with ostracods, gastropods and charophytes. It is characterized by the ocurrence of diverse forms of the Candonidae family (*Candona* sp. aff *dravensis*)

Table 2.—Facies associations with the interpretation and stratigraphic unit



Facies associations	Type	Log	Facies	Interpretation
LACUSTRINE/PALUSTRINE FACIES ASSOCIATIONS	LFA TYPE	3,00 m – 0,00 m	Cr M	Lacustrine/palustrine
	PFA TYPE	2,50 m – 0,00 m	Bm L	Lacustrine/palustrine
TRANSITIONAL FACIES ASSOCIATIONS	DFA TYPE	2,00 m – 0,00 m	Gm/Gt Sm Fm	Progradation of low sinuosity channels over flood plain
	BFA TYPE	5,00 m – 0,00 m	Sgo Gt Gt	Filling of proximal low sinuosity channels
ALLUVIAL-FLUVIAL FACIES ASSOCIATIONS	FA TYPE	4,00 m – 0,00 m	Fm Sm St Gt	Filling of low sinuosity channels
	AFA TYPE	6,00 m – 0,00 m	St/Sm Gt Gt Gm St/Sm	Filling of proximal low sinuosity channels

and *Cypridarum*, gastropods (highly fragmented) and Charophytes.

Interpretation. The micropaleontological and the lithological association indicate lacustrine conditions of low energy, below the lower limit of the water level. The occurrence of charophytes suggests the existence of a algae belt on the edge of the lake. The traces of emersion, represented by a porosity which can be attributed to bioturbation due to roots, indicate fluctuations in the water level that affect to the shallow areas of lakes. The lack of appreciable amounts of organic matter reveals that these lakes would have had a well oxygenated water column, a fact that favours the existence of well-developed benthic fauna.

Moreover, the detritic sedimentation shown in the L facies (Table 1) takes place in relatively deep areas, due to some kind of bottom flow which causes the dragging of material which is basically skeletal (mainly fragments of gastropod and ostracods) and, at the same time causes the entry of oxygen into the bottom waters. The abundance of mud in L facies also corresponds to periods of floods during which important coarse detritic sedimentation occurs in marginal border areas. During these periods, fresh water enters the lacustrine basin, thus causing a rise in the water level of the lake.

This lacustrine system would have had a complete water circulation to the bottom and a palustrine strip with partial signs of exposure. This suggests that there were oscillations in the coastline, thus causing the more or less developed uncovering of the subaquatic deposits according to Freytet (1973). This idea is corroborated by the association of clay minerals since it entails an evident arid soil generation (Reheis, 1990).

The LFA facies association forming a thickening-upward, and it is made up of marl (M) and limestones (Cr) (Table 2). The white and cream marls are massives, and they form layers that extend laterally hundreds of meters. LFA is characterized by the ocurrence of diverse forms of complete or fragmented gastropods (*Hydrobia* and *Valvata*), charophytes, remains of pharyngeal pieces from fishes and also ostracods. The latter are represented in this section by *Cyprideis* in over 90% of the association.

Cr facies are microcrystalline, white and they include marmorisation, nodulisation, pedogenic recrystallisation, and traces of burrows and roots.

The dominant clays are illite, smectites and palygorskite. Under the microscope, they are mudstone with massive appearance, nodular and fairly compact with fossils of gastropods, charophytes and ostracods. This facies shows a clotted peloidal texture and two types of porosity. The first represented by planar and curved pores (crack planes) is due to shrinkage processes (drying). The second other consisting of channel pores, sometimes horizontal trend in porosity, these ones due to bioturbation. The criptocrystalline characteristics and impregnative compound nodules are probably due to presence of iron oxy-hydroxides.

Interpretation. The presence of marl at the base of the facies association indicates conditions of stability in the lacustrine environment. The great abundance of *Cyprideis* in the marls and their morphological characteristics (reticulate ornamentation, etc.) must have been related to the highly oxygenated lacustrine subenvironments according to Bodergat (1983).

The Cr facies derivates from the lowering of the water-bearing stratum, with the installation of more or less extensive palustrine areas colonized by vegetation. The presence of vegetation suggests the development of a shallow, fresh, groundwater table before the next lake transgression. The presence of palygorskite (Mg-rich clay) would be in relation to palustrine processes (brecciation and nodulisation) (cf. Bustillo and Alonso-Zarza, 2007).

The LFA is an example of the trend towards shallowing and the constant repetition of this type in the vertical would suggest the stacking of deepening-shallowing cycles.

Microfaunal assemblages and evolution of lake cycles

For the biostratigraphic characterization of the area it has been studied in detail outcrops where the sedimentary succession is more complete (Fig. 3). This has allowed to define two completely different microfaunal associations.

In the lower part (Fig. 3), the microfauna of ostracods is very abundant and its state of preservation is considered as excellent, because completely whole valves of very fragile taxa, as well as very delicate both structural and ornamental details can be found. The association is clearly dominated by *Cypridarum* and by different forms of Candonidae. Among the latter, the highest percentage corresponds to *Candona albicans* Brady (Fig. 5a) being minority *Candona procera* Straub, *Candona* aff. *dravensis* Sokac (Figs. 5b and 5c) and *Candona* sp. Other secondary forms of ostracods are *Paralimnocythere rostrata* Straub and *Cyprinotus salinus* Brady. Also is remarkable the presence of gastropoda (very fragmented) and *Characeae* with abundant very well preserved gyrogonites. The association of ostracods with *Cypridarum* is indicative of freshwater conditions (oligohaline).

In the upper part (Figs. 3 and 6), the fossils association show a great wealth of ostracods in excellent state of preservation. It highlights the abundance of *Cyprideis* (Fig. 5d), not present in the lower lake, and represents more than 90% of the association of ostracods. The most common set of ostracod species in the studied samples is defined in similar percentages by *Candona* cf. *bitruncata* Carbonell, *Candona* aff. *dravensis* Sokac, *Candonopsis kingsleyi* Brady & Robertson, *Ilyocypris gibba* Ramdhor (Fig. 5e) and *Limnocythere inopinata* Baird (Fig. 5f). Also is remarkable the presence of *Characeae*, remains of pharyngeal pieces of fishes and some gastropods, which include *Hydrobia* and *Valvata* specimens.

The presence of *Cyprideis* allows obtain lake paleoenvironmental qualitative conditions, as well as its ecophenotipics features. For example, the ornamentation of this species is marked by environmental conditions, thus the smooth ornamentation of valves indicates a typically oxygenated environment (Bodergat, 1983). Currently, *Cyprideis* is considered an opportunistic genus being able to survive with changes in salinity of the water in the lake basin. The way of life that is indicated for this genus is very shallow endobiontic within the first millimetres of sediment and with a type of limicole feeding (Rodríguez Lázaro, 1988).

Rich and diverse ostracod associations (mainly *Cyprideis*, candonids and *Ilyocypris*) refer to a rise in salinity up to mesohaline waters (Gross, 2004; Rundić, 2006). Extant *Cyprideis* is able to cope with fluctuating salinities; however, it mainly occurs in mesohaline waters (cf. Meisch, 2000). In addition, the great abundance of *Cyprideis* in the ostracods community indicates an increase in ion sulphate dissolved in the water, and a replacement to the freshwater ostracods fauna from the preceding association (cf. Gross *et al*., 2011).

Based on the palaeolimnological information obtained by the study of the microfaunal associations, in the Miocene sedimentary record two intervals/cycles from a lower carbonated lake to upper stable sulphated-saline lake are distinguished.

In the study area, appears only the top of first cycle. It is constituted by lacustrine environment characterized by marls and packstone/grainstones with bioclasts. These representing a shallowing upward cycle in the carbonated margin lake.

The second cycle begins with alluvial fan and fluvial deposits of channel-fill and bars of conglomerates and sandstones of red colour and it ends with shallow margin lake/palustrine and deep lacustrine deposits. Lithofacies of the upper saline lake-cycle are a mix of interbedded marls, muds and mudstone with bioclasts. The upper part of this cycle represent the retrogradation of lake deposits, with a shallowing-upward trend (Figs. 3 and 6).

On the other hand, in both lacustrine microfaunal associations are widely represented ostracods valves well preserved and occasionally even articulated, together with gastropods shells complete and very fractured. This fact, has likely to be related to the existence of two different communities. One represented by ostracods native and complete gastropods and other with partially re-mobilised, made up of fragments of gastropods and mixed tractive-current.

The paleoenvironmental conditions were not constants on the lake. There are variations on the bathymetry, the internal circulation and the concentration of dissolved salts, as it is clear from the change in the species that dominate at one time or another. As a result, comparing the associations of both lacustrine microfaunal association we can say

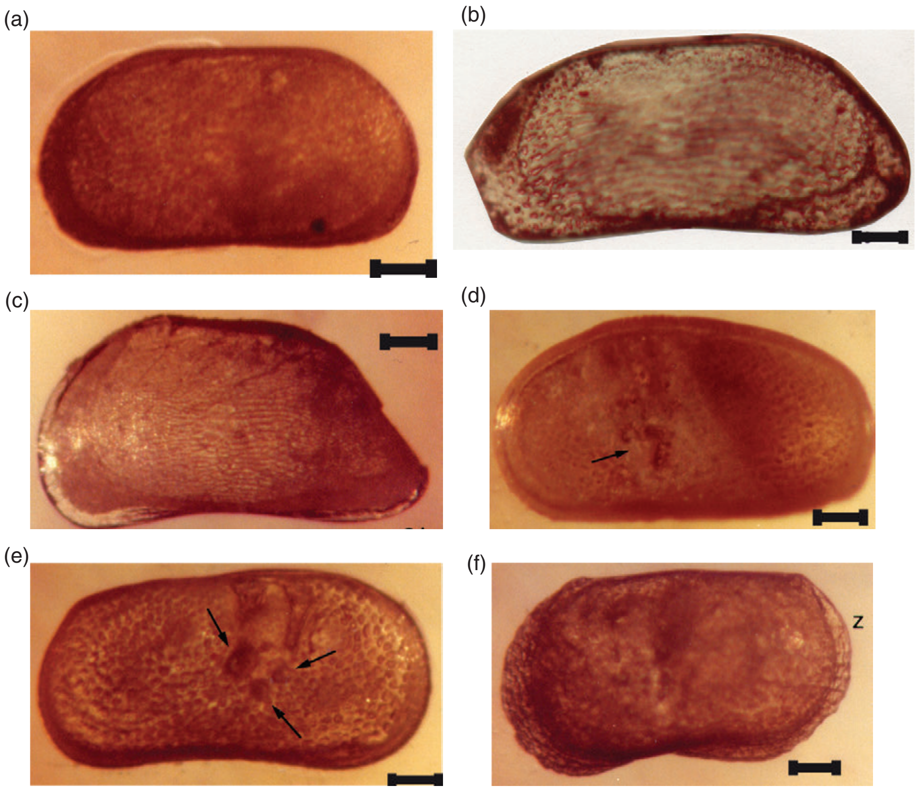


Fig. 5.—Microphotographs of ostracods. a) *Candona albicans* Brady, external morphological appearance of the left valve showing ornamentation. x100. b) *Candona procera* Straub. x100. c) *Candona* aff. *Dravensis Sokac*, left valve, external view. x100. d) *Cyprideis,* right valve, the arrow indicates the muscle impressions. x100. e) *Ilyocypris gibba* (Ramdhor), right valve, external view. x100. f) *Limnocythere inopinata* (Baird), left valve, external view. x100.

that waters evolved from oligohaline to mesohaline as a result of the increase in sulphate ions dissolved in water.

Sequence stratigraphy. Interpretation and discussion

The facies associations and sedimentary environments indicated that the continental Miocene deposits of northeastern Duero basin were deposited by an interaction between alluvial-fluvial distal and lacustrine sedimentary systems (Fig. 7). The microfaunal association can be linked to the large-scale lake basin evolution from a lower carbonated lake to a upper stable sulphated-saline lake. This evolution and the systematic environmental changes in vertical of these facies associations allows define the existence of two higher-rank lacustrine cycles.

We can establish the hierarchy of the higher order sequences stratigraphic with two depositional sequences in the sense of Mitchum *et al*. (1977); Mitchum (1977) established for marine environments. The concept of hierarchy used in this paper is refers to the classification of sequences based on their relative scale and stratigraphic significance. In the absence of precise geochronological control, it is recommended to refer to sequences in a relative sense, such as lower versus higher frequency, or lower versus higher rank, and interpret their relative stratigraphic significance based on criteria that can be observed in the rock record (Catuneanu *et al*., 2011).

These would represent the evolution of the sedimentary basin over a period of time and they are genetically related strata; i.e., first-order sequences, (allostratigraphic units of NASC, 1983; unconformity-bounded stratigraphic units of the ISSC, 2001), or low frequency (or high rank) sequences of Catuneanu (2006); Catuneanu *et al.* (2011).

The stratigraphic units in the Villadiego area have been subdivided into two depositional sequences, referred to herein as Dueñas Depositional Sequence (DDS) and Cuestas Depositional Sequence (CDS). Both depositional sequences represent higher-rank cycles, related to alluvial fan-fluvial systems progradations and retrogradations and/or lacustrine water level risings and falls.

The transition vertical facies in the study area comprising alluvial-fluvial sands and conglomerates interbedded with underlying basinal carbonates and marls lacustrine/palustrine deposits (Fig. 7). This model is valid for both depositional sequences; however, not all facies associations are represented in them. In the DDS is more represented the PFA type, while in CDS the LFA type is more developed.

The DDS comprises the upper part of the Dueñas Facies in the south sector, and the lower part of the Alar del Rey and Grijalba-Villadiego Facies to the north. Only appears the top of this depositional sequence. The CDS sequence includes by north, the upper part of the Alar del Rey Facies and Grijalba-Villadiego Facies, and by south the distal part of the Grijalba-Villadiego Facies, Cuestas Facies and the Páramos Facies.

In the outcrops appears the top of DDS, and it represents the final shallowing higher-rank cycle and the progradation basinward of the alluvial fan and fluvial systems. The final part of this shallowing cycle is represented by lacustrine, palustrine deposits (Dueñas Facies), and distal fluvial deposits indicating the end of regression (Grijalba-Villadiego Facies). The alluvial fan and fluvial systems and the shoreline lacustrine position migrate basinward (maximum regressive lacustrine surface, MRLS).

In the beginning of the CDS, the mappable stratigraphic surface marks a change in stratal stacking patterns from regression to lacustrine transgression. The marls and lutites indicate a rises of lake level, the coastline migrates landward (maximum flooding lacustrine surface, MFLS). According to the concepts of sequence stratigraphy the lacustrine deposits reached their most landward position.

Towards the middle of the CDS and in the upper part of the CDS shows a gradual shallowing trend. The limestones of the Páramo Facies manifest a change in environmental conditions which are progressively shallower.

Both sequences show in the northern sectors conglomerates (AFA association) which are interpreted as the result of discontinuous accretion and migration of longitudinal or diagonal bars. In the Alar del Rey Facies the thicker, laterally extensive and multistory conglomerate deposits are probably accumulated on active sectors of the alluvial fan dominated mostly by low-sinuosity fluvial systems. The carbonated composition of the clasts suggests the erosion of Mesozoic reliefs located to the north

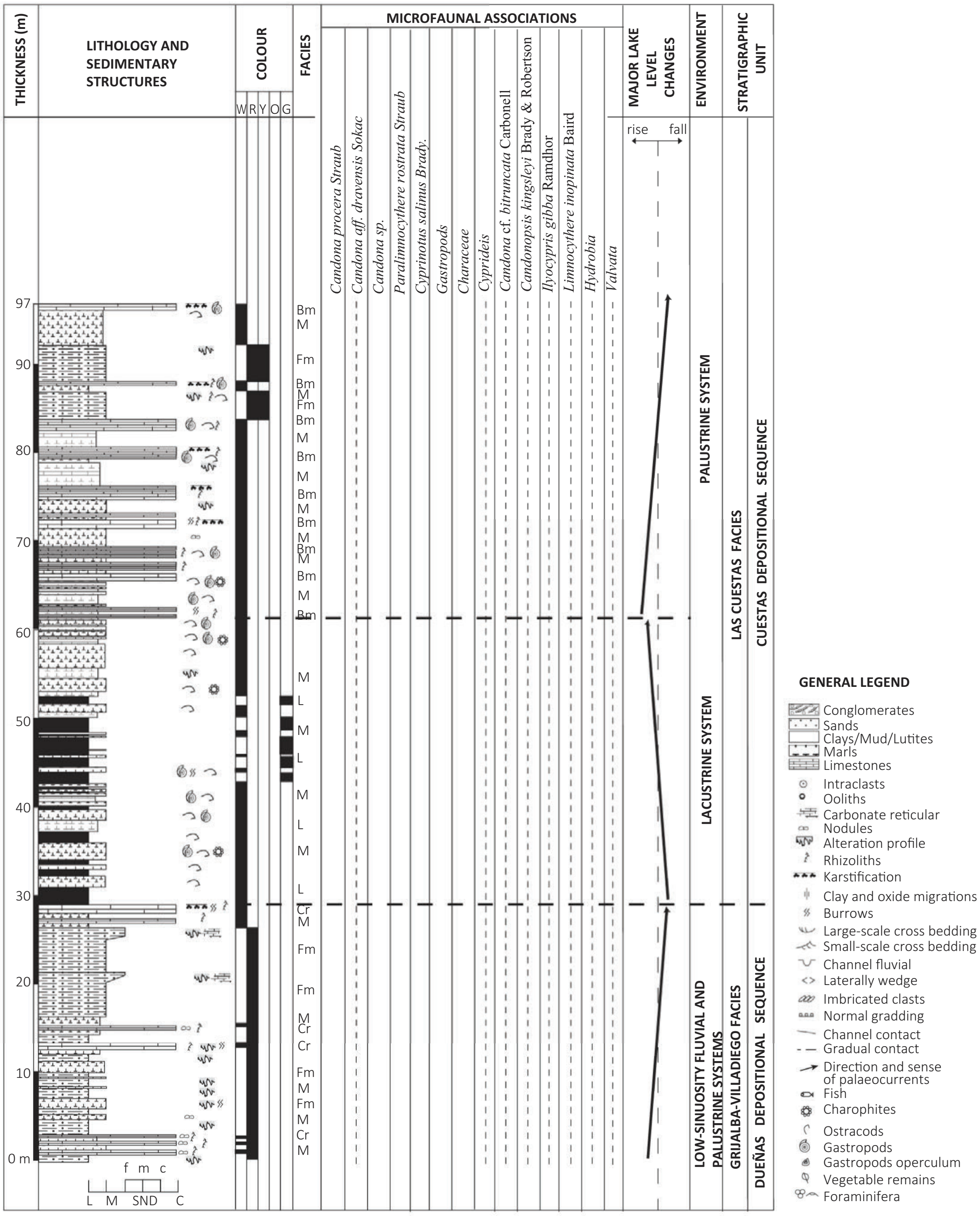


Fig. 6.—Lithological characteristics, and interpretation of the stratigraphic section of Brullés, location in Fig. 2.

(direction of the paleocurrents towards the S and SSE). The distance between the inferred edge of the basin and lacustrine deposits is approximately 6 Km, so the radial distance of the alluvial fan did not exceed 10 Km.

Laterally to the south the FA facies associations represent the filling of active fluvial channels with longitudinal and transverse gravel-sand bars and deposition of floodplain areas. The well-developed paleosoils (calcretes) in the Grijalba-Villadiego Facies suggest that sedimentation rates are slow relative to rates of pedogenesis. These processes are favoured by biological activity of plant roots.

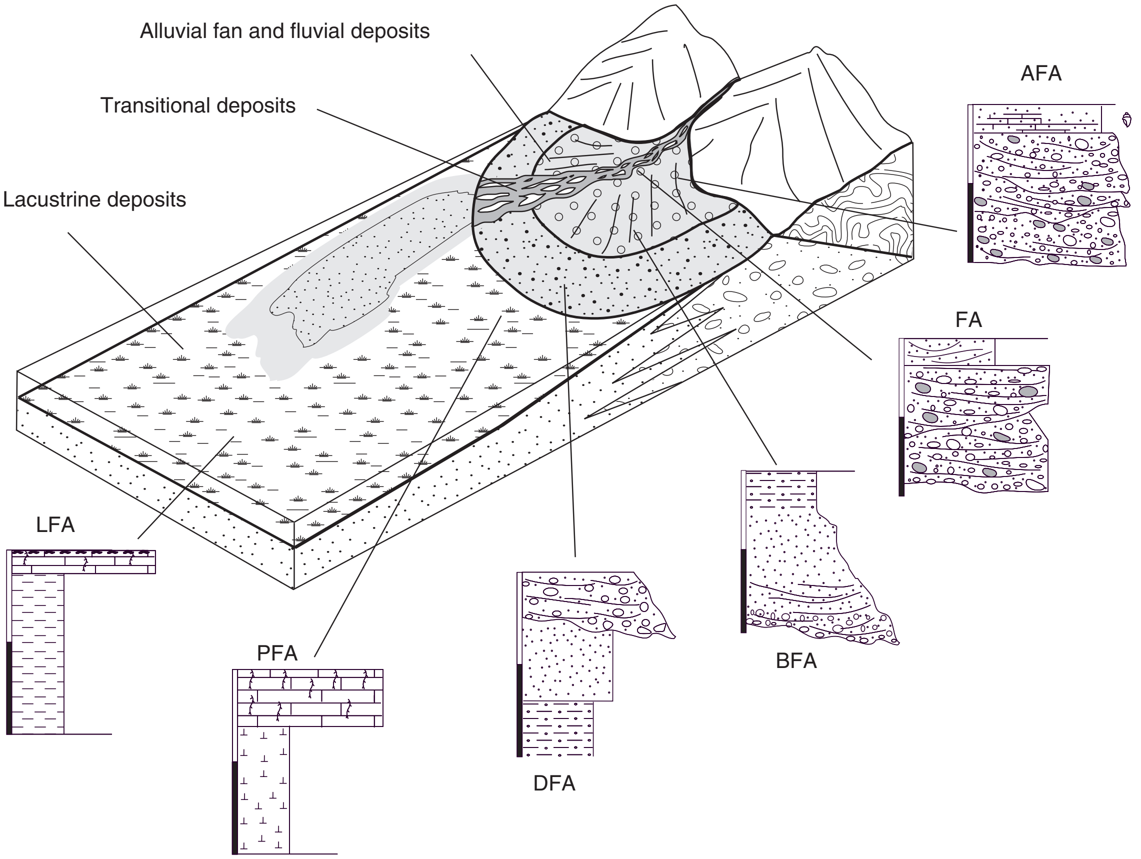


Fig. 7.—Sedimentary model and distribution of facies associations.

Further south, the sedimentary environments of both depositional sequences are represented by the PFA and LFA associations. Both are interpreted as a product of sedimentation in lakes, low slope with palustrine margins. In dry and wet seasons alternating produces rising and fall level-lake and cause extensive sectors be first covered by water and then with subaerial exposure. In the basin, the seasonality of climate (e.g. Mediterranean) could be the mainly allogenic processes, versus absence of sedimentary discontinuities that does not seem to point to tectonic control in the depositional model. This climate is corroborated by the analysis of pollen in sediments from adjacent areas (cf. Valle *et al*., 2006).

The change in the microfaunal associations in the sedimentary record indicates a change in lake chemical conditions of the waters, from oligohaline in the DDS to mesohaline in the CDS. Other lithological indicators suggest the same change and can corroborate that the microfauna points out. This is corroborated by the presence of *Hydrobia*, which indicates episodes of greater salinity in the environment (cf. Adam, 1960). The endobiotic? and limicolous characters of this gastropod indicate the depth of the waters on CDS would not exceed 30 m.

Conclusions

This study presents the sequence stratigraphy for the Miocene sediments and new depositional model in the northeastern domain Duero basin. The interpretation of the higher-rank depositional sequences allows (1) the environmental interpretation of the variations of level lake, and (2) the construction of a sedimentary model based on fluctuations of level lake.

The depositional sequences, DDS and CDS are linked alluvial fans, fluvial systems and shallow and deep lacustrine sedimentary environments interconnected from north to south. In the northern sectors conglomerates Alar del Rey Facies (AFA and FA) are dominant. Southward the transition to Grijalba-Villadiego Facies is manifested by sands and conglomerates (BFA and DFA). These facies associations are connected laterally towards the south with Dueñas Facies and Las Cuestas Facies represented by marls and limestones (PFA and LFA).

The microfaunal associations reveal a change in the chemical environmental conditions of the lacustrine waters, from oligohaline and carbonated in the DDS, to mesohaline and sulphated in the CDS. Also notes a greater depth in the waters of CDS.

The DDS represent the final shallowing of a higher-rank cycle with a maximum regressive lacustrine surface to top. The CDS show a transgressive-regressive higher-rank cycle with a maximum flooding lacustrine surface in the middle, and finally, a progressive shallowing at top.

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