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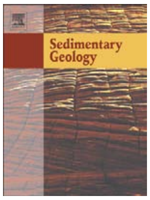

Major controls on sedimentation during the evolution of a continental basin: Pliocene–Pleistocene of the Guadix Basin (Betic Cordillera, southern Spain)

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ABSTRACT

Sequence stratigraphy, based on climatic, tectonic, and base level parameters, can be used to understand carbonate sedimentation in continental basins. The uppermost continental fill of the Guadix Basin (Betic Cordillera), containing both siliciclastics and carbonates, is investigated here. In its central sector a thick succession of fluvio-lacustrine sediments appear, hosting several important Pliocene and Pleistocene macrovertebrate sites (Fonelas Project). The need to characterize the stratigraphic and sedimentologic context of these important paleontologic sites has lead to litho-, magneto- and biostratigraphic studies. These data, together with the sedimentologic analysis of the Pliocene and Pleistocene siliciclastic and carbonate successions, establish a sedimentary model for the fluvio-lacustrine sedimentation of the two last stages of sedimentation in the Guadix Basin (Units V and VI). Unit V comprises mostly fluvial siliciclastic sediments with less abundant carbonate beds interpreted as floodplain lakes or ponds. The latter, Unit VI, is dominated by vertically-stacked, carbonate palustrine successions. Using two pre-existent continental stratigraphic models, the influence of climate, tectonism, and stratigraphic base level during the last 3.5 Ma on the sedimentary evolution of the fluvio-lacustrine system in the Guadix Basin, especially the carbonate sedimentation patterns, is outlined.

1. Introduction

The influence of allogenic factors, such as climate and tectonism, on nonmarine deposition in fluvial and lacustrine basins has been a topic of great controversy (e.g. Van Houten, 1964; Picard and High, 1981; Talbot and Allen, 1996; Valero Garcés et al., 1997; Carroll and Bohacs, 1999; Bohacs et al., 2000; Martinsen et al., 1999; Alonso-Zarza and Calvo, 2000; Anderson and Cross, 2001; Gierlowski-Kordesch and Buchheim, 2003; Alonso-Zarza, 2003; Pietras et al., 2003; Bohacs et al., 2003; Dunagan and Turner, 2004; Luzón, 2005; Scherer et al., 2007; Bohacs et al., 2007). The integration of continental sequences within general allocyclic models has evolved with the recognition of single forcing mechanisms or allogenic processes controlling the distribution of facies in a basin. For nonmarine sequences, climate is proposed as the major control on carbonate deposition (Cecil, 1990; Drummond et al., 1996; Tanner, 2000; Armenteros and Huerta, 2006), while tectonics is also suggested as a major control (Platt, 1989; Sanz et al., 1995; Armenteros et al., 1997; De Wet et al., 1998). Recently, sequence-stratigraphic depositional models for fluvial and lake basins have established that climate and tectonics work in tandem to control sediment input, subsidence, and water input (hydrology) as sedimentation evolves through time (e.g. Martinsen et al., 1999; Bohacs et al., 2000, 2003; Gierlowski-Kordesch and Buchheim, 2003; Alonso-Zarza, 2003; Gierlowski-Kordesch et al., 2008; Bohacs et al., 2007).

Base level (eustacy in coastal marine environments) is the third allocyclic factor affecting fluvio-lacustrine architecture. There are two definitions of base level. The former, geomorphic base level, is used in sequence stratigraphy and refers to sea level. The latter, the stratigraphic base level, can be applied in continental environments where the sea level influence is not significant. It is defined as the “potential energy surface that describes the direction in which a stratigraphic system is likely to move, toward sedimentation and stratigraphic preservation or sediment bypass and erosion” (Shanley and McCabe, 1994). Changes in stratigraphic base level increase or decrease the accommodation space or available space for potential sediment accumulation (Jervey, 1988). Therefore, the stratigraphic base level can be formulated as the ratio between accommodation space and sediment supply (A/S ratio) (Martinsen et al., 1999).

The present study in the Guadix Basin (Betic Cordillera, southern Spain) outlines the influence of the three allocyclic factors controlling carbonate deposition in continental basins. The Guadix Basin hosts a

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complete succession of continental sediments dated from the end of the Miocene to the Late Pleistocene. The deep incision of the Holocene drainage network into the sedimentary infilling of the basin is the result of the intensive erosion in the basin since the Late Pleistocene, when the basin drainage changed by becoming part of the Guadalquivir hydrographic basin (Vera, 1970; Viseras and Fernández, 1992; Calvache et al., 1996; Calvache and Viseras, 1997). With exceptional outcrop exposure in the Guadix Basin, especially for the sediments of the uppermost continental stage, it is an excellent location for studies focused on patterns of continental infilling (Fernández et al., 1993; Viseras and Fernández, 1994; Viseras et al., 2005, 2006; Pla-Pueyo et al., 2007, among others). In addition, many paleontologic vertebrate sites are well exposed. In fact, the stratigraphic, sedimentologic, and paleoecologic characterization of the Pliocene and Pleistocene macromammal sites in the central sector of the basin has been the aim of multidisciplinary studies in the Guadix Basin since 2001 (Viseras et al., 2006; Arribas and Garrido, 2007; Pla-Pueyo et al., 2007, 2008; Garrido and Arribas, 2008). The paleontologic sites are found in the siliciclastic and carbonate sedimentary rocks interpreted as the floodplain of the main fluvial system of the Guadix Basin during the Pliocene and Pleistocene. This environmental characterization of the sediments is crucial to understand the ecologic and geologic processes leading to the formation of some of the most significant large-mammal sites in Europe (Viseras et al., 2006; Arribas and Garrido, 2007; Garrido and Arribas, 2008).

The stratigraphy and origin of the architectural elements forming the floodplains and channels of the Guadix fluvial system have been previously characterized (Fernández et al., 1996b; Soria et al., 1998), in addition to preliminary studies on the carbonate facies in the area (Pla-Pueyo et al., 2007). This work integrates the current knowledge about the siliciclastic and carbonate sedimentology of the fluvio-lacustrine system in the sector of the basin containing the paleontologic sites in a sequence-stratigraphic context for insight into the evolutionary development of continental siliciclastic and carbonate sedimentation in the Guadix Basin over the last 3.8 Ma.

2. Geologic setting

The Betic Cordillera is located on the southern Iberian Peninsula (Fig. 1), and together with the North-African Rif, encircles the western end of the Mediterranean Sea, representing the most western belt of the Alpine chains. The Guadix Basin (Fig. 2) is situated in the central sector of the Betic Cordillera, within the Granada province of southern Spain. It is located on the ancient contact between the two main structural realms of the Betic Cordillera: the Internal Zones (or Alboran Block) (Andrieux et al., 1971) and the External Zones (corresponding to the folded and faulted South Iberian paleomargin) (Vera, 2001; Viseras et al., 2005).

The Guadix Basin, as well as the other Neogene intramontane basins in the Betic Cordillera, shows two main sedimentary stages during its evolution (Vera, 1970; Viseras et al., 2005). The older stage of Late Tortonian age, is marine, while the younger is continental, lasting from the Late Tortonian to the Late Pleistocene (Fernández et al., 1996a; Viseras et al., 2005).

Following Fernández et al. (1996a), the sedimentary filling of the basin can be divided into six genetic units (Fig. 3). The two lower units (Units I and II) correspond to the marine sedimentation stage. Unit III involves shallow marine sediments, deposited through the latest Tortonian sea withdrawal from the Betic Cordillera. During the continental stage of infilling (Late Tortonian–Late Pleistocene), corresponding to the three youngest units (IV, V and VI), the basin evolved into an endoreic depression, reaching its final filling stage in the Late Pleistocene (top of Unit VI) (Fernández et al., 1996b; Soria et al., 1998, 1999).

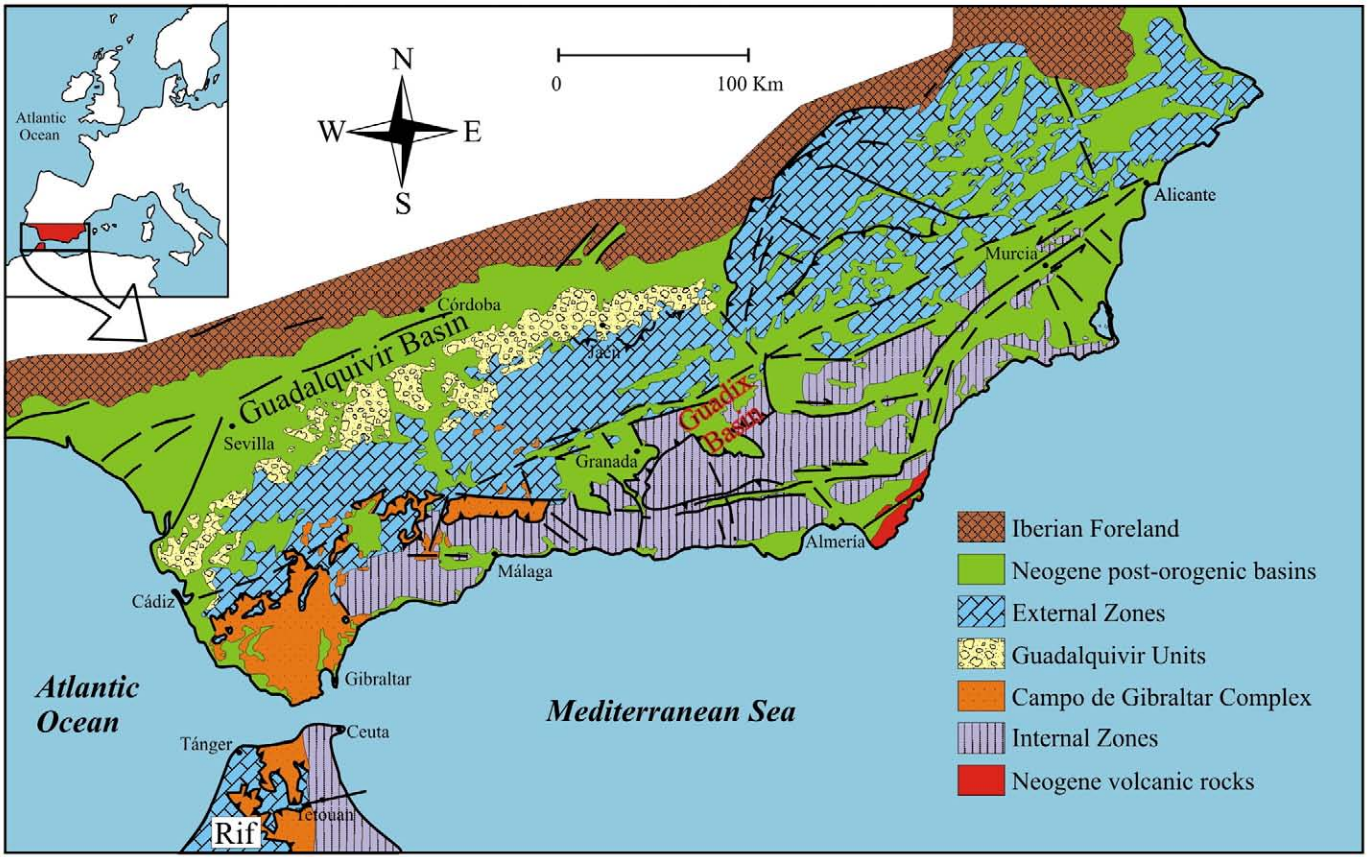

Fig. 1. Geologic map of the Betic Cordillera, showing the position of the Guadix Basin in its central sector.

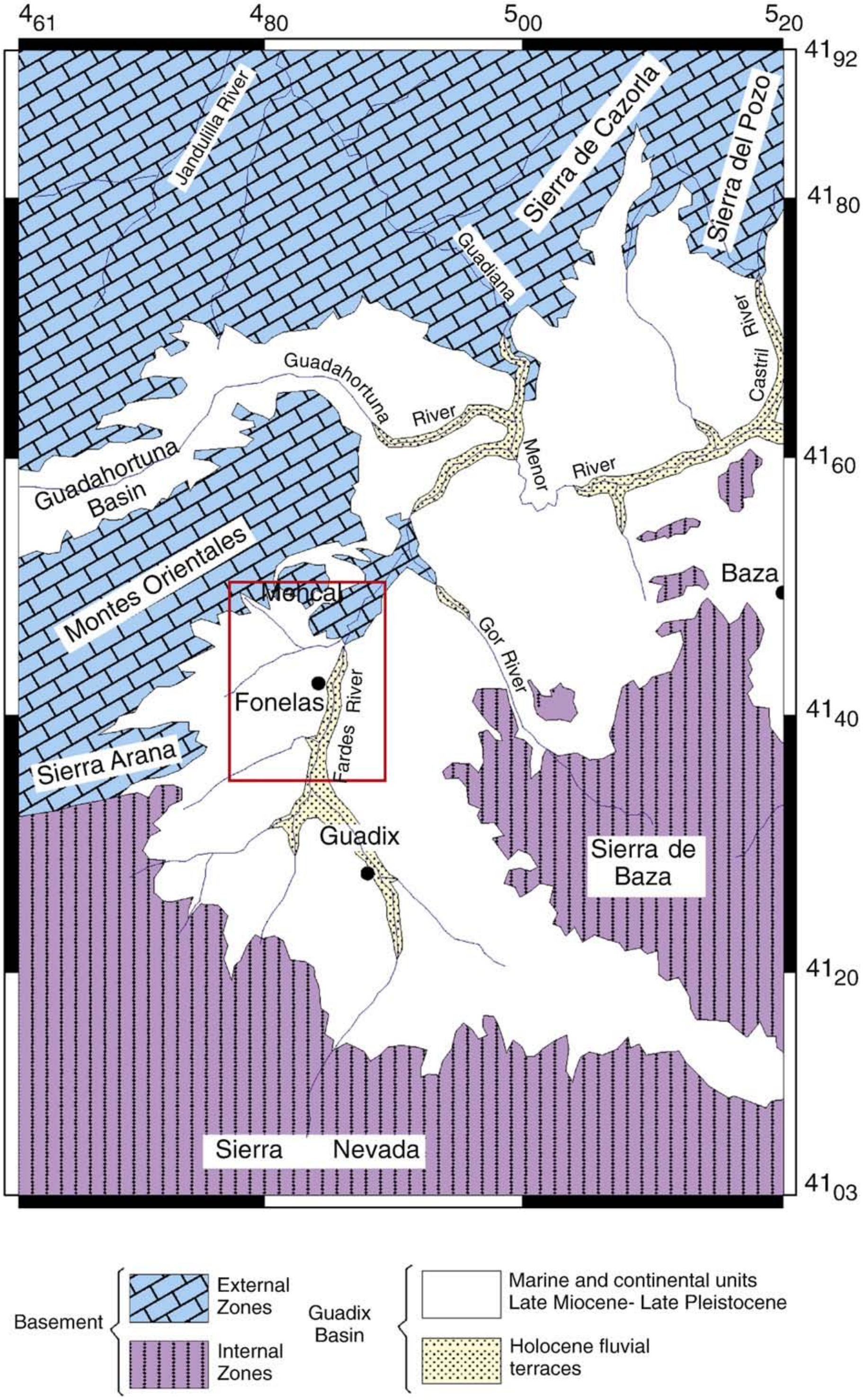

Fig. 2. Geologic context of the Guadix Basin. The rectangle represents the studied area (modified from Viseras et al., 2006).

Three main drainage systems can be distinguished within Units V and VI of the Guadix Basin (Fernández et al., 1996b; Viseras et al., 2006) (Fig. 4). The so-called Axial System (AS) flowed towards the NE following the paleogeographic axis of the basin. This longitudinal drainage system was composed of a highly sinuous, fluvial meander belt, draining into a large shallow lake, located to the east in the neighboring Baza Basin (see also Fig. 2), which acted as base level for the entire drainage system. The Axial System was fed by two transverse alluvial systems. The Internal Transverse System (ITS) (Viseras and Fernández, 1994, 1995) was composed of large coalescent alluvial fans, with their source area located on the Internal Zones of the Betic Cordillera. The External Transverse System (ETS) (Fernández et al., 1991, 1993) had small isolated alluvial fans, which received their inputs from the erosion of the External Zones of the Betic Cordillera.

The siliciclastic and carbonate fluvial deposits of the Axial valley (AS) host a number of important macromammal fossil sites in the transition between the Pliocene and Pleistocene, representing an

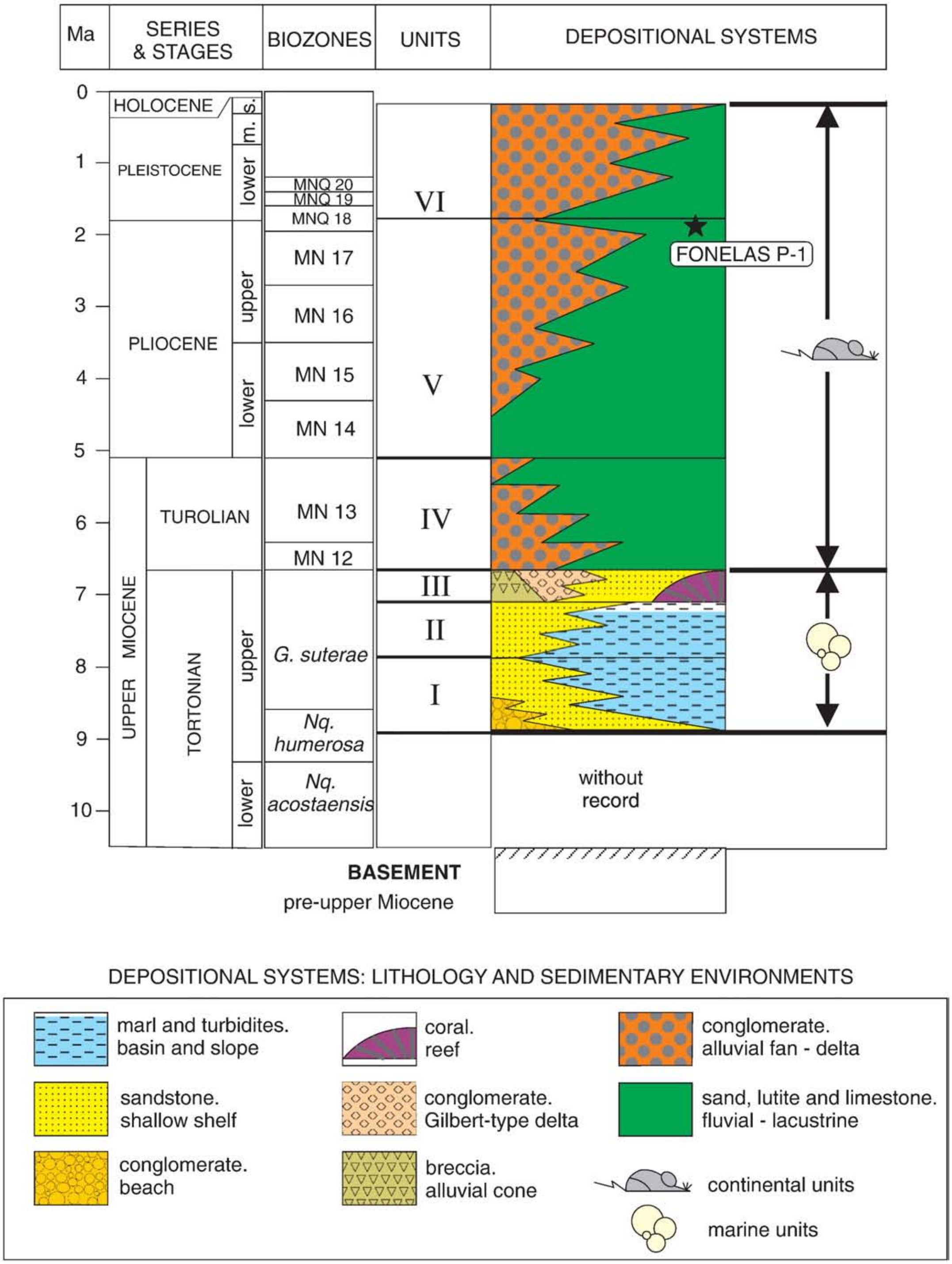

Fig. 3. Genetic units in which the infilling of the Guadix Basin can be divided (modified from Fernández et al., 1996a).

important faunistic dispersion (Viseras et al., 2006). This paper focuses on the Axial System and the sedimentologic features of the siliciclastics and carbonates hosting the macromammal sites, establishing the sedimentary evolution of the central part of the basin from the Pliocene to middle Pleistocene.

3. Stratigraphic architecture

A detailed lithostratigraphic study (Pla-Pueyo et al., 2008) involved a set of eleven stratigraphic profiles (Fig. 5) measured in the field, including those from the most important paleontologic sites (FPB-4, FP-1, FSCC-1, FSCC-2, FSCC-3, FBP-SVY-1, M-2, M-3, M-4, M-5, M-8 and M-9). Magnetostratigraphic data are also available for three of the stratigraphic sections (Pla-Pueyo et al., 2008), those with the most accurate biochronologic information (FP-1, FSCC-1, and M-9) (Viseras et al., 2006).

The correlation of the sampled sections with the geomagnetic polarity time scale (Lourens et al., 2004) dates more precisely the most important fossil sites of the studied area (Fig. 6) as well as determines the age of the boundary between Units V and VI (Pla-Pueyo et al., 2008). This boundary is an unconformity, but conformable towards the basin center with no appreciable stratigraphic gap (Viseras, 1991; Soria et al., 1998). It was previously considered to be older (within the Pliocene), using biochronologic data (Viseras, 1991;

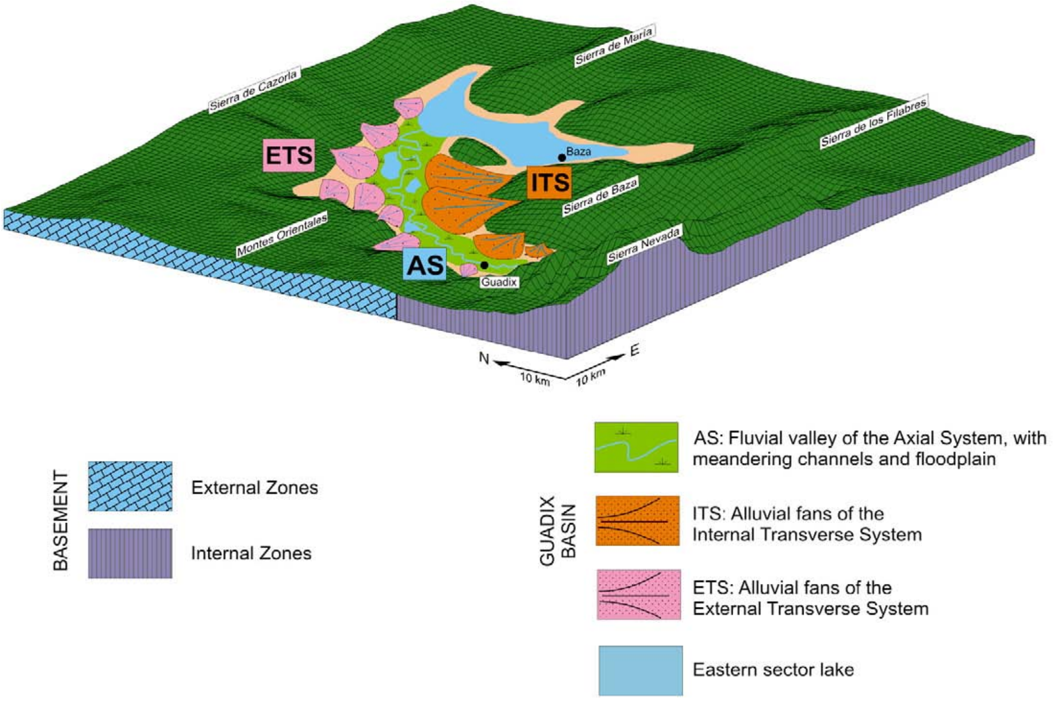

Fig. 4. 3D representation of the paleogeography of the Guadix Basin through the Pliocene and the Pleistocene, showing the spatial distribution of the three main drainage systems: the Axial System (AS), the Internal Transverse System (ITS), and the External Transverse System (ETS) (modified from Viseras et al., 2006).

Fernández et al., 1996b; Soria et al., 1998, 1999), but recent lithologic, sedimentologic, magnetostratigraphic, and paleogeographic criteria (Pla-Pueyo et al., 2008) relocate it to 1.778 Ma. Lithologic and sedimentologic differences between both units are more visible in the center of the Guadix Basin, especially in the AS sediments, where sedimentation rates and accommodation space can be better estimated. The differences are reflected as (1) an increase in carbonate sediments in Unit VI with respect to Unit V; (2) distinctive sedimentary patterns defining each unit, and (3) changes in the paleogeographic distribution of the three main drainage systems (AS, ITS, and ETS) during each unit. In this sense, the maximum expansion of the AS marks the boundary between both units (Pla-Pueyo et al., 2008).

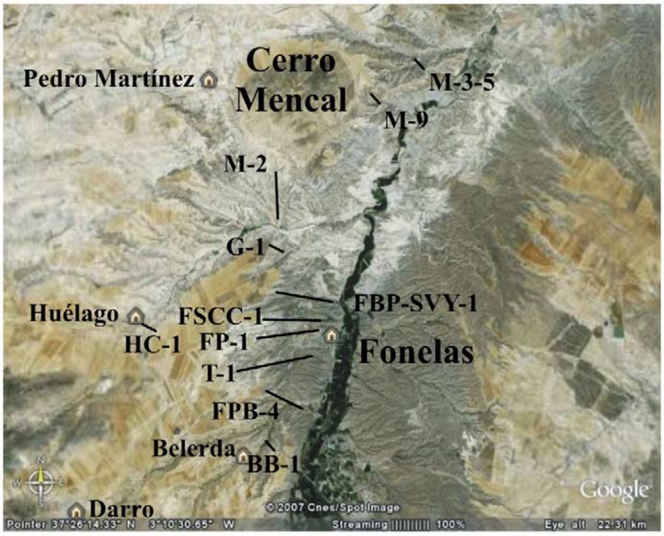

Fig. 5. Image from Google Earth© showing the study area in the Guadix Basin. The eleven measured stratigraphic profiles are represented by lines.

Therefore, the boundary between Units V and VI appears to reflect an important switch in the factors controlling sedimentation within the Guadix Basin, especially enhancing carbonate deposition in the AS in the center of the basin. The aim of this paper is to describe the sedimentary pattern of the AS sediments for both Units V and VI. Then, a sedimentary model for the fluvio-lacustrine system in each unit will be constructed identifying the variation of the factors controlling carbonate sedimentation.

4. Provenance

The source area of the sediment not only determines the lithology of the siliciclastics deposited in a continental basin, but also allows thick carbonate accumulations when widespread carbonate rocks are present in the watershed (Jones and Bowser, 1978; Gierlowski-Kordesch, 1998). It is clearly important to consider the provenance controlling sediment input for the Guadix Basin in order to understand the change in carbonate deposition between Units V and VI (Table 1).

The resultant depositional lithology present in the three drainage systems (AS, ITS, and ETS) is directly related to the bedrock of their source areas (Fig. 7). There are two main source areas for these systems, the Internal and the External Zones of the Betic Cordillera (Table 1).

The main bedrock in the source area of the AS is comprised of quartzites and mica schists from the Nevado-Filábride Complex (Internal Zones) (Table 1), so the proximal sedimentary lithology is dominated by siliciclastics. In the medial and distal parts of the AS successions where ITS and ETS join the axial drainage, more carbonates appear (Fig. 7), depending on the relative influence of each transverse alluvial system and their provenance. The ITS source area (Table 1) contains quartzites and mica schists from the Nevado-Filábride and Alpujárride Complexes (Internal Zones) (Fig. 7) and abundant grey dolomitic marbles from the Alpujárride Complex (Internal Zones). The provenance of ETS occurs in the External Zones, where Mesozoic limestones dominate. Some chert beds can also be found in this source area, interbedded with the limestones (Table 1).

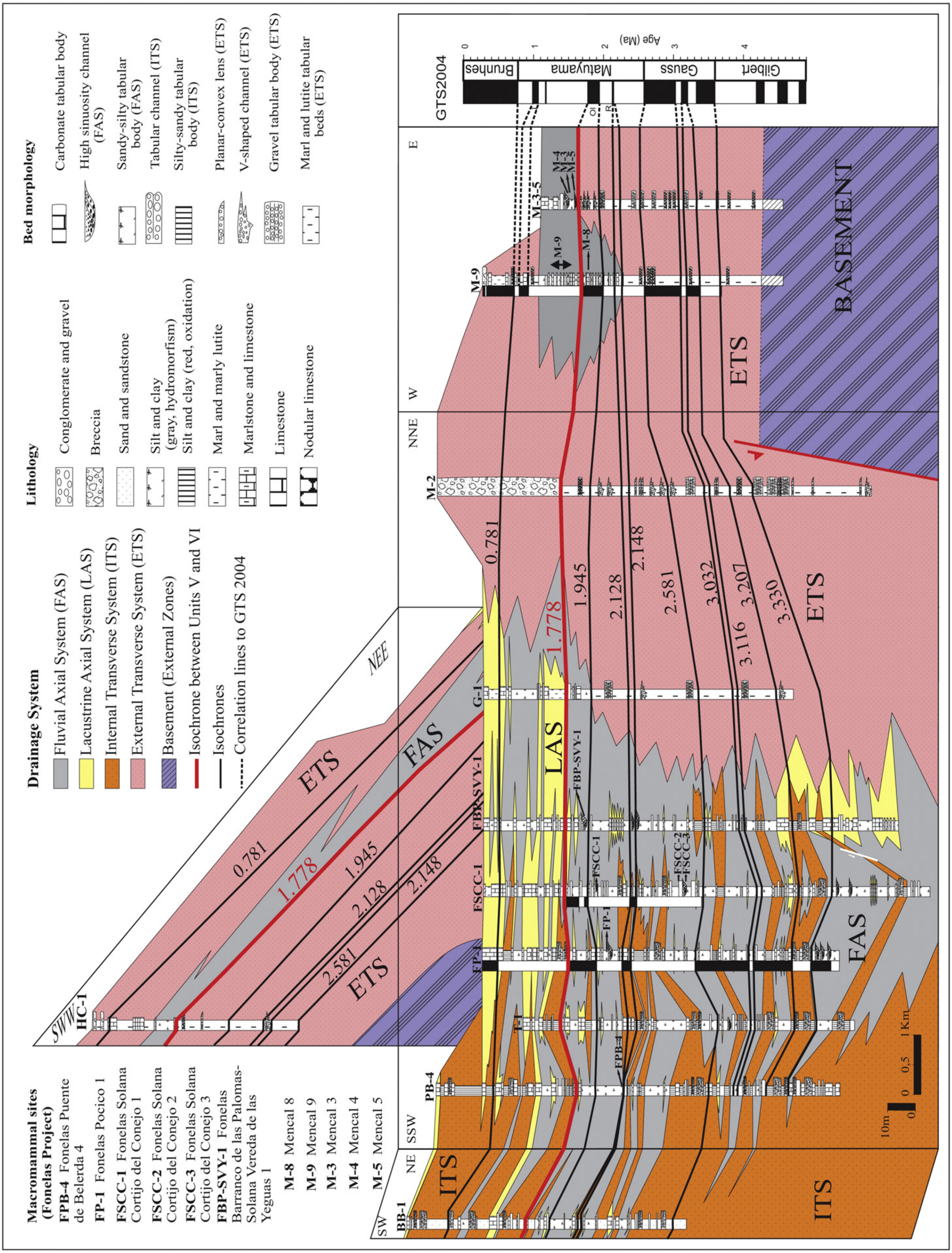
Macromammal sites (Fonelas Project)
FPB-4 Fonelas Puente de Belerda 4
FP-1 Fonelas Pocico 1
FSCC-1 Fonelas Solana Cortijo del Conejo 1
FSCC-2 Fonelas Solana Cortijo del Conejo 2
FSCC-3 Fonelas Solana Cortijo del Conejo 3
FBP-SVY-1 Fonelas Barranco de las Palomas-Solana Vereda de las Yeguas 1
M-8 Mencal 8
M-9 Mencal 9
M-3 Mencal 3
M-4 Mencal 4
M-5 Mencal 5
Drainage System
Fluvial Axial System (FAS)
Lacustrine Axial System (LAS)
Internal Transverse System (ITS)
External Transverse System (ETS)
Basement (External Zones)
Isochrone between Units V and VI
Isochrones
Correlation lines to GTS 2004
Lithology
Conglomerate and gravel
Breccia
Sand and sandstone
Silt and clay (gray, hydromorfism)
Silt and clay (red, oxidation)
Marl and marly lutite
Marlstone and limestone
Limestone
Nodular limestone
Bed morphology
Carbonate tabular body
High sinuosity channel (FAS)
Sandy-silty tabular body (FAS)
Tabular channel (ITS)
Silty-sandy tabular body (ITS)
Planar-convex lens (ETS)
V-shaped channel (ETS)
Gravel tabular body (ETS)
Marl and lutite tabular beds (ETS)
SW
NE
SSW
SWW
NEE
NNE
W
E
BB-1
PB-4
FPB-4
T-1
FP-1
FSCC-1
FSCC-2
FSCC-3
FBP-SVY-1
G-1
HC-1
M-2
M-9
M-8
M-3-5
M-4
M-3
M-5
ITS
FAS
LAS
ETS
BASEMENT
0.781
1.778
1.945
2.128
2.148
2.581
3.032
3.116
3.207
3.330
10m
0
0 0,5 1 Km
GTS2004
Brunhes
Matuyama
Gauss
Gilbert
Ol
R
Age (Ma)
0
1
2
3
4

Table 1
Provenance of the sediments in the studied area in the Guadix Basin.

Drainage system	Main source area	High reliefs in the source area	Resultant depositional lithology
Axial System (AS)	Internal Zones (Nevado-Filábride Complex) + transverse inputs	Sierra Nevada	Quartzites, mica schists
Internal Transverse System (ITS)	Internal Zones (Nevado-Filábride, Alpujárride and Maláguide Complexes)	Sierra Nevada Sierra de Baza	Quartzites, mica schists, dolomitic marbles
External Transverse System (ETS)	External Zones (Subbetic Zone and Betic Dorsal)	Cerro Mencal, Sierra Arana	Mesozoic limestones and chert

This transverse alluvial system (ETS) probably represents the main carbonate input to the Guadix Basin sediments during the Pliocene and Pleistocene.

5. Sedimentary pattern and facies analysis of the Axial System (AS) sediments

The AS deposits in the studied sector correspond to the medial to distal facies of a high-sinuosity river system (Viseras, 1991; Viseras et al., 2006) containing floodplain deposits of both siliciclastic and carbonate sediments. A number of lithofacies, as well as their associations, forming three-dimensional sedimentary bodies, considered as architectural elements in the sense of Miall (1985, 1996), are identified and described below for Units V and VI. Standard field methods in the identification and measurement of all lithofacies were followed, but the carbonate lithofacies were more closely examined through 147 hand samples from sections FPB-4, FP-1 and FBP-SVY-1 and 231 thin sections from sections FPB-4, FP-1, FSCC-1 and FBP-SVY-1.

5.1. Unit V

The siliciclastic and carbonate sedimentary deposits of Unit V in the AS (Fig. 8) are divided into five architectural elements (Table 2). Facies and facies associations are defined by lithology, geometry, and 3-D relationships. General descriptions of the six architectural elements follow.

5.1.1. Gravel–sand channels

5.1.1.1. Description. These architectural elements, appearing within silt–clay units, are represented by rare 3 to 8 m thick, single to multi-storey bodies consisting of gravel and sand. The co-sets in the case of multi-storey bodies range in thickness from 1 to 4 m on average.

The basal, erosional bounding surface of these bodies is concave-up. They may reach a lateral extent from 15 to 20 m with a channel *W*/*T* between 2 and 7, but always lower than 15, the range of values characterizing narrow ribbon bodies of high-sinuosity rivers (Gibling, 2006). The single bodies contain several lateral-accretion sets with a fining-upward trend going from gravel to fine-grained lithofacies (Gt/St, Gp/Sp, Sla, Sr, Sh, Fl, Fo) (Tables 3A and 3B). Epsilon bedding and trough and planar cross-bedding occur in the coarser sediments, and horizontal bedding or massive structure in the finer sediments. The paleoflow measurements indicate a dispersion angle of 134°.

5.1.1.2. Interpretation. Following interpretations for other larger river examples (Allen, 1970; Nijnman and Puigdefábregas, 1978; Eberth and Miall, 1991), they are interpreted as high-sinuosity ribbon channels (Gibling, 2006), where lateral accretion predominates and the dispersion angle of the paleoflow is high. If the channels are multi-storey, they are filled in consecutive stages (Table 2). These rare elements may be interpreted as the different positions of the main fluvial channel of the AS.

5.1.2. Sand bodies

5.1.2.1. Description. Within the sandy-clay units, isolated bodies with a thickness from 50 cm to 2 m appear (Fig. 9A). Their lateral extent is usually between 5 and 10 m, and lateral asymmetry in a transverse section is common. With an average *W*/*T* lower than 15, they mostly fit in the ribbon type of Gibling (2006). They typically exhibit a fining-upward sequence formed by sandy lithofacies (Sla-St/Sr-Sh-So) grading upwards to finer sediments, sometimes showing lateral-accretion structures (Sla facies) (Fig. 9B).

5.1.2.2. Interpretation. These bodies are interpreted as small channels with a ribbon-like morphology interbedded with the fine floodplain sediments (sandy-clay units). The grain size of the sediment and the size of the bars and other bedforms suggest that these bodies do not represent the main channel of the Axial System, but rather the secondary channels crossing the distal plain of the system (Viseras and Fernández, 1995; Fernández et al., 1996b). The literature contains many examples of similar interpretations of this lithofacies sequence (McGowen and Garner, 1970; Bluck, 1971; Jackson, 1976; Nijnman and Puigdefábregas, 1978; Miall, 1996; Stouthamer, 2001; Bridge, 2003).

5.1.3. Sandy-clay units

5.1.3.1. Description. This element is predominant in the study area (Fig. 9C); the rest of the architectural elements essentially are embedded within it (Table 2). These units are comprised of massive, grey-brown hectometer- to kilometer-scale tabular beds, with a thickness ranging from 50 cm to 8 m. The granulometry of these beds ranges from coarse sand to clay size sediment (So, Fo/Fb) (Tables 3A and 3B). Yellow–orange–red mottling is associated with iron nodules in these units. These units can be rich in organic matter.

5.1.3.2. Interpretation. The sandy-clay units can be interpreted as overbank vertical-accretion deposits (Nanson and Croke, 1992), the coarser sediments corresponding to floodplain areas next to small channels, perhaps pedogenetically altered, and the finer being deposited in floodplain areas rich in vegetation and far from the fluvial channels (Table 2). These deposits could also include palustrine siliciclastic deposits; more research is needed to confirm this. The common presence of mottling, associated with rhizoliths, is interpreted as iron remobilization because of redox processes related to poor drainage conditions in a paleosol (Kraus and Hasiotis, 2006). As completely developed paleosol profiles were not identified in any outcrop of the studied area, the paleosols found within the sandy-clay units are interpreted as immature paleosols. This interpretation is consistent with examples provided in the literature, as the paleosols described in the Bighorn Basin (Kraus and Gwinn, 1997), whose maturity and hydromorphic conditions depend on the grain size and therefore on the distance from a local sediment source (Kraus, 1999). In the studied Guadix sector, the scarcity of gravel–sand channels interpreted as the main channel of the fluvial system probably involves a distal position from the sediment source of the floodplain sediments. This would enhance the accumulation of fine-grained sediment, as in less permeable clay, leading to immature and poorly-drained paleosol formation.

Fig. 6. Correlation scheme where litho-, bio- and magnetostratigraphic data are represented. The lines crossing the diagram horizontally are isochrons, extrapolated from the paleomagnetic data. The thick line at the top of the normal polarity chron marked Olduvai is the boundary between Units V and VI (modified from Pla-Pueyo et al., 2008).

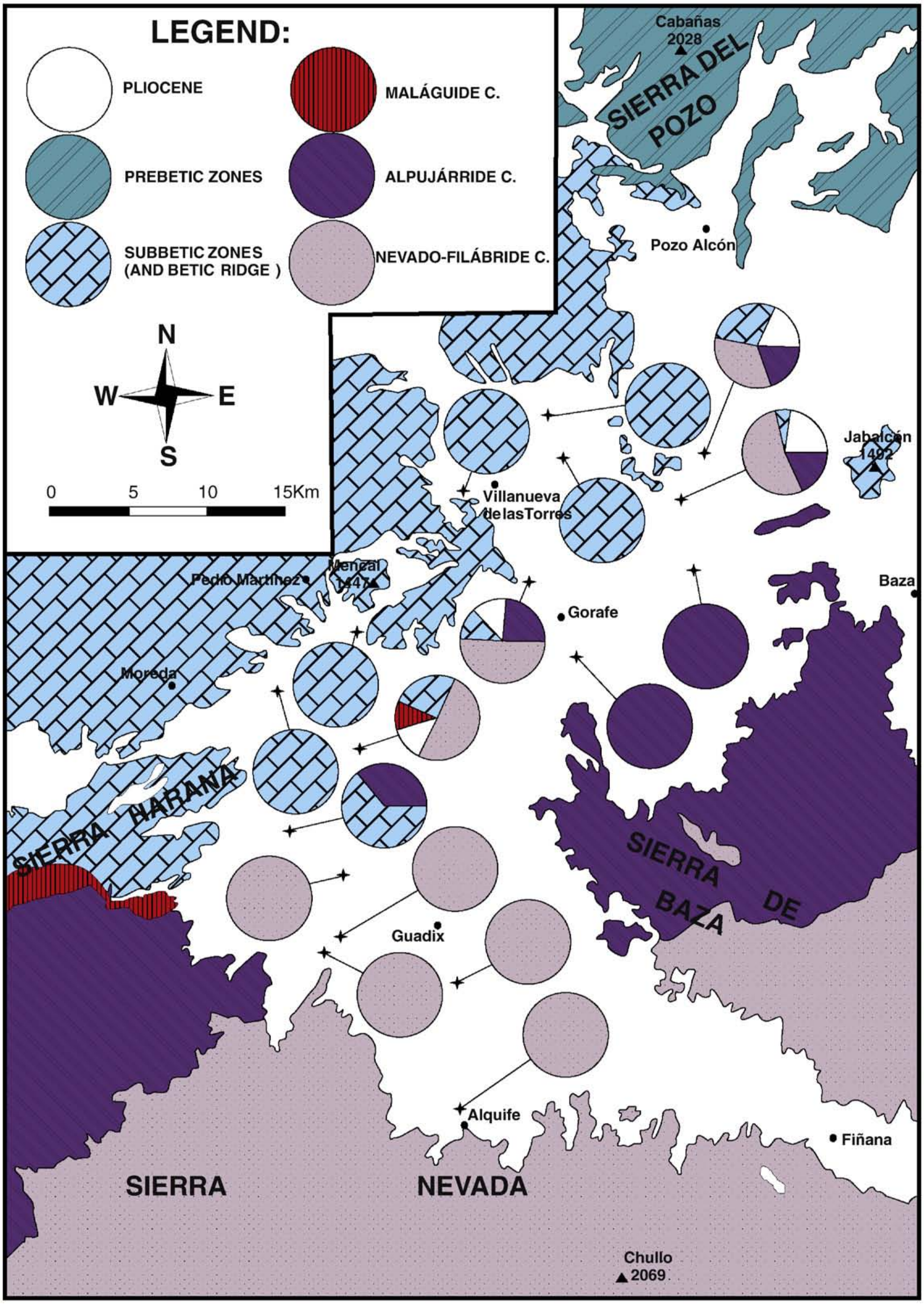

Fig. 7. Lithologic distribution of the clasts belonging to the alluvial and fluvial sediment of the Guadix Basin (modified from Viseras, 1991).

5.1.4. Phytohermic framestone

5.1.4.1. Description. These rare carbonate deposits extend laterally for less than 20 m, and their average thickness is 1.5 m. They appear in lateral association with the sandy-clay units, and consist of mound-like marly limestones with cylindric plant molds in life position (Fig. 10A) or as non-transported clasts as well as stem and leaf fossils floating in the marly matrix (lithofacies T) (Table 3C). The cylindrical to elongated plant molds are comprised of fringe calcitic cements, where micritic and sparitic layers alternate (Fig. 10B). The top of the element presents a higher degree of cementation.

5.1.4.2. Interpretation. These plant molds are interpreted as frameworks of reed-like plants living in a fresh, but shallow water body

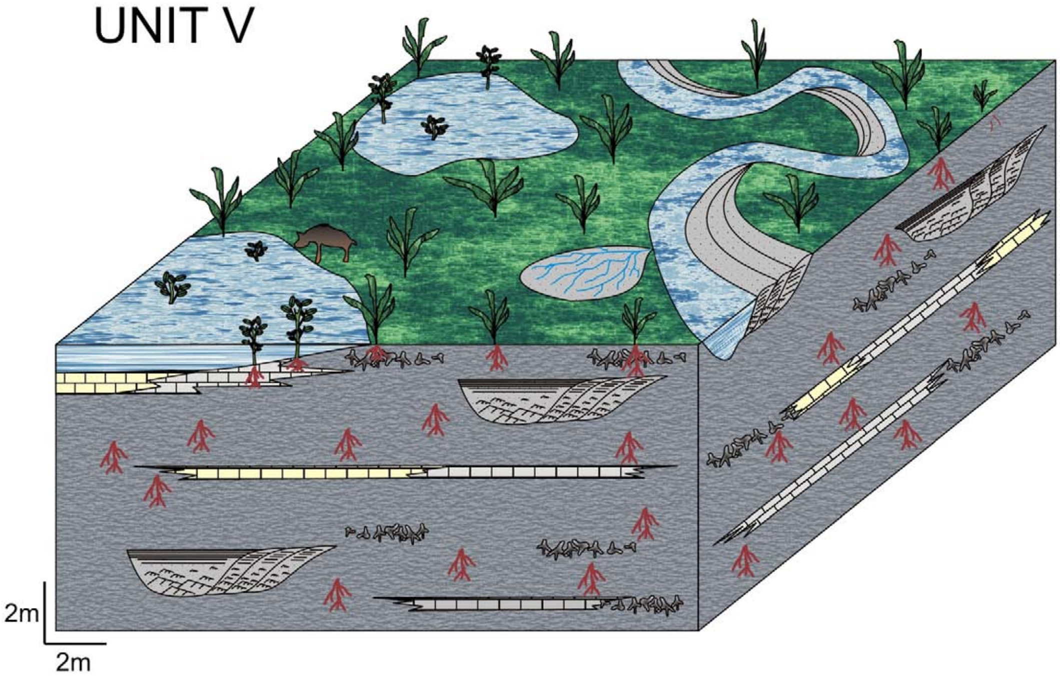

Fig. 8. Reconstruction of the paleoenvironment interpreted for Unit V. Transverse sections of channels showing lateral accretion and tabular carbonate beds appear within sandy-clay sediments with root activity, representing the typical sedimentary pattern in cross-section. A crevasse splay is along the margin of a high-sinuosity channel and carbonates accumulate in protected floodplain areas.

(Table 2), enhancing the carbonate precipitation by their activity and surrounded by micrite settling in the quiet, protected environment (Pedley, 1990; Arenas et al., 2000, 2007). Early diagenesis could cement these deposits, allowing the preservation of the organic framework.

5.1.5. Tabular carbonate beds

5.1.5.1. Description. The most carbonate bodies in Unit V present a lenticular to tabular morphology (Table 2), with a thickness ranging from 5 to 50 cm and a lateral extent that varies on a meter- to kilometer-scale (Fig. 9C). From the detailed study of thin sections and hand samples several lithofacies (Cm, Co, Cr, Cs, M, Lo, Ln, Lg) are distinguished (Fig. 11). Their petrography is described in Tables 3B and 3C, showing different degrees of pedogenic alteration following the criteria of Alonso-Zarza (2003). They range from a low degree of alteration, in the case of those lithofacies presenting only root molds and/or mottling (e.g. lithofacies Cm, Co), to a higher degree, even showing features as grainification (lithofacies Lg) (Alonso-Zarza et al., 1992).

Commonly, carbonate content increases upwards within these bodies. Lithofacies Cs, Cm, Co and Lo are usually at the bottom of the sequence, associated laterally and changing gradually from one to another and into the Fo lithofacies of the sandy-clay units. Vertically these successions may present an intermediate stage where lithofacies M marks a transition to lithofacies Lo/Ln/Lg, but the vertical change from calcilutite to limestone may also be direct. These carbonate sequences can be found complete, or lacking some of the stages, but they commonly present a sharp contact with the overlying fine siliciclastic sediments.

5.1.5.2. Interpretation. These carbonate beds exhibit petrographic features (Tables 3B and 3C) that point to frequent subaerial exposure (Freytet and Verrecchia, 2002), such as root molds, mottling, and

Table 2
Architectural elements defined for Units V and VI in the studied sector of the Guadix Basin.

Unit	Element	Geometry	Dimensions (thickness and lateral extent)	Lithofacies association	Interpretation
V	Gravel–sand channels	Ribbon	th.: 5–8 m l.e.: 15–20 m	Gt/St, Sla, Gp/Sp, Sr, Fl	Single to multi-storey ribbon channel filled in several stages
	Sand bodies	Ribbon	th.: m l.e.: m	Sla-St/Sr-Sh-So-Fl-Fm/Fo	Secondary single ribbon channel
	Sand–clay units	Tabular	th.: cm–m l.e.: hm–km	So-Fo/Fb	Floodplain deposits with paleosol development
	Phytohermic framestone	Mound-like	th.: 1–2 m l.e.: 5–20 m	Cm, T	Palustrine tufa mounds
	Tabular carbonate beds	Lenticular/Tabular	th.: 5 cm–50 cm l.e.: hm–km	So-Cs-Cr-Cm/Co/M-Lo/Ln/Lg (T)	Ephemeral lake on the floodplain
VI	Silt–clay units	Tabular	th: cm–m l.e.: hm–km	Fo	Distal floodplain deposits with paleosol development
	Carbonate sheets	Sheet	th.: 10 cm–2 m l.e.: hm–km	Co/M-Lo/Ln	Long-term palustrine conditions
	Carbonate layer	Thin layer	th.:1–10 cm l.e.: hm–km	Ll	Laminar calcrete

For lithofacies descriptions, see Tables 3A and 3B.

Table 3A

Lithofacies found in the studied area of the Guadix Basin.

Lithofacies	Gravel		Sand						
	Gp	Gt	Sm	Sla	Sp	St	Sh	Sr	So
Description	Granule-2 cm Planar cross-bedding Clast-supported	Granule-pebble Trough cross-bedding Clast-supported	Fine–medium sand Massive <30% floating granules and pebbles Normal grading	Coarse–very coarse sand with some gravels Epsilon cross-bedding	Coarse–very coarse sand Planar cross-bedding	Medium–coarse sand Trough cross-bedding	Fine–very coarse sand Horizontal lamination or low angle cross-lamination Parting lineation	Fine–medium sand Small scale ripple cross-lamination	Very fine–fine sand Massive Mottling Root molds
Thickness	10–50 cm	15–25 cm	20–150 cm	15–180 cm	15–50 cm	10–150 cm	20–50 cm	25–50 cm	50–100 cm
Interpretation	Bar-tail (chute bar) Channel	Channel fill	Pedoturbation? of a sandy deposit on the floodplain or in a channel	Lateral-accretion deposits a) Lateral bar b) Point bar	Bar-tail, channel	Dune migration within a channel	Crevasse splay (floodplain next to channel)	Ripple migration (channel or crevasse splay)	Floodplain deposits affected by redox processes (floodplain with abundant vegetation and flooding)

(A) Gravel or sand simple lithofacies.

Table 3B

Lithofacies found in the studied area of the Guadix Basin.

Lithofacies	Silt–clay				Calcilutite			
	Fm	Fl	Fo	Fb	Cm	Co	Cr	Cs
Description	Massive <30% floating gran-peb-cob	Horizontal to wavy lamination	Massive Mottling Root molds Vertebrates	Massive to vaguely laminated Bluish–blackish color Medium–high content in organic matter Gastropods Vertebrates Plant molds	Massive Malacofauna remains	Massive Mottling Root molds Mudcracks Sparry cements Vadose silt Malacofauna remains Alveolar and fenestral structures Nodulization	Massive Rhizocretions	Massive >30% floating siliciclastic sand–gravel size grains
Thickness	30–250 cm	30–250 cm	30 cm–8 m	5–100 cm	10–50 cm	10–50 cm	10–50 cm	10–50 cm
Interpretation	Floodplain Abandoned channel	Floodplain Abandoned channel	Floodplain deposits with vegetation and flooding	Marsh/pond on the floodplain	Palustrine deposits with low degree of subaerial exposure	Palustrine deposits with medium–high degree of subaerial exposure	Calcified roots in wet sediments of the floodplain	Transition between the siliciclastic floodplain and a carbonate ephemeral pond/lake

(B) Clay and calcilutite lithofacies.

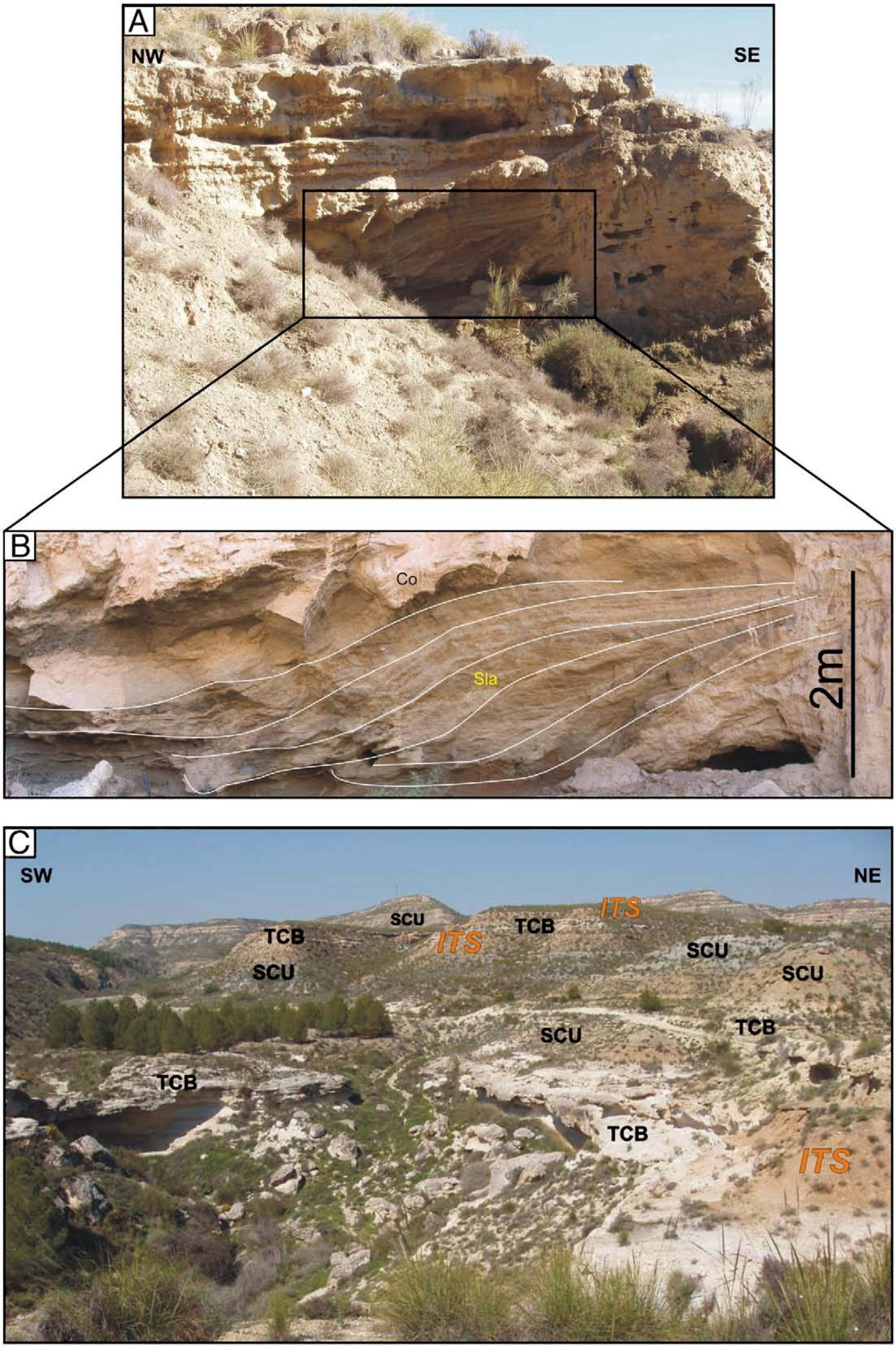

Fig. 9. (A) Outcrop of a sand body embedded in sandy-clay units in the FSCC-1 section within Unit V. (B) Detail of the sand body from (A), where lateral-accretion surfaces are marked (facies Sla, see Table 3A for more information). (C) Outcrop relationships of the lower-middle part of the FBP-SVY-1 section (see Fig. 6) of Unit V. The intercalated beds of the Internal Transverse System facies, corresponding in this area to distal sand- to clay-sized sediments, are indicated by "ITS". The architectural elements of the Axial System are the sandy-clay units (SCU) and the tabular carbonate beds (TCB).

nodulization. Therefore, we interpret them as palustrine lithofacies (Pla-Pueyo et al., 2007) (Table 2) characterizing shallow ephemeral water bodies located on protected ponded areas of the floodplain. As the features are homogeneously distributed within the thickness of all the carbonate beds, and not just affecting their top surface, a seasonal drying of the ponds is surmised, with the Lg facies representing the

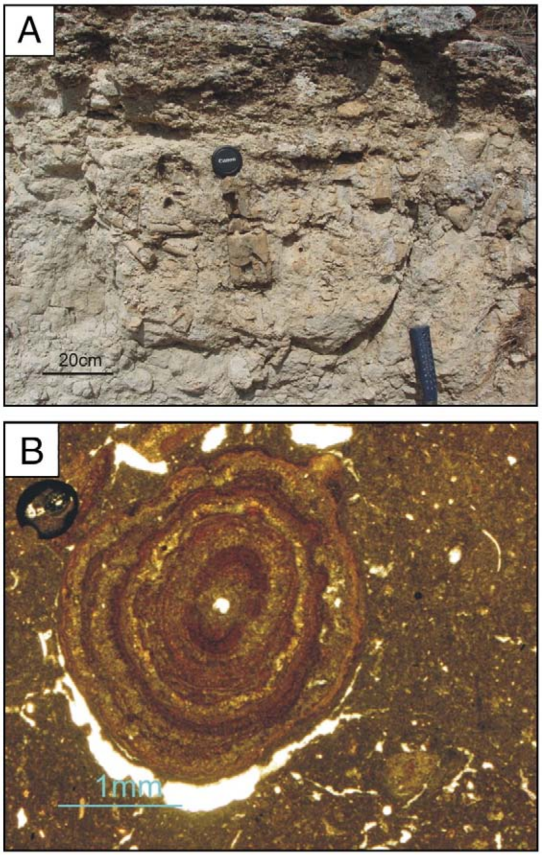

Fig. 10. (A) Field photograph of a phytohermic framestone from section FBP-SVY-1 from the studied sector of the Guadix Basin. Hammer at lower right for scale. (B) Thin section of a plant stem of the same phytohermic framestone, showing alternating micrite and sparry cement layers.

most altered of the carbonate facies from repeated subaerial exposure. Examples of these limestone beds on siliciclastic floodplains of perennial paleorivers include the Pennsylvanian–Permian Cutler Formation (USA) (Eberth and Miall, 1991) and the Jurassic Morrison Formation (USA) (Dunagan and Turner, 2004). The textures found in these palustrine deposits (Tables 3B and 3C) can be interpreted in terms of hydrologic conditions and exposure index (Platt and Wright, 1992). The textures indicate intermediate to sub-humid conditions with seasonal drying and an exposure index of 40–70%.

5.2. Unit VI

The main architectural elements belonging to Unit VI in the AS in the study area are described below (Table 2). Only fine-grained architectural elements (both siliciclastics and carbonates) appear in this sector of the fluvial system (Fig. 12).

5.2.1. Silt–clay units

5.2.1.1. Description. Similar to the sandy-clay units described for Unit V, these elements are hectometric to kilometric tabular grey-brown fine-grained beds, with a common yellow to red mottling. Sand is rare, so grain sizes range from silt to clay (lithofacies Fo) (Table 3B), with thicknesses of beds on a centimeter- to meter-scale.

5.2.1.2. Interpretation. Like the sandy-clay units in Unit V, this architectural element is interpreted as overbank vertical accretion (Nanson and Croke, 1992) and possible siliciclastic palustrine deposits with development of paleosols (Kraus and Hasiotis, 2006). As no fluvial channels are preserved in Unit VI in this sector of the basin, probably silty-clay units have a more distal position in the floodplain of the Axial System in comparison to sandy-clay units from Unit V (Table 2). This idea is supported by a generally smaller grain size in these bodies than in the sandy-clay units of Unit V.

5.2.2. Carbonate sheets

5.2.2.1. Description. Carbonates of Unit VI appear mainly as extensive bodies (lateral continuity over km) of mainly micritic and nodular limestones (lithofacies M, Lo, Ln, Lg, and rarely Co). These continuous beds have an average thickness of 50 cm and are stacked in successions 2–3 m thick. In thin section, these carbonate sheets show quite similar petrographic features to those of tabular carbonates from Unit V. The main features are the presence of root molds and mottling, together with a lower siliciclastic content with lithofacies Cs not present (Tables 3B and 3C). Laterally these carbonates grade into silt–clay units, but as they are so extensive, it is difficult to see this change directly in the field. Vertically the carbonate sheets increase in their carbonate content, as in Unit V, going from lithofacies M to pure limestone lithofacies (Lo, Ln, and Lg) (Fig. 11). Interestingly, the highly-altered facies Lg is less common in Unit VI than in Unit V. In the northern part of the studied sector, some of these carbonate successions contain interbedded thin coal levels (5 cm average thickness), that extend laterally only around 1–2 m.

Table 3C
Lithofacies found in the studied area of the Guadix Basin.

Lithofacies	Marl and marlstone	Limestone				
	M	Lo	Ln	Lg	Ll	T
Description	Massive to laminated Mottling Carbonate nodules Rhizocretions Rhizohalos Peloids Intraclasts Vertebrate remains Coal	Micrite Mottling Root molds Mudcracks Sparry cements Vadose silt Malacofauna remains Alveolar and fenestral structures	Micrite Nodulization Mottling Root molds Mudcracks Sparry cements Vadose silt Malacofauna remains Alveolar and fenestral structures	Grainstone texture Mottling Sparry cements Intraclasts Cross-bedding Peloids Pseudo-microkarst	Micrite Thick and uneven lamination Brecciated texture	Framestone Macrophytic stem and leave casts Phytoclasts Oncolites Malacofauna remains
Thickness	5–150 cm	10–200 cm	10–200 cm	10–200 cm	5–15 cm	5 cm–100 cm
Interpretation	Palustrine deposits in distal floodplain with a variable degree of pedogenic alteration	Palustrine deposits in distal floodplain with a low degree of pedogenic alteration	Palustrine deposits in distal floodplain with a medium degree of pedogenic alteration	Palustrine deposits in distal floodplain with a high degree of pedogenic alteration	Calcrete	Tufa

(C) Marly and limestone lithofacies.

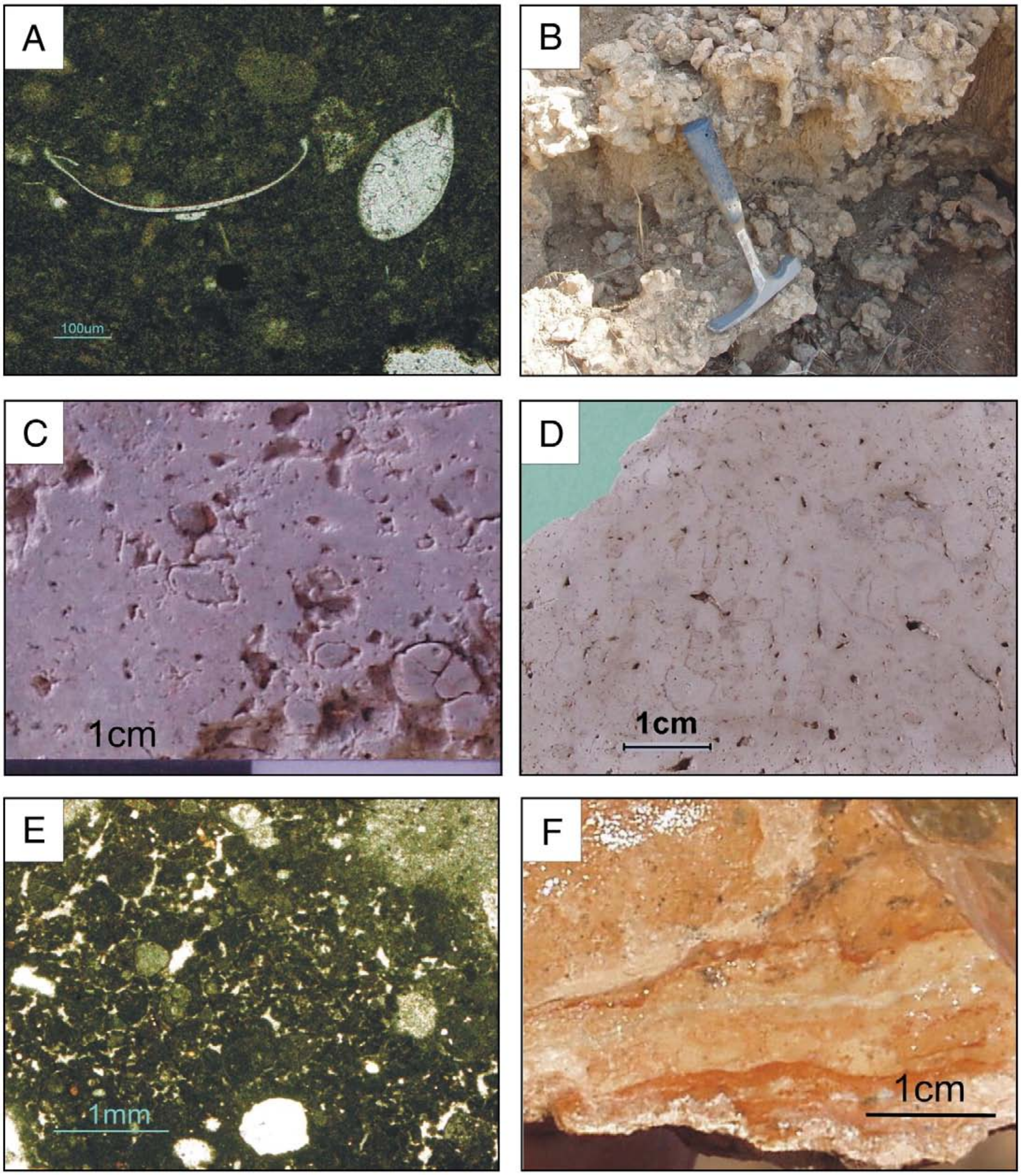

Fig. 11. (A) Photograph of a calcilutite with ostracodes from section FBP-SVY-1 in thin section with the typical features of a Cm lithofacies. The bar scale is 100 μm long. (B) Field photograph of rhizocretions (lithofacies Cr). (C) Hand sample of lithofacies M from section FBP-SVY-1. (D) Nodular limestone from section FBP-SVY-1 in hand sample. (E) Peloidal texture in thin section (lithofacies Lg, section FBP-SVY-1). (F) Hand sample from section FPB-4 showing a laminar/brecciated texture (lithofacies Ll). The geographic position of each measured section is shown in Fig. 5.

5.2.2.2. Interpretation. Following other examples in the literature (Freytet and Plaziat, 1982; Platt, 1989), these carbonates are interpreted as vertically-stacked palustrine sequences formed during periods of permanence of large water bodies on floodplains (Table 2). The vertical distribution of the ubiquitous features involving subaerial exposure within the carbonate units, such as root molds, mottling, and nodulization, indicates a seasonal drying of the ponded zones affecting not just the surface but the whole carbonate thickness. The carbonate textures also may indicate deposition in a sub-humid, but seasonally hydrologic conditions (Platt and Wright, 1992), as supported by the presence of intercalated, thin coal levels (Gierlowski-Kordesch et al., 1991; Cabrera and Sáez, 1987). The exposure index is calculated to be 0–50%.

5.2.3. Carbonate layer

5.2.3.1. Description. There is just one well-preserved example of this sedimentary body in the studied sector with a thickness ranging from 5 to 10 cm, but at least two of these carbonate layers have been observed in the area at different elevations, both situated on top of the Unit VI sedimentary succession.

This carbonate layer (Ll) comprises thick and uneven lamination (see Fig. 11F). In some places, the texture is brecciated with a laminar carbonate coating the clasts and micrite filling the spaces between clasts. The brecciated texture commonly changes upwards into a laminar layer.

5.2.3.2. Interpretation. This architectural element is interpreted as a pedogenic calcrete (Esteban and Klappa, 1983; Wright and Tucker, 1991; Alonso-Zarza, 2003) that in some places exhibits features of iterative processes related to subaerial exposure. These processes involve exposure and erosion producing angular clasts, the coating of the clasts with carbonate cement, remobilization of these clasts, and diagenetic precipitation of carbonate in the spaces between the clasts (pisolitic horizons in the sense of Alonso-Zarza, 2003). Then, calcrete

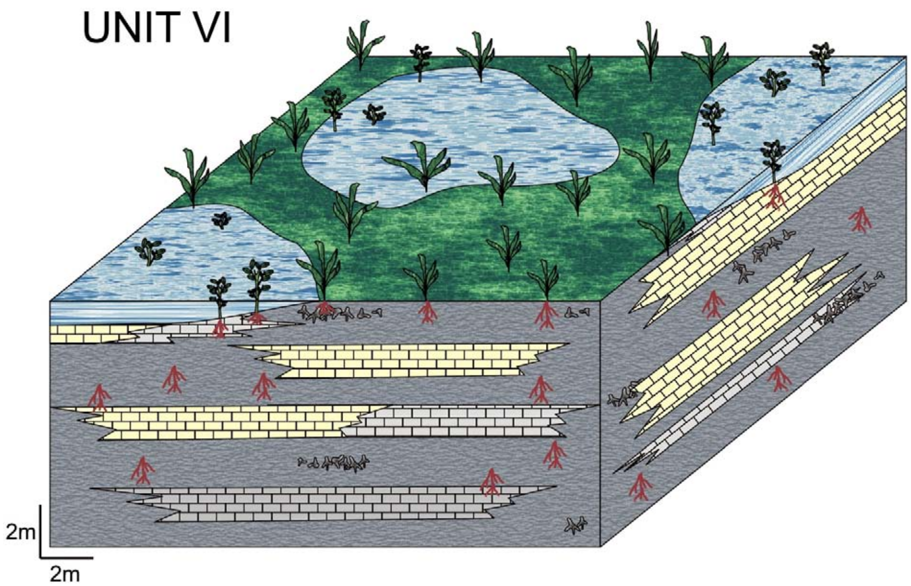

Fig. 12. Reconstruction of the paleoenvironment interpreted for Unit VI in the studied sector, showing in cross-section the typical sedimentary pattern for this unit, dominated by carbonate sheets stacked vertically in the Axial System. The surface is mostly occupied by shallow but laterally extensive ponds with root activity.

formation continues on top of the brecciated and cemented layer (platy horizon in the sense of Alonso-Zarza, 2003).

The highest carbonate layer appearing in the study area could be correlated to the calcrete studied by Azañón et al. (2006) in the Arroyo de Gor section, located northwards of the study sector. Further field work will help to confirm this.

6. Discussion

The differences between sedimentary conditions and fluvial architecture of Units V and VI are controlled by the relative influence of tectonism, climate/hydrology, and base level changes during the last 3.5 Ma in the Guadix Basin. Sequence-stratigraphic principles can be applied to reconstruct paleoconditions. Martinsen et al. (1999) recommend the conventional nomenclature for sequence stratigraphy (lowstand, transgressive, and highstand systems tracts) in continental settings when a detailed and unambiguous correlation from the nonmarine to marine part of a basin can be made, assuming the geomorphic base level (sea level) controls the sedimentary architecture (Allen, 1978; Bridge and Leeder, 1979; Wright and Marriot, 1993).

When the sedimentary pattern is completely independent of sea level, because a basin is too far from the shoreline, or it is a closed basin disconnected from the sea, Martinsen et al. (1999) propose a new nomenclature, using stratigraphic or local base level (Table 4). Changes in the stratigraphic base level can be expressed as the A/S ratio where tectonism controls accommodation space (A) and climate/hydrology controls the sediment supply (S). This is a simplification of nature because, for example, tectonism can control sediment supply as well. However, this ratio is useful to relate changes in base level to sedimentation patterns. Where the A/S ratio<0, meaning that there is no accommodation space at all, no accumulation occurs because of sediment bypass and regional erosion surfaces or sequence boundaries form. Where $0<A/S$ ratio<1, sediment supply is greater than the available accommodation space, which is always filled by sediment. This situation leads to the formation of a “Low Accommodation Systems Tract” (LAS), a sequence lacking preservation of fine material and dominated by multi-storey, multi-lateral stacking of channels. With an A/S ratio$=1$, the balance between accommodation and sediment supply results in expanded successions with the formation of systems tract boundaries. Where the A/S ratio>1, sediment is not able to fill all the available accommodation space and the probability of flooding on the alluvial plain increases. In this case, widely spaced channels and high preservation of fine materials occur, representing a “High Accommodation Systems Tract” (HAS) (Martinsen et al., 1999).

Although the Martinsen et al. (1999) model deals with nonmarine siliciclastic fluvial sequences dominated by changes in the stratigraphic base level, there is no mention in this model about nonmarine carbonate deposition on a floodplain related to changes in the A/S ratio. Alternatively, Alonso-Zarza (2003) proposes a fluvial–lacustrine model involving palustrine sediments (Table 4) with two different patterns affected by the interaction between accommodation space, controlled by tectonics, and sediment plus water supply, controlled by climate/hydrology. In her High Activity Pattern, an active alluvial/

Table 4

Comparison of Martinsen et al. (1999) and Alonso-Zarza (2003) sequence-stratigraphic models for continental basins.

Martinsen et al. (1999)			Alonso-Zarza (2003)	
$A/S>1$	LAS	Multi-storey, multi-lateral stacking of channels, no preservation of fine material, possible flooding	Low Activity Pattern	Vertically-stacked palustrine sequences in the alluvial/fluvial floodplain
$A/S=1$	Boundary between system tracts	Expanded successions with high probability of being flooded		Typical at final stages of the infilling of closed basins
$0<A/S<1$	HAS	Widely spaced channels, high preservation of fine material	High Activity Pattern	Thick floodplain deposits with isolated channels, small ponds and weakly-developed soils interbedded with siliciclastic alluvial deposits
$A/S\leq 0$	Boundary between system tracts	Sediment bypass and regional erosion surfaces development	Sequence boundaries	Calcretes and paleosols, their maturity depending on duration of exposure

Table 5
Classification in terms of sequence stratigraphy of Units V and VI in the studied sector in the Guadix Basin.

Genetic unit	Accommodation space	Sedimentary pattern	Classification after the Martinsen et al. (1999) model	Classification after the Alonso-Zarza (2003) model
On top of Unit VI	Basin totally infilled (no accommodation space available)	Mature pedogenic calcrete and paleosol development	$A/S \leq 0$	Sequence boundaries
Unit VI	Low accommodation space	Vertically-stacked carbonate palustrine sequences Floodplain sediments with some immature paleosol development	LAS[a]	Low Activity Pattern
Unit V	High accommodation space	Thick and fine floodplain deposits and isolated single to multi-storey channels Some immature paleosol development Few tabular carbonate beds with palustrine features	HAS	High Activity Pattern

For further information about both models, see Table 4.

[a] The sedimentary pattern for Unit VI is carbonate-dominated, which differs from original LAS description.

fluvial system with high accommodation space forms lakes and ponds on floodplains. The resultant fluvial sedimentary pattern is represented by thick floodplain deposits with isolated channels, ponds and lakes, and weakly-developed soils. The Low Activity Pattern represents a situation with limited accommodation space and stacked palustrine sequences in an alluvial/fluvial floodplain. This situation usually occurs at the final stages of the infilling of basins, reflecting the change in topography from a steeper to more gentle gradient or the reduced bedload input of the alluvial/fluvial system. For unconformities or sequence boundaries formed by erosion or no sedimentation (comparable to $A/S<0$ from Martinsen et al., 1999), calcretes and paleosols can develop.

The integration of both sequence-stratigraphic models (Martinsen et al., 1999 and Alonso-Zarza, 2003) explains the fluvial architecture and carbonate depositional patterns of Units V and VI in the central sector of the AS in the Guadix Basin (Table 5). According to Soria et al. (1998), during deposition of Units V and VI, the Guadix Basin experienced continuous uplift and a steady decrease in the subsidence rate. The amount of sediments in Unit V is almost twice than the amount in Unit VI. This difference in thickness is interpreted as a lower accommodation space available for Unit VI, due to a lower subsidence rate (Viseras, 1991; Fernández et al., 1996a,b; Soria et al., 1998). There are several facts supporting these assertions. First of all, the differences in the sedimentation rates in both units have been recently confirmed (Pla-Pueyo et al., 2008) for the central sector of the basin, when comparing the margin (a tectonic horst, the Mencal relief) and the center (a subsiding area, affected by the Mencal fault) of the study area. While there is a large difference between sedimentation rates of the margin versus the center of the sector for Unit V, sedimentation rates for Unit VI are the same at every measured point of the sector, but always lower than the rates calculated for Unit V (Pla-Pueyo et al., 2008). Moreover, the thickness of sediments between two isochrons decreases in Unit VI in comparison to Unit V (Viseras, 1991), and the geometry of the changing facies surfaces between the three main drainage systems become flatter in Unit VI due to a lower accommodation rate (Viseras, 1991; Soria et al., 1998). The sedimentation conditions for each unit will be addressed separately below.

6.1. Unit V

Although a general situation of continuous uplift and decreasing accommodation space is assumed for the Guadix Basin throughout Units V and VI (Viseras, 1991; Soria et al., 1998), Unit V in the studied sector presents a relatively high rate of accommodation. This is probably due to the activity of the Mencal normal fault, creating a subsidence zone to the south of the Mencal relief (see Fig. 5 and Fig. 6). A relatively high sediment accumulation rate (an average of 5.2 cm/Ky) (Pla-Pueyo et al., 2008) is also projected for Unit V. The high sedimentation rate is probably related to uplift of the source areas for both the Axial System (AS) and the Internal Transverse System (ITS) (Soria et al., 1998).

Applying the model of Martinsen et al. (1999), the A/S ratio for Unit V would be >1 (Table 4). The presence of relatively confined channels, isolated from one another by thick fine-grained, siliciclastic floodplain sediments as overbank and palustrine deposits in a distal setting, weakly-developed soils, and less abundant, ephemeral carbonate ponds and lakes in protected areas is interpreted as a High Accommodation Systems Tract (HAS) (Martinsen et al., 1999), where the probability of flooding is high. This sedimentary pattern reflects the activity of the AS in its medial to distal area with a lithology dominated by mostly siliciclastic and minor carbonate beds. In this case, the source area (Internal Zones) and the transverse inputs (dominated by the ITS) contained mostly schists and quartzites with minor marbles. Following Alonso-Zarza (2003), Unit V fits in the High Activity Pattern (Table 4), reflecting a fluvial architecture influenced by a high accommodation rate and characterized by high levels of storage of floodplain sediments. Both classifications (Martinsen et al., 1999 and Alonso-Zarza, 2003) match the depositional patterns in Unit V. The limited accumulation of palustrine carbonates on the floodplain is explained by the high siliciclastic input from the Internal Zones with limited input of carbonates from the External Zones. The exposure index (40–70%) of the palustrine carbonate indicates groundwater tables lower seasonally between flooding events allowing for significant pedogenic alteration (after Wright, 1999).

6.2. Unit VI

This unit is the last sequence in the evolution of the Guadix Basin (Fernández et al., 1996a). Since the Mencal fault is not active anymore, the general uplifting of the basin predominates. The end of the uplift stage is the final filling of the basin at 1000 m paleoelevation in Late Pleistocene times (Soria et al., 1998). Accommodation space decreases gradually, leading to the event that Soria et al. (1998) refer to as “topping-up”. Because of this, topography of the basin during this unit exhibits lower gradients. Although climatic fluctuations related to glacial/interglacial stages probably took place during the Pleistocene, hydrologic patterns clearly do not reflect a drastic change in climate between Units V and VI. In Unit VI, the palustrine carbonate textures with thin interbeds of coal in marginal areas reflect an exposure index of 0–50%. Coupled with a decrease in the abundance of the highly-altered facies Lg as well, the groundwater table did not seasonally lower as drastically or for as long a period in comparison to the hydrologic conditions represented in the carbonates of Unit V. Since most other carbonate textures are similar between the two units, climate may not have changed too much or the slower subsidence rate in Unit VI allowed groundwater levels to stay higher seasonally in comparison to Unit V.

Therefore, the sedimentation input during Unit VI may have been similar to the sediment supply during Unit V or lower, but because of the widening of the basin and the reduction of the bulk accommodation space, the sedimentation rate is lower. The reduction in the storage capacity of the basin during the last stages of infilling is mentioned by Wright and Marriott (1993).

Because accommodation space decreased upwards during Unit VI and there was an expansion of the depositional area of this unit over Unit V, the slope of the transverse alluvial fans would be lower due to the widening of the basin (Fernández et al., 1996a,b). If the sediment supply overwhelmed the accommodation, then the available space was filled and other new areas received sediment, expanding the fluvial/alluvial system as the basin widened. Therefore, the A/S ratio for Unit VI would be a value between 0 and 1 (Table 5), which corresponds to a Low Accommodation Systems Tract (LAS) (Martinsen et al., 1999).

Using the model of Martinsen et al. (1999), there are two possible divisions between accommodation systems tracts: sequence boundaries (A/S ratio ≤ 0) or expansion surfaces or zones (A/S ratio $= 1$) (Table 4). Considering that Unit V is classified as a HAS and that Unit VI would correspond, with some modifications, to a LAS, it is clear that there is a decrease of the A/S ratio between both units, so A/S ratio for the boundary between them would be close to 1. One of the criteria to establish the boundary between both units is the moment of maximum expansion of the AS with respect to the transverse systems. Therefore, the boundary between Units V and VI should be classified as an expansion surface in the sense of Martinsen et al. (1999).

It is not suitable to classify Unit VI applying only the Martinsen et al. (1999) model, because the sedimentary pattern (vertically-stacked palustrine sequences) is quite different than the one expected for a LAS (multi-storey channels). The model of Martinsen et al. (1999) for the low accommodation space situations does not take into account the possibility of carbonate sedimentation (Table 4). The abundant carbonate deposits in Unit VI may be related to changes in the provenance of the sediment in this part of the basin. Provenance is an important control on carbonate sedimentation in continental depositional systems, since all basinal sediments are erosional products of the surrounding watershed (Gierlowski-Kordesch, 1998). In Unit V, siliciclastic sedimentation predominates, the AS and ITS (Internal Zones) playing the main role in sediment distribution. In Unit VI, with no significant climate or hydrology change, a change in provenance best explains the predominance of carbonate lithology. The relative importance of ETS activity (External Zones) in the study area during the deposition of Unit VI obviously changed as subsidence slowed. Although the AS and the ITS were still important, the displacement of the AS north-eastwards, closer to the External Zones (Fernández et al., 1996a), allowed a higher input from the carbonate-dominated ETS alluvial fans into the AS valley. Moreover, the decrease of the gradient due to the filling of the basin, together with the base level rise associated with this infilling, point to the fluvial style within the studied sector as being a vertically-aggrading anastomosing river system (Makaske, 2001; Gibling, 2006; Makaske et al., 2007) with a high influx of suspended carbonate load (Valero Garcés et al., 1997; Gierlowski-Kordesch, 1998).

Because the outcrops of Unit VI are not well preserved due to the incision of the Holocene hydrologic network and the study area comprises only the distal and finest facies of the three drainage systems, no coarse-grained sedimentary bodies can be found to confirm the anastomosing character of the Guadix river system at this time interval. In addition, widespread carbonate deposits as those appearing in Unit VI are not typically found on the floodplain of a meandering fluvial system (Valero Garcés et al., 1997; Gierlowski-Kordesch, 1998). Interesting enough, the W/T ratio of the channel sands and gravels of Unit V fall into the general range for sand-dominated high-sinuosity rivers of Gibling (2006) in which anastomosing rivers are classified. In addition, carbonates are predominant in Unit VI in the studied sector, but not in the whole basin. Siliciclastic sedimentation at this time interval in other points of the basin also exhibit the same low sedimentation rate (Soria et al., 1998), taking into account compaction rates. Provenance patterns and resultant sediments need to be studied throughout the basin and its watershed. Considering that $^{87}Sr/^{86}Sr$ signals from the waters of a source area are directly comparable to the rocks/sediments of the receiving continental deposit (Davis et al., 2008, 2009; Gierlowski-Kordesch et al., 2008), future studies involving the use of Sr isotopes to determine the precise source for the carbonate sediments in each stage of infilling of the Guadix Basin will confirm projected provenance patterns.

Thus, using the model proposed by Alonso-Zarza (2003), Unit VI would represent the Low Activity Pattern, with a decreased siliciclastic and an increased carbonate input of the AS with respect to Unit V. The fluvial style, together with a lower depositional gradient in a widening basin, would give rise to the formation of extensive shallow ponds where thick palustrine carbonate sequences could accumulate. This situation is surmised to occur at the final stages of the infilling of closed basins (Alonso-Zarza et al., 1992), which is actually the case here because the top of Unit VI represents the final fill of the basin (Fernández et al., 1996a; Soria et al., 1998). At least two different calcretes are recognized capping the sediments of Unit VI, indicating the lack of sedimentation above this unit, as it is shown for other sectors of the basin (Azañón et al., 2006).

7. Conclusions

It is clear that an integrated sequence-stratigraphy model involving both siliciclastic and carbonate, nonmarine sedimentation sequences is needed. The modification of two models based on nonmarine sequence stratigraphy (Martinsen et al., 1999 and Alonso-Zarza, 2003) has been used to interpret the last two units (Units V and VI) of the fluvial–lacustrine basin fill of the Guadix Basin, Betic Cordillera, southern Spain. Unit V reflects a high accommodation space situation, with a sedimentary pattern of the Axial System dominated by thick floodplain, fine siliciclastic sediments composed of pedogenically-altered overbank and possible palustrine deposits, where coarser sediments belong to high-sinuosity channels. The fabrics of the less abundant palustrine carbonate deposits of the floodplain indicate seasonal intermediate to sub-humid hydrologic conditions (Platt and Wright, 1992) with abundant highly-altered Lg facies. Unit VI exhibits vertically-stacked carbonate palustrine sequences reflecting a low accommodation situation in sub-humid seasonal conditions with perhaps a higher groundwater table, as surmised from carbonate fabrics (Platt and Wright, 1992) and the interbedded thin coals. However, the decreasing depositional gradients characterize the last stages of the infilling of this ever-widening basin, evidenced by lower sedimentation rates across the study sector in comparison to Unit V. The increase in carbonates within the floodplain of the Axial System in the study area is attributed to a change in the drainage patterns of the fluvial system, coinciding with its north-eastwards displacement towards the External Zones which exposes dominantly limestones.

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