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Climatic control on palaeohydrology and cyclical sediment distribution in the Plio-Quaternary deposits of the Guadix Basin (Betic Cordillera, Spain)

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Abstract

A cyclical pattern can be observed in the central sector of the Guadix Basin (southern Spain) in the Late Pliocene-Quaternary alluvial fan deposits prograding into its axial valley. A climatic significance has been attributed to this cyclicity on the basis of sedimentological and preliminary isotopic studies. The progradation phases of the alluvial fans are here attributed to more arid time intervals in which the vegetation cover would be less developed, erosion and sediment supply would be higher, and base level would be lower. In contrast, the time intervals during which the fluvial system sediments dominated the area are inferred to be wetter and base level higher, with vegetation cover retaining the soils and preventing erosion. Permanent water supply to the river would therefore facilitate the aggradation of the floodplain and prevent progradation of the fans. Starting from a litho-, bio- and magnetostratigraphical frame provided for the area, an age is assigned to the alternation of the reddish sediments of the transverse alluvial fans and the greyish to white fluvio-lacustrine sediments of the axial drainage system. A cyclicity of ca. 100 ky has been identified in most of the alluvial fan progradation phases, falling within Milankovitch high-frequency eccentricity periodicities. Correlation of the phases with insolation curves is accordingly discussed as a possible origin for the cyclicity. Finally, the results offer new insights into early hominin occupation patterns in the region, through the identification of predictable resources of permanent fresh water that would have remained available throughout the recorded time span (that includes the Early-Middle Pleistocene transition) even during times of aridification.

Keywords: climatic change; continental sediments; cyclostratigraphy; Guadix Basin; hominid; Pliocene-Pleistocene.

1. Introduction

The Mediterranean region preserves some of the earliest evidence for early hominin occupation in Europe. A diverse range of Mode 1-type (non-handaxe) assemblages has been reported from as early as 1.3-1.7 Ma (e.g. Carbonell et al., 1999; Arzarello et al., 2007), some of them associated with human remains (e.g. Toro-Moyano et al., 2013). However, the paucity of sites over such an extended period of time suggests that these reflect only short-lived dispersal events, with several phases of depopulation and recolonisation and southern Europe probably driving a source-sink dynamic of ebb and flow (Parfitt et al., 2005, 2010; Carrión et al., 2011). The origins of handaxe-making (Mode 2) behaviour are seen rather later, with the first Acheulean evidence in southern Europe generally appearing at around 600 ka, followed by a rapid colonization of the northwest at 500 ka (Coltorti et al., 2005; Tuffreau et al., 2008; Lefèvre et al., 2010; Jiménez-Arenas et al., 2011; Barsky and de Lumley, 2010; Moncel et al., 2013). Southern Europe is therefore a key source area from which repeated dispersal events of hominids and mammal fauna occurred and in which technological and behavioural advances may have evolved. Interpreting the palaeoclimatic and palaeoenvironmental record of this region is consequently of singular importance for understanding both the environments of occupation and timing of dispersals of early hominins in Europe.

The Guadix basin in southern Spain provides a rare example of a continuous sedimentary record, dating to the time period of interest, where such palaeoclimatic and palaeoenvironmental patterns can be assessed. Here, the exposures span the Early-Middle Pleistocene transition, also called Middle Pleistocene Revolution by some authors (around 1 Ma, close to the Jaramillo subchron), a major global climate transition characterised by an increase in the magnitude of warming and cooling climate cycles and by the periodic extension of grassland habitats into higher latitudes, thereby opening and/or closing corridors for migration northwards (Ashton and Lewis, 2012). A key aim of the present research has therefore been to develop new palaeoclimatic and palaeoenvironmental records from before, during, and after the Early-Middle Pleistocene transition in the Guadix basin, in order to examine potential correlations between phases of hominid occupation and major climatic shifts.

2. Geological setting

The Guadix Basin is located in the central sector of the Betic Cordillera (Fig. 1), sealing the contact between the two main geological realms that conform this mountain system: the Internal Zones to the south (allochthonous metamorphic complexes, mainly Palaeozoic and Triassic in age) and the External Zones to the north (para-autochthonous sedimentary cover of the Iberian Massif, with an age ranging from Triassic to Early Miocene) (Viseras et al., 2005).

The Guadix Basin sedimentary infill is divided into six genetic units and was deposited during two main stages. The lower one, formed by units I, II and III, is a marine sedimentation stage, dating to the late Tortonian, while the upper one (units IV to VI) is continental, and dates from the late Tortonian to the upper Pleistocene (Soria et al., 1998, 1999; Viseras et al., 2005). During the deposition of continental units V and VI (Pliocene and Pleistocene), the basin was endorheic and characterised by a marginal border of alluvial fans connecting transversally with an axial valley (Fernández et al., 1996) (Fig. 2). A fluvio-lacustrine system, the so-called Axial System (AS), was confined to the central valley and flowed almost parallel to the palaeogeographical axis of the basin (Fernández et al., 1996; Viseras et al., 2006). In the study area, the central sector of the Guadix Basin, where a depocentre was located, high sinuosity channels and shallow palustrine-lacustrine environments identified as wetlands characterised this system (Pla-Pueyo et al., 2009, 2011a, 2011b, 2012a). The two transverse alluvial fan systems, the so-called Internal Transverse System (ITS) and External Transverse System (ETS), were very different in terms of lithology, sedimentology and morphology of the fans, mainly due to differences in their source areas (Internal or External Zones, respectively).

The ITS received sediments from the Internal Zones of the Betic Cordillera. The ITS alluvial fans (Viseras and Fernández, 1992, 1994, 1995) had a large radius (10-11 km), over half the width of the basin (which was locally 15 km wide), as they lay against a basin margin with a high sediment supply/subsidence ratio, as occurs in many examples described in the literature (e.g. Alexander and Leeder, 1987, Viseras et al 2003). Therefore, their morphology was conditioned, among other factors, by the lithology of their source area (mainly metamorphic rocks) and the high tectonic activity of the basin margin related to their formation (Internal Zones, mainly the Sierra Nevada and Sierra de Baza). Although the relief of the External Zones (formed by Mesozic carbonates and occaional chert beds) was high enough to trigger alluvial fan deposition, producing the alluvial fans of the ETS (Fernández et al., 1991, 1993), their low tectonic activity, involving even a slight subsidence, would prevent them from generating alluvial fans as extensive as the ITS ones.

The palaeogeographical distribution of the Guadix basin changed in the Late Pleistocene, when the watershed was captured by the drainage net of the Guadalquivir River, changing into an exorheic regime (Calvache and Viseras, 1997). As a result of this change in the hydrologic regime, large-scale intense erosion started, giving rise to the entrenchment of the fluvial network by up to 400 m since the Late Pleistocene.

3. Litho-, bio- and magnetostratigraphy

The deep incision produced by the current drainage network in the Guadix Basin infill has exposed excellent outcrops of its continental sediments where a cyclical behaviour is readily observed between the sediments of the AS and the ITS. The presence of several large mammal sites within the Axial System sediments in the Fonelas sector (Fig. 3) provided relevant information about the fauna inhabiting the Guadix Basin during the Pliocene and the Pleistocene. The importance of these sites led to the development of significant stratigraphical, sedimentological, chronological and palaeontological studies in this area (Viseras et al., 2006; Arribas et al., 2009; Pla-Pueyo et al., 2009, 2011a, among others). Most of these studies show how stratigraphical relationships between the Internal Transverse System (ITS) and the Axial System (AS) are best exposed in the Fonelas area, located in the central sector of the Guadix Basin.

The litho-, bio- and magnetostratigraphic framework for this central sector has been recently published (Pla-Pueyo et al., 2011a). Its stratigraphical architecture was established by bed-to-bed correlation starting from field observations and geological mapping at a 1:25 000 scale (Pla-Pueyo et al., 2011a). Palaeomagnetic sampling was subsequently carried out, in order to date the palaeontological sites exposed in the area and to confirm the previous lithostratigraphical correlation (Pla-Pueyo et al., 2011a), using the astronomically tuned Global Polarity Time Scale (ATNTS2004; Gradstein et al., 2004) as a reference.

As a result, a time range has been assigned to the sedimentary processes taking place in the central sector of the Guadix Basin from ca. 3.8 Ma to the late Pleistocene. In addition, the palaeontological sites were dated and the sedimentation rates were calculated for each genetic unit (Pla-Pueyo et al., 2009, 2011a).

From the resulting litho-, bio- and magnetostratigraphical correlation scheme, six stratigraphical profiles in which the ITS sediments are optimally represented have been selected in the present study (Figs. 3 and 4), in order to analyse the interplay between the AS and the ITS (stratigraphical profiles BB-1, FPB-4, T-1, FP-1, FSCC-1 and FBP-SVY-1).

The stratigraphical architecture of the central sector of the Guadix Basin reveals distinctive cyclical changes in the drainage systems occupying the axial valley (see Fig. 4), a cyclicity shown by the ITS and the AS sediments in both units. The ITS sediments change laterally and vertically into the AS facies. As the progradation of the ITS sediments is very extensive, it is usually very hard to see in the field the lateral change between both systems' facies. However, the apparent vertical alternation between both system sediments is easy to observe, especially in the centre of the study area (see fig. 4). Where the fluvio-lacustrine system dominates, the axial valley is represented by the greyish floodplain sediments of the AS. In contrast, the time intervals in which the ITS sediments prograde extensively into the Axial Valley, reaching the opposite margin of the basin in some cases and reducing the lateral extension of the fluvial system (even blocking it), are represented by reddish deposits corresponding to the medial-distal part of the ITS alluvial fans. The cyclicity of the ITS progradational phases is easily observed in the litho-, bio- and magnetostratigraphical correlation representing the infill of the Guadix Basin over the last ca. 3.8 Ma (Pla-Pueyo et al., 2011a), showing a cylcicity of ca. 100 ky.

4. Sedimentology of the study area

Based on previously published sedimentological descriptions of these facies (Viseras and Fernández, 1992, 1994, 1995; Viseras et al., 2006; Pla-Pueyo et al., 2009, 2010) and some additional field observations, a detailed sedimentological analysis was performed and the resulting interpretation, in terms of palaeoenvironmental conditions, is given for the sediments of each system.

As there were several sedimentary processes taking place on different time scales in the basin during the Pliocene and Pleistocene, a hierarchy of sequences and architectural elements, inspired in the one proposed by Miall (1996), has been used in previous work when describing the sedimentology of the deposits in the study area (e.g. Pla-Pueyo et al., 2009; 2011b). Thus, Order 5 elements comprise genetic units V and VI and Order 4 elements comprise the group of sequences (each of them individually an Order 3 element) of a determinate drainage system (in this case, ITS or AS) dominating the sedimentation in the axial valley for a given period of time. In the case of ITS, this would reflect a progradation phase on the axial valley and in the case of AS, those intervals when the axial valley was exclusively fluvially-dominated). Each Order 3 elements (3D elements represented by several 2D vertical sequences laterally correlated) within a drainage system would comprise several Order 2 elements (3D sedimentary bodies conforming to a subenvironment, such as a channel or a palustrine body), formed by associations of simple lithofacies (Order 1 elements).

As the cyclicity described in the present paper is formed by an alternation of the Axial and the Internal drainage systems in the centre of the basin, it entails the alternation of Order 4 elements. In order to avoid extensive descriptions and to permit closer consideration here of the sedimentary cyclicity itself, two tables are provided (Tables 1 and 2), summarising the architectural elements of Order 1 to 3 identified in the study area for each system and their interpretation. The reader is referred to the published literature mentioned above for more detail.

4.1. Axial System elements

The sediments of the AS show different architectural elements and sequences depending on the genetic unit to which they belong, Unit V or Unit VI. Due to the significant erosion affecting the basin after the capture process (Calvache and Viseras, 1997), the sediments of Unit VI are less well represented than those of Unit V. Therefore, the inferences for this unit will be more tentative.

There is a thorough description of each architectural element (Order 2) and the lithofacies forming them (Order 1) in Pla-Pueyo et al. (2009), and a summary in Table 1.

The characteristic sequence (Order 3) of the AS in Unit V (Fig. 5A) is a 3 m thick, fining-upward sequence, starting with a high sinuosity channel (usually sandy, but can be dominated by gravels), showing lateral accretion and grading laterally and vertically into the sand and clays of the floodplain, in which immature palaeosols often appear. The characteristic features of these palaeosols are a grey colour, yellow-orange-red mottling, and bioturbation by roots (Pla-Pueyo et al., 2009), which characterise them as poorly drained palaeosols (following the classification after Kraus and Hasiotis, 2006). This interpretation is consistent with other examples described in the literature (Kraus and Aslan, 1993; Kraus and Gwinn, 1997; Kraus, 1999; Kraus and Hasiotis, 2006, among others). In the palaeosols studied in the Bighorn Basin (Wyoming, United States) (Kraus and Gwinn, 1997), it is shown how the maturity and hydromorphical conditions may depend on the grain size and therefore on the distance with respect to the local sediment source (Kraus, 1999). In the AS sediments of the central sector of the Guadix basin, the scarcity of coarse-grained bodies probably implies a relatively distal position from the main sediment supply in the floodplain. In this situation, impermeable fine grained sediments would accumulate, leading to the formation of grey poorly-drained palaeosols. The low maturity of the palaeosols developed in the AS floodplain points to a relatively humid climate, which would allow the palaeosols to retain the water during their development but which would prevent long subaerial exposure periods.

Sometimes the sequence shows carbonate content increasing upwards and a palustrine carbonate may be present at the top of the sequence. The features of these palustrine sediments have been attributed to an environment with an exposure index (percentage of days of subaerial exposure of the sediment throughout the year, defined by Platt and Wright, 1992) between 40 and 70%. Both the palaeosols and the palustrine carbonates show features pointing to a seasonal subaerial exposure in a sub-humid environment, meaning that the water table would remain high for long periods. The most common situation is to find incomplete sequences, some of them lacking the channel facies, showing only floodplain sediments and sometimes palustrine carbonates on top.

The sedimentary model for each Order 4 element (each of the intervals dominated by the AS in the axial valley) would therefore be a network of high-sinuosity channels flowing through the central valley of the basin, which would be dominated by floodplain fine sediments (Fernández et al., 1996; Viseras et al., 2006; Pla-Pueyo et al., 2009). The AS characteristic sequence in Unit V is interpreted as a rising base level sequence, starting when there is a fall in the base level (erosive base) and increasing its content of fine sediments and carbonates as the base level rises (Fernández et al., 1993; Pla-Pueyo et al., 2009). The moments of sudden base level fall would coincide with the erosive base of some of the sequences, causing erosion of the older fluvial sediments through entrenchment of the channels, and enhancing edaphisation in the areas further from the channels. Afterwards, the base level would rise again, allowing the deposition of the channel and floodplain sediments and even flooding of large areas of the floodplain. A high water table situation would allow the flooding of lower areas in the floodplain, generating wetlands formed mainly by ephemeral ponds where palustrine carbonates of around 30 cm thick would be deposited (Pla-Pueyo et al., 2011b). The seasonal desiccation deduced from the features of the palustrine limestones and the development of immature palaeosols could indicate an oscillating base level (water table) during the last part of the development of the sequence (Pla-Pueyo et al., 2009), related to more minor fluctuations.

The main architectural elements in the Axial System in Unit VI in the study area in this unit are dominated by fine-grained floodplain sediments and palustrine carbonates (Pla-Pueyo et al., 2009) (Table 1). The basic sequence in the study area (Fig. 5B) comprises a lower siliciclastic part, characterising the fine floodplain sediments, evolving (vertically and/or laterally) into a palustrine carbonate, with the carbonate textural features pointing to a more perennial behaviour with respect to the ponds in Unit V (Pla-Pueyo et al., 2009). Moreover, there are some channeled coarser-grained sediments eastwards from the study area, but there are almost none of them in the study area in Unit VI. Because of these reasons, it is difficult to establish a sedimentary model for the AS deposits in Unit VI in the central sector of the basin. However, the vertically stacked and widespread palustrine carbonates point to a higher base level than in Unit V, to a more stable fluvial system in general (Pla-Pueyo et al., 2009) and to the formation of extensive and relatively permanent wetlands (Pla-Pueyo et al., 2011b; 2012a).

4.2. Internal Transverse System elements

The phases of the ITS prograding on the axial valley in the study area (Order 4 elements) are very similar in both units, V and VI. A general sedimentological description of the ITS has been previously provided for the Guadix Basin (Viseras and Fernández, 1992, 1994, 1995), but we will describe it briefly for the study area, with its particularities (see Table 2). Each progradation phase (Order 4 element) of the ITS is represented by one or several vertical sequences (Order 3 elements) that are formed by channeled pseudotabular complexes grading laterally and vertically to red lutites related to a pedogenically altered floodplain, palustrine carbonates and/or an immature nodular calcrete at the top (Fig. 6A).

The sheet gravel bodies of the ITS outcropping in the study area are interpreted as sheet-type braided complexes developed in the distal part of an alluvial fan with its proximal part located at the foot of the Sierra Nevada mountains and Sierra de Baza (Viseras and Fernández, 1995). This system presented a high rate of lateral migration of the channels, which were rarely more than 1-1.5 m deep and 10-15 m wide (Fig. 6B).

The red colour of the floodplain fine-grained sediments and the presence of carbonate pedogenic nodules are attributed to the development of well drained palaeosols (after the classification by Kraus and Hasiotis, 2006), where the iron is oxidized and carbonate precipitates form nodules. Sometimes, when the subaerial exposure lasted long enough, these facies evolved into a nodular calcrete (Pla-Pueyo et al., 2009). All these features indicate an increasing edaphisation from the base to the top of the sequence. The basic sequence is therefore representing a slow fall of the base level from base to top, the opposite situation that has been interpreted from the Axial System characteristic sequence.

In other parts of the study area, a palustrine limestone with an average thickness of 20 cm and a variable lateral continuity (decametres to hectometres) may be found capping this sequence. Where a palustrine limestone is found at the top of the sequence, it may be interpreted as the result of a relatively fast rise in the base level (water table) after a period of dry conditions. A rise in the base level, together with the low gradient of the topography in the axial valley, would cause ponding of very extensive areas, including those that would have been previously occupied by the distal ITS sediments.

These architectural elements form the basic sequence (Order 3) characterising the ITS (Fig. 6A), which can be repeated several times within each progradation phase (Order 4) and may reach 4 m in thickness. However, the most frequent situation in the field is to find only reddish lutites forming the ITS progradation sediments. When channels appear, they are usually on top of a floodplain lutite, rarely at the base of the progradation eroding the Axial System sediments. This fact points to a gradual progradation of the ITS, starting with fine facies and recording more proximal facies upwards, which become more distal towards the top of the progradation. When several channels appear within a progradation phase, it is common to observe channels in the same section showing opposite migrating directions (Fig. 6B). This behaviour is reflected in the sedimentary model proposed for the ITS (Viseras and Fernández, 1994 1995), which consists of a pendular movement of the channels located in the medial-distal part of the alluvial fan. As a whole, the facies attributed in the field to the ITS exhibit grain sizes and sedimentary bodies characteristic of the medial-external alluvial fan, suggesting an intermediate to distal position within the *bajada* system formed by the coalescence of the fans.

There are no significant differences in the characteristic sequence described for the ITS in Unit V and the one observed for VI in the study area. Therefore, the same description of the ITS siliciclastic sediments may be applied to Unit VI in the study area (Table 2, Fig. 6). There are differences in the margin of the basin but in the central sector, the only difference that may be noticed is that in general, the channels become rarer in the sequences, with a predominance of fine-grained sediments, as is seen in the AS sediments. However, the important development of calcretes in Unit VI and the increase in their maturity in comparison with those from Unit V could be associated to longer subaerial exposure periods, and therefore, to drier palaeohydrological conditions affecting the sediments of the ITS during deposition of Unit VI.

5. Stable isotopic evidence for palaeohydrological conditions

As outlined above Unit V and VI sediments of both the AS and ITS are rich in freshwater and terrestrial carbonates, the $\delta^{18}O$ and $\delta^{13}C$ values of which can provide important palaeoenvironmental information (Cerling, 1984, Cerling and Quade, 1993, Alonso-Zarza, 2003; Alonso-Zarza et al., 2012; Andrews, 2006; Candy et al., 2011, 2012). The isotopic analysis of such materials from the various units in the Guadix system may, therefore, provide palaeoenvironmental information that can establish the climatic context of the different phases of sediment deposition (Pla-Pueyo et al., 2012b). Candy et al. (2012), in a review of the $\delta^{18}O$ and $\delta^{13}C$ values of European meteoric carbonates, has shown that, in the Mediterranean, carbonates forming under dry or arid climates are characterised by co-variance between $\delta^{18}O$ and $\delta^{13}C$ values. This is because evaporation will cause the preferential removal of the “lighter” $H_2{}^{16}O$ and the degassing, as a result of decreasing water volume, of the lighter $^{12}CO_2$. In more humid regions, e,g. the British Isles, the $\delta^{18}O$ and $\delta^{13}C$ signals are driven by different environmental factors, temperature and vegetation type respectively, consequently such regions show limited evidence for co-variance between the isotopic values of oxygen and carbon. In this study we focus on the isotopic values of palustrine carbonates as these are abundant in both the AS and ITS sediments, whereas calcretes are more abundant in the ITS.

5.1. Methods

The palustrine carbonates were sampled from the stratigraphical profiles selected for the present study (Figs. 3, 4 and 7). A total of 45 samples were collected from the Axial System carbonates (33 for Unit V and 12 for Unit VI), and 36 from the Internal Transverse System ones (15 for Unit V and 11 for Unit VI).

The analyses of the palustrine carbonates were performed using bulk samples but only micritic facies showing a minimum alteration degree were subsampled, in order to minimise contamination due to diagenetic (e.g. cements) and pedogenetic (e.g. fluid circulation related to desiccation cracks and marmorization) processes. The carbonates were powdered using a pestle and mortar, and the $\delta^{13}C$ and $\delta^{18}O$ isotopic composition was established by analysing CO2 liberated from the sample reaction with phosphoric acid at 90º C. Internal (RHBNC-PRISM) and external (NBS-19, LSVEC) standards were analysed every 8 samples. The carbonate stable isotopes were analyzed using a VG PRISM series 2 mass spectrometer at the laboratories of the Royal Holloway University of London (UK). In this study, all isotopic values are quoted in reference to V-PDB.

5.2. Results and interpretation

The $\delta^{13}C$ and $\delta^{18}O$ data of palustrine carbonates sampled from the five profiles (Fig. 7) are shown in Table 3 and the correlation between both sets of data is plotted in Figure 8. The analysis from the dataset was performed by differentiating between the two drainage systems (Axial System and Internal Transverse System). The isotopic values for palustrine carbonates from the Axial System (Fig. 8, Table 3) show no significant correlation (R^2=0.51), with the $\delta^{13}C$ values (mean= -7.50‰) showing a range of -8.86 to -5.91‰ and the $\delta^{18}O$ values (mean= -6.69‰) a range of -9.55 to -4.82‰. In the case of the ITS (Fig. 8, Table 3), the palustrine carbonates show a more significant degree of correlation than the AS carbonates, (R^2=0.67), with $\delta^{13}C$ values (mean= -7.38‰) in the range between -8.60 and -4.77‰, and $\delta^{18}O$ values (mean= -6.86‰) ranging from -8.60 to -5.48‰. All of these values are all in the observed range of typical Quaternary freshwater palustrine carbonates (Alonso-Zarza and Wright, 2010; Alonso-Zarza et al., 2012).

6. Discussion

The present article proposes the use of palustrine carbonates to infer the factors controlling the depositional cyclicity in the central valley of the Guadix Basin throughout the Pliocene and Pleistocene. In this sense, the data collected so far points to a clear alternation in palaeohydrological conditions between the periods in which the axial valley was dominated by the Axial System, and the times in which it was occupied mainly by the Internal Transverse System sediments.

It is generally accepted that the main controls on sedimentation in an endorheic basin are related to tectonism, base level and/or climate. Each factor will be briefly discussed for the sediments alternating in the central part of the Guadix Basin (see also Pla-Pueyo et al., 2009).

6.1. Tectonism

Although the Guadix Basin has experienced continuous uplift since the Late Miocene (Sanz de Galdeano and Peláez, 2007), the fault systems that affect it have created several subsiding areas or depocentres, one of which is located in the study area (Fig. 3) (Sanz de Galdeano and Alfaro, 2004). Most of the tectonic processes in the Guadix Basin (faulting, subsidence, tectonic horst uplift) started in the late Miocene (Soria et al., 1998) but it is not known whether these processes were continuous through time or whether they have undergone punctuated development from the Late Miocene to the present day (Sanz de Galdeano and Peláez, 2007). However, it is improbable that tectonic processes would have presented such a regular cyclicity.

6.2. Base level

The changes in base level deduced from the sedimentological features of the characteristic sequence for each system (AS and ITS) have been discussed before when talking about the sedimentology of the study area. Stratigraphical base level (equivalent to eustasy in coastal marine environments), as defined by Shanley and McCabe (1994), affects fluvio-lacustrine architecture and its changes may increase or decrease the available space for potential sediment accumulation (Jervey, 1988). In a previous study of the central sector of the Guadix Basin (Pla-Pueyo et al., 2009), Units

V and VI were characterised in terms of the ratio between accommodation space and sediment supply (A/S ratio) (Martinsen et al., 1999), which is directly related to stratigraphical base level. As a result, Unit V was considered to be a High Accommodation Systems Tract (HAS) and Unit VI, a Low Accommodation Systems Tract (LAS) (Pla-Pueyo et al., 2009). The cyclicity identified between the AS and the ITS is constant in both units, and therefore, does not seem to be dependent on the base level conditions.

6.3. Climatic model from sedimentological and geochemical data

Once tectonism and base level had been ruled out as the main potential causes for the cyclicity observed, two climatic models were proposed (Pla-Pueyo et al., 2011c) to explain the cyclicity presented by the AS and the ITS in the central sector of the Guadix Basin.

The first model invoked similar climatic conditions for both the AS and the ITS during the Pliocene and Pleistocene (an intermediate climate, as deduced from the textures of the continental carbonates and the features of the fluvial and alluvial sediments by Pla-Pueyo et al., 2009). Here, differences in the precipitation regime were considered responsible for the progradation of the ITS on the axial valley, coinciding with extreme seasonality and longer winters with intense precipitation related to the orography, as found today in the Sierra Nevada of southern Spain (Pla-Pueyo et al., 2011c). Under these conditions, the times in which the AS was dominating the axial valley corresponded with periods when the seasonality was less pronounced and precipitation was evenly distributed throughout the year. In contrast, the second model proposed relatively different climatic conditions for the AS and the ITS. These differences included not only the precipitation regime but also the annual amount of precipitation. In this model, the ITS progradation phases were correlated with typical glacial (dry and cold) conditions, with poor vegetation cover (high erosion in source areas) and water discharge concentrated in short periods (melting peaks). The AS occupation of the axial valley, on the other hand, was considered to reflect typical interglacial conditions (wet and warm), with abundant vegetation cover (less erosion in source areas) and more abundant precipitation (Pla-Pueyo et al., 2011c). These conditions would have enhanced the formation of palustrine-lacustrine carbonates and tufas, and the presence of large mammal sites within the sediments of the Axial System would also support this second model.

In the study area, the AS in Unit V presents mainly high sinuosity fluvial channels (Viseras et al., 2006; Pla-Pueyo et al., 2009) (Table 1) indicating that water was perennially present (major breaks in sedimentation as indicated by the presence of mature palaeosols and noticeable erosion of the older deposits, were not observed). These channels grade vertically and laterally into fine floodplain sediments. In most of the cases, these sediments are affected by edaphisation, evolving into immature poorly drained palaeosols (in the sense of Kraus and Hasiotis, 2006). In Unit VI, abundant water availability is inferred from the vertically stacked palustrine beds extending lateral for kilometres, interpreted as extensive wetlands (Pla-Pueyo et al., 2011b; 2012a).

This climatic interpretation can be supported by the stable isotopic data. At the most basic level the difference between the isotopic characteristics of the palustrine carbonates in the AS and ITS sediments can be explained by a difference in aridity. Candy et al. (2012) have suggested that, in the Mediterranean the $\delta^{18}O$ and $\delta^{13}C$ values of continental carbonates, primarily calcretes, tufa and groundwater carbonates, increasing environmental aridity will promote increasing evaporation in surficial waters resulting in the increase in the resultant values of both $\delta^{18}O$ and $\delta^{13}C$. This is also true for carbonates precipitated in surface water bodies from smaller palustrine systems to larger lacustrine systems (Leng and Marshall, 2004; Roberts et al., 2008). The degree of significance in R^2 values of both the AS and the ITS carbonates are moderate but stronger in the ITS sediments. This would suggest that evaporation played a stronger role, and, therefore, that aridity was more pronounced, during the accumulation of the ITS sediments than during the accumulation of the AS sediments. A preliminary analysis, which requires further testing, would be that the AS sediments were deposited under a more humid environment that the ITS sediments which would have accumulated under more arid conditions (Table 3, Fig. 8).

The ITS sediments analysed are not characteristic of an arid climate, but they show some features pointing to a drier climate than the sediments of the Axial System, such as the braided style of their channels, the abundant presence of soil nodules and the development of nodular immature calcretes and reddish well drained palaeosols (Table 2, Fig. 6). However, the inmature calcretes and the channelization of the deposits would indicate a certain degree of humidity. It is important to state that debris flows and steep slopes, usually associated with alluvial fans developed in dry climate contexts, are more likely to be found in the proximal parts of the fans (see Viseras and Fernández 1992, 1994, 1995). In the study area, the medial-distal part of the fans has been analysed, where sheet floods and channelization stages are to be expected. In addition, the coalescence between fans would probably enhance the extension of the fan to the front rather than to the sides, and therefore, their progradation onto the axial valley.

The carbon and oxygen isotopic values of the ITS palustrine carbonates (Table 3, Fig. 8) show a higher correlation than those for the Axial System, corroborating the enhanced influence of evaporation and aridity. As a result, a generally drier climate can be inferred for the ITS sediments in comparison with the AS ones. The deposition of alluvial fans under arid conditions is widely recorded in the literature (Bull and Schick, 1979; Wells et al., 1987; Harvey and Wells, 1994, among others) and is exemplified in Southern Spain by the Quaternary alluvial fans studied by Viseras et al. (2003).

It is proposed, therefore, that the progradation phases are related to a drier climate. A cycle of fan deposition would be triggered as a result of the transition from a wetter to a relatively drier climate when a reduction in effective soils moisture resulted in a reduction in the vegetative cover on hillslopes. This would, in turn, result in an increase in soil erosion and a concomitant increase in sediment supply (Harvey and Wells, 1994; Harvey et al, 1999). As an example, Blair and McPherson (1994) explained alluvial fan aggradation in the Mojave Desert of the southern USA as being triggered by transitions from a wetter to a dryer climate, helped by ephemeral processes such as storms. In support of this idea, Sheets et al. (2002) demonstrated experimentally that the bulk deposition in an alluvial fan is accomplished by short-lived flows caused mainly by overbank spills, flow expansions and failed avulsions, a phenomenon for which there is field evidence as well.

The ephemeral nature of the ponds forming in the As and ITS is probably the reason why malacofauna is not often present in the carbonate sediments throughout the infill of the Guadix Basin; our studies are accordingly performed on the palustrine carbonates instead. However, taking into account the abundant literature and the quality of the palaeoenvironmental interpretations obtained from the stable isotopic analyses of the malacofauna in the neighbouring Baza Basin for the studied time span (e.g. Anadón and Gabás, 2009; Anadón et al., 1986, 1994, 2014; Ortiz et al., 2006, among others), the hydrogeochemical data for the Pliocene and Quaternary could be further expanded in the Guadix Basin by studying biogenic carbonates isolated from the bulk rock in those beds where malacofauna is present.

6.4. High-frequency orbital forcing?

In the Guadix Basin, starting from the astronomical ages of the magnetic reversal boundaries, the data corroborate a repeating pattern of ca. 100 ka of the Internal Transverse System progradations, a cyclicity that falls in the Milankovitch periodicity of high-frequency eccentricity. As a result, a possible astronomical origin of such climatic changes was considered from the beginning (Pla-Pueyo et al., 2011b). Although there are documented astronomically-forced cycles in continental sediments (Agustí et al., 2001; van Vugt et al., 2001; Kruiver et al., 2002; Steenbrink et al., 2006; Amorosi et al., 2008; García-García et al., 2009; Abels et al., 2010), most of them are focused on lacustrine settings with a recording of precessional cycles (e.g. van Vugt et al., 2001) or cyclicity corresponding to changes in obliquity and/or eccentricity (e.g. Steenbrink et al., 2006; Jiménez-Moreno et al., 2013). Studies on astronomical forcing in the fluvial and palustrine settings of the peri-Mediterranean domain are scarce, focusing mainly on the eccentricity cycles identified in floodplain sediments, palustrine environments, and carbonate palaeosols associated to these deposits, such as those from Kruiver et al. (2002), Amorosi et al. (2008) or Abels et al. (2010). In these works, the cyclicity is usually reflected by changes in the colour of the sediments or in the abundance of carbonate in the sequence.

Most literature on the long-term palaeoenvironmental history of the Mediterranean basin suggests that “warm stages” in the marine isotope record, i.e. MIS 5, 7, 9 and 11, are characterised by the expansion of woodland vegetation ecosystems and are, consequently, dominated by relatively humid climates (Tzedakis et al., 2001, 2006). Conversely, “cold stages” in the marine isotope record, i.e. MIS 2/4, 6, 8, 10 etc, are characterised by the development of *Artemisia* steppe, reflecting the development of arid/semi-arid climatic conditions (Tzedakis et al., 2001, 2006).

In the present work, the progradations of the ITS have been interpreted as corresponding to a relatively dry climate, so they are correlated with periods of “high” global ice volume (Lisiecki and Raymo, 2005) which broadly correspond with lows in eccentricity (Laskar et al., 2004), and given the model for most Mediterranean basins, it would appear reasonable to correlate them with “cold stages”. Conversely dominance of the AS have been interpreted as corresponding to a relatively humid climate, so they are correlated with periods of “low” global ice volume (Lisiecki and Raymo, 2005), which broadly correspond with highs in Eccentricity, and by the previous model, with “warm stages”. This correlation must be regarded as tentative (Viseras and Pla-Pueyo, 2013), although it is supported by the existing evidence.

The work by Agustí et al. (2001) supports this tentative correlation, as it proposes a similar interpretation for the sediments of the Zújar section (northern-eastern part of the Guadix Basin, whereas the present study focuses on the central sector of the basin). These authors propose a terrestrial climate model for the easternmost Guadix basin, where cyclicity is broadly correlated to a ca 100 ky period (and also 400 ky). They identify maximum aridity intervals based on the sedimentary and faunal data that they link with eccentricity minima peaks. As a result, they conclude that all the recorded aridity intervals in the Zújar section can be associated with periods of climatic cooling.

However, problems arise when trying to interpret the progradations of the ITS as glacial stages and the AS moments a interglacial periods:

1) The climatic context of the Guadix Basin during Quaternary times was possibly influenced by the glaciations taking place in Sierra Nevada. Until recently, the Sierra Nevada contained the southernmost modern glacier in Europe (Hughes et al., 2006a, b, 2007). Although some attempts have been made to distinguish phases of glaciation (e.g. Messerli, 1980), information regarding the cycles of glaciation in Spain is scarce, and good information is only available for the most recent (Würmian, MIS 2), since local evidence for older glacial cycles has been mostly lost through erosion (Pérez-Alberti et al., 2004). Moreover, neither glacial nor periglacial sediments have been recognized in the Guadix Basin sediments.

2) Each progradation has a different thickness and therefore, covers a different time-span, leading to uncertainty when correlating them with insolation maxima.

3) One of the criteria to support AS dominance periods corresponding with warmer periods is the presence of fauna in the sediments, which is absent in the Internal Transverse System. However, although the presence or absence of fauna is strongly determined by the sedimentary environment, there is also a preservation problem. The faunal remains would be better preserved in reduced environments in a floodplain, where the sedimentation rate is high, than in an alluvial fan, suffering long subaerial exposure and intense oxidation processes. Moreover, microfaunal remains have been proved to be crucial to determine temperature ranges in past environments (e.g. Blain et al., 2013), but although the macrofauna is relatively abundant in the study area, the microfaunal remains are scarce in the studied sites (Viseras et al., 2006; Arribas et al., 2009)

4) The dating in the Guadix Basin has been supported mostly by palaeomagnetic data. The scale of these data means that they cannot distinguish accurately cycles of precession and obliquity, so whether the cycles would correlate to eccentricity, obliquity or precession cycles becomes more a matter of guesswork. This links to the difficulty in detecting allogenic cyclicity within the fluvial sediments of the Axial System, which can vary substantially both laterally and vertically over just several meters.

5) This study is based on the use of palustrine carbonates to determine the climatic nature of the cyclicity. For the scale that the cycles present, the palustrine carbonates provide important information to distinguish between more arid and wetter conditions. However, it has been recently proved that palustrine carbonates may not be reliable when trying to get climatic interpretations in detail (Alonso-Zarza et al., 2012). In this case, the support that may be provided by analyses of biogenic carbonates where available may be useful to confirm or discard some of the proposed interpretations.

7. Conclusions

A new set of stable isotopic data from palustrine carbonates has allowed the preliminary interpretation of a climatic-driven cyclicity in the Guadix Basin (southern Spain), based on the combination of the new data with previous lithological, palaeomagnetic and biostratigraphical information. The conclusions of the study are as follow:

1) There are differences between the isotopic results obtained for the palustrine carbonates of each of the studied drainage systems (Axial System and Internal Transverse System).

2) The isotopic results show how the fluvial system (Axial System), located at the bottom of the valley, was less affected by climatic shifts than the alluvial fans of the Internal Transverse System.

3) The available data point to a higher permanence of water when the Axial System was predominant in the centre of the valley.

4) A palaeohydrological alternation has been interpreted as the main cause for the cyclicity, with the ITS progradations corresponding to more arid periods. The AS sediments would dominate the Axial valley during wetter periods.

5) Although the potential record of high frequency eccentricity (c.a. 100 Ka) has been considered and discussed, no astronomical tuning is finally proposed for the cyclicity, as the data available lack the accuracy/precission necessary to be certain about the correlation between the progradations of the ITS and insolation curves.

6) The new identification of permanent fresh water bodies in the Axial System has profound importance for the interpretation (and indeed future prediction) of Palaeolithic archaeological and palaeontological sites in this otherwise arid region. The stable isotopic evidence presented above indicates that although aridification was ongoing from at least 1.8 Ma, the water bodies of the Guadix basin would have served as key focal points in the landscape, supplying predictable resources to hominins and other mammals against a backdrop of long-term climate change.

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Figure captions

Figure 1. Geographical and geological setting of the Guadix Basin, located in the central sector of the Betic Cordillera (South of Spain) (modified from Pla-Pueyo et al., 2009). Study area marked with a star.

Figure 2. Paleogeography of the Guadix Basin during the Pliocene and the Pleistocene, showing a main fluvial system (Axial System, AS) and two transverse systems of alluvial fans (Internal Transverse System or ITS and External Transverse System or ETS). The main topographic heights in relation with the source areas (External and Internal Zones) are indicated.

Figure 3. Aerial view of the study area, showing the position of the selected stratigraphic profiles (base photograph from Google Earth).

Figure 4. Litho-, bio- and magnetostratigraphical correlation of the six stratigraphical profiles used in the present study (BB-1, FPB-1, T-1, FP-1, FSCC-1 and FBP-SVY-1). The data of the nature and thickness of the beds shown at the lower part of the correlation are not speculative, but based on field observations and the lithostratigraphical mapping performed in the area, even when the stratigraphical sections used for the scheme do not record the lower part of the represented scheme.

Figure 5. Characteristic sequences for the Axial System sediments in the central sector of the Guadix Basin. A) Unit V; B) Unit VI. A detailed explanation of the different architectural elements (i.e. SCn, CPm, etc) is given in Pla-Pueyo et al., 2009. See Table 1 for meaning of codes.

Figure 6.A). Characteristic sequence for the Internal Transverse System sediments in the central sector of the Guadix Basin. B) Photomosaics showing the sedimentological features of the ITS sediments in the study area and the lateral aggradation of channels in opposite directions, following the pendular movement proposed by Viseras and Fernández (1995). See Table 1 for meaning of codes.

Figure 7. Location of the stable isotope samples taken on palustrine carbonates in each of the selected stratigraphical profiles.

Figure 8. Cross-plots of $\delta^{13}C$ vs. $\delta^{18}O$ for palustrine limestones outcropping in the central sector of the Guadix Basin.

Table 1. Summary of the order 1-3 architectural elements representing the AS in the central sector of the Guadix Basin.

Table 2. Summary of the order 1-3 architectural elements representing the ITS in the central sector of the Guadix Basin.

Table 3. Isotopic composition ($\delta^{13}C$ and $\delta^{18}O$ in ‰) of the palustrine carbonates sampled in units V and VI in the central sector of the Guadix Basin. The samples are shown in stratigraphical order and organised by location (margin, profiles BB-1 and FPB-4, or centre, profiles FP-1, FSCC-1 and FBP-SSVY-1). The lateral white and black bands represent the magnetic chrones from the ATNTS2004. Dark grey cells with white font represent sediments sampled from the ITS interdigitations (labeled with Arabic numbers), while light grey cells with black font correspond to AS samples.

Figure 1

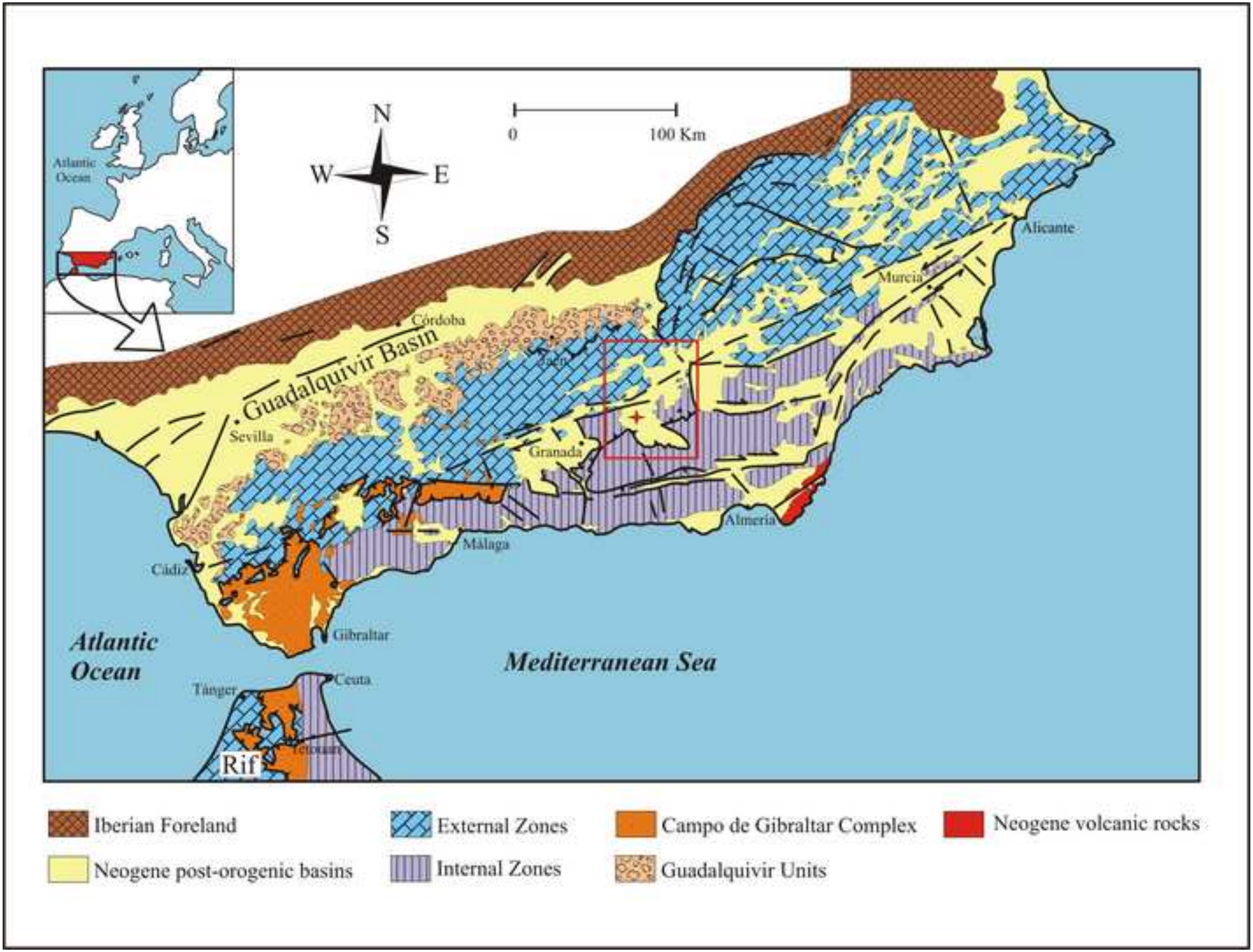
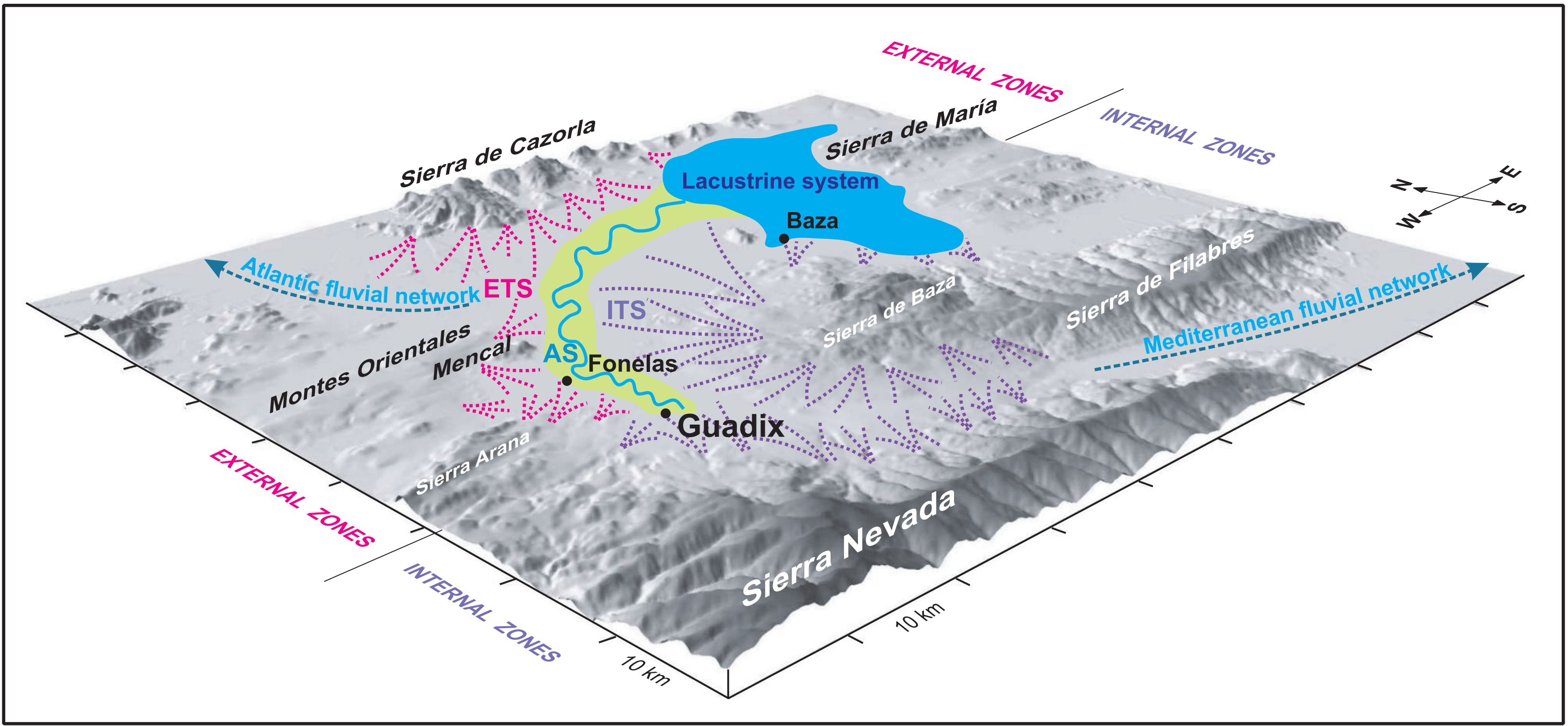

Atlantic Ocean
N
W
E
S
0
100 Km
Córdoba
Guadalquivir Basin
Jaén
Sevilla
Granada
Murcia
Alicante
Almeria
Málaga
Cádiz
Gibraltar
Atlantic Ocean
Mediterranean Sea
Tánger
Ceuta
Tetouan
Rif
Iberian Foreland
Neogene post-orogenic basins
External Zones
Internal Zones
Campo de Gibraltar Complex
Guadalquivir Units
Neogene volcanic rocks

Figure 2



EXTERNAL ZONES
INTERNAL ZONES
Sierra de Cazorla
Sierra de María
Lacustrine system
Baza
Atlantic fluvial network
ETS
ITS
Montes Orientales
Mencal
AS
Fonelas
Guadix
Sierra de Baza
Sierra de Filabres
Mediterranean fluvial network
Sierra Arana
EXTERNAL ZONES
INTERNAL ZONES
Sierra Nevada
N
E
S
W
10 km
10 km

Figure 3

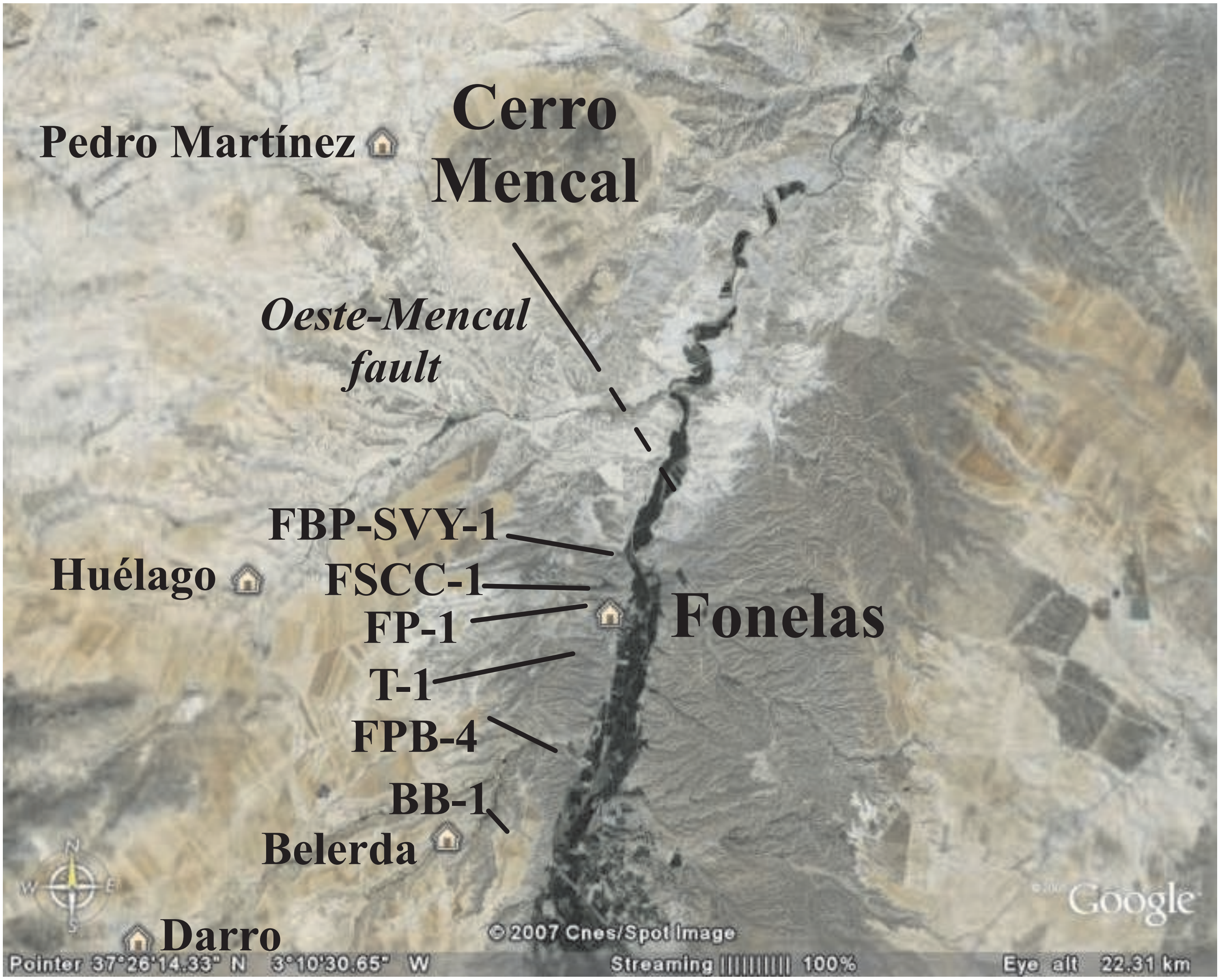

Cerro Mencal
Pedro Martínez
Oeste-Mencal fault
FBP-SVY-1
Huélago
FSCC-1
FP-1
Fonelas
T-1
FPB-4
BB-1
Belerda
Darro
N
W
E
S
© 2007 Cnes/Spot Image
Google
Pointer 37°26'14.33" N 3°10'30.65" W
Streaming |||||||||| 100%
Eye alt 22.31 km

Figure 4

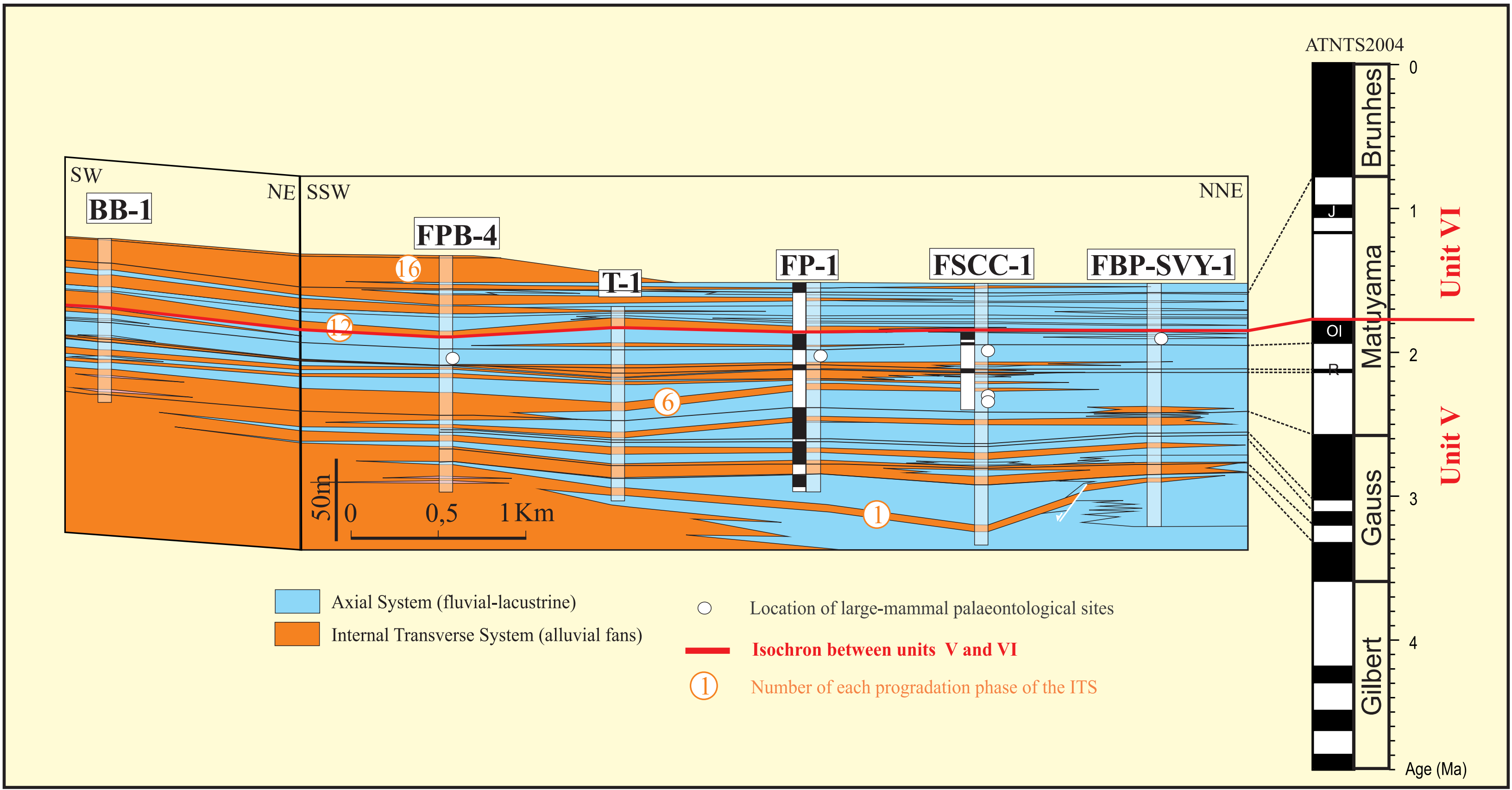

SW
NE
SSW
NNE
BB-1
FPB-4
T-1
FP-1
FSCC-1
FBP-SVY-1
16
12
6
1
50m
0
0,5
1 Km
Axial System (fluvial-lacustrine)
Internal Transverse System (alluvial fans)
Location of large-mammal palaeontological sites
Isochron between units V and VI
Number of each progradation phase of the ITS
ATNTS2004
Brunhes
Matuyama
Gauss
Gilbert
J
Ol
0
1
2
3
4
Age (Ma)
Unit VI
Unit V

Figure 5

Click here to download high resolution image

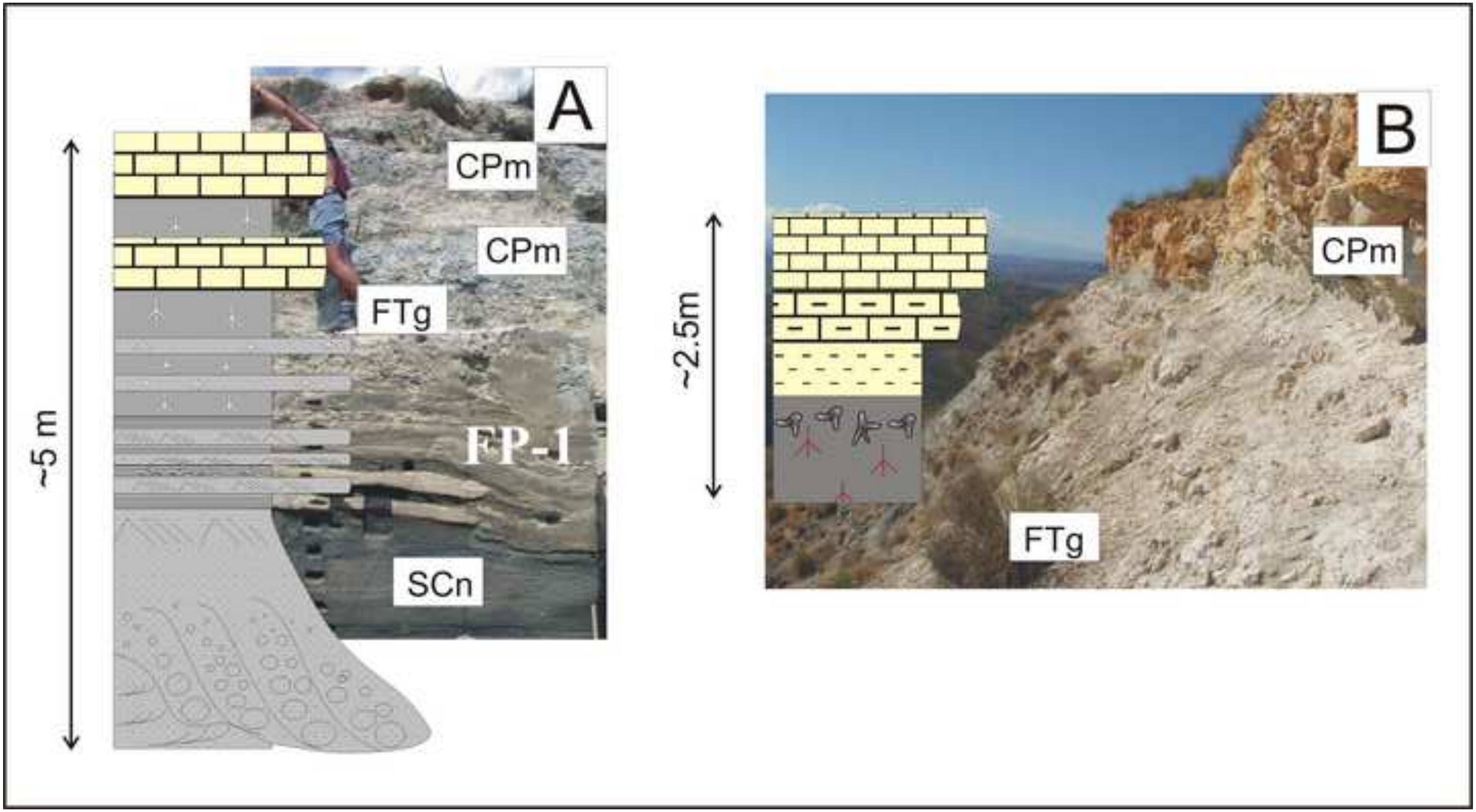


Figure 6A

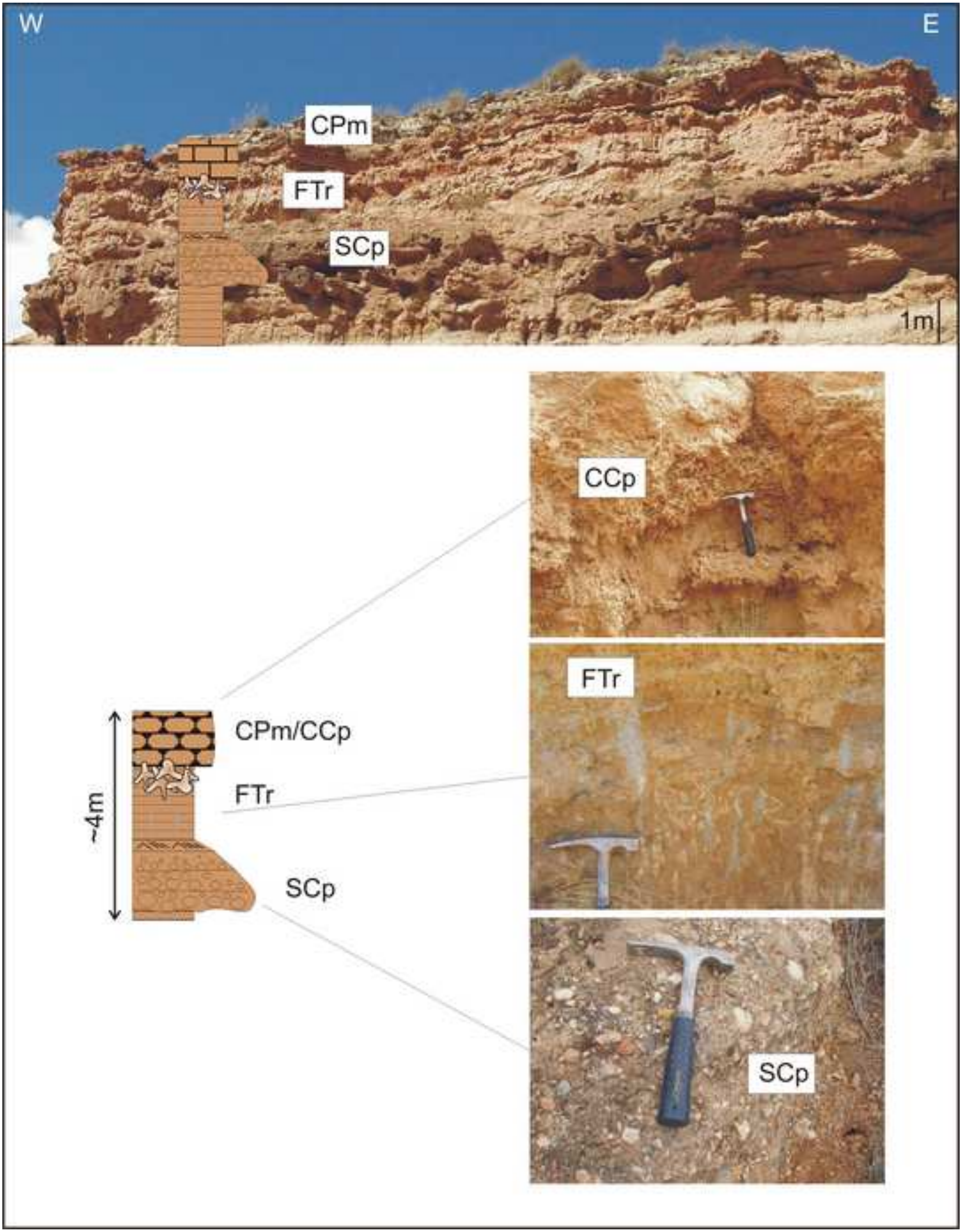


Figure 6B

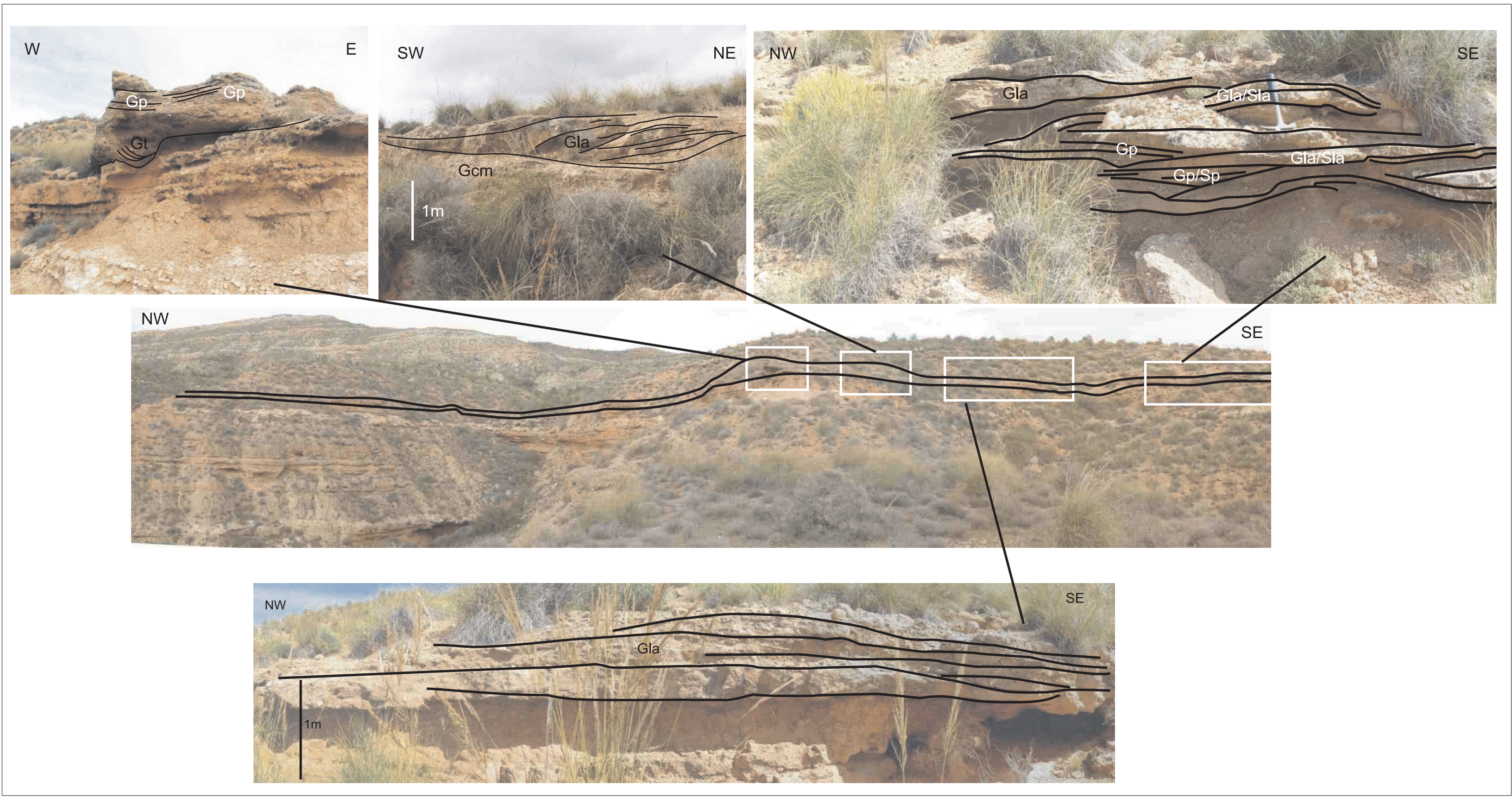

W
E
Gp
Gp
Gt
SW
NE
Gla
Gcm
1m
NW
SE
Gla
Gla/Sla
Gp
Gla/Sla
Gp/Sp
NW
SE
NW
SE
Gla
1m

Figure 7

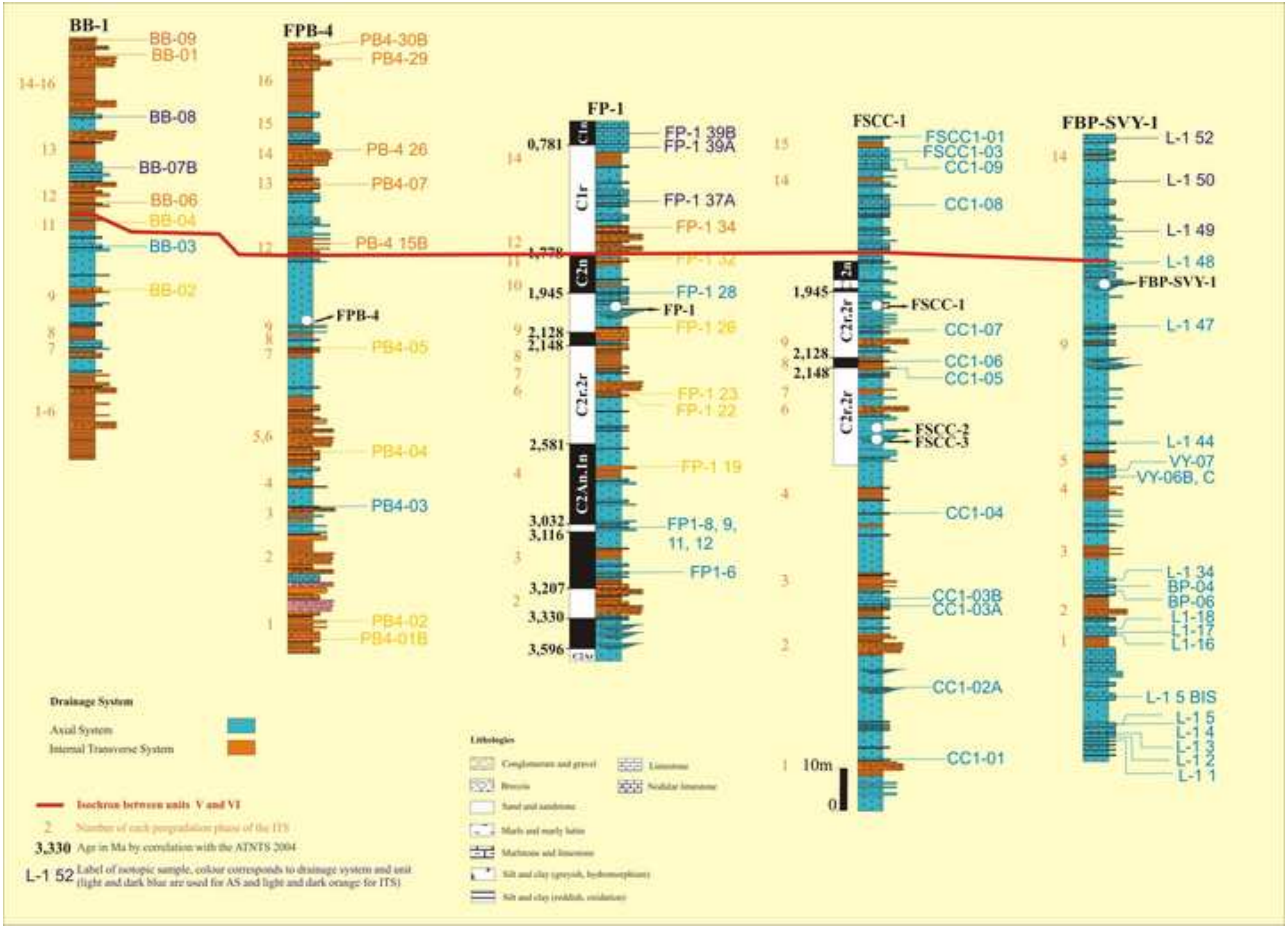

BB-1
BB-09
BB-01
14-16
BB-08
13
BB-07B
12
BB-06
11
BB-04
BB-03
BB-02
9
8
7
1-6
FPB-4
PB4-30B
PB4-29
16
15
14
PB-4 26
13
PB4-07
12
PB-4 15B
FPB-4
9
8
7
PB4-05
5,6
PB4-04
4
3
PB4-03
2
1
PB4-02
PB4-01B
FP-1
C1n
C1r
C2n
C2r.2r
C2An.1n
C2An
0,781
1,778
1,945
2,128
2,148
2,581
3,032
3,116
3,207
3,330
3,596
14
12
11
10
9
8
7
6
4
3
2
FP-1 39B
FP-1 39A
FP-1 37A
FP-1 34
FP-1 32
FP-1 28
FP-1
FP-1 26
FP-1 23
FP-1 22
FP-1 19
FP1-8, 9, 11, 12
FP1-6
FSCC-1
2n
C2r.2r
1,945
2,128
2,148
15
14
9
8
7
6
4
3
2
1
FSCC1-01
FSCC1-03
CC1-09
CC1-08
FSCC-1
CC1-07
CC1-06
CC1-05
FSCC-2
FSCC-3
CC1-04
CC1-03B
CC1-03A
CC1-02A
CC1-01
10m
0
FBP-SVY-1
14
9
5
4
3
2
1
L-1 52
L-1 50
L-1 49
L-1 48
FBP-SVY-1
L-1 47
L-1 44
VY-07
VY-06B, C
L-1 34
BP-04
BP-06
L1-18
L1-17
L1-16
L-1 5 BIS
L-1 5
L-1 4
L-1 3
L-1 2
L-1 1
Drainage System
Axial System
Internal Transverse System
Isochron between units V and VI
2 Number of each progradation phase of the ITS
3,330 Age in Ma by correlation with the ATNTS 2004
L-1 52 Label of isotopic sample, colour corresponds to drainage system and unit (light and dark blue are used for AS and light and dark orange for ITS)
Lithologies
Conglomerates and gravel
Breccia
Sand and sandstone
Marls and marly lutites
Marlstone and limestone
Silt and clay (greyish, hydromorphisms)
Silt and clay (reddish, oxidation)
Limestone
Nodular limestone

Figure 8

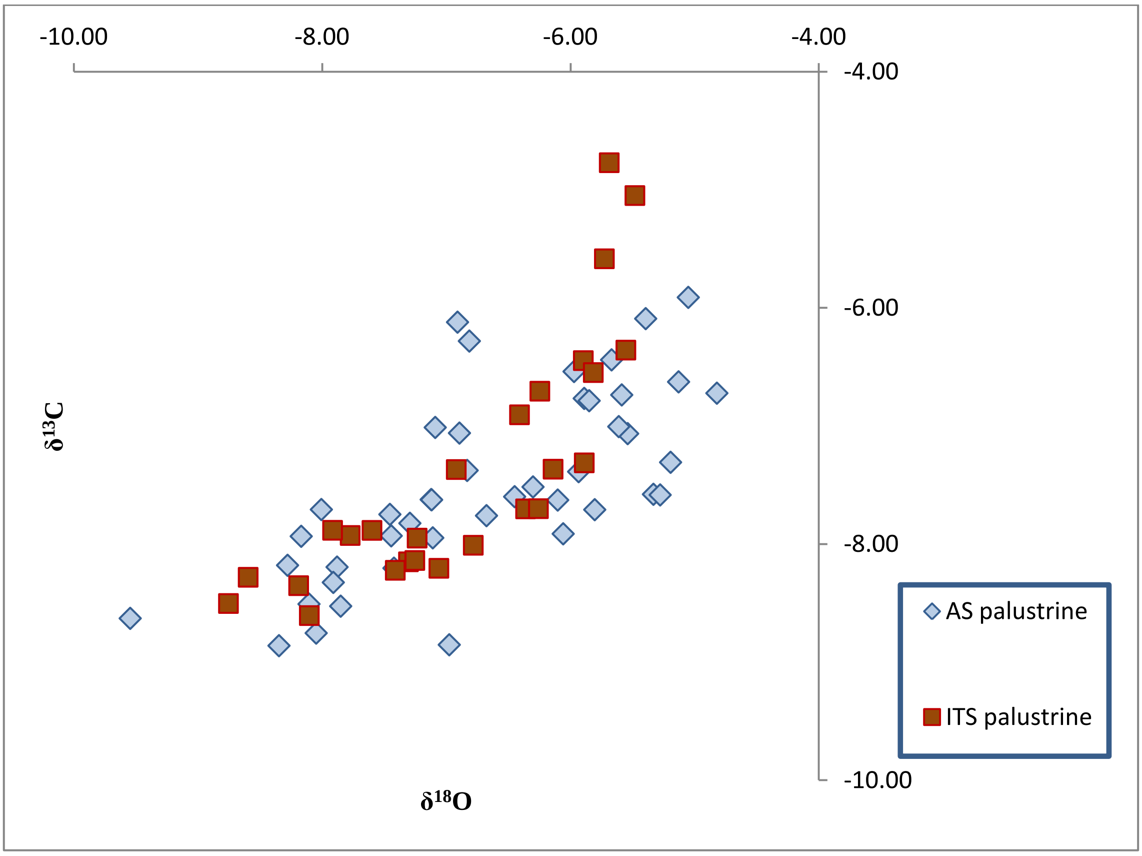
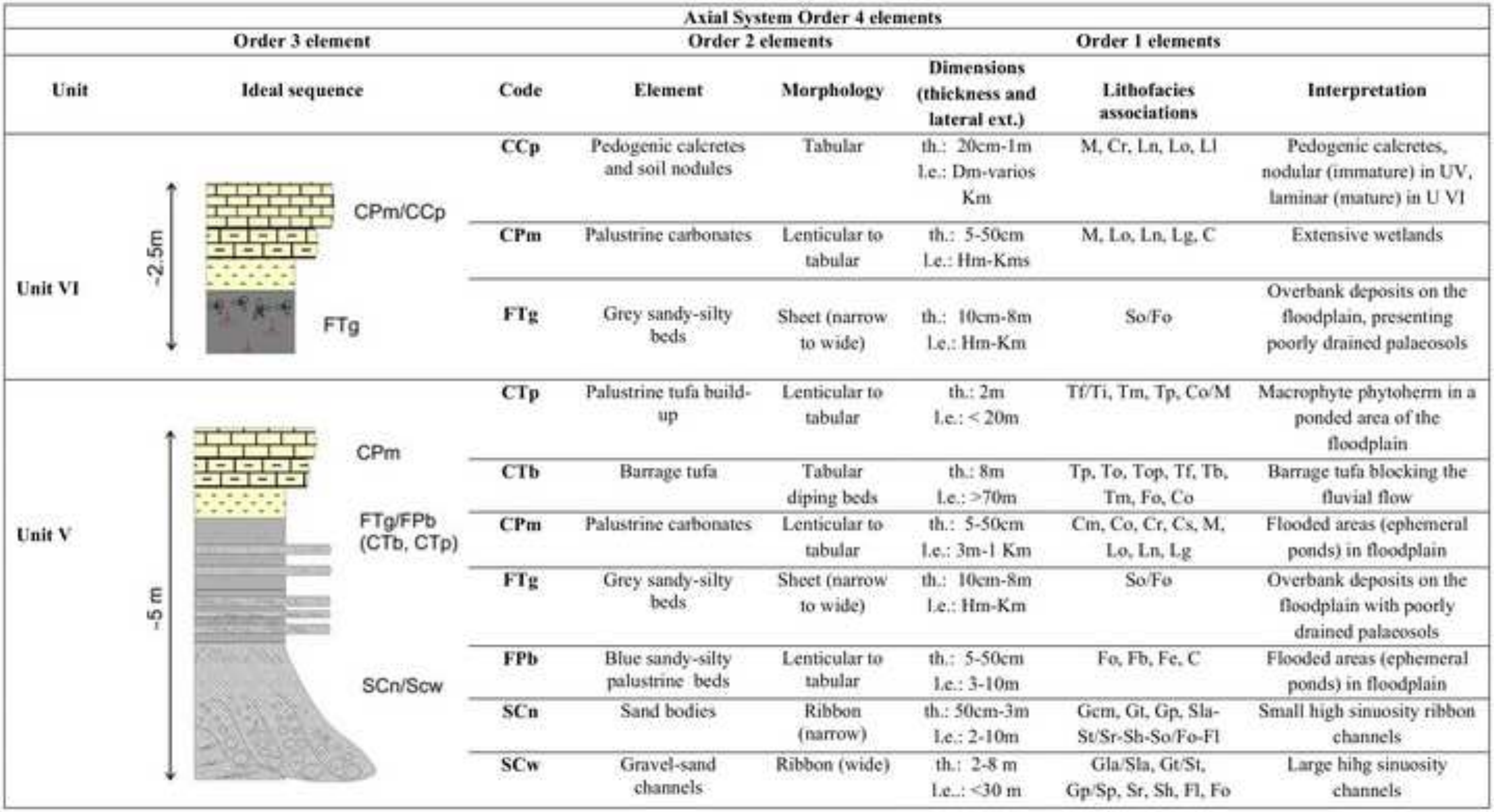

-10.00
-8.00
-6.00
-4.00
-4.00
-6.00
-8.00
-10.00
$\delta^{13}C$
$\delta^{18}O$
◇ AS palustrine
■ ITS palustrine

Table 1



Axial System Order 4 elements							
Order 3 element		Order 2 elements				Order 1 elements	
Unit	**Ideal sequence**	**Code**	**Element**	**Morphology**	**Dimensions (thickness and lateral ext.)**	**Lithofacies associations**	**Interpretation**
Unit VI	~2.5m CPm/CCp FTg	**CCp**	Pedogenic calcretes and soil nodules	Tabular	th.: 20cm-1m l.e.: Dm-varios Km	M, Cr, Ln, Lo, Ll	Pedogenic calcretes, nodular (immature) in UV, laminar (mature) in U VI
		CPm	Palustrine carbonates	Lenticular to tabular	th.: 5-50cm l.e.: Hm-Kms	M, Lo, Ln, Lg, C	Extensive wetlands
		FTg	Grey sandy-silty beds	Sheet (narrow to wide)	th.: 10cm-8m l.e.: Hm-Km	So/Fo	Overbank deposits on the floodplain, presenting poorly drained palaeosols
Unit V	~5 m CPm FTg/FPb (CTb, CTp) SCn/Scw	**CTp**	Palustrine tufa build-up	Lenticular to tabular	th.: 2m l.e.: < 20m	Tf/Ti, Tm, Tp, Co/M	Macrophyte phytoherm in a ponded area of the floodplain
		CTb	Barrage tufa	Tabular diping beds	th.: 8m l.e.: >70m	Tp, To, Top, Tf, Tb, Tm, Fo, Co	Barrage tufa blocking the fluvial flow
		CPm	Palustrine carbonates	Lenticular to tabular	th.: 5-50cm l.e.: 3m-1 Km	Cm, Co, Cr, Cs, M, Lo, Ln, Lg	Flooded areas (ephemeral ponds) in floodplain
		FTg	Grey sandy-silty beds	Sheet (narrow to wide)	th.: 10cm-8m l.e.: Hm-Km	So/Fo	Overbank deposits on the floodplain with poorly drained palaeosols
		FPb	Blue sandy-silty palustrine beds	Lenticular to tabular	th.: 5-50cm l.e.: 3-10m	Fo, Fb, Fe, C	Flooded areas (ephemeral ponds) in floodplain
		SCn	Sand bodies	Ribbon (narrow)	th.: 50cm-3m l.e.: 2-10m	Gcm, Gt, Gp, Sla-St/Sr-Sh-So/Fo-Fl	Small high sinuosity ribbon channels
		SCw	Gravel-sand channels	Ribbon (wide)	th.: 2-8 m l.e..: <30 m	Gla/Sla, Gt/St, Gp/Sp, Sr, Sh, Fl, Fo	Large hihg sinuosity channels

Table 2

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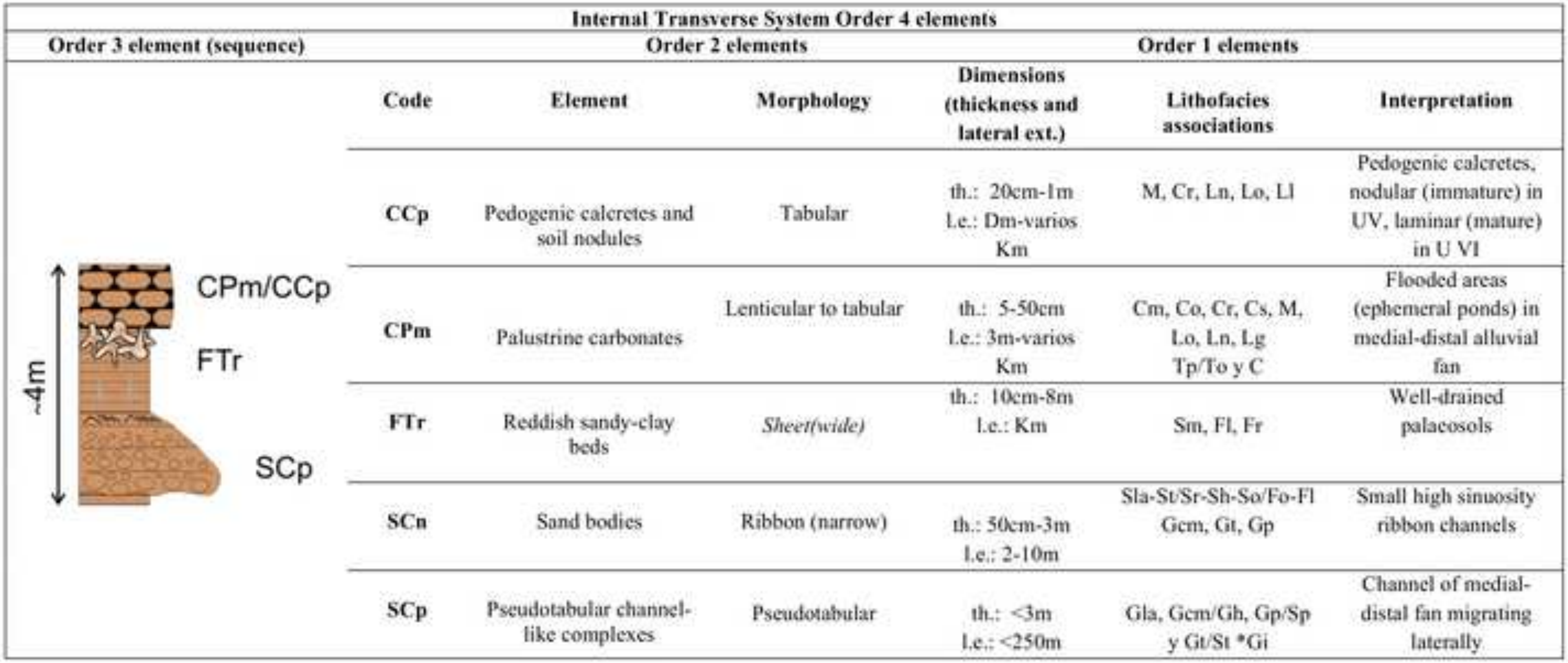

Internal Transverse System Order 4 elements						
Order 3 element (sequence)	**Order 2 elements**			**Order 1 elements**		
	Code	**Element**	**Morphology**	**Dimensions (thickness and lateral ext.)**	**Lithofacies associations**	**Interpretation**
	CCp	Pedogenic calcretes and soil nodules	Tabular	th.: 20cm-1m l.e.: Dm-varios Km	M, Cr, Ln, Lo, Ll	Pedogenic calcretes, nodular (immature) in UV, laminar (mature) in U VI
	CPm	Palustrine carbonates	Lenticular to tabular	th.: 5-50cm l.e.: 3m-varios Km	Cm, Co, Cr, Cs, M, Lo, Ln, Lg Tp/To y C	Flooded areas (ephemeral ponds) in medial-distal alluvial fan
	FTr	Reddish sandy-clay beds	*Sheet(wide)*	th.: 10cm-8m l.e.: Km	Sm, Fl, Fr	Well-drained palaeosols
	SCn	Sand bodies	Ribbon (narrow)	th.: 50cm-3m l.e.: 2-10m	Sla-St/Sr-Sh-So/Fo-Fl Gcm, Gt, Gp	Small high sinuosity ribbon channels
	SCp	Pseudotabular channel-like complexes	Pseudotabular	th.: <3m l.e.: <250m	Gla, Gcm/Gh, Gp/Sp y Gt/St *Gi	Channel of medial-distal fan migrating laterally

Table 3

	ATNTS 2004	Age (Ky)	Margin of basin	δ13C	δ18O	Centre of basin	δ13C	δ18O
UNIT VI	BRUNHES C1n	capture	16 PB-4 30B	-6,36	-5,55			
			BB-09	-5,58	-5,73			
			BB-01	-7,31	-5,89			
			PB-4 29	-6,70	-6,25	FSCC1-01	-6,77	-5,89
			15					
						CC1-09	-6,74	-5,59
						FSCC1-03U	-7,06	-5,54
						FSCC1-03M	-7,58	-5,33
						FSCC1-03L	-7,31	-5,19
		0,781				L-1 52	-7,00	-5,61
	MATUYAMA C1r	0,781-1,778	14			FP-1 39B	-7,70	-6,26
						FP-1 39A	-7,70	-6,36
			PB-4 26	-4,77	-5,69			
			BB-08	-7,01	-7,09			
						L-1 50	-7,39	-5,93
			13 PB4-07	-8,20	-7,06	CC1-08	-7,60	-6,45
			BB-07B	-7,62	-7,12			
						FP-1 37A	-6,79	-5,85
						L-1 49	-6,63	-5,13
			12			FP-1 34	-6,90	-6,41
			PB-4 15B	-7,37	-6,92			
			BB-06	-7,06	-6,89	FP-1 32	-7,37	-6,14
UNIT V	OLDUVAI C2n	1,778-1,945				L-1 48	-6,72	-4,82
			11 BB-04	-7,66	-7,22			
						10		
	C2r.1r	1,945-2,128				FP-1 28	-7,63	-6,10
			BB-03	-8,20	-7,42			
						CC1-07	-7,91	-6,06
						L-1 47	-6,12	-6,91
			9 BB-02	-7,93	-7,77	FP-1 26	-6,55	-5,82
	Reunion C2r.1n	2,128-2,148	8-9			CC1-06	-6,45	-5,90
	C2r.2r	2,148-2,581				CC1-05	-5,05	-5,48
			7 PB4-05	-8,60	-8,10			
			6			FP-1 23	-8,14	-7,25
						FP-1 22	-8,01	-6,78
						L-1 44	-8,85	-6,98
	GAUSS C2An.1n	2,581-3,032	5 PB4-04	-8,28	-8,60			
						VY-07	-8,19	-7,88
			4			FP-1 19	-7,95	-7,23
						VY-06C	-8,22	-7,41
						VY-06B	-7,88	-7,60
						FP1-I-01U	-7,95	-7,11
						FP1-I-01M	-7,93	-7,44
						FP1-I-01L	-7,75	-7,45
						CC1-04	-7,71	-8,01
	GAUSS C2An.1r	3,032-3,116				FP-1 12	-8,32	-7,91
						FP-1 11	-6,28	-6,81
						FP-1 9	-8,52	-7,85
						FP-1 8	-7,38	-6,83
	GAUSS C2An.2n	3,116-3,207	PB4-03	-8,51	-8,11			
			3					
						FP-1 6	-8,86	-8,35
						L-1 34	-7,82	-7,29
						BP-04	-8,75	-8,05
	GAUSS C2An.2r					BP-06	-7,06	-6,89
						CC1-03B	-8,18	-8,28
						CC1-03A	-7,93	-8,17
						FP-1 4	-8.40	-8.19
		3,330-3,207	2			FP-1 4A	-8.43	-8.15
	GAUSS C2An. 3n	3,330- 3,596				L-1 18	-7,52	-6,30
						L-1 17	-7,62	-7,12
						L-1 16	-7,76	-6,68
	GILBERT C2Ar					CC1-02A	-8,63	-9,55
			1 PB4-02	-8,35	-8,19			
			PB4-01B	-7,88	-7,92			
						L-1 5BIS	-7,71	-5,80
						L-1 5	-5,91	-5,05
						L-1 4	-6,54	-5,97
						L-1 3	-6,09	-5,39

				L-1 2	-6,44	-5,67
				L-1 1	-7,58	-5,28
				1 CC1-01	-8,50	-8,75