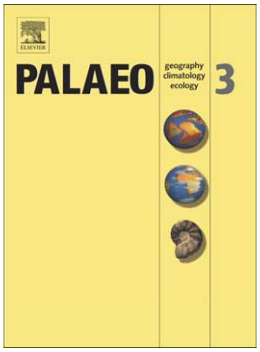

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Paleohydrological significance of trace fossil distribution in Oligocene fluvial-fan-to-lacustrine systems of the Ebro Basin (Spain)

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Abstract

The ichnological study of fluvial fan and lacustrine Oligocene deposits in the NE Ebro Basin has allowed the recognition of three ichnoassemblages having a strong correlation with depositional facies associations. Lacustrine deposits lack bioturbation due to the hydrologically closed character of the lake that caused hypersalinity and made it inhospitable for benthic life. Terminal lobe deposits of the fluvial fan, which were sedimented in low wetland areas around the lake, bear a moderately diverse ichnoassemblage dominated by horizontal *Taenidium barretti*, *Cochlichnus anguineus* and bird footprints (*Gruipeda* isp.). This assemblage can be assigned to the 'shorebird ichnofacies', a subset of the *Scoyenia* ichnofacies that characterizes the subaerial part of low-energy shore areas. Crevasse splay deposits in medial fluvial fan areas present a different assemblage also belonging to the *Scoyenia* ichnofacies. It includes most of the trace fossils found in the terminal lobes, except for the bird tracks, plus very abundant vertical burrows (*Taenidium barretti* and unnamed ornamented burrows). The presence of deep-tier traces of terrestrial invertebrates is consistent with the more proximal fan setting, having greater relief and consequently a lower mean groundwater position than lowland areas. Fluvial channels only bear irregularly clustered tunnel structures of unknown affinity formed after abandonment of the channel. Thus, trace fossil assemblages are mostly controlled by the position and fluctuations of water tables, which are the cause for their composite nature.

Keywords: Ichnology; *Scoyenia* ichnofacies; *Mermia* ichnofacies; Fluvial fan; Lake.

1. Introduction

Diverse factors control trace fossil assemblages in continental settings: grain size, plant cover, climate, availability of organic matter in the sediment, etc. Among them, paleohydrological parameters have a paramount effect on ichnofaunas. Thus, water chemistry in permanently subaquatic (lacustrine) settings has a direct effect on the diversity and composition of the ichnoassemblages, while the position and oscillations of the water table in permanently or temporarily subaerial settings control the type of tracemaking animals able to inhabit the substrate (e.g., Buatois and Mángano, 2004, 2007; Hasiotis, 2007). In fact, the position of the water table is the major factor governing the three continental archetypal ichnofacies currently accepted (e.g. Buatois and Mángano, 2007).

Water table fluctuations are especially important in low-gradient fluvio-lacustrine systems in which relatively small oscillations, due to fluvial discharge or lake expansion, may temporarily flood extensive areas. This is the case of the transition between fluvial fans and lacustrine systems in the Ebro Basin during the Paleogene. The Oligocene fluvial fans of the eastern Ebro Basin have been the subject of a recent sedimentological study focusing on their modes of transition with contemporaneous lacustrine systems (Sáez et al., 2007). Trace fossils are abundant and diverse in certain subenvironments of these depositional systems, which allows for detailed ichnological study.

The objectives of this paper are: (1) to fully describe for the first time the bioturbation in the deposits of medial to distal parts of the Oligocene Solsona-Sanaüja fluvial fan and their distal lacustrine equivalents; (2) to establish the correlation between trace fossil assemblages and sedimentary facies associations, contributing to the refinement of the sedimentary model proposed by Sáez et al. (2007); (3) to establish certain diagnostic features of such assemblages that may help to interpret similar sedimentary successions in core expression or small outcrops lacking information on depositional architecture; and (4) to discuss the significance of those trace fossil assemblages for the continental archetypal ichnofacies model.

2. Sedimentary setting: The Solsona-Sanaüja Fluvial Fan and the Noguera Lacustrine System

From the Late Eocene to the Late Miocene, the depositional setting of the Ebro Basin (NE Spain) was characterized by the development of fluvial fans attached to the basin margins grading distally into low-gradient, hydrologically closed, shallow lakes located in the central basin areas (Cabrera and Sáez, 1987; Arenas and Pardo, 1999; Luzón, 2005; Nichols and Fisher, 2007; Sáez et al. 2007) (Fig. 1A). The major factor controlling the sedimentary evolution of these sedimentary systems was thrusting and folding along the basin margins (Anadón et al. 1989). This was particularly intense in the northern margin, where the Pyrenean thrust front shifted about 100 km to the south during the Paleogene (Muñoz, 1992).

The Sanaüja area, which is the object of this study, is located in the central eastern Ebro Basin where the basin fill structure is characterized by NE-SW- and NW-SE-trending anticlines (Fig. 1B). These folds are linked to underlying Upper Eocene evaporites of the Cardona Formation, which acted as the main décollement level. The partial erosion of the anticlines provides excellent outcrops of medium to distal fluvial fan and lacustrine deposits. These occur at Sanaüja in a continuous, W-E oriented, 5 km-long exposure, which corresponds to the north flank of the Ponts-Calaf anticline (Fig. 1B).

The outcropping sedimentary succession corresponds to the distal parts of the Solsona-Sanaüja fluvial-fan, which constitutes a 600 km^2 fan, with a radius of about 35 km and northern provenance developed during the Paleogene (Sáez et al., 2007) (Fig. 1A). The overall stratigraphic organization constitutes a vertical superposition of several evaporite/carbonate lacustrine grey to white units, intercalated within red alluvial deposits (Fig. 2). They form a coarsening-upward megasequence resulting from the southward progradation of the fluvial fan, which was linked to the N-S advance of the Pyrenean thrust front and to the growth of hinterland catchment areas. Mammal and charophyte studies (Sáez et al. 1987; Anadón et al. 1992; Feist et al., 1994) and lithological mapping (Del Santo et al. 2000) cannot date the age of the studied sequence more precisely than Lower Oligocene. During the Early Oligocene a mid-latitude warm (tropical to subtropical) climate with a dry season characterized the eastern Ebro Basin (Solé and Porta, 1982; Sáez 1987, Cabrera and Sáez, 1987; Cavagnetto and Anadón, 1996).

Proximal to medial parts of the fluvial fan are composed of channel fill sandstones and conglomerates, crevasse-splay sandy deposits and floodplain red mudstones (Solsona Formation). Most of the channel fill deposits have ribbon geometry and show multistorey fill, incised basal scours, and low width/height ratio in transverse section. The distal part of the fluvial fan is dominated by tabular sandstone beds and red mudstones formed in the terminal lobes of the fan (Súria Formation) (Sáez, 1987; Sáez et al. 2007). Interbedded with the lobe deposits are lacustrine intervals that may include playa-lake evaporites (Barbastro Formation), deltaic sandstones and offshore carbonate siltstones (Torà Formation). Low-gradient and hydrologically closed conditions of the Noguera Lacustrine System favored frequent and important shifts of the lake shoreline. This fact combined with the fan progradation pulses, induced the formation of four coarsening-fining upward sequences recognized at the Sanaüja zone. Each of these sequences is made up of lacustrine and very distal fine-grained deposits passing vertically into sandy distal fluvial fan deposits and then again into lacustrine deposits (Fig. 2A) and represents progradation-retrogradation cycles of the fluvial fan system. Trace fossils studied here are recorded in sandy deposits from the third and fourth of these cycles (Fig. 2B).

The sedimentary model proposed by Sáez et al. (2007), based on the lithofacies analysis, includes two different scenarios depending on the lake water level (Fig. 3). During periods of low lake level, mudflats characterized by exposed surfaces and isolated ponds were well developed in the distal fringes of the fluvial fans. When water and sediment input from the fluvial fan increased, mudflats were replaced by prograding terminal lobes. In this scenario, composite terminal lobe progradation occurred in front of the fluvial active channels, resulting in a continuous sand fringe formed by coalescing terminal single lobe bodies (Fig. 3A). During high lake level conditions, floods from active fluvial channels built fluvial-dominated deltas at the lake shoreline. The delta systems included channel and mouth bar sandy deposits and offshore and interdistributary bay muddy deposits. Deltaic sandy deposits did not form a continuous sandy belt (Fig. 3B).

3. Invertebrate trace fossils

Among invertebrate trace fossils, *Cochlichnus anguineus*, *Taenidium barretti*, vertical burrows with bioglyphs and irregularly clustered tunnels are very abundant. The rest have been more rarely observed. Ichnotaxa are here listed in alphabetical order with those left in open nomenclature at the end.

3.1. Cochlichnus anguineus *Hitchcock, 1858 (Fig. 4A-C, 6B)*

Description. Small, regularly sinusoidal horizontal trails. They are preserved as full reliefs although they can be displayed as positive or negative epi- and hyporeliefs. The trace is very thin, never reaching more than 0.2 mm, although it can be rather long, up to several cm. Its wavy morphology is very regular with wavelength and amplitude fairly constant in each specimen. Wavelength (λ) ranges from 0.9 to 4.0 mm (average 2.0), while amplitude (A) varies from 0.2 to 0.7 mm (average of 0.4). Note that amplitude is used here as commonly used in mathematics; other authors (e.g., Elliot, 1985; Uchman et al., 2004) used it to refer to the distance between opposite wave crests measured perpendicularly to the main axis of the trace, which actually is twice the amplitude (2A). The λ/A ratio varies between 3.5 and 8.7 with an average of 5.7. The correlation coefficient between both parameters (r^2) is 0.77 (n=27). Occasionally, some specimens may lose the wavy pattern and grade into forms similar to *Helminthoidichnites*. Second-order sinuous meanders are seen only in one specimen; most of them show instead a rather rectilinear or gently curved overall morphology.

Remarks. Rindsberg (1994) considered that the ichnogenus *Cochlichnus* had to be used only for epigenic trails, and thus erected a new ichnogenus, *Cymataulus*, for endogenic dwelling burrows with the same regularly sinuous pattern although generally of rather short length. Later, Pickerill and Narbonne (1995) regarded *Cymataulus* as a junior synonym of *Cochlichnus*, an ichnogenus that should include both epigenic and endogenic trails as they are often impossible to distinguish. Although *Cochlichnus* is known both from continental and marine settings, marine specimens are usually larger (Stanley and Pickerill, 1998). Continental *Cochlichnus* have been seen in modern substrates (Moussa, 1970; Metz 1978). Although several insect larvae (Ceratopogonidae, Therevidae, Chironomidae) have been suggested as likely tracemakers, experiments demonstrate that nematode worms do produce this type of trails (see Uchman et al., 2004 for references).

3.2. Gordia *isp. (Fig. 4C) and* Helminthoidichnites *isp. (Fig. 4D)*

Description. Small simple and thin trails showing no definite meandering or sinusoidal pattern. They occur associated with *C. anguineus* and have a similar width (0.2-0.4 mm). They are most often rectilinear or gently sinuous (*Helminthoidichnites*) but in some cases may form loops (*Gordia*). Some *Helminthoidichnites* may be continuous with *Cochlichnus*.

Remarks. Helminthoidichnites and *Gordia* are thought to be produced in continental settings by nematodes or insect larvae (Uchman et al., 2004). Their association and even connection with *Cochlichnus* seem to confirm this assignation.

3.3. Scoyenia gracilis *White, 1929 (Fig. 4G)*

Description. Horizontal traces with external ornamentation consisting of short longitudinal ridges. These traces are not abundant. They have widths between 6 and 10 mm and are usually displayed as rectilinear or slightly curvy segments that are lost when they penetrate into the rock. The bioglyph consists of 2 to 4 mm-long and 0.2 to 0.4 mm-wide scratchmarks seen as ridges in the outer wall. Scratchmarks are as oblique as 20º to the axis of the trace and are arranged in transverse groups, resulting in apparent constrictions along the trace.

Remarks. Although the internally meniscate structure present in *Scoyenia* has not been observed, the scratchmark pattern is very characteristic and allows for ichnospecific assignation. *Scoyenia* is a common trace fossil in continental settings (e.g. Frey et al., 1984). It is most likely produced by an arthropod, probably an insect (see Retallack, 2000 for discussion).

3.4. Taenidium barretti *(Bradshaw, 1981) morphotype A (Fig. 4E, F)*

Description. Small, horizontal, meniscate, epichnial, hypichnial and endichnial traces. Their width remains constant in each specimen while variation among specimens is small between 0.7 and 3 mm, averaging 1.8 mm. Their trajectory is rectilinear to gently curved and only a few specimens show an inclined attitude in short portions of the trail. Differential weathering reveals clearly defined, alternatively sandy and muddy menisci only 0.2-0.3 mm thick. The menisci are arcuate or very rarely more chevron-like. In some cases they seem to be composed of sediment pellets that cause an outer knobby appearance. Real branching does not occur.

Remarks. Keighley and Pickerill (1994) reviewed the taxonomy of *Taenidium* and we follow here their proposal. These same authors showed that *T. barretti* is only found in continental settings, while other ichnospecies are typical of marine settings. Although in many occurrences *T. barretti* may be an order of magnitude larger that the material studied herein, some authors have described examples of similar size for this ichnospecies (Melchor et al., 2006; Minter et al., 2007). *T. barretti* records the activity of an infaunal invertebrate moving (and maybe feeding) through the sediment. Insect larvae and adults, as well as earthworms have been proposed as possible tracemakers for this type of backfilled traces in continental settings (references in Melchor et al., 2006); nevertheless more experimental work with modern organisms is needed for a more precise assignation.

3.5. Taenidium barretti *(Bradshaw, 1981) morphotype B (Fig. 5A, B)*

Description. Large, vertical, meniscate traces. Width ranges between 6 and 10 mm. Most of them are vertical and rather straight, only a few are horizontal or oblique. Menisci are commonly concave-up, indicating a predominantly upward movement. Menisci are thin and arcuate and do not exhibit differential weathering.

Remarks. These traces are significantly different from those described as morphotype A in being distinctly larger, predominantly vertical and having different menisci features. Nevertheless, they have the diagnostic features of *T. barretti*. Keighley and Pickerill (1994) do not consider attitude in regard to bedding to be a diagnostic ichnotaxobase for the ichnospecies, despite pointing out that most known occurrences corresponded to horizontal traces. An appropriate ichnotaxonomic treatment of this problem is beyond the scope of this paper, as it would need revision of material from other localities. However, as discussed below, both morphotypes are not only morphologically different but may have a different paleoecologic meaning. Such large vertical meniscate burrows are very likely produced by insects. O’Geen and Busacca (2000) described very similar traces as produced by modern cicada nymphs

(Homoptera), but other groups of insects such as coleopterans can produce similar structures.

3.6. Irregularly clustered tunnels (Fig. 5E)

Description. Vertical or inclined structures located in the upper part of thick sandstone (fluvial channel) beds, constituting a random cluster of smaller burrows. These structures typically have a length between 10 and 15 cm and a width between 6 and 12 mm. They are partly empty due to weathering and partly filled by irregularly clustered 1-to-3-mm wide burrows. There is no particular arrangement of these smaller elements but the overall morphology has been observed to be recurrent. In one case, a similar structure has been seen displaying a possible camerate morphology empty but surrounded by such smaller burrows.

Remarks. These structures are rather puzzling but their abundance, general morphological recurrence and particular facies distribution (see below) make them worth describing as a distinctive type of trace fossil. Neither their ichnotaxonomy nor their biotaxonomic affinities are clear. One possible interpretation would be that they were composite structures recording the burrowing activity of small invertebrates over a previously existing larger structure, such as a plant root or a larger invertebrate burrow. Alternatively, these structures are somewhat similar to traces interpreted as termite nests from the Upper Jurassic Morrison Formation (Hasiotis, 2003; Figure 23), although this interpretation has been challenged by Bromley et al. (2007). Hasiotis (2003) and Genise (2004) state that termite and ant nests bear tunnels and chambers, but the latter have not been recognized in our material. Thus, the affinity of these trace fossils remains unknown.

3.7. Vertical ornamented burrows (Fig. 5C, D)

Description. Vertical burrows with an external ornamentation of short longitudinal ridges. They are passively filled and vertical to steeply inclined. They are straight or slightly curvy. Diameter of the burrows ranges between 6 and 12 mm. Scratches are short (2-4 mm) and thin (about 0.2 mm). They are parallel to the burrow axis or slightly divergent (less than 15º) to both sides. Maximum observed length was 20 cm.

Remarks. Vertical burrows with bioglyphs such as those described herein have not been figured or described to the knowledge of the authors. Other continental traces bearing bioglyph sculptures are *Scoyenia* and *Steinichnus/Spongeliomorpha. Scoyenia* is commonly horizontal, displays a very different scratch pattern and has an internal meniscate backfill. *Steinichnus* is an open burrow system consisting mostly of horizontal elements (Bromley and Asgaard, 1979). The ichnogenus has been considered as a junior synonym of *Spongeliomorpha* (Ekdale et al., 1984; Metz, 1993). Our material is abundant, consistently vertical and it never displays any branches and thus, does not comply with the diagnostic features of *Steinichnus*/*Spongeliomorpha*. Hasiotis (2004) mentioned that *Camborygma* shafts may display longitudinal scratch marks. However, this crayfish-produced ichnogenus displays a whole array of other features (branching, chambers, knobby linings, etc.) not seen in our material. The bioglyph pattern is indicative of the digging activity of a multilegged animal, namely, an arthropod. Thus, these traces could represent dwelling burrows of crayfish (Decapoda) or more likely insects. Diverse insects are known to construct vertical dwellings similar to the those described herein (Bryson, 1939; Ratcliffe & Faggerstrom, 1980)

4. Vertebrate trace fossils

Four different types of footprints have been recognized in the Sanaüja section. Bird tracks are very common, while mammal footprints are much rarer.

4.1. Gruipeda *isp. (Fig. 6 A, B)*

Description. Bird footprints are very abundant and preserved both as epi- and hyporeliefs. They are small tetradactyl tracks, although the posterior toeprint is not always preserved. The central anterior toeprint is the longest (10-25 mm), while the two lateral ones are slightly shorter (7-20 mm). The angle between the central and lateral toeprints ranges between 55º and 70º. The imprint of the posterior digit, when present, is oriented backwards and it is smaller than those of the other three. No trace of interdigital web has been observed.

Remarks. Footprints similar to those described herein have been described from several Tertiary localities. Different ichnogenera have been used to designate them: *Charadriipeda* Panin and Avram, 1962 (see also Payrós et al., 2000; Astibia et al. 2007), *Gruipeda* Panin and Avram, 1962 and *Antarctichnus* Covacevich & Lamperein, 1970 (see also Doyle et al., 2000) .

Sarjeant and Langstrom (1994) (see also de Valais and Melchor, 2008) considered *Antarctichnus* and some *Charadriipeda* as synonyms of *Gruipeda*. They emmended the diagnosis of *Charadriipeda* to include only footprints with an interdigital web. This feature is absent in our material, which has to be assigned to *Gruipeda*.

4.2. Plagiolophustipus *cf.* montfalcoensis *Santamaría et al., 1990 (Fig. 6E, F)*

Description. Tridactyl, bilaterally symmetrical footprints with a larger central toeprint. Length of these tracks varies between 37 and 41 mm, while width ranges between 27 and 36 mm. The central digit print is larger and wider than the two lateral prints. These are similar in length and width and form an angle of approximately 25º-30º to the central digit.

Remarks. Similar trydactyl footprints from other Oligocene localities in the same basin were named *Plagiolophustipus montfalcoensis* by Santamaría et al. (1990; see also Prats and López, 1995). These authors attributed these type of traces to the paleotherid perissodactyl *Plagiolophus*.

4.3. Small artyodactyl footprints (Fig. 6C,D,F)

Description. Small didactyl footprints. These tracks are slightly longer (12-16 mm) than wide (11-14mm), and exhibit bilateral symmetry. Each one of the dactyl traces has a rounded posterior boundary and a more acute anterior end in which a claw-like imprint may be preserved. The two digit prints are commonly well separated and exhibit a slight forward divergence, thus the distance between the anterior tips ranges between 5 and 8 mm.

Remarks. Similar didactyl footprints have been described under several ichnogeneric names: *Pecoripeda* Vialov, 1965, *Entelodontipus* Casanovas and Santafé, 1982, and *Bifidipes* Demathieu et al., 1984. Discussion of the validity of these ichnogenera is beyond the scope of this paper, and so we prefer to use an informal open nomenclature to designate these trace fossil. Nevertheless, attribution of these traces to a small artyodactyl seems straightforward. Footprints with a similar morphology, but larger than those described herein, are known from other Oligocene localities in the Ebro basin (Casanovas and Santafé, 1982; Astibia et al., 1994, 2007). They have been described as *Entelodontipus* and assigned to the suiform *Entelodon* or to an animal of similar size and autopods. Antón et al. (1993, 2004) recorded smaller didactyl tracks from the Miocene of the Ebro Basin and considered them as produced by a cainotherid, a rabbit-size artyodactyl. This later interpretation could be also valid for the material from Sanaüja. *Cainotherium* body fossils (teeth) are known from several Oligocene localities located a few kilometers south of Sanaüja (Anadón et al., 1987).

4.4. Large indeterminate footprints (Fig. 6G)

Description. Vertical structures seen in cross-section that cut and deform beds. These structures tend to be columnar or discoid with diameters between 7 and 15 cm and heights between a few and 15 cm. They are typically filled with sand and bedding around them bows downward. Their basal part is in some cases rather flat.

Remarks. These structures are interpreted to be large mammal tracks. The weight of the animal and the moisture of the substrate would have resulted in such a deep penetration of the feet within the substrate. These traces have been seen only in vertical section, and without a bedding plane view it is not possible to assign them to any particular mammal group.

5. Trace fossil assemblages and depositional paleoenvironments

5.1. Lacustrine deposits

Three lacustrine facies associations, fully described in Sáez et al. (2007), are recognized in the Sanaüja area: (1) The e*vaporitic playa-lake association* occurs in cycles 1, 2 and 3. It consists of tabular, laminated-to-nodular, dm-thick gypsum beds organized in dm-to-m thick intervals that alternate with grey-blue and yellow mudstones. The nodular gypsum formed interstitially in the clayey sediments in marginal subaerial zones of the lake, whereas the laminated gypsum formed in saline subaqueous environments that experienced evaporative concentration alternating with clay deposition during floods. (2) *Deltaic facies* are identified in cycle 3. They are arranged in m-thick coarsening-upwards sequences consisting of (from base to top): (a) yellow to brown mudstones, (b) grey-yellow, tabular, dm-thick, fine-grained sandstones with climbing ripple and planar lamination, and (c) grey-yellow ribbon sandstones to sheet-like channelized sandstones with trough cross-bedding, flat lamination and rip-up clasts at the base (Fig. 2B). These facies are interpreted as interbay-prodelta, mouth bar and channel deposits, respectively, of a prograding fluvial-dominated delta. (3) The *offshore carbonate-rich lake association* occurs in the upper part of cycle 3 and the lower part of cycle 4 above deltaic facies (Fig. 2B). It consists of siltstone-dominated facies with variable carbonate content. The siltstone contains gypsum casts and chert nodules and may be finely laminated, massive, or display lenticular bedding of fine sand. Some carbonate-rich intervals show irregular and wavy stromatolitic lamination. These facies originated in a shallow lacustrine environment with an oscillating water level, and consequent saline and more diluted phases.

No trace fossils have been recognized in the lacustrine facies at Sanaüja (Fig. 7). Their absence in the evaporitic playa-lake facies is easy to explain as due to hypersaline conditions that typically prevented the existence of any benthic infauna, although some bioturbated lacustrine gypsum units are known elsewhere in the Ebro Basin (Rodríguez Aranda and Calvo, 1998; Ortí et al., 2003). Hypersalinity can also explain the apparent lack of bioturbation in the carbonate siltstones. Nevertheless, taphonomic factors may also have played a role as the homogeneous character of these facies does not favor preservation and recognition of trace fossils. Such taphonomic control can be ruled out in the heterolithic deltaic facies. Thus, the absence of bioturbation must be related to paleoecologic factors. The most likely scenario is that the colonization windows generated by freshwater discharges into the lake were too brief and local to allow for benthic colonization and subsequent bioturbation as hypersaline conditions of the body of water were rapidly reestablished after such events.

5.3. Distal fluvial fan (lakeshore) deposits

During periods of low lake level, sand transported into the distal parts of the fluvial fan did not reach the lacustrine area but was instead deposited in the form of terminal lobes in a muddy wetland surrounding the shore (Sáez et al., 2007). The terminal lobe facies association constitutes minor, meter-thick, coarsening- and/or fining-upward sequences formed by 10 to 20 cm thick, tabular sandstone beds, with a lateral extent ranging between 100 and 600 m. These sandstone beds are very well sorted with normal grading from very-fine or fine sand to very-fine-sand or silt. They show mainly climbing-ripple and planar lamination, although some layers may be structureless or bear discontinuous convolute lamination. The assemblage of features indicates that the sandstone layers were deposited by quasi-steady hyperpycnal turbidity currents, formed when sediment-laden fluvial flood discharges entered standing water bodies of lower density. Moreover, temporary shallow lakes where hyperpycnal turbidity currents occurred may have formed during peak flood conditions. Nevertheless, postdepositional inorganic structures indicating subaerial exposure, such as rain drop marks and desiccation cracks, often occur atop sandstone beds in medial and upper parts of the coarsening-upward sequences. Thus, sedimentary structures suggest underwater deposition of the sands in very shallow, ephemeral standing bodies of water that onlapped the fan toes during and immediately following flood events in distal fluvial fan areas followed by subaerial exposure due to water evaporation and/or infiltration.

The trace fossil assemblage associated to terminal lobe deposits (Fig. 7) is characterized by abundant horizontal *Taenidium barretti* (morphotype A) and common *Cochlichnus anguineus.* Other invertebrate traces include rare *Helminthoidichnites* isp. and *Scoyenia gracilis*. Bird tracks (*Gruipeda* isp.) are also very frequent in this setting, while other tracks produced by mammals (*Plagiolophustipus* cf. *montfalcoensis* and small artyodactyl footprints) are also recorded. The constituents of this ichnoassemblage are diverse and record short-term changes taking place in the area surrounding the lake. *Cochlichnus*, which was most likely produced by aquatic nematodes (see above), is most characteristic of permanently or ephemerally submerged trace fossil assemblages (see Buatois and Mángano, 2007 for an updated literature review). This distribution seems to include also modern *Cochlichnus*-like structures that occur in floodplain settings below a film of water (Moussa, 1970; Metz, 1978). Thus, the presence of this shallow-tier trace fossil may indicate subaquatic conditions from offshore lacustrine to situations with a water table just a few microns above the substrate. A similar paleohydrological setting can be interpreted for *Helminthoidichnites*, which is found in close association with *Cochlichnus* in the assemblages studied herein as well as in other published ichnological studies (see Buatois and Mángano, 2007). In contrast, meniscate traces such as *Taenidium barretti* are commonly regarded as produced in wet but not submerged settings (Keighley and Pickerill, 1994; Buatois and Mángano, 2007) probably by air-breathing animals. *Scoyenia gracilis* corresponds to bioturbation in drier firmgrounds (Buatois and Mángano, 2004), which allowed for the preservation of the digging sculpture, as indicated by their association with desiccation cracks (Fig. 4G). Finally, vertebrate tracks are best preserved in wet but unsaturated substrates (cf. Scrivner and Bottjer, 1986). Thus, the overall paleohydrological scenario deduced from bioturbation structures is consistent with a low-gradient lake margin, extremely sensitive to water table oscillations causing frequent exposure and submersion of large areas. *Cochlichnus* and *Helminthoidichnites* were probably produced under short-term, very shallow, subaquatic conditions related to expansion of the lake and/or flooding events due to fluvial discharges, while *Taenidium barretti* A and the vertebrate tracks were formed in a wet substrate after emersion. The rarity of the firmground *Scoyenia* indicates a predominance of wetgrounds in this environment.

5.4. Medial fluvial fan deposits

The medial fluvial fan deposits are composed of sandy channel-fill and crevasse splay facies alternating with red-mudstone-dominated floodplain facies. The channel-fill facies consists of very coarse- to fine-grained grey sandstone bodies displaying isolated ribbon geometries. They are up to 3.5 m thick and 30 to 500 m wide, with a multi-storey infill characterized by structureless and planar- or trough-cross bedded sandstones and mudstones. Downfan, the channel bodies show less incision and have a wider lateral extent (about 500 m) than in more proximal settings. Low-angle, sigmoidal cross stratification can be recognized as lateral accretion packages within the ribbon channel deposits. Crevasse-splay facies consist of tabular and graded, fine-grained sandstone beds, 10 to 20 cm thick, around 100-200 m wide, packed in 0.5 to 1 m thick intervals, showing locally intense bioturbation and remains of low energy current lamination.

Trace fossils in the fluvial channels are found in their uppermost part, and thus they correspond to colonization of sandy filled, abandoned channels. The only ichnofossils observed are irregularly clustered tunnels (Fig. 7). Nevertheless, although their facies restriction seems to point out a good correlation of this trace with specific paleoenvironmental conditions, the difficulty to assess the paleobiology of the trace prevents any further interpretation.

In contrast, crevasse splay facies host a variety of trace fossils (Fig. 7) including abundant vertical and horizontal *Taenidium barretti* (morphotypes B and A) and vertical ornamented burrows, but also common *Cochlichnus anguineus*, occasional *Gordia* isp. and *Helminthoidichnites* isp. and very rare indeterminate large vertebrate footprints. This assemblage shares several ichnotaxa with the one found in terminal lobe/lakeshore facies but shows important differences, most remarkably the abundance of vertical structures and the absence of bird footprints. Both the vertical *Taenidium barretti* and the vertical ornamented burrows were most likely produced by air-breathers (probably insects) and thus, their vertical penetration indicates unsaturated conditions in the first centimeters or decimeters of soil. This is consistent with the occurrence of this assemblage in the medial parts of the fluvial fan. The topographic altitudinal difference between medial and distal parts of the fan was probably responsible for the distribution of the vertical burrows. Their absence in distal facies may have been a consequence of the higher relative position of the water table in lowland areas that would have prevented the deep penetration of air-breathing animals. Hence, the whole assemblage found in crevasse-splay lobes is indicative of important fluctuations of the water level that would have been above ground during and shortly after the flood (subaquatic *Cochlichnus, Gordia* and *Helminthoidichnites*), near but below ground after the flood (*Taenidium barretti* A) and well below the ground in periods between floods (*Taenidium barretti* B and vertical ornamented burrows). The dominance of vertical structures indicates a dominantly lower water table than in the terminal lobes where these vertical traces are absent.

6. Discussion

6.1. Use of trace fossils to discriminate facies in fluvio-lacustrine transitions

Trace fossil assemblages in the fluvio-lacustrine system recorded in the Sanaüja section show a positive correlation with sedimentary facies associations corresponding to particular depositional subenvironments (Fig. 7). Thus, trace fossils are highly informative for paleoenvironmental interpretation as they complement and refine sedimentological data. Though the trace fossil assemblages share some elements, also have some diagnostic trace fossils. This is in part due to the fact that they are palimpsest assemblages that record changes in the position of the water table. Combining what we know about the tracemaker and paleoecology of each trace fossil, its facies distribution and the paleoenvironmental information derived from sedimentological data, we can differentiate 3 ichnosuites (~ichnocenoses) that reflect different paleohydrological scenarios (Fig. 8): (1) a *subaquatic ichnosuite* consisting of *Cochlichnus anguineus*, *Gordia* isp. and *Helminthoidichnites* isp. formed during episodes of submersion due to lake expansions or river floods in the lake shore or in ephemeral interchannel ponds respectively; (2) a *wetground, high-*

groundwater-level ichnosuite constituted by *Taenidium barretti* A, *Scoyenia gracilis*, and vertebrate footprints (*Gruipeda* isp., *Plagiolophustypus* cf. *montfalcoensis*, small artyodactyl footprints and large indeterminate footprints) recording emerged but poorly drained situations with a high water table preventing deep penetration of air-breathing invertebrates in lakeshore or interchannel overbank zones after flooding events; and (3) a *low groundwater ichnosuite* formed by vertical burrows (*Taenidium barretti* B and vertical ornamented burrows) produced in unsaturated soils in interchannel areas. A fourth ichnosuite would be composed exclusively of irregularly clustered tunnels structures produced in abandoned channels but their paleohydrological significance is uncertain.

Trace fossil assemblages in terminal and crevasse-splay lobes are the result of the combination and superposition of some of these ichnosuites as a consequence of oscillations of groundwater level, and thus they can record the overall paleohydrological scenario, which is related to sedimentary dynamics, topographic gradient and position relative to the lakeshore. The horizontal *Taenidium* ichnoassemblage is found in terminal lobe deposits of the distal fluvial fan and includes two overprinted ichnosuites: the subaquatic ichnosuite and the wetground ichnosuite. In contrast, the *vertical* Taenidium *ichnoassemblage* bears trace fossils corresponding to those two ichnosuites plus vertical structures recording a lower groundwater level. This is consistent with the most proximal position of this assemblage, which occurs associated to crevasse splay lobes in the medial fluvial fan. The higher topography of this setting allowed for periods of well aerated soils and deeper penetration of terrestrial invertebrates. Thus, the vertical burrows (*Taenidium barretti* B and vertical ornamented burrows) are diagnostic of the medial fluvial fan crevasse splay deposits and allow their differentiation from the similar terminal lobes. Nevertheless, there is also another difference. The terminal lobe deposits have abundant bird footprints, which are absent in the medial fluvial fan deposits. Those footprints can be assigned to shorebirds living in the wet, lowland areas near the lake.

The lacustrine deposits are devoid of any bioturbation. We could expect to find some traces belonging to the subaquatic ichnosuite which are known in other fossil examples from lacustrine deposits (see Buatois and Mángano, 2007). However, despite the diversity of lacustrine lithofacies (evaporitic, detritical, carbonatic), none of them produced any trace fossils. As discussed above, this can be explained by unfavorable conditions of the water, that is hypersalinity. The hydrologically closed character of the Paleogene lakes and the abundance of gypsiferous Triassic deposits in the catchments in the Ebro basin suggest that their water often had high salinities preventing the presence of benthic life.

The deltaic, terminal lobe (distal fluvial fan) and crevasse splay (medial fluvial fan) deposits are all heterolithic and bear similar sedimentological features. In the case we studied, the availability of extensive outcrops allowed recognition of their geometry and relations with other facies, which greatly contributed to their interpretation. Nevertheless, the discrimination of those same facies in core or limited outcrops may be difficult. In this case, trace fossils may be of great help. The Sanaüja section shows an increase of vertical structures in medial fluvial fan facies that are absent in distal fluvial fan facies.

This criterion of proximality (which is related to topographic gradient and position of groundwater) may be of help to interpret other similar successions.

6.2. Relation of the ichnoassemblages to archetypal ichnofacies

The study of continental trace fossils and ichnoassemblages has experienced an important development in the last decade. This has led to the development of the current continental ichnofacies model, which includes three archetypal ichnofacies (see Buatois and Mángano, 2007 for an updated review): (a) the *Mermia* ichnofacies (Buatois and Mángano, 1995) typifies assemblages dominated by horizontal grazing and feeding traces formed under low-energy, permanently subaqueous conditions such as those found in lakes; (b) the *Scoyenia* ichnofacies (Seilacher, 1967; Frey et al, 1984) consists mainly of meniscate structures that may be associated with vertical burrows, arthropod trackways and vertebrate footprints, and it is characteristic of low-energy settings affected by periodically subaerial or subaqueous conditions such as those found in lake margins, fluvial overbanks or even wet interdune areas; and (c) the *Coprinisphaera* ichnofacies (Genise et al., 2000) is characterized by coleopteran and hymenopteran nesting structures associated with paleosoils related to herbaceous communities.

The absence at Sanaüja of a trace fossil assemblage belonging to the *Mermia* ichnofacies is a common feature in hydrologically-closed lake systems where stressful conditions due to hypersalinity prevent benthic colonization in permanently subaquatic settings. In this type of lakes, trace fossils are characteristically found only along lake margins where bioturbation is dominated by the activity of terrestrial animals, and ichnoassemblages can be attributed to the *Scoyenia* ichnofacies (Buatois and Mángano, 2007). This lakeshore assemblage is recorded in the Solsona-Sanaüja fluvial fan by the trace fossils found in the terminal lobe deposits.

The trace fossil assemblages found in terminal lobe and crevasse splay deposits bear abundant meniscate structures (*Taenidium*), which are a diagnostic feature of the *Scoyenia* ichnofacies, but also *Cochlichnus*, *Gordia* and *Heminthopsis*, which are among the most common trace fossils of the *Mermia* ichnofacies. These composite assemblages are common in fluvial and fluviolacustrine settings due to high frequency of water table oscillations and some have chosen to talk about composite ichnofacies (Keighley and Pickerill, 2003; Kim et al., 2005). Nevertheless, other authors (Bromley and Asgaard, 1991; Gibert et al. 2007) accept that some recurrent palimpsest assemblages, such as the *Nereites* ichnofacies, may be considered as ichnofacies despite not recording one single ichnocoenosis. Thus, we prefer to consider these composite assemblages as belonging to the *Scoyenia* ichnofacies as they record a wetground setting with periods of exposure and submersion. Differences between the two assemblages (terminal lobe and crevasse-splay) are related to the different ranges of these groundwater oscillations. Thus, the abundance of vertical structures in the medial fluvial fan deposits is indicative of the existence of episodes in which the soil is mostly dry, while their absence in distal fluvial fan indicates an average higher position of the water table in areas closer to the lake. Another interesting feature is the distribution of bird footprints, which are abundant in the distal fan and absent in more proximal settings. Abundance of shorebird tracks is a common feature in numerous Cretaceous and Cenozoic lakeshore (and also intertidal) trace fossil assemblages. This led Lockley et al. (1994; see also Doyle et al., 2000) to distinguish a ‘shorebird ichnofacies’, which was defined as part of a proposal for a vertebrate ichnofacies model independent of the Seilacherian model. Later, Hunt and Lucas (2007) renamed this ichnofacies as the *Avipeda* ichnocoenose and consider it a temporal subset of the so-called *Grallator* ichnofacies. Nevertheless, typical assemblages include not only vertebrate footprints but also horizontal invertebrate trails, among which *Cochlichnus* is recurrently present. Thus, considering the complete assemblage of vertebrate and invertebrate traces, the ‘shorebird ichnofacies‘ can be considered as a subset of the *Scoyenia* ichnofacies (an ichnosubfacies for Melchor et al., 2006) or may even be upranked to an archetypal ichnofacies of the same hierarchy as the three currently accepted in continental settings. The latter would need detailed analysis of described examples and further discussion, which is beyond the scope of this paper.

7. Conclusions

1. Lacustrine deposits of the Oligocene Noguera Lacustrine System are devoid of bioturbation. This absence is very common in hydrologically closed (playa-lake) lacustrine deposits as a consequence of high salt content, which in the studied case was also favored by the arid climate and the presence of abundant Triassic evaporite deposits in the source areas. Trace fossils are absent not only in evaporitic lacustrine units but also in carbonates associated with small terrigenous deltaic systems confirming that conditions during those

intervals equally were unsuitable for a permanent resident benthic community. Possible freshwater windows linked to fluvial discharges were too short to allow benthic colonization.

2. The absence of ichnological features in lacustrine deposits contrasts with the abundance and diversity of trace fossils seen in the contemporaneous Solsona-Sanaüja fluvial fan deposits. Three different trace fossil assemblages have been recognized, that correlate very well with different facies associations, and which reflect different paleohydrological scenarios ultimately controlled by the oscillation and mean position of the water table.

3. Deposits from lowland areas around the lake, affected by periodic flooding but where water table was always very near the surface, display a composite trace fossil assemblage composed of small trails produced by aquatic organisms (*Cochlichnus*, *Helminthoidichnites*), shallow-tier horizontal traces produced by terrestrial invertebrates (*Taenidium barretti* A, *Scoyenia gracilis*), and bird and mammal footprints. They occur in terminal lobe deposits of the distal parts of the fluvial fan. This horizontal *Taenidium* ichnoassemblage can be considered as an example of the 'shorebird ichnofacies', a subset of the *Scoyenia* ichnofacies commonly found around low-energy shorelines (lacustrine, intertidal).

4. Medial fluvial fan deposits, where the sedimentation style was typically fluvial, present different trace fossil assemblages with a greater dominance of vertical structures as a consequence of a lower mean position of water table that allowed for a good aeration of the soil. Such a hydrological setting is consistent with the higher topography of the more proximal areas. A vertical *Taenidium* ichnoassemblage characterizes crevasse splay deposits. It includes

those ichnosuites present in terminal lobes, plus a third consisting of vertical insect burrows (*Taenidium barretti* B and vertical ornamented burrows). Nevertheless, shorebird footprints are absent and other vertebrate tracks more rarer than in the terminal lobe deposits. The assemblage belongs also to the *Scoyenia* ichnofacies and its composite nature is a consequence of water table oscillations. The ichnoassemblage bearing only irregularly clustered tunnels characterizes channel deposits; they occur atop these sandstone bodies and record colonization after channel abandonment.

5. The presence or absence of vertical structures produced by terrestrial invertebrates may be a good proxy to interpret paleohydrological conditions, and thus a good indicator or proximality-distality in fluvial fan systems.

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Figure captions

Figure 1. A. Simplified geological map of NE Spain showing the main Paleogene fluvial-fan systems on the margins of the Ebro Basin. The square indicates the area enlarged in B that corresponds to the Solsona-Sanaüja fluvial fan, the distal deposits of which are studied here. B. Schematic map of the Upper Eocene-Lower Oligocene units in the central area of the eastern Ebro Basin around Sanaüja.

Figure 2. A. General succession of the Paleogene deposits in Sanaüja comprising four coarsening-fining upward sequences corresponding to fluvial fan progradation-retrogradation cycles. B. Detailed log showing the well exposed succession of cycles 3 and 4 southeast of Sanaüja. Paleoenviromental interpretation and minor sequential arrangement of deposits are included.

Figure 3. Two transition modes in the distal part of the Solsona-Sanaüja fluvial fan. A. Low-lake level scenario: active fluvial-fan channels (white) spread out on a mudflat surface forming terminal lobes that coalesce to form a continuous sandy fringe in the distal fan area. B. High-lake level scenario: medial fluvial-fan active channels (white) reach the lake and thus, deltas are formed at the lake shore. Proximal and medial parts of the model are modified from Sáez et al. (2007) to eliminate distributary channel networks and to differentiating active and non-active parts of the fan following the recent discussion by North and Warwick (2007) about the fluvial fan model.

Figure 4. Invertebrate trace fossils from Sanaüja. A and B. *Cochlichnus anguineus*. C. *Cochlichnus anguineus* and *Gordia* isp. D. *Helminthoidichnites* isp. E. *Taenidium barretti* morphotype A. F. Detail of *Taenidium barretti*

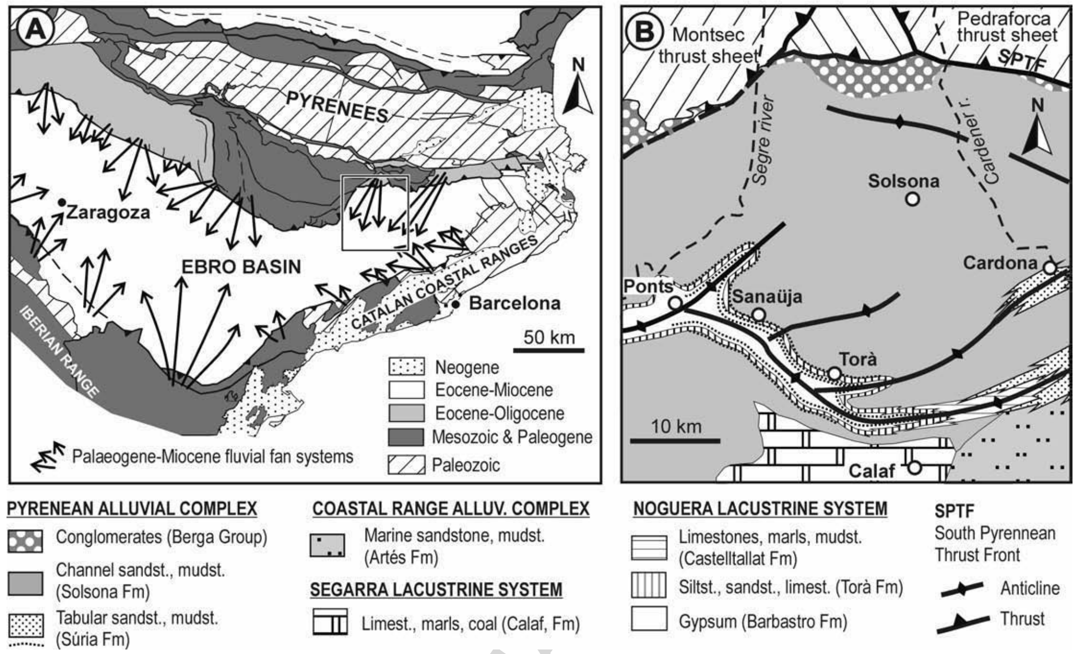
morphotype A displaying the internal meniscate filling and the outer irregular sculpture. G. *Scoyenia gracilis* associated with desiccation cracks.

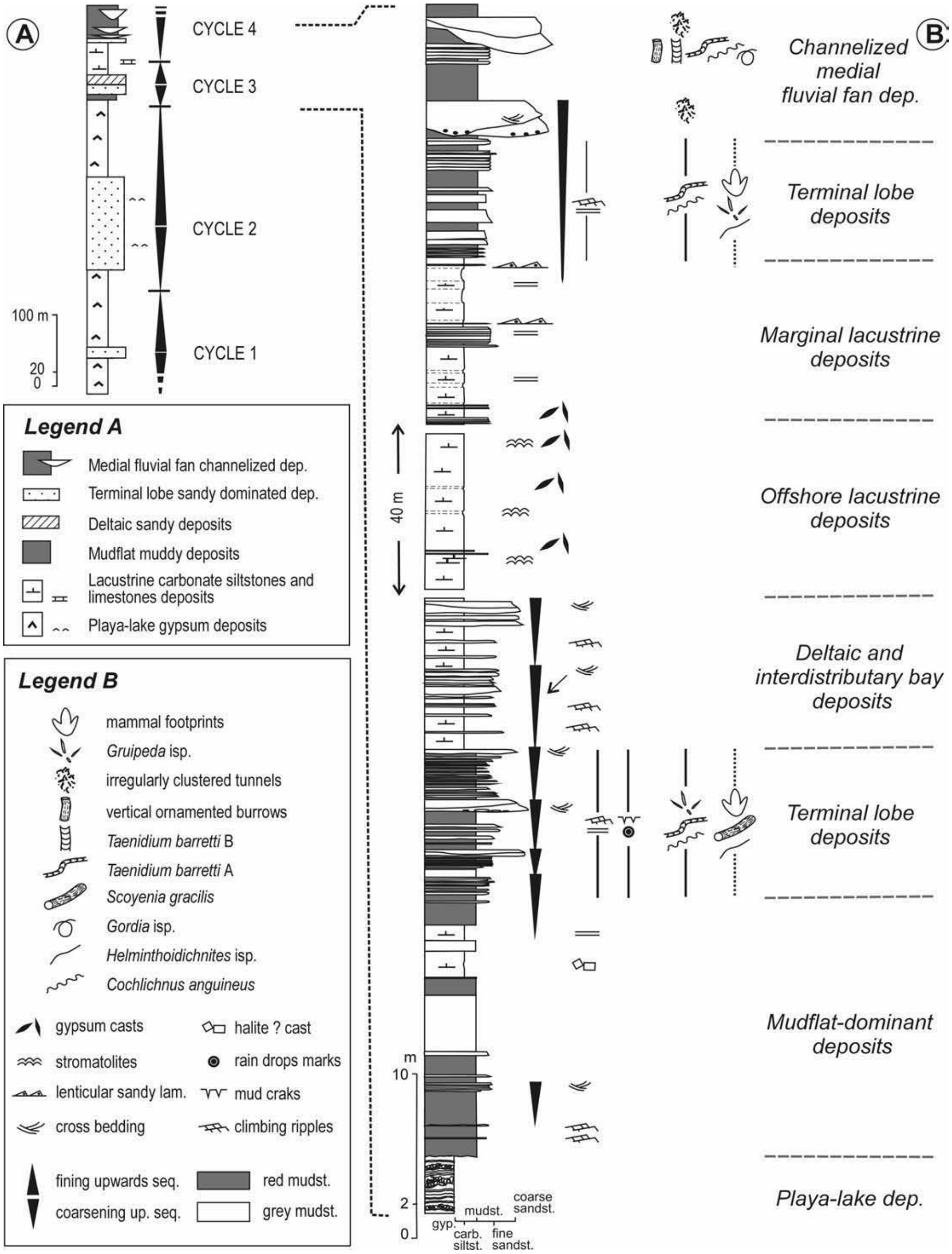
Figure 5. Invertebrate trace fossils from Sanaüja. A and B. *Taenidium barretti* morphotype B. C and D. Vertical ornamented burrows. E. Irregularly clustered tunnels.

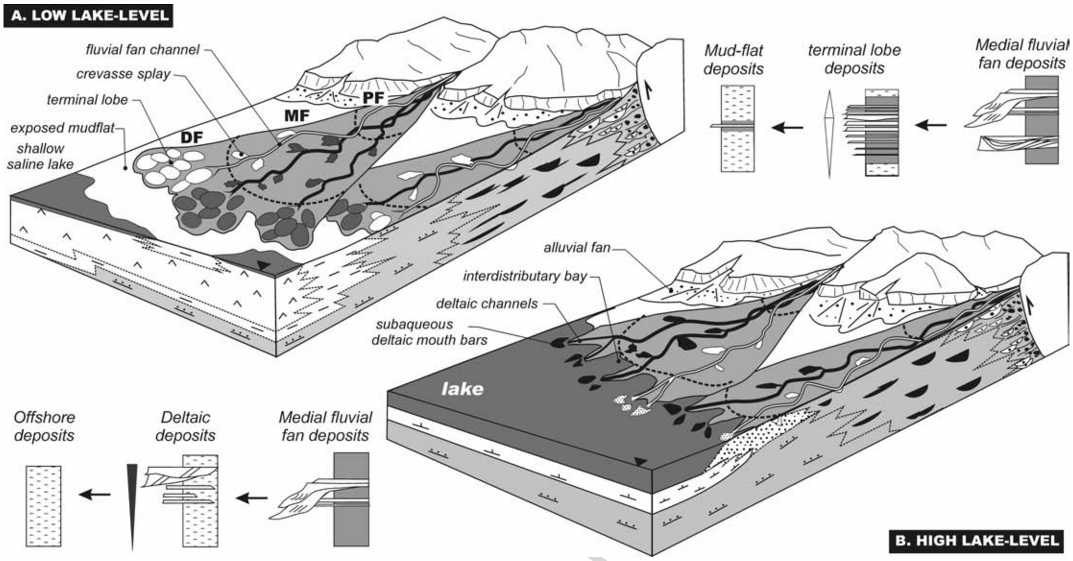
Figure 6. Vertebrate trace fossils from Sanaüja. A. *Gruipeda* isp. B. *Gruipeda* isp. associated with *Cochlichnus anguineus* and raindrop marks. C. Small artyodactyl footprints. D. Detail of the previous picture showing the presence of claw-like imprints in some of the tracks. E. *Plagiolophustipus* cf. *montfalcoensis*. F. *Plagiolophustipus* cf. *montfalcoensis* and small artyodactyl footprints.

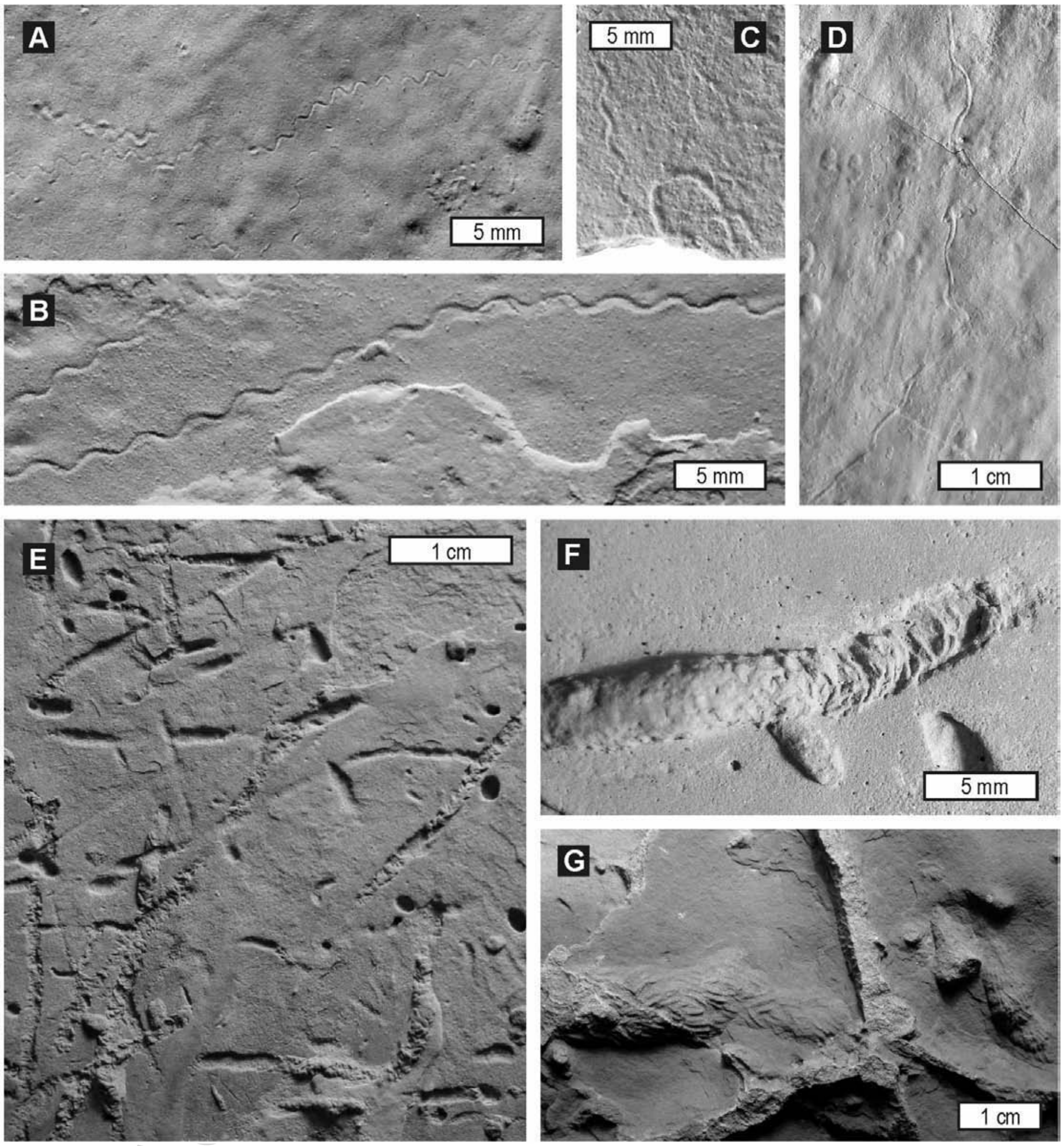
Figure 7. Trace fossil assemblages recognized at Sanaüja and their paleoenvironmental distribution during high and low lake level intervals.

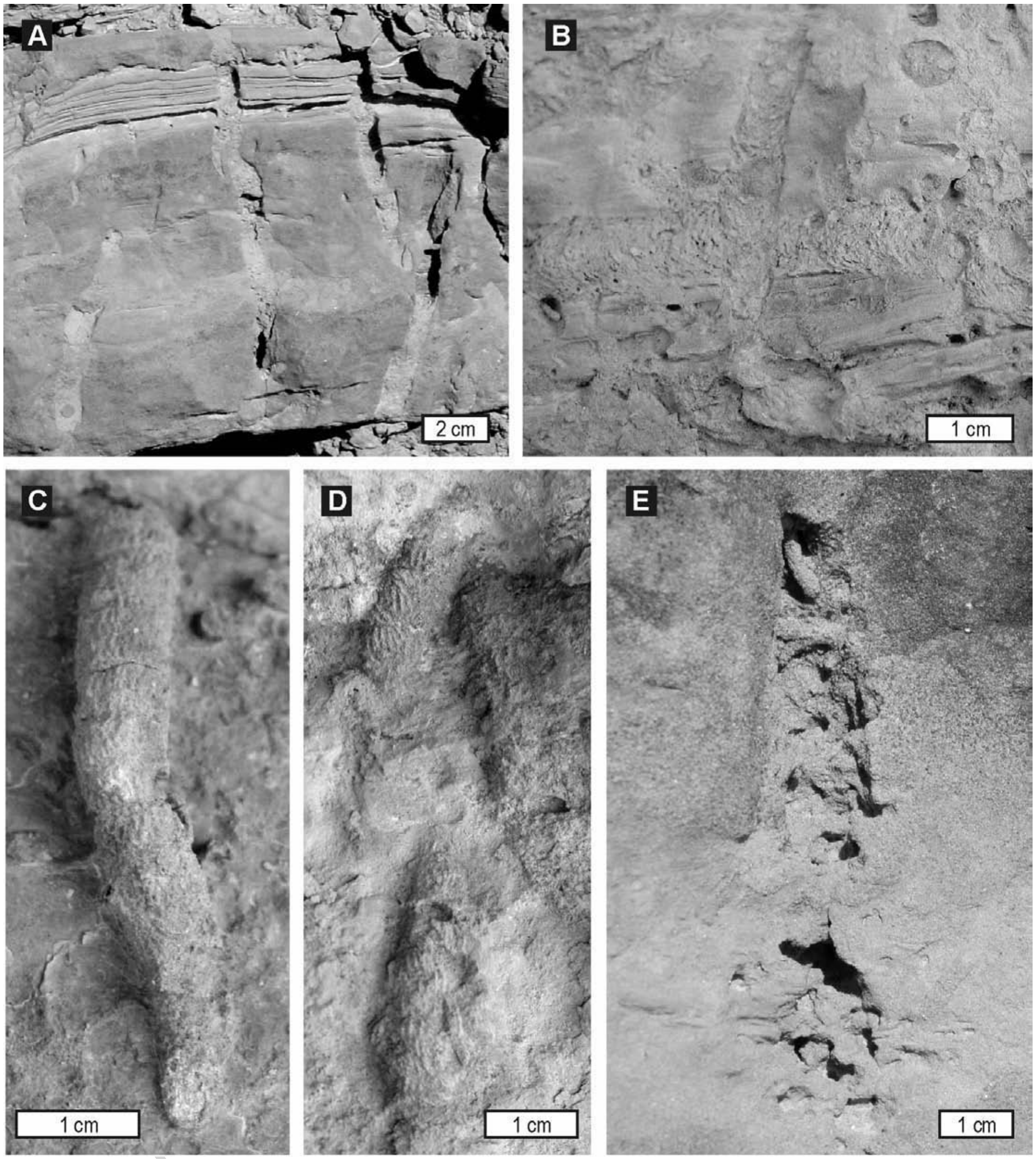
Figure 8. Paleohydrological scenarios inferred for the production and preservation of the traces found at Sanaüja. Legend of trace fossil is the same as in figure 2.

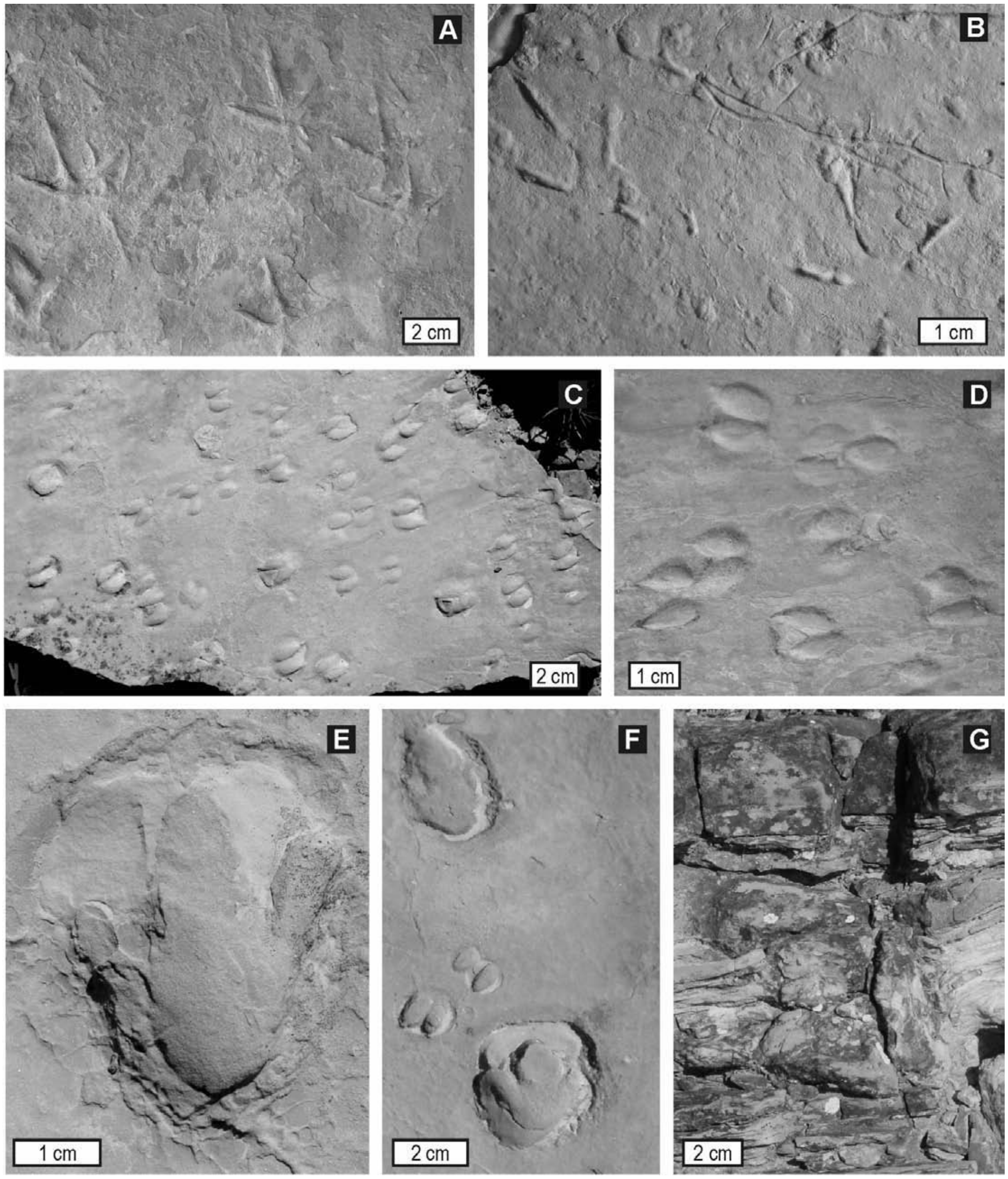

A
PYRENEES
Zaragoza
EBRO BASIN
CATALAN COASTAL RANGES
Barcelona
IBERIAN RANGE
N
50 km
Neogene
Eocene-Miocene
Eocene-Oligocene
Mesozoic & Paleogene
Paleozoic
Palaeogene-Miocene fluvial fan systems
B
Montsec thrust sheet
Pedraforca thrust sheet
SPTF
N
Segre river
Cardener r.
Solsona
Cardona
Ponts
Sanaüja
Torà
Calaf
10 km
PYRENEAN ALLUVIAL COMPLEX
Conglomerates (Berga Group)
Channel sandst., mudst. (Solsona Fm)
Tabular sandst., mudst. (Súria Fm)
COASTAL RANGE ALLUV. COMPLEX
Marine sandstone, mudst. (Artés Fm)
SEGARRA LACUSTRINE SYSTEM
Limest., marls, coal (Calaf, Fm)
NOGUERA LACUSTRINE SYSTEM
Limestones, marls, mudst. (Castelltallat Fm)
Siltst., sandst., limest. (Torà Fm)
Gypsum (Barbastro Fm)
SPTF
South Pyrennean Thrust Front
Anticline
Thrust

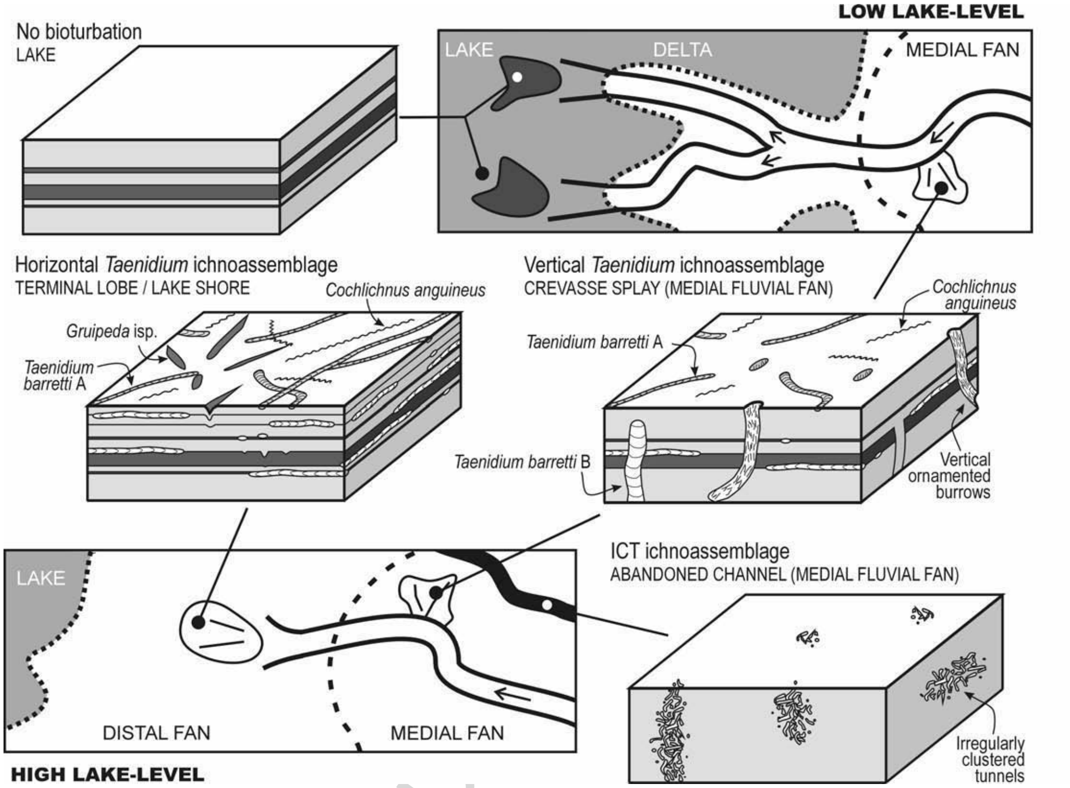

A
CYCLE 4
CYCLE 3
CYCLE 2
CYCLE 1
100 m
20
0
Legend A
Medial fluvial fan channelized dep.
Terminal lobe sandy dominated dep.
Deltaic sandy deposits
Mudflat muddy deposits
Lacustrine carbonate siltstones and limestones deposits
Playa-lake gypsum deposits
Legend B
mammal footprints
Gruipeda isp.
irregularly clustered tunnels
vertical ornamented burrows
Taenidium barretti B
Taenidium barretti A
Scoyenia gracilis
Gordia isp.
Helminthoidichnites isp.
Cochlichnus anguineus
gypsum casts
halite ? cast
stromatolites
rain drops marks
lenticular sandy lam.
mud craks
cross bedding
climbing ripples
fining upwards seq.
coarsening up. seq.
red mudst.
grey mudst.
B
Channelized medial fluvial fan dep.
Terminal lobe deposits
Marginal lacustrine deposits
Offshore lacustrine deposits
Deltaic and interdistributary bay deposits
Terminal lobe deposits
Mudflat-dominant deposits
Playa-lake dep.
40 m
m
10
2
0
gyp.
carb. siltst.
mudst.
fine sandst.
coarse sandst.

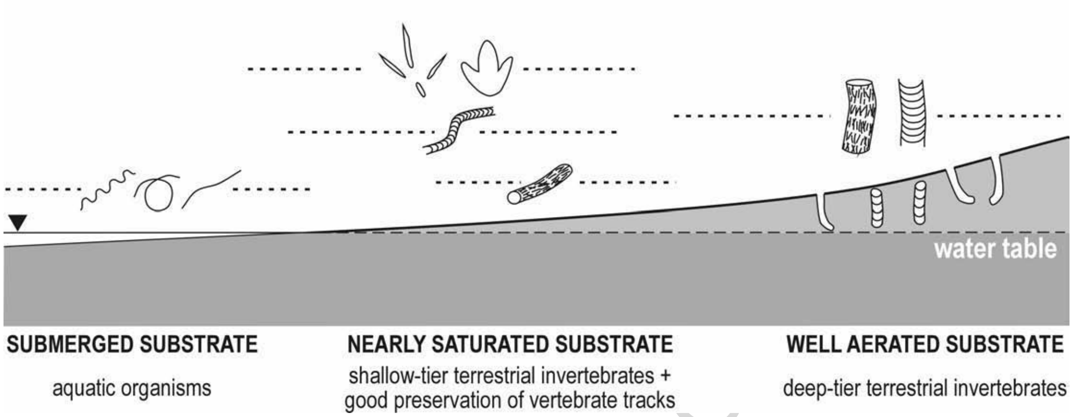

A. LOW LAKE-LEVEL
fluvial fan channel
crevasse splay
terminal lobe
exposed mudflat
shallow saline lake
DF
MF
PF
Mud-flat deposits
terminal lobe deposits
Medial fluvial fan deposits
alluvial fan
interdistributary bay
deltaic channels
subaqueous deltaic mouth bars
lake
Offshore deposits
Deltaic deposits
Medial fluvial fan deposits
B. HIGH LAKE-LEVEL


A
5 mm
5 mm
C
D
B
5 mm
1 cm
E
1 cm
F
5 mm
G
1 cm


A
2 cm
B
1 cm
C
1 cm
D
1 cm
E
1 cm


A
2 cm
B
1 cm
C
2 cm
D
1 cm
E
1 cm
F
2 cm
G
2 cm


LOW LAKE-LEVEL
No bioturbation
LAKE
LAKE
DELTA
MEDIAL FAN
Horizontal *Taenidium* ichnoassemblage
TERMINAL LOBE / LAKE SHORE
Cochlichnus anguineus
Gruipeda isp.
Taenidium barretti A
Vertical *Taenidium* ichnoassemblage
CREVASSE SPLAY (MEDIAL FLUVIAL FAN)
Cochlichnus anguineus
Taenidium barretti A
Taenidium barretti B
Vertical ornamented burrows
ICT ichnoassemblage
ABANDONED CHANNEL (MEDIAL FLUVIAL FAN)
LAKE
DISTAL FAN
MEDIAL FAN
HIGH LAKE-LEVEL
Irregularly clustered tunnels


water table
SUBMERGED SUBSTRATE
aquatic organisms
NEARLY SATURATED SUBSTRATE
shallow-tier terrestrial invertebrates +
good preservation of vertebrate tracks
WELL AERATED SUBSTRATE
deep-tier terrestrial invertebrates