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The Upper Eocene South Pyrenean Coastal Deposits (Liedena Sandstone, Navarre): Sedimentary Facies, Benthic Foraminifera and Avian Ichnology

Aitor **Payros**, Humberto **Astibia**, Alejandro **Cearreta**, Xabier **Pereda-Suberbiola**,
Xabier **Murelaga** and Ainara **Badiola**, Bilbao

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CONTENTS

SUMMARY

During the 1960's and the 1970's the Liedena Sandstone was a type deposit for "flysch-like facies" (sandstone and lutite alternations) of coastal sedimentary systems. However, the depositional system of these beds was never accurately defined. The sedimentological analysis along 100 km of outcrops in the western part of the South Pyrenean Zone (Navarre) allows these peculiar facies to be assigned to a mixed intertidal flat. Furthermore, sandy beach facies, different types of heterolithic, backbarrier deposits and conglomeratic, fluviatile facies have been recognized associated with these intriguing deposits. Generally, a northwestward-facing barrier-island system or wave-dominated delta was the likely depositional environment.

The benthic foraminiferal assemblage in the intertidal deposits exhibits the typical characteristics of a marginal marine environment: extremely high dominance of one species (*Pararotalia inermis*), low species diversity, and a hyaline dominance with discrete amounts of miliolids. Furthermore, the most abundant species indicates that the Liedena Sandstone was deposited during the Late Eocene.

Abundant footprints of aquatic birds are known in the tidal flat deposits. Six morphotypes have been distinguished: two (types 1 and 2) are ciconiiforme-like; type 1 is here assigned to a new ichnotaxon, *Leptoptilostipus pyrenaicus* and is one of the oldest occurrences of Ciconiiforme-like ichnites in the fossil record. Two other morphotypes (5 and 6) are similar to those of the Charadriiformes and are referred to as *Charadriipeda*. Finally, the affinities of the two remainder morphotypes (3 and 4) are unclear; they could have been made by Charadriiformes.

Synsedimentary tectonic activity controlled the evolution of the depositional system, as the area of deposition of the Liedena Sandstone was progressively incorporated into the active thrust sheets of the Pyrenean Orogen during the Late Eocene. The structural uplift and the large amount of sediments derived from the adjacent highlands induced progradation of the depositional system and the definitive retreat of the sea from the South Pyrenean Zone.

1 INTRODUCTION

The siliciclastic deposits of ancient coastal sedimentary systems are of great geological interest. Firstly, they are the best indicators of the boundaries between the emerged and marine areas and their importance for palaeobiogeographical reconstructions is obvious (e.g. SMITH et al., 1994). Also, they record accurately transgressive and regressive events throughout the stratigraphic record (POSAMENTIER & VAIL, 1988). Finally, these deposits are of great economic value as they are "sources of silica sands, refractories and heavy minerals, act as hosts to uranium mineralisation, and form excellent reservoir rocks for hydrocarbons" (HEWARD, 1981, p. 247). For

Address for all authors: Universidad del País Vasco/Euskal Herriko Unibertsitatea, Facultad de Ciencias, Departamento de Estratigrafía y Paleontología, Apartado 644, E-48080 Bilbao. Fax: +34 94 464 85 00; e-mail: gpppaaga@lg.ehu.es

these reasons, special attention has been paid during the 1960's and 1970's in the adequate characterization of ancient coastal deposits. In this respect, MANGIN's work (1962) on the study of the Eocene Liedena Sandstone in the western part of the South Pyrenean Zone (Navarre) had a considerable impact. This author described flysch-like alternations of sandstones and lutites and emphasized the coexistence of turbiditic structures, hitherto interpreted as exclusive of "bathyal environments", and of well-preserved bird footprints, regarded as "indicative of littoral or neritic environments". This interpretation was not widely accepted, but the Liedena Sandstone became later a reference deposit to recognize or reinterpretate other similar formations as coastal sedimentary systems (see, among others, PLAZIAT, 1964; PANIN, 1964; BEAUDOIN & GIGOT, 1970; ROEP et al., 1979). Moreover, MANGIN (1962) was one of the pioneer workers with regard to the sedimentological interpretation of the bird tracks.

The interest raised by MANGIN's (1962) work led to a number of new investigations on the Liedena Sandstone (RAAF, 1964; RAAF et al., 1965; PUIGDEFABREGAS, 1975; GRÜNIG, 1977, 1985; LEON-CHIRINOS, 1985). Some of this research was made as part of comprehensive stratigraphical studies and other work dealt with local aspects of the matter. However, the deposits that were used as a facies model were not studied from a palaeoenvironmental perspective. On the other hand, the well-preserved bird footprints of the Liedena Sandstone were illustrated in a number of geology books, but no detailed ichnological analysis was ever published. In order to fill this gap, we have carried out a sedimentological and palaeontological study of the Liedena Sandstone. In this paper, we report on: (a) the general geology of the studied area, including some new mapping that shows that the Liedena Sandstone should be extended 35 km westwards; (b) sedimentological analysis over 100 km of a stretch of outcrops as a mean to recognize different sedimentary palaeoenvironments and to accurately attribute the flysch-like facies described by MANGIN (1962) and RAAF (1964) to a precise depositional setting; (c) the study of the micropalaeontological content (benthic foraminifera) of the flysch-like deposits; (d) the systematical study of the bird tracks (ichnology); and finally, (e) the proposal of a depositional model for the Liedena Sandstone based on the sedimentological and palaeontological data.

2 GEOLOGICAL SETTING

The current distribution of the Eocene rocks in the South Pyrenean Zone shows the geometry of the basin in which they were deposited (Fig. 1A). During the Eocene, the South Pyrenean Basin was a NW-trending narrow marine gulf opening to the Bay of Biscay. It was a complex foreland basin stretching parallel to the front of the tectonically rising Pyrenean axial zone (PLAZIAT, 1981; PUIGDEFABREGAS et al., 1992). The foreland basin was progressively incorporated into the southward propagating thrust-sheets and became part of the emergent orogen. The tectonic uplift was diachronous, beginning in the east and extending to the west. Consequently, when the eastern areas of the South Pyrenean Basin were emergent, the western areas remained submerged.

This complex tectonosedimentary evolution is clearly recorded in the shallowing-upward Eocene stratigraphic succession of the studied area: deep-water turbidites of the flysch stage of foreland-basin development are overlain by shallow-marine deposits attributable to the molasse stage (MUTTI et al., 1972; PUIGDEFABREGAS, 1975; PAYROS et al., 1999) (Figs. 1B, 2). The Liedena Sandstone forms part of the upper molasse facies. These deposits are limited to the western area of the South Pyrenean Zone and represent the final deposits which show a marine influence in this region; the equivalent deposits to the east were deposited by a braided fluviatile system (Martes and Biban formations of PUIGDEFABREGAS, 1975). The palynological analysis of ORTI et al. (1986) of the underlying deposits shows that the Liedena Sandstone could be as old as Late Eocene, but an Early Oligocene age has also been proposed (RAAF, 1964; RAAF et al., 1965).

PUIGDEFABREGAS (1975) included the Liedena Sandstone within the Gendulain Formation, which is divided into three distinct members (Fig. 2): the lower member consists of about 100-150 m of evaporites (anhydrite, halite, carnallite and sylvite) alternating with euxinic marls deposited in restricted marine troughs (ORTI et al., 1985, 1986; CENDON et al., 1998); the middle member is composed of 50-100 m of laminated red marls, with gypsum layers and calcite crusts with halite moulds, probably deposited in sabkha environments (LEON-CHIRINOS, 1985); the upper member corresponds to the Liedena Sandstone. The upper boundary of the Liedena Sandstone is gradational into the overlying Oligocene terrestrial formations (PUIGDEFABREGAS, 1975). Here, all the beds showing the features described below have been considered to belong to the Liedena Sandstone.

3 SEDIMENTOLOGY

In order to interpret correctly the sedimentology of the flysch-like deposits described by MANGIN (1962) and to define them accurately, all the outcrops of the Liedena Sandstone were studied, including those with different facies. The Liedena Sandstone crops out in four geographical areas isolated from each other: Urbasa, Biurrun-Undiano, Izaga and Liedena-Javier (Fig. 1B). Most of the previous works only focused on the latter two areas and, therefore, showed only a partial view of the sedimentary system as interpreted here.

The thickness of the stratigraphic successions varies approximately from 60 to 120 m. The deposits are mainly sandstones with more than 90% of fine to medium-sized quartz grains, but mica, feldspar, bioclasts, quartz granules and pebbles also occur in variable quantities. The cementation of the sandstones is essentially calcareous, but it is variable from site to site; in the Urbasa and Biurrun-Undiano areas, where the weathering and leaching is stronger, the sandstones are only lightly cemented. The colour of the rocks differs from light grey to red, the latter being dominant

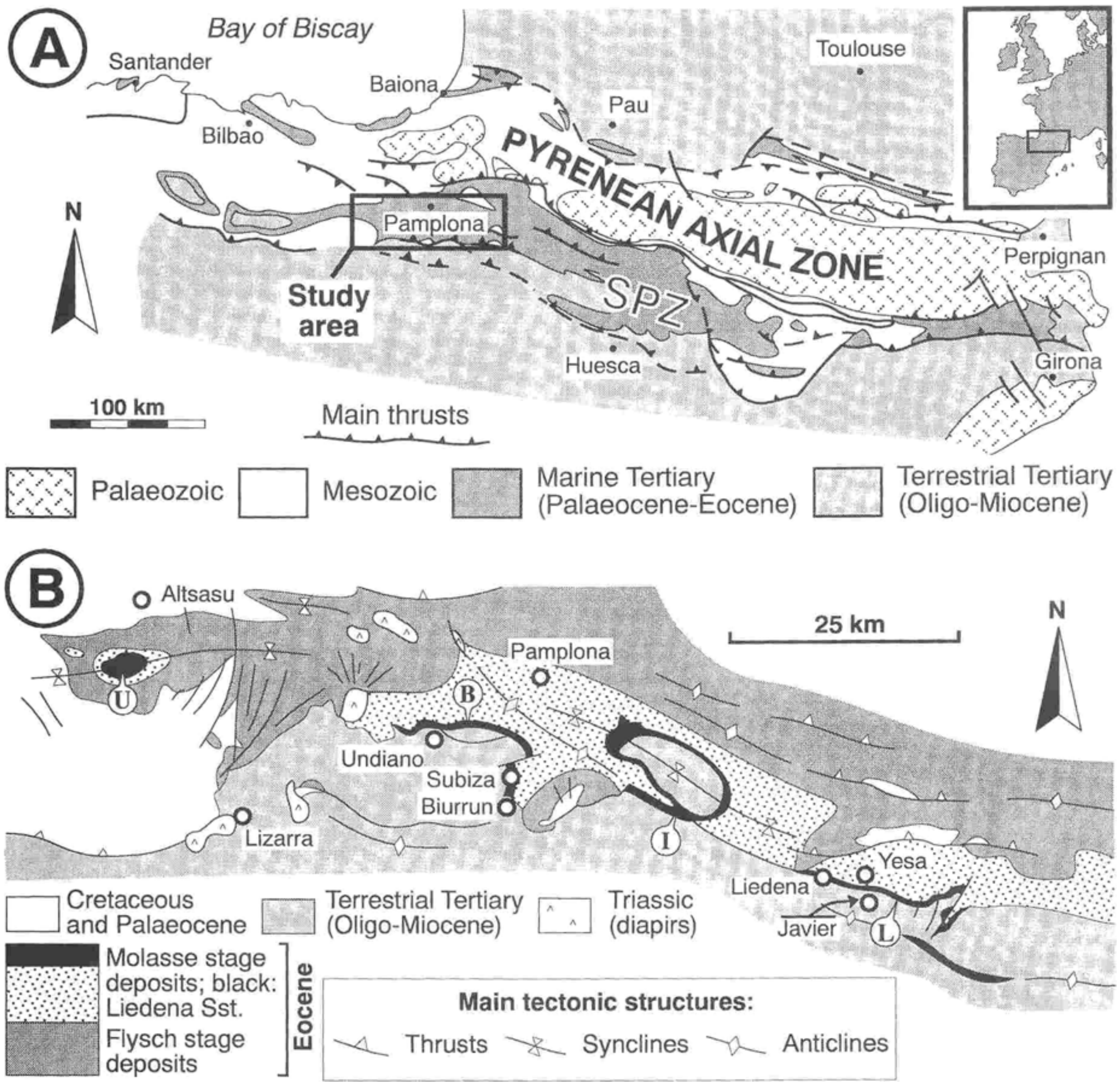


Fig. 1. (A) Outcrop map of the Pyrenees (SPZ: South Pyrenean Zone). (B) Simplified geological map of the study area in the western part of the South Pyrenean Zone. Encircled letters correspond to the four outcrop zones of the Liedena Sandstone: U: Urbasa; B: Biurrun-Undiano; I: Izaga; L: Liedena-Javier. Localities referred to in the text are shown in Figs. 1B and 4.

in the sections where the weathering is greater. The sandstone beds show generally sheet or linear geometries, 0.05-3 m in thickness. Other lithologies, which are of variable importance depending on location, are conglomerates, siltstones, lutites, marls and gypsum. All these deposits are arranged in a thinning and fining-upward sequence.

On the basis of the lithological and petrological characteristics, the sedimentary structures and the fossil assemblage, it is possible to differentiate three facies associations: (A) sandy beach facies association; (B) heterolithic, backbarrier facies association; and (C) conglomeratic, fluviatile facies association.

3.1 Facies association A: sandy beach deposits

The best outcrops and the most complete and thickest series are situated in the eastern part of the Biurrun-Undiano area, where five types of facies can be differentiated (Fig. 3, Pl. 19/1). From bottom to top, they are: (A1) lutites with tempestitic sandstones; (A2) sandstone and lutite alternation with load casts and convolute lamination; (A3) wave-rippled sandstones; (A4) parallel-laminated sandstones; and (A5) cross-bedded sandstones.

3.1.1 Facies A1: Lutites with tempestitic sandstones

Description: The main bulk of deposits are grey to reddish lutites. The faunal content is scarce because of intense leaching, but some layers have yielded very poorly preserved ostracods and benthic foraminifera. Locally, the lutites show strong bioturbation, but the original horizontal lamination (composed of milimetric clay and silt laminae) is preserved. Interbedded with the lutites are layers, 2-20 cm thick, of fine-grained micaceous sandstones (Fig. 3, Pl. 19/

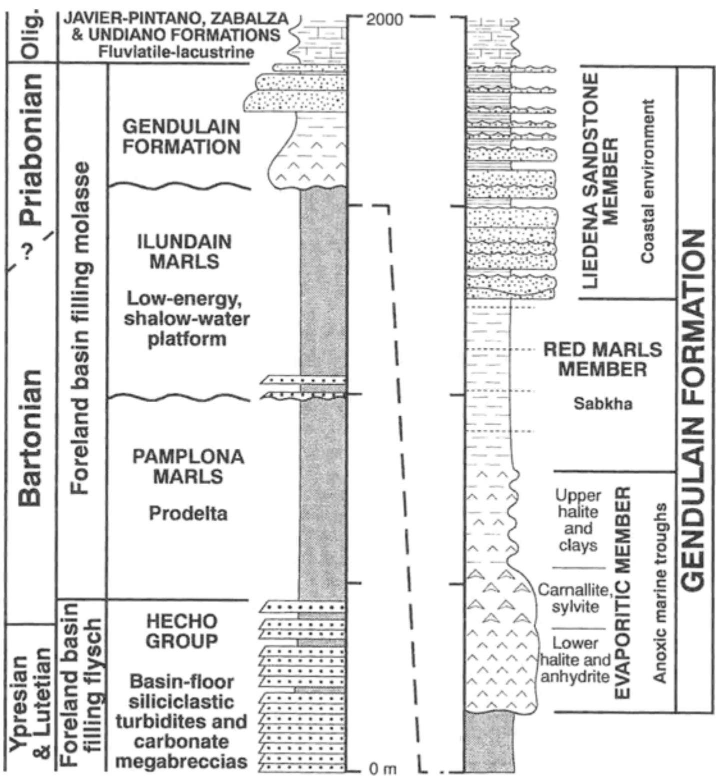


Fig. 2. Representative columnar section of the Eocene succession in the study area, with its constituent lithostratigraphic units and the depositional environments so far proposed in the literature (based on Mutti et al., 1972; Puigdefabregas, 1975; Orti et al., 1985; Leon-Chirinos, 1985; Cendon et al., 1998; and our own data). The Upper Eocene Gendulain Formation, where the Liedena Sandstone is included, is enlarged on the right.

2). The lower boundaries of the sandstones are sharp and have occasional sole-marks. On the basis of the internal structures, two types of sandstone beds are recognized: some beds show grain-size grading associated with parallel and current cross-lamination; the other beds have undulating parallel to low-angle cross-lamination, with symmetrical oscillatory ripples at the top. Some sandstone beds display load casts, convolute lamination and other soft-sediment deformation structures, making it difficult to ascribe them to any of the two types. In addition to these, there are occasional massive sandstone beds up to 1 m thick, with irregular bottoms and which are channel-like in shape and are without well-defined internal structures. Palaeocurrents, determined from sole marks, cross-laminae, channel axes and crest directions of symmetrical ripples on sandstones, indicate a transport orientation of N 140° E; the preferential orientation is to the NW but the degree of variation is important (Fig. 3).

Interpretation: The deposits of this facies are interpreted as those of a relatively low-energy marine setting, because of the predominance of lutites. However, the sandstones layers show sedimentary structures typical of storm episodes (Allen, 1984; Myrow & Southard, 1996). Thus, facies A1 formed below fair-weather wave base but above storm wave base in the transition between lower shoreface and offshore zones (McCubbin, 1982; Reading & Collinson, 1996).

3.1.2 Facies A2: Sandstone and lutite alternation with load casts and convolute lamination

Description: This facies displays a coarsening and thickening-upward sequence, with lutites and thin sandstones at the bottom and thick sandstone layers (up to 1 m) at the top (Fig. 3). Observation of original sedimentary structures is difficult because of the abundance of load casts in the sandstone layers, which in places form pseudonodules and ball-and-pillow structures. Moreover, the sandstones show contorted internal bedding and large-scale convolute lamination. Despite postdepositional deformations, some synsedimentary structures such as trough cross-lamination, wave-ripple cross-lamination (Raaf et al., 1977) and subhorizontal burrow fills are preserved. There are sporadic carbonized remains of wood.

Interpretation: Deformational structures of poor-consolidated sediments form in a large variety of sedimentary environments; they indicate a high sedimentation rate and the occurrence of instabilities leading to liquefaction (Allen, 1984). The interpretation of facies A2, based entirely on its position between facies from the lower and upper parts of the shoreface (facies A1 and A3), is that it is transitional between them.

3.1.3 Facies A3: Wave-rippled sandstones

Description: Vertical changes are observed in this facies. At the bottom it consists of sandstones, 15-20 cm thick, with alternating wave-ripple cross-lamination (Fig. 3, Pl. 19/3) and convolute lamination, although postdepositional deformational structures become scarce upwards. Some thin layers of lutites have occasionally been observed. Quartzitic sandstones with climbing wave ripples are dominant in the middle part of facies A3 and locally thin lutitic partings drape the troughs between adjacent wave ripples (flaser

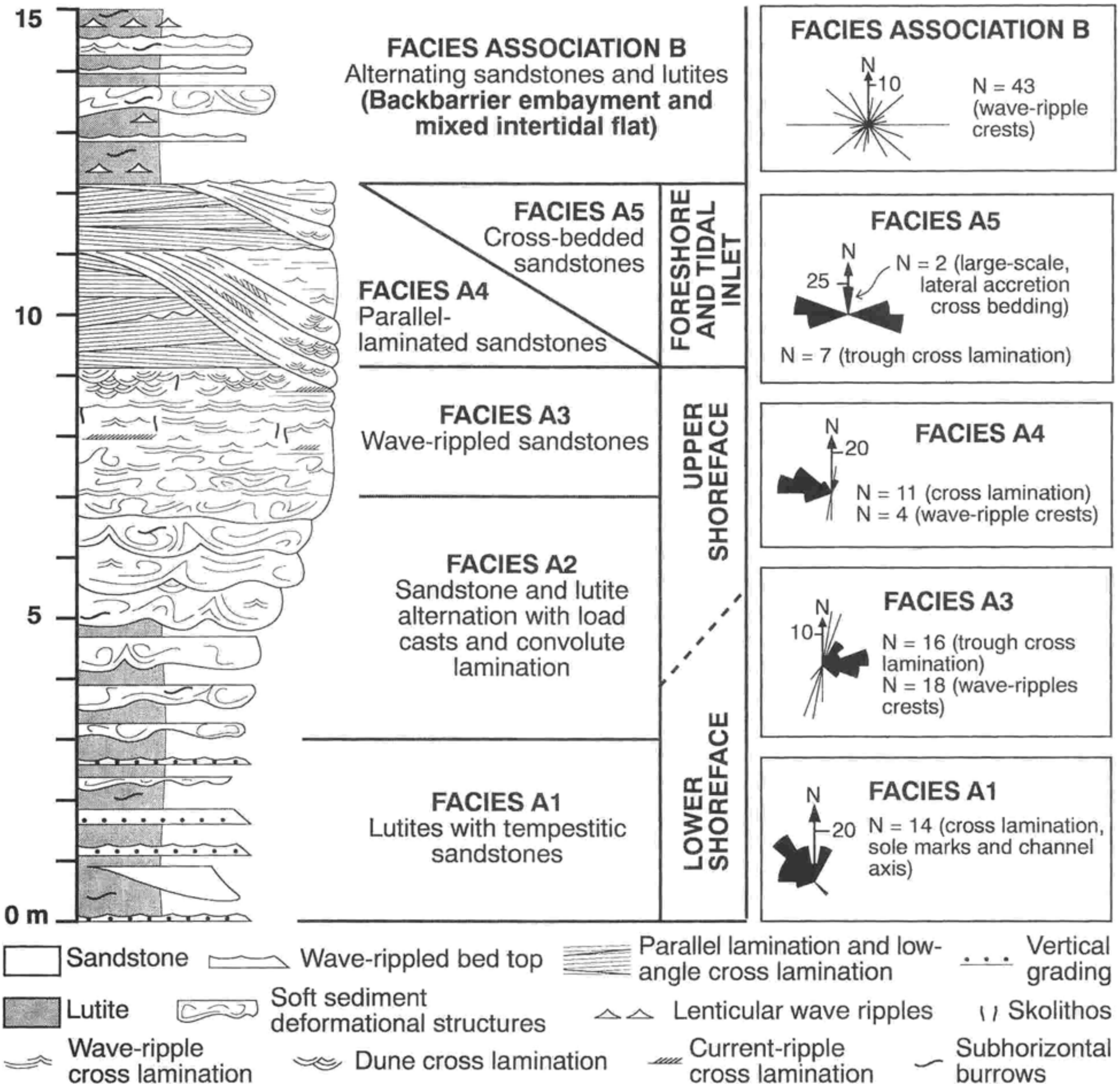


Fig. 3. Stratigraphic profile of the sandy beach deposits (facies association A) in the eastern part of the Biurrun-Undiano zone, showing the vertical succession of facies discussed in the text, palaeocurrent data and palaeoenvironmental interpretation.

lamination). In the upper part wave ripples and small to medium-sized sets (2-30 cm) of trough cross-lamination occur. The palaeocurrents, determined from symmetrical ripples, indicate SE-NW oscillatory flows; on the other hand, the trough cross-laminations suggest a transport towards the E and NE (Fig. 3). Bioturbation is less abundant than in the preceding facies, but *Skolithos*-like vertical burrows are occasionally present.

Interpretation: These features are indicative of a marine environment above the fair-weather wave base, where the frequent oscillatory wave-induced currents winnowed out the fine siliciclastic particles and redistributed the large ones. Facies A3 represents an upper shoreface deposit (HEWARD, 1981; MCCUBBIN, 1982). The mud content decreasing upwards and the sequence of sedimentary structures indicate a progressively higher energy. The increasing energy is a consequence of the shoaling of waves towards the beach and the transformation of oscillatory currents into unidirectional currents directed landwards (i.e., eastwards) and, to less degree, alongshore (northeastwards) (see READING & COLLINSON, 1996). The palaeocurrents indicate that the open sea was located westwards of the present Biurrun-Undiano outcrops.

3.1.4 Facies A4: Parallel-laminated sandstones

Description: This facies consists of parallel-laminated sandstones which are well sorted, clean, medium-grained quartzarenites organized into 15-20 cm thick strata. These are horizontal or gently dip westwards and cut each other at low angles (Fig. 3). Internally, the beds show parallel lamination (i.e., typical upper flow-regime deposits) and low

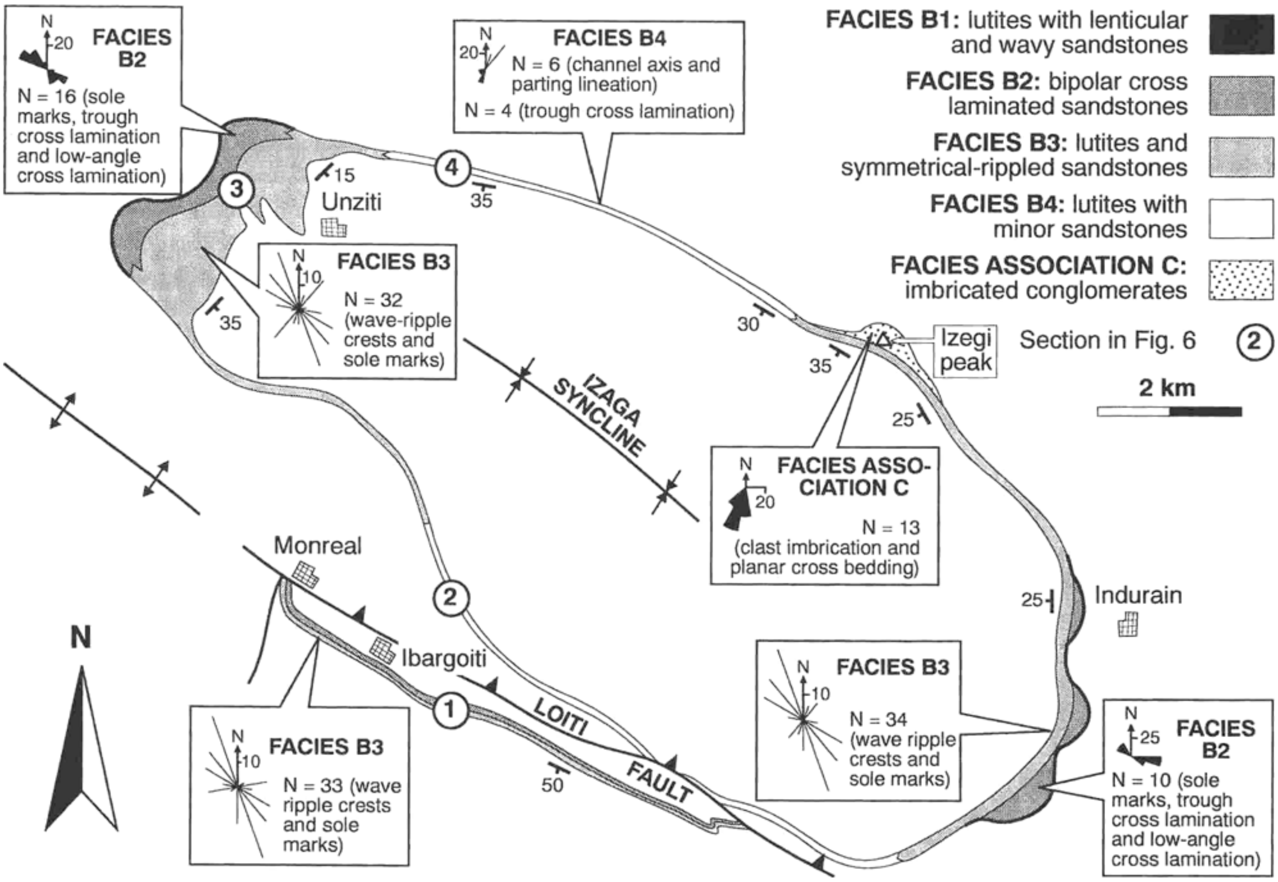


Fig. 4. Facies distribution of the Liedena Sandstone in the Izaga zone. Palaeocurrent data for each facies are shown in different localities. Encircled numbers correspond to stratigraphic sections in Fig. 6.

angle (about 10° W) planar cross-lamination. Trough cross-laminations produced by the westward migration of asymmetrical ripples and megaripples, and discontinuous sets of symmetrical wave ripples locally occur. Whereas bioturbation is generally scarce, in some localities these deposits show a nodular aspect, presumed to be due to intense bioturbation.

Interpretation: The parallel-laminated sandstones are interpreted as foreshore deposits, where swash action of waves favoured the development of upper-stage plane beds and the sorting of the sediment (HEWARD, 1981; MCCUBBIN,

Plate 19 Sandy beach and heterolithic, backbarrier facies associations in the Upper Eocene South Pyrenean Liedena Sandstone.

Fig. 1. General view of the Liedena Sandstone near Subiza (eastern part of the Biurrun-Undiano zone), where sandy beach deposits occur. A1, A2 and A3 correspond to facies described in the text. Staff (arrowed) is 1 m long.

Fig. 2. Facies A1 (lutites with tempestitic sandstones deposited in the lower shoreface) in the Subiza outcrop (Biurrun-Undiano zone). Staff is 1 m long.

Fig. 3. Wave-rippled sandstones (facies A3; upper shoreface environment). Subiza, Biurrun-Undiano zone.

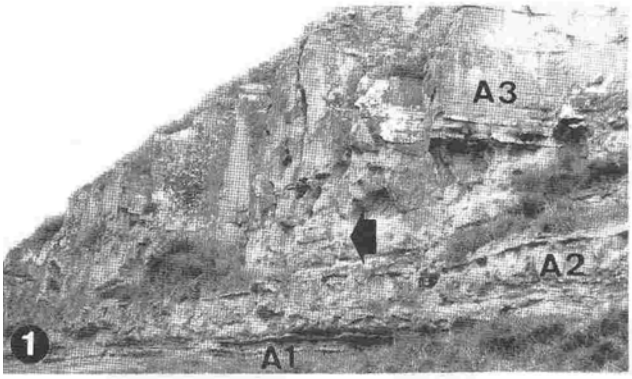
Fig. 4. Foreshore, parallel-laminated sandstones (A4) cut by a sharp, erosive surface (dashed) and overlain with tidal inlet filling cross-bedded sandstones (A5). Biurrun, eastern Biurrun-Undiano zone. Staff is 1 m long.

Fig. 5. Lutites with lenticular and wavy sandstones (facies B1, subtidal coastal embayment). Lower part of the Liedena Sandstone in Javier (Liedena-Javier zone).

Fig. 6. Amalgamated sandstone beds (facies B2, tidal channel) overlying low-energy subtidal lutites (facies B1). The cliff is 15 m high and is located to the west of Indurain (Izaga zone).

Fig. 7. Parallel-laminated, foreshore sandstones (facies A4) overlain with backbarrier lutites and wave-rippled sandstones (facies B1 and B3). Thick beds to the top of the outcrop correspond to washover sheet deposits (w). The village in the background is Subiza (Biurrun-Undiano zone). Staff (arrowed) is 1 m long.

Fig. 8. Thin-bedded sandstone and lutite alternations (facies B3) accumulated in a mixed intertidal flat. Upper part of the Liedena Sandstone in Javier (Liedena-Javier zone).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A2
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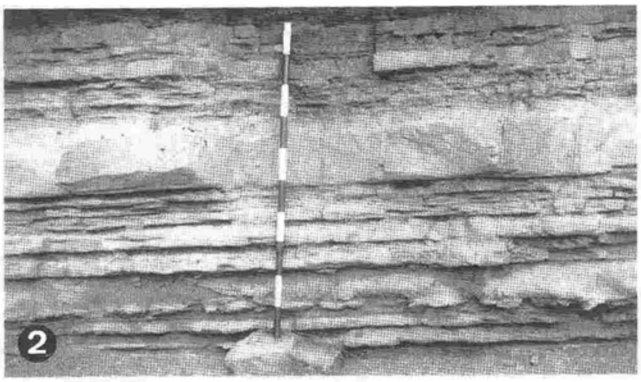
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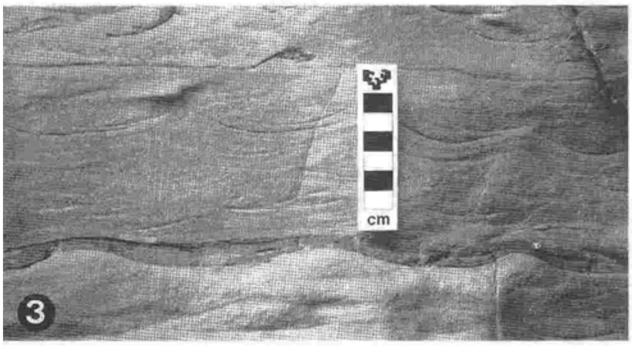
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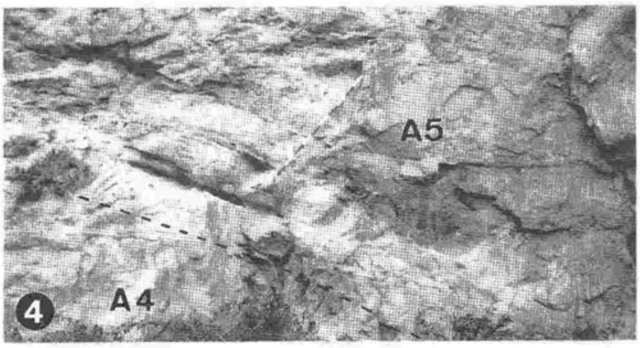
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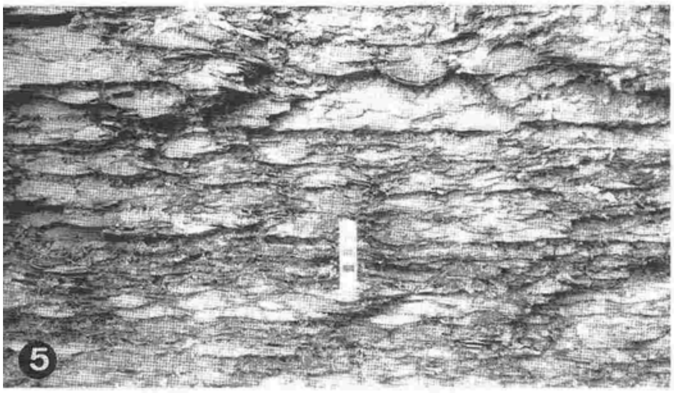
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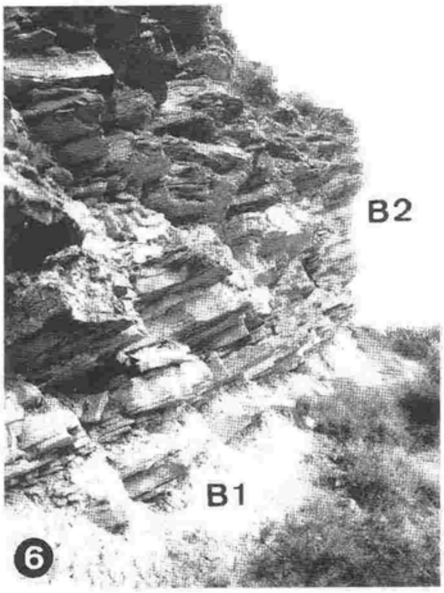
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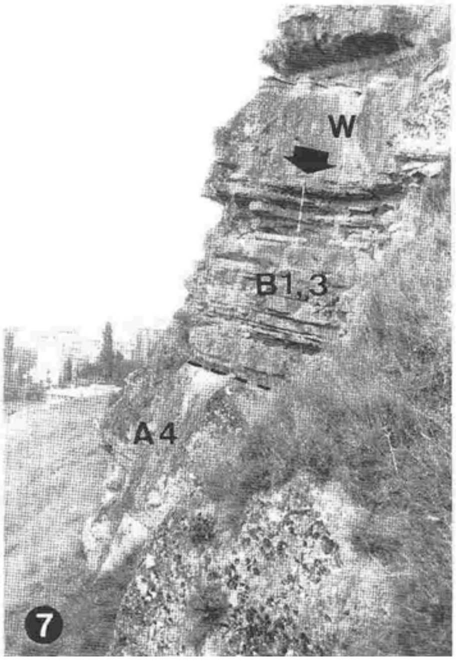
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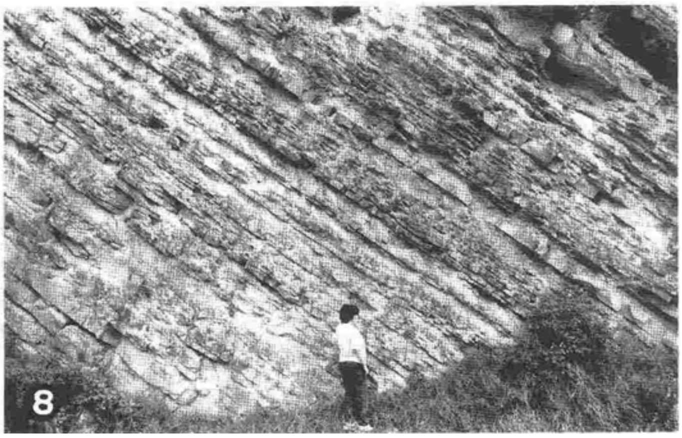
A4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1982; ALLEN, 1984; READING & COLLINSON, 1996). The westward dip of the planar beds indicates that the open sea was located in this direction. The nodular aspect in some localities was probably produced by subsequent bioturbation.

3.1.5 Facies A5: Cross-bedded sandstones

Description: The wide lateral continuity of the parallel-laminated sandstones (facies B3) is interesting for cartographical purposes. Nevertheless, two erosional surfaces cut the parallel-laminated sandstones at different stratigraphical positions. Both are overlain by large-scale sets of cross-bedded sandstones (Fig. 3, Pl. 19/4). The lower set is up to 2.5 m thick and the upper set up to 2 m thick. Both sets consist of strata about 20 cm thick with a maximum dip between 15° and 25° N (Fig. 3). The strata are sigmoidal-shaped and disposed parallel to the erosional surfaces which separate them from the parallel-laminated sandstones (Pl. 19/4). Lutitic drapes and centimetrical mud clasts occur between the sigmoidal strata. The internal structure of the cross-bedded sandstones changes vertically. The lower parts of the sigmoidal strata show medium-scale dunes with trough cross-lamination, indicating E-W palaeocurrents. Clayey drapes occurring as flasers occur in the bottomsets of some dunes. In the upper parts of the sigmoidal strata the following structures are dominant: small-scale cross-lamination, even lamination parallel with the large-scale cross bedding, and discontinuous clay partings. The cross-bedding sets extend down dip only a few metres. Overlying the last sigmoidal strata are sandstones with discontinuous parallel-lamination and symmetrical wave ripples (Fig. 3).

Interpretation: The large-scale cross-bedded sandstones fill erosional troughs with E-W axial directions. They are interpreted as small channel-fill deposits transverse to the coastline. The northward dip of the sigmoidal strata and their arrangement parallel to the channel borders indicate lateral accretion. The internal sedimentary structures, which suggest a higher energy in the lower parts of the channels and a transport perpendicular to that of the sigmoidal strata, agree with this interpretation. The presence of lutitic drapes and mud clasts between the sigmoidal strata and the flaser laminations in the troughs of the channel-floor megaripples indicate alternating conditions of high energy with migrating sandy bedforms, and those of slack waters with mud settling. Recurring changes of flow regime are common in tidal environments (ALLEN, 1984). Therefore, the cross-bedded sandstones are the result of northward lateral accretion within tidal channels. These features indicate laterally migrating shallow tidal inlets affected by northward-directed longshore currents (MCCUBBIN, 1982; BOOTHROYD, 1985; READING & COLLINSON, 1996). The discontinuously parallel-laminated and wave-rippled sandstones covering the large-scale foresets probably correspond to the abandonment stage of the active tidal-inlet channel. In fact, the sequence described as facies A5 is very similar to the facies model proposed by CAPLAN & MOSLOW (1999) for tidal inlets on wave-dominated shorelines.

In the Urbasa area, the outcrops are scarce and poorly preserved. This is probably why these deposits were not included in the Liedena Sandstone before. The features are similar to those of facies A2 and A3 (shoreface deposits), but the bioclastic content (fragments of bivalves, echinoderms and red algae) is greater in Urbasa. Moreover, the bioturbation is higher in Urbasa and there are cross-bedded sets up to 1 m thick dipping to the E, which possibly were produced by longshore bars (HUNTER et al., 1979) and/or dunes developed from landward moving storm surges (ROSSETTI, 1997).

3.2 Facies association B: heterolithic, backbarrier deposits

These facies occur mostly in the Izaga and Liedena-Javier areas, but also in the upper part of the Biurrun-Undiano series. The percentage of lutites is very high,

Plate 20 Heterolithic, backbarrier deposits (facies association B) and fluviatile conglomerates (facies association C) in the Upper Eocene South Pyrenean Liedena Sandstone.

Fig. 1. Lenticular, wavy and flaser bedding in alternating wave-rippled sandstones and lutites (facies B3, mixed intertidal flat). Subiza section, eastern Biurrun-Undiano zone).

Fig. 2. Flat-topped wave-ripples with ladder-back ripples in their troughs (sandstone bed from facies B3 in Indurain, Izaga zone).

Fig. 3. Slightly sinuous wave-ripples with tuning fork junctions (facies B3, Undiano, Biurrun-Undiano zone). Hammer is 32 cm long.

Fig. 4. Double-crested wave ripples on a sandstone bed top (facies B3, Indurain, Izaga zone).

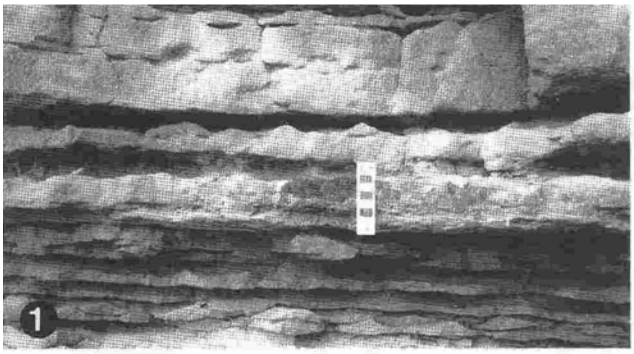
Fig. 5. Flute casts on the bottom of a thick, erosional-based sandstone bed in Liedena (Liedena-Javier zone, facies B3). Palaeocurrent from bottom to top.

Fig. 6. Polygonal desiccation cracks on the bottom of a sandstone bed (facies B3 in Indurain, Izaga zone). Hammer head is 18 cm long.

Fig. 7. Salt-crystal marks on the bottom of a sandstone-bed (facies B3, Liedena, Liedena-Javier zone).

Fig. 8. Erosional-based, thick sandstone beds in the middle part of the Javier section (Liedena-Javier zone), attributed to multiepisodic distributary channels incised into thin-bedded sandstone and lutite alternations deposited in the intertidal flat (facies B3).

Fig. 9. Clast imbrication in conglomeratic, fluviatile deposits (facies association C in the Izegi peak, Izaga zone). Palaeocurrent from left to right.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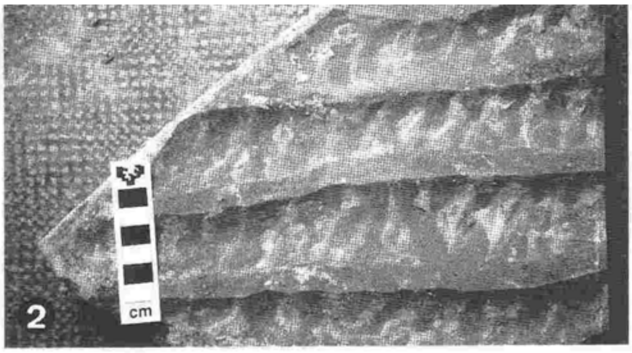
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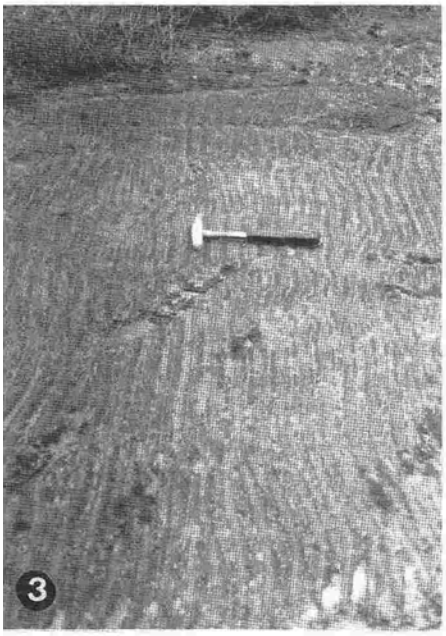
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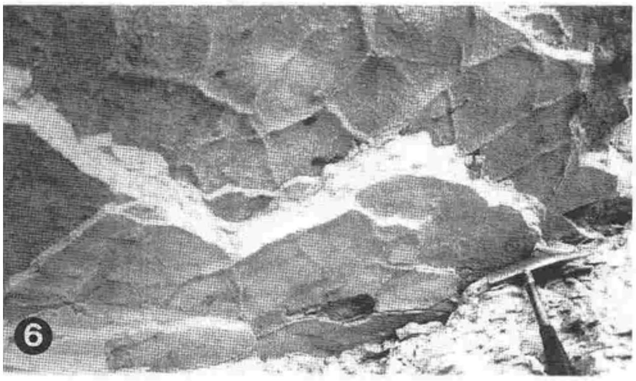
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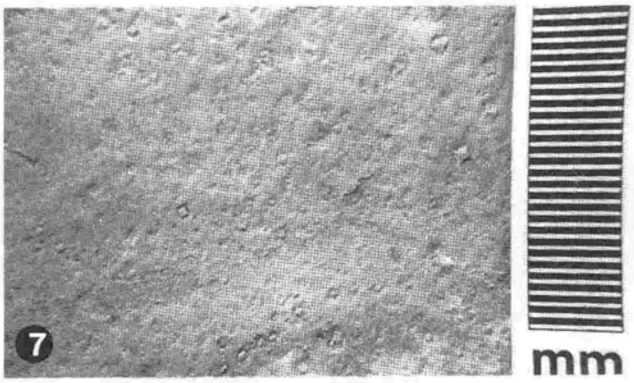
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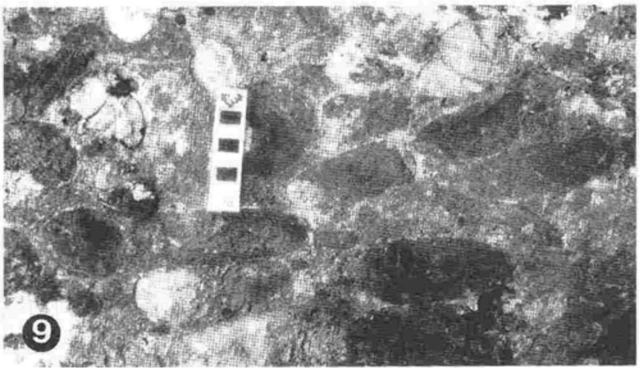
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although other lithologies are locally dominant. Four types of facies are distinguished: (B1) lutites with lenticular and wavy sandstones; (B2) bipolar cross-laminated sandstones; (B3) lutites and symmetrical rippled sandstones; and (B4) lutites with minor sandstones. The relationship between the different facies is complex; lateral and vertical transitions occur (Fig. 4).

3.2.1 Facies B1: Lutites with lenticular and wavy sandstones

Description: Together with B3, this facies constitutes a large volume of the Liedena Sandstone and form the bulk of the successions in the Biurrun-Undiano, Izaga and Liedena-Javier areas. In the Biurrun-Undiano area facies B1 overlies facies A4 (Fig. 3, Pl. 19/7). In the Izaga and Liedena-Javier areas, it occurs at the base of some sections (Fig. 4).

This facies forms a thickening and coarsening-upward sequence. The basal part consists of lutites with ostracods, calcispheres and poorly preserved benthic foraminifera, as well as disseminated carbonaceous material. Siltstones and fine-grained sandstones with lenticular and wavy bedding, starved wave-ripples within lutite layers and series of symmetrical ripples occur on the top of thin-bedded, laterally continuous sandstones (Pl. 19/5). Also, some sandstone beds have concave-upwards mud partings, defining a flaser lamination. The wavelength and the height of the ripples, as well as their crest orientations, are variable (Fig. 3). In general, the number of sandstone layers increases upwards in the succession. The sand content is greater in the Biurrun-Undiano area, where sharp-based sandstone beds up to 1 m thick are randomly scattered within facies B1 (Pl. 19/7). Their internal sedimentary structures include parallel-lamination and cross-lamination of small and medium scale, although these features are frequently obscured by later liquefaction processes.

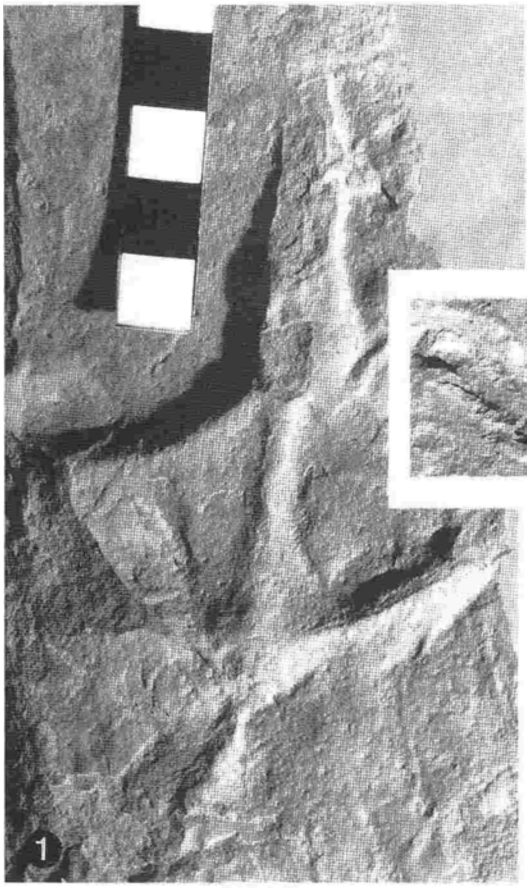
Interpretation: The fossil content is in agreement with a marine environment. The dominance of lutites indicates a low energy environment, but the sandy layers suggest that waves reworked the deposits. Lenticular, wavy and flaser bedding are usually associated with tidal currents (Reineck & Wunderlich, 1968; Allen, 1984). Nevertheless, there are no clear criteria of tidal effects such as double-clay drapes, rhythmically bundled sequences or vertical cyclic variations in bed thickness, making the tidal argument plausible rather than compelling (e.g., Lanier et al., 1993). A coastal embayment is proposed, with a standing body of marine water above fair-weather wave base, relatively sheltered from the effects of the open sea and perhaps influenced by tides (Heward, 1981; Reading & Collinson, 1996). The thicker sandstone layers in the Biurrun-Undiano area show evidence of rapid sedimentation, and are similar to washover sheet deposits associated with storm events (McCubbin, 1982; Reading & Collinson, 1996).

3.2.2 Facies B2: Bipolar cross-laminated sandstones

Description: The rocks of this facies crop out in places along the axis of the Izaga syncline (Fig. 4, Pl. 19/6). They consist of medium to coarse-grained sandstones and quartz granules with some bioclasts (bivalve shell fragments). The lutitic content is limited and occurs as discontinuous layers, less than 10 cm thick. The sandstones are organized in packages mainly 10-20 cm thick, although some of them reach a thickness up to 150 cm. In some cases they have erosional bases with abundant sole-marks (mainly groove casts, but also bounce and prod casts) indicating NW-SE palaeocurrents. The internal structures are parallel-lamination, low-angle (less than 5°) cross-lamination and small to medium-scale trough cross-lamination. The palaeocurrents are bipolar oriented to the N 100/160° E and N 290/355° E (Fig. 4), but no herringbone structures have been observed. Symmetrical wave ripples occur, both within sandstone beds as well as forming wavy or lenticular beds in the lutitic layers. The wavelengths of the ripples reach up to 20 cm and the maximum height is 2 cm; the strike of crests varies between N 20° E and N 160° E. The beds show abundant ball-and-pillow structures, lutite flames, convolute lamination and sand pipes as a consequence of differential loading and water escape. The bioturbation is scarce, but some vertical burrows occur (*Skolithos*, *Diplocraterion* and *Conichnus*).

Interpretation: The medium to coarse-grained particle size demonstrates the energy of the environment was relatively high. The sedimentary structures indicate a zone affected by strong bidirectional currents to the NW and SE. Moreover, the occurrence of structures representing different flow regimes shows that the strength of the currents was variable, and sufficiently low to allow the mud to settle. All this suggests a tidal environment (Weimer et al., 1982), although sedimentary cycles are lacking. The abundance of soft sediment deformational structures indicates rapid depo-

Plate 21	Morphotypes of bird footprints (Late Eocene, Liedena Sandstone, Southern Pyrenees, Navarre). Scale in cm.
Fig. 1.	Type 1, *Leptoptilostipus pyrenaicus* nov. ichnogen. nov ichnosp., epireliefs from Javier.
Fig. 2.	Type 2, epirelief from Javier.
Fig. 3.	Type 3, epirelief from Javier.
Fig. 4-5.	Type 4, epireliefs from Javier and Zabalza.
Fig. 6-7-8.	Type 5, *Charadriipeda* ichnosp. 1; epirelief from Javier (6F), hyporelief from Liedena (7G) and epirelief from Indurain made on soft and watery ground (8H).
Fig. 9-10.	Type 6, *Charadriipeda* ichnosp. 2; hyporeliefs from Zabalza.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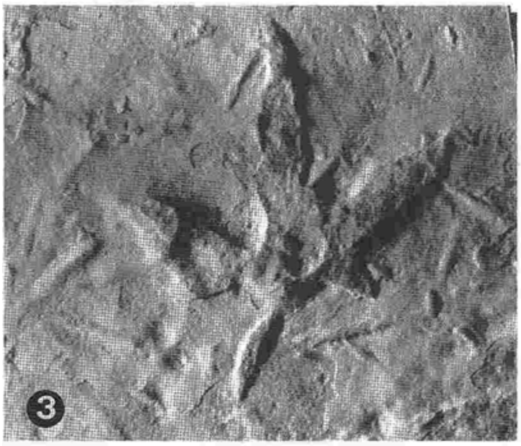
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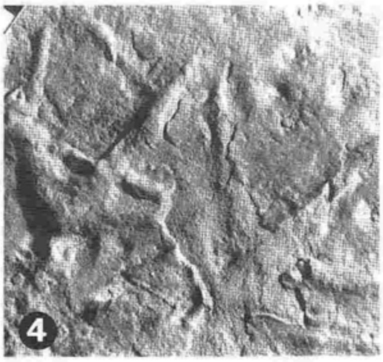
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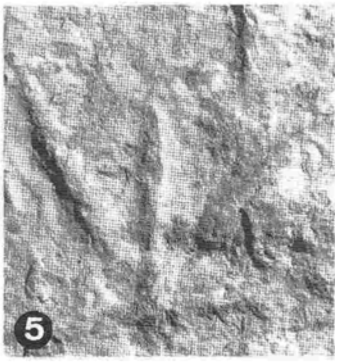
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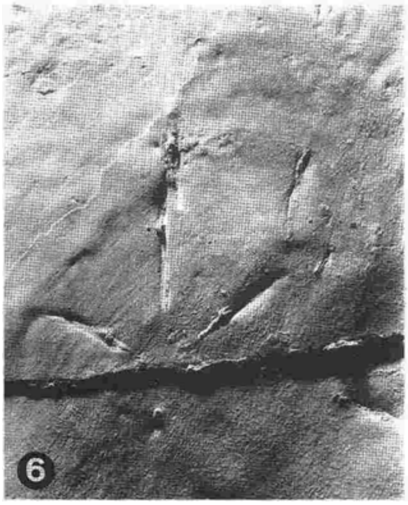
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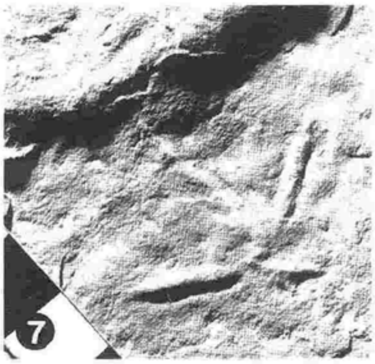
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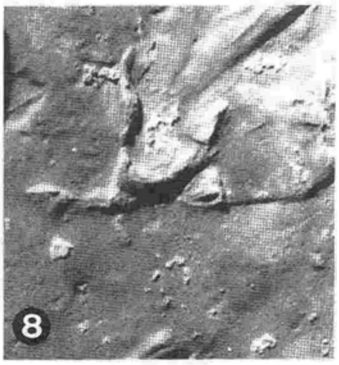
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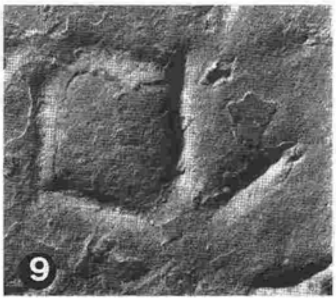
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sition. The bioturbation is typical of a high energy environment inhabited by suspension feeders (PEMBERTON et al., 1992). Burrows are rare because of a high sedimentation rate, so the biogenic galleries were filled and limited the colonization and development of life (BUATOIS et al., 1993). These features, together with the fossil content, are typical of a marine environment above fair weather wave base and influenced by high energy tidal currents. The analysis of lateral facies changes adds information on the palaeoenvironment. The bipolar cross-laminated sandstones pass laterally into lutites and wave-rippled sandstones (facies B3, indicating a mixed intertidal flat) on the northern and southern limbs of the Izaga syncline. Thus, the bipolar cross-laminated sandstones are regarded as having been deposited in a sandy subtidal setting where ebb and flood currents were confined to lower zones (WEIMER et al., 1982).

3.2.3 Facies B3: Lutites and symmetrical-rippled sandstones

Description: This facies corresponds to the flysch-like facies described by MANGIN (1962) and RAAF (1964). It overlies either the facies B1 and B2, or the facies association C (Fig. 4).

This facies consists of greyish to reddish lutites and marls with an ubiquitous marine fauna. Locally, discontinuous gypsum layers up to 15 cm thick are intercalated. Plane-parallel strata of siltstones and fine-grained micaceous quartzarenites, up to 30 cm thick, are randomly interstratified with the fine-grained deposits (Pl. 19/8, 20/1). In some sections of the Izaga area, these beds contain marine bioclasts (nummulitids, echinoderm remains and bivalve shells). The sandstone beds occasionally display soft-sediment deformational structures (load casts and water escape structures). Most significant is the large number of symmetrical wave ripples. Some ripples contain lutitic partings in their troughs (flaser lamination). The ripple crests are straight or slightly sinuous, with many Y-shaped tuning fork junctions (Pl. 20/3). Their orientation is highly variable (up to 90° in successive beds; see Fig. 4). Sometimes they show polygonal patterns as the result of interferences of structures with different strikes. Most of the ripples have very sharp crests and wide troughs, with wavelengths from 3 to 15 cm and heights between 0.6 and 2 cm. Some symmetrical ripples have double crests (Pl. 20/4). Other crests are flat and contain adhesion ripples or orthogonal, small ladder-back ripples in the ripple troughs (Pl. 20/2). Extremely small secondary wave ripples occur in other ripple troughs, whith crests parallel to the major ones. In addition to the common wave-ripple cross lamination, other internal structures of the sandstone beds are climbing current cross-lamination and parallel-lamination with associated parting lineation. The bottom of these strata show abundant drag marks, mainly groove and bounce casts, in general less than 5 mm wide. Some of them have a twisted appearance and are slightly curved. Palaeocurrents show a wide dispersion (Fig. 4), but they systematically tend to run normally to the strike of overlying ripple crests; this shows that the same oscillatory current created both drag marks and wave ripples. On bedding surfaces, and more abundant in the upper part of the successions, raindrop marks, hexagonal polygons delimited by desiccation cracks (Pl. 20/6), synaeresis cracks, 1-5 mm long halite moulds (Pl. 20/7) and adhesion ripples occur. Bedding surfaces show also many biogenic structures, with abundant invertebrate bioturbation (*Planolites*, *Palaeophycus*, *Cochlichnus* and *Gordia*). However, the most spectacular and significant biogenic structures are the bird tracks, which occur on the top and the bottom of the sandstone strata. The footprints were imprinted in different substrata (cohesive plastic substratum, cohesive semi-consolidated substratum and rippled sandy substratum), as indicated by their depth, degree of deformation, and quality of preservation. Locally, some rhizocretions have been observed.

In the Liedena-Javier area this facies contains sandstone beds with different features (Pl. 20/8). The thickness of these strata varies from 0.5 to 4 metres. The beds are thinner from the E to the W, whereas in the outcrops they show local variations because of the erosive character of their bases. Load-casts are present. Internally, there are irregular stratification surfaces with flute casts (Pl. 20/5), prod casts and groove casts, which indicate palaeocurrents oriented to the N 280-290° E. These surfaces delimit 20 to 75 cm thick

Plate 22 Different samples of bird footprints (Late Eocene, Liedena Sandstone, Southern Pyrenees, Navarre). Scales in cm.

Fig. 1. Epireliefs of the six morphotypes differentiated in this work; in the photograph, the number represents the type of footprint. Sample J2 (Javier).

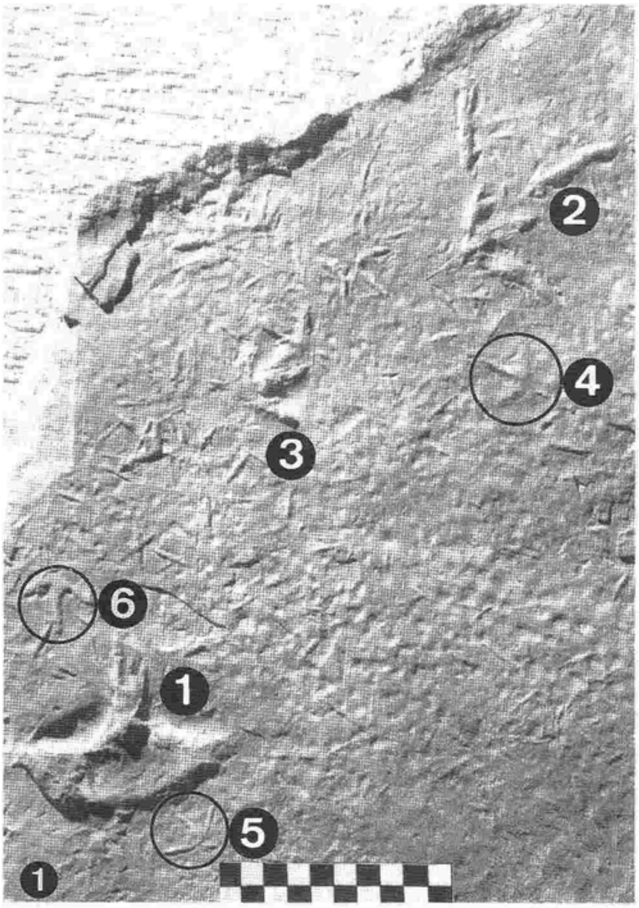
Fig. 2. Epireliefs of morphotype 5 (*Charadriipeda* ichnosp. 1); the arrows indicate the impression of a proximal web between toes III and IV. Sample LH2 (Liedena).

Fig. 3. Hyporeliefs of morphotypes 2 (left corner of the photograph) and 6 (*Charadriipeda* ichnosp. 2). Sample Z1 (Zabalza).

Fig. 4. Epireliefs of morphotypes 1 (*Leptoptilostipus pyrenaicus* nov. ichnogen., nov. ichnosp., without impression of toes I and II; numbers indicate the morphotypes on ripple marks and casts of small salt crystals. Sample LI8 (Liedena).

Fig. 5. Top of sample I1 showing the hyporeliefs of morphotype 6 (*Charadriipeda* ichnosp. 2) on ripple marks.

Fig. 6. Bottom of sample I1 showing the epireliefs of morphotype 5 (*Charadriipeda* ichnosp. 1) on a soft and watery ground. Note the presence of other bioturbations, probably made by invertebrates.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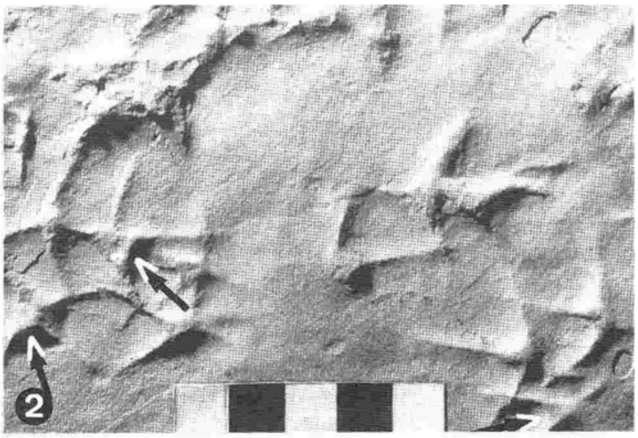
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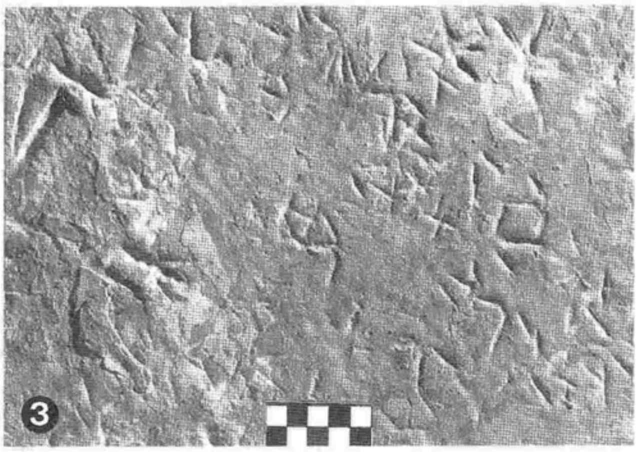
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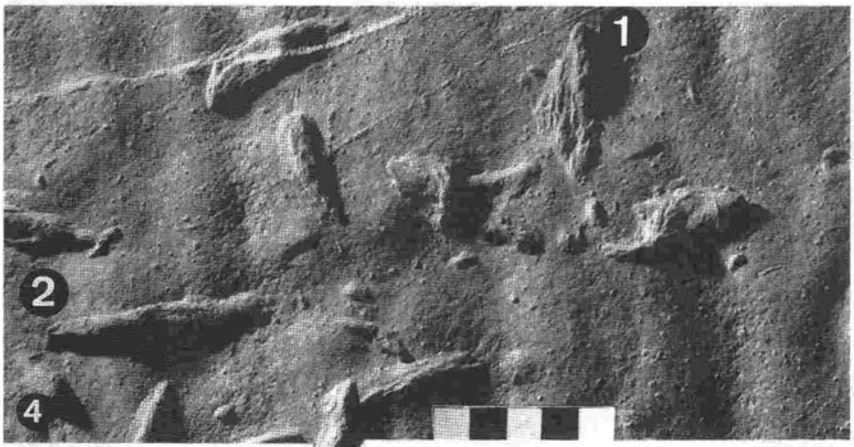
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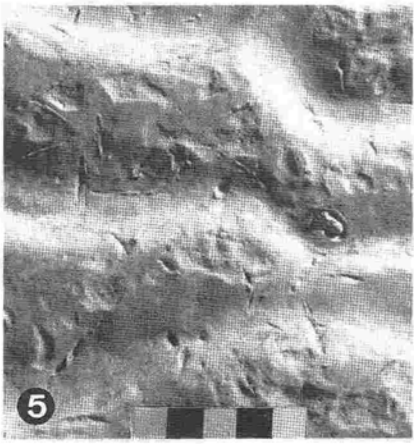
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strata. They have numerous mud clasts at the bottom, and consist of fine-grained mixed sandstones with abundant vegetal remains. They are poorly graded but show a distinctive sequence of sedimentary structures: parallel or medium-scale trough cross-lamination which passes upwards to climbing current ripples and finally to symmetrical wave ripples.

Interpretation: The bird tracks, synaeresis cracks and flat-topped wave ripples with ladder-back ripples indicate falling water levels, whereas the raindrop marks, desiccation cracks and adhesion ripples are clear evidence of subaerial conditions (ALLEN, 1984). These structures occur throughout the lutitic succession containing a marine fauna and indicate an area which was alternately emerged and submerged because of tidal action. The abundant lutites were formed by mud settling in quiet waters, in a low-energy environment. On the other hand, the sandstone beds with symmetrical ripples demonstrate higher energy periods with oscillatory currents, although the sharp-crested ripples indicate a moderate wave action (ALLEN, 1984). The double-crested wave ripples and the small secondary crests in the troughs of the major ripples resulted from the modification of previous bedforms during diminishing wave energy (ALLEN, 1984; ASPLER et al., 1994). The slightly curved morphology of tool marks in the sole of the sandstone beds is the result of combined flows, with weak unidirectional currents superimposed on the oscillatory flows (BEUKES, 1996). In general, the palaeocurrents determined from these sandstone beds are widely dispersed and suggest that the water movement resulted mainly from local winds. The superb preservation of the sedimentary structures indicates some early acquired cohesion due either to wind action (RAAF et al., 1965), a surficial local cementation, capillary moisture, or salt encrusting (HADDOX & DOTT, 1990). The isolated cubic moulds of halite crystals indicate saline and low energy environments (HANDFORD, 1990) and the discontinuous gypsum layers correspond to minerals precipitated in ephemeral saline ponds. ALLEN (1984) pointed out that synaeresis cracks and the hexagonal polygons delimited by desiccation cracks occur in environments influenced by salt water. All the evidence indicates a relatively confined marginal marine environment. Therefore, the facies B3 is assigned to a mixed intertidal flat developed in a partially protected embayment or a marginal lagoon (WEIMER et al., 1982; ALLEN, 1984; READING & COLLINSON, 1996). The development of mud cracks involves long-lived subaerial conditions on an upper intertidal flat. The increase of subaerial sedimentary structures towards the upper part of the series is good evidence that the emergent periods became progressively more and more frequent.

The thicker sandstone layers in the Liedena-Javier area correspond to the multiepisodic fill of wide channels incised in the intertidal flat. In previous studies, they were considered to be the fillings of fluvial channels (PUIGDEFABREGAS, 1975) or of tidal channels (LEON-CHIRINOS, 1985). Instead, the repetitive vertical sequence of sedimentary structures in the channel-fill strata are more likely the result of waning, episodic unidirectional currents, with the internal erosional surfaces and mud clasts recording successive episodes of channel reactivation. The unidirectional orientation of the palaeocurrents, the absence of reliable tidal structures, the abundance of wood remains and the episodic character of the channel fills resemble the deposits of minor distributary channels (HEWARD, 1981; VOS, 1981; COLEMAN & PRIOR, 1982). The westward-oriented palaeocurrents show that the permanently emerged terrains were located to the east. The trace-fossil assemblage supports the above palaeoenvironmental interpretation. Similar ichnogenera associations have been reported from tidal environments under the influence of fresh waters (ARCHER et al., 1995; GREB & ARCHER, 1995).

3.2.4 Facies B4: Lutites with minor sandstones

Description: The rocks of this facies crop out exclusively in the northern and southern limbs of the Izaga syncline (Fig. 4). They represent the lateral transition from facies B3. They are similar to those of facies B3 but the sandstone layers are less common and are less than 10 cm in thickness. Some strata usually have a small lateral continuity and show shallow, channel-shaped geometries whith axes oriented N-S. In the northern limb sets of cross-laminated sandstones indicate a southwards transport (Fig. 4). The lutites are mostly red and contain a small number of poorly preserved marine microfossils.

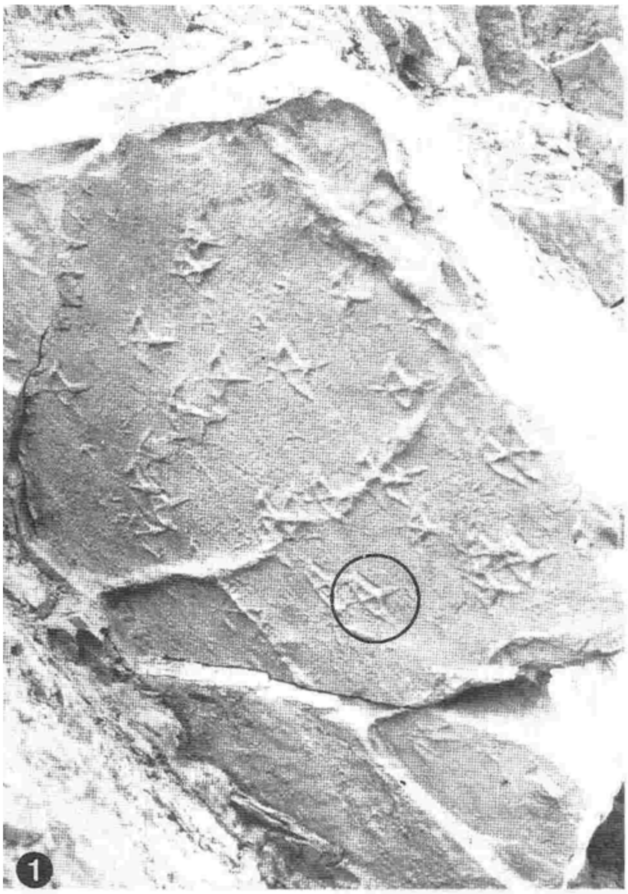
Interpretation: The lateral transition from facies B3 to B4 indicates that the deposits of facies B4 formed in a palaeoenvironment genetically related to the mixed intertidal flat. The smaller amount of sand relative to facies B3 indicates lower energy conditions, and the reddish colour of the lutites was probably produced by long subaerial exposure. However, the occurrence of marine fossils and the lack

Plate 23 *Leptoptilostipus pyrenaicus* nov. ichnogen., nov. ichnosp. (Late Eocene, Liedena Sandstone, Southern Pyrenees, Navarre). Scales in cm.

Fig. 1. Javier outcrop, showing the sample J3 *in situ* before its fall on 1994. The epireliefs of this block, now kept at the Leyre Monastery (Navarre), agree with the hyporeliefs figured by RAAF et al. (1965), kept at the Rijkmuseum van Geologie en Mineralogie (RGM 445320) of Leiden (The Netherlands).

Fig. 2. Holotype, specimen J3.1 in the block sample J3 of Pl. 23/A (encircled).

Fig. 3. Hyporeliefs of sample LI3 (Liedena).



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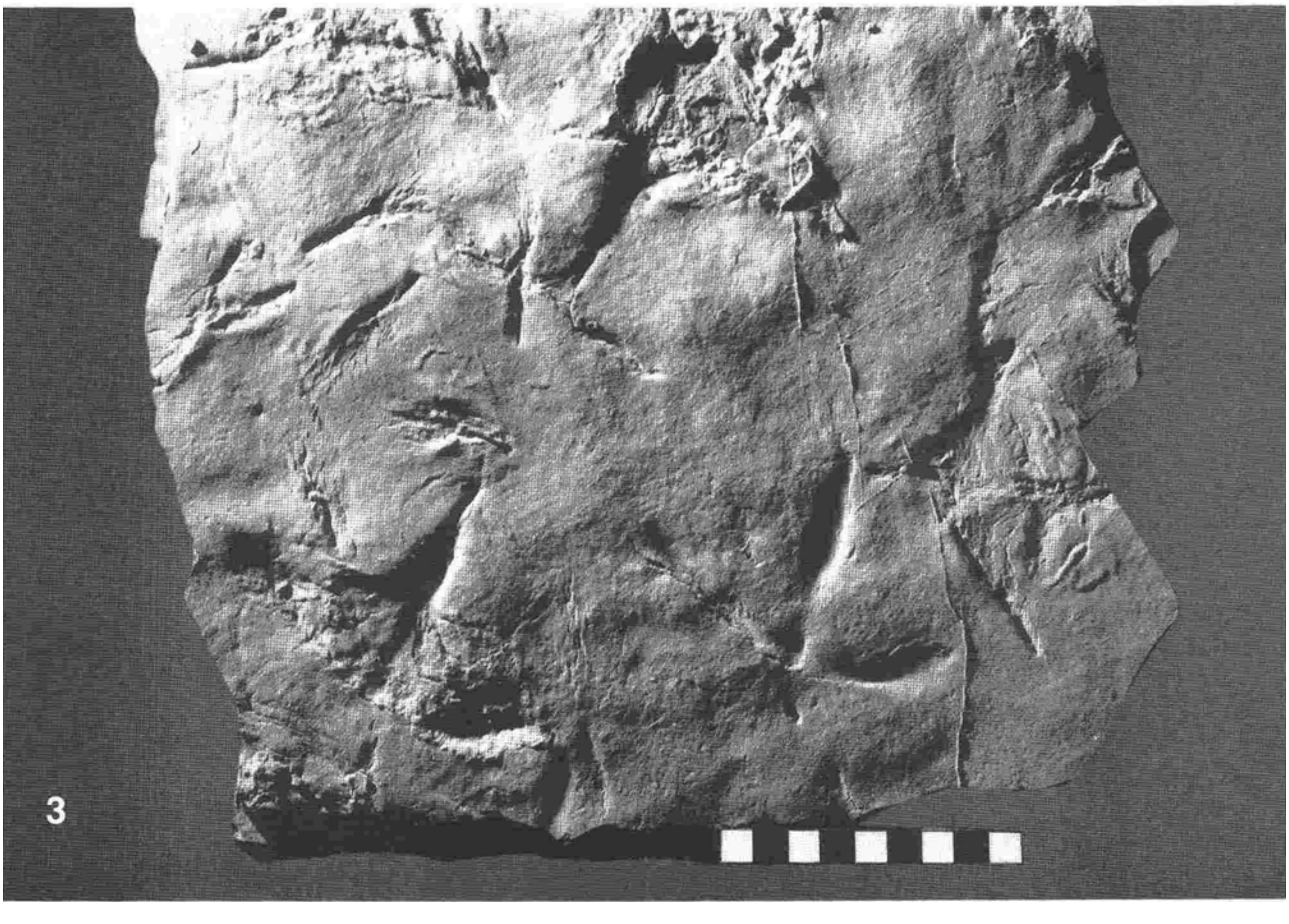

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of *in situ* plant remains shows a frequent influence of marine waters. The lutites with minor sandstones were deposited in the upper part of the intertidal flat or in the lower part of the muddy supratidal plain, flooded only during storms or spring tides. The channel-shaped sandstones are similar to deposits of ephemeral streams or tidal creeks.

3.3 Facies association C: conglomeratic, fluviatile deposits

Description: The conglomeratic deposits are rare in the Liedena Sandstone, restricted to the lower part of the succession in the NE of the Izaga syncline (Fig. 4). They form an erosive-based lenticular lithosome, 30 m thick in the central part and 2 km wide along strike. These deposits form a generally fining-upward sequence, with dominant conglomerates at the bottom and sandstones towards the top. This general sequence is arranged into 3-7 cm thick, fining-upward minor sequences bounded by erosional surfaces. Cobble-sized clasts are most abundant in the lower part of the minor sequences. The clasts are composed of both carbonate (mainly Eocene shallow marine bioclastic calcarenites) and siliciclastic (medium and fine-grained, parallel-laminated sandstones) rocks. The clasts are well-rounded, but the sphericity is variable (spherical carbonate clasts and disc-shaped sandstone clasts). The mean diameter is about 10 cm, but some of them reach up to 40 cm. Clast imbrication shows that the palaeocurrents ran to the S (Pl. 20/9 and Fig. 4). In the upper parts of the minor sequences there are medium to coarse-grained mixed sandstones with carbonate and quartz granules and pebbles. The sandstones show planar cross-bedding sets, up to 25 cm thick, oriented to the N 210° E (Fig. 4).

Interpretation: The geometry of the sedimentary body, the lithology and the sequential organization are all characteristic of the multiepisodic filling of a fluvial channel scoured by currents carrying a mixed bedload of gravel and sand (Collinson, 1996). The imbricated conglomerates correspond to channel fill deposits, whereas the cross-stratified sandstones are associated with dunes and longitudinal bars. Thus, the fining-upward minor sequences are the result of bar migration into the channels. The southward-oriented palaeocurrents show that the emergent areas were located to the N.

4 MICROPALAEONTOLOGY

4.1 Materials and Methods

Benthic foraminifera of the heterolithic, backbarrier facies association were analyzed to aid the environmental interpretation of the flysch-like deposits. 32 samples for micropalaeontological analysis were taken from eleven sections covering different outcrop zones and facies types. Nine samples were collected from three sections in the Undiano-Biurrun zone, six from facies B3 and three from facies B4; fourteen samples from five sections in the Izaga zone were studied, three from facies B1, seven from facies B3 and four from facies B4; nine samples were collected from three sections in the Liedena-Javier area, two from facies B1, five from facies B3 and two from facies B4. Samples were passed through a 63 micron aperture sieve, washed with water and dried at 60°C. Tests were studied under a stereoscopic binocular microscope.

4.2 Results

The foraminiferal content is very low and poorly preserved in most of the samples. Although fourteen samples were barren of foraminifera, samples from all facies types contain a few hyaline individuals, very small in size, and impossible to identify due to their poor preservation. The only exception was the fauna from facies B3 of the Indurain section (Izaga zone), which contained an abundant and well preserved benthic foraminiferal assemblage. This assemblage was accompanied by echinoids, bryozoa, gastropods and ostracoda fragments. Seventeen different forms were observed, although most of them were present as only one or two individuals. The samples were dominated by the species *Pararotalia inermis* (Terquem) which formed, on average, 90% of the assemblage. Other forms with relative abundance ranging from 1-4% belonged to the *Quinqueloculina, Triloculina* and *Elphidium*. The Fisher alpha diversity index (Fisher et al., 1943) showed a moderate average value of 4. The average foraminiferal test composition in the assemblages was 92% hyaline, 7% porcellaneous, and 1% agglutinated tests.

These results agree with those obtained by Grünig (1977, 1985) in the same area. She included the Liedena Sandstone in the Indurain section within her Assemblage Zone 5. This zone is characterized by an average 87% dominance of *Pararotalia inermis* (morphologically variable *Pararotalia audouini* in her work) together with rare *Nonion scaphum, Quinqueloculina juleana* and *Halkyardia minima*. Grünig (1977, 1985) considered this assemblage as indicative of a very shallow marine environment.

The micropalaeontological content of facies B3 indicates that the sediments formed in a marginal marine environment with extremely high dominance of one species, *Pararotalia inermis*. This form has been defined as a normal marine, inner shelf organism (Murray & Wright, 1974; Jenkins & Murray, 1981) and it was probably transported to the depositional area as bed load by processes typical of wave-dominated coastal areas, as observed in the modern Bay of Biscay (Cearreta & Murray, 2000). This species, which ranges from Middle to Late Eocene, further confirms the already suspected Late Eocene age for the Liedena Sandstone on the basis of palynological studies carried out by Orti et al. (1986) of the underlying evaporitic deposits.

5 AVIAN ICHNOLOGY

5.1 Material

The studied material consists of twenty-two sandstone slabs with bird footprints collected from the localities of Javier (samples J1-J3) and Liedena (LH1-LH2 and LI1-LI8) in the Yesa-Javier outcrop zone (Facies B3), and Indurain

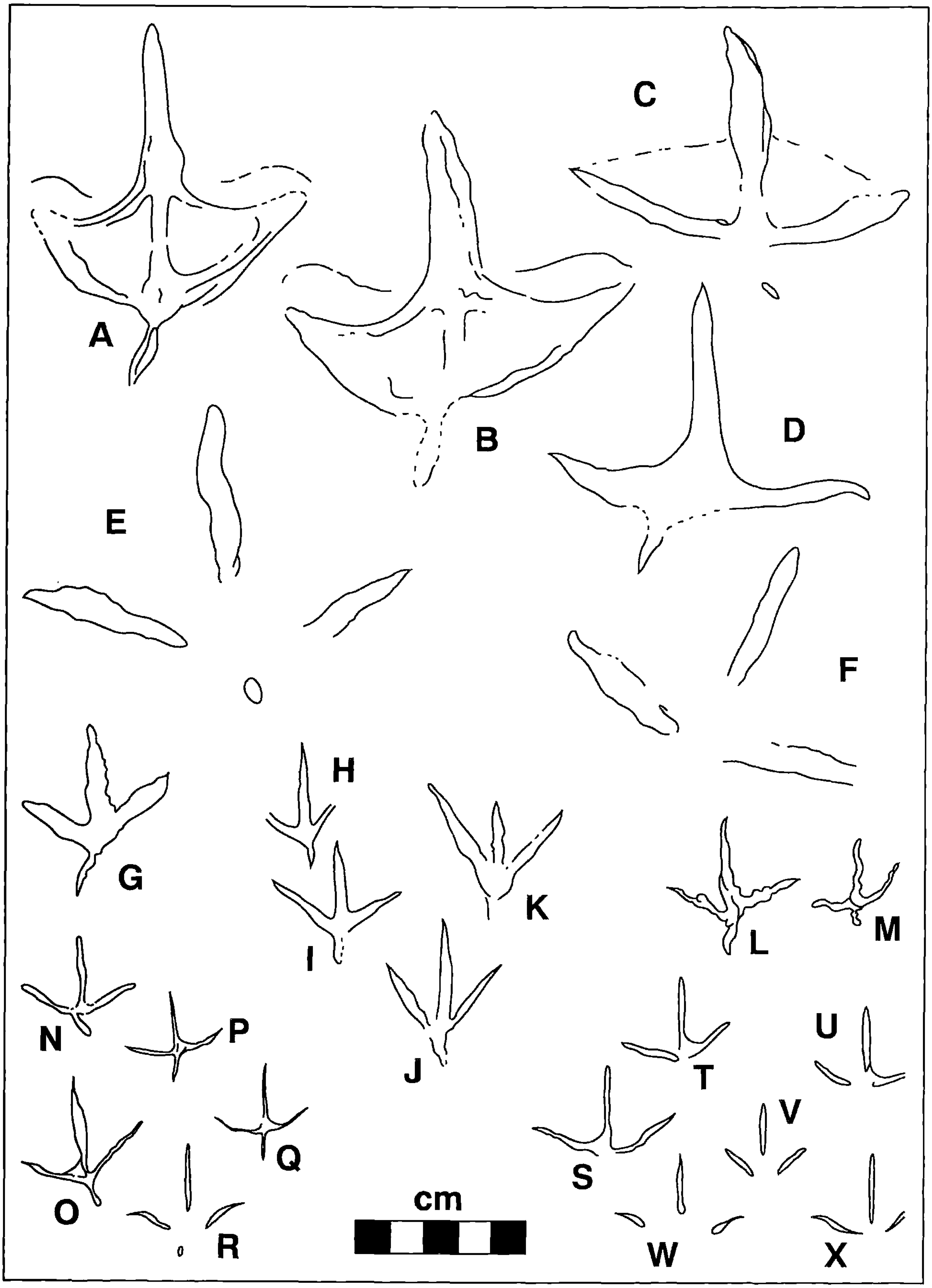

Fig. 5. Bird footprint morphotypes from the Upper Eocene Liedena Sandstone. Type 1 *Leptoptilostipus pyrenaicus* n. ichnogen. & n. ichnosp.: A, B (Javier); intermediate type 1-2: C (Liedena), D (Zabalza). Type 2: E (Javier), F (Zabalza). Type 3: G (Javier). Type 4: H, I (Javier), J, K (Zabalza). Type 5 *Charadriipeda* ichnosp. 1: L, M (Indurain), N (Javier), O-R (Liedena). Type 6 *Charadriipeda* ichnosp. 2: S (Liedena), T-V (Zabalza), W-X (Indurain).

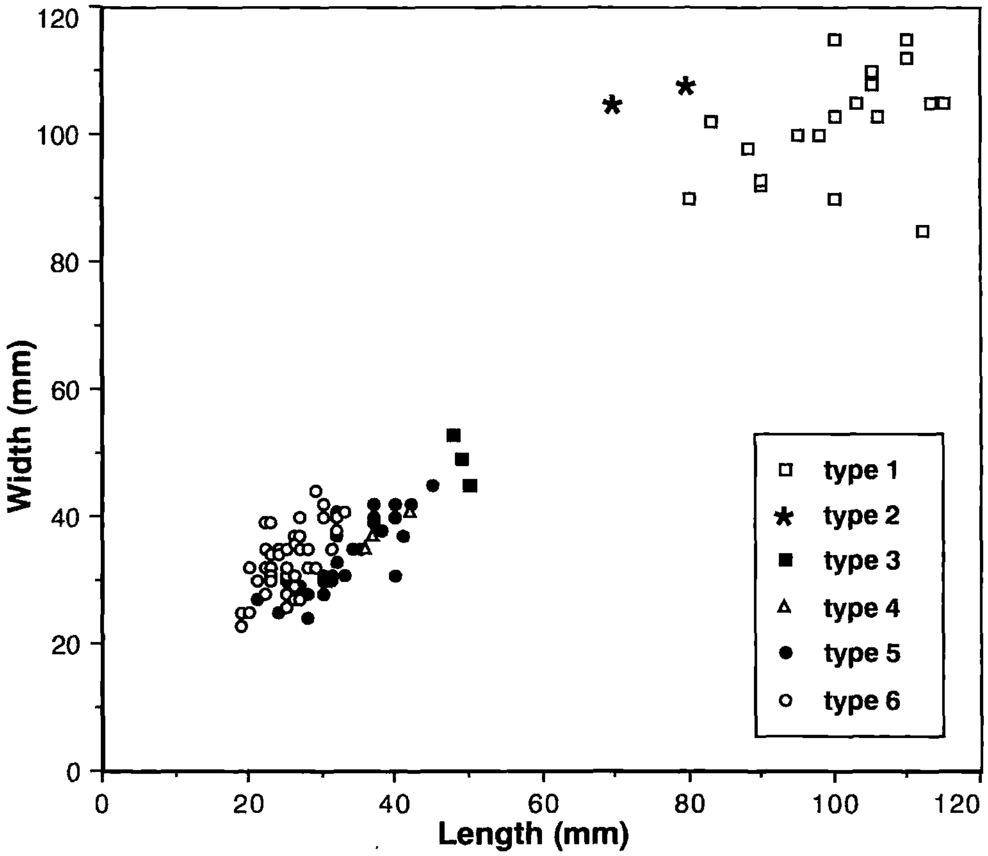

Fig. 6. Diagram length/width from the different bird footprints morphotypes observed in the studied samples from the Upper Eocene Liedena Sandstone. 20 measured prints type 1; 2 measured prints type 2; 3 measured prints type 3; 3 measured prints type 4; 32 measured prints type 5; 48 measured prints type 6.

(I1-I8) in the eastern part of the Izaga outcrop zone (Facies B3). An additional sample was collected much earlier from the vicinity of Zabalza-Ibargoiti (Z1), in the southern part of the Izaga zone. Nowadays, this outcrop is weathered and covered by vegetation and it is not possible to determine the exact stratigraphic and sedimentological context of sample Z1, although its association to facies B3 is likely. The samples are provisionally deposited in Bilbao at the Departamento de Estratigrafía y Paleontología, Facultad de Ciencias of the Universidad del País Vasco/Euskal Herriko Unibertsitatea, with the exception of sample J3, which is in the Leyre Monastery (Navarre).

Six different morphotypes of footprints, coded by numbers from 1 to 6, have been recognized. Their main characteristics and distinctive features are explained below.

Type 1 (Figs. 5A-D, 6; Pls. 21/1, 22/1, 4, 23/1-3; Table 1). Abundant (I7, I8, J1, J2, J3, LI3, LI8, Z1). Large-sized footprints, slightly asymmetrical, with 3 toes (II, III and IV) which point forwards, and generally a short hind toe (I) medially rotated. The central toe (III) is longer than the lateral ones (II and IV). The latter are slightly curved forwards at an angle of about 120°. Claw marks are sometimes visible. An interdigital mesial web is commonly well-developed between toes II, III and IV. This web extends from the tips of the lateral toes to the middle part of the central toe. In samples I7 and LI3, some type 1 footprints are deformed, as they were probably made on a soft and water-saturated sediment surface.

Type 2 (Figs. 5E-F, 6; Pls. 21/2, 22/1, 4; Table 1). Scarce (J2, LI8, Z1). Large footprints, similar to those of type 1. They differ, however, in being somewhat more symmetrical and by the absence of an interdigital web. The impression of the toes is not complete, as the mark of the proximal tip is lacking. The outline of the lateral toes is straighter than in the type 1, with a wide-angle opening (130° to 150°).

Type 3 (Figs. 5G, 6; Pls. 21/3, 22/1; Table 1). Scarce (J2). Medium to small footprints, slightly asymmetrical, with four robust toes. The hind toe (I) is medially turned; toes II to IV are thick, slightly lobed and converge posteriorly. They show claw marks. The central toe (III) is the longest one. The angle between toes II and IV is about 110°.

Type 4 (Figs. 5H-K, 6; Pls. 21/4-5, 22/1; Table 1). Scarce (J2, LI4). Small footprints. They are nearly symmetrical and generally four-toed. The impression of toe I is more or less parallel to the long axis of the footprint. The fore toes are straight and become pointed toward the tip. Toes II and IV at an angle from 70° to 110°.

Type 5 (Figs. 5L-R, 6; Pls. 21/6-8, 22/1-2, 6; Table 1). Very abundant (I1, I2, I4, I5, I6, J2, LH1, LH2, LI1, LI2, LI5, LI6, LI7). Small, slightly asymmetrical and four-toed footprints. Toe I is short and medially turned; the angle relative to the long axis of the footprint is variable (6° to 55°), and

MORPHO-TYPE	SAMPLE	LOCALITY																			
		INDURAIN					JAVIER					LIEDENA					ZABALZA				
		Number	length/width			Stride	Number	length/width			Stride	Number	length/width			Stride	Number	length/width			Stride
			min.	mean	max.			min.	mean	max.			min.	mean	max.			min.	mean	max.	
1	I7+I8	3	88/93	92/97	98/100	460															
	J1+J2 +J3						12	90/90	104.2/102.5	115/115											
	LI3+LI8											5	80/90	92/103.4	105/115	410					
	Z1																2	88/92	88/95	88/98	460
2	J2						1		80/118												
	Z1																1		70/105		
3	J2						3	48/45	49/49	50/53	245										
4	J2						4	35/33	37.5/36.5	42/41	190										
	Z1																2	36/30	37/37	38/44	
5	I1+I4	9	21/24	27.5/29.5	40/40	130															
	J2						5	33/31	36.4/34.8	40/39											
	LI1											2	40/37	40.5/39.5	41/42						
	LI2											5	30/28	31.8/33.6	34/41						
	LI7											4	35/35	37.7/39.7	42/42						
	LH2											7	24/25	30.5/32.4	45/45	135					
6	I1	3	20/25	23.3/28.3	28/32																
	I6	3	25/32	28/35.6	32/38																
	J2						2	19/25	22/28	25/31											
	LI1											2	25/26	25/27	25/28	135					
	LH1											8	25/35	29.1/39.8	33/44						
	Z1																30	19/23	24.1/32.6	31/39	155

Table 1. Measurements of the bird footprints from the studied samples of the areas of Izaga (Indurain, Zabalza) and Yesa (Liedena, Javier), Upper Eocene South Pyrenean Liedena Sandstone (Navarre).

commonly small. The fore toes are slightly lobed; toe III is the longest. In some cases there is evidence of claw marks. The impression of the toes is either complete, with the toes converging toward the base, or incomplete, showing discontinuous marks. The angle between the toes II and IV is about 125°. In some samples from Liedena (LH1, LH2, LI1, LI2), a small proximal web is present between toes III and IV. In other samples from Indurain and Liedena (I1, I2, I4, I6), the footprints are deformed and have a sinuous outline. These footprints were probably made on a plastic, soft and saturated sediment.

Type 6 (Figs. 5S-X, 6; Pls. 21/9-10, 22/1-5; Table 1). Very abundant (I1, J2, LI1, Z1). The size and shape are similar to those of morphotype 5, but there is no impression of toe I. As well as the previous ones, these tracks are pointing inwards, with slightly straddled walking trails.

With regard to the diversity in each outcrop, the Javier levels are the richest: all the morphotypes described here are present in the Javier samples (see list of material in Table 1). Moreover, the morphotype 3 is only known at Javier.

5.2 Comparisons

Hernandez-Pacheco (1929) described bird footprints from the Palaeogene of the South Pyrenean region of Peralta de la Sal (Huesca). Mangin (1962), and later Raaf et al. (1965), first mentioned the presence of fossil bird tracks in the Liedena Sandstone of Navarre and illustrated the footprints of the types 1, 5 and 6 described above. According to RAAF et al. (1965), several species of Charadriiformes were represented by small tracks, while the largest tracks (type 1) are likely to belong to Ciconoiidae (sic). PUIGDEFABREGAS (1975) noted the occurrence of *Charadriipeda minima* and *Charadriipeda disjunta* in the outcrops of Indurain and Liedena-Javier. Both ichnospecies were erected by PANIN & AVRAM (1962) from the Miocene footprints of the South-Carpathian area of Romania. The smallest tracks of the type 5 described here are morphologically and biometrically similar to those of *Charadriipeda minima*; the footprints of type 6, with isolated impressions, are more similar to those of *Charadriipeda disjunta*.

PLAZIAT (1964) described bird footprints similar to those of types 5 and 6 from the Lutetian (middle Eocene) of Aude, Languedoc. Similar fossil tracks were described from the Eocene of Utah (North America) and assigned to the Charadriiformes by MOUSSA (1968). The presence of wader tracks has also been pointed out in lacustrine deposits from the Ludian (Late Eocene) of the Mormoiron Basin of Provence (TRUC, 1978), and of the Garrigues-Ste. Eulalie, Gard (ELLENBERGER, 1980). The latter described and figured some footprints similar in size and shape to the type 5 of Navarre, and assigned them to the ichnogenus *Ludicharadripodiscus* (ichnospecies *L. edax*).

CLERCQ & HOLST (1971) and WEIDMANN & REICHEL (1979) described bird footprints from the Oligocene and Miocene of the Swiss molasse, and they noted that charadriiforme-like tracks are dominant. Many of these ichnites are similar in size and shape to morphotypes 5 and 6 described here; moreover, some of the Swiss footprints are thought to have been made on soft and water-saturated surfaces and are similar to those of samples I1, I4 and LI7 from Navarre.

SCRIVNER & BOTTJER (1986) noted the presence of six bird ichnospecies from the Neogene of the Death Valley National Monument of California, and referred them to *Avipeda* spp. A to E. The present type 1 shares some morphological features with *Avipeda* sp. A, an ichnospecies attributed to the Order Ciconiiformes by SCRIVNER & BOTTJER (1986). However, the type 1 of Navarre is bigger than *Avipeda* sp. A and, contrary to it, shows a web impression. Morphotype 2 of this study is similar to the smallest footprints of *Avipeda* sp. B, which has tentatively been referred to the Ciconiiformes by SCRIVNER & BOTTJER (1986). The morphotype 5 of Navarre looks similar to but is bigger than *Avipeda* sp. D, assigned to the Charadriiformes. Finally, the shape of type 6 is very close to that of *Avipeda* sp. C, an ichnospecies attributed to the Order Ralliformes by SCRIVNER & BOTTJER (1986).

5.3 Relationships and parasystematic proposal

Following PUIGDEFABREGAS (1975), types 5 and 6 of Navarre are tentatively referred to the ichnogenus *Charadriipeda*; we attribute them provisionally to *Charadriipeda* ichnosp. 1 and 2, respectively. There are no significant differences between *Charadriipeda* PANIN & AVRAM, 1962 and *Ludicharadripodiscus* ELLENBERGER, 1980, so it is likely that they are the same ichnogenus. Based on the priority rule, *Ludicharadripodiscus* could be a junior synonym of *Charadriipeda*. As already noted by previous authors, these footprints are similar to those of the recent Charadriiformes. This order is a diversified group of small wading birds such as sand-pipers, gulls and snipe-like birds living mainly in marginal marine habitats, known as early as the Late Cretaceous (OLSON, 1985).

The footprints included in types 3 and 4 have some morphological features similar to those of the types 5 and 6; it is likely, therefore, that types 3 and 4 were made by Charadriiformes as well. Type 3 looks like type 5, but is larger and more robust (Table 1, Fig. 6). On the other hand, type 4 lies within the biometrical interval of type 5, but it shows a slightly different morphology. Owing to the scarcity of the available material, a conservative approach has been adopted and types 3 and 4 have not been assigned to a formally defined ichnotaxon.

The types 1 and 2 are different from Charadriiforme-like ichnites and represent a distinct bird morphology. The type 2 is similar, but is generally smaller than, *Avipeda* sp. B of SCRIVNER & BOTTJER (1986). These authors considered this ichnospecies to be related to the Ciconiiformes. Nevertheless, a close relationship of the type 2 of Navarre with the Gruiformes cannot be excluded. The order Gruiformes includes cranes, limpkins and rails and most inhabit an aquatic or swampy environment.

RAAF et al. (1965) regarded the ichnites of the type 1 as possibly related to Ciconiidae, and we agree with this interpretation. In fact, this morphotype looks similar to that of the storks, especially the marabou and closely related forms (Leptoptilini). In these storks, the interdigital webs extend to the tips of the lateral toes II and IV. In other Ciconiiformes such as the herons (Ardeidae) and hamercops (Scopidae), the hind toe (I) is notably much longer. Earliest remains of Ciconiidae come from the Upper Eocene of France and the main radiation of the group seems to have taken place in the Oligocene (OLSON, 1978; HOYO et al., 1992). Whether the Navarrese ichnites belong to Ciconiidae, this may be one of the earliest records of this bird family (and of the Order Ciconiiformes) in the world. However, it is not definitively excluded that there is a possible relationship with the primitive anseriformes, such as the magpie goose (Anseranatinea) or the screaners (Anhimidae), current inhabitants of the southern hemisphere with a digital morphology similar to the type 1 of Navarre.

As the footprints of the type 1 have never been described in the literature, it is suitable to erect a new ichnotaxon for them as follows:

Ichnogenus *Leptoptilostipus* nov.

Type ichnospecies: *Leptoptilostipus pyrenaicus* nov. ichnosp. Monospecifical ichnogenus.

Derivatio nominis: In allusion to a close likeness to the marabou (*Leptoptilos crumeniferus*) footprints.

Diagnosis: Large and slender footprints (overall length from 80 to 113 mm); slightly asymmetrical; four-toed, with three fore toes (II, III y IV) pointing forwards and a short, medially rotated hind toe (I); central toe (III) longer than the lateral toes (II and IV), the latter being slightly curved forwards; angle between toes II and IV about 120°; mesial interdigital web commonly visible extending from the tips of the lateral toes to the middle part of the central toe.

Leptoptilostipus pyrenaicus nov. ichnosp.

Pls. 21/1, 22/1, 4, 23/1-3; Figs. 5A-D, 6; Table 1

Holotype: Footprint J3.1, from the block sample J3 of the Javier outcrop (Navarre); provisionally kept in the Leyre Monastery, located near the track site. The holotype and other ichnites of the block are epireliefs corresponding to the hyporeliefs of the slab figured by Raaf et al. (1965), now kept at the Rijkmuseum van Geologie en Mineralogie (RGM 445320) of Leiden (The Netherlands).

Locus typicus: In the vicinity of the village of Javier, southeast of Pamplona (Navarre).

Stratum typicum: Liedena Sandstone Member of the Gendulain Formation, Upper Eocene.

Derivatio nominis: In allusion to the geographical and geological location of the track site.

Diagnosis: The same as the ichnogenus.

Referred material: One footprint from the sample J1, one footprint from J2 and twenty six footprints from J3 (Javier); two footprints from I7 and one more from I8 (Indurain); four footprints from LI3 and one more from LI8 (Liedena). All the material except the sample J3 is kept at the Departamento de Estratigrafía y Paleontología of the Universidad del País Vasco/Euskal Herriko Unibertsitatea, Bilbao.

5.4 Typology and taxonomic diversity

The ichnite morphology is controlled by several factors, such as the lithological composition, grain size and water content of the sediment (Scrivner & Bottjer, 1986), as well as the intraspecific variability and speed of movement of the animal. Taking into consideration these factors, the Navarrese ichnites of types 1 (*Leptoptilostipus pyrenaicus*) and 2 could be made by the same bird species, corresponding the type 1 to a more complete support of the autopodial on the ground. Even though the two types of footprints are present on the same surface, as for example in samples J1, LI8 and Z1, the previous interpretation cannot be ruled out: the original heterogeneous nature of the sediment and the fact that the tracks may have been made at very different times can explain the differences between types 1 and 2. In fact, intermediate shapes between types 1 and 2 are known in the outcrops of Liedena and Zabalza-Ibargoiti.

The same interpretation can explain the differences between the morphotypes 5 and 6, here referred to as *Charadriipeda* ichnosp. 1 and 2 respectively. Thus, it is very difficult to establish a species-type relation. If their wide biometrical interval is considered, each of types 5 and 6 could be made by more than one bird species, but taking into account their similar general form and overlapping size, the same bird species could have produced the two types of ichnites.

Type 3 shows morphological and biometrical characteristics which themselves clearly suggest a different bird species. With regard to type 4, its peculiar morphology could correspond to a different species, but a similar size to that of ichnites of type 5 might indicate the same bird (or birds) for both types of tracks.

To summarize, it is estimated that the minimal number of bird species is three (morphotypes 1-2, 3, and 4-5-6) and the maximal number is six. Yet, if types 5 and 6 represent more than two species, the maximal number of species could be greater.

6 DISCUSSION

6.1 Depositional system

The lack of internal unconformities in the Liedena Sandstone shows that the different facies represent a series of

Fig. 7. General longitudinal section and facies distribution of the Liedena Sandstone along the study area (based on the correlation of representative lithologs of the four outcrop zones in Fig. 1B). A westwards prograding depositional architecture is envisaged. Explanation within the text.

genetically related palaeoenvironments. The vertical successions of sand-dominated facies in the Urbasa and Biurrun-Undiano areas indicate a prograding, wave-influenced shoreline setting (e.g., ROEP et al., 1979; PEMBERTON et al., 1992; ROSETTI, 1997). The palaeocurrent data show that the open sea was situated towards the NW (Fig. 3). Towards the E, the deposits of the heterolithic facies association of the Izaga and Liedena-Javier areas were developed in a diverse range of restricted, marginal marine subenvironments (coastal embayment and intertidal flats). The benthic foraminiferal assemblage of these deposits supports this sedimentological interpretation. Also, the fossil bird tracks of this facies association were made by aquatic birds (tentatively Charadriiformes and Ciconiiformes) living preferentially in coastal habitats.

The Liedena Sandstone was deposited in a wave-dominated coastal complex. The observed features correspond either to a barrier-island complex or a wave-dominated delta with a large variety of subenvironments (VOS, 1981; COLEMAN & PRIOR, 1982; HADDOX & DOTT, 1990; READING & COLLINSON, 1996). The indirect data discussed below support the deltaic interpretation. The relative scarcity of burrowing organisms and the prograding character of the sandy beach deposits indicate a very high rate of sedimentation in a delta system. In addition, there is evidence of an important fluviatile influence upon the sedimentary system, supporting the delta hypothesis. The evidence includes fluviatile deposits (facies association C) and distributary channels (facies B3) flowing from emergent terrains located to the N and E respectively. On a regional scale, the Liedena Sandstone is related to large fluvial systems in SE (Martes and Biban formations; see PUIGDEFABREGAS, 1975), suggesting that rivers whose sources were located far away to the SE fed the area of deposition of the Liedena Sandstone. During the Late Eocene, the rivers of the South Pyrenean Zone flowed towards the NW parallel to the front of the Pyrenean Orogen. Where the rivers reached the coast, the waves redistributed the sediments to create a NE-SW oriented beach complex. The incidence of the waves was approximately perpendicular to the coastline. However, the palaeocurrents obtained from the beach facies association (Fig. 3) suggest the presence of longshore currents towards the NE. Tidal and storm currents had a significant influence.

In most of the study area, the Liedena Sandstone overlies red marls deposited in sabkha environments (Fig. 2). This indicates that the onset of the Liedena Sandstone deposition commenced after a rapid transgression. Nevertheless, the sedimentary successions are shallowing-upwards and record a westwards progradation of the sedimentary system and a progressive regression (Fig. 7). The final phase of this regression is recorded by the superposition of the terrestrial deposits of the Oligocene formations. Naturally, because of the progradational character of the sedimentary system, similar facies from different outcrops are of slightly different age (Fig. 7). On a larger scale, the whole of the Liedena Sandstone is diachronous in the western South Pyrenean Zone. However, the lack of good biostratigraphical data does not allow this to be undoubtedly confirmed.

6.2 Controlling factors

The relationship between climate, sediment supply, sea level changes and contemporaneous tectonism governed the evolution of the depositional system. The main factor was probably synsedimentary tectonism. A global sea-level fall took place during the Late Eocene owing to an important climatic cooling (HAQ et al., 1988). However, the regional tectonic subsidence of the South Pyrenean foreland basin was sufficiently fast to compensate for the overall regression and to create new accommodation space. This favoured the accumulation of the Liedena Sandstone. At the same time, the axial Pyrenean zone was uplifted as a consequence of increased tectonic compression. A broad area of intensive denudation was created, which fed the South Pyrenean foreland basin with a huge volume of sediments (PUIGDEFABREGAS et al., 1992; TEIXELL, 1998). Consequently, the tectonically induced high sediment supply was greater than the rate of tectonic subsidence and this favoured the progradation of the Liedena Sandstone depositional system.

In addition to exerting a regional control, synsedimentary tectonic activity had a local effect controlling the distribution of facies and sedimentary environments. Fluviatile conglomerates that include spherical clasts of shallow-marine Eocene limestones and disc-shaped sandstone clasts outcrop at the NE of the Izaga area (facies association C). The texture of these deposits indicates that their source area was relatively close to the N. However, according to PAYROS et al. (1999), there is no evidence of the existence of an Eocene carbonate platform in the North of the Izaga area which could have provided limestone clasts. The siliciclastic turbidites and carbonate megabreccias of the Hecho Group are the most probable source for these conglomerates (PAYROS et al., 1999): the disc-shaped sandstone clasts are similar to the sandstones of the turbidite beds, whereas the spherical limestone clasts can be explained as reworked clasts from the carbonate megabreccias. This hypothesis involves the erosion of at least 1500 m of Middle Eocene deposits (Fig. 2) and, accordingly, a gradual tectonic uplift of the same magnitude of the source area.

The tectonic control on the deposition of the Liedena Sandstone is evident in a N-S cross section of the Izaga area (Fig. 8). In this outcrop zone the Liedena Sandstone reaches its maximum thickness in the south of the Loiti fault and along the axis of the Izaga syncline. In both of these areas the oldest deposits were deposited in subtidal channels with high energy sedimentary structures oriented parallel to the strike of tectonic structures (facies B2; Fig. 4). In contrast, on the limbs of the syncline the sediment thickness is much smaller and the facies consists of inter- to supratidal lutites with palaeocurrent indicators perpendicular to the synclinal axis (facies B4). Thus, the facies distribution and thickness variation faithfully record the presence of areas of greater subsidence to the south of the Loiti fault and along the axis of the Izaga syncline (Monreal and Izaga syncline troughs, respectively). This reflects a gentle synsedimentary warping of the study area, with NW-SE long-shaped tectonic struc-

Fig. 8. (A) Representative lithologs of the Liedena Sandstone along a N-S section of the Izaga zone, showing facies and thickness changes (location of lithologs in Fig. 4). (B) Tentative cross-section based on the correlation of the stratigraphic profiles above. A more realistic reconstruction is given below, with a much smaller vertical exaggeration. Facies distribution seems to have been controlled by synsedimentary SE-trending folds. Thick subtidal sands accumulated in the subsiding troughs. Sedimentation rate was reduced on the adjacent uplifting highs, where inter- and supratidal lutites deposited. Explanation within the text.

tures. The synsedimentary activity of the Loiti fault controlled the inception of this flexure. The Loiti fault acted as a southward-directed blind thrust and produced a continuously sustained hangingwall palaeohigh. South of the Loiti fault the load of the thrust sheet caused strong subsidence and created a footwall syncline named here the Monreal trough. A small piggy-back basin was developed in the posterior part of the thrust sheet and prefigured the Izaga syncline. All this suggests that the western South Pyrenean Basin had begun to be incorporated into the tectonically uplifting Pyrenean Orogen during the Late Eocene.

Due to the movements of these and other tectonic structures, earthquakes occurred frequently in the study area. The seismic shocks resulted in sedimentary instabilities that led to the liquefaction of the poorly consolidated sediments (GUIRAUD & PLAZIAT, 1993; STOLLHOFEN, 1998), which explains the great abundance of soft-sediment deformational structures observed in the Liedena Sandstone.

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