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Understanding the Ichnology of Ancient Wetlands: ecosystem engineering in the Lastres Formation, Asturias

Introduction

The Late Jurassic Lastres Formation (Asturias, N Spain) has long been recognised for the exceptional record of dinosaur footprints it contains, leading to the area being known as Spain's "dinosaur coast". However, the formation also bears a high diversity invertebrate ichnofauna, recording the significant ecological impacts of bioturbating arthropods and molluscs. This invertebrate ichnofauna has never been studied in detail, or accurately placed in the context of the palaeoenvironments, despite its clear abundance and diversity.

The formation is comprised of approximately 450 m of sandstone, mudstone, and marlstone (García-Ramos et al., 2002, 2004, 2006), cropping out for 57 km along the coast of eastern Asturias between Gijón and Ribadesella (Figure 1). Structural deformation is minimal, although faulting throughout the outcrop area leads to repetition of parts of the stratigraphy. Outcrops are mostly stepped cliff type exposure with some areas of stepped exposure (sensu Shillito & Gougeon, 2023) and abundant large loose blocks, providing a comprehensive record of both vertical and surficial features. The exceptional quality of the exposure and the preservation of sedimentary structures and trace fossils is rare, and makes the Lastres Formation particularly suited as a case study to understand animal-sediment interactions.

The formation has traditionally been interpreted as being deposited in a river-dominated deltaic setting, with strata recording permanently subaerial, transitional, and permanently subaqueous parts of the system, the latter encompassing freshwater and brackish marine conditions (García-Ramos et al., 2006). The subaqueous delta plain is interpreted as extensive lagoons forming a coastal wetland system. These lagoons would have been intermittently cut off from the marine realm due to closure of inlets, and otherwise subject to coastal processes.

The Late Jurassic age of the formation is based on ammonites, ostracodes, and palynomorphs. Ammonites close to the base of the formation suggest an early Kimmeridgian age (Olóriz et al., 1988), whereas those from the middle part were dated as late Kimmeridgian (Dubar & Mouterde, 1957; Suárez Vega, 1974). The ostracod fauna dates the lower and middle parts of the formation as Kimmeridgian, and the upper part as early Tithonian (Schudack & Schudack, 2002). This is consistent

with palynological data indicating a Kimmeridgian-Tithonian age for the whole formation (Santos et al., 2022).

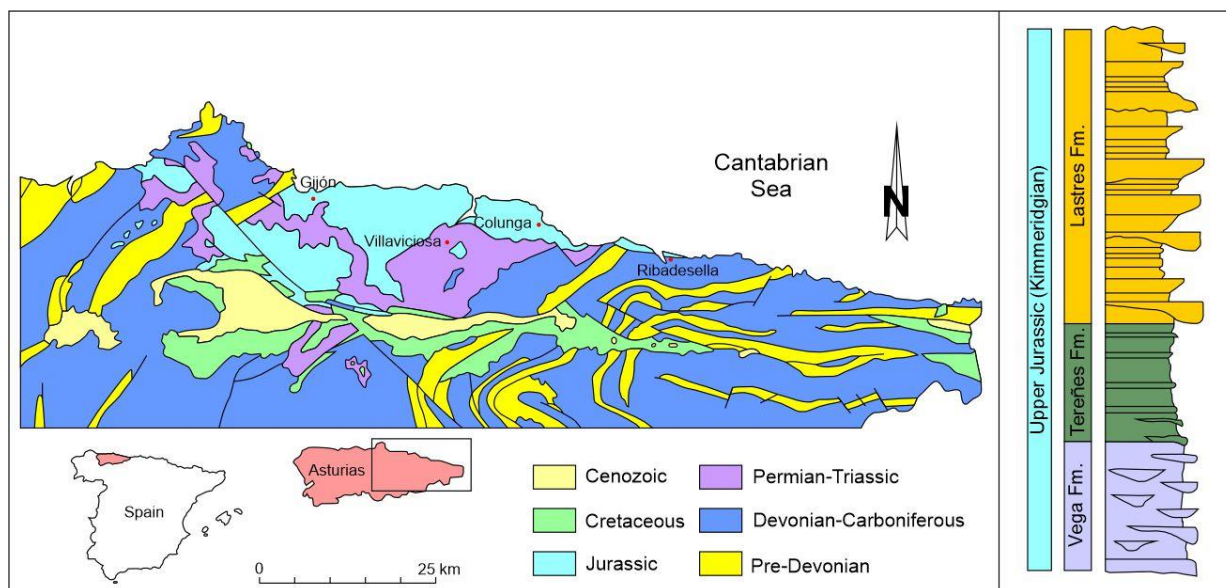


Figure 1 – Geological map of the “Dinosaur Coast” region of Asturias. Sites for this study were on the coast near Colunga, Ribadesella, and north of Villaviciosa. Stratigraphic column shows relationships and broad depositional character of the Kimmeridgian stratigraphy.

Aims and Objectives

The purpose of this project is to characterize the ichnological signatures and palaeoenvironments of the Lastres Formation, to address the question: “How did invertebrates sculpt their sedimentary habitats in ancient deltaic wetlands?”.

This question be done through meeting a series of objectives during fieldwork and subsequent analyses.

1. Make detailed observations, supported by photographs and sedimentary logs, of all of the different facies in the Lastres Formation
2. Conduct a full census of the ichnological record of the Lastres Formation and place each separate ichnoassemblage in sedimentary context.
3. Record any interactions between invertebrate traces and other organisms, such as vertebrates and plants, to fully understand how the constituents of this complex community interacted with one another, and with their surroundings.

Methods

Sedimentological and ichnological data were collected in the field from eight sites, along with re-study of material in collections held at the Museum of the Jurassic of Asturias (MUJA). Sedimentological data were collected in the form of photographs and stratigraphic logs, which were recorded through all the distinct facies, with multiple logs taken where possible to observe lateral variations. Bedding planes in outcrop and large loose boulders were photographed wherever they occurred, so any True Substrates could be accurately mapped out and examined for palaeoecological insight.

Ichnological data were collected as a census of ichnotaxa, as well as bioturbation index (in cross-section) and bedding plane bioturbation index to quantify differences within and between facies. Bioturbation index (BI) is a grade scale where the degree of bioturbation in vertical section is assigned a value between 0-6, where 0 is no bioturbation and 6 is complete bioturbation (Taylor & Goldring, 1993). Bedding plane bioturbation index (BPBI) is a grade scale where degree of bioturbation on a bedding surface is assigned a value between 1-5, where 1 is no bioturbation and 5 is > 60% bioturbation (Miller & Smail, 1997).

Results

Floodplain palaeosols

Sedimentological characteristics: Floodplain palaeosols consist of red or grey siltstone to mudstone with common green mottling (Figure 3A). Intervals range in thickness from 1 cm to 3 m and are interbedded with very fine- to medium-grained sandstones of the crevasse splay facies. Original bedding is not discernible, but some horizons picked out by colour variations. Calcrete typically occurs as small nodules, but also as large vertical concretions interpreted as rhizoliths.

Ichnological content: Trace fossils are largely indistinct bioturbation structures. However, theropod and sauropod footprints occur on some surfaces, both as discrete impressions in

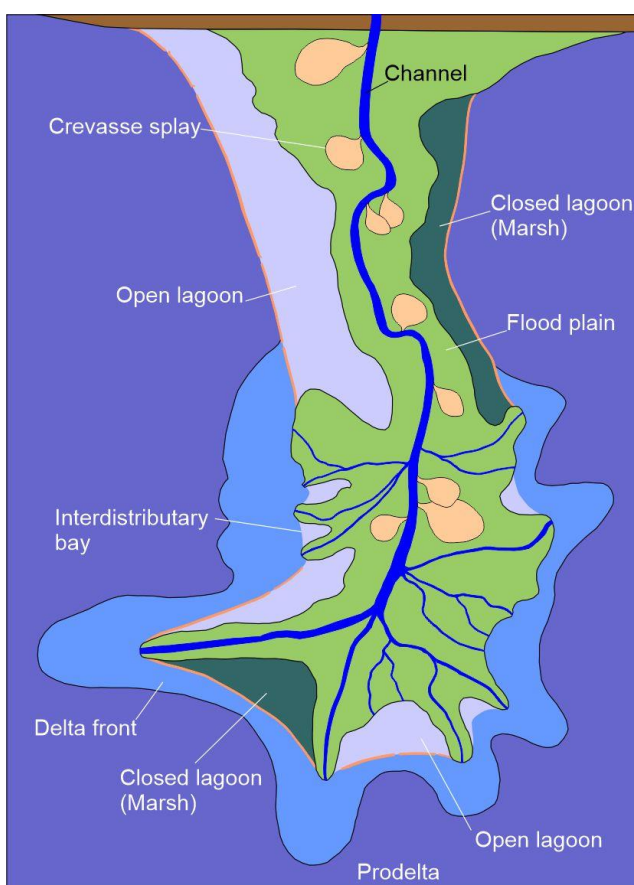


Figure 2 – Schematic illustration showing the interpreted deltaic depositional setting of the Lastres Formation.

series and as amalgamated trampled areas. BI is up to 3. As there were no definitive bedding surfaces observed, BPBI could not be measured.

Crevasse splays

Sedimentological characteristics: Crevasse splay deposits are made of very fine- to medium-grained yellow-brown sandstone (Figure 3B), 0.1 – 1.5 m thick and laterally extensive over tens of metres (the maximum observable range of the outcrops). They locally occur as discrete beds and otherwise as bedsets, with burrowed horizons at the individual bed tops/bases. Bedding is typically planar laminated, but there is rare cross-bedding or climbing ripple lamination.

Ichnological content: Typically a low diversity assemblage of burrows composed of *Taenidium* isp. and *Taenidium barretti*. Infrequent *Arenicolites* isp., *Polykladichnus irregularis* and *Skolithos linearis*. One pristine surface out of situ hosts theropod tracks and *Protichnites* isp. BI ranges from 0 towards the base of some thicker beds, to 4 towards the upper part of thicker beds. BPBI ranges from 2 to 5.

Distributary channels

Sedimentological characteristics: Proximal distributary channel deposits closely resemble true fluvial deposits and correspond to the subaerial delta plain, whereas their distal distributary channel counterparts occur on the subaqueous delta plain. These deposits are comprised of two distinct facies, the majority recording downstream accretion and the remainder showing evidence for lateral accretion. Downstream accreting facies are thick (1 – 6 m) accumulations of stacked, amalgamated, trough cross-bedded medium- to coarse-grained sandstone packages. Some beds contain a high abundance of large plant fossils. Laterally accreting facies are heterolithic cross-bedded strata, c. 2.5 m thick. Strata are interbedded medium- to coarse-grained sandstone, mudstone-chip conglomerate, and plant debris horizons. A thin (10 cm thick) layer of parallel-laminated black mudstone rich in organic material occurs immediately above the cross-bedded strata.

Ichnological content: Ichnological content: Throughout most of this facies no trace fossils were observed. However, the top surfaces are bioturbated with a similar ichnological assemblage to that observed in crevasse splays. One bedding surface mid-section contained theropod footprints alongside indistinct burrow apertures (Figure 3E). Trace fossils include *Taenidium* isp. and undetermined burrow tops, with BPBI up to 4. BI is 0 throughout, other than just below the bioturbated surfaces where it increases to 2.

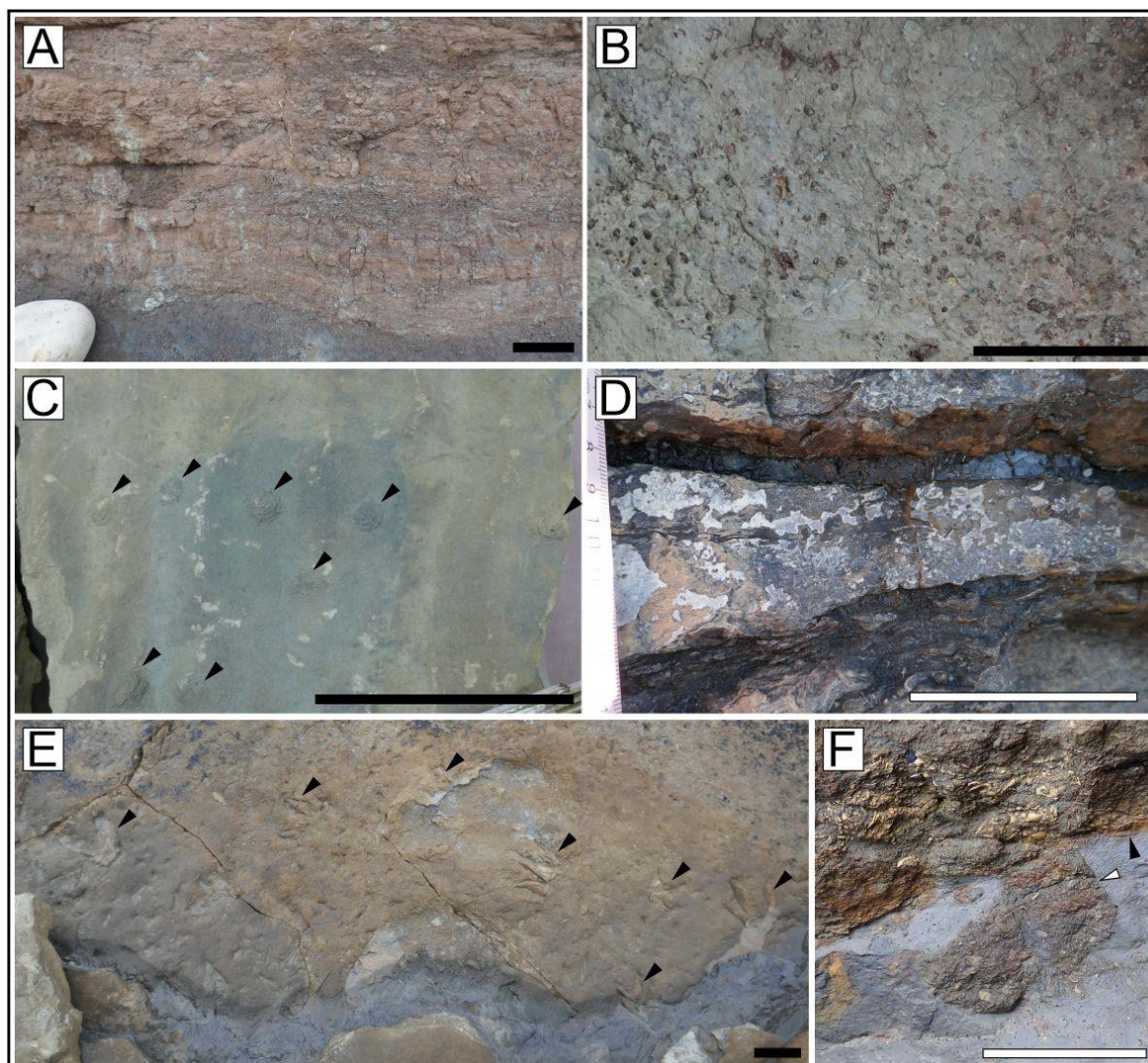


Figure 3 – Strata of the Lastres Formation A) Horizontation in palaeosol deposits with layers picked out by slight colour variation. These may not be original depositional layers, but instead due to post depositional differentiation of the soil profile. B) Typical bedding surface from the crevasse splay facies. Surface is degraded and contains a dense assemblage of non-distinct burrow apertures. C) Rippled bedding surface from open lagoon/interdistributary bay facies, with *Cumulusichnus asturiensis* (black arrows). D) Bands of coal interbedded with mudstone and shell accumulations. This is interpreted as deposits in a closed lagoon, cut off from normal marine activity except when the marginal barrier is overtopped by a transgressive event leading to deposition of the shell beds. E) Theropod footprints on a shallowly dipping bedding surface deposited as a point bar in a distributary channel. Footprints are well defined and shallow suggesting that the sediment was not entirely saturated when they were produced. F) Ravinement surface at the boundary between delta front and transgressive deposits marking an interval of stasis preserved in vertical section. Black arrow – irregular ravinement surface. White arrow - ?*Thalassinoides* in cross section, protruding from the base of the ravinement surface. Black scale bar – 20 cm, white scale bar – 5 cm.

Closed Lagoon - Marsh

Sedimentological characteristics: Accumulations of organic material preserved as coal interbedded with parallel-laminated dark grey-black mudstone (Figure 3D) and dense shell accumulations (likely related to transgressive deposits). Beds are mm to cm scale and are laterally discontinuous and locally convoluted. No other sedimentary structures were observed, although this facies was only observed in vertical section.

Ichnological content: No invertebrate or vertebrate trace fossils were observed.

Open/Restricted Lagoon – Interdistributary Bay

Sedimentological characteristics: Interdistributary bay deposits comprise interbedded fine- to medium-grained yellow-grey sandstone and mudstone with local marl. Bedding is mostly parallel-laminated, with subordinate wave ripple cross-lamination and flaser bedding. Sedimentary structures observed on bedding surfaces include symmetrical ripples (Figure 3D), in places bifurcating or with flat tops or drainage marks, synaeresis cracks, and microbially induced sedimentary structures (MISS), including the pseudofossil *Aristophycus*. Ripple troughs may host accumulations of phytodetrital material.

Ichnological content: Trace fossils are most diverse in this facies, with the following ichnotaxa represented: *Archaeonassa fossulata*, *Cumulusichnus asturiensis*, *Diplocraterion parallelum*, *Gordia marina*, *Gyrochorte comosa*, *Koupichnium* isp., *Lockeia siliquaria*, *Ophiomorpha nodosa*, *Palaeophycus tubularis*, *Planolites montanus*, *Polykladichnus* isp., *Ptychoplasma* isp., *Spongiomorpha* isp., *Teichichnus rectus*, *Thalassinoides suevicus*, and *Treptichnus bifurcus*. BI ranges from 0-5, with most beds in the range 0-2, and BPBI ranges from 1-5.

Transgressive deposits

Sedimentological characteristics: Beds up to 50 cm thick, comprised mostly of gastropod or bivalve shells, with a matrix of grey mudstone or yellow fine-grained sandstone.

Ichnological content: Most occurrences of this facies contain no trace fossils. Locally dense burrows protrude from the base of the beds (Figure 3F), forming a “*Glossifungites* suite” comprised of *Rhizocorallium* isp. and *Thalassinoides* isp. BI is 2-3 at the bases of these beds, and 0 further up the beds.

Delta front

Sedimentological characteristics: These deposits consist of packages of mudstone interbedded with siltstone to medium-grained sandstone, in some incidences showing a coarsening upward trend within

the mudstone-sandstone couplets. Mudstone is parallel laminated with limited bioturbation, whereas siltstone-sandstone vary from planar to trough cross-bedded and contain a greater diversity of trace fossils. This facies has a transitional contact with underlying prodelta facies deposits, and overlying subaqueous delta plain deposits.

Ichnological content: Trace fossils present include: *Arenicolites* isp., *Diplocraterion parallelum*, *Skolithos linearis*, and *Taenidium* isp., as well as poorly preserved dinosaur tracks. BI ranges from 0-5, and BPBI from 1-5.

Prodelta

Sedimentological characteristics: Prodelta deposits consist of parallel-laminated mudstone, siltstone, and marl, interbedded with transgressive lag facies. Mudstone is fissile and contains cm-scale nodules locally. Bioturbation is mostly sparse, but a few beds are densely bioturbated.

Ichnological content: Trace fossils present include *Lockeia siliquaria*, *Palaeophycus tubularis*, *Rhizocorallium* isp., *Skolithos* isp., *Teichichnus rectus*, and escape structures (Fugichnia). BI ranges from 0-4 and BPBI from 1-4.

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