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Paleoenvironment and ichnofacies diversity in the Maastrichtian of the Western High Atlas, Morocco

Naji Jdaba[1*], Ahmed Algouti[2], Ali Aydda[1], Fatiha Hadach[1], Mohcine Jdaba[2]

[1] Department of Geology, Faculty of Sciences, Ibn Zohr University, 80000, Agadir, Morocco
[2] Laboratory Sedimentary Basins Geology of Morocco, "2GRNT" Geology Department, Faculty of Science Semlalia, University Cadi Ayyad, BP 2390, 40000, Marrakech, Morocco
* Corresponding author's e-mail: naji.jdaba@edu.uiz.ac.ma

ABSTRACT

This study aims to reconstruct the paleoenvironmental conditions of the Maastrichtian phosphate series in the Western High Atlas region of Morocco, with particular focus on the Oued Lahouar and Erguita sections. The research investigates the diversity and distribution of ichnofossils—trace fossils that preserve evidence of biological activity – to better understand the ecological and sedimentary dynamics of the Maastrichtian epoch. A detailed field survey and stratigraphic analysis were conducted across key phosphate-bearing formations, during which a variety of ichnotaxa were identified and classified into distinct ichnofacies. These ichnofacies, including Thalassinoïdes, Arenicolites, Diplocraterion, Lockeia, Ophiomorpha, and Skolithos, provide critical insight into depositional settings ranging from well-oxygenated shoreface environments to nutrient-rich marine substrates. They also reflect parameters such as sedimentation conditions, substrate stability, and the intensity of biological activity. Photographic documentation and sedimentological descriptions supported the ichnological interpretations. The main results reveal notable ichnodiversity and clear spatial variation in ichnofacies, suggesting a dynamic paleoenvironment influenced by fluctuations in sea level and sedimentation rates. These findings contribute to a more refined understanding of Maastrichtian paleogeography in the region. While the study is limited to two key stratigraphic sections, the results offer a valuable baseline for broader regional comparisons. Future research could extend to adjacent basins to validate and deepen the paleoenvironmental interpretations. The practical value of this research lies in its contribution to paleoecological modeling, geoconservation, and the understanding of Morocco's geological heritage. This detailed ichnofacies-based study comparing two sections of the Western High Atlas highlights the originality and scientific significance of using ichnological evidence to reconstruct late Cretaceous environments.

Keywords: paleoenvironment, ichnofacies, Maastrichtian, High Atlas, Morocco.

INTRODUCTION

The southern sector of the Western High Atlas, referred to as the "Souss-Ouarzazate Gulf" (Figure 1), exhibits a distinctive geological framework shaped by the orogenic uplift of the High Atlas Range. This region showcases a progressive transition from marine to lagoonal and ultimately continental sedimentary environments along a west-to-east gradient (Algouti et al., 1998, 2015, 2022; Hadach et al., 2015, 2017). The Maastrichtian epoch in this area provides crucial insights into biostratigraphy, lithostratigraphy, and paleogeography, with a particular emphasis on fossil and trace fossil assemblages. Key findings include Maastrichtian ostracods, echinoderm remains, and diverse ichnofossils, such as Thalassinoïdes, Arenicolites, and Lockeia traces.

Paleogeographically, the Maastrichtian was characterized by an Atlantic transgression that isolated the Erguita Basin from the phosphorus-rich Atlantic waters. The phosphate series in the Erguita Basin is marked by rhythmic sedimentation, alternating between carbonate and phosphate-rich strata with organic residues. This sedimentation pattern indicates active phosphatogenesis driven by intense benthic activity in warm, shallow, and well-oxygenated environments. In contrast, the

Agadir Basin to the west reflects an open marine connection, featuring deeper fossiliferous sediments but lacking evidence of phosphatogenesis. To the east, the Aoulouz sector displays lagoonal to brackish influences, suggesting that this area functioned as a collection of small sedimentary basins.

The study of Maastrichtian strata within the Western High Atlas has provided valuable data on biostratigraphy, lithostratigraphy, ichnology, and paleogeography. The primary aim of this study has been the identification of trace fossils from the Agadir Basin in the west, and the Erguita Basin in the central region of the Western High Atlas, each showing distinct environmental conditions conducive to phosphate precipitation and influenced by morphological traps (Jdaba et al., 2023), which provides a comprehensive paleoenvironmental framework that simplifies the sedimentary history and geological evolution of the study region during the Maastrichtian epoch.

Geological setting

The study area is located in the Western High Atlas (Figure 1), bounded by the Western Meseta to the north, the Anti-Atlas to the south, the Central High Atlas to the east, and the Atlantic Ocean to the west. It includes the South Sub-Atlasic Trough, extending from the Agadir and Boulaajlate trench in the west to the Aoulouz region in the east.

Paleogeographical setting of the Senonian in the Atlas Domain

During the Senonian (Upper Cretaceous), three distinct gulfs of varying sizes formed in Morocco as a result of the Atlantic Ocean transgression (Choubert and Salvan, 1950):

- The Gulf of the Phosphate Plateau of the Eastern Meseta: Also referred to as the "Grand Inter-Atlas Gulf."
- The Gulf of Haouz in Marrakech: Known as the "Northern Sub-Atlas Gulf," it was separated from the Grand Inter-Atlas Gulf by the Jebilet Massif.
- The Gulf of Souss-Ouarzazate: Often called the "Southern Sub-Atlas Gulf," this gulf was isolated from the others by the uplift of the High Atlas range.

At the onset of the Senonian, the uplift of the High Atlas range delineated the Northern and Southern Sub-Atlas Gulfs (Choubert and Faure-Muret, 1962). As the Senonian progressed, the Atlantic Ocean retreated from much of the High Atlas range (Choubert and Salvan, 1950; Choubert and Faure-Muret, 1962). A significant Maastrichtian transgression of the Atlantic followed, forming the gulfs along the Jebilet, Rehamna, and High Atlas regions, with "finger-like" projections shaped by the underlying topography.

This study focuses on the Southern Sub-Atlas Gulf, which exhibits a west-to-east transition from marine facies to lagoonal, lacustrine, and finally continental facies (Algouti et al., 2015). These transitions provide critical insights into the paleogeographical and depositional dynamics during the Maastrichtian.

MATERIALS AND METHODS

To reconstruct the paleogeography of the Maastrichtian epoch in the Western High Atlas, several field missions were conducted. Sedimentological facies analysis was carried out in the field to identify depositional environments by

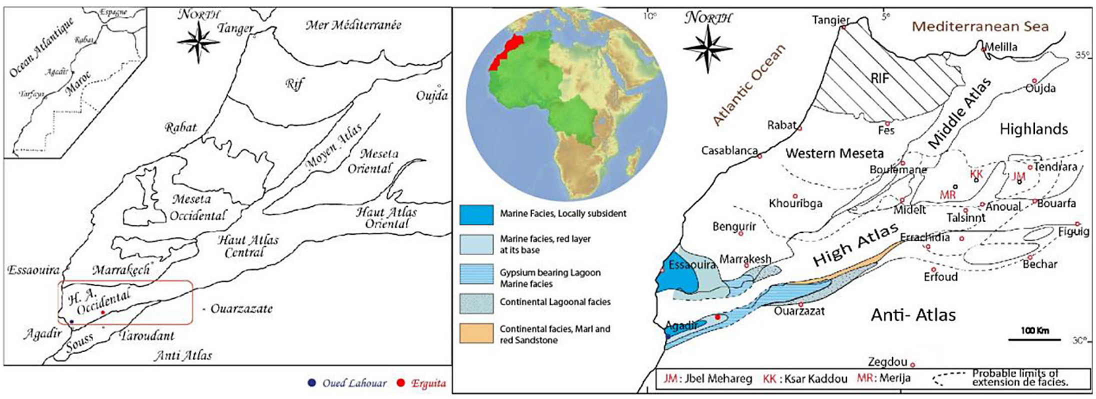

Figure 1. Geological and geographical location maps of Oued Lahouar and Erguita sections

examining sediments and comparing them with similar facies in other regions.

Fieldwork focused on identifying sedimentary structures, with detailed lithological observations made in two primary study areas: *Oued Lahouar* (Figure 2) and *Erguita* (Figure 3). These investigations revealed a general lithostratigraphic subdivision into three units, although Oued Lahouar preserves only the first two.

Ichnological analysis involved observing and documenting trace fossils visible in outcrops. The most prominent fossil traces were photographed, and their paleoenvironmental significance interpreted based on the surrounding sedimentary context. For the creation of location maps, geological cross-sections, and trace fossil plates, a suite of software tools was employed, including *Adobe Illustrator*, *Adobe Photoshop*, *Photofiltre*, and *Inkscape*.

RESULTS

Oued Lahouar section

Two major unconformities were observed in the Oued Lahouar section. The lower boundary separates Campanian marls lithologies from the overlying Maastrichtian carbonates, while the upper contact marks a transition to Oligocene conglomerates (Ambroggi, 1963). Based on lithological and sedimentological features, two stratigraphic units (U1 and U2) were identified within the Maastrichtian formation (Jdaba et al., 2024).

- Unit U1:
  - Subunit 1 (22 m) – this subunit displays a three-term elementary sequence, transitioning from fossiliferous lumachellic limestone (wackestone texture), less fossiliferous marly dolomitic limestone (mudstone texture), and finally to grayish azoic marl. This sequence reflects an environmental gradient from mediolittoral to supralittoral settings, indicating bathymetric changes and increasing environmental confinement. Bioturbated and perforated surfaces were noted throughout (see Fig. 2).
  - Subunit 2 (30 m) – composed of marly layers interbedded with limestone beds and characterized by lenticular tidal channels, hummocky tempestite structures, bioturbation (e.g., Skolithos, Arenicolites, Lockeia),

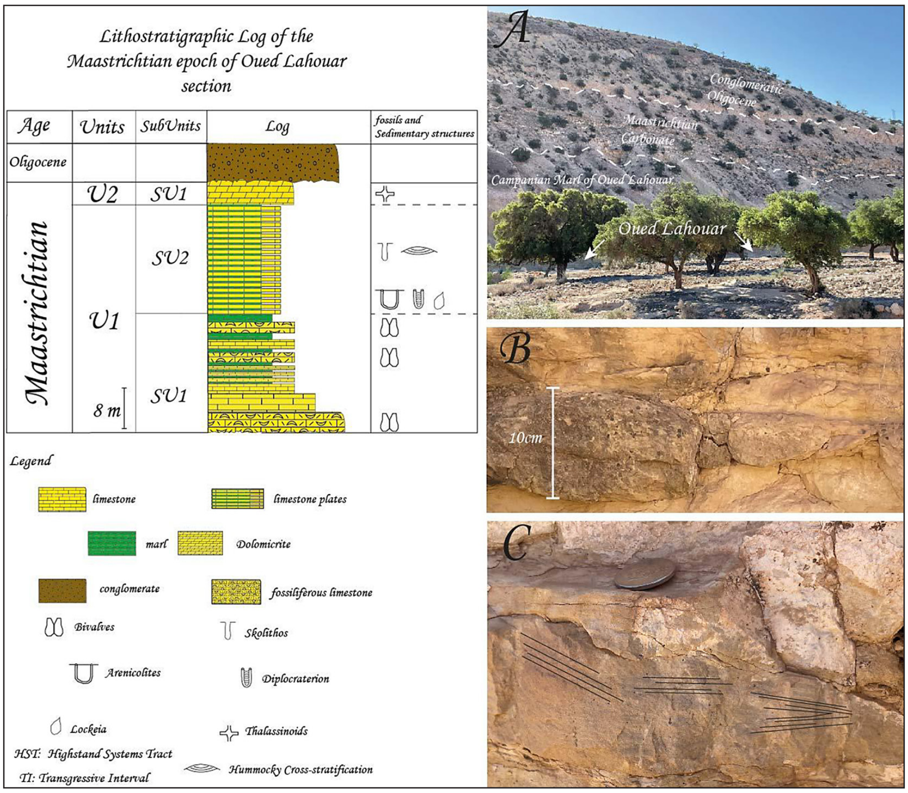

Figure 2. Lithostratigraphic Log of the Oued Lahouar section: (a) a panoramic view of the section showing the upper and lower discontinuities, limiting the Maastrichtian carbonates, (b) lenticular tidal channels, (c) parallel and cross laminae

and carbonate nodules. These features suggest episodic high-energy conditions and varying levels of environmental stability (see Fig. 2b–c; Fig. 4c–h).

- Unit U2:
  - Subunit 1 (10 m): this unit features two lenticular dolomicrite beds with prominent Thalassinoïdes burrows at the top (Fig. 4a–b). These ichnofossils, associated with well-oxygenated, nutrient-rich environments and firmground substrates, indicate post-depositional burrowing activity by decapod crustaceans. The unit is capped by an erosional unconformity overlain by Oligocene conglomerates (Ambroggi, 1963).

Erguita section

The Maastrichtian succession in the Erguita section spans approximately 205 m, bounded by erosional contacts with underlying Campanian and overlying Eocene strata (Jdaba et al., 2023). Three units (U1, U2, and U3) were defined based on sedimentological variability and ichnological features.

- Unit U1 (73 m):
  - Subunit 1 (42 m): this subunit begins with phosphatic micro-conglomerates, rich in fish teeth and bone debris (Fig. 3b, 3d), underlain by an erosive surface. The sequence progresses into phosphatic sands interspersed with fossiliferous carbonate benches and marly laminae with flint nodules (Fig. 3e). Bioturbation, particularly sub-vertical burrows, is prominent, alongside stromatolitic structures and parallel laminae (Fig. 6a–b).
  - Subunit 2 (31 m): dominated by azoic phosphatic sands and bioturbated carbonate benches, this subunit features stromatolitic structures, silicified marl levels, and erosive-based detrital lenses, indicating fluctuating depositional energy and substrate conditions.

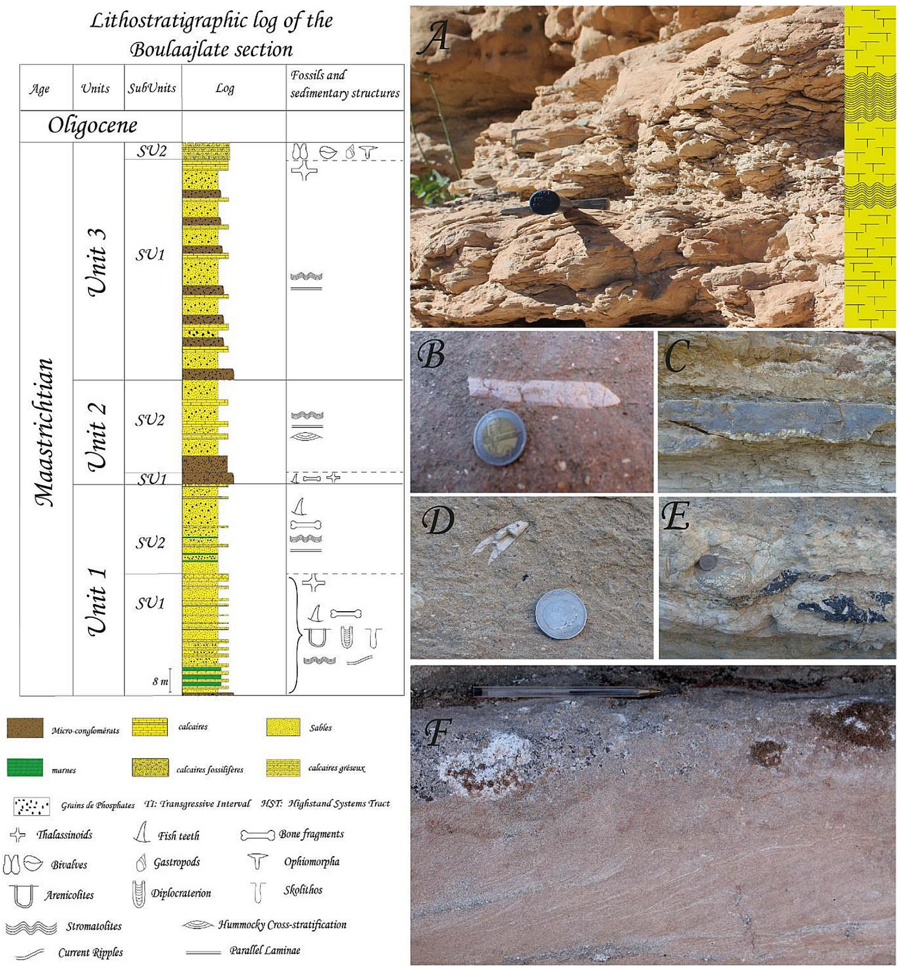

Figure 3. Lithostratigraphic Log of the Erguita section, with the main sedimentological facies characteristics: (a) stromatolites, (b) bone fragments found in the microconglomerates, (c) channel-shaped lenses, (d) fish teeth found in the microconglomerates, (e) flint nodules found in limestones, (f) current Ripples

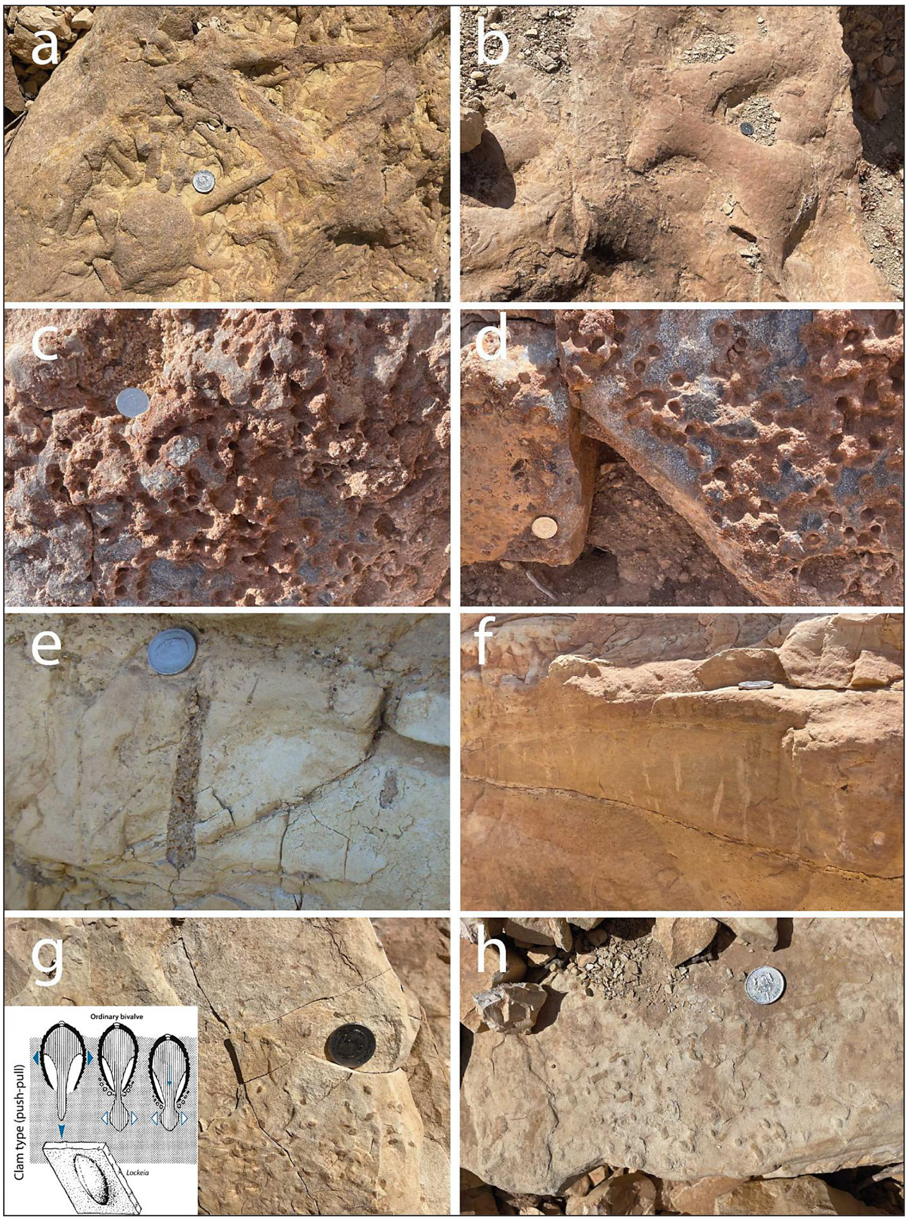

Figure 4. Ichnofossils of Oued Lahouar section, (a and b) Thalassinoides, (c and d) Arenicolites mixed with Diplocraterion, (e and f) Skolithos trace fossils, (g and h) Lockeia trace fossils

- Unit U2 (36 m):
  - Subunit 1 (4 m): a basal fossiliferous conglomerate level, rich in vertebrate remains, exhibits an erosive base and granule-decreasing textures.
  - Subunit 2 (32 m): sandy-phosphatic and azoic layers alternate with carbonate benches containing stromatolitic features and parallel lamination, indicating depositional variability.
- Unit U3 (98 m):
  - Subunit 1 (82 m): consists of alternating micro-conglomerates, phosphatic sands, and carbonate levels. Bioturbation increases towards the summit, with Thalassinoïdes burrows (Fig. 5a–f), indicating firmground conditions and nutrient-rich substrates.
  - Subunit 2 (16 m): Lumachelic carbonate benches containing gastropod and lamellibranch remains culminate in a bioturbated and perforated level (see Fig. 3), suggesting paleoenvironmental stability with episodes of increased biological activity.

Ichnological analysis of the Oued Lahouar and Erguita sections

This study documents, for the first time in the Western High Atlas, the distribution and

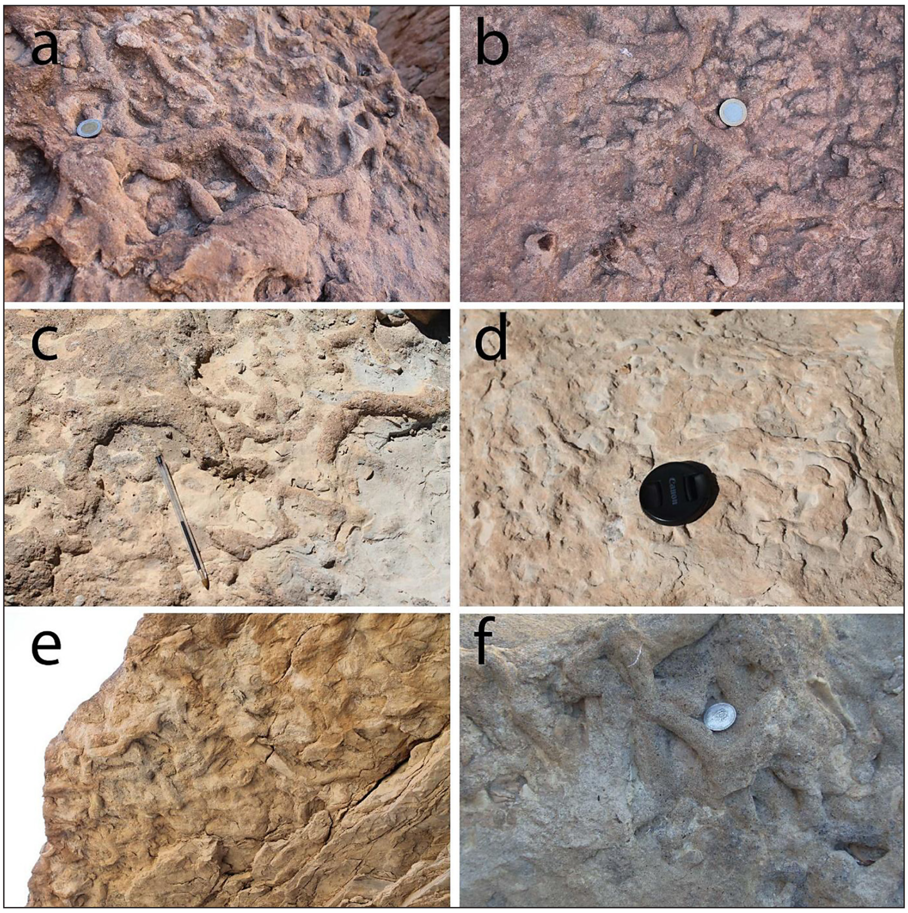

Figure 5. Different thallassinoids trace fossils found in the Erguita section, (a and b) Thalassinoides-type trace fossils found in all the SIM levels of the Erguita section, (c and d) altered thallassinoides in carbonate facies, (e and f) Thalassinoides found in the base of the micro-conglomerates

diversity of well-preserved Maastrichtian ichnofossils across two stratigraphic sections. These trace fossils provide critical insight into the paleoenvironmental settings and ecological dynamics of the region during the Late Cretaceous.

Arenicolites

Arenicolites is a U-shaped ichnofossil that appears as paired circular impressions preserved in positive hyporelief on the top surfaces of sandstone beds (Fig. 4 c and d). In weathered sections, these impressions become hollowed, creating distinct, symmetrical openings. The diameter of the burrows typically ranges between 1 and 3 cm. Arenicolites is interpreted as a domichnion—a dwelling trace – produced by suspension-feeding or detritus-feeding organisms, likely polychaetes or other deposit feeders (Hantzschel, 1975; Jensen, 1997). Modern analogs include burrows of coastal polychaetes such as *Spionida* and *Capitellida* (Gingras et al., 1999; Dashtgard, 2011). This ichnofossil indicates a shallow marine environment with moderate energy and nutrient availability.

Diplocraterion

Diplocraterion consists of vertically oriented U-shaped burrows with spreiten, often preserved in positive hyporelief (Fig. 4 c and d). The spreiten are indicative of sediment reworking by burrowing organisms, potentially for feeding or dwelling purposes. These traces suggest an environment with frequent sediment deposition and reworking, typical of shoreface to shallow marine settings. Diplocraterion reflects the activity of suspension-feeding or detritus-feeding organisms, thriving in oxygenated and well-sorted substrates (Seilacher, 2007).

Thalassinoïdes

Thalassinoïdes are horizontally branching burrow networks with T- or Y-shaped intersections (Fig. 5, Fig 4a and 4b), characterized by

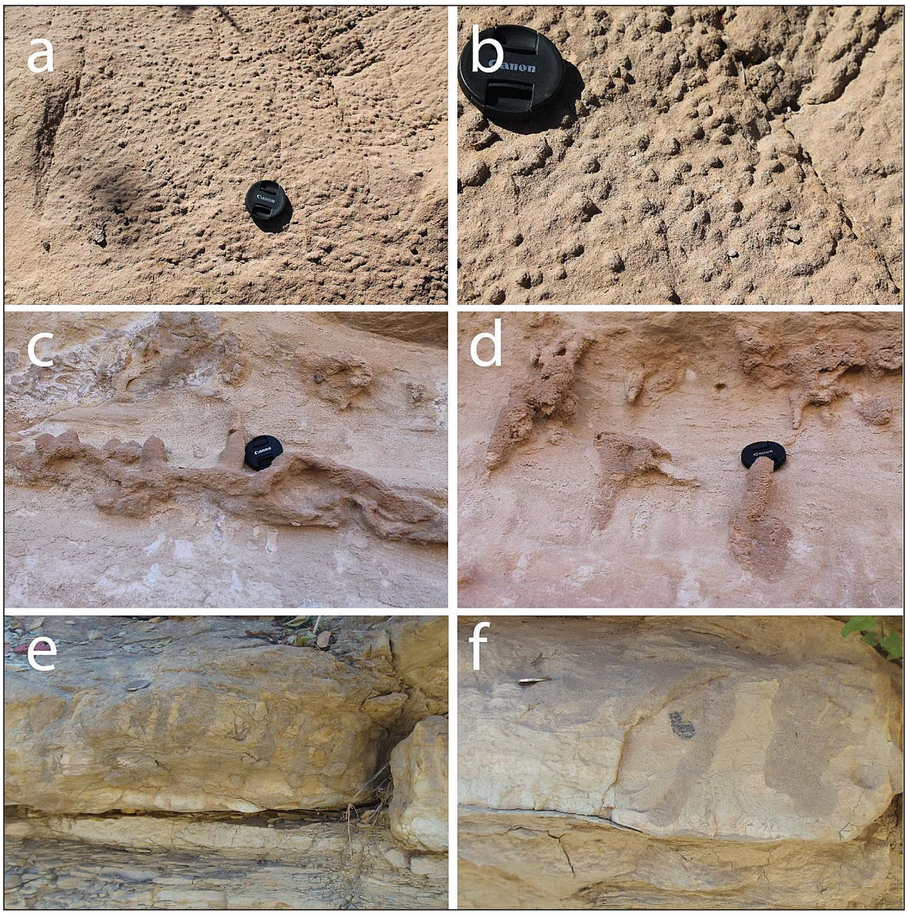

Figure 6. Ichnofossils of Erguita section: (a and b) Skolithos/Arenicolites-type trace fossils found in the lower levels of the section, (c and d) Ophiomorpha-type trace fossils found in the upper levels of the last unit of the section, (e and f) Skolithos-type trace fossils viewed in cross-section

well-defined walls. These ichnofossils are preserved as full reliefs and are often associated with firmground substrates indicative of early consolidation stages. Thalassinoïdes are attributed to decapod crustaceans, which utilized these burrows as both dwelling (*domichnia*) and feeding (*fodinichnia*) structures (Rodríguez-Tovar et al., 2009). Their abundance in the dolomitic limestones of Oued Lahouar (Fig. 4 c and d) and the bioturbated carbonate benches of Erguita (Fig. 5 a and b) indicates oxygenated, nutrient-rich conditions with low sedimentation rates (Frey & Pemberton, 1984).

Skolithos

Skolithos is a vertical, cylindrical burrow typically associated with high-energy environments, such as shoreface and shallow marine settings (Fig. 4 e and f, Fig. 6 e and f) (Seilacher, 1967). The burrows are narrow, 2–3 cm wide and 7–8 cm deep, and are often found in fine to medium-grained sandstone, with occurences that can be found from somewhat deeper areas off the coast (Alpert, 1974). Skolithos reflects opportunistic colonization by suspension-feeding organisms, thriving in environments characterized by frequent sediment movement and rapid deposition.

Lockeia (*Oued Lahouar section*)

Lockeia traces are almond-shaped impressions preserved in positive hyporelief (Fig. 4 g and h), interpreted as resting traces (cubichnia) of bivalves (Seilacher, 2007). These ichnofossils suggest periods of stability within intertidal to shallow subtidal environments, where bivalves temporarily settled on the sediment surface (Maples and West, 1989).

Ophiomorpha (*Erguita section*)

Ophiomorpha consists of lined burrows with knobby walls, formed by pellets compacted by the burrowing organism (Fig. 6 c and d). These traces are attributed to crustaceans, such as shrimp, that created reinforced burrows in sandy substrates to prevent collapse (Bromley and Frey, 1974; Frey et al., 1978). The presence of Ophiomorpha suggests a high-energy environment with abundant organic matter, suitable for decapod activity (Häntzschel, 1952).

Paleoenvironmental implications

The trace fossil assemblages reflect a dynamic depositional system influenced by shifting sea levels and sedimentation rates. The dominance of Skolithos and Thalassinoïdes ichnofacies points to transitions between high-energy shoreface and low-energy marine environments. Arenicolites and Diplocraterion suggest moderate sedimentation and substrate reworking, while Lockeia and Ophiomorpha highlight substrate stabilization phases and intense biotic activity. The spatial and vertical variation in ichnofacies between the Oued Lahouar and Erguita sections underscores their utility in reconstructing the paleoenvironmental evolution of the Maastrichtian in the Western High Atlas.

DISCUSSION

The sedimentary succession of the Oued Lahouar and Erguita sections has revealed an ichnological assemblage comprising five ichnospecies: *Arenicolites*, *Diplocraterion*, *Thalassinoïdes*, *Skolithos*, and *Lockeia*. Each ichnospecies provides insights into the depositional environments, energy conditions, and paleoecological dynamics of the studied sections.

The *Arenicolites* ichnofacies occurs in fine- to medium-grained sandstone layers, often associated with ripple marks and moderate bioturbation. These U-shaped burrows reflect dwelling traces of detritus feeders, likely polychaetes or other suspension feeders. *Arenicolites* is commonly associated with shallow marine environments influenced by moderate energy conditions and periodic nutrient influx (Hantzschel, 1975; Jensen, 1997). The association with ripple-marked sandstone beds indicates episodic wave or tidal activity, while the absence of spreiten suggests relatively stable sedimentation conditions.

The *Diplocraterion* is preserved as U-shaped vertical burrows with spreiten, indicative of sediment reworking by the tracemakers. These features are characteristic of shoreface to shallow marine environments with frequent sediment deposition and reworking. The dominance of *Diplocraterion* in the Erguita section suggests episodic sedimentation and relatively high oxygenation, supporting a dynamic and well-oxygenated substrate (Frey & Pemberton, 1984). Its abundance in the studied sections underscores its role as an indicator of energetic marine conditions, potentially linked to wave or current activity.

The horizontally branching burrow networks of *Thalassinoïdes* are indicative of decapod crustacean activity, associated with both dwelling and feeding behaviors. The presence of *Thalassinoïdes* in the dolomitic limestone and carbonate-rich benches of both sections reflects nutrient-rich, low-energy conditions. The abundance of these burrows in bioturbated horizons aligns with environments where sedimentation rates are low, allowing for prolonged tracemaker activity. *Thalassinoïdes* is considered a hallmark of firmground substrates, highlighting periods of early diagenesis and substrate consolidation.

The vertical burrows of *Skolithos* are primarily observed in medium-grained sandstone, often associated with high-energy environments such as shorefaces. The burrows' narrow, cylindrical morphology suggests colonization by suspension feeders in sandy substrates, with high sediment mobility and frequent deposition (Seilacher, 1967). *Skolithos* assemblages are a reliable indicator of shallow marine environments subject to wave and tidal action, and their distribution in the Oued Lahouar section confirms the prevalence of such conditions during deposition.

The almond-shaped *Lockeia* traces, interpreted as cubichnia or resting traces of bivalves, suggest periodic stability in intertidal to shallow subtidal zones (Maples and West, 1989). Their association with sandy substrates and occasional bioturbation reflects low-energy intervals within otherwise dynamic depositional settings. The distribution of *Lockeia* in the Oued Lahouar section aligns with temporary pauses in sediment influx, allowing for benthic colonization and preservation.

The *Ophiomorpha* ichnofossils, observed specifically in the Erguita section, are characterized by large, lined burrows with knobby walls, commonly attributed to the burrowing activity of decapod crustaceans (Bromley and Frey, 1974; Frey, Howard and Pryor, 1978). These burrows indicate well-oxygenated, high-energy nearshore environments with loose, sandy substrates (Häntzschel, 1952). The presence of Ophiomorpha in the Erguita section suggests significant bioturbation in a shoreface setting, where wave and tidal currents facilitated sediment reworking. The lined nature of the burrows indicates active reinforcement by the tracemakers to maintain burrow stability in shifting sands, reinforcing its association with dynamic coastal environments (Howard, 1978).

Paleoenvironmental implications

The ichnological and sedimentological data collectively suggest that the Oued Lahouar and Erguita sections were deposited in shallow marine environments, with varying energy levels and nutrient availability. The predominance of *Skolithos* and *Arenicolites* points to high-energy shoreface conditions, while the presence of *Thalassinoïdes* and *Diplocraterion* indicates localized areas of lower energy and prolonged substrate stability. The assemblage of *Lockeia* traces further highlights periods of reduced sedimentation, facilitating bivalve colonization. The presence of *Ophiomorpha* in the Erguita section adds further evidence of high-energy nearshore conditions, influenced by strong currents and sediment reworking.

The abundance of bioturbation structures, particularly in carbonate-rich horizons, underscores the role of biological activity in shaping sedimentary fabrics. This biogenic reworking aligns with depositional settings where sediment supply was episodic, allowing for prolonged organism activity and preservation of ichnological features.

Comparison with modern and ancient analogues

The ichnological characteristics of the studied sections closely resemble modern shallow marine and marginal marine environments influenced by wave and tidal processes. Similar ichnofacies have been reported in Lower Paleozoic shoreface deposits, where *Arenicolites* and *Diplocraterion* are commonly associated with tidal flats and estuarine settings (Hofmann et al., 2012). Additionally, the firmground-associated *Thalassinoïdes* traces align with carbonate platform environments, where early cementation and reduced sedimentation enhance preservation potential (Frey & Pemberton, 1984).

The ichnofacies distribution in the Oued Lahouar and Erguita sections highlights the lateral and vertical variability in depositional environments. This heterogeneity is consistent with dynamic sedimentary regimes, influenced by fluctuating energy conditions and episodic sedimentation (Jdaba et al., 2024). The ichnological evidence corroborates sedimentological data, confirming a shallow marine setting with periodic transitions to more restricted, nutrient-enriched conditions.

CONCLUSIONS

This study presents new and significant ichnological and sedimentological data from two key Maastrichtian sections in the Western High Atlas – Oued Lahouar and Erguita – providing one of the most comprehensive ichnofacies-based reconstructions for this period and region. The findings demonstrate distinct and contrasting depositional settings: Oued Lahouar reveals a shallow, confined environment transitioning from mediolittoral to supralittoral zones, while Erguita exhibits a more dynamic system marked by episodic high-energy events, phosphatogenesis, and increased bioturbation (Jdaba et al., 2023).

The identification and in situ documentation of six ichnotaxa – *Arenicolites*, *Diplocraterion*, *Thalassinoïdes*, *Skolithos*, *Lockeia*, and *Ophiomorpha* – represent a novel contribution to the ichnological record of the Maastrichtian in Morocco. The detailed analysis of their distribution within well-defined stratigraphic and sedimentological frameworks provides new insights into paleoecological conditions, such as substrate consistency, oxygenation levels, energy regimes, and sedimentation rates. Notably, the widespread presence of Thalassinoïds in both sections highlights periods of stable, nutrient-rich, well-oxygenated marine conditions, supporting a refined interpretation of firmground colonization in the late Cretaceous.

The study also identifies a clear spatial variation in ichnofacies, marking a key advancement in understanding lateral paleoenvironmental gradients in the region. This variation reflects the influence of fluctuating sea levels, storm dynamics, and sediment influx, contributing valuable information to regional paleogeographic models of the Upper Cretaceous.

Furthermore, ichnological comparisons with other Moroccan formations, such as the Upper Visean of the Eastern Jebilet (Kodiat Sidi Boumediane and Kodiat Oulad Abid), which indicate shallow marginal marine conditions, highlight the value of ichnofacies analysis for reconstructing paleoenvironmental settings across geological periods.

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