Sedimentology and ichnology of a shallow-marine clastic system from the Silurian-Devonian Furada Formation of Asturias, Spain: Benthic response to event deposition and environmental disturbance

A Thesis Submitted to the College of Graduate and Postdoctoral Studies In Partial Fulfillment of the Requirements For the Degree of Master of Science In the Department of Geological Sciences University of Saskatchewan Saskatoon

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ABSTRACT

The Furada Formation of Asturias, Spain, represents a clastic, wave-dominated shallow-marine unit deposited during the middle Silurian to the Early Devonian. This formation contains abundant evidence of event deposition and non-uniform distribution of bioturbation structures representing a benthic response to multiple stressors. The 170 m-thick succession was measured and described, and the ichnotaxa were recorded and associated with lithofacies. Most shallow-marine environments are characterized by periodic events of environmental disturbance, mainly by episodic deposition, which may be recorded by a change in both the degree of bioturbation and ichnodiversity. The general depositional setting for this formation has been previously interpreted as a wave-dominated and storm-influenced shallow-marine environment. However, sedimentologic features described in this study such as anomalous heterolithic units and fluid mud flow deposits suggest the influence of fluvial discharge, making it a more complex depositional setting. Body fossils are restricted to a single subfacies and include disarticulated and fragmented echinoderms, brachiopods and bryozoans. The trace-fossil assemblages of this formation reflect environmental stress factors introduced by fluvial input (e.g., sedimentation rate, hydrodynamic energy, substrate consolidation), resulting in reduced ichnodiversity and low abundance. The overall trace-fossil content of the Furada Formation is generally representative of the Cruziana Ichnofacies. Integration of sedimentologic and ichnologic datasets allows for a refined depositional interpretation of the formation and greater understanding of the environmental diversity of wave-dominated shallow-marine clastic systems, including middle Paleozoic shallow-marine benthos and their responses to event sedimentation and environmental disturbance.
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CHAPTER 1
INTRODUCTION

The integration of ichnology and sedimentary facies analysis is a powerful tool that can be used to interpret and reconstruct paleoenvironments (e.g., MacEachern et al., 2005; MacEachern and Gingras, 2007; Desjardins et al., 2012; Dasgupta et al., 2016; Paz et al., 2022b; Bayet-Goll et al., 2023). However, and despite the many models available, there are still major gaps in our knowledge regarding how the trace-fossil record can be read as a response to changes in controlling factors during time of environmental disturbance. Under so-called normal shallow-marine conditions (e.g., dominance of fair-weather processes, good oxygenation), sediments tend to be fully bioturbated and a wide diversity of trace fossils is usually present (Pemberton et al., 1992; Pemberton et al., 1997). In contrast, during times of environmental disturbance, infaunal communities are affected, typically resulting in sparse bioturbation and reduced ichnodiversity (Frey and Goldring, 1992; MacEachern et al., 2005; Buatois et al., 2015; Fürsich et al., 2018; MacEachern and Bann, 2020).

Notably, most shallow-marine environments are characterized by periodic times of environmental disturbance, mostly due to episodic deposition (e.g., Pemberton and Frey, 1984; Frey and Goldring, 1992; Pemberton et al., 1997; Netto et al., 2014; Buatois et al., 2016, 2019; Campbell et al., 2016; Wang et al., 2024). Still, our understanding of benthos response to these sedimentation events suffers from a lack of finely tuned integration of sedimentologic and ichnologic datasets. For example, discrimination of the specific stress factors associated (e.g., high rate of sedimentation, salinity dilution, oxygen depletion) is not always straightforward.

Outstanding cliff exposures of the approximately 170 m thick, Silurian-Devonian (upper Wenlock-Lochkovian) Furada Formation of Asturias (northern Spain) provides an opportunity to examine the trace-fossil record of middle- to high-latitude shallow-marine environments affected by rapid episodes of sedimentation. Published work on the Furada Formation is currently limited, including studies summarizing the sedimentology (Wallace, 1972; García-Alcalde et al., 2002; Gutiérrez-Marco et al., 2019), ichnotaxonomic composition (Suarez de Centi, 1989), the expression of the Furada Formation (as the San Pedro Formation) in León (Dale, 2013), and
aspects of its paleontologic content (e.g. ophiuroids) in the Cantabrian Mountains (Blake et al., 2015). Overall, this unit contains a diverse ichnofauna, comprising a wide variety of ethological categories (Suarez de Centi et al., 1989), with a recent study documenting 33 ichnotaxa in the succession exposed in the Munielles and Bahínas beaches (Ornia et al., 2024). However, distribution of trace fossils is not uniform, with intervals of low to moderate degrees of bioturbation dominant and presence of more thoroughly bioturbated intervals locally. The underlying reasons for this pattern are thought to be related to recurrent environmental disturbance due to event sedimentation, resulting in stressors that have negatively impacted on the benthos. The results of this study will allow refining available trace-fossil models of shallow-marine clastic environments.

1.1 Research Goals

The goals of this thesis are threefold: (1) to document sedimentary facies and associated trace fossils of the Furada Formation, (2) to integrate sedimentologic and ichnologic data with the aim of producing a refined interpretation of the depositional environment, and (3) to assess the response of benthic fauna to event sedimentation through an analysis of the resulting biogenic structures. To complete this, fieldwork was conducted where the Furada Formation outcrops at Playa de Munielles and Playa de Bahínas on the coast of Asturias, Spain (Fig. 1.1) to measure a stratigraphic section and collect samples.
Figure 1.1. Location of study area in Asturias, Spain. (A) Map of Spain and the Principality of Asturias in green. (B) Geologic map of the area surrounding the study area. The outcrop occurs between two access points, Playa de Muniñelles and Playa de Bahínas. (C) Stratigraphy of local geology. Basemap modified from Julivert et al. (1972).
CHAPTER 2
LITERATURE REVIEW

2.1 Depositional Dynamics and Sedimentary Facies of Shallow-Marine Environments
Affected by Event Deposition

It is now generally accepted that much of the sedimentary record is a representation of episodic depositional events (Dott, 1982; Brenchley et al., 1986; Dumas and Arnott, 2006; Bhattacharya and MacEachern, 2009) instead of fairweather sedimentation, which represents a relatively small proportion despite its dominance in real-time. Episodic depositional events have hydrodynamic conditions and depositional mechanisms that are highly variable according to basin architecture, seasonality, and global climate. Therefore, the resultant deposits can be characterized by a wide range of stratal thicknesses, bedforms, and internal sedimentary structures. In shallow-marine environments, defined as the area stretching between the high-tide line and the shelf break (Plint, 2010), the best-known mechanisms for episodic deposition are storm events and hyperpycnal flows. In addition to these, oceanic floods are considered as a mechanism of episodic shelf deposition resulting from short-term rapid increases in precipitation and fluvial discharge of a coastal river.

2.1.1 Storms

The basic mechanism of wave action occurs by wind moving across the surface of water, generating oscillatory current patterns in the water column which flatten into ellipses and eventually become a back-and-forth motion on the seafloor. The asymmetry in these patterns results in a stronger current moving towards the shoreline, resulting in the preferential landward transport of coarser-grained sediment and deposition of coarsening-upward facies successions (Plint, 2010). During a storm, the drastic increase in wind speed increases friction on the water surface, dragging the water downwind and entraining deeper layers of water in the flow. This flow is deflected by the Coriolis force, driving the water towards the shoreline and raising the sea-surface up to several meters, forming a storm surge (Brenchley et al., 1986; Plint, 2010). Elevation of the sea-surface results in a pressure gradient, generating a bottom current flowing in the opposite direction that is deflected by the Coriolis force, forming a geostrophic current (Brenchley et al.,
Geostrophic currents may be erosive enough to generate scours and gutters on the seafloor, later filled in by storm deposits.

Dumas and Arnott (2006) conducted wave-tunnel experiments to understand the hydraulic conditions under which hummocky and swaley cross-stratification form. By separately controlling the oscillatory and unidirectional current components, Dumas and Arnott (2006) observed that as oscillatory currents reached 50-100 cm/s with a weak unidirectional component (less than 5 cm/s), large symmetrical ripples formed with wavelengths of 2 m and discontinuous crests. As the unidirectional component was increased to 5-10 cm/s, dome-shaped hummocks formed with heights of 10-25 cm and wavelengths of 1.5-3 m. As the unidirectional component was increased further, the stable bedform changed to three-dimensional asymmetrical ripples; increasing the oscillatory current resulted in upper flow regime planar beds. Generation of swaley cross-stratification requires stronger unidirectional currents in shallower-water depths, resulting in the preferential formation of swales due to sediment aggradation being outpaced by wave scouring (Plint, 2010). The structure of an idealized storm deposit records the intensifying and waning of hydrodynamic energy during a storm event (Figure 2.1). Storm-dominated sequences begin with erosively-based sandstone beds with planar lamination at the base changing upwards into hummocky cross-stratification (Brenchley et al., 1986; Plint, 2010), reflecting the change from dominantly unidirectional to oscillatory currents and the increase in wave orbital velocity at the seabed (i.e., increasing wave energy as the storm intensifies lowers the wave-base and increases orbital velocity). As the environment shallows, the ability of waves to remove mud deposited between events increases and causes amalgamation of sandstone beds. The increasing thickness of sandstone beds is a product of consistent amalgamation rather than increasing frequency of storm events. This is a function of the reworking ratio (bed thickness that is resuspended vs. accumulation rate) increasing during shoaling of storms when the ability of wave resuspension is much higher than accumulation rate (Brenchley et al., 1986). A general proximal-distal trend can be derived as well: erosion from the geostrophic current forms scours and gutters along the depositional profile, which are infilled by normally graded and rippled silty sandstone in distal tempestites, parallel-laminated and hummocky cross-stratified sandstone in medial tempestites (the location of the ideal model), and hummocky cross-stratified sandstone with increasing amalgamation in proximal shoreface positions. Once the wave energy decreases to fairweather conditions, background
sedimentation resumes and the tempestite may be covered by a mantle of mud in depths below fairweather wave base.

Figure 2.1. Development of an idealized sandstone storm event bed. The theoretical environment is a shoreline with fairweather mud deposition that experiences a storm event dominated by a strong combined flow produced by wave-generated oscillatory currents and a unidirectional component derived from the geostrophic flow during the storm peak. From Plint (2010).

2.1.2 Hyperpycnal Flows

Hyperpycnal flows occur when a dense, fluvial-derived gravity flow enters a marine or lacustrine water body (Zavala, 2020). The density contrast results in the flow to continue its path under the less dense water body and along the basin floor. Zavala (2020) proposed grouping hyperpycnal flows by flow origin: cohesive debris flows, hyperconcentrated, and concentrated flows typically generate high density short-lived flows derived from a local sediment source such as small mountainous rivers or landslides and require a steep slope to accelerate, while sediment-laden turbulent flows generate lower density long-lived flows associated with large fluvial systems.
that can continue to flow on a shallowly sloping shelf due to continuous river discharge. Hyperpycnal flows may also be generated by a sediment plume in which rapid flocculation and settling of clays is enhanced by wave action, resulting in a wave-aided hyperpycnal flow that is detached from the river mouth but fed by the sediment plume (Fig. 2.2) (Bhattacharya and MacEachern, 2009). In addition to grouping by flow origin, hyperpycnites may also be recognized by their resultant deposits. Cohesive debris flows have an internal cohesion enabled by muddy matrix, allowing them to carry large objects such as boulder-sized clasts and organic debris. Deposition occurs when the shear stress of the flow falls below the internal matrix strength, resulting in en masse deposition or cohesive “freezing” of the sediment (Zavala, 2020); the deposit is characterized by an immature fabric with a mud-rich matrix, poor sorting and terrestrially derived clasts including plant material. Hyperconcentrated flows are laminar flows with high sediment concentration and supported by matrix strength and grain-to-grain interaction as the flow advances, representing a transition between plastic and fluid behaviour (Mulder and Alexander, 2001). Hyperconcentrated flows are bedload-dominated with liquefaction as a common trigger, resulting in the bottom layer of the flow becoming supported by the upward force of fluids and reducing friction and erosion at the base (Mulder and Alexander, 2001). Deposits of hyperconcentrated flows are poorly sorted and commonly contain fluid escape structures and local inverse grading caused by grain-to-grain collisions (Mulder and Alexander, 2001; Zavala, 2020). Concentrated flows have higher erosive power than hyperconcentrated flows due to lower density allowing water to escape upwards from the bottom layer. Resultant deposits are generally erosively-based, normally graded or massive sandstone with fluid escape structures (Zavala, 2020). Sediment-laden turbulent flows are typically generated during periods of very high river discharge, becoming hyperpycnal with increasing sediment concentration. These flows are commonly tripartite: a basal layer of bedload under high shear stress, a middle layer of suspended sediment, and an overlying plume of fine sediment that is lofted by the lift of interstitial freshwater escaping the flow and moving upwards (Zavala, 2020). Due to the density contrast between fresh and saltwater, this lofting process is only possible in saline basins. Deposits formed by sediment-laden turbulent flows reflect the tripartite division: eroded channels are filled with poorly sorted, matrix-rich conglomerates representing sediments carried as bedload, suspended load sediments are deposited in channels as well as forming lobes of massive and climbing ripple cross-laminated
sandstone, finally, the lofted plume settles out of suspension as siltstone and mudstone that drape the underlying layers (Zavala, 2020).

Hyperpycnite deposits in the Dunvegan Formation and the Ferron Sandstone Member of the Mancos Shale Formations occur as thick mudstone units built up by hyperpycnal flows derived from prodeltaic mud belts (Bhattacharya and MacEachern, 2009). Both the Dunvegan and Ferron deltas were fed by moderately sized rivers that drained relatively small active mountain belt basins during the Cretaceous of North America. The prodelta deposits in this unit are characterized by abundant, centimeter- to decimeter-thick normally or inversely graded siltstone and very fine-grained sandstone, as well as some scoured surfaces, wave ripple cross-lamination, and local hummocky cross-stratification (Bhattacharya and MacEachern, 2009).

Figure 2.2. Hyperpycnal and hypopycnal plumes in river mouths. (A) River-fed hyperpycnal plumes form on steeper slopes. (B) Hyperpycnal flows that are detached from the river mouth may form on lower slopes through wave-aided plume collapse. From Bhattacharya and MacEachern (2009).

2.1.3 Oceanic Flooding

Oceanic floods are a relatively new type of flood included in the seasonal systems of delivering fluvial sediment into continental shelves and slopes. Wheatcroft (2000) described oceanic floods as short-lived increases in discharge that are caused by extreme rainfall events,
including rainfall-induced snowmelt. They are most common in small fluvial and basin systems, enabling the storm system to influence both the fluvial discharge and shallow-marine deposition. Short flood duration and large sediment input facilitates channel aggradation and overbank sedimentation, which generally occur infrequently or not at all during non-flooding periods. Therefore, when flooding does occur, the drainage system is overwhelmed by increased volumes of water and sediment that exceed its capacity. Sediment dispersal systems in shallow coastal ocean regions are overwhelmed as well, leading to the generation of fluid mud flows and characteristic seabed structures.

A modern example of this type of event deposition is the Eel River in northern California, a river which terminates at a continental margin characterized by a narrow shelf and large volume, short-term discharge events (Hill et al., 2000; Mullenbach and Nittrouer, 2000; Ogston et al., 2000; Wheatcroft and Borgeld, 2000). While the drainage basin area is relatively small and mountainous, the Eel River has extremely high sediment yield with episodic discharge fluctuations and especially large volumes during the winter months (Mullenbach and Nittrouer, 2000). Surrounded by high-relief terrain, the river lacks extensive overbanks or an estuary at its mouth, resulting in the majority of its suspended load to be delivered directly into the ocean.

During an oceanic flooding, an initial freshwater pulse forms a plume over the inner shelf followed by pulses of suspended fine-grained material that flocculates and sinks from the plume (Ogston et al., 2000). The sediment settles in the inner shelf or is carried basinward by gravity-driven flows, generating fluid muds when concentration reaches 10 g/L (Ogston et al., 2000). Sediment in the inner shelf may be resuspended by storm wave action and carried basinward. Deposits generated during oceanic floods in the Eel River are characterized by alternating high- and low-bulk density layers reflecting alternation between deposition of flood layers (high-density mud), poorly sorted fluid mud layers, fine-grained sediment deposited after resuspension (low-density mud), and coarser-grained material deposited under wave influence (Mullenbach and Nittrouer, 2000). These deposits are observed to have a depositional locus in the mid-shelf (Wheatcroft and Borgeld, 2000). Bioturbation in the oceanic flooding deposits is minor and structures are clustered near the top of flood layers (Wheatcroft and Borgeld, 2000), indicating a colonization window that occurs between successive sediment pulses from the river. Repeated patterns of oceanic flooding deposits occur at deeper levels of sediment record at this locality.
(Mullenbach and Nittrouer, 2000; Wheatcroft and Borgeld, 2000), indicating the dominance of this oceanic flood system on the shelf adjacent to the Eel River and a common locus of deposition in the mid-shelf over the lifetime of the river.

2.2 Benthic Response to Event Sedimentation in Shallow-Marine Environments

As physical representations of the behaviour of organisms, trace fossils are a powerful tool that can be used to measure the response of individuals or a community to biotic and abiotic environmental factors including salinity, nutrient availability, hydrodynamic energy, sedimentation rate, substrate consolidation, and oxygenation. Changes in these conditions illicit a shift in behaviour, resulting in tracemakers producing a different structure. Event sedimentation can cause extensive sediment redistribution and rapid sedimentation, requiring the abandonment of ecospace under extreme conditions (Zonneveld and Greene, 2010), while high hydrodynamic energy flows may transport infaunal and epifaunal organisms as larvae (Zonneveld and Greene, 2010; Dasgupta et al., 2016) resulting in changes to the assemblage of organisms in successions influenced by episodic sedimentation. Trace fossils also preserve aspects of a benthic community that may be underrepresented in body fossil assemblages.

2.2.1 Storms

Storm events and deposition of tempestites are characterized by rapid and drastic increases in hydrodynamic energy, erosion, and sedimentation rates. Progressively increasing frequency and intensity of storm events generates a shift from horizontal, deposit feeding and grazing structures to vertical, suspension feeding and passive predator burrows as hydrodynamic energy increases, requiring deeper emplacement of structures to withstand increased rates of sedimentation and erosion (Buatois and Mángano, 2011). Storm-dominated shallow-marine environments may result in the development of two discrete assemblages: a high ichnodiversity fairweather suite representative of the *Cruziana* Ichnofacies, and a lower ichnodiversity storm-weather suite representative of the *Skolithos* Ichnofacies (Pemberton and MacEachern, 1997; Buatois and Mángano, 2011). These two suites alternate in response to changing hydrodynamic energy (Fig. 2.3); the ratio and preservation of these suites will depend on the frequency and erosive power of subsequent storm events. High frequency storm events result in closed or very short colonization
windows and amalgamation of tempestites where the only bioturbation structures present are escape traces and deeply emplaced burrows belonging to the storm-weather suite. Moderate frequency storm events open longer colonization windows, during which the tempestite is burrowed by organisms belonging to the storm-weather suite. When sedimentation returns to fairweather conditions, the infaunal community becomes dominated by deposit feeders of the fairweather suite which begin to rework the upper layers of sediment. If the following storm event has high erosive power, the fairweather deposits will be removed partially or entirely and result in the amalgamation of tempestites. If the subsequent storm deposit is only capable of minor erosion, a “lam-scram” colonization pattern will develop, representing the alternation of fairweather (“lam”) and tempestite (“scram”) deposits and their respective benthic communities (Buatois and Mángano, 2011).

Figure 2.3. Illustration of the development of a typical shoreface tempestite. (1) Fairweather deposits are colonized by the climax assemblage. (2) Rapid deposition of a sandy tempestite with an erosive base truncating underlying trace fossils. Contemporary bioturbation represents escape traces and transported larvae. (3) After tempestite deposition, colonization by opportunistic fauna occurs. (4) Return to fairweather sedimentation and climax assemblage. From Pemberton and MacEachern (1997).
In the middle Pleistocene Ichiono Member of Japan, Nara (2002) described storm-
influenced shallow-marine sediments with a dense ichnofabric composed of stacked *Rosselia socialis* burrows (Fig. 2.4). *R. socialis* is an equilibrichnia structure attributed to detritus-feeding terebellid polychaetes (Nara, 1995) that form a vertical cone-shaped burrow with a continuous central shaft. The organism migrates its burrow upwards in response to periods of rapid aggradation of the seafloor, generating a sequence of vertically stacked cones. Population density reached a maximum of 400 individuals per square meter, with the longest specimen formed by ten instances of upward migration over 1.2 meters during the producer’s lifetime (Nara, 2002). With population densities reaching such high levels, the tracemakers effectively prevented the settlement of epifaunal organisms by passive predation, while the densely packed burrows stabilized the substrate enough to prevent the intrusion of other infaunal organisms. The development of the dense *R. socialis* ichnofabric present in this locality is a result of recurring storm events rapidly depositing a layer of sand, followed by the population of tracemakers simultaneously adjusting their burrow position to the new seafloor. The vertical extent of the ichnofabric and consistency of the trace-fossil morphology indicates the environmental conditions of the storm-dominated offshore transition were similar for a long period of time during the transgression. Despite abundant organic matter delivered by transgressive erosion of the organic-rich coastal marshes (Nara, 2002), the intense wave ravinement and rapid deposition prevented colonization by other less stress-tolerant infauna, allowing the *R. socialis* producers to flourish.

2.2.2 Hyperpycnal Flows

Hyperpycnal flows are efficient systems of transporting terrestrial material into more distal shallow-marine settings and may generate an influx of nutrients when the flow is rich in organic material. Periods of elevated precipitation, such as during storms, generate increased freshwater discharge as well as increased weathering releasing high concentrations of sediment carried by the river. Frequent and rapid emplacement of thick sediment gravity flow deposits, which may be mobile for some time after the event begins, inhibits infaunal colonization (MacEachern et al., 2005). In addition, frequent high-volume freshwater pulses result in an overall stressed community with restricted biodiversity and low burrowing intensity. Like bioturbation patterns in tempestites, the deposition of hyperpycnites generates a pattern of alternating suites, representing fairweather and rapid depositional conditions.
A shallow-marine succession recording an offshore-transitional hyperpycnal system in the upper Miocene of the Betic Cordillera, Spain, was analyzed by García-García et al. (2021). The sequence contains alternating structureless or well-sorted sandstones rich in extrabasinal debris and burrowed siltstones, recording deposition of hyperpycnal flow lobes in the prodelta of a prograding deltaic system into a sediment-starved offshore dominated by suspension-fallout deposition of siltstones (García-García et al., 2021). In the hyperpycnal flow-dominated transitional setting from prodelta to offshore, benthic communities are most strongly affected by changes in hydrodynamic energy, sedimentation rate, substrate consistency, and salinity, resulting in colonization by different trace-fossil assemblages characterized by two expressions of the Cruziana Ichnofacies (high and low energy) and the Nereites Ichnofacies. Fairweather conditions in the prodelta-offshore environment facilitate bioturbation by dominantly deposit feeders; however, the ichnodiversity is somewhat restricted by salinity fluctuations caused by freshwater discharge from the nearby delta. During deposition of hyperpycnites, hydrodynamic energy and sedimentation rates increase drastically while salinity may drop due to the large influx of freshwater. The low bioturbation index and occurrence of trace fossils only near the top of the thicker sandy hyperpycnites (García-García et al., 2021) indicate hydrodynamic energy and sedimentation rates that are too high for colonization, but as the flow wanes a short colonization window opens and is exploited by a second ichnoassemblage. The occurrence of the backfilled deposit-feeding burrow Taenidium in both prodelta-offshore assemblages suggests the producers were able to adapt to both fairweather and hyperpycnal flow conditions, while other producers were more strongly affected. The third ichnoassemblage represents the activity of a mature community of shallow- and deep-tier deposit feeders in a relatively stable, low energy environment interrupted periodically by channelized hyperpycnal flows. With the more distal occurrence of the Nereites Ichnofacies from the river mouth, salinity fluctuations would be minimal to absent, and the major controlling factors become sedimentation rate and hydrodynamic energy, both of which would increase during hyperpycnal flows and the subsequent settling of a lofted plume, if present. The localized concentrations of the Nereites Ichnofacies may suggest zones of oxygen depletion, particularly if the material within the hyperpycnal flow is rich in organic material. The oxidation of organic detritus at the seafloor produces pockets of oxygen-poor waters in environments below fairweather wave base with poor oxygen circulation (MacEachern et al., 2005), which may occur
more easily in the sediment-starved offshore and result in low ichnodiversity and restricted areas of bioturbation by deeper-tier ichnotaxa.

2.2.3 Plume Collapse

MacEachern et al. (2005) describe a paradox in clean sandy substrates colonized by deposit feeding traces instead of the expected suspension feeding traces. This is a result of wave action winnowing the mud from the sediment surface, keeping it in suspension in the water column and therefore inhibiting filter feeding organisms (MacEachern et al., 2005). These conditions are common in storm-influenced deltaic systems; however, such processes have low preservation potential due to overprinting by deposition and amalgamation of tempestites during frequent storms. A significant environmental control introduced by hypopycnal plume formation and collapse is water turbidity. Fine siliciclastic particles in the water column clog the feeding apparatus of suspension-feeding organisms and lower the concentration of food particles, forcing suspension feeders to ingest and process more inorganic material to acquire nutrients (MacEachern et al., 2005). These conditions lead to the suppression or impoverishment of the Skolithos Ichnofacies and the over-representation of deposit feeding traces representing the Cruziana Ichnofacies (Buatois and Mángano, 2011; Bhattacharya et al., 2020). Environments affected by hypopycnal flows and plume collapse may have infaunal communities characterized by restriction of ichnodiversity through the suppression of suspension feeding organisms of the Skolithos Ichnofacies and deposit feeding traces of the Cruziana Ichnofacies if turbidity is extreme, and/or poorly defined and highly deformed traces where soft mud forms soupy substrate. The combination of soupgrounds, rapid sedimentation, and salinity fluctuations result in an impoverished trace-fossil assemblage with the preferential colonization of opportunistic ichnogenera exploiting short colonization windows.
Fig. 2.4. *Rosselia socialis* in the middle Pleistocene Ichiono Member, Japan. (A) Individual stacked *R. socialis*. Scale bar is 3 cm. (B) *R. socialis* ichnofabric. Erosional truncation is observed where stacked *R. socialis* have a common termination surface. Scale bar is 50 cm. Modified from Nara (2002).
CHAPTER 3
GEOLOGIC SETTING

3.1 Paleogeography

Paleogeographic reconstructions of the late Silurian period reveal a different continental arrangement than that of the present (Fig. 3.1) (Scotese, 2014; Torsvik and Cocks, 2017; Golonka et al., 2023). The supercontinent Gondwana was positioned over the paleosouth pole, made up of present-day South America, Africa, Antarctica, Australia, India, and parts of the Middle East. Other paleocontinents included Laurentia (most of North America, northwest Ireland, south Scotland, and Greenland), Baltica (parts of eastern and northern Europe), Siberia, and Avalonia (an archipelago of microcontinents including Newfoundland, Nova Scotia, New Brunswick, New England, and parts of Ireland, Scotland, England, France, Germany, and Poland). During the late Silurian, the Caledonian orogeny led to the closure of the Iapetus Ocean and the collision of Laurentia, Baltica, Siberia, and Avalonia to form the supercontinent Laurussia, positioned south of the paleoequator (Torsvik and Cocks, 2017; Golonka et al., 2023). The Panthalassic Ocean occupied most of the Northern Hemisphere, while the Rheic Ocean was positioned between Laurussia and Gondwana, eventually closing during the formation of Pangea in the Carboniferous (Torsvik and Cocks, 2017).

The Iberian Peninsula existed as part of the Gondwanan landmass, located on the northern coastline and across the Rheic Ocean from Laurussia. The Iberian Peninsula has been interpreted as a small island separated from the rest of Gondwana by a shallow sea (Scotese, 2014) as well as part of a microcontinent called the Armorican Terrane Assemblage (Torsvik and Cocks, 2017). Both interpretations position the Iberian Peninsula at approximately the same latitude, about 30 to 40 degrees south.
3.2 Paleoclimate

The Silurian was a time of transition, and the climate oscillated between warm and cool conditions during the change from the Late Ordovician glaciation to Devonian greenhouse conditions (Bowman et al., 2019). On land, vascular plants diversified and colonized during the “Siluro-Devonian primary radiation of land biotas” (Bateman et al., 1998). The spread of vascular plants would have had a significant effect on global weathering rates (Frýda et al., 2021). Berner (2005) estimates an increase of silicate weathering rates up to a factor of 10, triggering a decrease in atmospheric CO$_2$ and further affecting rock weathering and therefore seawater composition and nutrient flux (Algeo and Sheckler 1998; Algeo et al., 2001). At least five globally observed carbon isotope excursions have been identified from the mid-Llandovery to the Early Devonian (Saltzman and Thomas, 2012). The timing of these carbon isotope excursions has been compared to oxygen isotope values from conodont fossils found on either side of the Rheic ocean, revealing repeated ecosystem turnovers, rapid climate oscillations, and sea-level fluctuations (Calner, 2005; Žigaitė et al., 2010; Trotter et al., 2016; Bowman et al., 2019; Frýda et al., 2021).
In the late Silurian strata of Gotland, Sweden, one of these carbon isotope excursions (the Lau Event) is marked by an abundance of brachiopod shell coquinas, followed by a substantial decrease in bioturbation and the appearance of oncolites, stromatolites, wrinkle structures, and microbially stabilized rippled bed tops (Calner, 2005). Calner (2005) referred to these features as characteristics of “anachronistic facies”, representative of an environment under stress. Sampling and analysis of conodont apatite oxygen isotopes from contemporary strata in the Prague Basin were compared to carbon isotope records; this revealed an increase in carbon burial and deposition of shale enriched in redox-sensitive trace metals related to widespread anoxic and euxinic conditions in deeper waters (Bowman et al., 2019). Expansion of anoxic waters onto the shelf coupled with warming and eustatic sea level rise (Trotter et al., 2016) would have a significant effect on benthic faunal communities, facilitating the growth of microbial mats and suppressing infaunal activity.

3.3 Stratigraphic Framework

The Paleozoic succession of the Iberian Peninsula is divided into pre-, syn-, and post-orogenic series (Martínez Catalán et al., 2008). The pre-orogenic series, ranging in age from the Cambrian to the end of the Devonian, contains several clastic wedges prograding towards the west and representing deposition in a shallow, stable platform (Martínez Catalán et al., 2008). The Furada Formation lies within this pre-orogenic series, spanning the Silurian-Devonian boundary and dated as late Wenlock to early Lochkovian (approximately 430-412 Ma) in age (Suarez de Centi et al., 1989) (Fig. 3.2). The Paleozoic strata of the Iberian Peninsula represent the western margins of the European Variscan Belt (Martínez Catalán et al., 2008). The Variscan orogeny generated a complex network of curved shear zones and thrust belts over the Iberian, Armorican, Central, and Bohemian Massifs. The Cantabrian Zone lies in the foreland of the Variscan Belt, which was sheltered from deformation associated with the Central Iberian Arc (Fig. 3.3) (Martínez Catalán et al., 2008; Domeier and Torsvik, 2014; Fernández et al., 2016). This protection from orogenic deformation resulted in units affected only by tectonic uplift, such as the overturned strata observed in the Furada Formation.
Figure 3.2. Correlation chart of sedimentary units in the Cantabrian Zone showing continuity of deposition through the Silurian and Devonian within the Iberian Massif. Note stratal placement of the Furada Formation as spanning the Silurian-Devonian boundary and conformable with the underlying Formigoso Formation and overlying Rañeces Group. The Furada Formation is named the San Pedro Formation in the neighbouring province of Léon. Modified from Gutiérrez-Marco et al. (2019).
During the end of the Middle Paleozoic, the region was covered by a shallow shelf sea, resulting in the accumulation of fossiliferous limestone, shale, and sandstone (Wallace, 1972; Truyols et al., 1990). The major sediment source during this time was the Asturian Arc, a topographic high that enabled continuous deposition across the Silurian-Devonian transition in the Iberian Massif. In the late Silurian, it is estimated that the Iberian Massif was located at a latitude of 40-35°S, under a temperate climate (Gutiérrez-Marco et al., 2019). Silurian sedimentation in the Iberian Massif is interpreted to have taken place on a passive margin platform during the
spreading of the Rheic Ocean. Deposition continues into the Devonian, characterized by nearshore to offshore settings of the same platform (Gutiérrez-Marco et al., 2019).

Conformably underlying the Furada Formation is the Formigoso Formation, a highly fissile shale-dominated unit which is typically poorly exposed. This formation contains thin sandstone and black, graptolite-bearing shale of late Llandovery to Ludlow age (Wallace, 1972). This period of black shale deposition is shared across the Mediterranean and has been interpreted as a result of relative sea-level rise in the early Silurian caused by the combination of eustasy and increased local subsidence (Gutiérrez-Marco et al., 2019). The depositional environment of the Formigoso Formation is thought to be a calm but relatively shallow basin under reducing conditions (Wallace, 1972).

Sand supply ceased abruptly during deposition of the 400-600 m-thick Rañeces Group, which is dominated by carbonates (García-Alcalde et al., 2002). The lowermost unit of the Rañeces Group is the Nieva Formation, which lies conformably over the Furada Formation, and is characterized by grey dolomite with lamination suggesting stromatolite growth in an intertidal environment (Wallace, 1972). These deposits pass upwards to bioclastic limestone layers rich in spiriferid and rhynchonellid brachiopods in addition to increasing bioturbation (Wallace, 1972; García-Alcalde et al., 2002), indicating a return to more normal marine conditions. Argillaceous limestone, thin shale, and rare pebble lag deposits occur further upwards, with the Nieva Formation capped by biostrome and patch reef growth. The Nieva Formation is laterally replaced by the Bañugues Formation. The Bañugues Formation contains thick intercalations of dolomitized bioclastic limestone with sandstone; the dolostone contains inorganic and organic laminations, mud cracks, and intraformational breccias. This unit is followed upwards by the La Ladrona Formation, comprised of fossiliferous grey argillaceous limestone alternating with dark shale and punctuated by rhythmic hummocky cross-stratified storm deposits. The Rañeces Group is capped by the Aguión Formation, a lithologically heterogeneous formation containing fossiliferous, pink-coloured crinoidal limestone and grey marl and shale. The top of the overlying Aguión Formation displays evidence of frequent episodes of biostrome and patch reef building, signifying the start of major reef development in the Cantabrian Zone, as represented by the upper Emsian Moniello Formation (García-Alcalde et al., 2002).
CHAPTER 4
FIELD WORK AND METHODOLOGY

4.1 Study Area Location

The Furada Formation outcrops as a continuous cliff between the public beaches Playa de Munielles and Playa de Bahinas (Fig. 4.1). The outcrop was primarily accessed from Playa de Munielles, whereas the top of the section required access from Playa de Bahinas, possible only at exceptionally low tides.

![Image of study area at high tide. From Google Earth.](image)

**Figure 4.1.** View of study area at high tide. From Google Earth.

4.2 Methodology

The studied section was logged using a measuring tape and removable bed markers. Bed thickness was recorded along with grain size, sedimentary structures, bedding contacts, and fossil content (body and trace fossils). Strata in this area are overturned; a Freiberger geological compass was used to measure bedding attitude. Photographs were taken at regular intervals to demonstrate typical sedimentary features. Samples were collected based on their representation of the general characteristics of the formation, trace and body fossil content, as well as weathering potential (i.e., if the sample was in danger of damage by weathering, it was selected preferentially over a sample.
that required potentially damaging the outcrop to collect). A stratigraphic section (Fig. 4.2) was generated using CorelDRAW 2021©. The drawn section accurately represents the sedimentology of the Furada Formation. Sedimentologic analysis involved classification of lithology, grain size, sedimentary structures, bioturbation, and body fossil content. Photographs were taken from a distance and used to stitch together a panorama, as well as close-up views of sedimentary features. Ichnologic data collection involved sample selection, recognition and identification of ichnofossils present, measurement of degree of bioturbation, and estimation of ichnodiversity. Detailed documentation of the trace fossils is presented in table 1. Systematic ichnology and analysis of specimens identified in the field during this study as well as material previously collected and deposited in museums is presented in Ornia et al. (2024). Degree of bioturbation in cross-section was estimated based on the bioturbation index (BI) scheme by Taylor and Goldring (1993). Selected samples were prepared to produce polished slabs and thin sections for observation under a petrographic microscope to refine granulometric data including grain size, sorting, cement and/or matrix characteristics, as well as identify biogenic structures visible on a microscopic scale.
Figure 4.2. Stratigraphic section for the exposure of the Furada Formation at Playa de Munielles displaying thickness, lithofacies, descriptive interval (Basal, Lower (L), Middle, Upper), grain size, sedimentary structures, bioturbation index, and trace fossils.
5.1 Facies Descriptions and Interpretations

Four sedimentary facies have been characterized. Of these, facies 1 was subdivided into three subfacies, and facies 2 and 4 into two subfacies each. The metamorphic grade of this formation is extremely low, with the minor development of chlorite minerals visible in thin sections. Bioturbation intensity is assessed using the bioturbation index (BI) proposed by Taylor and Goldring (1993). In this scheme, a value is assigned based on the visual percentage of bioturbation in a sedimentary unit. Sediments with no bioturbation (0%) equals a BI of 0. Sediments with sparse bioturbation (1 to 4%) and few discrete trace fossils correspond to a BI of 1. Sediments displaying low intensity of bioturbation (5 to 30%) and still preserving some sedimentary structures equals a BI of 2. Sediments with distinguishable bedding surfaces, discrete trace fossils, and moderate intensity of bioturbation (31 to 60%) correspond to a BI of 3. Deposits with intense bioturbation (61 to 90%), high density of commonly overlapping trace fossils, and mostly reworked primary sedimentary structures correspond to a BI of 4. A BI of 5 is characterized by sediments thoroughly reworked by intense bioturbation (91 to 99%). Complete reworking of sediments (100% bioturbation) leading to a mottled appearance corresponds to a BI of 6.

5.1.1 Facies 1

Facies 1 consists of trough cross-bedded fine-grained sandstone, ripple cross-laminated very fine-grained sandstone, and mudstone intercalated in various proportions. Three subfacies have been identified.

Facies 1a (Figs. 5.1, 5.2) - Trough cross-bedded, fine-grained sandstone with intraclasts and discontinuous mudstone layers

Description - Facies 1a is dominated by dark red-purple, trough cross-bedded, fine-grained sandstone. Beds are 50-270 cm thick and commonly amalgamated or locally separated by laterally discontinuous, grey, 0.3-1 cm thick mudstone layers. Facies intervals are 1.4-7.8 m thick. Mudstone intraclasts occur in most of the sandstone beds and show their long axis oriented parallel
to paleoflow. Tops show asymmetrical ripples. Facies 1a occurs mainly in the basal interval of the formation, where it is the dominant facies.

**Fossil Content** - No body fossils have been found.

**Ichnology** - BI = 0-2; trace fossils are concentrated on sandstone bases, most commonly comprising overlapping horizontal cylindrical burrows with massive sandstone fill. Sandstone tops have few sand-filled horizontal burrows. Recorded ichnotaxa in order of decreasing abundance are: *Rosselia socialis, Planolites montanus, Palaeophycus tubularis, Asterosoma ludwigae,* and *Helminthoidichnites tenuis.*

**Interpretation** - Presence of trough cross-bedding indicates high-energy unidirectional flow resulting in the migration of three-dimensional dunes (Wignall et al., 1996; Plint, 2010). Bed amalgamation is caused by constant wave action and current activity removing and resuspending fine-grained sediment. Physical sedimentary structures and the association with underlying hummocky cross-stratified sandstone units are suggestive of a middle to upper shoreface depositional setting.

![Figure 5.1. Detailed stratigraphic column of facies 1a.](image-url)
Figure 5.2. Facies 1a. (A) General view of a facies 1a interval at the base of the Furada Formation. Field of view is approximately 30 m. Younging direction is to the left. (B) Sandstone base with *Rosselia socialis*. Scale bar is 2 cm. (C) Mudstone intraclasts within trough cross-bedded sandstone. Scale bar is 2 cm. (D) Sandstone base with *Palaeophycus tubularis*. Scale bar is 2 cm. (E) Thin section of facies 1a sandstone with mudstone intraclast. PPL. Magnification 1.25x, field of view is 11.3mm.
Facies 1b (Figs. 5.3, 5.4) - Bioclastic, trough cross-bedded, fine-grained sandstone with discontinuous mudstone layers

**Description** - Dark red-purple, trough cross-bedded, fine-grained sandstone. Beds are 40-170 cm thick. Sandstone beds are commonly amalgamated or locally separated by grey 0.3-1 cm thick mudstone layers. Facies intervals are 1.9-4 m thick. Trough cross-bedding is much more visually pronounced in facies 1b due to bioclasts concentrated at the base of each bedset as lags (Fig. 5.4A, B, D). At 142m above the base of the section, facies 1b occurs with unique geometry of the bedset: three sandstone beds thin laterally and pinch out completely over a lateral distance of 13.4m. The thickest point of the bedset is 1.2 m, inferred to be the center of an elongate lens-shaped element made up of four amalgamated sandstone beds (Fig. 5.4C). Facies 1b occurs mainly in the basal interval of the formation.

**Fossil content** - Crinoid ossicles, brachiopod shell fragments, and bryozoan fragments. Bioclasts are less than 5 mm in length, with few large crinoid ossicles 1-2 cm across. One intact bryozoan specimen, 3 cm across, was observed.

**Ichnology** - BI = 0-1; trace fossils are concentrated in mudstone intervals. Sandstone surfaces have fewer trace fossils than in facies 1a. Recorded ichnotaxa in order of decreasing abundance are: *Rosselia socialis, Palaeophycus tubularis, Cruziana quadrata,* and *Bifungites munizi.*

**Interpretation** - Trough cross-bedding is indicative of high energy unidirectional flow resulting in the migration of three-dimensional dunes within a middle to upper shoreface depositional setting (Wignall et al., 1996; Plint, 2010). Bioclasts occur as lags resulting from migration of dunes (Kidwell et al., 1986). Disarticulated echinoderm ossicles, fragmented bryozoans, and fragmented punctate orthid brachiopods support transport by high energy currents. The occurrence of a lenticular body represents an architectural feature in the middle shoreface, possibly a rip current channel. Rip currents are generated by alongshore variations in breaking wave vector directions because of bathymetric variations in shallow-marine settings. (Moulton et al., 2017). Breaking waves reaching the shoreline from an oblique angle drive longshore currents, which in turn drive offshore-directed flows which may carve channels into the sediment surface by exploiting depressions as direct paths for efficient offshore transport (Plint, 2010; Moulton et al., 2017). High wind speeds increase breaking wave energy, which in turn accelerates these offshore-directed currents.
Figure 5.3. Detailed stratigraphic column of facies 1b.


**Figure 5.4.** (Previous page) Facies 1b. (A) Bioclasts in sandstone block. Scale bar is 15 cm. (B) Bryozoan (left), crinoid ossicles, and brachiopod shell fragments. Scale bar is 2 cm. (C) Architectural feature at 142 m above the base of the section. Beds narrow and form a wedge shape (outlined in yellow). Scale bar is 40 cm. Younging direction is to the left. (D) Bioclastic lags in each trough define bedding (indicated by dotted lines). Scale bar is 15 cm. Bed top is to the left. (E) Crinoid ossicles and punctate brachiopod shell fragment in sandstone. (F) Echinoderm ossicle in sandstone. (G) Bryozoan fragment in sandstone. Thin sections shown in E, F, and G were taken under PPL and 1.25x magnification with a field of view of 11.3 mm.

**Facies 1c** (Figs. 5.5, 5.6) - Mudstone, siltstone, and discontinuous very fine- to fine-grained sandstone

**Description** - Dark grey mudstone occurs in 1-4 cm thick intervals and is parallel laminated or structureless. Some mudstone layers coarsen upwards into siltstone. Red sandstone beds are parallel- or wave ripple cross-laminated, 0.3-0.7 cm thick and locally discontinuous. Mudstone dominates sandstone with a ratio of 3:1. Facies intervals are 0.3-0.6 m thick. Facies 1c occurs in the basal and upper intervals of the formation.

**Ichnotology** - BI = 2-3. Primary fabrics are locally disrupted by infaunal burrowing, leading to a patchy appearance. Burrows within mudstone layers are small (0.1-0.4 cm wide) with contrasting fill, while larger burrows (1.5-2 cm wide) are concentrated on bases of the thin sandstone beds. Recorded ichnotaxa in order of decreasing abundance are: *Rosselia socialis, Asterosoma ludwigae, Palaeophycus tubularis, Planolites montanus, Helminthoidichnites tenuis, Phycodes circinatum, Psammichnites plummeri, Rusophycus pudicus, Trichophycus isp., Teichichnus rectus, Rusophycus isp., Curvolithus multiplex, Bifungites munizi, Halopoa imbricata, and Cruziana quadrata.*

**Interpretation** - The occurrence of facies 1c as thin intervals of heterolithics between recurrent units of trough cross-bedded sandstone suggests facies 1c is also deposited in the middle to upper shoreface. Facies 1c is the result of event deposition caused by periods of high sediment discharge from a nearby fluvial system. Structureless, parallel lamination, wave ripple cross-lamination, and inversely graded mudstone intervals are indicative of the generation of fluid muds and sediment-gravity flows (Hovikoski et al., 2008; Paz et al., 2022a). During phases of exceptionally high fluvial discharge, the fine-grained sediment load enters coastal waters and forms a sediment plume.
where flocculation is facilitated by wave energy to generate a wave-enhanced fluid mud flow (Mullenbach and Nittrouer, 2000). This fluid mud then forms a layer of viscous material on the seafloor capable of damping incoming wave energy (Rodriguez and Mehta, 1998; Sheremet and Stone, 2003; Draut et al., 2005); reduction of wave energy in the middle and upper shoreface enables the accumulation of a thick layer of mud and silt. Once fluvial discharge decreases to pre-event levels, formation of fluid mud ceases and wave energy, no longer inhibited, can erode and resuspend some thickness of accumulated mud, and marks a return to fair-weather deposition (i.e., deposition of facies 1a and facies 1b).

Figure 5.5. Detailed stratigraphic column of facies 1c.
Figure 5.6. Facies 1c. (A) Recessive nature of facies 1c forming “caves” between intervals of the more resistant facies 1a. Field of view is approximately 2.5 m. Younging direction is to the left. (B) Sandstone top preserving combined flow ripples. Notebook is 21 cm long. (C) Sparsely bioturbated mudstone and siltstone. Scale bar is 2 cm. (D) Bioturbated mudstone and siltstone. Scale bar is 2 cm. (E) Sandstone base with Halopoa imbricata. Scale bar is 2 cm. (F) Helminthoidichnites tenuis preserved as negative epirelief in sandstone. Scale bar is 2 cm.
5.1.2 Facies 2

Facies 2 consists of hummocky cross-stratified very fine- to fine-grained sandstone either amalgamated or forming discrete beds. Two subfacies have been identified.

Facies 2a (Figs. 5.7, 5.8) - Hummocky cross-stratified very fine- to fine-grained sandstone

**Description** - Commonly amalgamated, erosively based red very fine- to fine-grained sandstone beds with internal structure displaying smooth, undulating laminae grading upwards into wave ripple cross-lamination in the top 5 cm. Beds are 20-65 cm thick and locally separated by parallel-laminated dark grey mudstone. Facies intervals are 0.6-1.4 m thick. Some bed tops preserve wave ripples. Internal stratification is locally obscured by iron crusts. One set of amalgamated beds in the lower unit contains a basal pebble conglomerate (Fig. 5.8G). This amalgamated sandstone bed has no visible internal lamination. The conglomerate is matrix supported and very poorly sorted. The clasts are subrounded to well-rounded, 1-45 mm in size and clustered into circular patches. 5-20 mm wide mudstone intraclasts are also present. Facies 2a occurs throughout the lower, middle, and upper intervals of the formation, alternating with facies 2b and facies 3.

**Ichnology** - BI = 0-1. Trace fossils are concentrated on sandstone bases. Recorded ichnotaxa in order of decreasing abundance are: *Asterosoma ludwigae, Rosselia socialis, Bergaueria hemispherica, Cruziana quadrata, Bifungites munizi, Arenicolites isp.*, and *Rusophycus pudicus*.

**Interpretation** - Deposition of hummocky cross-stratified sandstone indicates high energy waves generated during storm events. The nature of the internal stratification suggests an oscillatory-dominant combined flow and variable aggraduation rate (Dumas & Arnott, 2006). Amalgamation of sandstone beds observed in facies 2a is the result of frequent storm events eroding and resuspending fair-weather sediments (Dott and Bourgeois, 1982), representing deposition in a strongly storm-affected lower shoreface. The basal conglomerate is interpreted as a lag deposit resulting from wave scouring during a storm (Dott and Bourgeois, 1982). The massive appearance of the sandstone with a basal conglomerate suggests a period of wave ravinement generating an irregular erosive surface, including depressions in the sediment surface later infilled by sand and pebbles.
Figure 5.7. Detailed stratigraphic column of facies 2a.
Figure 5.8. Facies 2a. (A) General appearance of facies 2a, the thicker red sandstone beds occurring between intervals of facies 3. Surface indicated is shown in B. Scale bar is 1 m. Younging direction is to the left. (B) Top of sandstone bed with preserved swale indicated by dotted line. Notebook is 21 cm long. (C) Internal structure of sandstone bed showing hummocky cross-stratification. Scale bar is 2 cm. (D) Sandstone base with Bifungites munizi. Scale bar is 4 cm. (E) Asterosoma ludwigae on sandstone base. Scale bar is 2 cm. (F) Arenicolites isp. (Ar) and Rosselia socialis (Ro) on sandstone top. Scale bar is 2 cm. (G) Basal pebble conglomerate in sandstone bed. Scale bar is 2 cm.
**Facies 2b** (Figs. 5.9, 5.10) - Hummocky cross-stratified very fine- to fine-grained sandstone with mudstone intervals

**Description** – Red, very fine- to fine-grained sandstone beds with hummocky cross-stratification. Beds are 15-40 cm thick and generally observed to be thinner than beds in facies 2a. Sandstone tops preserve wave ripples more commonly and grey, 1-4 cm thick mudstone intervals are present between beds with laminae that drape rippled sandstone tops. Lamination of mudstone intervals is locally disrupted by bioturbation. Facies intervals are 0.8-1.6 m thick. Beds display little to no amalgamation, and single hummocks are observed. One loose block associated with facies 2b shows a sandstone base with pustulose microbial mat texture. Facies 2b occurs throughout the middle and upper intervals of the formation, alternating with facies 2a and facies 3.

**Ichnology** - BI = 0-2. Trace fossils are concentrated in mudstone intervals and on sandstone bases. Recorded ichnotaxa in order of decreasing abundance are: *Rosselia socialis, Psammichnites* cf. *P. implexus, Gordia marina, Palaeophycus tubularis, Cruziana quadrata, Helminthopsis abeli, Helminthoidichnites tenuis,* and *Protovigularia dichotoma.* The block with microbial mat texture contains a specimen of *Cruziana quadrata.*

**Interpretation** - The presence of hummocky cross-stratification indicates deposition by large-scale oscillatory waves generated during storm events. Aggradation rate in facies 2b may be higher than facies 2a due to equal preservation of hummocks and swales, as well as fewer truncation surfaces (Dumas and Arnott, 2006). A larger proportion of mudstone relative to facies 2a suggests lower wave energy and/or more time under fair-weather conditions between storm events. Facies 2b displays a decrease in storm activity, representing deposition under marginally deeper water (i.e., the offshore transition).
Figure 5.9. Detailed stratigraphic column of facies 2b.
Figure 5.10. (Previous page) Facies 2b. (A) General appearance of facies 2b. Notebook is 21 cm tall. Younging direction is to the left. (B) Top of sandstone bed with preserved wave ripples. Scale bar is 5 cm. (C) Internal Structure of sandstone bed showing undulating laminations. Scale bar is 2 cm. (D) Loose block preserving pustulose microbial mat texture and *Cruziana quadrata* specimen. Scale bar is 10 cm. (E) *Cruziana quadrata*. Scale bar is 2 cm.

5.1.3 Facies 3

Facies 3 (Figs. 5.11, 5.12) - Interbedded parallel to wave ripple cross-laminated, very fine- to fine-grained sandstone and mudstone

**Description** - Facies 3 consists of regularly interbedded dark grey mudstone and 3-12 cm thick, light grey very fine- to fine-grained sandstone. Within the mudstone intervals are mm-scale, erosively based, light grey, fine-grained sandstone lenses. The ratio of mudstone to sandstone is 1:1. Facies intervals are 0.3-13.2 m thick. Sandstone beds and lenses are locally stained red and have developed an iron crust that obscures internal lamination. Where visible, the sandstone beds display a progression from parallel lamination to wave ripple cross-lamination from base to top. Tops display wave or combined flow ripples. Facies 3 is by far the most common facies in the Furada Formation, dominating the lower interval.

**Ichnology** - BI = 1-4. Localized zones of BI = 2-3 are the most common, reaching a maximum BI of 4 in very thin mudstone intervals. Trace fossils are concentrated on sandstone bases; most of these surfaces are dominated by *Asterosoma ludwigae*. Trace fossils in mudstone interbeds are patchy. In order of decreasing abundance, these are: *Asterosoma ludwigae, Rosselia socialis, Helminthoidichnites tenuis, Palaeophycus tubularis, Cruziana quadrata, Phycodes circinatum, Trichophycus* isp., *Planolites montanus, Heimdallia chatwini*, and *Arenicolites* isp.

**Interpretation** - A 1:1 ratio of regularly alternating sandstone to mudstone within facies 3 suggests deposition between fairweather and storm weather wave bases. The upper offshore is placed immediately below fair-weather wave base, therefore deposition of sand occurs mainly under storm conditions. The sequence of parallel lamination to wave ripple cross-lamination observed in many sandstone beds reflects the waning energy of a storm event, while mudstone intervals represent fair-weather deposition.
Figure 5.11. Detailed stratigraphic column of facies 3.
Figure 5.12. Facies 3. (A) Alternating mudstone and sandstone. Scale bar is 2 cm. (B) Sandstone base with *Heimdallia chatwini*. Scale bar is 2 cm. (C) Laterally continuous sandstone beds with thinly alternating mudstone and sandstone. (D) Closeup of sandstone bed in figure 5.12C showing progression from parallel lamination to wave ripple cross-lamination. Scale bar is 2 cm. (E) Sandstone base densely populated by *Asterosoma ludwigae* (As) and *Rosselia socialis* (Ro). Scale bar is 10 cm.
5.1.4 Facies 4

Facies 4 consists of very fine- to fine-grained sandstone intercalated with mudstone and siltstone. Two subfacies have been identified.

Facies 4a (Figs. 5.13, 5.14) - Massive or parallel-laminated mudstone and siltstone with thin, discontinuous very fine-grained sandstone

Description - Mudstone intervals are up to 7 cm thick and are parallel-laminated or massive. Some mudstone laminations appear wavy due to draping over rippled sandstone beds. Siltstone occurs as 0.1-0.7 cm thick layers with no clear internal lamination and locally irregular surfaces. Light grey fine-grained sandstone forms erosively based lenses, while red very fine-grained sandstone forms thin (0.5-4 cm) beds with parallel to wave ripple cross-lamination from base to top. Mudstone dominates sandstone with a ratio of 5:1. Facies intervals are 0.4-17 m thick. Red sandstone bed tops preserve wave or combined flow ripples. Locally, load casts filled with slightly deformed fine- to medium-grained grey laminated sandstone displace underlying mudstone laminae (Fig. 5.14D). Casts are 2-5 cm deep, increasing in size to 5-7 cm deep stratigraphically upward. One exceptionally large example (15 cm deep) was observed. Facies 4 occurs in the middle interval of the Furada Formation, where it is the dominant facies.

Ichnology - BI = 0-1, 3; mudstone intervals are either unbioturbated or contain very few simple horizontal burrows filled with fine- to medium-grained sand, indicating colonization surfaces associated with the sandstone lenses. Areas of BI = 3 are up to 10 cm thick, showing bioturbation capable of mixing sandstone and mudstone vertically. Simple horizontal burrows are dominant, with subordinate occurrence of inclined cylindrical burrows and small Rosselia socialis and Trichophycus isp. are locally present in some sandstone bases. A few basal surfaces at the same stratigraphic level contain Monomorphichnus isp, Dimorphichnus isp., and small Cruziana quadrata that commonly overlap (Fig. 5.14E). Recorded ichnotaxa in order of decreasing abundance are: Rosselia socialis, Cruziana quadrata, Bifungites munizi, Monomorphichnus isp., Dimorphichnus isp., Planolites montanus, Palaeophycus tubularis, Lockeia siliquaria, Rusophycus pudicus, Nereites isp., and Curvolithus multiplex.

Interpretation - The dominance of mudstone in facies 4a suggests deposition below fair-weather wave base, with siltstone and sandstone layers being emplaced during storms (Plint, 2010). Some
mudstone intervals are remarkably unbioturbated and structureless, suggesting events of rapid mud deposition. The presence of combined flow ripples and low bioturbation intensity may support the occurrence of continent-derived flows carrying high concentrations of fine sediment resulting in event deposition of mud and silt (Paz et al., 2022a) Facies 4a reflects deposition in the lower offshore affected by both storms and events of rapid deposition of fine-grained material.

Figure 5.13. Detailed stratigraphic column of facies 4a.
Figure 5.14. Facies 4a. (A) General appearance of facies 4a. Scale bar is 60 cm. Younging direction is to the left. (B) Sandstone block with combined flow ripples preserved on the upper surface. Scale bar is 10 cm. (C) Mudstone-dominated and sparsely bioturbated interval characteristic of facies 4a. Scale bar is 2 cm. (D) Load cast with deformed internal lamination. Scale bar is 2 cm. (E) Sandstone base with high density of shallow-tier trace fossils, dominantly arthropod scratch imprints. Scale bar is 2 cm. Photograph by M.G. Mángano. (F) Monomorphichnus isp. preserved as positive hyporelief in sandstone. Pen is 15 cm long. (G) Cruziana quadrata exposed on a sandstone base. Scale bar is 1 cm. (H) Lockeia siliquaria (Lo) and Dimorphichnus isp. (Di) preserved as positive hyporelief in sandstone. Scale bar is 2 cm.
**Facies 4b** (Figs. 5.15, 5.16) – Parallel-laminated mudstone interbedded with very fine- to fine-grained sandstone

**Description** - Mudstone intervals are 0.5-5 cm thick and parallel laminated. Rare siltstone layers are 0.1-0.5 cm thick and commonly disrupted by bioturbation. Red sandstone beds are 1-4 cm thick, locally discontinuous, and display parallel to wave ripple cross-lamination from base to top. Sandstone also forms erosive lenses, possibly gutter casts as seen in cross-section. Mudstone dominates sandstone with a ratio of 4:1. Facies intervals are 0.8-4 m thick. Facies 4b occurs at the top of the middle interval and the base of the upper interval.

**Ichnology** - BI = 2. Bioturbation is more consistent throughout facies 4b packages and a change in infaunal community is reflected in recorded ichnotaxa. Trace fossils are concentrated on sandstone bases: simple horizontal burrows are dominant with basal surfaces becoming increasingly populated with trace fossils and showing an increase in ichnodiversity stratigraphically upwards. *Gordia marina* and an unidentified horizontal trace occur on the top of a red sandstone bed with combined flow ripples; the horizontal trace is oriented parallel to ripple crests. Recorded ichnotaxa in order of decreasing abundance are: *Rosselia socialis, Cruziana quadrata, Gordia marina, Palaeophycus tubularis, Rusophycus pudicus, Trichophycus* isp., *Protovigularia dichotoma, Nereites* isp., and *Curvolithus multiplex*.

**Interpretation** - The dominance of mudstone in facies 4b suggests deposition below fair-weather wave base. The mudstone intervals are laminated, reflecting deposition by suspension fallout under fair-weather conditions, while the sandstone beds containing parallel to wave ripple cross-lamination reflect the waning energy of a storm event (Plint, 2010). Facies 4b displays the typical features of a wave-dominated, storm-influenced lower offshore.
Figure 5.15. Detailed stratigraphic column of facies 4b.
Figure 5.16. Facies 4b. (A) General appearance of facies 4b. Beds thicken and sandstone component increases upwards, transitioning into shallower-water facies. Scale bar is 1 m. Younging direction is to the left. (B) Lightly bioturbated mudstone and sandstone. Scale bar is 2 cm. (C) Sandstone top with unidirectional current ripples. Scale bar is 2 cm. (D) Sandstone base with high density of *Palaeophycus tubularis*. Scale bar is 2 cm. (E) Sandstone base with *Trichophycus* isp. Scale bar is 4 cm. (F) Sandstone top with *Gordia marina*. Scale bar is 2 cm. (G) Sandstone top preserving wave ripples. Notebook is 21 cm tall.
5.2 Sedimentologic Trends

The Furada Formation can be broadly divided into four major parts: a sandstone-dominated basal interval, an alternating sandstone and mudstone lower interval, a mudstone-dominated middle interval, and a sandstone-dominated upper interval. The basal interval is dominated by trough cross-bedded, fine-grained sandstone (i.e., facies 1a, 1b, and 1c). The sandstone is ferruginous and deep red purple in colour, which has also stained mudstone interbeds because of weathering (Fig 5.2C). The lower interval shows a change from trough cross-bedding to hummocky cross-stratification with beds becoming undulating to lenticular in shape (i.e., facies 2a and 2b). Stratigraphically upwards, mudstone interbeds increase in thickness and become regularly alternated with parallel-laminated to wave ripple cross-laminated sandstone (i.e., facies 3). At a stratigraphic height of 67 meters, a fault associated with minor deformation results in the repetition of a small section of sandstone beds (throw is approximately 1 m; Fig. 5.17). The middle interval is dominated by structureless and parallel-laminated mudstone intervals (i.e., facies 4a) that are interrupted by thin, discontinuous, siltstone and sandstone beds and lenses. Sandstone tops commonly preserve wave and combined flow ripples in the middle unit. Near the top of the middle interval, beds thicken upwards, and the sandstone component increases (i.e., facies 4b). The upper interval of the Furada Formation is far more weathered than the others, with many beds covered by a black coating obscuring internal structure. The upper interval is like the lower interval in being dominated by commonly amalgamated, trough cross-bedded and hummocky cross-stratified sandstones. The top of the formation contains repeated cycles of hummocky cross-stratified beds followed by a muddy interval with thin, wave ripple cross-laminated sandstone beds. The uppermost strata lie below the waterline at Playa de Bahínas.
Figure 5.17. Fault in lower unit of the formation.

5.3 Trace-Fossil Distribution

Thirty-three ichnotaxa have been recorded in the Furada Formation, namely Arenicolites isp., Asterosoma ludwigae, Bergaueria hemispherica, Bifungites munizi, Chondrites isp., Cruziana acacensis, Cruziana quadrata, Cruziana isp., Curvolithus multiplex, Davichnia cantabrica, Dimorphichnus isp., Gordia marina, Halopoa imbricata, Heimdallia chatwini, Helicodromites mobilis, Helminthoidichnites tenuis, Helminthopsis abeli, Imponoglyphus isp., Lockeia siliquaria, Monomorphichnus isp. A and B, Nereites isp., Palaeophycus tubularis, Phycodes circinatum, Planolites montanus, Psammichnites plummeri, Psammichnites cf. P. implexus, Ptychoplasma excelsum, Rosselia socialis, Rusophycus pudicus, Rusophycus isp. A and B, Skolithos isp., Teichichnus rectus, Trichophycus isp., and one indeterminate trackway (Ornia et al., 2024). Ethological categories, possible producers, associated lithofacies, and associated trace fossils for each ichnotaxa are summarized in table 1.

Collectively, the trace fossils of the Furada Formation represent the Cruziana ichnofacies, whose characteristics are (1) dominance of horizontal traces and secondary presence of vertical
and inclined structures; (2) wide ethological range; (3) predominance of structures produced by detritus and deposit feeders, accompanied to a lesser extent by those of suspension feeders and predators; (4) dominance of tracks and trails produced by a mobile fauna and secondary presence of permanent burrows; (5) high ichnodiversity; and (6) high abundance (Seilacher, 1967; MacEachern et al., 2007; Buatois and Mángano, 2011). If individual occurrences of trace-fossil assemblages are considered, however, a more complex pattern is revealed. Ichnodiversity of the formation as a whole is high but fluctuates significantly across the succession due to environmental factors such as sedimentation rate, substrate stability, and hydrodynamic energy. Bioturbation indices throughout much of the formation are low and trace fossils are restricted in size, especially in the fine-grained middle interval.

Similarities may also be drawn between the trace fossils of the Furada Formation and the Phycosiphon and Rosselia Ichnofacies put forward by MacEachern and Bann (2020). The Phycosiphon and Rosselia Ichnofacies have been proposed as case-specific alternatives to the Cruziana and Skolithos Ichnofacies respectively, to enhance the recognition and interpretation of deltaic systems and other shallow-marine environments affected by river-sediment input and consequent stress factors. The Phycosiphon Ichnofacies records animal responses to sedimentary processes in the prodelta, including generally low-energy conditions with periodic high-energy events, high sedimentation rate of both sand and mud alternating with periods of slower deposition, temporary freshening of normal marine salinity, and variable substrate consistency; resultant biogenic suites are dominated by deposit-feeding and surface grazing structures, highly variable bioturbation indices, equilibrichnia and fugichnia, mantle-and-swirl burrows, and, most notably, the juxtaposition of suites characterized by open marine ichnogenera with suites of opportunistic facies-crossing ichnogenera (MacEachern and Bann, 2020). The Rosselia Ichnofacies records animal responses to environmental factors in the delta front, including high sedimentation and erosion rates and storm events coupled with river flooding resulting in high water turbidity, flocculation of mud, and reduced salinity; suspension-feeding structures are inhibited by water turbidity and trace-fossil suites are dominated by opportunistic ichnogenera with variable bioturbation indices and few specialized structures associated with normal marine conditions (MacEachern and Bann, 2020). Further research needs to be done to evaluate the expression of these ichnofacies in subaqueous deltas, such as those associated with hyperpycnal systems (e.g., Wang et al., 2024).
The basal and upper intervals of the Furada Formation are dominated by amalgamated, fine-grained sandstone containing sedimentary structures indicative of high hydrodynamic energy (i.e., trough cross-bedding). These beds lack trace fossils or have very low ichnodiversity, reflecting the high erosion and sedimentation rates in a dynamic shoreface setting. Observed trace fossils consist of robust structures such as *Rosselia socialis*, *Palaeophycus tubularis*, and *Asterosoma ludwigae*, whose producers would have burrowed during short breaks in sedimentation.

The lower interval of this formation is dominated by regularly interbedded sandstone and mudstone intervals with interspersed hummocky cross-stratified sandstone beds. While the hummocky cross-stratified beds show the same low ichnodiversity suites as the basal unit, the interbedded sections display high diversity of trace fossils and ethological categories with *Rosselia socialis* and *Asterosoma ludwigae* as the most dominant ichnotaxa. Other ichnotaxa present are *Cruziana quadrata*, *Bifungites munizi*, *Helminthoidichnites tenuis*, *Palaeophycus tubularis*, *Phycodes circinatum*, *Trichophycus isp.*, and *Rusophycus pudicus*.

The fine-grained middle interval contains mid-tier vertical (e.g., *Bifungites munizi* and *Rosselia socialis*) and shallow-tier and surficial trace fossils (e.g., *Protovigularia dichotoma*, *Lockeia siliquaria*, *Cruziana acacensis*, *Cruziana quadrata*, *Cruziana isp.*, *Rusophycus pudicus*, *Rusophycus isp.*). Simple trails (*Gordia marina* and *Curvolithus multiplex*) are also present, as well as a few complex structures (e.g., *Nereites isp.*) Trace fossils are sparse and restricted in size with few exceptions: some sandstone beds show concentrated areas of activity with “scratch” type traces including *Monomorphichnus* isp. and *Dimorphichnus* isp. Simple trails (*Gordia marina* and *Curvolithus multiplex*) are also present. Abundance of trace fossils and bioturbation index in the middle unit increases upwards in conjunction with an increase in the number of sandstone beds.

**5.4 Paleoenvironmental Interpretation**

The depositional setting of the Furada Formation is a wave-dominated shallow-marine environment with strong storm influence recorded as well developed hummocky cross-stratification. Thick layers of unbioturbated to sparsely bioturbated mudstone in the basal and middle intervals indicate rapid deposition of fine-grained sediments by hyperpycnal flows, fluid
muds, and sediment plume collapse derived from a fluvial source. The proposed environment for the Furada Formation (Fig. 5.18) shares similarities with hyperpycnal littoral deltas proposed by Zavala et al. (2021, 2024) and storm-flood-dominated deltas, proposed by Lin and Bhattacharya (2020) and further developed by Saleh et al. (2020). Hyperpycnal littoral deltas are low-gradient littoral deltas partially equivalent to prodeltaic shelves (Bhattacharya and MacEachern, 2009) and storm-flood-dominated deltas (Lin and Bhattacharya, 2020). These deltas develop where sediment-laden rivers enter brackish or normal-salinity basins as diluted currents resulting in light (fine-grained) hyperpycnal plumes with limited erosive power and easily kept in suspension by the hydrodynamic energy supplied by tides, waves, or ocean currents in the basin (Zavala et al., 2024), enabling the transport of fine-grained sediments a great distance from the river mouth. Flume experiments by Smith et al. (2019) showed that the addition of wave action in gravity-driven currents (hyperpycnal flows) results in a greater distance of downslope transport of suspended sediment. Low-angle slopes that facilitate the development of a hyperpycnal littoral delta may also facilitate distribution of fine-grained sediment by bottom currents (Schieber, 2016). Hyperpycnal littoral deltas can accumulate mud and silt that are not conveniently explained by fluid mud flows (Zavala et al., 2024). In the Furada Formation, hypopycnal sediment plumes are interpreted as a source of wave-enhanced fluid mud flow deposits (such as those in facies 1c). This indicates the activity of both hyperpycnal and hypopycnal flows depending on sediment concentration of the fluvial discharge, a variable highly connected to seasonality. In addition, hyperpycnal deposits in the shoreface may be representative of marine littoral delta processes (generation of hypopycnal plumes, Fig. 5.19A; Zavala et al., 2024), while deposition reaching the offshore is the result of hyperpycnal littoral delta processes (Fig. 5.19B).
Figure 5.18. Block diagram showing the depositional environment and distribution of facies with characteristic trace fossils. (A) Subenvironments follow that of a wave-dominated shoreline with the addition of fluvial discharge generating mud-rich flows that reach as far as the lower offshore. OT = offshore transition. (B) Facies 1a. (C) Facies 1b. (D) Facies 1c. (E) Facies 2a. (F) Facies 2b. (G) Facies 3. (H) Facies 4a. (I) Facies 4b. For legend, see Fig. 4.2.
Figure 5.19. Diagram showing two categories of deltas with processes influencing episodic deposition in the Furada Formation. (A) Hypopycnal flow processes in a marine littoral delta: inflow water has a lower bulk density than water in the basin, generating a buoyant plume containing fine-grained sediment (e.g., facies 1c). (B) Flow processes in a hyperpycnal littoral delta: inflow water has a higher bulk density than water in the basin, fine-grained sediment is kept in suspension and transport distance is increased by wave action (e.g., facies 4a). Notation: \( \rho_r = \) density of river water, \( \rho_w = \) density of basin water. Modified from Zavala et al. (2021, 2024).

Heterolithic units occurring in the basal interval (facies 1c) are produced by an accumulation of fine-grained sediment in the middle to upper shoreface during periods of high fluvial discharge. Structureless, parallel lamination, wave ripple cross-lamination, and inversely graded mudstone intervals are indicative of the generation of fluid muds and sediment-gravity flows (Hovikoski et al., 2008; Paz et al., 2022a). For the observed thickness of heterolithic intervals to be preserved, the fluvial sediment flux must provide enough fine-grained material to withstand subsequent erosion by migrating sand dunes (Mullenbach and Nittrouer, 2000; Draut et al., 2005). This may have occurred through a combination of high sediment load combined with supression of wave energy due to fluid mud on the seafloor. During periods of exceptionally high fluvial discharge, the fine-grained sediment load enters coastal waters and forms a sediment plume where flocculation is facilitated by wave energy to generate a wave-enhanced fluid mud flow (Mullenbach and Nittrouer, 2000). This fluid mud then forms a layer of viscous material on the seafloor capable of damping incoming wave energy by more than 80% (Rodriguez and Mehta, 1998; Sheremet and Stone, 2003; Draut et al., 2005); reduction of wave energy in the middle
shoreface enables the accumulation of a thick layer of mud and silt. Once the period of increased fluvial discharge ceases, formation of fluid mud stops and wave energy increases to pre-event levels. This results in the erosion and resuspension of some thickness of the accumulated mud, exposure of consolidated material below, and a return to sand deposition under fairweather conditions. Cohesive mud exposed by increased wave energy serves as a potential firmground colonization surface such as those observed in facies 4a (discussed further in section 6.2), as well as being incorporated as mudstone intraclasts, as observed in the trough cross-beded sandstone.

Accumulation of mud flow deposits in the middle interval (facies 4a) are generated the same way, with some flows becoming channelized to reach greater distances from the river mouth (Dasgupta et al., 2016; Lin and Bhattacharya, 2020). Fairweather deposits in the middle interval are less contrasting than those in the basal interval, however, they are recognized by an increase in bioturbation index (facies 4b). Seasonal changes in fluvial discharge is a possible cause for the proposed mechanism of deposition of heterolithics. Periods of high fluvial discharge and associated wave damping by fluid mud resulting in nearshore accumulation of fine-grained sediment has been observed in the Eel River (Mullenbach and Nittrouer, 2000) and Louisiana coast off the Atchafalaya River (Allison et al., 2000; Sheremet and Stone, 2003) due to strong cold fronts during winter seasons associated with peak levels of fluvial discharge and suspended sediment load. Another component of this depositional system may be a narrow shelf coupled with a strong longshore current. A narrow shelf may restrict suspended fine sediment to the nearshore (Allison et al., 1995), which, when coupled with a strong longshore current may deflect a sediment plume or wave-enhanced fluid mud flow along the coastline for a considerable distance downflow of the river mouth. Due to the lack of deltaic deposits within the Furada Formation or in contemporary formations, the existence of a nearby delta or fluvial system must be inferred based on sedimentary and biogenic structures observed.
CHAPTER 6
DISCUSSION

6.1 Response to Stress Factors

As evidence of the behaviour of organisms, trace fossils are powerful tools that can be used as a proxy to evaluate the response of individuals or communities to biotic and abiotic environmental factors. While the diversity of individual ichnotaxa is high, abundance and intensity of bioturbation is low and not uniformly distributed through the succession, indicating environmental stressors affecting the benthic population. The environmental controls with the greatest influence on benthic organisms in the Furada Formation include hydrodynamic energy, sedimentation rate, water turbidity, and substrate consolidation; food supply, oxygenation, and salinity are also considered.

6.1.1 Hydrodynamic Energy

Hydrodynamic energy is one of the most common limiting factors in all aquatic environments due to its influence over the distribution and behaviour of organisms and taphonomy of resultant structures. As hydrodynamic energy increases, burrow orientation changes from dominantly horizontal to dominantly vertical, and feeding strategies in shallow-marine settings shift from detritus and deposit feeding and active predation to suspension feeding and passive predation (Pemberton et al., 2001; Buatois and Mángano, 2011). High hydrodynamic energy also hampers infaunal colonization by resuspending larvae (Qian, 1999) and destabilizes the sediments surface, preventing sessile epifauna from securely attaching to the substrate (Rhoads and Young, 1970). These impacts are evident in the mudstone-dominated middle interval in association with hyperpycnal flow events. The basal, lower, and upper intervals of the Furada Formation contain sedimentary structures indicative of high hydrodynamic energy during both fair-weather (trough cross-bedding) and storm-weather (hummocky cross-stratification) conditions. Ichnotaxa representative of the Skolithos Ichnofacies would be expected in such deposits but are generally absent in the Furada Formation due to high water turbidity, a controlling factor discussed in section 6.1.3.
6.1.2 Sedimentation Rate

The most significant effect of sedimentation rate on benthic fauna is its impact on colonization windows. Periods of low sedimentation rate enable thorough bioturbation of a deposit, generating a mottled appearance through the overprinting of trace fossils (Pemberton et al., 1992). Periods of high sedimentation rate restrict the colonization window and commonly result in bioturbation of only the top of a deposit, representing colonization in the time between depositional events (Frey and Goldring, 1992; Buatois et al., 2015). Amalgamated sandstone beds such as those observed in facies 1a, 1b, 2a, and 2b are deposited under alternating times of high sedimentation and erosion rates, reducing the colonization window and removing any shallow-tier traces. \textit{Rosselia socialis} is one of the most abundant ichnotaxa found throughout the formation, occurring as both domicichnia (one burrow instance) and equilibrichnia (a vertically repeated burrow). This suggests organisms capable of adjusting their vertical position with respect to the sediment-water interface in response to aggradation or degradation of the substrate (Nara, 1995, 1997, 2002; Bromley, 1996; Buatois et al., 2016; Campbell et al., 2016) are suited to survival in this environmental setting. \textit{Rosselia socialis} is most likely produced by detritus-feeding polychaete worms (Nara, 1995), which are commonly found in shallow-marine settings affected by episodic deposition resulting from storms and fluvial discharge (Nara, 1995; Pemberton et al., 1997; MacEachern et al., 2005), like the conditions observed in the Furada Formation. \textit{Curvolithus multiplex}, although very rare, is another trace that is present in the Furada Formation; \textit{Curvolithus} has been associated with shallow-marine and delta or fan-delta settings in response to episodic rapid sedimentation (Buatois et al., 1998).

6.1.3 Water Turbidity

The Furada Formation shows a paucity of suspension feeders, suggesting water turbidity as a significant stress factor. High levels of water turbidity limit primary productivity, affecting the food supply for both suspension and deposit feeding infaunal organisms (Leithold and Dean, 1998), as well as restricting the colonization of suspension feeders by clogging filtering structures (Rhoads and Young, 1970; MacEachern et al., 2005), resulting in the impoverishment of the \textit{Skolithos} Ichnofacies in shallow-marine settings. Increased water turbidity may be due to the episodic deposition of fine-grained material in the system and resuspension of fine-grained material between periods of high river discharge. The benthic response present in the studied
deposits consist of an overall reduction in ichnodiversity and burrowing intensity and the dominance of deposit-feeding structures.

6.1.4 Substrate Consolidation

Changes in substrate consistency led to variability in burrow morphology as organisms adapt locomotion strategies through different degrees of substrate consolidation. Most of the deposits studied are representative of softgrounds at the time of deposition, which would not be a major inhibitor of infaunal colonization (Ekdale, 1985). The middle interval of the formation contains many layers of mudstone attributed to rapid sedimentation of fine-grained material through fluid mud flows, hyperpycnal flows, and plume collapse, likely generating soupgrounds. When organisms swim through the soupy substrate, any structures would immediately be destroyed by the flow of displaced sediment, resulting in an extremely low preservation potential (Ekdale, 1985) and the generation of mantle and swirl structures (Lobza and Schieber, 1999) or structureless deposits (MacEachern et al., 2005). This suggests decreased bioturbation intensity in fluid mud flow deposits may also be a result of taphonomic barriers.

Some examples of mudstones deposited by fine-grained hyperpycnal flows (Bhattacharya and MacEachern, 2009; Wilson and Schieber, 2014) show soft-sediment deformational structures including convolute lamination and load casts as well as massive and graded deposits and mantle and swirl structures representing bioturbation in soupy substrate (Lobza and Schieber, 1999). Soft and soupy substrate conditions are related to the liquified nature of sediment-gravity flows due to water becoming trapped in high sediment concentrations (Paz et al., 2022a). These structures match those observed in facies 4a of the Furada Formation along with traction structures such as parallel and ripple cross-lamination, indicating the additional presence of flows with lower sediment concentration (Schieber and Southard, 2009; Paz et al., 2022a).

Trace fossils found in mudstone intervals (i.e., facies 1c and 4a) emplaced by rapid depositional mechanisms are shallow-tier and infilled by sandstone from an overlying bed, indicating a colonization window after some amount of compaction modifies the substrate into softgrounds. Conversely, some surfaces in the mudstone-dominated middle interval are densely covered in scratch-type trace fossils, indicating the exhumation of firmgrounds capable of
preserving more detailed morphological features. The generation and colonization of these surfaces is discussed in section 6.2.

### 6.1.5 Food Supply

Most of the ichnotaxa recorded are produced by deposit-feeding organisms, suggesting a constant supply of new organic material. A river plume containing nutrients and organic particulates provides food for benthic microbes and macrofauna and may reach as far as the outer shelf through plume collapse and hyperpycnal flows (Bourgeois et al., 2011; Dasgupta et al., 2016). Bioturbation in the Furada Formation is concentrated in mudstone-dominated interbeds, reflecting the higher concentration of nutrients available in these deposits in comparison with that in more sandstone-dominated intervals. The appearance of unspecialized grazing traces such as *Gordia marina* and *Helminthopsis abeli* may reflect organisms exploiting an influx of new material (Buatois and Mángano, 2011) delivered via river-derived sediment flows. The lack of specialized feeding strategies (e.g., *Chondrites*, *Zoophycos*) and poorly developed tiering in mudstone-dominated intervals may be attributed to food-rich conditions (Wetzel, 1991) with frequent input of organic matter via fluvial discharge.

### 6.1.6 Oxygenation

Restricted oxygenation in bottom and interstitial waters is reflected in benthic activity through decreasing size and depth of burrows as well as dominance of grazing traces produced by deposit feeders (Buatois and Mángano, 2011). Ekdale and Mason (1988) proposed a model for oxygen-dependent trace-fossil associations in which the dominant ethological category changes with decreasing oxygen in bottom and interstitial waters: domicinia in fully oxygenated conditions, pascichnia in oxic bottom waters and dysoxic interstitial waters, fadinichnia in dysoxic bottom waters and anoxic interstitial waters, and the absence of trace fossils in fully anoxic conditions. Dominant ethological categories observed in the Furada Formation are fadinichnia and pascichnia, suggesting the possibility of some oxygen restriction. However, the ichnotaxa *Zoophycos*, *Chondrites*, *Teichichnus*, and *Trichichnus*, typically considered “classic” indicators of poorly oxygenated substrates (Ekdale and Mason, 1988; Savrda, 1992; Buatois and Mángano, 2011), are absent or rare in the Furada Formation.
In Devonian black shale deposits within the Appalachian Basin, ichnofabric index was used to evaluate infaunal activity in conditions known to be dysoxic to anoxic based on trace metal analysis (Boyer et al., 2021). The shale is commonly laminated with limited bioturbation indicating dysoxic to anoxic bottom waters; some more proximal localities had higher levels of bioturbation consistent with an environment experiencing prolonged oxygen stress with short oxygenation pulses (Boyer et al., 2021). Mudstone intervals in the Furada Formation show somewhat similar trends; however, sedimentary structures consistent with fluid mud flows and sediment plume collapse (e.g., structureless and inversely graded mudstone) indicate that the sparse bioturbation in mudstone intervals is a result of rapid deposition rather than poor oxygenation.

The late Silurian saw climate perturbations associated with widespread ocean anoxia and euxinia (the Mulde event during the latter half of the Wenlock and the Lau event during the late Ludlow). The Mulde event is identified by elevated carbon isotope values in carbonates from Sweden, England, and the midcontinent United States and is contemporaneous with a fall and subsequent rise in eustatic sea level (Danielsen et al., 2019). Similarly, the Lau event is identified by a rapid increase in carbon isotope values indicating a warming period associated with recorded eustatic sea level rise, resulting in changes in ocean circulation and the spread of anoxic water onto shelf environments (Trotter et al., 2016; Bowman et al., 2019). Evidence of the Mulde and Lau events is dominantly collected from locations that existed on the paleocontinent Laurussia, located across the Rheic Ocean from the Iberian Peninsula, suggesting that these anoxic events may have been restricted to areas closer to the paleoequator.

6.1.7 Salinity

There is localized evidence in the Furada Formation that suggests a central role of salinity as an environmental control. Body fossils found in the basal and upper intervals place no specific restriction on salinity range, as well as no structures suggesting salinity fluctuations, such as syneresis cracks. Brachiopods are commonly associated with normal marine conditions, but it is likely they would be capable of withstanding short-lived salinity reduction during a pulse of freshwater (Fürsich and Hurst, 1980). The responses of benthic fauna to salinity fluctuations are characterized by reduction in ichnodiversity and burrow size, presence of simple vertical and horizontal marine traces representative of the Skolithos and Cruziana ichnofacies, dominance of infaunal traces over epifaunal trails, variable abundance, and presence of monospecific
associations (Pemberton and Wightman, 1992; Buatois and Mángano, 2011). Ichnofabrics dominated by small *Planolites* and *Teichichnus* suggest times of salinity stress (Buatois et al., 2005; Mángano et al., 2023) and have persisted in fine-grained marginal-marine settings since the Cambrian (Buatois et al., 2005). Assemblages containing only *Planolites* and *Teichichnus* in the Furada Formation are associated with mudstone intervals deposited by fluid mud flows and plume collapse (e.g., facies 1c, 4a). This suggests the possibility of temporary freshening due to the influence of a channelized hyperpycnal flow during periods of high fluvial discharge (Dasgupta et al., 2016), leading to periodic salinity stress.

6.2 Taphonomy of Firmground Surfaces

Firmgrounds are defined as stiff but uncemented sediment layers that were close to the sediment-water interface at some point in time (Ekdale, 1985; Droser et al., 2002). The stiff quality of firmgrounds allows for the preservation of more detailed morphological features than softgrounds. Firm sediments enable the preservation of delicate structures such as scratch imprints, referred to as bioglyphs. Seilacher (2007) described bioglyphs as “fingerprints” of an organism, left behind as engravings in the walls of burrows or borings produced by the animal. Bioglyphs offer various potential insights, including the method of burrowing, the use of a burrow, anatomical features of the tracemaker (provided the use of an appendage or body part), and the substrate consistency at the time of burrowing (Ekdale and Gibert, 2010). Bromley (1996) restricted the definition of bioglyphs to only include carvings or engravings on burrow walls produced by the appendages or rigid shell structure of the tracemaker.

Within the Furada Formation, trace fossils on firmground surfaces (Fig. 5.14E-G) include *Monomorphichnus* isp. A, *Monomorphichnus* isp. B, and *Dimorphichnus* isp., with these structures associated with the scratching and raking of jointed appendages (Ekdale and Gibert, 2010; Gibb et al., 2017). Moreover, specimens of *Cruziana acacensis*, *Cruziana quadrata*, and *Cruziana* isp. exhibit well-defined scratches on their lobes. These trace fossils are all generally attributed to the activity of trilobites, in which the use of various appendages produces scratch imprints used to distinguish specimens at an ichnospecific level (Seilacher, 1970, 1992; Ekdale and Gibert, 2010).
To preserve such structures, the substrate must be firm enough to remain in its modified position as well as fine-grained enough so as not to obscure fine surface details.

Firmgrounds are commonly associated with trace fossils representing the *Glossifungites* Ichnofacies, which reflect colonization of allogetic surfaces exposed by ravinement during sea-level changes (MacEachern et al., 1992; Buatois et al., 2002). The *Glossifungites* Ichnofacies also occurs on autogenically produced firmgrounds and may be distinguished by their limited spatial extent, similarity to surrounding lithofacies and ichnofacies, shallow burrow depth, impoverishment of the trace-fossil suite, and evidence of deformation by compaction (Abdel-Fattah et al., 2016; Villegas-Martín et al., 2020). Based on sedimentologic processes interpreted in the facies hosting these firmgrounds (i.e., hyperpycnal flows), it is posited that the erosional exhumation of firm substrates was an autogenic process, resulting from the removal of overlying soft sediment layers during successive hyperpycnal flows in zones of sediment bypass.

The development of firmground surfaces may be facilitated by the rapid accumulation of silty to muddy substrates, which remain unaffected by bioturbators. Compaction and dewatering in these deposits tend to happen quickly (Droser et al., 2002), resulting in the formation of a cohesive substrate. Evidence of microbial growth, notably a pustulose texture associated with a *Cruziana quadrata* specimen (Fig. 5.10D-E), is also observed. The growth of microbial mats and biofilms can stabilize sediments and enhance the preservation of shallow-tier traces (Seilacher, 2008; Luo and Chen, 2013) such as the scratch-type structures *Monomorphichnus* isp. A and B and *Dimorphichnus* isp., as well as serving a food source. The critical variable for the generation of these surfaces is a colonization window between erosional exhumation and subsequent deposition that is open long enough to accommodate the bioturbation event.

### 6.3 The Significance of Intensely Bioturbated Deposits

Intervals of increased bioturbation in environments affected by episodic deposition are often interpreted as a reflection of colonization windows that are open long enough to enable the development of a climax community (MacEachern et al., 2005; Desjardins et al., 2012; García-Garcia et al., 2021; Paz et al., 2022b). Climax ichnofaunas are characterized by high ichnodiversity, low density, and the production of permanent structures during long-term colonization, while
opportunistic ichnofaunas are characterized by low ichnodiversity, high density, and simple morphologies produced during short colonization windows (Ekdale, 1985). In the Furada Formation, intensely bioturbated intervals occur in offshore transition heterolithics (facies 3) and in beds overlying offshore event deposits (facies 2 and facies 4a). Trace-fossil assemblages in these intervals display low ichnodiversity and high density, for example, sandstone bases densely colonized by Asterosoma ludwigae in the lower interval (Fig. 5.12E). In these cases, the infaunal activity appears to match the characteristics of an opportunistic community. It is possible that zones of more intense bioturbation vary laterally, forming a patchwork of communities in response to seafloor features such as potentially channelized hyperpycnal flows, changes in substrate consolidation, and areas of higher nutrient concentration. Significant spatial heterogeneity of bioturbation has been observed in muddy shorelines (Potter et al., 2005; Hovikoski et al., 2008; Buatois and Mángano, 2011); however, this study was restricted to a single exposure of the formation that provided a continuous vertical succession but little opportunity to track lateral changes. This is due to the steep cliff exposure positioned close to the water level and only accessible during low tide.

The nature of sedimentation in the Furada Formation may be described by three general environmental states: (a) storm events during which sedimentation rate and hydrodynamic energy are high, (b) periods of high fluvial discharge with rapid deposition of fine-grained sediment, high hydrodynamic energy, influx of organic matter, and a potential drop in salinity near channelized flows, and (c) fairweather periods with lower hydrodynamic energy and sedimentation rates. Colonization windows in states (a) and (b) are closed or short, resulting in the absence of or low trace-fossil density and low bioturbation indices. Colonization windows in state (c) are open for a longer period, allowing for higher degrees of bioturbation but not necessarily enabling an increase in diversity or burrow depth due to a relatively high level of background stress factors discussed in section 6.1. The scarcity of intensely bioturbated deposits in the Furada Formation suggests a high frequency of storms and episodic depositional events. The occurrence of intensely bioturbated deposits may also be a result of taphonomic influence. Variation in the erosive power of different processes of episodic deposition present in the studied section (storms, hyperpycnal flows, plume collapse, fluid mud flows) affect the preservation of bioturbated intervals. Due to shallow-tier trace fossils being dominant in the Furada Formation, events with moderate to high erosive power result in the removal of fairweather layers and the amalgamation of event beds (Buatois and Mángano,
2011; Buatois et al., 2015; Fürsich et al., 2018). In areas affected by events characterized by rapid deposition and low erosive power (e.g., plume collapse), the bioturbated interval is more likely to be preserved, producing an alternation of fairweather and storm-weather ichnofabrics as observed in facies 3.
CHAPTER 7
CONCLUSIONS

(1) Four sedimentary facies have been identified in the Furada Formation. Of these, facies 1 was subdivided into three subfacies, and facies 2 and 4 into two subfacies each.

(2) In the study area, the Furada Formation represents deposition in a siliciclastic wave-dominated shallow-marine environment affected by episodic deposition. Subenvironments include the upper-middle shoreface, lower shoreface, offshore transition, upper offshore, and lower offshore.

(3) Common amalgamation of hummocky cross-stratified sandstones (facies 2a, 2b) indicates high frequency of storm events.

(4) Structureless, parallel- and irregularly laminated, and inversely graded mudstones (facies 1c, facies 4a) suggest episodic deposition by fluvially derived hyperpycnal flows, fluid mud flows, and plume collapse.

(5) Thirty-three ichnotaxa have been identified in the studied formation, generally representing the Cruziana ichnofacies. Times of reduced storm and fluvial influence are associated with an increase in bioturbation intensity while the diversity of ichnoassemblages remains low.

(6) As an alternative ichnofacies interpretation, the trace-fossil assemblages of facies 1a, 1b, and 2a are representative of the Rosselia Ichnofacies, and trace-fossil assemblages of facies 1c, 2b, 3, 4a, and 4b are representative of the Phycosiphon Ichnofacies. These ichnofacies offer a more specific model for shallow-marine environments affected by fluvial input.

(7) Bioturbation is irregular and patchy due to different controlling factors throughout the formation including hydrodynamic energy, sedimentation rate, water turbidity, and substrate consolidation, food supply, oxygenation, and salinity.
LIST OF REFERENCES


TABLE 1: ICHNOTAXA AND ASSOCIATED LITHOFACIES

Table 1. Summary of ichnotaxonomic composition and associated facies (based on Ornia et al., 2024). Some ichnotaxa have been documented based on material housed in collections and their precise location within the stratigraphic succession is not known.

<table>
<thead>
<tr>
<th>Ichnotaxon</th>
<th>Ethological Group / Basic Description</th>
<th>Trophic Group / Producer</th>
<th>Facies / Associated Trace Fossils</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>Asterosoma ludwigae</em></td>
<td>Fodinichnia Fan-shaped burrow with arms branching from central axis.</td>
<td>Deposit feeder</td>
<td>Facies 1a, 1c, 2a, 3 vf/f sandstone. Dominant ichnotaxon in basal and lower units. Extremely common and locally high abundance, occurs with almost all recorded trace fossils.</td>
</tr>
<tr>
<td><em>Bergaueria hemispherica</em></td>
<td>Domicnichia Vertical plug-shaped burrow with rounded or conical base.</td>
<td>Suspension feeder</td>
<td>Facies 2a vf/f sandstone or siltstone. Rare and without uniform distribution, scattered towards the upper part of the lower unit. Occurs with common trace fossils including <em>Asterosoma ludwigae</em>, <em>Arenicolites</em> isp., <em>Cruziana acacensis</em>, <em>Cruziana quadrata</em>, <em>Cruziana</em> isp., <em>Rosselia socialis</em>, and <em>Phycodes circinatum</em>.</td>
</tr>
<tr>
<td><em>Bifungites munizi</em></td>
<td>Domicnichia U-shaped burrow with rectilinear</td>
<td>Suspension feeder</td>
<td>Facies 1b, 1c, 2a, 2b, 4a Occurs in thinly interbedded vf/f sandstone and mudstone. Relatively abundant throughout formation but rare in upper unit.</td>
</tr>
<tr>
<td><strong>Chondrites</strong> isp.</td>
<td><strong>Fodinichnia</strong></td>
<td><strong>Deposit feeder</strong></td>
<td><strong>Facies 4b</strong>&lt;br&gt;Contrasting fill (very fine siltstone) within a siltstone block.&lt;br&gt;Single sample found in lower unit.&lt;br&gt;No associated trace fossils.</td>
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<tr>
<td><strong>Cruziana acacensis</strong>&lt;br&gt;<strong>Cruziana quadrata</strong>&lt;br&gt;<strong>Cruziana</strong> isp.</td>
<td><strong>Repichnia</strong>&lt;br&gt;Bilobed horizontal trace with axial groove and regular scratches on lobes.</td>
<td><strong>Predator</strong>&lt;br&gt;<strong>Arthropods</strong></td>
<td><strong>Facies 1b, 1c, 2a, 2b, 3, 4a, 4b</strong>&lt;br&gt;vf sandstone.&lt;br&gt;Abundant throughout formation, some superimposed on other trace fossils.&lt;br&gt;Occurs with almost all recorded ichnotaxa. Preserved along with <strong>Dimorphichnus</strong> isp., <strong>Monomorphichnus</strong> isp., <strong>Gordia marina</strong>, <strong>Nereites</strong> isp., <strong>Lockeia siliquaria</strong>, <strong>Bifungites munizi</strong>, <strong>Rusophycus pucidus</strong>, <strong>Rusophycus</strong> isp., <strong>Trichophycus</strong> isp., <strong>Planolites montanus</strong>, <strong>Palaeophycus tubularis</strong>, and <strong>Rosselia socialis</strong> in fine-grained middle section.</td>
</tr>
<tr>
<td><strong>Curvolithus multiplex</strong></td>
<td><strong>Repichnia</strong>&lt;br&gt;Horizontal trace with 4 parallel lobes, outermost lobes are narrower than inner lobes. Flattened ribbon shape.</td>
<td><strong>Deposit feeder</strong>&lt;br&gt;<strong>Predator</strong>&lt;br&gt;<strong>Annelids</strong>&lt;br&gt;<strong>Gastropods</strong></td>
<td><strong>Facies 1c, 4a, 4b</strong>&lt;br&gt;f sandstone in heterolithics.&lt;br&gt;One specimen found in middle unit.&lt;br&gt;Associated with <strong>Bifungites munizi</strong>, <strong>Cruziana acacensis</strong>, <strong>Cruziana quadrata</strong>, <strong>Cruziana</strong> isp., <strong>Dimorphichnus</strong> isp., and <strong>Monomorphichnus</strong> isp.</td>
</tr>
<tr>
<td>Species</td>
<td>Description</td>
<td>Feeder Type</td>
<td>Facies</td>
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<td>-----------------------------------------------------------------------------</td>
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<tr>
<td>Davichnia cantabrica</td>
<td>?Fodinichnia Flat, horizontal, unbranched tubiform track with a smooth, locally concave central lobe and two narrower marginal lobes ornamented with regular submillimeter impressions.</td>
<td>?Deposit feeder</td>
<td>4a, 4b</td>
</tr>
<tr>
<td>Dimorphichnus isp.</td>
<td>Repichnia Paired impressions or scratches, overlapping or isolated. Scratches are elongate and straight or sigmoidal.</td>
<td>Predator Detritivore Arthropods</td>
<td>4a</td>
</tr>
<tr>
<td>Gordia marina</td>
<td>Pascichnia Thin, curved to winding and commonly overlapping horizontal trail with thin parallel ridges.</td>
<td>Detritivore Annelids Gastropods</td>
<td>2b, 4b</td>
</tr>
<tr>
<td>Halopoa imbricata</td>
<td>Fodinichnia Cylindrical to spindle-shaped burrows with</td>
<td>Deposit feeder</td>
<td>1c</td>
</tr>
<tr>
<td>Species</td>
<td>Description</td>
<td>Deposit Feeder</td>
<td>Facies</td>
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<tr>
<td><em>Heimdallia chatwini</em></td>
<td>Fodinichnia Horizontal burrow made of vertical to inclined spreite structure of chained and arched elements.</td>
<td>Deposit feeder Annelids</td>
<td>Facies 3</td>
</tr>
<tr>
<td><em>Helicodromites mobilis</em></td>
<td>Fodinichnia Horizontal trace formed by a row of tubiform segments aligned oblique to an axis, representing plane view of a spiral.</td>
<td>Deposit feeder Polychaetes Crustaceans</td>
<td>Facies 4b</td>
</tr>
<tr>
<td><em>Helminthoidichnites tenuis</em></td>
<td>Pascichnia Straight horizontal trail without ornamentation, commonly cross other specimens.</td>
<td>Detritivore Annelids</td>
<td>Facies 1a, 1c, 2b, 3</td>
</tr>
<tr>
<td><em>Helminthopsis abeli</em></td>
<td>Pascichnia Continuous and simple horizontal trail with no ornamentation,</td>
<td>Detritivore Polychaetes Annelids</td>
<td>Facies 2b</td>
</tr>
<tr>
<td><strong>Species</strong></td>
<td><strong>Description</strong></td>
<td><strong>Feeder</strong></td>
<td><strong>Associated with</strong></td>
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<tr>
<td><em>Lockeia siliquaria</em></td>
<td>Short, oval-shaped impressions with rounded terminations.</td>
<td>Filter feeder</td>
<td><em>Ptychoplasma excelsum</em> and <em>Dimorphichnus</em> isp.</td>
</tr>
<tr>
<td><em>Palaeophycus tubularis</em></td>
<td>Cylindrical</td>
<td>Deposit feeder?</td>
<td>Occurs in all facies</td>
</tr>
</tbody>
</table>

**Notes:**
<table>
<thead>
<tr>
<th>Trace</th>
<th>Description</th>
<th>Feeder</th>
<th>Occurrence</th>
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</thead>
<tbody>
<tr>
<td><strong>Phycodes circinatum</strong></td>
<td>Bifurcated burrows (hand of bananas) composed of groups of cylindrical, rectilinear or slightly curved sub horizontal tubes.</td>
<td>Deposit feeder</td>
<td>Facies 1c, 3vf/f sandstone. Present throughout formation and relatively abundant. Occurs with <em>Bergaueria hemispherica</em>, <em>Bifungites munizi</em>, <em>Cruziana acacensis</em>, <em>Cruziana quadrata</em>, <em>Cruziana</em> isp., <em>Gordia marina</em>, <em>Helminthoidichnites tenuis</em>, <em>Nereites</em> isp., <em>Rosselia socialis</em>, <em>Rusophycus puderus</em>, <em>Rusophycus</em> isp., and <em>Teichichnus rectus</em>.</td>
</tr>
<tr>
<td><strong>Planolites montanus</strong></td>
<td>Horizontal to sub horizontal curved burrows, lacking wall, contrasting fill, circular to elliptical section.</td>
<td>Deposit feeder</td>
<td>Facies 1a, 1c, 3, 4a vf/f sandstone and mudstone. Abundant throughout entire formation, especially in basal and middle units. Typically occurs with <em>Teichichnus rectus</em>, also found with most other common traces.</td>
</tr>
<tr>
<td><strong>Protovigularia dichotoma</strong></td>
<td>Continuous horizontal trail formed by chevron-like impressions, point in same direction.</td>
<td>Deposit feeder, Bivalves</td>
<td>Facies 2b, 4b vf/f sandstone and mudstone. Low abundance in basal and upper units. Occurs with <em>Arenicolites</em> isp., <em>Gordia marina</em>, <em>Helminthoidichnites tenuis</em>, <em>Palaeophycus tubularis</em>, <em>Planolites montanus</em>, and <em>Trichophycus</em> isp.</td>
</tr>
<tr>
<td><strong>Psammichnites plummeri</strong></td>
<td>Continuous horizontal meandering to</td>
<td>Deposit feeder</td>
<td>Facies 1c, 2b vf/f sandstone. Block near base of upper unit, uncommon and dispersed throughout basal and lower units.</td>
</tr>
<tr>
<td><strong>Psammichnites cf. P. implexus</strong></td>
<td></td>
<td>Deposit feeder</td>
<td></td>
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<tr>
<td>Trace Type</td>
<td>Description</td>
<td>Occurrence</td>
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<tr>
<td>sinuous trail with dorsal ridge defining longitudinal axis.</td>
<td>Occurs with <em>Bifungites munizi</em>, <em>Helminthopsis abeli</em>, and <em>Rosselia socialis</em>.</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
| *Ptychoplasma excelsum* | Repichnia Horizontal curved burrow with poorly defined lateral bulbs. Deposit feeder Bivalves | Facies 4a 
vf/f sandstone, very thin layer in mudstone interval. Single specimen found in the lower part of the middle unit. Occurs with *Lockeia siliquaria* (direct association) and *Dimorphichnus isp.* |
| *Rosselia socialis* | Equilibrichnia/ Fodinichnia Vertical conical to cylindrical burrow with central axis surrounded by concentric layers defining a funnel shape. Detritivore Polychaetes | Occurs in all facies. Present in sandstone beds. Most abundant ichnotaxon (along with *Asterosoma ludwigae* and *Palaeophycus tubularis*), occurs throughout formation. Locally concentrated into groups, others are solitary. |
| *Rusophycus pudicus* *Rusophycus* isp. (A/B) | Cubichnia Horizontal bilobate trace with central groove, deepening and widening to anterior part. Transverse scratches. Predator Deposit feeder Arthropods | Facies 1c, 2a, 4a, 4b 
| *Skolithos* isp. | Domichnia Vertical, cylindrical, unornamented, unwalled burrow Suspension feeder Annelids | Facies 1a 
Vf/f sandstone and mudstone (heterolithics). Rare, only found in lower part of middle unit. Occurs with *Planolites montanus* and *Teichichnus rectus.* |
|                | with contrasting fill. | Deposit feeder | Facies 1c  
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<tbody>
<tr>
<td><strong>Teichichnus rectus</strong></td>
<td>Fodinichnia Horizontal to inclined causative tube with vertical orientation spreite. Contrasting fill.</td>
<td>Annelids</td>
<td>vf/f sandstone and mudstone (heterolithics). Relatively common in basal, lower, and middle units. Occurs mostly with <em>Planolites montanus</em>, locally with <em>Asterosoma ludwiga</em>, <em>Rosselia socialis</em>, and <em>Skolithos</em> isp.</td>
</tr>
<tr>
<td><strong>Trichophycus isp.</strong></td>
<td>Fodinichnia Horizontal semi-cylindrical burrow with flattened bottom, thin longitudinal grooves. Vertical spreite arranged in U-shaped sheets.</td>
<td>Arthropods</td>
<td>Annelids</td>
</tr>
<tr>
<td><strong>Indeterminate trackways</strong></td>
<td>?Pascichnia Asymmetrical trace composed of distal and proximal impressions which are circular to ellipsoid, transverse to oblique to midline.</td>
<td>?</td>
<td>?</td>
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</tbody>
</table>