

Taphonomic analysis of storm-influenced shallow-marine deposits in the Tubul Formation (Pliocene-Pleistocene), Chile

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ABSTRACT

The Upper Pliocene – Lower Pleistocene Tubul Formation of south-central Chile contains one of the richest pre-Holocene marine faunas of the southeastern Pacific margin. While its fossil content, particularly the mollusk assemblages, has been extensively studied taxonomically, the unit has received little attention from a sedimentologic perspective, leaving uncertainties about its depositional setting and processes. Interpretation is further complicated by its largely homogeneous, fine-grained lithology and the scarce preservation of sedimentary structures. However, the fossil content provides several clues. The mollusk-dominated fossil assemblages occur predominantly as fossil concentrations, enabling the use of a taphonomic approach for their study. Integrating taphonomic, sedimentologic, and ichnologic evidence reveals deposition in the lower shoreface to upper offshore zones of a wave-dominated but protected coastline, with low sedimentation rates and sporadic storm influence. This setting promoted pervasive bioturbation by benthic organisms. Vertical changes in faunal composition (i.e., an increasing dominance of brachiopods) and a slight fining-upward trend suggest a marine transgression during the deposition of the upper succession. The Tubul Formation fossil concentrations and their taphonomic analysis prove to be a useful tool in the study of storm-influenced shallow-marine deposits, particularly as a case in which the lack of other well-preserved sedimentary structures and a relatively homogenous succession make its study difficult. This underscores the value of an integrated sedimentologic, ichnologic, and taphonomic approach in paleoenvironmental and paleoecologic studies.

1. Introduction

In Chile, Pliocene to Pleistocene marine strata are found at diverse localities, covering an ample latitudinal range spanning $\sim 22.5^{\circ}\text{S}$ – 45.0°S (Herm, 1969; Rivadeneira and Marquet, 2007; Kiel and Nielsen, 2010; Nielsen, 2013). This period represents a major turning point in global climate and environmental change, leading to widespread restructuring of marine ecosystems (Rivadeneira and Marquet, 2007; Le Roux, 2012; Pimiento et al., 2017). The Early Pliocene was characterized by a warmer climate, higher sea levels and smaller ice shields than today, patterns attributed to the presence of permanent El Niño-like

conditions in the Pacific (e.g., Wara et al., 2005; Fedorov et al., 2006; Bonham et al., 2008; Brierley et al., 2009; Salzmann et al., 2011; Karas et al., 2011; von der Heydt and Dijkstra, 2011; Maffre et al., 2023). The gradual decline of these conditions towards the end of the Pliocene triggered significant climatic and sea-level changes, disrupting established biotic communities and ultimately shaping modern marine faunas and ecosystems (Kiel and Nielsen, 2010; Pimiento et al., 2017).

These episodes of biotic turnover are reflected in the fossil record. Marine Pliocene – Pleistocene units in the southeastern Pacific are particularly rich in fossil content, especially in mollusks and vertebrates. The Pliocene – Pleistocene marine fauna of Chile has been the subject of

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several detailed taxonomic studies over the last decades (e.g. Herm, 1969; Frassinetti, 1995, 1997, 2000; Devries and Frassinetti, 2003; Griffin and Nielsen, 2008; Nielsen and Valdovinos, 2008; Nielsen, 2013). Many fossiliferous units from this period in Chile contain dense shell accumulations (i.e. coquina layers), providing insights into both the taxonomic composition of ancient communities and the depositional conditions under which their remains accumulated. However, while taxonomic studies are abundant, relatively little attention has been given to interpreting these depositional conditions through the use of taphonomic approaches.

Taphonomic studies have undergone major development in recent decades and now play a central role in both paleoenvironmental and paleoecologic research. Taphonomy involves the study of necrologic, biostratinomic, and diagenetic processes—steps that often remain obscure and are easy to overlook in the fossil record—that affect an organism's remains from death through decomposition, burial, and eventual preservation (e.g., Behrensmeyer and Kidwell, 1985; Kidwell et al., 1986; Savrda, 2007; Behrensmeyer et al., 2000; Anderson et al., 2023; Stoetzel et al., 2023). These taphonomic processes act as filters that can alter the fidelity of the fossil record, influencing the accuracy of ecologic and environmental interpretations (Brett and Baird, 1986; Kidwell and Bosence, 1991; Behrensmeyer et al., 2000). Given its importance, taphonomy has been applied to the study of strata throughout the Phanerozoic, encompassing a wide range of taxonomic groups (e.g., Speyer and Brett, 1988; Meldahl and Flessa, 1990; Brett et al., 1997; Moffat and Bottjer, 1999; Carroll et al., 2003; Lazo, 2004; Yesares-García and Aguirre, 2004; Dornbos et al., 2005; Harper and Pickerill, 2008; Zhao et al., 2009; Zabini et al., 2010; Huntley, 2012; Paik et al., 2012; Horodyski et al., 2019; Val-Péon et al., 2019; Bosio et al., 2021a, 2021b; García et al., 2021; Bassi et al., 2024). More specifically, taphonomic studies of dense skeletal accumulations (commonly referred to as fossil concentrations) have proven effective in reconstructing environmental conditions and transport processes during deposition in aquatic settings (e.g. Kidwell et al., 1986; Brett and Baird, 1993; Fürsich and Oschmann, 1993; Prado et al., 2015; Horodyski et al., 2019; Rodrigues et al., 2022). Fossil concentrations are defined as any relatively dense accumulation of skeletal elements produced by organisms, regardless of their taxonomic composition, preservation state, or degree of post-mortem modification (Kidwell et al., 1986; Kidwell and Holland, 1991). The taphonomic signals preserved in these concentrations reflect the depositional environments in which they formed, making them valuable tools for reconstructing marine paleoenvironmental conditions (Seilacher, 1970; Speyer and Brett, 1986).

The marine Pliocene–Pleistocene Tubul Formation of south-central Chile provides an excellent case study for taphonomic analysis, due to its rich fossil record and diversity of skeletal accumulations. Nonetheless, previous studies have focused primarily on taxonomy, with little assessment of the paleoenvironmental conditions or taphonomic processes associated with these fossils. The aim of this study is to provide new stratigraphic and sedimentologic insights into the depositional conditions under which the Tubul Formation strata were deposited, and the taphonomic agents and processes that led to the accumulation of its dense bivalve-dominated fossil concentrations. In doing so, this work contributes to the broader understanding of Pliocene–Pleistocene marine units in the southeastern Pacific. Furthermore, it represents one of the first taphonomy-based stratigraphic studies in Chile, highlighting the value of such approaches in marine settings where sedimentary structures are often scarce or poorly preserved.

2. Geologic setting

The subduction of the Nazca plate beneath the South American plate governs the tectonic and geomorphologic configuration of the Chilean accretionary margin and its overlying geologic features. At the latitude of the study area (37° S), the Chilean margin comprises, from west to east, three main morphostructural units: the Coastal Cordillera, the

Central Depression, and the Principal Cordillera (Jordan et al., 1983; Melnick et al., 2009; Ramos, 2010; Giambiagi et al., 2012; Becerra et al., 2013; Horton, 2018). In some regions, uplifted coastal platforms primarily composed of Cenozoic marine successions are present (Melnick et al., 2009). A notable example is the Arauco Peninsula, located west of the Coastal Cordillera, which represents a geologic anomaly in terms of topography, coastline morphology, and exhumation history (Rehak et al., 2008; Melnick et al., 2009; Geersen et al., 2011; Becerra et al., 2013). Within the homonymous peninsula lies the Arauco Basin, which contains more than 3000 m of Mesozoic and Cenozoic continental and marine deposits (Becerra et al., 2013). The sedimentary succession overlies the Upper Carboniferous to Triassic basement composed of granitoid and metasedimentary rocks. Sedimentary units include the shallow-marine Quiriquina Formation (Upper Cretaceous), the marginal-marine Lebu Group (Paleocene–Eocene), the deep-marine Ranquil Formation (Lower Miocene), the shallow-marine Tubul Formation (Pliocene–Pleistocene) and the fluvial-estuarine Cañete Formation (Pliocene–Pleistocene) (Kaizuka et al., 1973; Biró-Bagoczky, 1979; Glodny et al., 2008; Le Roux et al., 2008; Nielsen and Valdovinos, 2008; Salazar et al., 2010; Becerra et al., 2013; Encinas et al., 2021).

The studied section of the Pliocene–Pleistocene Tubul Formation, which hosts extensive fossil concentrations, is located on the coastal bluffs of the Las Peñas locality ($37^{\circ}14'$ S; $73^{\circ}25'$ W) within the Arauco Peninsula, south-central Chile (Fig. 1). This formation was formally defined by García (1968), who designated its type locality near the mouth of the Tubul river, at the Caleta Tubul village. This unit is approximately 100 m thick and unconformably overlies the Eocene Lebu Group and the Lower Miocene Ranquil Formation, while it is also overlain by Pleistocene Cañete Formation (Kaizuka et al., 1973; Melnick et al., 2009; Becerra et al., 2013; Encinas et al., 2021). The Tubul Formation consists of fine- to very fine-grained sandstone and sandy siltstone with abundant fossiliferous content, interpreted as having been deposited in a shallow-marine environment (García, 1968; Nielsen and Valdovinos, 2008).

The fossil content of the Tubul Formation is dominated by abundant and diverse marine bivalves and gastropods, which have been the focus of detailed taxonomic studies (Nielsen and Valdovinos, 2008). Other, less-studied macrofaunal groups include barnacles, crabs, bryozoans, echinoids, brachiopods, foraminifers, and shark teeth (Martínez and Osorio, 1968; Martínez, 1976; Biró-Bagoczky, 1979; Tavera, 1990; Nielsen and Valdovinos, 2008). Biostratigraphic analyses of benthic and planktonic foraminifera indicate a Late Pliocene age for the formation (Martínez and Osorio, 1968; Rojas, 2000), although studies of marine invertebrate macrofauna suggest that the unit may extend into the Pleistocene (Nielsen and Valdovinos, 2008; Nielsen, 2013). The Tubul fauna is broadly comparable to other Pliocene–Pleistocene assemblages in Chile, including those from the Coquimbo Formation in northern Chile, and the strata of the Guamblín and Guafó islands in the south (Frassinetti, 1997, 2000; Frassinetti and Covacevich, 1995; Nielsen, 2013).

3. Materials and methods

General descriptive analysis and nomenclature for fossil concentrations follow the framework proposed by Kidwell et al. (1986) and Kidwell and Holland (1991). Taphonomic features were assessed using both qualitative and quantitative parameters: qualitative features describe fossil associations, while quantitative features were measured on individual bioclasts. Only those bioclasts >2 mm were considered for quantitative analysis.

The specific criteria used in this study follow those established by Kidwell et al. (1986), Kidwell and Holland (1991), and Pineda-Salgado et al. (2022), and are divided into three categories: (1) sedimentologic, (2) paleontologic and (3) taphonomic features. Sedimentologic features include bioclast sorting, size, packing and geometry; paleontologic features include taxonomic composition and paleoecology; and

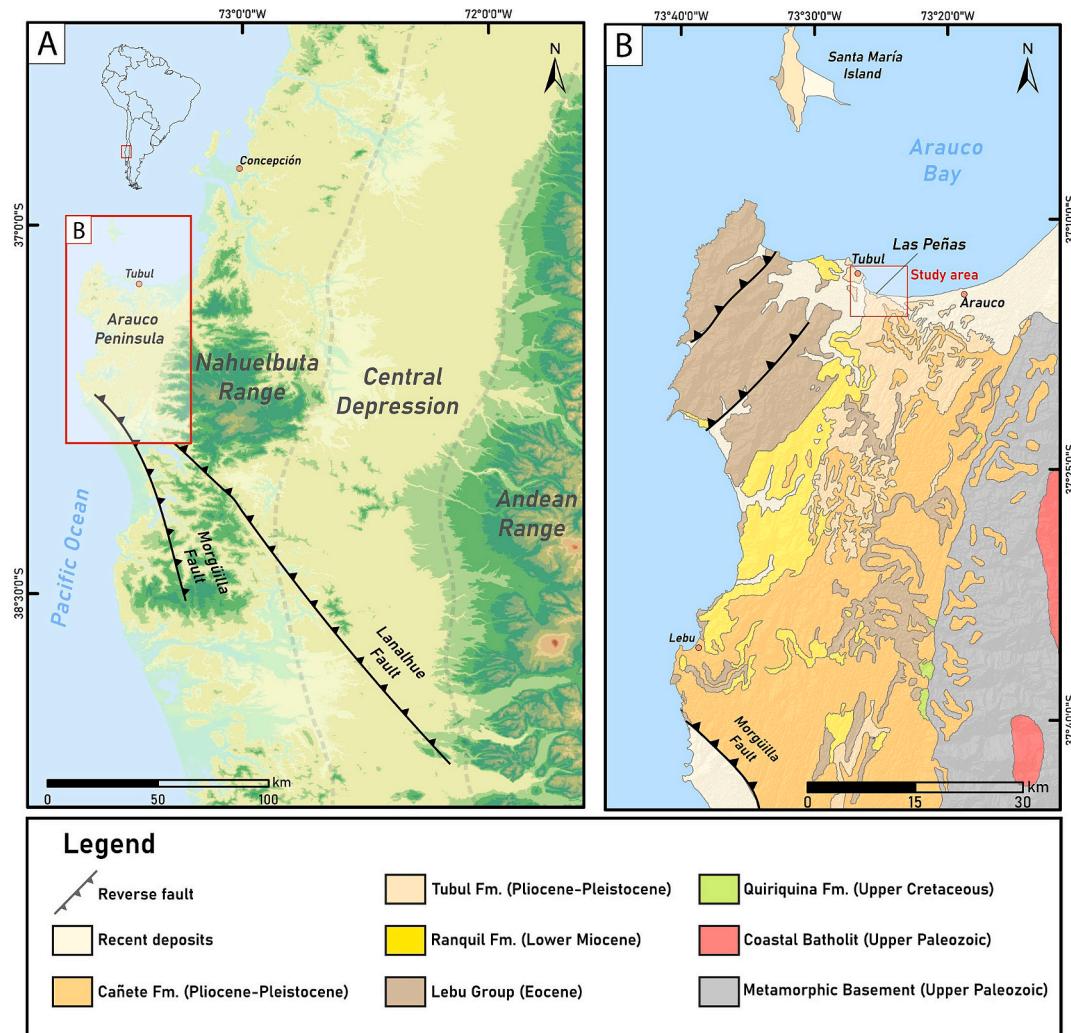


Fig. 1. Geologic overview of the study area. A: Geographic location of the study area. B: Geology of the Arauco Basin. Stratigraphic and structural information based on [Becerra et al. \(2013\)](#), [Finger \(2013\)](#), [Glodny et al. \(2008\)](#), [Kaizuka et al. \(1973\)](#), [Le Roux et al. \(2008\)](#), and [Melnick et al. \(2009\)](#).

taphonomic features encompass bioclast fragmentation, disarticulation, bioerosion, and encrustation. The criteria considered and their specific value ranges are detailed in [Table 1](#). Based on these attributes, different types of fossil concentrations were defined according to recurring parameter sets. No evidence for diagenetic processes (e.g., compaction, pressure solution, recrystallization) was observed in the analyzed samples. For paleoenvironmental interpretations, genetic models proposed by [Kidwell et al. \(1986\)](#), [Speyer and Brett \(1988\)](#), and [Fürsich and Oschmann \(1993\)](#) were primarily used to infer the mechanisms and depositional settings responsible for the identified types of concentrations.

Field measurements were taken directly on the outcrops. Additionally, seven 40×40 cm blocks containing representative fossil concentrations were collected for further analysis in the laboratory. Block collection was performed through chiseling and saw-cutting techniques on the outcrop walls. Individual fossil specimens were also examined to complement observations of their taphonomic features. A detailed record of each measured bioclast, along with corresponding descriptions is provided in Supplementary Material S1. The validity of species names was reviewed from the World Register of Marine Species (WoRMS) database (revision 11.2024) for extant species, in agreement with the taxonomic literature on fossil specimens (e.g., [Griffin and Nielsen, 2008](#); [Nielsen and Valdovinos, 2008](#); [Álvarez, 2019](#)). Laboratory work involved the manual cleaning of the rock blocks using mechanical tools, including dental picks and brushes, followed by measurement of the

features described above. All material is currently housed at the Museo de Historia Natural de Concepción (Concepción, Chile).

Ichnologic analysis involved the description of trace fossils in the field using currently accepted ichnotaxobases ([Bromley, 1996](#)) and assessing their ethological significance. Trace fossil assemblages were further characterized by evaluating the density and abundance of individual ichnotaxa, as well as identifying cross-cutting relationships between them. Based on these parameters and in combination with sedimentologic observations, trace fossil assemblages were interpreted within the framework of the ichnofacies model ([Pemberton et al., 1992](#); [Buatois and Mángano, 2011](#); [MacEachern et al., 2012](#)).

4. Results

4.1. Sedimentologic characteristics, trace fossils, and body fossil content

The Tubul Formation crops out sporadically along the Arauco Peninsula, and a complete succession including both its lower and upper boundaries has not yet been documented. Lithologically, the studied section at Las Peñas ($37^{\circ}14'S$; $73^{\circ}25'W$) is relatively homogenous in grain size, consisting of fine- to very fine-grained sandstone to sandy siltstone, stacked forming a large-scale fining-upwards succession ([Fig. 2A](#)). The base of the Tubul Formation is exposed nearby at the Punta de Fraile locality ($37^{\circ}12'S$; $73^{\circ}30'W$), where an unconformity marks the limit with the Miocene Ranquil Formation. Here, a basal

Table 1

Descriptive features and values used to characterize fossil concentrations.

Feature type	Criteria	Value	Definition
Sedimentologic features	Geometry	Beds, lenses, clumps	Defined by outline geometry and lateral extension
		Poor	No clear mode in bioclast size
	Sorting	Moderate	Bimodal distribution of bioclasts size
		Well-sorted	Unimodal distribution of bioclasts size
		Loose	Bioclasts more than one body length away from each other (Matrix-supported)
	Packing	Moderate	Bioclasts within one body length of each other or in contact (Clast- to matrix-supported)
		Dense	Bioclasts in contact with each other (Clast-supported)
		Monotypic	Associations dominated by one species or genus
	Taxonomic composition	Polytypic	Associations with no apparent dominant element
		Living mode	Epifaunal, infaunal or semi-infaunal. Sessile or free-living.
Paleontologic features	Paleoecology	Feeding mode	Suspension feeding, detritivorous or carnivorous.
		Low	Most shells only preserve <20 % of their original skeleton
		Moderate	Most shells preserve 20–80 % of their original skeleton
		High	Most shells preserve >80 % of their original skeleton
	Fragmentation	Low	<20 % of the bioclasts are disarticulated
		Moderate	20–80 % of the bioclasts are disarticulated
		High	>80 % of the bioclasts are disarticulated
	Taphonomic features	Low	<10 % of the bioclasts surface affected by bioerosion or encrustation
		Moderate	10–80 % of the bioclasts surface affected by bioerosion or encrustation
		High	>80 % of the bioclasts surface affected by bioerosion or encrustation
Taphonomic features	Disarticulation	Moderate	20–80 % of the bioclasts are disarticulated
		High	>80 % of the bioclasts are disarticulated
		Low	<10 % of the bioclasts surface affected by bioerosion or encrustation
	Bioerosion and encrustation	Moderate	10–80 % of the bioclasts surface affected by bioerosion or encrustation
		High	>80 % of the bioclasts surface affected by bioerosion or encrustation

sandstone layer contains mudstone rip-up clasts from the underlying Ranquil Formation. In other localities, the Tubul Formation presents a disconformity with the overlying Pleistocene Cañete Formation (Encinas et al., 2021).

The fossil content of the studied includes both macroinvertebrates and trace fossils. Bivalves are the most abundant and diverse elements, primarily represented by the venerid *Retrotapes exalbidus* (Dillwyn, 1817) and the pectinid *Zygochlamys patagonica* (King, 1832). In addition, several other bivalve species, as well as gastropods, brachiopods, and regular echinoids are present. Table 2 summarizes the recorded macrofauna for the measured section. Although many of the recorded species are typical components of shallow-water ecosystems, none of the identified mollusks provide sufficient resolution to infer more precise paleoenvironmental conditions, such as detailed divisions along the depositional profile. Indeed, most of the taxa either occupy a wide range

of substrate types and bathymetric depths, or their ecology and life habits remain largely unknown. Macrofossils appear either as isolated specimens or within fossil concentrations (Fig. 2B-F). The latter are more common in the lower to middle portions of the section and show considerable variation in geometry and taxonomic composition, including both mono- and polyspecific assemblages. Shells are preserved with their original mineralogic composition, with no evidence of recrystallization or selective dissolution of aragonite. Although shark teeth, foraminifers, and leaf impressions have also been reported in the Tubul Formation (Martínez and Osorio, 1968; Biró-Bagoczky, 1979; Nielsen and Valdovinos, 2008), no such material was encountered in this study. Bivalve are by far the most abundant taxonomic group in the section, with *Retrotapes exalbidus* and *Zygochlamys patagonica* being the only species consistently abundant throughout the succession. These taxa are the sole mollusks that form monospecific concentrations, although they also occur in polyspecific associations and as isolated fossils. In the lower parts of the section, the bivalves *Neilonella sulcata* (Gould, 1852) and *Ensis macha* (Molina, 1782) are locally abundant. The terebratulide brachiopod *Magellania venosa* (Dixon, 1789) is more common in the upper portion, where it occurs both as isolated remains and as dense monospecific concentrations. Gastropods, echinoids, and decapod chelae are comparatively scarce, appearing mostly as isolated remains, and only occasionally within polyspecific concentrations.

The preservation quality of trace fossils varies considerably across the outcrops. Four ichnotaxa were identified: *Chondrites* isp., ?*Cladichnus* isp., *Thalassinoides* isp., and *Ophiomorpha nodosa* Lundgren, 1891. *Chondrites* isp. occurs as very dense tunnel systems that branch in a dichotomous fashion (Fig. 3A-B, F). Tunnels are up to 1 mm wide. Burrow fill is passive and homogenous. This ichnotaxon is present throughout the succession, becoming dominant in the upper section. Due to the absence of more diagnostic features, identification to the ichnospecies level is not possible. ?*Cladichnus* isp. comprises radially branching burrows with a subtle annulated infill (Fig. 3C-D). Burrow segments are up to 2 mm wide. This ichnotaxon is rare in the succession and restricted to the lower section. *Thalassinoides* isp. comprises branching burrow systems made of vertical to oblique, curved burrows segments up to 5 cm wide (Fig. 3E-G). Burrows are characterized by their smooth walls with absence of pellets or knobs. Y-shaped branching is common. Burrow fill is passive, sandy and commonly homogenous, but in some cases it may be expressed as rhythmically alternating heterolithic couplets identified as tubular tidalites (Gingras and MacEachern, 2012; Gingras and Zonneveld, 2015). This ichnotaxon is most common in the lower section. Due to heavy weathering and the absence of complete tunnel systems, identification at the ichnospecies level was not possible. *Ophiomorpha nodosa* comprises branching burrow systems dominantly made of vertical burrows, up to 3 cm wide (Fig. 3H-J). T-shaped branching is common. Burrow walls are densely lined with spheroidal pellets. Burrow fill is passive, sandy, and homogenous. This ichnotaxon is most common in the lower section. Trace fossils can be grouped into two associations: (1) a *Thalassinoides* isp. – *Ophiomorpha nodosa* association and (2) a *Chondrites* isp. association. In addition to mid-tier *Thalassinoides* isp. and *Ophiomorpha nodosa*, the former includes deep-tier cross-cutting *Chondrites* isp. The *Chondrites* isp. association is typically monospecific but may locally contain ?*Cladichnus* isp.

The succession at the studied locality can broadly be subdivided into three sections. The lower section consists of massive, intensely bioturbated silty sandstone. The massive nature and apparent lack of sedimentary structures of this interval can likely be attributed to the combined effect of intense bioturbation and weathering. It is host to the *Thalassinoides* isp. – *Ophiomorpha nodosa* and *Chondrites* associations. Fossil content here is more commonly dispersed and represented by isolated and well-preserved remains of all taxa. Clumps dominated by the pectinid *Zygochlamys patagonica* are present locally, forming dense fossil concentrations. The middle section is a silty sandstone succession with poorly defined stratification, where layers are only distinguished by subtle grain-size variations. Strata are tabular, with thicknesses

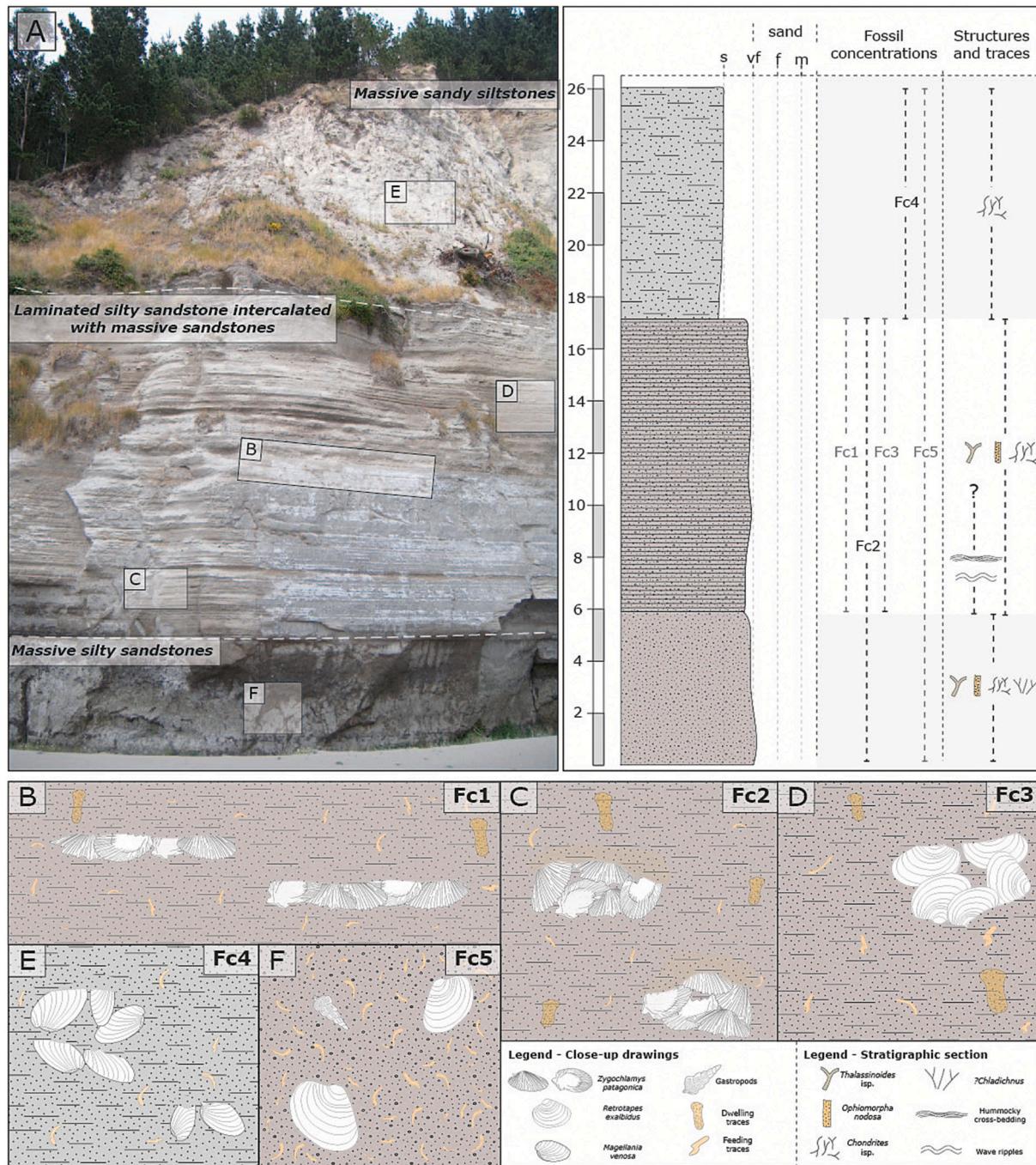


Fig. 2. General lithology and taphonomic features observed at the study location. For a detailed characterization of the taphonomic facies see chapter 4.2. A: Stratigraphic section of the Tubul Formation at the Las Peñas locality, with distribution intervals of the described fossil concentration types, sedimentary structures, and trace fossils. The presence of sedimentary structures in the middle, laminated part of the section is only well documented towards the base. A–B: Generalized diagrams of the different concentration types to illustrate their described characteristics. B: *Zygochlamys*-dominated lenses concordant to stratification (Fc1). C: *Zygochlamys* dominated clumps (Fc2). D: *Retrotapes*-dominated clumps (Fc3). E: *Magellania*-dominated clumps (Fc4). F: Well-preserved isolated mollusk remains (Fc5). Note the higher density of bioturbation, which is the likely cause of the apparent lack of sedimentary structures in the lower section.

ranging from decimeters to, more rarely, a few (< 2 m) meters. Some centimeter-scale intercalations of massive sandstone occur. Sedimentary structures are rarely preserved, as the original fabric has also been greatly obliterated. Nevertheless, local preservation of hummocky cross-stratification (HCS) and wave ripples can be observed (Fig. 4). The preservation of such structures, however, is uncommon and at times blurred by weathering. Still, the local presence of more discernible diagnostic features such as bedforms defined by low-amplitude mounds and depressions (HCS; Fig. 4C) and fine-scale symmetric profiles (wave

ripples; Fig. 4F) serve as reliable indicators. Trace fossil associations are the same as in the lower section, though bioturbation intensity appears slightly reduced. The macrofossil assemblage is also similar, but skeletal concentrations are more common. In addition to dense clumps dominated by the pectinid *Zygochlamys patagonica*, two other concentration types occur: planar *Z. patagonica* concentrations and clumps dominated by the venerid *Retrotapes exalbidus*. The upper section comprises massive sandy siltstone. As in the underlying deposits, intense bioturbation has obliterated primary sedimentary structures. This interval is

Table 2

Taxonomy and paleoecologic patterns of identified taxa in the stratigraphic section of this study. Paleoecology is based on family-level studies when no information at species or genus level is available.

Class	Species	Paleoecology	Paleoecology Reference
Bivalvia	<i>Cyclocardia velutina</i> (Smith, 1881)	Semi-infaunal suspension feeder	Carobene et al., 2023
	<i>Ennucula grayi</i> (d'Orbigny, 1846)	Infaunal subsurface deposit feeder	Leonard-Pingel et al., 2012
	<i>Ensis macha</i> (Molina, 1782)	Deep infaunal filter feeder	Gordillo et al., 2008
	<i>Malletia chilensis</i> Desmoulins, 1832	Shallow infaunal deposit feeder	Rabassa et al., 2009
	<i>Pandora cistula</i> Gould, 1850	Shallow infaunal filter feeder	Harper et al., 2006
	<i>Retrotapes exalbidus</i> (Dillwyn, 1817)	Shallow infaunal filter feeder	Gordillo, 2006
	<i>Neilonella sulculata</i> (Gould, 1852)	Shallow infaunal filter feeder	Allen and Sanders, 1996
	<i>Zygochlamys patagonica</i> (King, 1832)	Byssally-attached sessile filter feeder	Schejter et al., 2002; Alejandrino et al., 2011
	<i>Mangelia paessleri</i> (Strebel, 1905)	Epifaunal/Infaunal carnivore	Vermeij, 2017
	<i>Capulus compressus</i> Smith, 1891	Epifaunal filter feeder and/or parasitic	Fassio et al., 2021
Gastropoda	<i>Fusitriton magellanicus</i> (Röding, 1798)	Epifaunal/semi-infaunal carnivore	Beu, 1978
	<i>Nassarius taeniolatus</i> (Philippi, 1845)	Semi-infaunal carnivore	Galindo et al., 2016
	<i>Scaphander interruptus</i> Dall, 1889	Semi-infaunal carnivore	Eilertsen and Malaquias, 2013
	<i>Sassia leucostomoides</i> (Sowerby, 1846)	Epifaunal/Semi-infaunal carnivore	Beu, 1978
	<i>Xymenopsis muriciformis</i> (King, 1832)	Epifaunal carnivore	Rabassa et al., 2009
	<i>Magellania venosa</i> (Dixon, 1789)	Epifaunal sessile filter feeder	Försterra et al., 2008
Echinoidea	Indet spp.	Epifaunal carnivores	Lawrence, 2020

characterized almost exclusively by the *Chondrites* association, although observations are limited due to poor exposure and reliance on fallen blocks. Fossil content remains similar in composition, but relative abundances differ. The terebratulide brachiopod *Magellania venosa* becomes a dominant taxon, occurring in dense monospecific concentrations, whereas other taxa are restricted to more loosely dispersed remains.

4.2. Taphonomy

Based on the sedimentologic, taxonomic, and taphonomic attributes outlined in Table 1, five distinct types of fossil concentrations were recognized (Fig. 5). All the described types occur in similar sandy-siltstone- and silty-sandstone-dominated lithologies, except for Fc4 which was only identified from fallen blocks derived from the upper sections (Fig. 5). A detailed summary of the defining attributes for each concentration type, along with their associated paleontologic content, is provided in the Supplementary Material (S2 and S3, respectively).

Type 1 Fossil Concentrations (Fc1): This type consists predominantly of monospecific accumulations of the epifaunal bivalve *Zygochlamys patagonica*. Minor associated taxa include the bivalve *Retrotapes exalbidus*, the gastropods *Mangelia paessleri* (Strebel, 1905), *Xymenopsis muriciformis* (King, 1832), and *Scaphander interruptus* Dall, 1889, as well as unidentified regular echinoids. This concentration type displays a

planar geometry parallel to the stratification (Fig. 5A). Bioclasts are moderately to densely packed, well sorted, and arranged mainly in horizontal to slightly oblique orientations. Shells are mostly disarticulated, with concave surfaces facing downward, although a small proportion of articulated specimens is present. Articulated shells are commonly twisted along their axis. Valve fragmentation is mostly moderate; however, it is variable across the beds and most clasts have suffered a certain degree of fragmentation. However, intervals with higher proportions of articulated shells tend to show lower overall fragmentation. Encrustation is common, consisting of serpulid tubes on both the interior and exterior surfaces of the shells. Fc1 is the most common fossil concentration type in the section, occurring throughout the unit.

Type 2 Fossil Concentrations (Fc2): Fc2 closely resembles Type 1 in faunal composition, being strongly dominated by *Zygochlamys patagonica*. Associated elements are less common and include the gastropods *Mangelia paessleri*, *Nassarius taeniolatus* (Philippi, 1845), *Scaphander interruptus*, and *Fusitriton magellanicus* (Röding, 1798); the bivalves *Ennucula grayi* (d'Orbigny, 1846) and *Pandora cistula* Gould, 1850; as well as unidentified regular echinoids and decapod chelae. These concentrations form decimeter-scale lenses or clumps, generally concordant with the bedding (Fig. 5B). Bioclasts are loosely to moderately packed and moderately to well sorted. Bioclasts are almost entirely disarticulated, displaying chaotic orientations with no preferential alignment of concave surfaces. A minor degree of nesting occurs, whereby smaller bioclasts accumulate within the concave interiors of bivalve valves or gastropod whorls. Fragmentation is variable but overall moderate. Serpulid encrustations are common on the exterior surfaces of the valves.

Type 3 Fossil Concentrations (Fc3): Fc3 is dominated by monospecific concentrations of the infaunal bivalve *Retrotapes exalbidus*. Associated taxa include the bivalves *Neilonella sulculata*, *Zygochlamys patagonica*, and *Malletia chilensis* Desmoulins, 1832, as well as the gastropods *Fusitriton magellanicus* and *Xymenopsis muriciformis*. Concentrations form decimeter-scale lenses or clumps lacking a preferential orientation (Fig. 5C). Disarticulation is low to moderate, with shells arranged chaotically and without preferential concave-down orientation. Nesting of smaller elements within disarticulated valves is common. Fragmentation is mostly low to moderate. Predation traces (*Oichnus* sp.) are common, particularly in shells of the genera *Neilonella* and *Retrotapes*.

Type 4 Fossil Concentrations (Fc4): Type 4 consists of monospecific concentrations of the terebratulide brachiopod *Magellania venosa*. This type occurs as decimetric-scale clumps recorded in the upper part of the succession (Fig. 5D). In the lower part of the succession, *M. venosa* is rare, whereas its occurrence as dense concentrations has been recorded solely in fallen blocks derived from slightly finer-grained deposits of the upper section, dislodged by erosional processes. Bioclasts are moderately to densely packed and moderately sorted. Shells are mostly articulated, although their arrangement is chaotic, with no apparent preferential orientation. Fragmentation is low to moderate. Bioerosion and encrustation are rare, limited to occasional serpulid tubes on external shell surfaces.

Type 5 Fossil Concentrations (Fc5): Fc5 corresponds to the diverse assemblages of isolated bioclasts distributed throughout the entire section (Fig. 5E). Due to their dispersed occurrence within beds, these assemblages cannot be analyzed as dense concentrations like the other types, and parameters such as geometry or sorting are not applicable. While taxonomic composition is diverse, relative abundance is skewed towards a predominance of infaunal and semi-infaunal burrowing bivalves and gastropods (Supplementary material S2). Conversely, epifaunal bivalves (e.g., *Zygochlamys patagonica*) are scarce. Bioclasts are densely distributed, with very low disarticulation; most specimens are preserved in life position. Disarticulation is restricted to a small proportion of epifaunal bivalves. Fragmentation is generally low, with most specimens preserving their entire shells, although some epifaunal

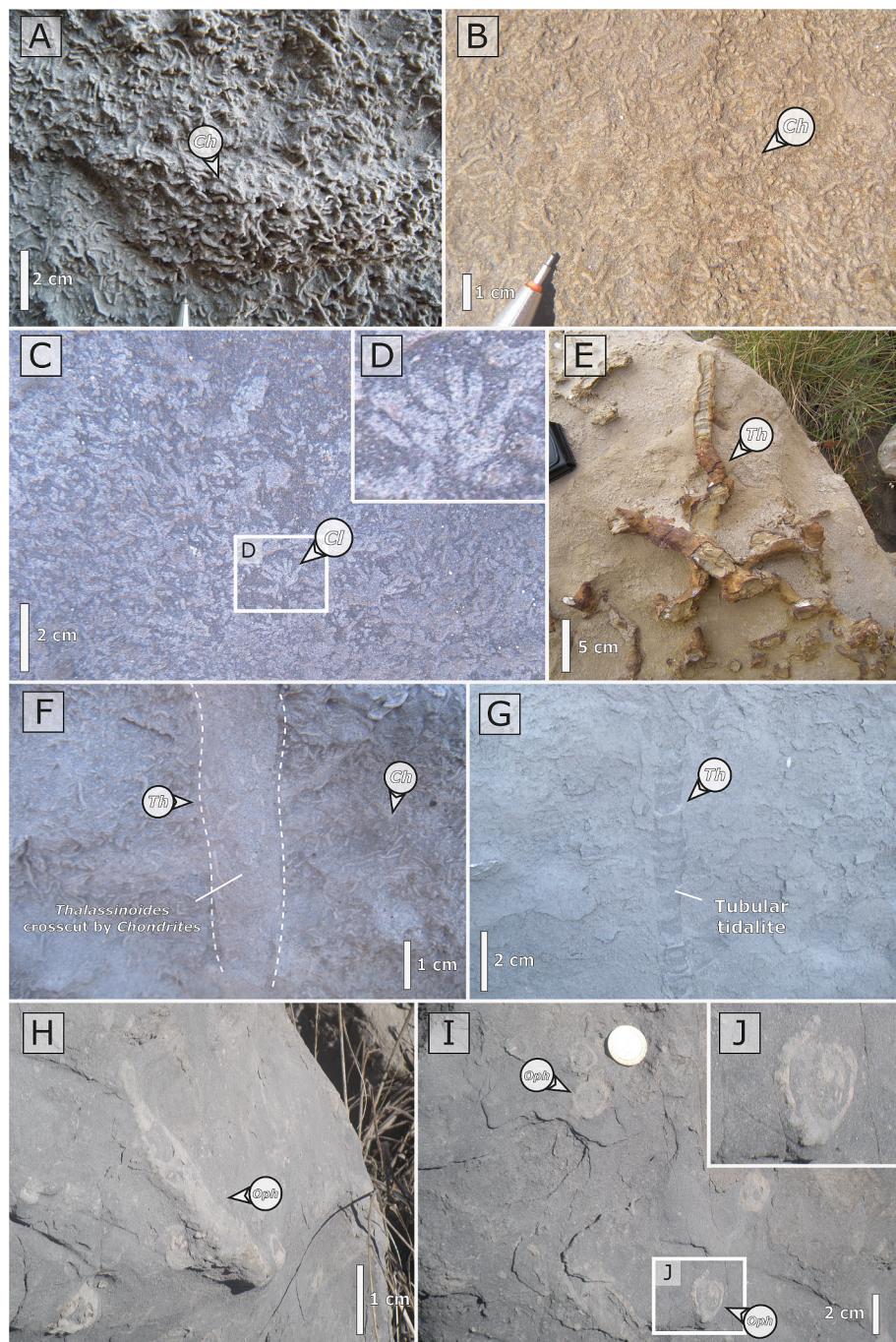


Fig. 3. Trace fossils observed at the Las Peñas Section. A-B: Densely bioturbated fabric dominated by a *Chondrites* isp. monospecific association from the lower section. C: General view of surface dominated by *Chondrites* isp. with subordinate ?*Cladichnus* isp. from the lower section. D: Close-up of ?*Cladichnus* isp. showing poorly developed radial pattern. E: *Thalassinoides* isp. from the lower section. F: *Thalassinoides* isp. cross-cut by *Chondrites* isp. G: *Thalassinoides* isp. showing passive laminated burrow-fill interpreted as tubular tidalites. H-I: *Ophiomorpha nodosa* from the lower section. J: Close-up of *Ophiomorpha nodosa* in cross section, showing characteristic pelletoidal wall. Ch: *Chondrites* isp., Cl: ?*Cladichnus* isp., Th: *Thalassinoides* isp., Oph: *Ophiomorpha nodosa*.

taxa may show a minor degree of fragmentation. Bioerosion and encrustation are taxonomically biased, being common only on the outer shell surfaces of epifaunal elements, typically in the form of serpulid tubes and other small, indeterminate traces.

5. Discussion

5.1. Depositional environment

Given the sedimentologic, ichnologic, and paleontologic features

observed in the study section (e.g., wave ripples, hummocky cross-bedding, abundance of marine body fossils and trace fossils), the deposits are interpreted as having accumulated in a wave-dominated shallow-marine setting (MacEachern and Pemberton, 1992; Baniak et al., 2014; Wesolowski et al., 2018; Odino-Barreto et al., 2020). The trace fossil assemblages collectively illustrate the *Cruziiana* Ichnofacies (Pemberton et al., 1992; MacEachern and Bann, 2008; Buatois and Mángano, 2011; MacEachern et al., 2012). The overall low ichnodiversity is interpreted as a taphonomic artifact resulting from the preferential preservation of the deeper-tier traces that may have obliterated

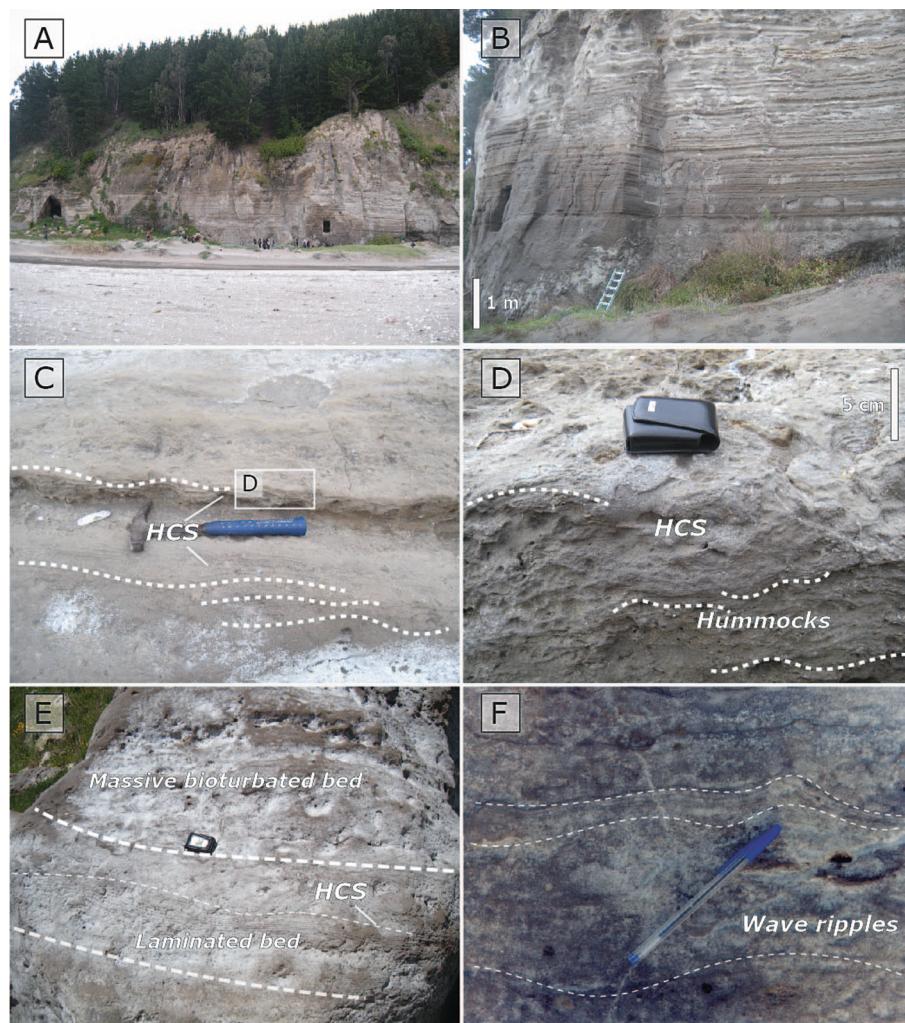


Fig. 4. Sedimentologic features and structures present at the Las Peñas Section. A: General view of the outcrop, showing planar horizontal stratification. B: Close-up on the outcrop, showing the transition from massive to stratified intervals. C: Probable hummocky cross-stratified intervals intercalated with massive beds. D: Close-up on the hummocky cross stratification. E: Massive, highly bioturbated intervals intercalated with laminated intervals. F: Symmetric wave ripple cross lamination.

shallow-tier ones. *Ophiomorpha* and *Thalassinoides* are conspicuous but scarce; they are both common of shallow and well-oxygenated marine floors (MacEachern and Bann, 2008; Pemberton et al., 2012). In contrast, the monospecific dominance of *Chondrites* is generally regarded as an indicator of dysoxic conditions, with tracemakers penetrating deeply into oxygen-depleted substrates to exploit buried organic matter. This pattern is consistent with slightly deeper-water conditions represented by the upper parts of section. Nonetheless, substrate dysoxia does not necessarily imply oxygen-depleted bottom waters, and *Chondrites* can be considered an extremotolerant ichnotaxon associated with a diversity of marine environments and depths (Buatois and Mángano, 2011; Baucon et al., 2020). In fact, comparable superabundant monospecific *Chondrites* assemblages have been documented in the shallow-marine Cretaceous Cardium Formation (Canada), where they have been interpreted as reflecting the opportunistic exploitation of organic-rich storm deposits (Vossler and Pemberton, 1988).

The dominantly sandy siltstone and silty sandstone lithologies with wave-ripple cross-lamination are interpreted as deposits formed just below (upper offshore) and above (lower shoreface) the fair-weather wave base, respectively. Fluctuations in hydrodynamic energy are reflected in the inconspicuous parallel stratification of the beds and in the sedimentary structures, which include occasional hummocky cross-stratification (HCS) and wave ripples. The occurrence of silty sandstone in the basal part of the succession, displaying wave ripples,

parallel lamination, and HCS, is characteristic of the lower shoreface (Pemberton et al., 2012). The lower shoreface is commonly marked by high variability in both sedimentologic and ichnologic attributes (MacEachern and Pemberton, 1992). Episodic storm-wave influence is indicated by the presence of HCS together with fossil concentrations that lack internal order (e.g., fossil concentrations types 2–4). However, storm intensity must have been relatively weak to moderate, as there is no evidence of significant input of coarser-grained material, and HCS is both rare and never observed in amalgamated sets.

The lower shoreface can be categorized according to the frequency and magnitude of storm influence into strongly, moderately, and weakly storm-affected regimes (MacEachern and Pemberton, 1992). Weakly to moderately storm-affected shorefaces are typified by a reduced abundance of hummocky cross-stratification (HCS), with a greater prevalence of weak wave- and current-ripple cross-lamination. Consequently, the lower intensity and frequency of storm events promotes colonization by benthic organisms, resulting in pervasive bioturbation that commonly obliterates primary sedimentary structures (MacEachern and Pemberton, 1992; Buatois and Mángano, 2011; Buatois et al., 2015; Wesolowski et al., 2018). These environments generally form along protected shorelines where storm energy is diminished, such as in large embayments or coastlines oriented obliquely to prevailing storm-wave approach (Dashtgard et al., 2012; Wesolowski et al., 2018).

In this context, alternations of laminated, weakly bioturbated

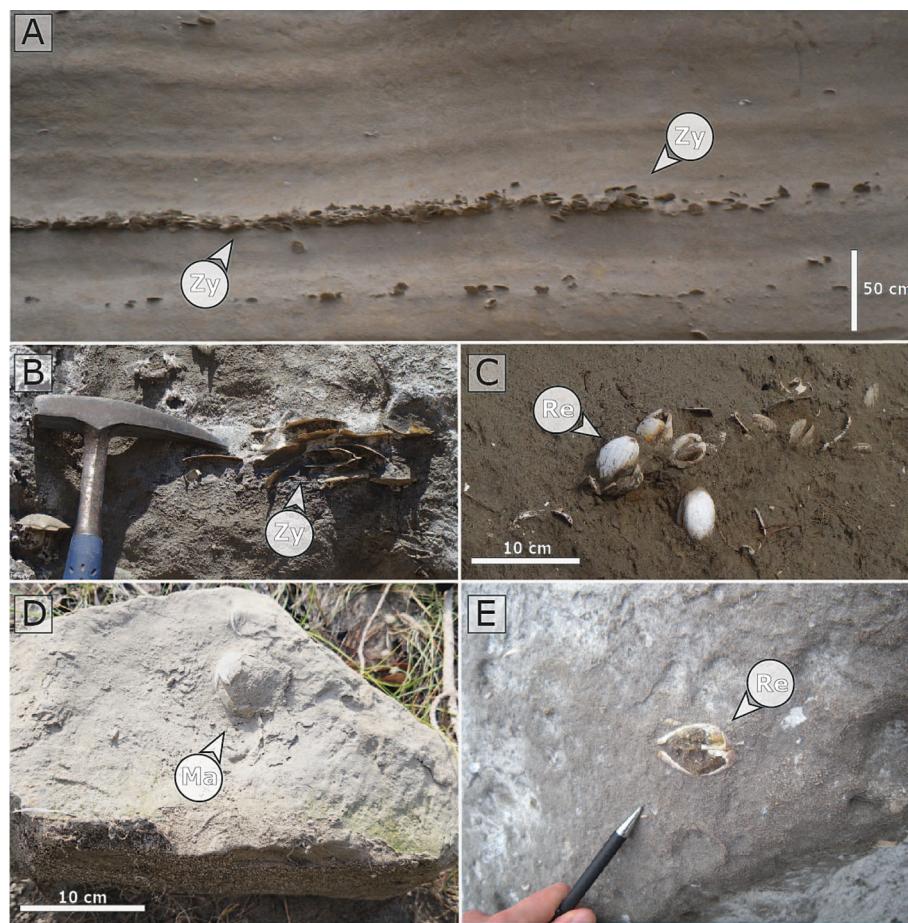


Fig. 5. Fossil concentration types defined for the Las Peñas section. A: Fc1. Thin horizontal beds parallel to the stratification, composed mainly by disarticulated *Zygochlamys patagonica* shells. B: Fc2. Small chaotic lenses dominated by *Zygochlamys patagonica* shells. C: Fc3. Chaotic lenses dominated by *Retrotapes exalbidus* valves. D: Fc4. Monospecific clumps of *Magellania venosa* shells. E: Fc5. Isolated remains of well-preserved articulated remains. *Retrotapes exalbidus* shell partially eroded by surface processes. Zy: *Zygochlamys patagonica*. Re: *Retrotapes exalbidus*. Ma: *Magellania venosa*.

intervals grading into intensely bioturbated deposits reflect fluctuations between storm events and subsequent fair-weather sedimentation. Laminated facies record episodes of higher energy, which were followed by calmer conditions that enabled colonization by infauna and the progressive obliteration of the primary fabric. Comparable examples are documented in the Upper Jurassic Ula Formation (Norwegian North Sea), where highly bioturbated lower shoreface facies representing the proximal *Cruiziana* Ichnofacies were interpreted as the product of a weakly to moderately storm-influenced setting (Baniak et al., 2014). Another analogue is found in the Lower-Middle Jurassic Bardas Blancas Formation (Neuquén Basin, Argentina) (Schwarz et al., 2021), where a full offshore-to-upper shoreface succession includes highly bioturbated deposits in distal facies and a *Chondrites*-dominated ichnofabric similar to that of the Tubul Formation, restricted to the offshore-transition. Furthermore, pervasively lower shoreface to offshore transition deposits have likewise been recorded in the Miocene Chenque Formation of Patagonia (Carmona et al., 2008, 2012).

Tidal influence also tends to be minor to non-existent in these conditions (Dashgard et al., 2012), which is consistent with the scarcity of recorded tidal-current generated structures in the studied section. The only potential evidence is represented by vertical *Thalassinoides* with laminated fills, here interpreted as possible tubular tidalites. Such structures are the result of the passive infill of burrows by tidal action, denoted by the rhythmically arranged sedimentation of couplets of intercalated silt-dominated and fine-grained sand-dominated layers. This infilling event can occur when sediment is trapped in open burrows connected to the water-sediment interface (Gingras et al., 2012).

Tubular tidalites are representative of environmental conditions characterized by low sedimentation rates, bimodal grain sizes, and marine salinities (Gingras and MacEachern, 2012; Gingras and Zonneveld, 2015), conditions compatible with the lithologic features of the Las Peñas section. Although tubular tidalites are most common in shallow, tidal-modulated environments such as intertidal flats or low-energy tidal channels (Gingras et al., 2012; Gingras and Zonneveld, 2015), they can still occur, albeit rarely, in deeper upper to lower shoreface environments (e.g., Baniak et al., 2014; Wetzel et al., 2014). Nevertheless, confirmation of the tidal origin of these structures would require systematic analysis of their laminated fill since the alternative interpretation of the infill reflecting alternation of fair-weather deposition and storm events cannot be disregarded.

Ecologically, the assemblage is dominated by soft-bottom, suspension-feeding benthic organisms, which typically thrive in well-oxygenated, relatively low-depth waters within the photic zone and under conditions of sustained nutrient input. These environmental attributes are consistent with a shallow-marine setting. The high taxonomic and ecological diversity of the fauna, encompassing a range of feeding strategies and life habits (Table 2), further reinforces this interpretation.

Based on sedimentologic and ichnologic evidence, and in particular on the predominance of the massive, highly bioturbated facies with potential minor tidal influence, deposition of this unit likely took place in a relatively protected and calm setting. Slow sedimentation rates under these conditions would have favored colonization and bioturbation by benthic organisms. A plausible scenario is the existence of a large embayment that partially sheltered the coastline and mitigated the

effects of storm events. This interpretation partly aligns with previous work. Based on her study on the foraminiferan fauna of the Tubul Formation, Rojas (2000) inferred a relatively shallow-water deposition, suggesting a depth range of 0–130 m. However, such maximum depths are inconsistent with the observed sedimentary features. Conversely, Biró-Bagoczky (1979) proposed a very shallow marginal-marine setting based on fossil leaves found, albeit with rapid sedimentation rates. Our observations do not support these conclusions since no leaves were found in the Las Peñas section, and pervasive bioturbation indicates slow rather than rapid deposition. A similar analogue of an intensely bioturbated shoreface developed in a protected, embayed shoreline can be found in the Upper Cretaceous Quiriquina Formation of south-central Chile (Buatois and Encinas, 2011).

5.2. Taphonomic model and interpretation

All identified fossil concentrations support a lower shoreface depositional interpretation. The occurrence of highly contrasting taphonomic signatures (Fig. 6) within the same lithologies suggest their occurrences are dictated mainly by intermittent changes in energy conditions, rather than major variations across the onshore-offshore position.

Type 1 fossil concentrations (Fc1) are interpreted as forming under weak fair-weather waves. Skeletal material was subsequently transported and accumulated towards the lower limits of the fair-weather wave base level. In shallower, high-energy environments (fore-shore–upper shoreface), skeletal concentrations typically exhibit very high fragmentation and disarticulation with poor sorting and limited bioerosion (Fürsich and Oschmann, 1993). By contrast, Fc1 shows only moderate fragmentation and disarticulation, consistent with slightly deeper, lower-energy conditions. The predominance of *Zygochlamys patagonica* further supports this interpretation, as this species is not a common component of very shallow settings (Lomovasky et al., 2007). The predominant trend of a horizontal orientation of flat shells indicates fair-weather wave influence, where prolonged exposure to wave action results in this hydrodynamically stable position (Kidwell and Bosence, 1991). The association of epifaunal pectinids with infaunal taxa suggests limited reworking, where weak wave energy was sufficient to exhume and transport buried individuals but only across short distances. Shell morphology also supports a low transport interpretation, as thin, weakly ribbed and flat shelled pectinids tend to inhabit soft and fine-grained (muddy to fine-grained sand) substrates (Aguirre et al., 1996), which would otherwise be more easily fragmented when subjected to longer periods of transport. Experimental work has shown that plane-parallel shell fabrics may accumulate under fair-weather shoaling and storm wave reworking in the lower shoreface (Fick et al., 2018). After their

short transport to their final deposition site, skeletal remains were exposed to surface processes (i.e., taphonomically active zone) for a prolonged period due to the low sedimentation rates of the environment, as evidenced by the colonization and encrustation by serpulids. Post-mortem colonization by serpulids is suggested by the presence of encrustation on the inner surfaces of the shells. Given the mostly monospecific nature of this assemblage and overall abundance of *Zygochlamys* shells across the unit, the pectinids must have formed densely populated bank systems, like those observed in extant populations (Bogazzi et al., 2005; Schwarz and Campodónico, 2020). The very low presence (or lack in some cases) of non-*Zygochlamys* shells further evidences the short transport suffered by the shells, likely being restricted to only the proximity of the banks, since there is no substantial incorporation of other taxa that lived beyond the range of the mono-specific *Zygochlamys* banks. While living *Zygochlamys* are most common today in outer-shelf settings (Lomovasky et al., 2007, 2008), the observed taphonomic features of Fc1, especially wave-induced shell alignment and moderate fragmentation, indicate that in this case they were sourced from shallower environments within reach of fair-weather wave energy.

Type 2 fossil concentrations (Fc2) are compositionally similar to Fc1, but taphonomic features indicate a more complex preservational history. The predominance of disarticulated shells of *Zygochlamys* with moderate fragmentation suggests prolonged fair-weather action, comparable to Fc1. However, the chaotic distribution and bioclast nesting of the skeletal remains within the matrix evidences accumulation under short-lived turbulent conditions (Speyer and Brett, 1988). Bioclast nesting consists in the accumulation of smaller-sized shells into the concavities of larger-sized bioclasts, as a natural result from exposure to turbulent flows (Kidwell et al., 1986; Kidwell and Bosence, 1991). Shell fragmentation in these concentrations is best explained as an inherited fair-weather feature. Experimental and field evidence show that breakage intensity depends primarily on exposure time to waves and substrate hardness rather than transport distance or turbulence (Kidwell and Bosence, 1991). Alternative fragmentation mechanisms, such as predation, burrowing, bioerosion, or diagenetic dissolution (Zuschin et al., 2003), are not significant in this case, as supporting evidence is lacking (Kidwell and Bosence, 1991). Fc2 thus represents storm-influenced concentrations with inherited fair-weather wave taphonomic signatures. That is, an amalgamation of fair-weather signatures (moderate fragmentation and high disarticulation) and storm-weather signatures (chaotic distribution, bioclast nesting). Thus, after an initial process of abrasion and fragmentation under previous, slightly shallower conditions and fair-weather wave action, the resulting accumulation is subsequently reworked and redeposited by storm waves,

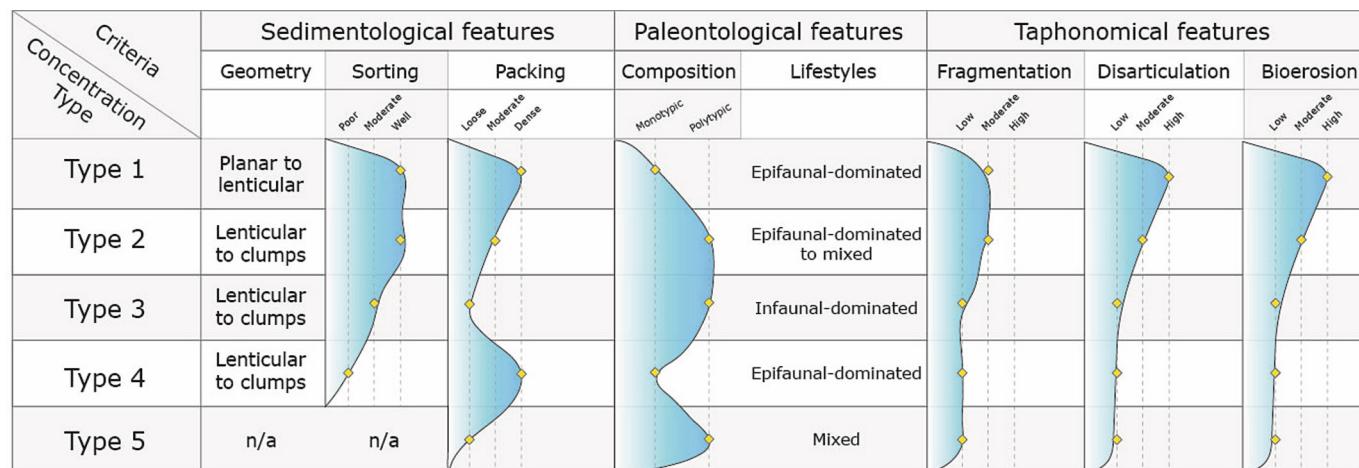


Fig. 6. Measured criteria for each of the defined fossil concentrations. Graphics represent the predominant value for a given parameter. Value can vary locally across the section. Due to Fc5 not forming fossil concentrations, geometry and sorting descriptive parameters do not apply.

acquiring new taphonomic signatures that overprint into the preexisting ones.

Type 3 fossil concentrations (Fc3) display fabrics broadly comparable to Fc2 (i.e., concentration geometry, chaotic bioclast disposition), but differ in a more loosely packed structure and better shell preservation, in terms of both fragmentation and articulation, as well as a substantially contrasting taxonomic composition. Unlike Fc1 and Fc2, which are dominated by epifaunal *Zygochlamys*, Fc3 assemblages are composed primarily of infaunal taxa, particularly *Retrotapes exalbidus*. Therefore, Fc3 is interpreted as concentrations formed exclusively through action of storm waves, without an inherited fair-weather signature. The rapid burial by storm events allowed the better preservation of skeletal remains, as this process minimizes the time spent in the surface, reducing further fragmentation or disarticulation caused by decay or epifaunal colonizers.

Type 4 fossil concentrations (Fc4) differ greatly from other types in terms of taxonomic composition, with a clear dominance of the epifaunal brachiopod *Magellania venosa*. Bioclasts are chaotically ordered and well preserved, with low fragmentation and disarticulation rates. These features suggest rapid accumulation and burial by storm waves. However, due to the shell morphology (and specifically the hinge type) of terebratulide brachiopods, their skeletal remains are more likely to be better preserved and stay articulated despite mechanical perturbation (Alexander and R., 1990; Alexander and Gibson, 1993; Daley, 1993; Tomašových et al., 2023), meaning that special consideration must be taken for taphonomic interpretations. Analogous accumulations have been described from the Jurassic Rotzo Formation in Italy (Bassi et al., 2024), where dense and largely autochthonous terebratulide assemblages developed under low sedimentation and low-energy conditions, with many shells preserved in life position. In contrast, the disordered orientation of *M. venosa* in the Tubul Formation points to allochthonous accumulation, where storm processes reworked and redeposited shells. The scarcity of *Magellania* remains outside of concentrated beds mirrors the distribution patterns of *Zygochlamys* in Fc1 and Fc2, suggesting localized bank development. Extant *Magellania* species occupy a wide bathymetric range (up to thousands of meters), but tend to be less abundant in shallower zones, where they might compete with filter feeding bivalves. Nonetheless, present-day *Magellania venosa* banks in southern Chile can already be found at depths slightly below 10 m (Baumgarten et al., 2014; Gordillo et al., 2019). This fact explains the increased presence of *Magellania venosa* towards the upper, finer-grained part of the studied succession that are interpreted as deposited in relatively deeper-water than the lower part of the studied succession. Their environmental preferences also include low-temperature and nutrient-rich waters, which characterize the Magellanic Strait zone that represents the main geographic limits of their extant representatives (McCammon, 1973; Baumgarten et al., 2014). Although their extant geographic distribution can reach beyond the Magellan Strait, their presence in lower latitudes is severely limited and restricted to deep-water zones that are influenced by cold water currents coming from Antarctica (McCammon, 1973). Finally, the low incidence of encrustation and bioerosion on *Magellania* shells contrasts with the more heavily colonized *Zygochlamys* remains elsewhere in the unit. This improved preservation reflects both rapid storm burial and the ecological behavior of *M. venosa*, which actively removes sediment from its shell surface, inhibiting settlement by epibionts (Försterra et al., 2008).

Type 5 fossil concentrations (Fc5) represent fair-weather sedimentation and predominantly in-situ (i.e., life position) preservation of autochthonous fossil elements under slow sedimentation rates. Skeletal remains in Fc5 exhibit low values across all taphonomic signatures, reflecting the minimal influence of physical reworking. Variations are mainly lifestyle-dependent: infaunal taxa such as *Retrotapes exalbidus* and *Cyclocardia velutina* (Smith, 1881) were protected within the sediment and thus show minimal fragmentation or disarticulation, whereas epifaunal forms (e.g., *Zygochlamys patagonica*) exhibit slightly higher degrees of breakage, and bioerosion. Even in such mostly calm and low-

energy environments, fragmentation of epifaunal shells can occur due to low energy waves if exposure time is prolonged. Pre-occurring bioerosion of the shells may also enhance fragmentation of the bioclasts. Bioerosion can be a trigger for higher degrees of fragmentation when shells are subjected to moderate (or longer) exposure times in the surface (Zuschin et al., 2003). This is consistent with the findings and the low sedimentation rates interpreted for the Tubul Formation, where the generally more fragmented shells correspond to the more bioeroded specimens (*Zygochlamys patagonica*). Fc5 concentrations are also strongly associated with highly bioturbated deposits, underscoring their development under conditions of low sediment supply. Such conditions create a preservational bias favoring infaunal suspension feeders and shallow burrowers, which are commonly found articulated and in life position. In contrast, in-situ preservation of epifaunal elements is rare. This scarcity suggests a low preservation potential for epifauna, likely due to the combined effects of bioerosion (e.g., serpulids) and the episodic removal of shells to deeper settings during increased wave action.

Both the sedimentologic and taphonomic evidence collectively support deposition in a weakly storm-affected shoreface within a protected coastal environment, specifically corresponding to the lower shoreface (Fig. 7). The weakly to moderately storm-affected nature is indicated by the pervasive bioturbation of the substrates, poor preservation of storm-influenced sedimentary structures, and the abundance of fair-weather deposits (Wesolowski et al., 2018). The latter, although not clearly evidenced by sedimentary structures (e.g., wave ripples), is mainly represented here by the abundant Type 1 fossil concentrations (Fc1), which reflect fair-weather wave taphonomic signatures. A subtle fining-upward trend, along with minor changes in faunal composition, in terms of relative abundances and the disappearance of dense *Zygochlamys* banks towards the upper part, suggests slight deepening, possibly reaching the upper offshore zone. However, no sedimentologic or taphonomic evidence supports deposition in substantially deeper-water environments. All described fossil concentrations are identified as dominated by sedimentologic processes (sedimentologic-type concentrations sensu Kidwell et al., 1986). Two other types of dominant processes controlling the formation of fossil concentrations were defined by Kidwell et al. (1986). Biogenic-type concentrations are more common in even shallower zones such as tidal flats and lagoons, where events of mass mortality attributed to stranding of organisms, short-lived colonization by opportunistic faunas or fluctuations in water conditions (e.g., salinity, temperature) result in the accumulation of skeletal parts. Diagenetic-type concentrations are not particularly common in any subenvironment, as they directly depend on the degree of diagenetic modification suffered by the concentrations and can therefore be more relevant for carbonate-type rocks where recrystallization is far more likely to substantially modify the original concentrations (e.g., a noticeable increase in component size). Within the studied succession, only Fc1 (*Zygochlamys* banks) and Fc4 (*Magellania* lenses) show a mixed influence of sedimentologic and biogenic processes, as both originated from reworked accumulations of gregarious taxa. Importantly, there is no evidence for diagenetic modification, since shells retain their primary mineralogy, with no signs of recrystallization or preferential dissolution of aragonitic taxa, consistent with the expected preservation potential in siliciclastic successions (Foote et al., 2015).

6. Conclusions

1. The Tubul Formation at the Las Peñas locality in southern Chile was deposited in the lower shoreface to upper offshore zone of a wave-dominated, protected coastline, under conditions of very low sedimentation rates and sporadic storm influence. This setting provided favorable conditions for the colonization of benthic organisms which pervasively bioturbated the deposits, resulting in a highly bioturbated sediment.

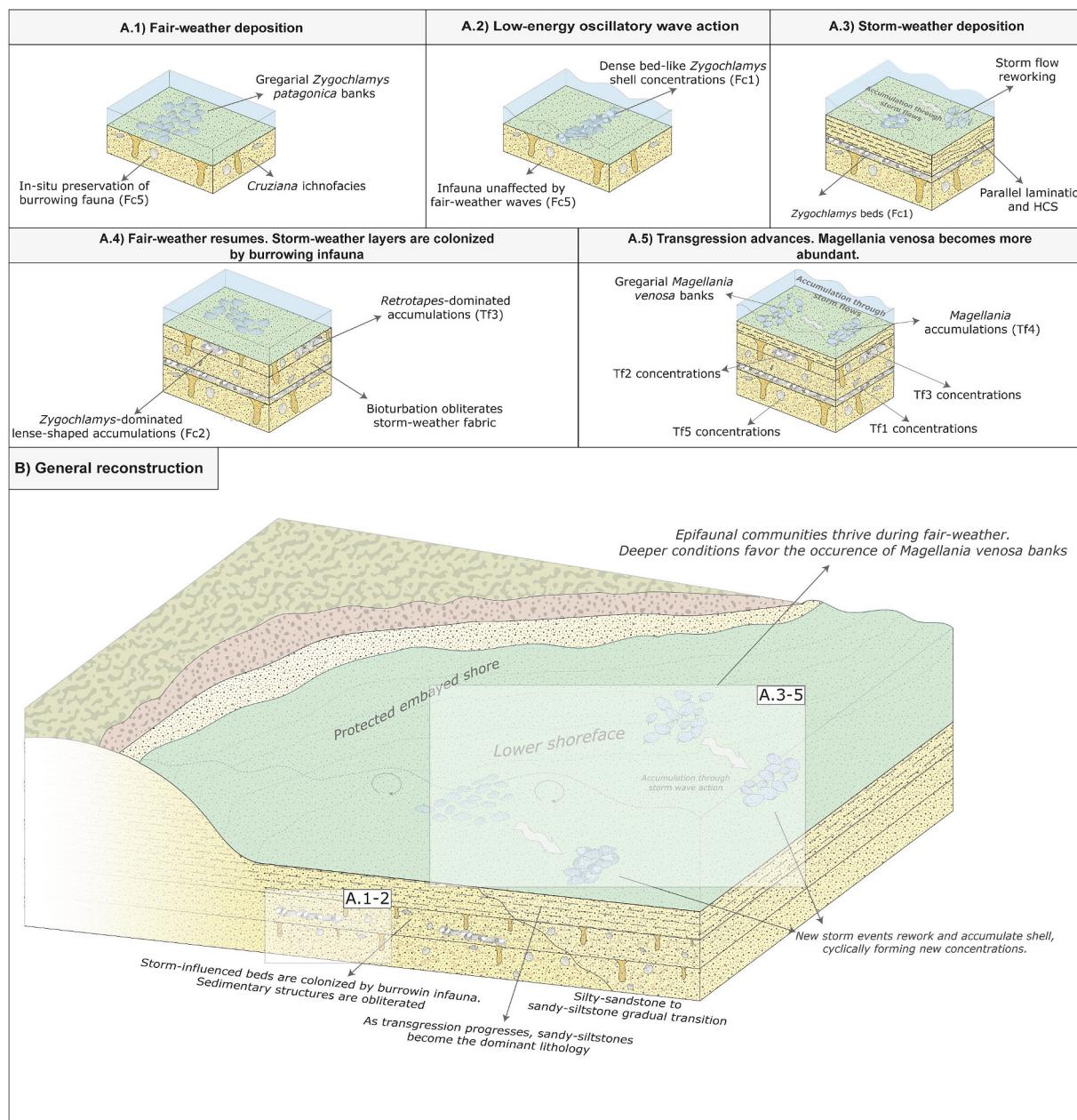


Fig. 7. Generalized reconstruction and evolution of the Tubul Formation at the studied section, illustrating the sedimentologic and taphonomic processes that influence the formation of each fossil concentration type.

2. A diverse fossil fauna characterizes the Tubul Formation. These faunal elements are heterogeneously distributed throughout the section, preserved both as isolated remains and as fossil concentrations. Based on the sedimentologic, paleontologic, and taphonomic features of the studied fossil associations, five types of fossil concentration were recognized. Collectively, these confirm deposition in a lower shoreface setting, but also record subtle changes in environmental conditions and depositional processes. This interpretation is consistent with the pervasive presence of the *Cruziana* Ichnofacies.
3. The basal part of the succession is dominated by fossil concentrations with the gregarious epifaunal bivalve *Zygochlamys patagonica*. This species formed dense monospecific banks shallower zones, which were incorporated into slightly deeper settings by the action of fair-weather and storm waves. Additional fossil concentrations dominated by the infaunal bivalve *Retrotapes exalbidus* provide further evidence of reworking by storm-wave activity.

4. Taxonomic diversity is lower in the upper part of the succession. A compositional shift into a more brachiopod-dominant fauna is inferred from the occurrence of a monospecific fossil concentrations comprised of the terebratulide brachiopod *Magellania venosa*. Like *Zygochlamys patagonica*, this taxon formed dense monospecific banks later reworked and redeposited by storm waves. The increased abundance of *Magellania venosa*, combined with a subtle fining-upward trend, suggests a marine transgression during this time.
5. The Tubul Formation fossil assemblages and their features provide valuable insights into storm-influenced coastal deposits. In particular, they demonstrate the potential of fossil concentrations to refine paleoenvironmental reconstructions in successions where sedimentary structures are scarce and lithologies relatively homogeneous, making purely sedimentologic or ichnologic approaches insufficient.

CRediT authorship contribution statement

Diego Volosky: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation. **Camila Vargas:** Writing – original draft, Investigation, Conceptualization. **Katherine Cisterna:** Writing – review & editing, Investigation, Funding acquisition, Conceptualization. **Alfonso Encinas:** Writing – review & editing, Supervision, Investigation, Funding acquisition, Conceptualization. **Sandra Gordillo:** Writing – review & editing. **Fernando Muñiz:** Writing – review & editing. **Luis A. Buatois:** Writing – review & editing. **Patricio Zambrano:** Writing – review & editing, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.palaeo.2025.113257>.

Data availability

Data will be made available on request.

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