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PALEONTOLOGY

Bioestratinomic Classification and Genesis of Shell Beds (Coquinas) from the Santa Marta Formation (Upper Cretaceous) of James Ross Island, Antarctica

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Abstract: Shell beds, or coquinas, have a complex origin, limiting their utility in paleoecology. However, such accumulations can serve as crucial paleoenvironmental indicators, since their bioestratinomic and diagenetic properties explain the physical-chemical and biological processes of their formation, as well as the ancient environments linked to their development. In 2016, the PALEOANTAR Project sampled coquinas from the James Ross Island (Antarctic Peninsula) in Passo São José (PSJ – San José Way) and Muro do Castelo (MDC – Castle Wall), two new localities with outcrops of the lower Lachman Crags Member, Santa Marta Formation, Marambio Group, Cretaceous of Larsen Basin. The paleontological content and sedimentary structures indicate a shallow marine depositional system. The PSJ coquina are composed by gastropods bioclasts, with predominantly dense/loose packing. The MDC presents a larger variety of bioclasts with bivalve dominance on a loose packing and conglomeratic horizons, that varies from granule to pebble. Sedimentary and biostratinomic features observed in samples from both localities indicate their genesis from high-energy events, characterized as a proximal tempestite. These descriptions allow a more accurate reconstruction of the depositional environments, highlighting the importance of these rocks in the geological record during the Cretaceous of Antarctica.

Key words: Antarctic Peninsula, *Coquinas*, Fossil Bivalves, James Ross Island.

INTRODUCTION

Extensive accumulation of fossil shells requires specific circumstances for their formation and can offer important perspectives on the sedimentary conditions that promote such accumulations (Ávila et al. 2015). The term coquina refers to sedimentary rocks primarily composed of mollusk shells and their fragments, which may also contain a variety of carbonate and/or siliciclastic grains as secondary constituents (e.g., Kidwell & Holland 1991). Despite their complex origin limiting their utility in paleoecology, coquinas can serve as crucial paleoenvironmental indicators. The bioestratinomic and diagenetic characteristics of coquinas elucidate the physical-chemical and biological processes, as well as the ancient environments associated with their formation (Kidwell et al. 1986, Simões & Kowalewski 1998). Furthermore, coquinas hold significance in biostratigraphy as numerous taphonomic features indicate the temporal mixing of skeletal remains from different populations or communities (time-averaging). Within the sedimentary record, one can observe a spectrum of skeletal accumulations, ranging from those rapidly formed during episodes of environmental instability (e.g., storms or mass mortality events) to condensed deposits that span extended periods (Kidwell et al. 1986). Additionally, skeletal concentrations can be examined in the context of bathymetric gradients, providing further insights for sedimentary basin analysis.

In the Antarctic region, the first description of a coquina-type concentration was carried out in Triassic sediments of the Gandara and Kopaitic Islands, Legoupil Formation, by Thomson (1975). Subsequent studies maintained a descriptive approach, documenting bioclast accumulations in various strata and basins of the Antarctic continent. Also, coquinas predominantly composed of trilobite fragments were reported from the Upper Cambrian Minaret Formation, Heritage Range, Ellsworth Mountains, deposited under normal coastal marine conditions of medium to high energy (Webers et al. 1992). The first record of Hokkaido-conchid gastropods in the Southern Hemisphere, occurred in the analysis of an Upper Jurassic coquina from Alexander Island (Kaim & Kelly 2009). Bradshaw et al. (2002) described shell beds in the Lower Devonian Horlick Formation, produced by episodic and powerful storms, containing mollusks, trilobites, and brachiopods. Spinicaudatan coquinas were also reported in the Devonian of Portal Mountain and in the Jurassic of Blizzard Heights and Storm Peak (Tasch 1987).

Despite these descriptions, studies focusing on the environmental analysis of coquinas are scarce. Accumulations of pectinid bivalves, locally called "*Pecten* Conglomerates" (Gaździcki 1984), occur in various regions of the continent and the peninsula, including Cockburn and King George Islands, Belen Fjord, McMurdo Sound, Heard Island, and Vestfold Hills (Gaździcki & Studencka 1997). The most studied deposits are those from the Oligocene Polonez Cove Formation on King George Island and the Pliocene Cockburn Island Formation (e.g. Gaździcki & Pugaczewska 1984, Gaździcki & Webb 1996, Quaglio et al. 2008, 2014). In the basal part of the Low Head Member (Oligocene), Polonez Cove Formation, King George Island, coquinas ("*Chlamys* coquinas," Gaździcki 1984) are commonly found, characterizing the most fossiliferous levels of this unit. Initially, these coquinas were interpreted as tempestites (Gaździcki 1984). However, subsequent sedimentological and taphonomic analyses proposed a new interpretation, suggesting that the genesis of the coquina is related to high-energy episodes of subaqueous gravity flows, associated with the progradation of fan-delta fronts, between fair-weather and storm waves (Quaglio et al. 2014).

The coquinas from Seymour Island (Upper Cretaceous, Marambio Group) have been interpreted as medium to high-energy deposits and thanatocenoses with little transport and low energy (Marenssi unpublished data, Marenssi et al. 1998). Other coquinas associated with storm conditions, including bivalves and gastropods, are well documented (Rinaldi et al. 1978, Olivero et al. 1986, Pirrie 1989, Crame et al. 1991, Scasso et al. 1991, Olivero 2012). These coquinas are described in the Beta Member (Olivero 2012, approximately equivalent to the Lachman Crags Member) and the Gamma Member (Olivero 2012, approximately equivalent to the Herbert Sound Member) of the Santa Marta Formation. In the upper part of the Lachman Crags Member, thicker coquinas containing belemnites, scaphopods, and trigoniid bivalves are commonly present (Olivero 2012). In the Herbert Sound Member, the presence of corals and ammonites associated with lenses of coquinas and conglomerates suggests normal marine conditions in these facies ("*Rotularia* Biofacies," Scasso et al. 1991).

This work aims to analyze facies characteristics and taphonomy of the coquinas from James Ross Island. Through the description of the mineralogical composition, texture, and structure of the rocks, we seek to understand the depositional processes and environmental conditions that led to the formation of these accumulations. The taphonomic analysis, including the packing and preservation of the bioclasts, provides valuable insights into the high-energy events, responsible for the deposition of the coquinas.

Geological Setting

James Ross Island, located in the northeastern portion of the Antarctic Peninsula (Fig. 1), has significant geological relevance due to its volcano-sedimentary sequences from the Cretaceous to the Paleogene, resulting from the fragmentation of Gondwana and the formation of the Larsen Basin, and is divided into the South and James Ross sub-basins (Macdonald et al. 1988). The James Ross Sub-basin is one of the most complete and thickest volcano-sedimentary sequences deposited from the Cretaceous to the Paleogene in the Southern Hemisphere (Crame et al. 1996). It was formed in a back-arc during the breakup of Gondwana (Hathway 2000). It is lithostratigraphically divided into the Nodenskjöld Formation (not cropping out in James Ross Island), the Gustav Group, and the Marambio Group (Hathway 2000, Hathway & Riding 2001, Riding & Crame 2002).

The Gustav Group occurs on the northwest edge of James Ross Island and in some isolated points on the adjacent margin of the Antarctic Peninsula. It is divided from base to top into the Lagelius Point, Kotick Point, Whisky Bay, and Hidden Lake formations, and its age ranges from the Aptian to the Coniacian (Crame et al. 1991, 2004), forming a fining-upward succession interpreted as a progressive increase in water depth in a marine environment (Riding & Crame 2002).

Only the two upper units of the Gustav Group crop out in the research area. They are characterized by conglomerates interbedded with sandstone layers and silty-clay levels (Whisky Bay Formation), which thin towards the top becoming more sandy (Hidden Lake Formation), until the conformable contact with the Marambio Group.

The Marambio Group crops out in some portions of James Ross Island and on Vega, Humps, Snow Hill, Seymour, and Cockburn islands. This rock package represents a prograding system composed of a variety of sandstones, siltstones, and mudstones, with levels of coquinas, deposited under storm conditions on the inner and outer shelf (Crame et al. 1991, 2004). It is divided into the Santa Marta, Snow Hill Island, Lopez de Bertodano, and Sobral formations. The coquinas of the present study are found in the Santa Marta Formation (Santonian – Maastrichtian, according to Marenssi et al. 2002, 2005, Castro & Carvalho 2015), corresponding to the basal unit of the Marambio Group. The unit is over 900 meters thick, composed of interbedded sandstones, siltstones, claystones with volcanic tuffs, and rare coquinas (Olivero 2012), and is interpreted as a sequence of surface volcaniclastic deposits in a deltaic environment (Scasso et al. 1991, Olivero 2012).

In the northwestern portion of James Ross Island, the Santa Marta Formation is divided into the Lachman Crags and Herbert Sound members (Crame et al. 1991). The basal Lachman Crags Member is approximately 850 meters thick and consists of claystones, siltstones, and sandstones, with rare conglomerates becoming more common in the upper portion. Fossil specimens come from the top of this member, dating from the Santonian to the Campanian

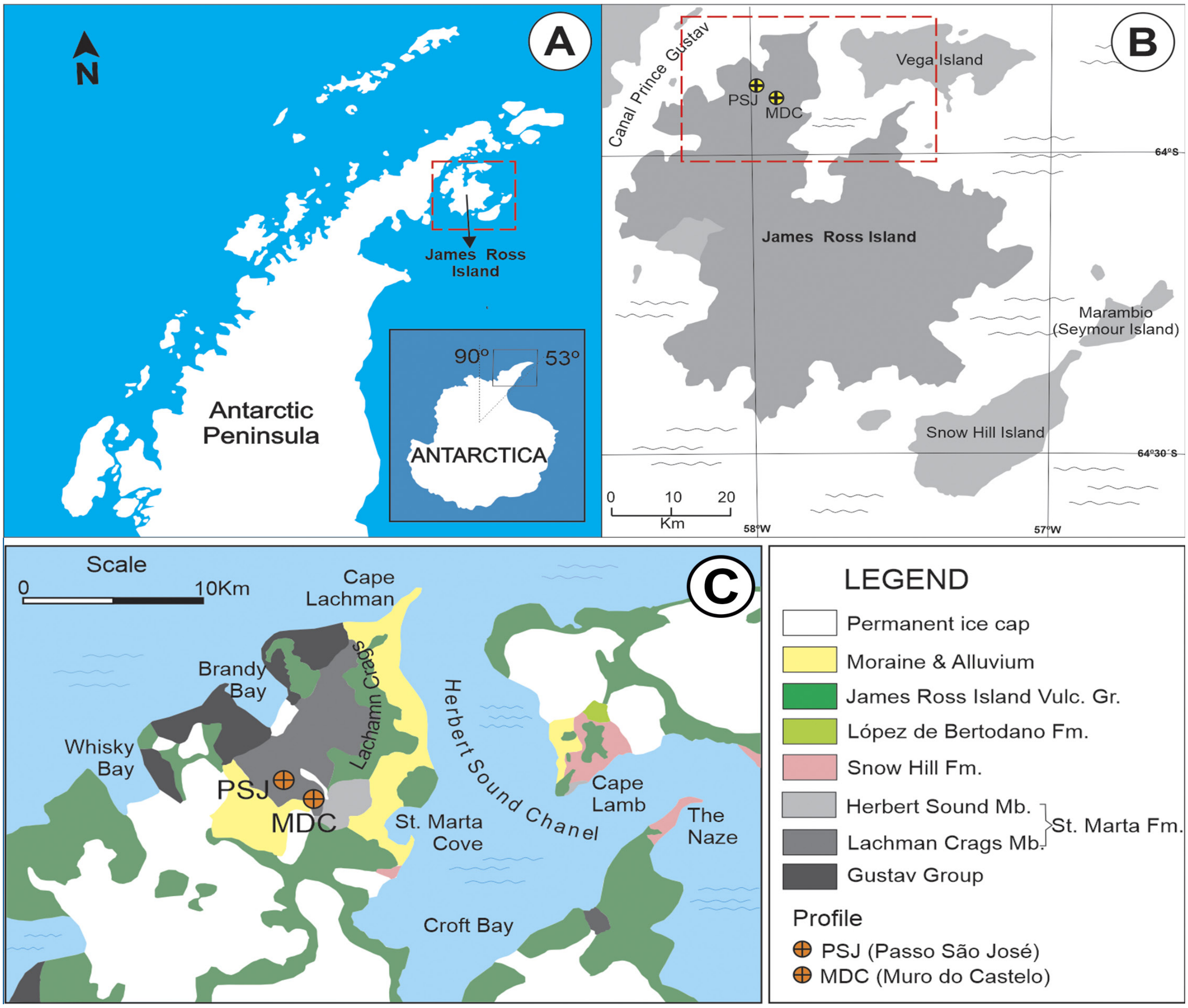

Figure 1. Location of the research area. a - location map of Antarctic peninsula with the position of the James Ross Island. b – Map of James Ross Island with the new areas: PSJ – Paso San Jose and MDC - Muro do Castelo. c – Geological map of the Santa Marta Cove and correlated areas.

interval (Crame et al. 1991). The upper Herbert Sound Member (Crame et al. 1991) is 250 meters thick and consists of fine sandstones with cross-stratification and coquinas, dating from the Campanian – Maastrichtian interval, based on fossils and isotope dating (Crame et al. 1991, 1999, Olivero et al. 1992, Olivero & Medina 2000).

MATERIALS AND METHODS

Fieldwork on James Ross Island was carried out by the PALEOANTAR Project, one of the projects supported by the Brazilian Antarctic Program – PROANTAR (Kellner 2022, 2023, Sampaio 2022, Simões et al. 2022, 2023). The first time of the team in James Ross Island was in the Austral summer of 2005-2006 (Kellner et al. 2011, Carvalho et al. 2013). Since then, several incursions have been made by the team in the region, in pre-determined areas for reconnaissance and collection (see Kellner et al. 2011, Carvalho et al. 2013, Pinheiro et al. 2020, Lima et al. 2021, Piovesan et al. 2021, Brum et al. 2022, 2023 for further prospected areas on James

Ross Island). In the Austral summer of 2015-2016 during the thirty-fourth Brazilian Antarctic Operation - OPERANTAR XXXIV, around one ton of fossils were collected by the PALEOANTAR team. Those comprises vertebrates (Kellner et al. 2019, Brum et al. 2023), invertebrates (Pinheiro et al. 2020, Videira-Santos et al. 2020, 2021) and plants (Lima et al. 2021), all belonging to the Santa Marta Cove region and surrounding areas, including the coquinas from the upper portion of the Lachman Crags Member (Santa Marta Formation) described here. After defining target areas, detailed geological/stratigraphic work and sample collection were conducted. Two sites with "*in situ*" coquina occurrences were surveyed and named respectively as Passo São José (PSJ - 63°53'46"S x 57°58'19"W) and the Muro do Castelo (MDC - 63°53'36"S x 57°55'03"W) profiles. Both sites consist of lithologies belonging to the upper portion of the Herbert Sound Member.

The descriptive procedure of the bioclasts followed Kidwell et al. (1986) and included the 3D arrangement of the shells that could be analyzed in the matrix: orientation of the cross-section in relation to the stratification (parallel, concordant, oblique, and convex up or down).

RESULTS

The PSJ Profile (Fig. 2a) is 20.50 meters thick, consisting mainly of fine/very fine to medium-grained sandstones with fine planar-parallel stratification, and levels of concretions that are highly cemented, with fossil occurrences (bivalves, ammonites, wood) in dispersed levels, referred to as fvff-cS Facies (fine, very fine, fossiliferous - cemented sandstone). Intercalated with these facies is the c-CS-c facies (calcareous-Conglomeratic Sandstone - shelly), composed of calcareous sandstone, with medium to coarse grain size, with intercalations of conglomeratic levels (granules and pebbles) predominantly containing gastropod fossils.

The MDC Profile (Fig. 2b) is 22.00 meters thick and, like the PSJ profile, consists of two predominant facies, the fvff-cS facies (fine, very fine, fossiliferous - cemented sandstone) consisting of fine to very fine, sometimes medium-grained sandstone, with fine stratification, highly cemented levels, sometimes concreted, exceptionally presenting ferruginous levels. Unlike the PSJ profile, no fossil occurrences were observed. At the top of this profile, there is a level referred to as the c-CS-c facies (calcareous-Conglomeratic Sandstone - shelly), with thickness varying laterally from 10 to 45 cm, formed by medium to coarse-grained calcareous sandstone, intercalated with thin conglomeratic levels of granules to pebbles, with fossil occurrences (bivalves, gastropods, chondrichthyan teeth) in both levels.

The PSJ coquina is stratigraphically positioned below the MDC coquina, although both belong to the Santa Marta Formation, specifically the upper portion of the Lachman Crags Member. The layer comprising the PSJ coquina has an average thickness of 35 cm in its approximately 15 meters of outcrop, has a reddish color, and a monotonous occurrence of bioclasts (gastropods), with the presence of siliciclastic levels in the conglomerate fraction (Fig. 3a).

The PSJ coquina possess a grain size as coarse calcarenite of allochemical origin, and texturally as poorly sorted biosparite, presenting poorly rounded grains and almost no presence of mud in the matrix, which would indicate a medium to high-energy environment during its deposition (Fig. 3b). Considering the bioclasts, it can be texturally classified as a Packstone (Dunham 1962). The degree of packing of the bioclasts is considered "dense/loose" according to the degrees proposed by Kidwell & Holland

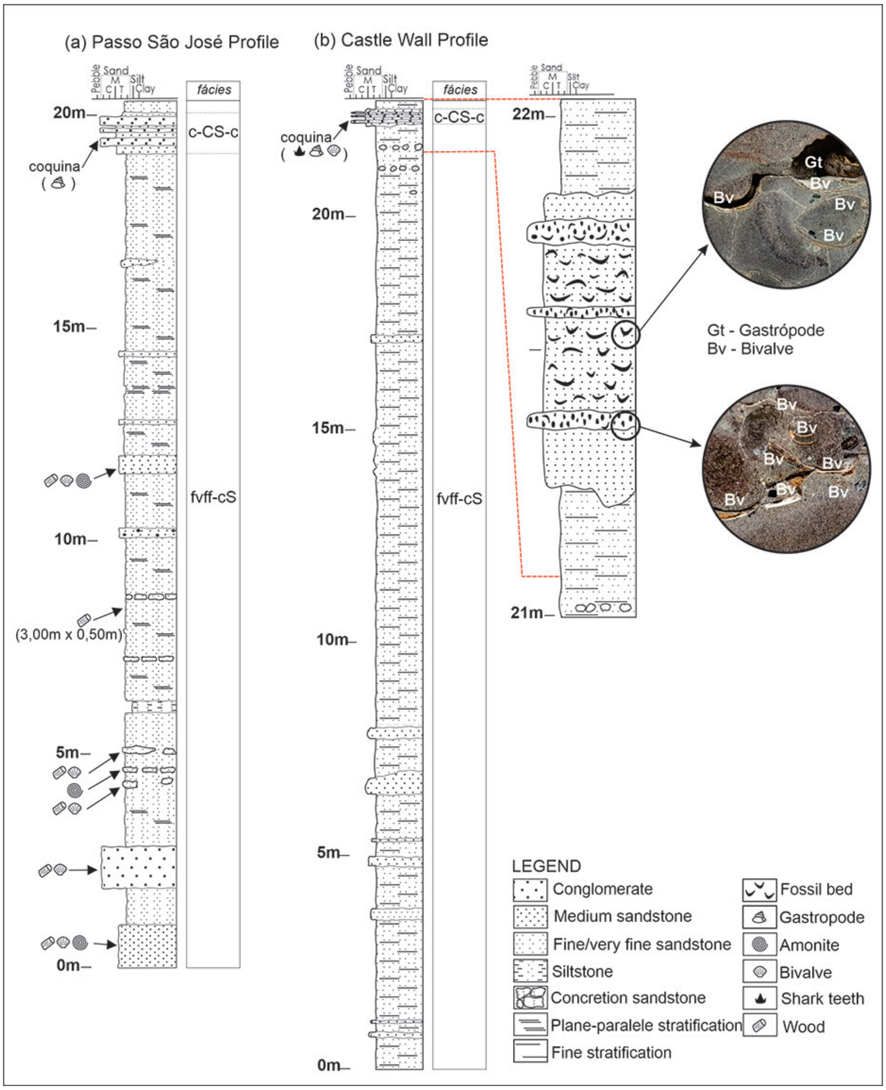

Figure 2. Comparison between the Paso San Jose (PSJ) and Muro do Castelo (MDC) profiles. a- PSJ geological profile (20m high) and fossil content. b – MDC geological profile and fossil content (22m high). Abbreviations: Facies c-CS-c - Medium to coarse calc-sandstone, with fossils (gastropods, bivalves, chondrichthyan teeth), interspersed with thin conglomeratic levels (granules to pebbles) that may contain fossils. Facies fvff-cS- Very fine, friable, finely stratified sandstone, with intercalations of fine to medium silicified sandstone, sometimes forming concretions and thatexceptionally presents ferruginous levels. Bv – bivalves. Gt – Gastropods.

(1991) and is marked by the predominance of mostly whole gastropods, may be an indicator of low transport. The sample composition contains 126 specimens, including 72 gastropods, 6 bivalves, and 48 shells of indeterminate taxa, with "dense/loose" packing.

The shells that could be analyzed are mostly oriented in a bedding-parallel arrangement (56.75%; n=21) and oblique/imbricate (43.25%; n=16), with disarticulated bivalves and their concavity facing downward (66.6%; n=4) and upward (33.3%; n=2). The stratigraphically lower PSJ coquina is primarily composed of naticid gastropod shells, with disarticulated bivalve mollusk shells present at the base (Fig. 4a, b, and c).

The name Muro do Castelo (introduced in the present study) refers to a geomorphological feature in the area where the MDC coquina occurs. It is formed by the differential erosion of a verticalized dyke of basic igneous rocks, with an average width of 50 cm and an outcropping extension of approximately 1.1 km, oriented NW-SE, cutting through the described sedimentary units. This structure resembles a medieval wall, hence the toponymic designation (Fig. 5c).

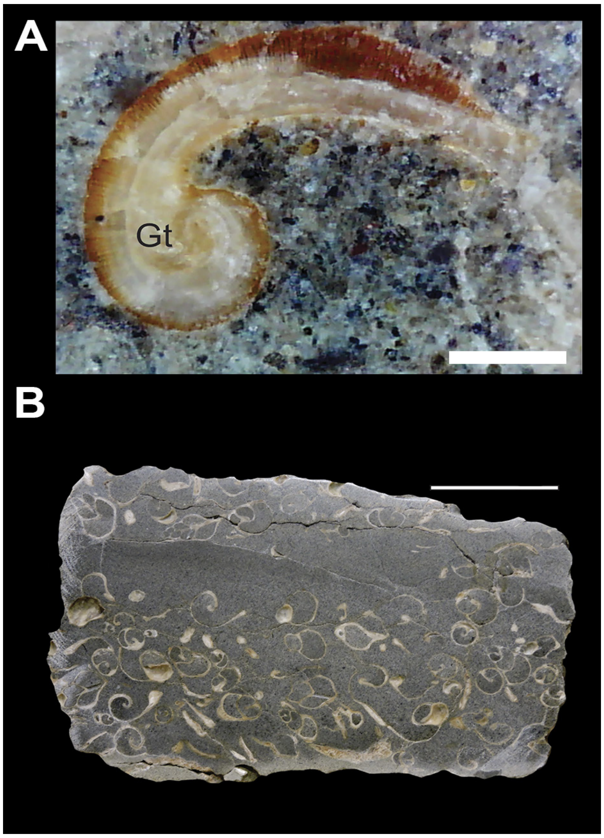

Figure 3. Coquina with bioclasts predominantly made of gastropods. a - Detailed photograph showing the occurrence of poorly rounded grains, filing the concave structure which is part of a gastropod. Scale bar 2 mm. b – General view of a coquina with the occurrence of bioclasts, predominantly gastropods. Scale bar 50 mm. Abbreviations: Gt – gastropods.

MDC coquina is stratigraphically positioned above the PSJ, at the top of an outcrop represented by a 17-meter-high ravine and comprises the Conglomeratic Shelly Sandstone facies (c-CS-c). It is also classified as allochemical calcarenite. It has a reddish color and a sparse distribution of bioclasts consisting of bivalves (predominant), gastropods, and rare "chondrichthyan" teeth. It presents strongly cemented levels in the conglomerate fraction (granules and pebbles) interbedded with massive sandstone levels (Fig. 5a).

It has an irregular thickness, varying laterally from 10 cm to 48 cm. In terms of texture, it is classified as poorly sorted biosparite, with poorly rounded grains and almost no presence of mud in the matrix, indicating a medium to high-energy environment and little transport of the grains. The sample contains 68 specimens, including 7 gastropods, 26 bivalves, and rare chondrichthyan teeth (Fig. 5b), with 35 bioclasts of indeterminate taxa, with "loose" packing (according to Kidwell & Holland 1991). Its bivalve composition corresponds to 80.77% (n=21) disarticulated shells, of which 71.42% (n=15) have concavity facing upward. Regarding bedding orientation, 56.25% (n=18) are concordant, 40.625% (n=13) oblique, and 3.125% (n=1) perpendicular.

Conversely to that observed in the PSJ, the MDC coquina predominantly comprises disarticulated and articulated bivalve mollusk shells from the Nuculidae, Trigoniidae (infaunal), and Pinnidae (semi-infaunal) families, in equal proportions, with rare occurrences of naticid gastropods and polychaeta shells (*Rotularia*) associated (Figure 4d, e, and f). Fragmentation is rare in these concentrations. There is a preferential size selection with shell heights varying between 1.5 cm and 2.0 cm, and no evidence of bioerosion or encrustation was found. At the base of the coquina, bivalve shells are frequently found obliquely disposed in the PSJ coquina or forming nesting and stacking patterns, as seen in the MDC coquina.

DISCUSSION

In fossil accumulations such as coquina deposits, factors like abrasion and fragmentation of bioclasts are related to environmental energy, exposure time, and particle size (Seilacher & Aigner 1991). Based on these observations, it can be concluded that a high degree of fragmentation and abrasion is associated with the reworking of shells, providing key attributes for differentiating

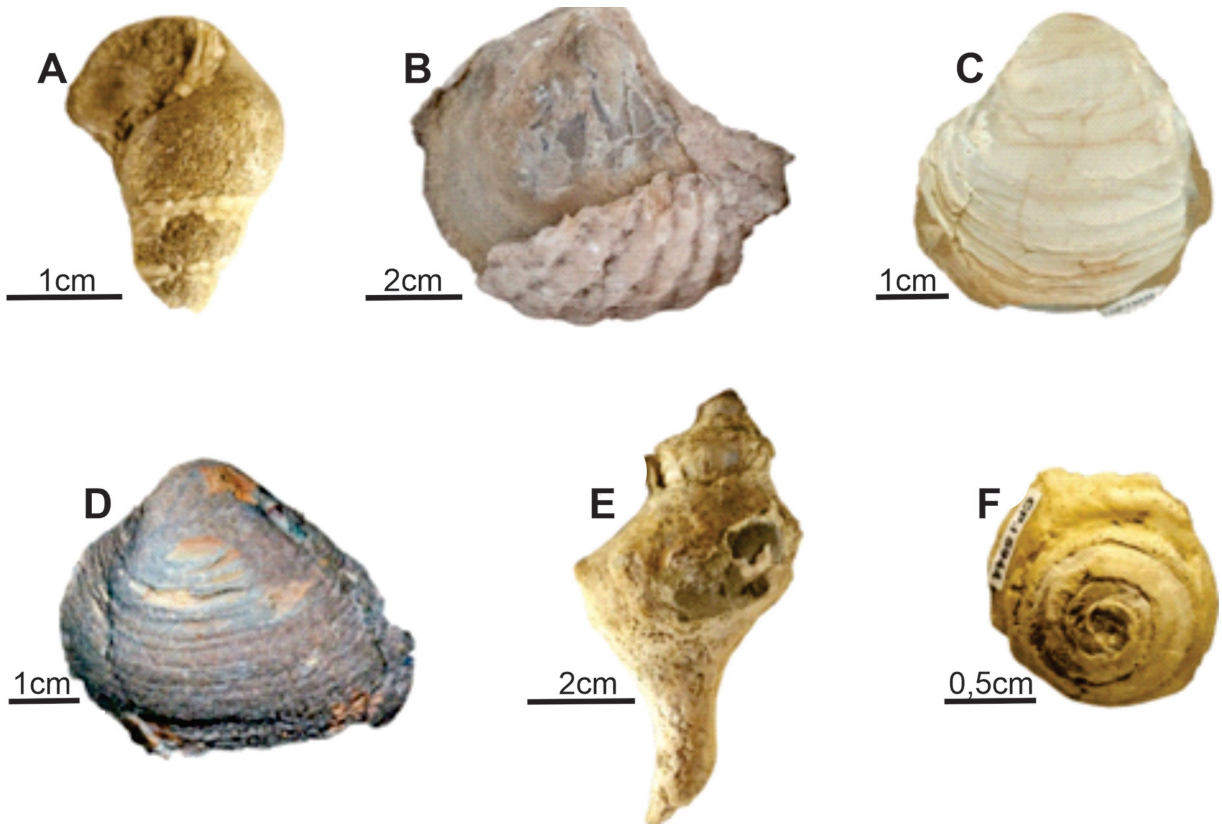

Figure 4. Taxonomic composition of the coquinas a-c from Paso San Jose (PSJ), d-f from Muro do Castelo (MDC). a - Naticid gastropod. b - Trigoniidae bivalve. c-d - Nuculidae bivalves. e – Gastropod. f - Polychaete (*Rotularia*).

in situ deposits from transported deposits (Aguirre & Farinati 1999). Storm deposits may exhibit similar characteristics (Aigner 1985, Sanchez et al. 1991, Fürsich & Pandey 1999, Li et al. 2007), where densely packed coquinas containing broken and disarticulated shells are linked to allochthonous deposits. The taphonomic features observed here, including the slightly rounded granules in the matrix and the low level of shell fragmentation, with almost no abrasion, indicate little to no transport from their original region. This suggests that the samples may be classified as autochthonous or parautochthonous (Brett & Baird 1986, Kidwell et al. 1986, Kidwell & Holland 1991, Fürsich & Oschmann 1993).

Although the PSJ coquina is stratigraphically positioned below the MDC coquina, both exhibit similar genetic processes, differing primarily in the taxonomic composition of the bioclasts. The bioclasts in the coquinas are generally well-preserved, chaotically distributed throughout the matrix, and loosely packed, with bioclasts supported by the calcarenite.

In both coquinas, the contact with the underlying calcarenite is sharp and erosive, indicating potential reworking of the substrate prior to deposition. This feature suggests deposition associated with storm flows or currents in a proximal marine environment (Fürsich & Oschmann 1986, 1993). The chaotic arrangement of bioclasts within the coquinas indicates possible action by turbulent bottom currents resulting from storm events (Kidwell & Bosence 1991). The presence of imbricated shells in the PSJ coquina and nested and

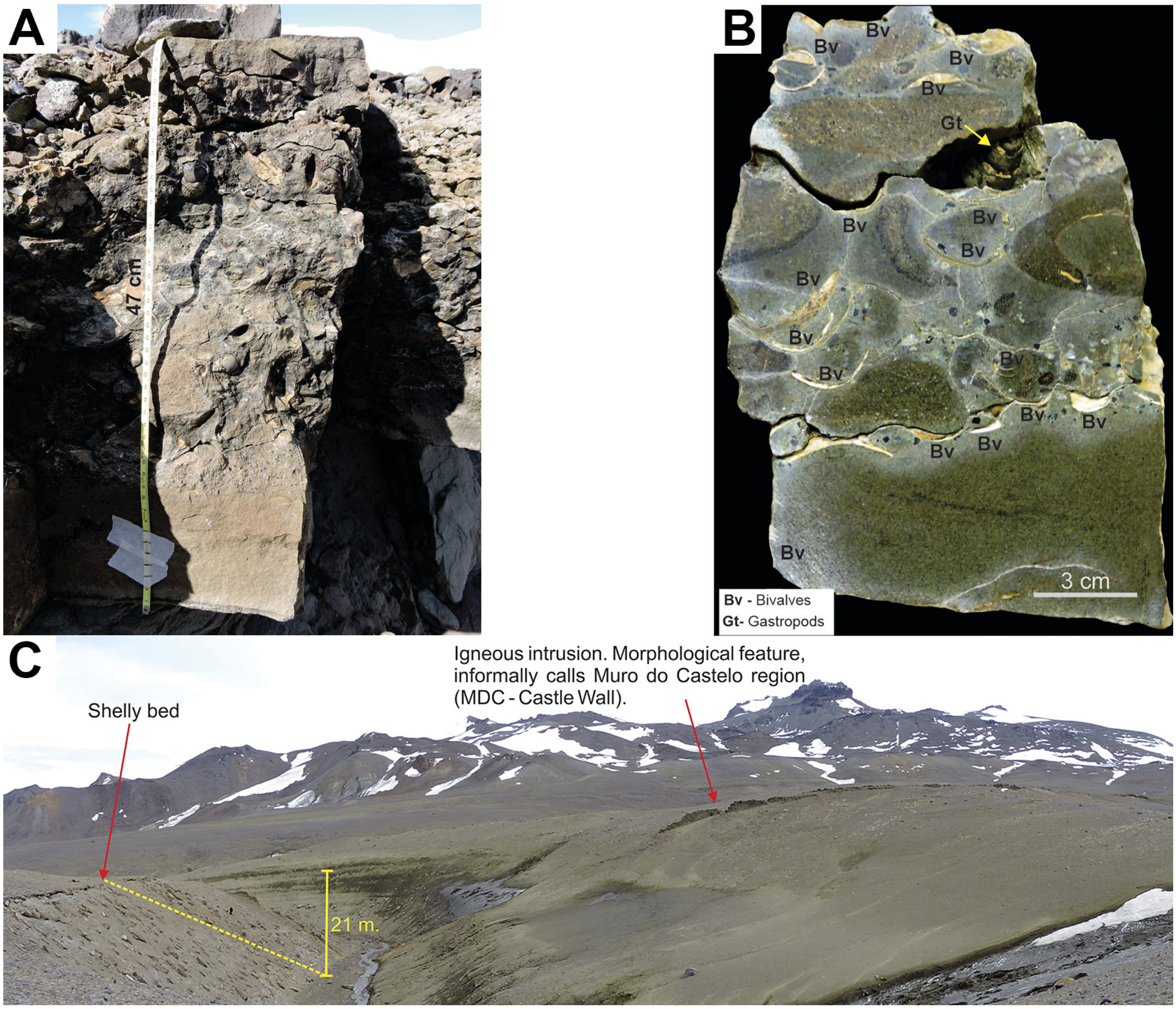

Figure 5. Overview of coquinas on site and after preparation. a- MDC Coquina, note the massive levels interbedded with conglomeratic levels. b - Photo and corresponding section of the lower portion of the MDC coquina highlighting the packing of the fossils. c - General view of the MDC coquina occurrence area, highlighting the toponymy.

stacked shells in the MDC coquina, at the base, supports this interpretation in addition, the constant size class of the bioclasts does not indicate mass flow. This is due to the contact between the bioclasts and their rapid deposition during storm events (Fürsich & Oschmann 1986, Banerjee & Kidwell 1991, Kidwell & Bosence 1991). Furthermore, skeletal concentrations generated by storm processes typically exhibit good preservation of bioclasts, with a frequent mixture of disarticulated and articulated shells (Fürsich & Oschmann 1986, 1993).

The presence of disarticulated bivalve shells at the base of the coquinas indicates that the bioclasts were exposed on the substrate prior to final deposition. The low concentration of fragmented shells suggests the absence of subaerial exposure in energetic environments in the taphonomically active zone (TAZ) prior to the storm event. The original littoral environment of the concentrations is located below the normal wave base level, comprising elements of epifauna (gastropods), semi-infauna (bivalves), and infauna (bivalves). During the storm event, part of the original soft-bottom environment is eroded, leading to size selection of bioclasts and skeletal types. The PSJ coquina, with its primarily univalve epifaunal elements, likely represents selective concentration where, alongside epifaunal elements, infaunal elements are exhumed and transported, resulting in the final skeletal concentration. In contrast, the MDC coquina, with its predominantly bivalve skeletal types capable of burrowing, likely indicates a concentration formed by exhumation and selection under comparatively lower energy conditions.

The PSJ coquina is amalgamated with at least two episodes of erosion and deposition within its profile. The MDC coquina exhibits at least three depositional episodes. The absence of epibiont organisms in the upper portions of the coquinas could indicates rapid sedimentation of the overlying calcarenite, precluding prolonged exposure of bioclasts at the water/sediment interface (Banerjee & Kidwell 1991).

Concerning the variation size of fossil samples preserved in both coquina accumulations, in the PSJ, the gastropods varied little, with standard deviations of 4.26, 3.80, and 4.10 for height, length, and width, respectively. On the other hand, the size of the MDC bivalves varied more, with a value of 7.00. The PSJ coquina, rich in gastropods, was deposited in a relatively deeper marine environment, whereas the MDC coquina, which contains a greater variety of bioclasts, including bivalves, formed in a shallower environment. These characteristics suggest that both coquinas were influenced by high-energy events, such as storms, which played a crucial role in their deposition. Thus, the bioestratinomic and sedimentary features observed in the storm-generated concentrations of the PSJ and MDC coquinas indicate their genesis from high-energy events, likely associated with storms, and considering the preservation of shells are best characterized as proximal tempestites.

CONCLUSIONS

In conclusion, the evidence presented in the study suggests that both the PSJ and MDC coquinas were formed by high-energy events, likely associated with storms, in proximal marine environments. The genetic processes involved in the formation of these coquinas are similar, with differences primarily in the taxonomic composition of the bioclasts. The presence of well-preserved, chaotically distributed bioclasts with minimal fragmentation, as well as the sharp and erosive contacts with the underlying calcarenite, support the interpretation of storm-driven deposition. The preferential size selection and lack of bioerosion or encrustation further indicate rapid sedimentation during storm events. Overall, the characteristics of the PSJ and MDC considering the preservation of shells in coquinas suggest their genesis as storm-generated concentrations, best characterized as proximal tempestites.

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Author contributions

LCW, AWAK and JMS conceived and designed the study; AWAK, LCW and JMS performed fieldwork in the Antarctic Peninsula collecting the coquinas presented here; LCW conducted the geological study and profile descriptions in the field; RPG and LCW did the taxonomic identification of the bioclasts and the taphonomic analysis. All authors wrote, reviewed, and contributed to the manuscript.