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TAPHONOMIC SIGNIFICANCE OF ARISTOTLE'S 'WHEEL PARADOX': AN EXAMPLE WITH THE CERITHID GASTROPOD *CERITHIUM ATRATUM* (BORN, 1778) FROM CONCEIÇÃO LAGOON, SANTA CATARINA STATE, SOUTHERN BRAZIL

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ABSTRACT – In the book *Mechanical Problems*, attributed to Aristotle, the author relates the differential degrees of wearing and rounding of pebbles and shells moved by waves on the seashore to the variable radii and diameters of these particles. This phenomenon, which became known as Aristotle's 'Wheel Paradox,' seems to explain the pattern of abrasion observed in shells of gastropods *Cerithium atratum* (Born) found in Conceição Lagoon, on the Island of Santa Catarina, Brazil. *In situ* observations show that the elongated turriform shells of *C. atratum* deposited at shallow (< 30 cm) depths on a sandy bottom with pavements of disarticulated valves of *Anomalocardia flexuosa* Gmelin are subject to bidirectional wave-generated currents under fairweather conditions. The 47 specimens analyzed exhibit a pattern of abrasion characterized by the loss of the shell wall, apparently proceeding from the wider last whorl toward the narrow apex, culminating in the exposure of the columella. Experiments designed to test whether this pattern could be related to the 'Wheel Paradox' principle show that under bidirectional flow, the shells describe circles on the vertical plane around the longitudinal axis (rolling) and a pendulum movement (revolution) on the horizontal plane centered on the apex. The whorls located farther from the apex have larger diameters and describe broader arc segments. Thus, they have higher tangential velocities and travel longer paths, which could explain why they are abraded earlier than the narrower whorls. Recognizing similar abrasion features in fossil shells can provide information on the local paleo-currents, hydrodynamics, and relative time-averaging of death assemblages and allow distinguishing between natural or anthropogenic modification in archaeological specimens. Although the effects vary between shells with different shapes, Aristotle's 'Wheel Paradox' principle explains the general abrasion pattern among gastropods under certain hydrodynamic conditions.

Keywords: Actualistic Taphonomy, *Aktuopaläontologie*, shell abrasion, shell orientation, biostratinomy, hydrodynamics.

RESUMO – No livro *Problemas Mecânicos*, atribuído a Aristóteles, o autor relaciona graus variáveis de desgaste e arredondamento de seixos e conchas movidas por ondas na praia aos raios e diâmetros dessas partículas. Este fenômeno, que se ficou conhecido como o 'Paradoxo da Roda' de Aristóteles, parece explicar o padrão de abrasão observado em conchas do gastrópode *Cerithium atratum* (Born) encontradas na Lagoa da Conceição, na Ilha de Santa Catarina, Brasil. Observações *in situ* mostram que as conchas turriformes alongadas de *C. atratum* depositadas em áreas rasas (< 30 cm) em fundo arenoso com pavimentos de *Anomalocardia flexuosa* Gmelin são sujeitas a correntes bi-direcionais geradas por ondas sob condições de tempo bom. Os 47 espécimes analisados exibem um padrão de abrasão caracterizado pela perda da parede da concha que aparentemente inicia na volta corporal e procede em direção ao ápice, culminando na exposição da columela. Experimentos designados para testar se esse padrão pode ser relacionado ao princípio do 'Paradoxo da Roda' mostram que sob fluxo bidirecional as conchas descrevem círculos no plano vertical ao redor do eixo longitudinal (rolamento) e um movimento pendular no plano horizontal (rotação) centrado no ápice. As voltas mais distantes do ápice têm diâmetros maiores e descrevem segmentos de arco mais longos, portanto têm maior velocidade tangencial e percorrem trajetórias mais longas, o que pode explicar porque são abradidas antes das voltas mais estreitas. O reconhecimento de feições de abrasão similares em conchas fósseis pode fornecer informações a respeito de paleocorrentes, hidrodinâmica e mistura temporal relativa em associações mortas, e permitir distinguir entre modificações naturais ou antropogênicas em espécimes arqueológicos. Embora os efeitos variem entre conchas com formas distintas, o 'Paradoxo da Roda' de Aristóteles parece explicar o padrão geral de abrasão entre gastrópodes sob certas condições hidrodinâmicas.

Palavras-chave: Tafonomia Atualística, *Aktuopaläontologie*, abrasão em conchas, orientação em conchas, bioestratinomia, hidrodinâmica.

INTRODUCTION

The book *Mechanical Problems*, or *Mechanica*, is a collection of texts written in Greek encompassing thirty-five questions on mechanics related to the principle of the lever (Hett, 1955). Although traditionally attributed to Aristotle himself, the actual authorship may belong to Architas of Terentum (Winter, 2007) or other authors from the Peripathetic school of philosophy (Coxhead, 2012).

In Problem 15 of the book, the author discusses the shape of pebbles found on the shore, concluding that the small, rounded pebbles are produced by the abrasion of larger and elongated stones and shells and that the rounding is caused by the fact that objects with a larger radius describe longer trajectories and rotate at higher velocities than smaller ones, and therefore strike harder against the bottom and other objects (Hett, 1955). The underlying cause of that phenomenon was explained in Problem 24, which became known as Aristotle's 'Wheel Paradox', and discusses the question of how two wheels of unequal diameters connected by an axis rolled around it describes a complete turn at the same angular rate despite the longer circumference of the larger wheel, concluding that the latter turns faster than the smaller wheel.

That conclusion seems counter-intuitive and has tormented many people for centuries (Figure 1). As put by the character Sagredo in Galilei's *Dialogues Concerning Two New Sciences* (1638), 'This is a very intricate matter. I see no solution'. Nevertheless, its influence on sedimentary particles is corroborated by different experimental procedures designed to assess the effects of motion or transport by water currents on the shape of particles of different sizes and shapes (Daubrée, 1879; Krumbein, 1941; Kuenen, 1956; Pettijohn, 1957; Force, 1969). The experiments have shown that larger particles are abraded, *i.e.*, lose mass and become more rounded, at faster rates than smaller particles, that round/spherical particles are reduced at lower rates than irregular particles, and that the abrasion of the particles is more intense in pebbly than on sandy bottoms. Although these studies aimed to understand the way inorganic particles become rounded to interpret the origin of sedimentary deposits in terms of hydrodynamic conditions, the results obtained likely can be extrapolated to biogenic skeletal elements as well.

Although the 'Wheel Paradox' has been corroborated experimentally on inorganic particles (rocks and mineral grains), its effect on organic sedimentary particles (skeletal remains) is poorly understood. Empty shells of invertebrates behave as sedimentary particles and are subject to physical taphonomic modifications (biostratinomic) through different mechanisms controlled mainly by environmental conditions (*e.g.*, type of substrate, hydraulic regime) that incorporate the skeletal remains into the sedimentary record; therefore the recognition of features left by those processes can aid in the reconstruction of ancient depositional environments (Müller, 1979; Dodd & Stanton, 1981; Kidwell & Bosence, 1991). Different observations and experiments have focused on the recognition of hydrodynamic effects on the orientation, movement, transportation and abrasion of modern shells as a way of identifying paleocurrents and understanding conditions that resulted in the formation of fossil assemblages (Ruedemann, 1897; Menard & Boucot, 1951; Krinsley, 1960; Potter & Pettijohn, 1963; Keeling & Williams, 1967; Nagle, 1967; Brenchley & Newall, 1970; Cataldo *et al*., 2013; Fick *et al*., 2018; Nebelsick *et al*., 2019). Studies addressing *post-mortem* physical modifications controlled by hydrodynamic regimes have shown that abrasion is the primary taphonomic process responsible for shell destruction in littoral environments (Tauber, 1942; Chave, 1960, 1964; Driscoll, 1967, 1970; Driscoll & Weltin, 1973; Milliman, 1974; Dodd & Stanton, 1981; Davies *et al*., 1989).

When interpreting paleo-environments from geological or paleontological records, it is essential to consider not only the products of depositional processes (*i.e.*, sedimentary structures or fossils) but also identify the processes responsible for generating those records, which can be extrapolated to the past (Chave, 1960), and thus allow to interpret how the records were formed. Taphonomic features

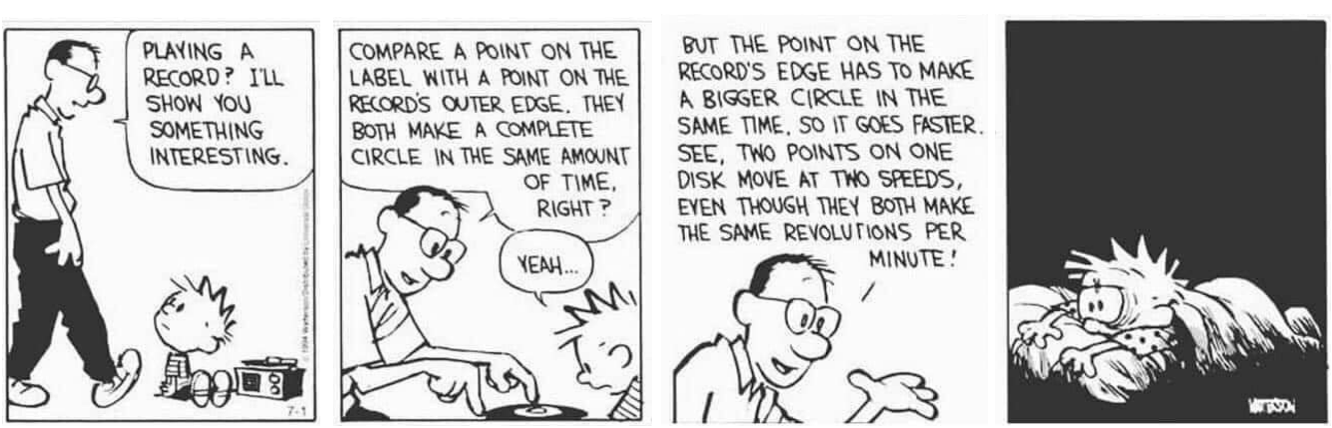

Figure 1. Poor Calvin gets tormented after learning about Aristotle's 'Wheel Paradox' from his father (*CALVIN AND HOBBES © Watterson. Reprinted with permission of ANDREWS MCMEEL SYNDICATION. All rights reserved*).

in fossils collected in different depositional settings are the products of biostratinomic processes. According to the concepts of Actualistic Taphonomy, these processes may aid in interpreting data obtained in the fossil record. They can be identified through *in situ* observations of shells and other skeletal remains in modern environments, complemented by field or laboratory experiments (Kowalewski & LaBarbera, 2004), although the latter may not reproduce the same conditions the sedimentary particles are subject in nature (Kuenen, 1956; Gorzelak *et al*., 2013).

The study presented here analyzes biostratinomic modifications observed in several empty shells of the gastropod *Cerithium atratum* (Born, 1778) collected at the shore of Conceição Lagoon in southern Brazil. The shells exhibit a peculiar pattern of abrasion that raised the question of whether these modifications could have been the result of differential abrasion between shell whorls of different diameters as they were moved by water, which could, in theory, be explained by the principles of Aristotle's 'Wheel Paradox '. To evaluate this possibility, an Actualistic Taphonomy approach that combined field observations and a simple experiment was used, with the objectives of (i) to describe the pattern and distribution of abrasion features within and between shells and (ii) to experimentally examine the way shells are moved under hydrodynamic conditions at the lagoon shore.

STUDY AREA

The shells of *Cerithium atratum* described here were collected at the shore of Conceição Lagoon, in the state of Santa Catarina, southern Brazil (Figure 2A). Conceição Lagoon is located on the eastern part of the Island of Santa Catarina (Figures 2B–C), and constantly receives seawater from the Atlantic Ocean through a ~3 km-long channel on its eastern shore which connects the lagoon to Barra da Lagoa Beach to the northeast. The study area is a southwestward-facing portion of the shore located adjacent to the channel outlet (Figure 2D). The lagoon is surrounded by rocky hills to the east and west and by Pleistocene sandy barriers to the north, sheltering the studied area from winds coming from these directions; as a result, the lagoon is subject to calm conditions for most of the year. The only significant waves are produced by strong S-SW winds driven by polar fronts blowing across the ~2.5 km-long fetch on the southern lagoon.

The lagoon bottom adjacent to the channel outlet is a low-gradient, shallow (≤ 1 meter-deep) flat shoal of fine to very fine sand. The sandy bottom surface is characterized by regularly spaced continuous, linear to slightly sinuous symmetrical ripples, with straight to bifurcated rounded crests oriented parallel to the shore (Figure 3A). The fairweather waves reach the shore parallel or oblique (Figure 3B) to its orientation, producing a usually narrow (< 0.5 m) swash zone

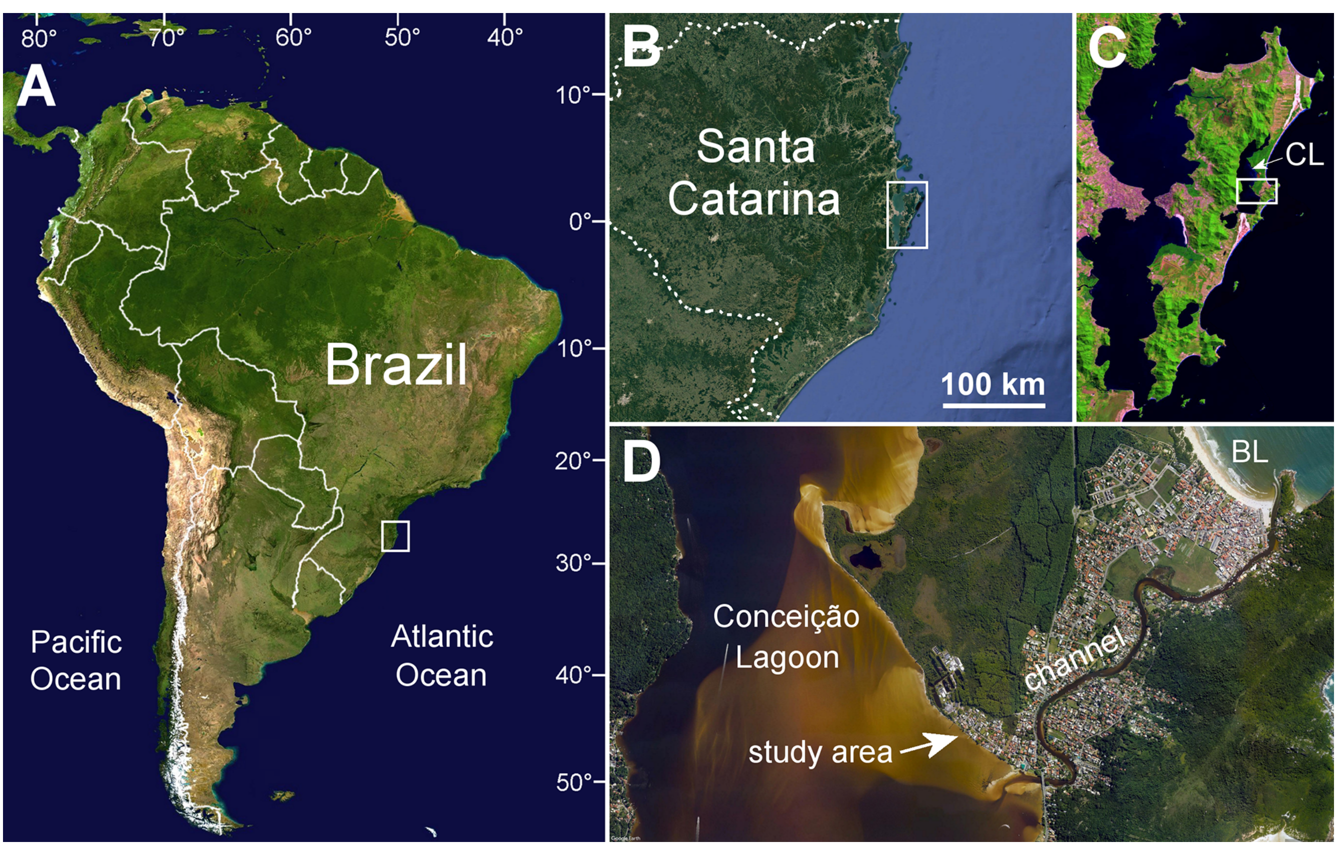

Figure 2. A, Blue Marble satellite image of South America, the white square highlights the location of Santa Catarina state. **B**, Google Earth image showing the location of the Island of Santa Catarina. **C**, LANDSAT image of the island with Conceição Lagoon (**CL**) and the study area indicated. **D**, Google Earth image of the area highlighted in C, showing the study site (**BL**, Barra da Lagoa Beach).

that widens when southerly wind-generated waves hit the shore. Together with the observed oscillatory movement of algae and other debris in suspension but virtually stationary under fairweather conditions (see Video 1 in Supplementary material), the ripples indicate weak hydrodynamics and predominantly wave-generated oscillating flow (Harms, 1969; Reineck & Singh, 1973; Komar, 1974; Allen, 1982).

Shell deposits

The shells of *Cerithium atratum* were collected on the shallowest part of the lagoon shore, where the sandy substrate is covered by a ~10 m-long and ~3 m-wide shell pavement (Figure 3B) formed mostly of densely packed, concave-down disarticulated valves of *Anomalocardia flexuosa* Gmelin, 1791 (Figure 3C). The pavement is usually below the narrow swash zone, and wind-generated waves are the primary process affecting shell orientation and mechanical re-working. The empty shells are probably transported and accumulated episodically on the shore by stronger waves and attain a concave-down stable position by constant action of fairweather waves. The stronger S-SW wind blowing for a few days in May 2018 generated stronger shoreward-directed waves that pushed up water onto the shore, enlarging the swash zone and re-working and accumulating shells removed from the pavement up to about 30 cm above the mean water level, forming a linear deposit of chaotically-oriented valves (Figure 3D; Lopes *et al*., 2021).

The death assemblage forming the shell pavements is dominated by *Anomalocardia flexuosa*. Besides *Cerithium atratum*, other gastropod species identified are *Vitta virginea* (Linnaeus, 1758), *Bulla occidentalis* A. Adams, 1850, and *Stramonita haemastoma* (Linnaeus, 1757), and the bivalves *Ostrea equestris* Say, 1834, *Phacoides pectinatus* (Gmelin, 1791) and *Eurytellina lineata* (W. Turton, 1819). Most of the bivalves are disarticulated, but empty articulated shells indicate a parautochthonous concentration *sensu* Kidwell (1986). Although the relative abundances were not measured, *V. virginea* and *O. equestris* are the most abundant species after *A. flexuosa*. Shells of *C. atratum* are common but not abundant.

METHODS

The gastropod *Cerithium atratum* is distributed in warm temperate to tropical waters along the western Atlantic from South Carolina (United States) to Santa Catarina in southern

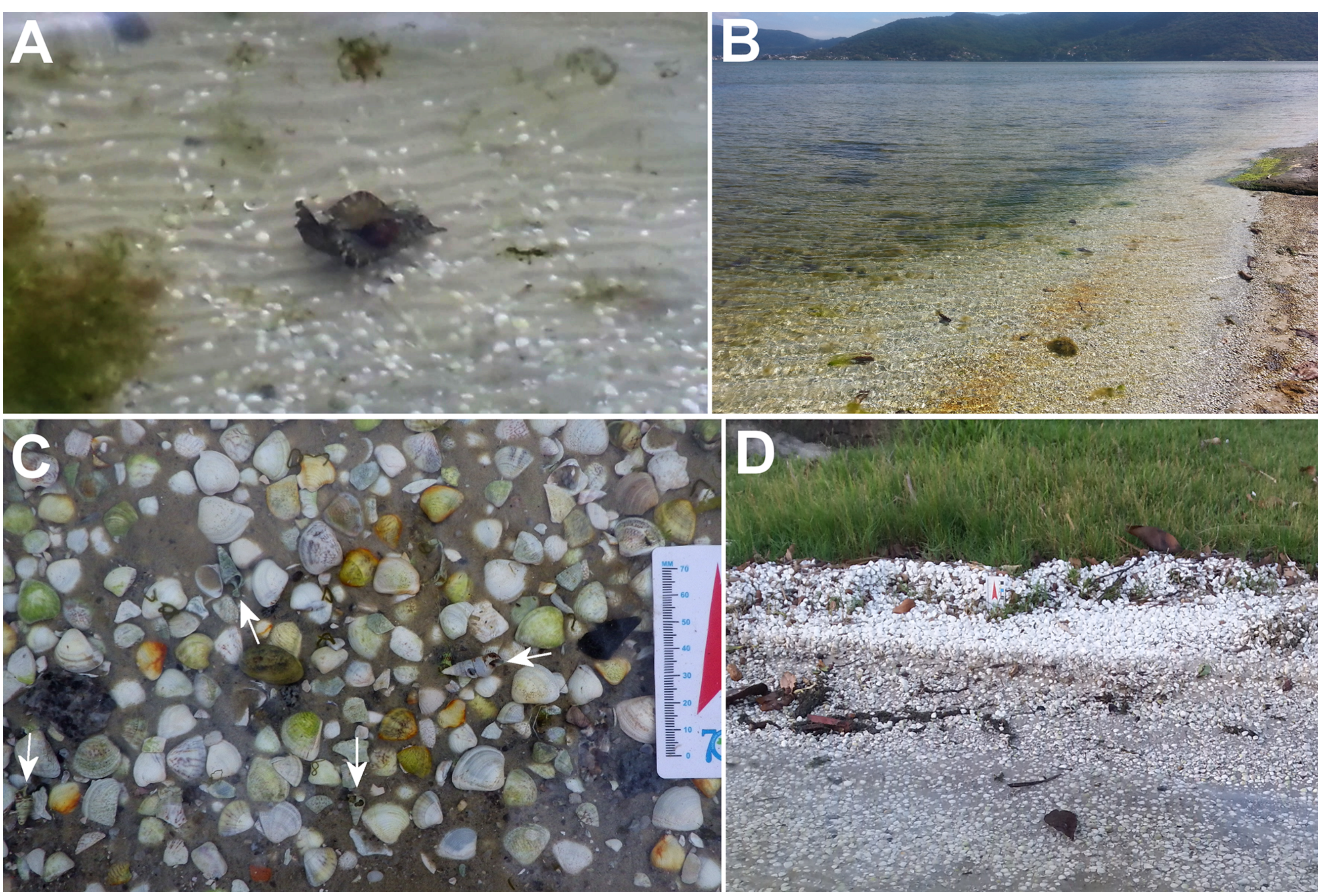

Figure 3. A, linear ripples on the bottom of the study site at Conceição Lagoon (see Video 1 in Supplementary material). **B**, shell pavement at the lagoon shore under fairweather conditions; the wavelet crests oblique to the shoreline indicate a westerly breeze. **C**, detail of the shell pavement showing the dominance of the bivalve *Anomalocardia flexuosa*, with four *Cerithium atratum* indicated by arrows (pointing to the direction the apices are oriented). **D**, shells piled up on the shore above the water line by southerly waves.

Brazil. Kobelt (1898, p. 193) mentioned its distribution up to Argentina, but it is not found living south of Santa Catarina, although putative Pleistocene fossils were found in creeks of the Uruguay River Basin in northern Argentina (Ihering, 1907; Rios, 1994; Gordillo, 1998). It is an epifaunal species found in soft to consolidated substrates, including shelly bottoms (Marcus & Marcus, 1964). It is an herbivore that also feeds on organic detritus; it burrows superficially when not feeding and occupies inter- to subtidal zones in habitats with vegetation and considerable ecological diversity, including sheltered bays, estuaries, seagrass meadows and coral reefs (Marcus & Marcus, 1964; Houbrick, 1974a, b).

The shell of *Cerithium atratum* (Figure 4) is conical-spiral, high-spired (turriform), with an oval aperture parallel to the plane of the coiling axis, flared outer lip, a short siphonal canal reflected to the left, and a columellar plica forms the anal canal. It exhibits surface ornamentation in the form of irregular spiral cords with beads or knobs, more prominent between the middle of the whorl and the suture, and fine spiral striae. The adults exhibit up to 10–13 whorls separated by moderately defined sutures, and a ventrolateral varix may be present in the last whorl opposite to the outer lip and also along the spire (Marcus & Marcus, 1964; Houbrick, 1974B; Sälgeback & Savazzi, 2006). The shell microstructure does not differ among species of the same genus, and thus, the shell of *C. atratum* probably is formed of an outer calcitic layer and a denser inner aragonitic layer (Gunduz *et al.*, 2014; Marin, 2020).

The shells of *Cerithium atratum* presented in this study were hand-picked from the shell deposits at the portion of the lagoon shore shown in Figure 3 between March 2018 and January 2019. The collected specimens exhibited a distinct pattern of abrasion characterized by loss of the shell wall, seemingly proceeding anteroposteriorly from the last whorl toward the apex (Figure 5). To obtain as many specimens as possible and better characterize the distribution of abrasion features, the site was visited multiple times, and during each visit, all shells of *C. atratum* found at the water line along a ~3 m-wide strip were collected. A total of 53 shells were found, six of these being incomplete. Most specimens exhibit signs of abrasion on the shell wall around the whorls.

To evaluate whether the apparent pattern of abrasion was coherent among the available specimens, the distribution of abrasion features was mapped by counting the position and number of abraded whorls along each shell. To assess a possible relationship between the shell dimensions and the observed abrasion features, measurements of the maximum length and width (across the last whorl) of the specimens were taken with a digital caliper with a precision of 0.01 mm.

The observed distribution of abrasion features raised the question of whether the pattern could be explained by Aristotle's 'Wheel Paradox': analogous to the wheels of unequal diameters described in the *Mechanica*, the conical shells of *Cerithium atratum* exhibit whorls of unequal diameters, therefore as they were moved across the lagoon bottom by waves or currents, the whorls could have been abraded to varying degrees. A simple experiment was designed

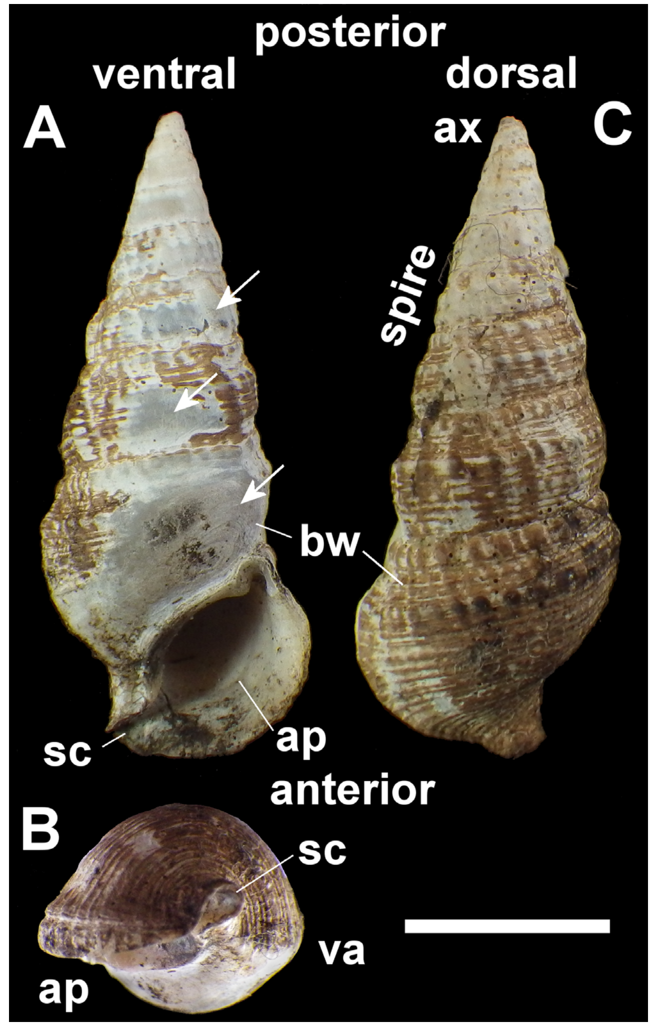

Figure 4. Shell of *Cerithium atratum* from Conceição Lagoon in ventral (**A**), anterior (**B**), and dorsal (**C**) views. The arrows indicate areas smoothed by abrasion. **Abbreviations: ap**, aperture; **ax**, apex; **bw**, body (or last) whorl; **sc**, siphonal canal; **va**, varix. Scale bar = 10 mm.

to test whether the shell motion under the hydrodynamic conditions observed at the lagoon shore could have originated the abrasion pattern. Linear ripples (Figure 3A, Video 1 in Supplementary material) form in low hydrodynamics settings in response to wave-generated oscillating flows reaching the bottom, being symmetrical where waves dominate over currents and asymmetrical where currents are stronger and thus cause the ripples to migrate (Kelling & Williams, 1967; Harms, 1969; Komar, 1974, Allen, 1982).

To simulate the wave-generated oscillating flow observed at the lagoon under fairweather conditions, a rectangular acrylic box measuring 20 cm in length, 10 cm in width and 8 cm in height (Figure 6A) was partially filled with a 1 cm-thick layer of fine sand and ~2.5 cm of water, and the sediment was left to settle. For the experiments, the box was equilibrated across its middle point on top of a 20 cm-long and 1.95 cm-high half plastic pipe cut longitudinally and placed in a concave-down position. The box was manually tilted in the vertical plane by ~10-12° in a seesaw movement to produce a single wave that propagated along the box until it was reflected on the other end and returned in the opposing direction, thus generating a bi-directional flow. A digital camera was mounted on a tripod facing down the interior of the open box to record the shell movements for analysis.

For the experimental procedures, one complete shell of *Cerithium atratum* was filled with water using a syringe to avoid fluctuation effects caused by air trapped inside the whorls and then placed on the bottom at the middle of the box. Two experimental procedures were performed: in experiment #1 the shell was placed directly on the fine sand bottom (Figure 6B), and in experiment #2 the sand was covered with concave-down valves of *Anomalocardia flexuosa* collected at the shore of Conceição Lagoon to simulate the shell pavements (Figure 6C). Each experiment consisted of subjecting the shell to bidirectional water flow starting from left to right by manually tilting the box on the vertical plane for thirty seconds. For each experiment, three tests were performed to assess whether the shell orientation relative to the water flow could affect its motion. One test started with the shell placed perpendicular to the flow, whereas the other two were made with the shell oriented parallel to the flow. One of the latter was initiated with the last whorl pointing toward the initial flow direction and the other with the last whorl pointing in the opposite direction. Each test was repeated three times to assess possible variations in shell response to the flow.

Figure 5. Shells of *Cerithium atratum* from Conceição Lagoon in ventral view showing the pattern of abrasive loss of the shell wall. The first shell from left to right exhibits the bioerosion traces *Entobia* isp. Scale bar = 10 mm.

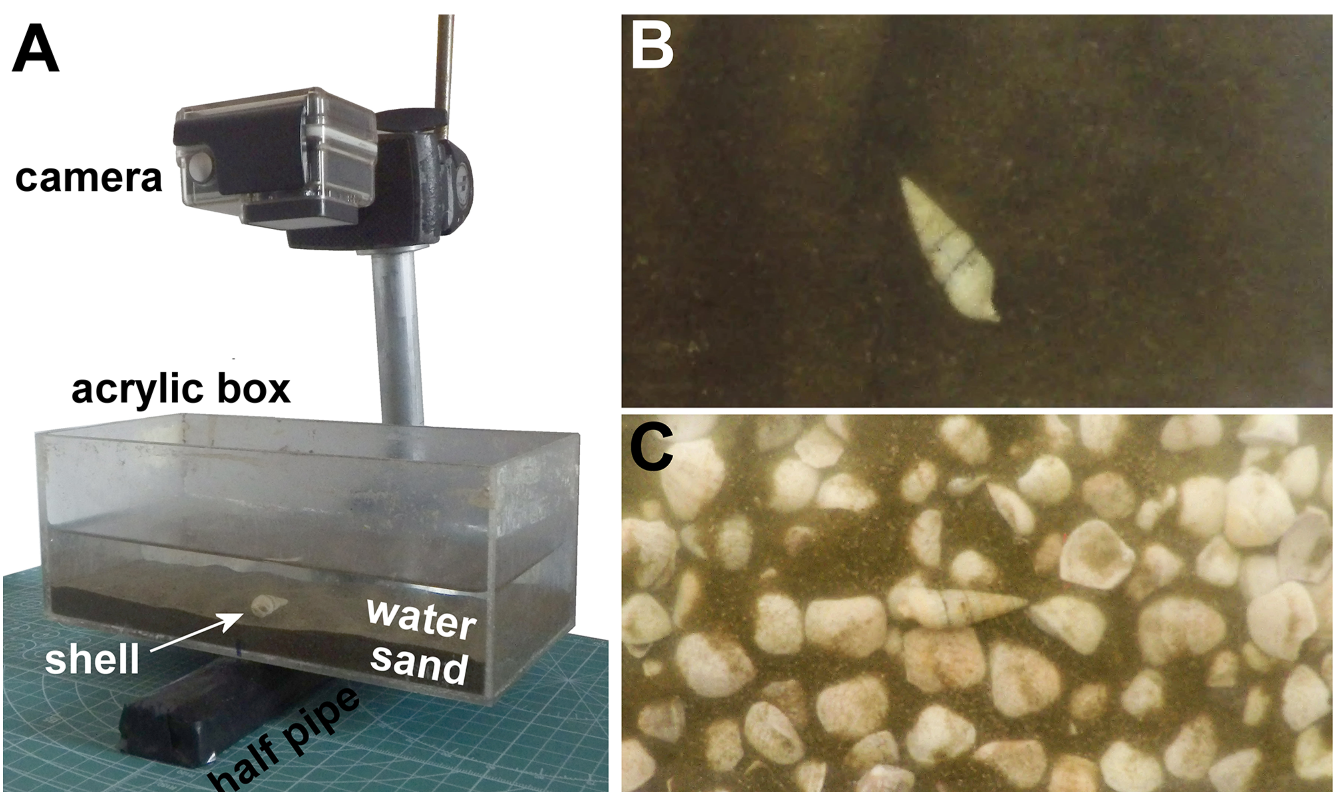

Figure 6. A, structure mounted for hydrodynamic experiments. **B**, experiment on the sand bottom. **C**, experiment on the shelly sand bottom.

RESULTS

Taphonomic features

According to the distribution of abrasion features (Figure 5) the shell wall around the whorls seems to have been lost sequentially in stages. The better-preserved specimens exhibit signs of abrasion in the form of smooth facets without ornamentation in some areas of the shell, as the specimen in Figure 4 that shows such facets on the ventral side but not on the dorsum. More abraded specimens exhibit subcircular to subelliptical holes with smooth margins in the last whorl and along the whorls of the spire, characteristic of mechanical abrasion (Gorzelak *et al.*, 2013). The most advanced stages of abrasion are characterized by the total loss of the shell wall, exposing the columella (Figure 5). All abraded specimens exhibit holes on the last whorl; on the other hand, no specimens with abraded spire whorls and unabraded last whorl were observed. Moreover, the last whorl is partial to totally lost in specimens with more extensive abrasion features (Figure 5). These patterns suggest that abrasion started at the last whorl and proceeded sequentially toward the shell apex.

Based on the distribution of the abrasion features along the shells, it was possible to recognize a succession of eight stages of abrasion (Figure 7A), numbered sequentially starting from 0 (no or minor abrasion, as in Figure 4). Stage 1 was defined as abrasion of the last whorl alone, and the successive stages were numbered according to the last abraded whorl along the spire; the most advanced stage recorded was 7, which included the partial or total exposure of the columella (as the specimen on the far right of Figure 5). Only three specimens belong to stage 0, and the highest proportion of abraded specimens (29.8%) belong to stage 1 (Figure 7B). Only two specimens, belonging to stages 5 and 7, exhibit the last abraded whorl preceded by one and two unabraded whorls, respectively.

The abrasion holes are usually located on one side of the last whorl in earlier stages, although holes on opposite sides were observed (Figure 5). The holes on different whorls may be located on different sides of the shell, and in some cases, more than one hole is present in the same whorl (see, for example, the fifth shell in Figure 5). The shell dimensions exhibit considerable dispersion, consistent with the morphological variation of the species (Marcus & Marcus, 1964; Houbrick, 1974b). Although adults can attain lengths of up to 50 mm, and the largest specimens found in southwestern Brazil (São Paulo State) measured 38 mm (Marcus & Marcus, 1964; Houbrick, 1974b), the length of the specimens reached from 18.78 to 29.78 mm, and the diameters (measured across the last whorl) ranged from 7.28 to 11.56 mm (Figure 7C), corresponding to fine (4–8 mm) to medium (8–16 mm) pebbles according to the Udden-Wentworth classification (Wentworth, 1922). The adults of this species exhibit up to 10–13 whorls (Houbrick, 1974b), but no specimen found at Conceição Lagoon had more than eight whorls. These features suggest stressing environmental conditions that limit the size of the individuals (Jackson, 1972) or that larger adults inhabit deeper areas of the lagoon (Houbrick, 1974a) and are not found at the shore. Most specimens belong to the 22–24 and 24–26 mm size classes (Figure 7D). No clear relationship between the abrasion stage and shell length was observed, although larger size classes exhibit mostly abrasion stages 1 to 3 (Figure 7E).

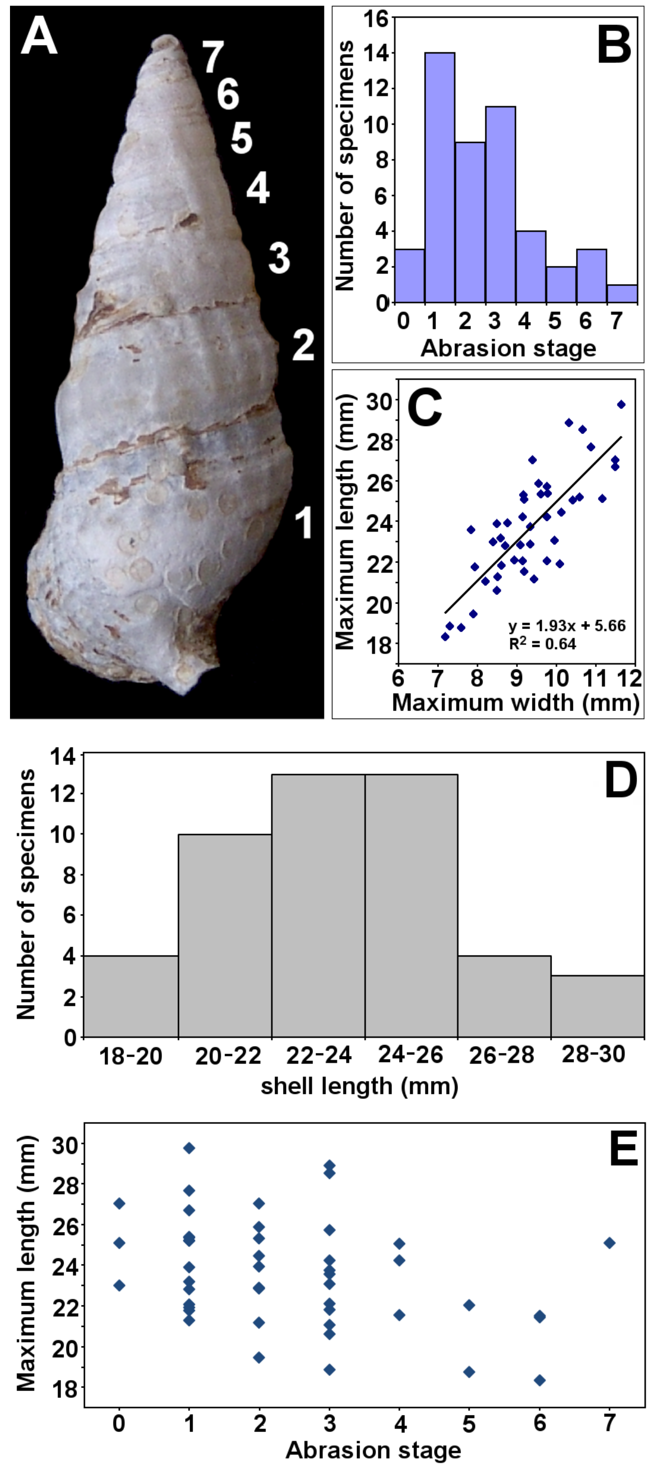

Figure 7. A, stages of abrasion numbered according to the last abraded shell whorl. **B**, number of specimens relative to abrasion stages. **C**, length and width of the specimens. **D**, size-class distribution of the studied specimens. **E**, distribution of abrasion stages according to shell lengths.

Other taphonomic modifications include the loss of periostracum in most of the specimens, possibly with the contribution of chemical corrosion during early stages of biostratinomic modification, as indicated by the presence of ornamentation in white-colored specimens (see the first two shells in Figure 5), followed by removal of fine ornamentation by mechanical processes in more advanced stages. Eight specimens exhibit borings of the ichnogenus *Entobia* (as in the first shell in Figure 5), and one has incrusted barnacles.

Hydrodynamic experiments

The vertical tilting of the box produced a wave that propagated back and forth across the box, simulating the conditions at the lagoon shore reasonably well, as indicated by the resulting sedimentary structures like those observed *in situ* at the lagoon bottom (see Figure 3A). Shortly after the start of the bidirectional water flow, linear, sinuous symmetrical ripples with concave to slightly convex-sided crests oriented perpendicular to the direction of wave propagation (Figures 8A–B), measuring 2–6 mm in amplitude and 20–40 mm between crests, began to form.

In all three tests made for each experiment, with the shell oriented either perpendicular or parallel to the flow, its response in terms of motion was essentially the same. The wave-generated current hit the shell from opposite directions every ~0.6 seconds, causing it to describe two circular movements: rolling around the coiling (long) axis on the vertical plane, facilitated by its circular cross-section (Figure 4B) and rotating around the apical or distal part of the shell (*S*) on the horizontal plane, thus causing broader movements of the last whorl relative to the apex. Because of the counter movement generated by the reflected wave, the shell did not describe complete rotations or remained stable with a preferential orientation but oscillated back and forth in a pendulum movement describing arc segments that reached maximum amplitudes ≥ 90° (Figures 8C–E). Regardless of the initial orientation (with the last whorl or apex pointing toward the initial wave direction) of the shell placed parallel to the wave propagation, it always started to oscillate when the wave hit the anterior end, probably because of the larger surface area of the last whorl relative to the shell apex.

Although the same movements were observed in the two experiments, the bottom types affected the overall shell response. At the beginning of experiment #1, the sandy bottom was flat and thus allowed for a wider rotation (Figure 8C, see Video 2 in Supplementary material) and more significant displacement (*v*) of the apex. As wave-generated ripples began to form, the shell became trapped in troughs between crests, thus limiting the amplitude of movement and resulting in minimal axis displacement (Figure 8D, see Video 3 in Supplementary material).

In experiment #2, the shell was subject to the same rolling-rotation movements (Figure 8E), but the bivalve shells on the bottom limited the generation of ripples. The concave-down valves created smooth and convex irregularities that allowed for a broader range of shell movement, including full 360° rotation in steps (see Video 4 in Supplementary material) and rotation of both the last whorl and apex, resulting in

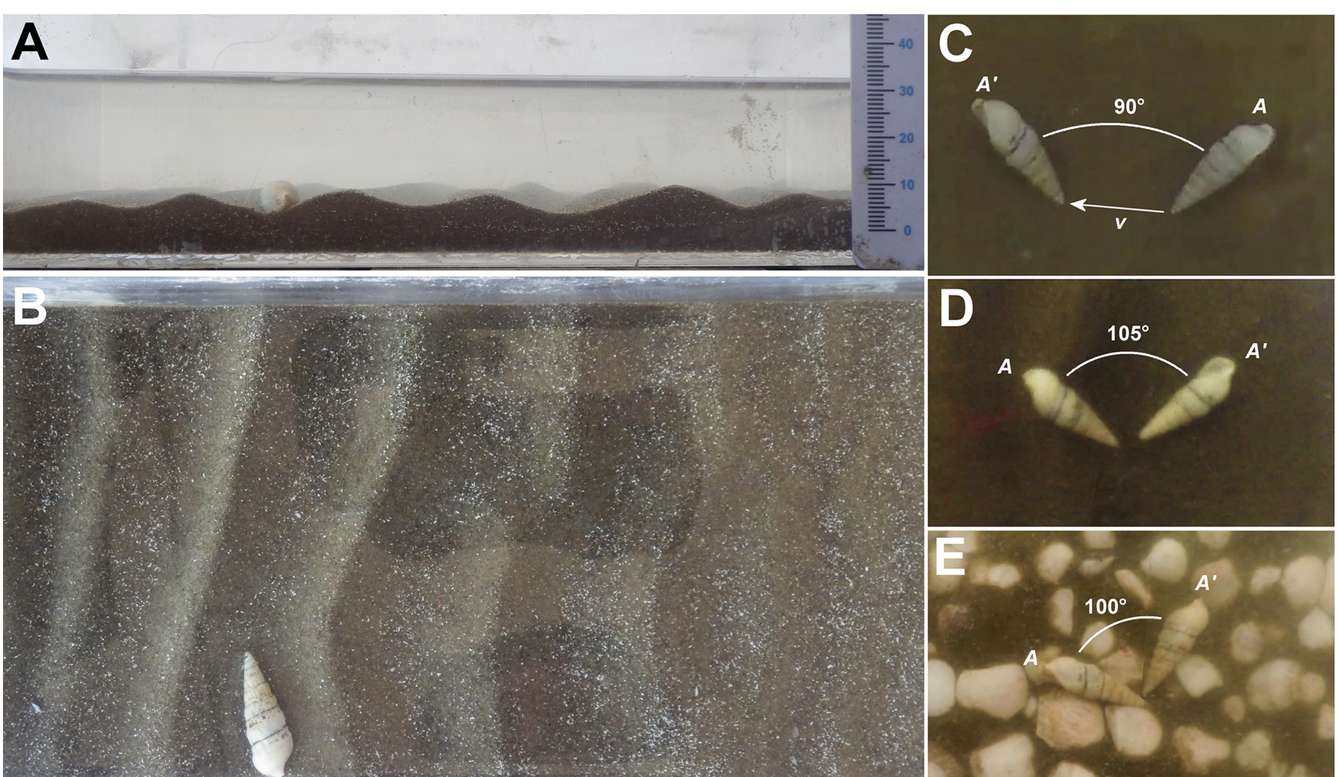

Figure 8. A-B, sinuous linear ripples formed on the sandy bottom during the experiment. Montage of video stills showing the angular rotation of the shell of *Cerithium atratum* within one oscillation cycle on a flat sand bottom (**C**), sand bottom with ripples (**D**), and shelly sand bottom (**E**).

more significant horizontal displacement and 'wandering' across the bottom (see Video 5 in Supplementary material). On the other hand, the depressions between the valves acted as obstacles that restricted the movement/displacement or trapped the *Cerithium atratum* in place in one test (see Video 6 in Supplementary material).

DISCUSSION

Skeletal remains behave as sedimentary particles during and after transitioning from the biosphere to the lithosphere, but due to their highly varied forms compared to inorganic minerals or rock grains, those remains exhibit more variable behavior when subject to flows. The overall response of skeletal remains to physical processes depends much on their form, composition, density, size, weight, and fluid properties. The recognition of the effects of flow conditions on the movement of shells and resulting taphonomic features that can be understood in terms of Aristotle's 'Wheel Paradox' may provide a valuable tool for interpreting biostratinomic modifications and hydrodynamic conditions of the depositional environment.

The abrasion process

Biostratinomic processes that affect skeletal remains are divided into those that modify the relationship between remains of the assemblage (orientation, articulation) and those that physically modify the remains, including mechanical abrasion (Parsons & Brett, 1992). Abrasion is a feature present in different skeletal remains of both vertebrate and invertebrate organisms subject to waves and currents in shallow settings, produced by the impact of remains against each other or the substrate or by the effect of the suspended particles in the water (sandblasting). However, the latter has no or minimal abrasive effect on particles smaller than cobbles (64–256 mm) and subject to current velocities > 70–80 cm*s^{-1} (Kuenen, 1955; Chave, 1964; Behrensmeyer, 1991; Parsons & Brett, 1992). In fluvial environments, bivalves remain stable (concave-down) in a current-dominated setting and suffer in-place abrasion on the umbonal area pointing upcurrent (Newell *et al*., 2007). The abrasion concentrated on the exposed parts of *Cerithium bidentatum* Defrance, 1832 spires found half-buried on the sandy bottom of coastal channels described by Tauber (1942; pl. XIV, fig. 9) was attributed to sandblasting. On the other hand, in particles/shells that are moved or transported by uni- or bi-directional flows (as in the case of *C. atratum* from Conceição Lagoon), abrasion is more evenly distributed around the particle and classified as progressive (Brewer & Lewin, 1993).

Abrasion of shells is a diagnostic of tumbling and wearing in high-energy settings where the shells are constantly moved (Dodd & Stanton, 1981; Cutler, 1995). According to Kuenen (1956), the abrasion process involves seven actions (splitting, crushing, chipping, cracking, grinding, chemical attack, and sandblasting) whose influence differs between sandy or pebbly substrates. Considering the bottom of Conceição Lagoon at the study site, composed of fine to very fine sand, with shell pavements along the shoreline, the abrasion of *Cerithium atratum* probably results from grinding and chipping. Grinding is the loss of material in particles rubbing against sandy bottoms. It is foremost responsible for shell breakdown and production of fine-sized (< 63 µm) carbonate sediments, although under similar hydrodynamic regimes the abrasion on well-sorted and fine sand proceeds at lower rates than in poorly sorted/coarse/very fine sand or pebbly bottoms (Chave, 1960, 1964; Force, 1969). In coarse sand bottoms, abrasion is caused by larger grains in contact with the shell, whereas in very fine sand, it results from the more significant number of particles in contact (Driscoll & Weltin, 1973). Quartz sand produces abrasion on particles faster than carbonate sand (Mitchell-Tapping, 1980).

Chipping is the loss of particle mass caused by impacts with larger pebbles. In the studied material, chipping would have resulted from effects with the concave-down valves of *Anomalocardia flexuosa* at the lagoon shore (Figure 3C). The irregular outline of holes on the last whorl (as in the second shell in Figure 5) suggest that chipping also contributed for mechanical destruction of the shell wall. In cases where the *Cerithium atratum* becomes 'locked' between valves (see Video 6 in Supplementary material), thus limiting its rotation, chipping could have increased due to more frequent hits against the valves, and abrasion would be concentrated on the parts in direct contact with the valves (thus characterized as in-place abrasion). Although chipping is more efficient than grinding, its abrasive effect can be reduced by 10–15% if sand is also present between larger pebbles (Kuenen, 1956).

The grinding and chipping result from the characteristics of the substrate over which the shell is moved. How the shell is affected by these actions also depends on its behavior when moved by wave- or current-induced flows, which in turn varies according to the form of the shell. Under bidirectional flows, conical turriform shells tend to oscillate with the growth axis parallel to the flow direction (Nagle, 1967). The movement produces two modifications on the shell surfaces (Müller, 1979): polishing is the loss of periostracum and fine ornamentation on the whole shell, whereas roll-faceting is characterized by the polishing on one side of the shell by the constant movement against the bottom, and the location of facets depends on the form of the shell and type of abrasive medium. In the studied specimens, both modifications seem to have acted, although the loss of ornamentation and periostracum (see Figures 5 and 9A), which was also observed in several valves of *Anomalocardia flexuosa* (Figure 3C), could have been influenced by chemical corrosion. This process is the primary destructive process in shells below the water-sediment interface (Driscoll, 1970), but in the case of the shells exposed on the bottom at Conceição Lagoon, it could result from changes in pH related to freshwater inputs. The loss of periostracum and the development of a chalky surface texture occurs very early in the process of shell dissolution in cerithid gastropods (Flessa & Brown, 1983).

The negligible sediment in suspension or accumulated on top of the pavements (Figures 3B–C) implies low rates of burial, thus exposing the *Cerithium atratum* for long periods on the benthic taphonomically active zone (TAZ) where biostratinomic processes are more active (Driscoll, 1970; Davies *et al*., 1989). Studies have shown that single events such as hurricanes do not produce discernible taphonomic features on shell remains other than breakage (Davies *et al*., 1989). Therefore, the abrasion patterns are unlikely to have been produced by the storm events that affect the lagoon shore episodically (Figure 3D), resulting from hydrodynamics under prevailing fairweather conditions instead.

Although it is not possible to estimate rates of abrasion from the collected specimens, it could have started during the short (~1 year) lifetime of the individuals because of the burrowing habit of *Cerithium atratum* (Marcus & Marcus, 1969; Houbrick, 1974a), would have increased the rubbing of the shell against the substrate. Initial abrasion could also have resulted from occasional rubbing against the sand bottom during locomotion, when its long turriform shell remains at a low angle relative to the substrate because its coiling axis is lowered relative to the foot, with the gravity center located on its anterior portion (Ponder *et al*., 2019, p. 64). Although long-spired gastropods are usually 'shell-draggers', *i.e*., carry the shell with the spire resting on the substrate (the 'Third Law' of Linsley, 1977), the radial aperture of *C. atratum* (Figure 4B) allows it to hold the shell above the substrate (Linsley, 1978). Burrowing and locomotion could explain the incipient signs of abrasion represented by the smooth facets devoid of periostracum and ornamentation on the ventral side of the shell illustrated in Figure 4.

The mechanical behavior of *Cerithium atratum*

The experiments presented here show that the turriform conispiral shell of *Cerithium atratum* describes a pendulum movement under wave-generated bidirectional flows. However, the period and amplitude of the shell oscillations in the natural environment are more variable according to changes in hydrodynamic conditions. Moreover, the differences in shell motion recorded in substrates of flat sand (Figure 8C, Video 2 in Supplementary material), sand with ripples (Figure 8D, Video 3 in Supplementary material), and sand with shells (Figure 8E, Videos 4–6 in Supplementary material) show that the characteristics of the bottom also affect the orientation of the shells relative to the flow direction, as exemplified by the *C. atratum* with apices pointing on different directions (Figure 3C), and probably influence the rates and extent of the resulting shell modifications.

The shell of *Cerithium atratum* is conispiral as a result of exponential growth (Rice, 1998) with a circular cross-section (Figure 4B) and on a soft sandy bottom such as in Conceição Lagoon, all points along the shell, except the narrower anteriormost part of the last whorl around the siphonal canal

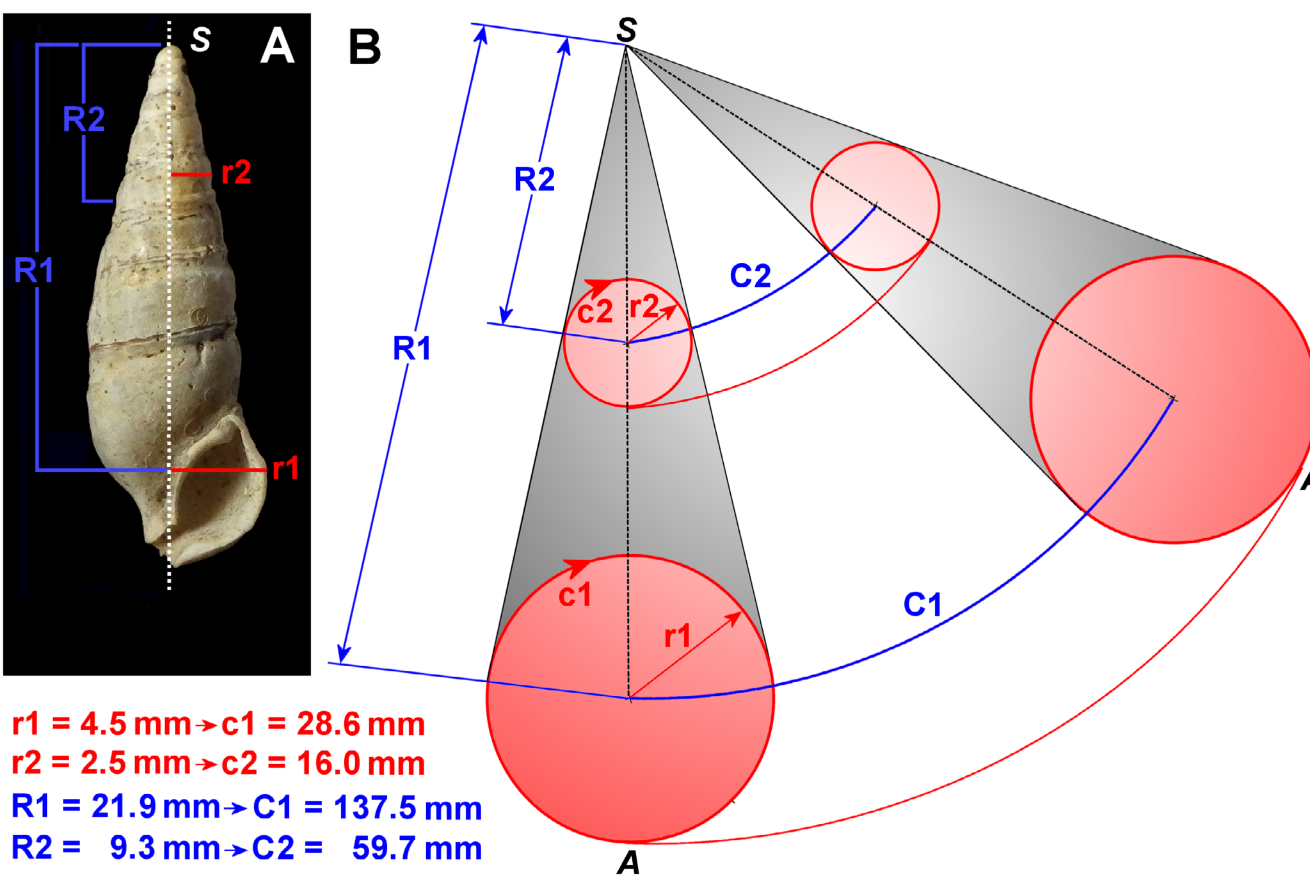

Figure 9. A, the shell of *Cerithium atratum* used in the experiment showing the measured radii of the growth axis (**R1**, **R2**), last whorl (**r1**), and 4th whorl (**r2**) used to calculate the respective circumferences (**C1**, **C2** and **c1**, **c2**). **B**, Geometry of the movements described by a 60° rotation of the shell from A to A' and rolling of the whorls. Scale bar = 10 mm.

(Figure 4A), contact the substrate as it is rotated and rolled by oscillatory flows. During movement, all whorls hit the bottom simultaneously and the same number of times, and thus should be abraded to the same degree, except if gases from decomposition are trapped inside the whorls, increasing the shell buoyancy, and reducing its contact with the bottom (Brenchley & Newall, 1970). The abrasion, however, is not uniform between whorls in the studied specimens but seems to develop in a sequence, initially as small holes on the shell wall that become enlarged, starting at the last whorl, and proceeding along the spire whorls toward the apex (see Figure 5), thus indicating other influencing factors. The abrasion rates are influenced by the microstructure of the skeletal remains (Chave, 1960; Driscoll, 1967; Dodd & Stanton, 1981), but as the phylogenetically constrained microstructure of mollusk shells is essentially the same at the genus level (Marin, 2020), this feature probably does not explain the observed differential abrasion.

The progressive and sequential pattern of abrasion recorded in shells of *Cerithium atratum* seems to be consistent with Aristotle's 'Wheel Paradox' principle. The combination of shell shape and bidirectional flow causes the shell to rub against the substrate and become abraded, initially at the last whorl because of its larger diameter. This process can be understood in terms of the relationship between the radius/diameter and circumference of different shell whorls, analogous to the wheels or particles of different diameters described in Problem 24 of the *Mechanica*.

Flowing water causes the shells to describe two circular movements: rolling vertically around the long axis and rotating horizontally around the apex. As exemplified by the specimen used in the experiments (Figure 9A), the geometric shape of *Cerithium atratum* can be described ideally as a cone; therefore, cross sections (slices) taken at different parts of the shell consist of a series of circles that increase in radius/diameter toward the last whorl (Figure 9B). Considering the shell lying horizontally on the bottom, the flowing water causes the whorls to roll on the vertical plane. During each complete roll, the last whorl with a radius r1 measuring 4.5 mm describes a circle c1 measuring 28.6 mm in circumference ($C=2*\pi*r$). For comparison, the 4th whorl, with a radius r2 = 2.5 mm, describes a c2 circle with 16.0 mm in circumference. Therefore, when c2 rolls one full turn, c1 completes a turn along a circumference that is 3.5 times longer. Because all whorls are interconnected, they roll at the same angular rate (degrees per time unit), but the wider whorls describe longer circumferences than the narrower ones. This makes the anterior whorls roll faster and thus should overtake the posterior ones, but because all whorls are connected along the growth axis, this results in a horizontal circular motion (rotation).

As shown in the experiments on the sand substrate, the bidirectional flow caused the shell to oscillate cyclically, moving back and forth as a pendulum centered on the shell apex (Figures 8C–D). This rotation then can be understood as a series of arc segments of different lengths described by the whorls according to the increase in their radiuses relative to the apex. If the shell rotates 60° during one oscillation cycle from the point A to A' (Figure 9B), the arc segment C1 described by the last whorl measures 22.9 mm in length, whereas the arc C2 described by the 4th whorl is only 9.9 mm-long, or 2.3 times shorter than C1. This relationship implies that the wider anterior whorls roll and rotate at faster angular velocities (but at the same angular rates) than the posterior narrower whorls and thus hit the substrate with stronger force than the latter, as proposed in Problem 15 of the *Mechanica*. The stronger hits would result in higher abrasion rates on the anterior whorls, as demonstrated experimentally with inorganic pebbles of different diameters (Daubrée, 1879; Krumbein, 1941; Kuenen, 1956; Pettijohn, 1957; Force, 1969). As the shell is continuously moved by flowing water, the abrasive destruction of the whorls would progress anteroposteriorly until the columella is exposed (Figure 5). Although this exposure can result from both chemical (dissolution) and mechanical (abrasion) processes (Flessa & Brown, 1983), the sequential destruction of shell wall and low degree of chemical dissolution recorded in *Cerithium atratum* indicates mechanical destruction as the leading cause. A similar pattern of abrasion on turriform gastropods (see below) but proceeding in the opposite direction (from the apex to the last whorl) was described by Tauber (1942).

In his *Dialogues* (1638), Galileo attempted to explain Aristotle's 'Wheel Paradox' by considering the two wheels connected by an axle as polygons with an infinite number of sides (Figure 10A). The fact that the two polygons describe lines of the same length and at the same time as they are rolled over a plane despite their different sizes, was explained as the line formed by the larger polygon consisting of an infinite number of points in a continuum, because all sides contacted the plane. The sides of the smaller polygon, on the other hand, 'jumped' to keep in pace with the larger polygon, and thus, not all sides touched the plane, producing a line formed of an infinite number of points intercalated by an infinite number of spaces. This explanation, however, considers the trajectory described by the wheels/polygons as straight lines (as in Problem 24 of the *Mechanica*). The experiments presented here show that if both wheels/polygons (in this case, the shell whorls) are connected, they will rotate around a common center (analogous to the shell apex) instead of describing straight lines. At the same time the larger one describes a wider arch segment at a higher angular velocity, the smaller wheel/polygon describes a shorter trajectory at a lower velocity, thus keeping in pace, and both wheels/polygons will produce lines formed of a continuum of points.

Influence on other skeletal remains

The results presented here indicate that the abrasion pattern on shells may depend largely on the interaction between their forms and the hydrodynamic fluxes (uni- or bidirectional, wave- or current-dominated). Shells with similar forms are likely to behave similarly under the same types of flow and thus exhibit similar abrasion features produced by motion. If, however, differences in abrasion are observed among specimens, this could indicate exposure to different

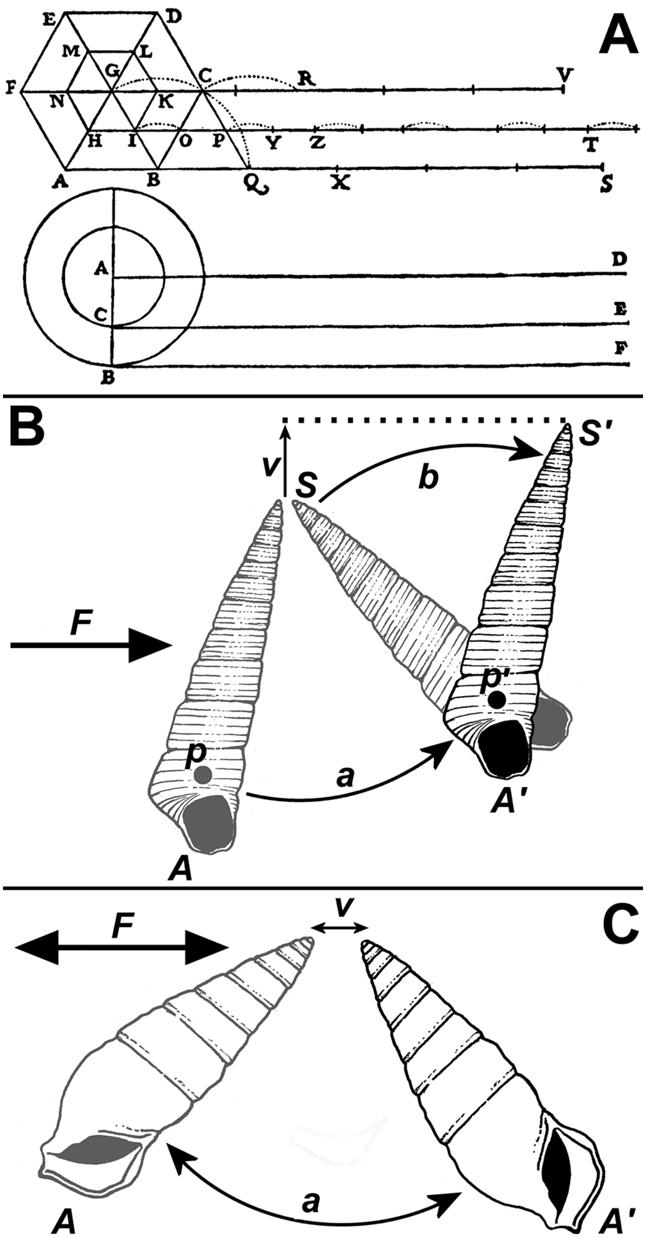

Figure 10. A, interpretation of Aristotle's 'Wheel Paradox' from Galilei's *Dialogues* (1638), using two polygons (on top) instead of wheels (shown below). **B**, movement of *Turritella* subject to current-generated unidirectional flow (*F*), according to Tauber (1942). **C**, movement of *Cerithium atratum* under wave-generated oscillating flow (*F*). **Abbreviations:** ***a***, trajectory of the gravity center of the shell; ***b***, trajectory of the apex.

types of flow. Tauber (1942) described the movement of shells of the conispiral gastropod *Turritella* on the sandy bottom of a channel subject to current-generated unidirectional flow (Figure 10B) as an alternate rotation *a* of the gravity center *p* close to the last whorl around the apex, followed by a rotation *b* of the apex around *p'* as the shell moves horizontally downcurrent, with a perpendicular component *v*. This movement caused abrasion to begin at the apical region and proceed toward the last whorl, because of the longer distances traveled by the spire compared to the last whorl as the shells were rotated. The abrasion of the apical region, however, could also have started by shell rubbing during locomotion of the living animal because the long-spired *Turritella* is a 'shell-dragger' (Ponder *et al.*, 2019, p. 64), as it lacks the radial aperture parallel to the coiling axis as in *Cerithium* (Figure 4B), which allows the latter to hold the shell above the substratum (Linsley, 1977; 1978).

As the oscillatory movement of shells of *Cerithium atratum* described in this study (Figure 10C) results from bidirectional flow, it is not possible to evaluate if *Turritella* behaves equally under the same conditions (and thus would exhibit similar abrasion patterns). Nevertheless, as the principle of Aristotle's 'Wheel Paradox' depends on variations in diameter along the shells, the similar shapes of both species suggest that this might be so. The experiment focused on the conispiral turriform shells of *C. atratum* but leaves the question of how gastropods with distinct shell forms will respond to similar flows and thus exhibit abrasion patterns compatible with the 'Wheel Paradox.'

Gastropod shells exhibit a wide range of morphologies, ranging from globose to elongated, with spires of variable lengths, from short naticoid to long turriform, as defined by the pleural and apical angles and growth rates (Easton, 1960; Ponder *et al.*, 2019). Differences in growth rates among species result in shells with whorls that do not change in diameter uniformly, as in conispiral turriform shells of *Cerithium* or *Turritella* that grow exponentially (Rice, 1998). This implies that other shells may be influenced by the 'Wheel Paradox' differently, as they would exhibit distinct behaviors in response to hydrodynamic conditions due to differences in the shell form.

Some inferences about the possible influence of Aristotle's 'Wheel Paradox' on other types of shells can be drawn from recent to subfossil specimens (Figure 11) collected at Cassino Beach, in the State of Rio Grande do Sul, about 590 km south of the Island of Santa Catarina. Cassino Beach is an open beach with a soft bottom of fine sand and a wave-dominated, high-energy environment. The shells were collected among the debris left above the mean water line by storm waves. They included low-spired (obconical) species of *Pachycymbiola* (Figure 11A), *Zidona* (Figure 11B), *Olivancillaria* (Figures 11C–D), and high-spired *Buccinanops* (Figure 11E). Except for two species that inhabit deeper areas, *P. brasiliana* (25–77 m) and *Z. dufresnei* (15–175 m), the others are common in shallower depths from 0 up to ~20 m (Rios, 1994).

The shells from Cassino Beach exhibit subcircular to elliptical holes with smooth to irregular margins on the wider last whorl, similar to those in *Cerithium atratum*, that can be attributed to abrasion by grinding (Gorzelak *et al.*, 2013), although the more irregular margins in *Pachycymbiola brasiliana* (Figure 11A) and *Zidona dufresnei* (Figure 11B) indicate also chipping by mechanical impacts. In the shells of *Z. dufresnei* (Figure 11B1) and the *Olivancillaria* (Figures 11C–D) the abrasion holes are of limited extent, possibly because their shells are thicker relative to *P. brasiliana* (Figure 11A) and several *B. cochlidium* (Figure 11E1–3) that exhibit much larger holes on different sides and have larger surface areas relative to the volume (Driscoll & Weltin, 1973).

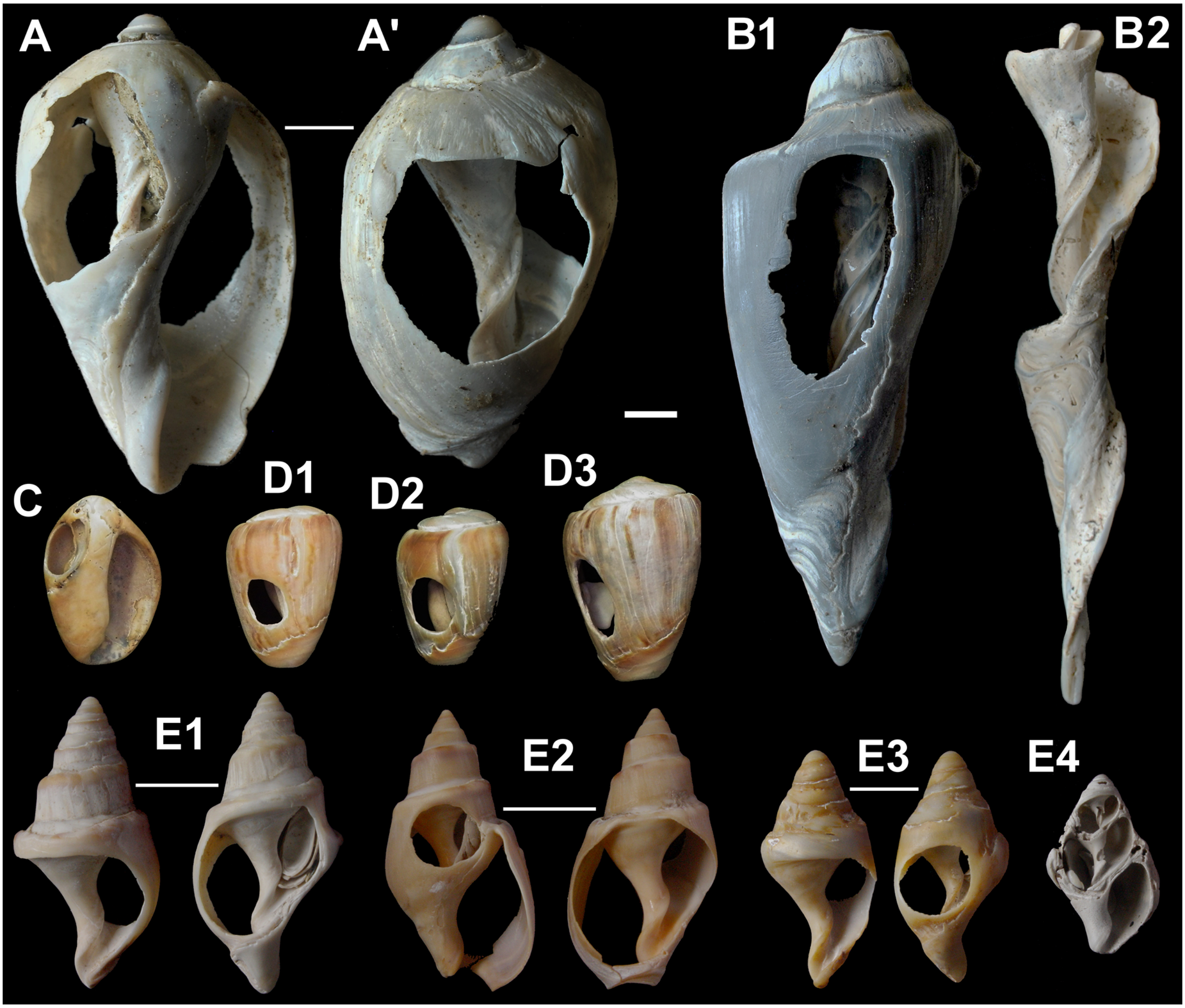

Figure 11. Recent shells of gastropods from Cassino Beach showing variable degrees of shell wall loss by abrasion. **A**, *Pachycymbiola brasiliana* (Lamarck, 1811); **B**, *Zidona dufresnei* (Donovan, 1823); **C**, *Olivancillaria* cf. *carcellesi* Klappenbach, 1965; **D**, *Olivancillaria urceus* (Röding, 1798); **E**, *Buccinanops cochlidium* (Dillwyn, 1817). Scale bar = 10 mm.

Despite some differences between the sampled species (Figure 11), the abrasion patterns seem consistent with the stage 1 observed in *Cerithium atratum* related to the 'Wheel Paradox' principle, *i.e.*, abrasion starting at the wider last whorl. It is likely that as abrasion progressed, the shells would have lost the last whorl (Figure 11E3), followed by abrasion of the spire (Figure 11E4), and culminating in total exposure of the columella (Figure 11B2). According to the principle, these features would be explained by abrasion under oscillatory flows acting on quasi-stationary shells, probably below the base level of fair weather waves until being transported to the beach by storm waves, because if they were rolled constantly in the breaker zone where longshore and onshore wave-generated currents prevail (Reading & Collinson, 1996), the shells would likely have been more evenly abraded. However, the absence of specimens showing intermediate stages and the variable shell forms do not allow to assess whether the 'Wheel Paradox' was the leading influence on the entire abrasion process. Nevertheless, these examples indicate that the principle could explain at least the early and latest stages of abrasion in shells of other species.

As the effects of the 'Wheel Paradox' seem related to the conical form, other similar-shaped types of skeletal parts could be affected by this principle as well. Cylindrical bones of vertebrates such as metacarpals or metatarsals that are rolled by fluvial currents exhibit evenly abraded sides (Hanson, 1980), and this is also observed in elongated vertebral centra moved continuously by waves in shallow marine settings (see fig. 8 in Lopes & Ferigolo, 2015). One fossilized cervical vertebra of a stork from Pleistocene fluvial deposits of the Santa Vitória Alloformation, in the southernmost coastal plain of Rio Grande do Sul, exhibits the wider cranial side more abraded than the narrower caudal side (Lopes *et al.*, 2019). This pattern was attributed to the difference between the wider subelliptical cross section of the cranial end and the subcircular cross section of the caudal end, which results in a subconical geometric form. This would have resulted an irregular rolling movement as the vertebra was transported down current, causing the cranial end to describe longer trajectories, and thus hitting the bottom with greater force, as explained in Problem 15 of the *Mechanica*.

FINAL REMARKS

Most studies using flume experiments have investigated the effects of different current regimes on shells and other skeletal parts as a tool for aiding on paleocurrent analyses from the orientation of fossils in geological records (Ruedemann, 1897; King, 1948; Menard & Boucot, 1951; Krinsley, 1960; Keeling & Williams, 1967; Nagle, 1967; Brenchley & Newall, 1970, Fick *et al*., 2018). However, identifying paleocurrents from shell orientation alone can be challenging (Potter & Pettijohn, 1963). For example, turriform shells parallel to each other but exhibiting bimodal orientation of the apices were attributed to unidirectional currents, which cause the shells to roll perpendicularly relative to the flow direction (Keeling & Williams, 1967). On the other hand, Nagle (1967) observed turriform shells with apices pointed upcurrent when subject to unidirectional flows. Brenchley & Newall (1970) observed in experiments that air trapped close to the aperture causes asymmetrical buoyancy in shells of *Turritella*, which can remain anchored to the bottom by the apex or be transported downcurrent with the anterior end partially floating and the apical end dragging over the substrate. Although Nagle (1967) reported that turriform shells under bidirectional flows tend to remain oscillating with the growth axis aligned parallel to the wave crests, the shells of *Cerithium atratum* pointing in different directions on the shelly bottom (Figure 3C) indicate that obstacles can restrict shell movement (see Video 6 in Supplementary material) and keep them 'locked' at variable orientations relative to the flow direction.

Because of such difficulties, additional paleocurrent indicators, such as primary sedimentary structures, are helpful (King, 1948), but these may not be preserved due to the constant movement of sand and migration of bedforms in shallow settings. In this sense, differential abrasion patterns in shells related to Aristotle's 'Wheel Paradox'principle in response to uni- or bidirectional flow may provide an additional tool for understanding hydrodynamic regimes. If it can be demonstrated that the anteroposterior progressive abrasion observed in *Cerithium atratum* is a common feature in conispiral turriform shells subject to bidirectional currents, then it would be possible to inferflow conditions from an assemblage containing abraded shells. The position of abrasion features on the shell, either anteriorly (as in *C. atratum*) or posteriorly (as in *Turritella*, according to Tauber, 1942) could allow to distinguish between bi- or unidirectional flows, respectively.

The presence of variable degrees of abrasion in shells of an assemblage (Figure 5) may also indicate mixture of individuals that died at different times. It thus can serve to distinguish between 'instantaneous' death assemblages formed of individuals buried at the same time or mass mortalities by catastrophic events and attritional assemblages formed by individuals that lived at different times. Another taphonomic implication of the seemingly progressive abrasive destruction as recorded in *Cerithium atratum* (Figure 5) is that shells with similar forms deposited in similar environmental settings have low preservation potential and are likely to be sub-represented in fossil assemblages, thus affecting inferences about paleocommunity structure and diversity (Lawrence, 1968).

The recognition that rounded to oval holes with irregular outlines localized in specific areas of gastropod shells, as recorded in *Cerithium atratum* (Figure 5) and other species (Figure 11), result from rolling and rotation according to the 'Wheel Paradox' principle can also help distinguish between natural or human-made modifications. Molluscan shells have been used for different purposes, such as tools or ornaments, since the Paleolithic, and both gastropod and bivalve shells with holes found in archaeological sites are usually interpreted as the products of anthropogenic modification (d'Errico *et al*., 2005; Theodoropoulou, 2014; André & Bicho, 2016; Szabó, 2017). There are examples, however, of archaeological shells with abrasion facets or holes produced by natural mechanical processes that were later used by humans (Bar-Yosef Mayer, 2014; Light, 2017). Simple experiments described here can help assess whether holes in archaeological specimens can be assigned to natural or anthropogenic processes, which bears implications on the recognition of ancient people's different technologies and cultural traditions.

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Supplementary material

Video 1: https://youtu.be/-amlcG4M94Q

Video 2: https://youtu.be/OTNLF_FKFBU

Video 3: https://youtu.be/2Ot-86tK4Hg

Video 4: https://youtu.be/MSTgasGxhaY

Video 5: https://youtu.be/wZmmhUuQyxc

Video 6: https://youtu.be/b_ziNtS5WB8

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