In memory of Acad. **Marian-Traian Gomoiu**,
most distinguished biologist and oceanologist.

RAPA WHELK (*RAPANA VENOSA*) TRAILS FROM THE BLACK SEA ROMANIAN INNER SHELF (SE MANGALIA)

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Abstract. The trail of *Rapana* from the Black Sea inner shelf, discussed in this paper, can be used to identify possible traces of this species in more recent deposits than the Upper Miocene. Traces of this type betray the presence of the invasive *Rapana* gastropod, when the animal cannot be observed directly, thus constituting the indirect evidence of the intruder's presence in new marine domains, conquered by active or inactive migration.

Key word: neoichnology, trail, Gastropoda, invasive species, *Rapana venosa*, Black Sea, Romanian inner shelf

1. INTRODUCTION

In the biosphere economy, molluscs are an important component due to the considerable number of over 80,000 current species and as many fossil species (Brusca *et al.*, 2013), starting with Cambrian (Moore *et al.*, 1952). Among these, the Gastropoda class has about 70,000 current species - marine, terrestrial and freshwater - belonging to the subclasses: Prosobranchiata (largely shelled marine snails), Opistobranchiata (marine slugs) and Pulmonata (terrestrial snails and slugs) (Brusca *et al.*, 2013). According to Brusca *et al.* (2013), most carnivorous marine gastropods belong to the superorder Neogastropoda, represented by about 30 families with many current species. Among these, some of the rock snails are of interest for this paper form the Muricidae family (i.e., *Rapana*).

Native species from SE Asia (Japan, China, and Korea adjacent seas), *Rapana venosa* was first reported in the Pontic basin in 1947 (Novorossysky Gulf) by Drapkin (1953, in Snigirov *et al.*, 2013). Subsequently, it quickly colonized the coastal waters of the Black Sea, reaching the Romanian coast in 1963 (Gomoiu, 1972, 2005; Begun *et al.*, 2006; Teacă *et al.*, 2008). Acclimatized in the Black Sea, *Rapana* crosses the Bosporus Strait and reaches the Mediterranean Sea (Grossu, 1986, in Skolka & Gomoiu, 2004).

Present in the ichnocoenosis from the Inchon intertidal zone from South Korea as trace-marker accessory (Frey *et al.*, 1987), *Rapana venosa* was identified as carnivore endobenthic element by Frey *et al.* (1987a). The above mentioned authors presented only crawling trails of *Umbonium thomasi* species (Trochidae Family), somehow similar to the ones produced by *Rapana* (Frey *et al.*, 1987, p. 575)

The Romanian Black Sea coast, without tides, is represented by cliffs and/or exposed beaches and by the permanently submerged area. This ecosystem was poorly studied in terms of neoichnological aspects, the literature recording only the works of Marinescu (1973) and Brustur (1996, 1998). Approaching a wider spectrum of invertebrate and vertebrate traces on the sand of Mamaia beach, Brustur (1996) highlights the role of mucus in the ephemeral preservation of traces produced by the pulmonary gastropod *Helicella candicans*.

In this paper, the bilobated trace produced by the movement of the invasive neogastropod *Rapana venosa* is, for the first time, represented and analysed based on the underwater photographs taken from the north-western sector of the 2 Mai – Vama Veche Marine Reserve (2MVVMR; Fig. 1). Previously, a summary of this investigation was the subject of an unpublished communication (Brustur & Bălan, 2008).

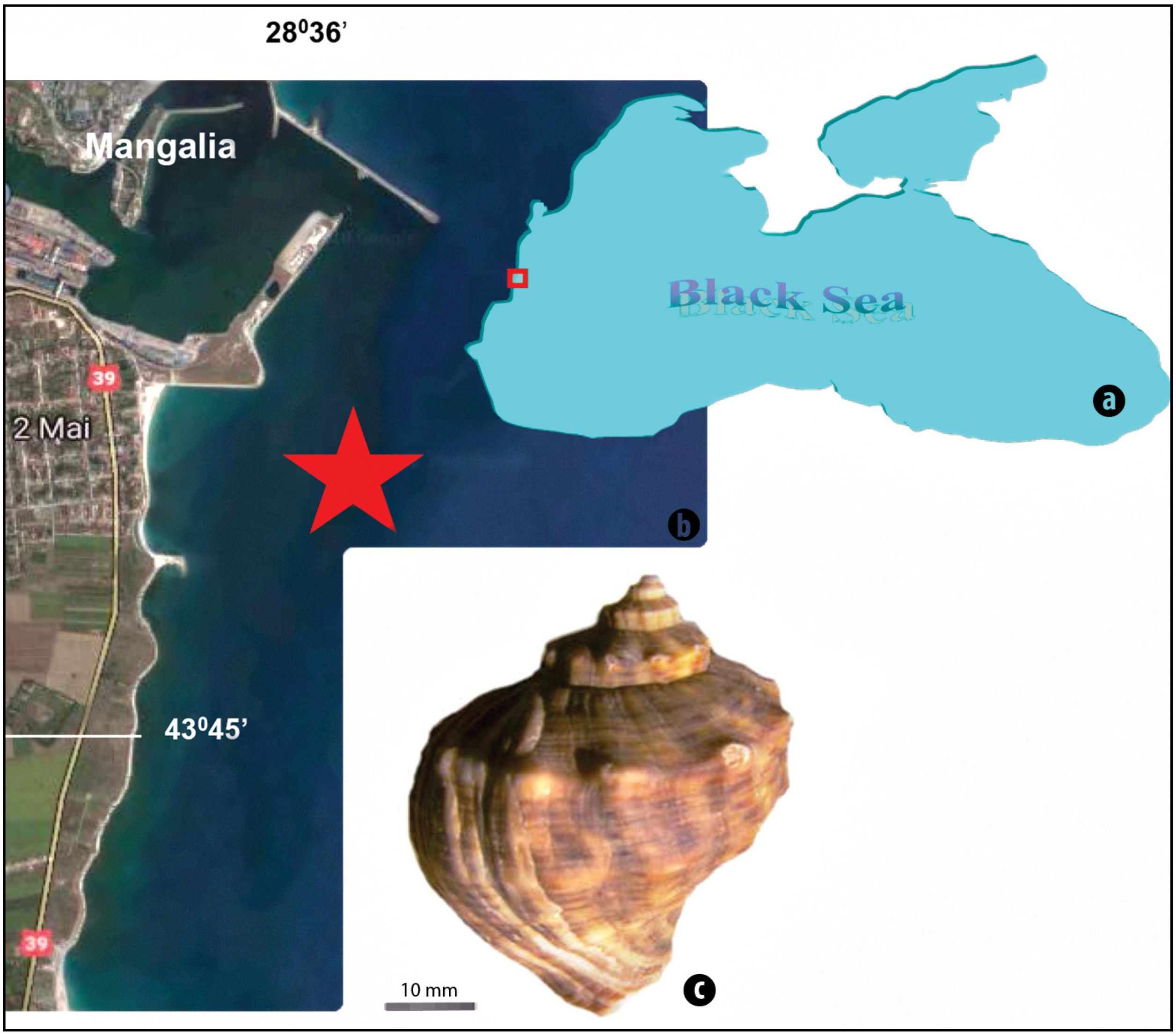

Fig. 1. Location of *Rapana venosa* trails in Marine Reservation 2 Mai-Vama Veche (red star): (**a**) Black Sea and south Mangalia area (www.google.ro/search); (**b**) NW Natura 2000 habitats from ROSCI0269, near Mangalia (explanations in text); (**c**) *Rapana venosa* (Valenciennes, 1846) from Corbu beach (photo T. Brustur, May 2006).

2. ENVIRONMENTAL SETTING

In the following, for the general presentation of the marine environment from the southern part of the Romanian Black Sea coast, we use the synthesis of data from Surugiu's monograph (2008), from the 2MVVMR Management Plan, as well as relatively recent information on Natura 2000 habitats of ROSCI0269 Site of Community Importance (Abaza *et al.*, 2011).

2.1. GEOMORFOLOGY & SEDIMENTOLOGY

With an area of about 5000 hectares, 2MVVMR is located in the southern part of the Romanian coast, consisting of cliffs formed of Sarmatian sandstones and limestones. These cliffs are covered with a thick layer of loess deposits, permanently subject to marine abrasion (Fig. 1-a). The Sarmatian limestones continue offshore, forming the submarine plateau (Cheval & Hogaş, 2001; Surugiu, 2008). According to the zonation of the Black Sea coasts (Panin, 2005), the continental sector of the marine reserve falls into the morphodynamic category "*Erosive coasts within low standing plateaux and plains, with active cliffs with very narrow beaches in front of the cliffs*". The distribution of sediments from the continental shelf of the Black Sea is controlled by the current hydrodynamic regime, with many relict aspects. The sandy sediments are found near the shore, but also at a depth of 30–35 m. The superficial sediments from the outer continental shelf are mainly represented by silty clays. In 2MVVMR, the sediments are dominated by coarse sands of organic origin, the stony bottom belonging to the Sarmatian limestones.

2.2. MARINE BIOLOGY

In 2MVVMR, circumscribed to the Natura 2000 site ROSCI0269, Abaza *et al.* (2011) identified and mapped 3 elementary habitat types (coenoses) with 14 sub-types. Without going into details, we specify that at the edge of the coast line there are well-sorted sands and coarse sands with fine gravel. The stony infralittoral, is present on more than half of the reservation surface, in the bathymetric interval of 20-30 m, and is represented by *Mytilus galloprovincialis* subcoenosis (Fig. 1-b). The firm substratum of the Sarmatian limestone plate and the attenuated hydrological conditions favoured the development of a homogeneous populations of *Mytilus galloprovincialis*, as well as of the invasive species *Rapana venosa* (Fig. 1-c), together with sponges, hydrozoans, polychetae worms, molluscs, crustaceans and fishes.

The submerged vegetation is represented by coralline algae (*Lithophylum incrustans*), articulated (*Corallina officinalis*) and macrophytes (*Ulva compressa*, *Enteromorpha* sp., *Cladophora* sp., *Ceramium* sp.).

3. MATERIAL AND METHODS

During the scuba diving session, a specimen of *Rapana venosa* was photographed with an Olympus Digital Camera (model C5050Z). The camera settings were the following: exposure time 1/60s, F-number f/2, normal exposure program, ISO 64, max. aperture value f/1.8, focal length 7.1 mm and auto exposure. The specimen was photographed in three different positions (Fig. 2), generating bilobated tracks with straight path during the movement (Fig. 2-a), slightly sinuous (Fig. 2-b) or sinuous (Fig. 2-c). The terminology and examples used by Knox & Miller (1985) and Frey *et al.* (1987a) were used to describe the bilobated trail.

4. RESULTS

The analysis of underwater photographs, obtained at a water depth of 24 m (transparency 7-8 m, sea water temperature 18-19ºC), on a substrate formed by silt with sand and clay, shows the presence of a bilobated trails produced by the gastropod *Rapana venosa*, which moved at an estimated speed of approx. 10-15 cm / minute (or approx. 1.6-2.08 mm / sec) (Fig. 3-a).

Although the photos were not obtained focusing perpendicularly on the travel tracks, we can highlight the morphological features of the track (Fig. 3-b) and appreciate its dimensions, relating them to the width of the shell, of approx. 50-52 mm. Thus, a longitudinal channel in the shape of a „U", with a flat base (Fig. 3-d) and a width (L2) of approx. 30 mm can be observed (Fig. 3-b and c). The channel is bordered by parallel semi-cylindrical ridges: two main (external), robust, with base and height of approx. 6 mm (Fig. 3-b, c(a); c(d1), d(h)) and two secondary (internal), with base and height of approx. 2 mm (Fig. 3-b, c(a1), d(a1)); the longitudinal channel bordered by the set of main and secondary ridges totals a width (L1) of approx. 40-45 mm.

Dividing the longitudinal channel into two equal halves, the median ridge (Fig. 3-b, c(b)) supports, at an angle of approx. 50º and a distance of approx. 10-12 mm from each other (Fig. 3-c(d2)), arched transverse ridges arranged alternately (Fig. 3-b, c(c)), with the concavity oriented towards the direction of movement of the gastropod.

Photographing the trail at an angle of approx. 45º, in poor lighting conditions, creates the impression of the presence of small depressions („*pedal depression*"), with asymmetrical section and slightly ascending slope, oriented towards the moving direction (Fig. 3-b_1). If this morphological feature is a reality, it can be admitted that these depressions were generated by the discontinuous movements of the leg which, in the last wave phase of muscle mass, rested on the back of the depression, driving the animal forward. Future observations could clarify this aspect. Following the postulate of Miller (1974a), according to which in the locomotion of muricides, the retrograde diagonal rhythmic-ditaxic type muscle wave dominates, we imagined the hypothetical model of the production of the *Rapana* trail illustrated in Fig. 4.

5. DISCUSSIONS AND FINAL REMARKS

Large gastropod, with a globular and robust shell that can reach 70-120 mm in height and 90 mm in width (Teacă *et al.*, 2008), *Rapana* can be considered as a bulldozer mollusk (*sensu* Seilacher, 2007) which by the way is moving on the seabed produces a trail with distinct morphological features (Fig. 4). Formed on the sediment surface, the stability of a track depends mainly on the consistency of the substrate, as demonstrated by Knox & Miller (1985) in the case of the *Polinices* trace. The morphology of the trail may be affected by the relative differences of the substrate induced by the grain-size (Knox & Miller, 1985). Thus, for example, the presence of a fine and medium sand explains, according to Miller (1997), the formation of two types of tracks of the gastropod *Oliva sayana*: one in the form of „V", short and with indistinct marginal ridges, in the case of soft sand and another, longer and U-shaped with a rectangular section, in the hardened wet sand. Current tracks produced by various metazoan invertebrates have been and are used to explain how locomotion traces formed in the geological past. Thus, the horizontal trails of cnidarians and platyhelminths (broad worms), produced by mucociliary locomotion, served Collins *et al.* (2000) to explain the genesis of several Neoproterozoic fossil traces (e.g., *Aulichnites*, *Gordia*, *Helminthopsis*). For the Proterozoic-Cambrian *Archaeonassa* trails, with the flat central part flanked by relatively high levees (similar to the *Rapana* trail), Jensen (2003) invokes the control exercised by the sediment manufacturer's position on the track morphology. Using present day gastropod trails (e.g., *Bullia*, *Hydrobia*, *Littorina*, *Polinices*), Getty (2007) and Getty & Hagadorn (2008) explain the formation of the famous *Climactichnites* trails in the Upper Cambrian of North America.

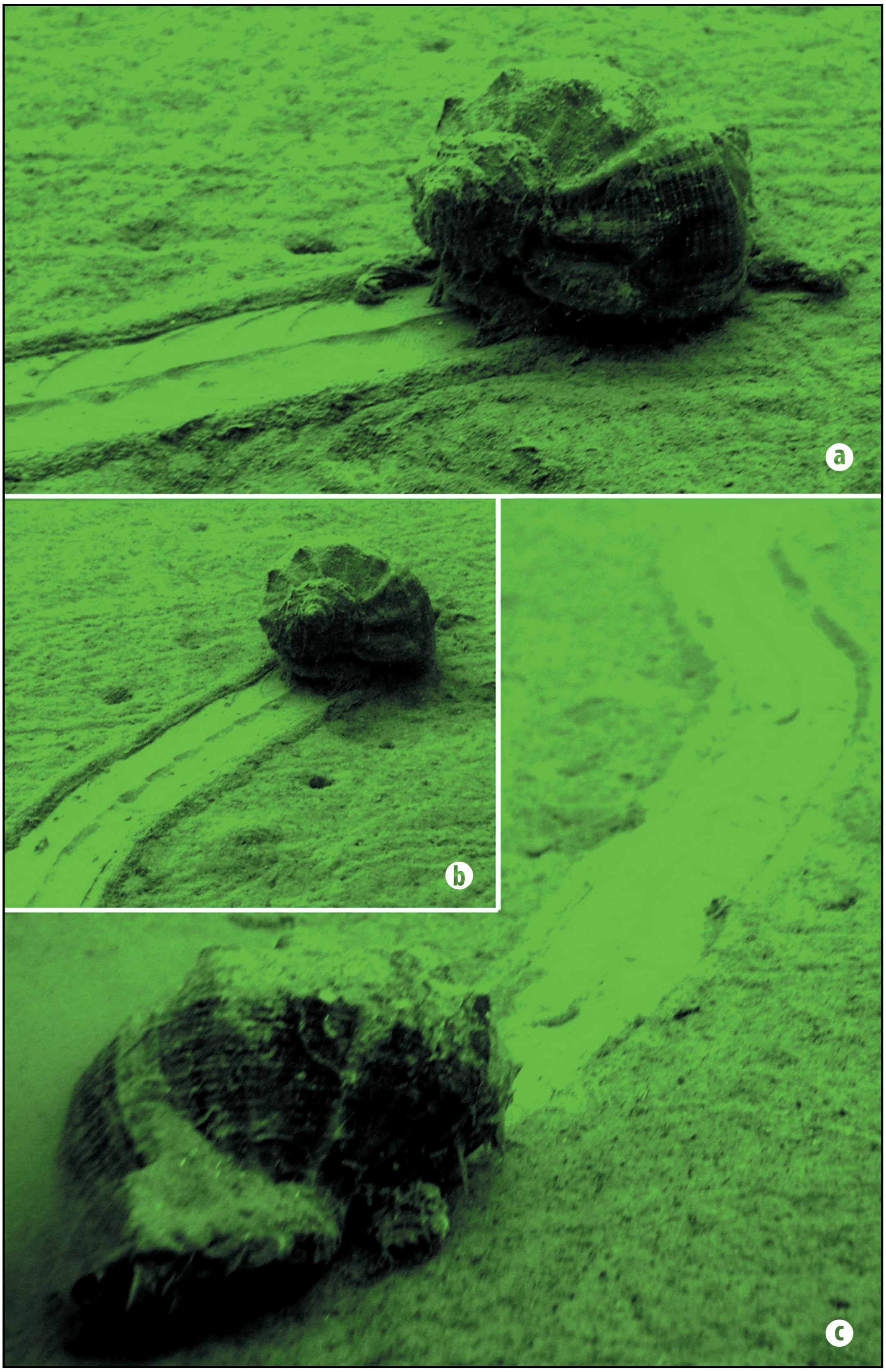

Fig. 2. Surficial trails made by *Rapana venosa*: (**a**) Straight segment of trail (lateral view); (**b**) Slightly sinuous trail; (**c**) Sinuous trail (photo by Sorin Bălan, September 2008, Black Sea inner shelf – N 43⁰46′33.93″, E 28⁰36′27.50″)

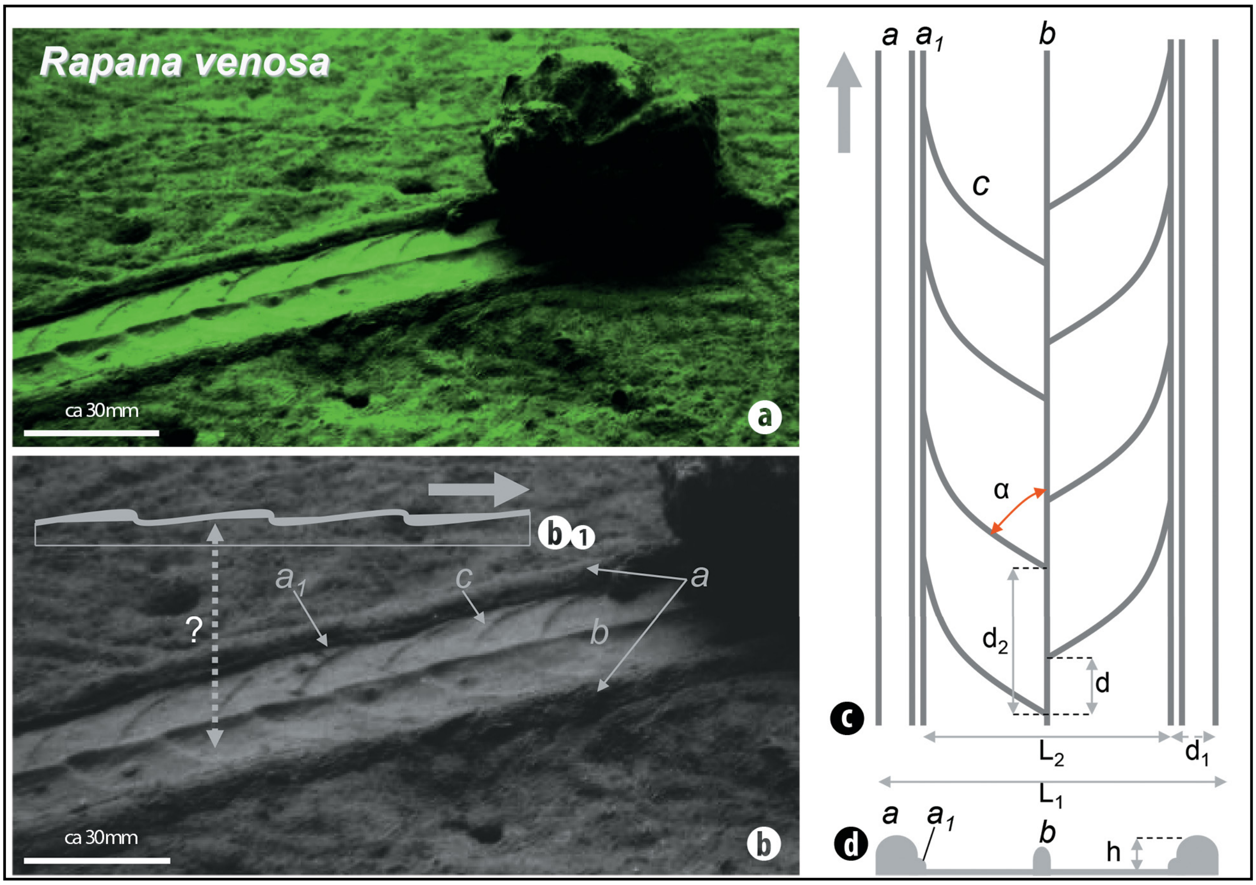

Fig. 3. Bilobed trail of *Rapana venosa:* (**a**) Original photo by Sorin Bălan; (**b**) The same photo convert to grayscale; (**b**$_1$) Probably "pedal" depression; (**c**) Line drawing of longitudinal trail: *a* - principal lateral ridge; a$_1$. secundary lateral ridge; *b* - central low ridge; *c* - distinct arched-transverse ridge; α = tangent angle between *b* and *c* (≈ 50°); *d* - distance between two alternate arched-transverse ridges (≈ 40% from L$_2$); *d*$_1$ - width of lateral ridges; *d*$_2$ - distance between two arched-transverse ridges; (**d**) Line drawing of transverse vertical section: L$_1$ - width of entire trail; L$_2$ - width of bottom of trail; h - heigh of principal lateral ridge (terminology from (**c**) and (**d**), adaptable after Knox & Miller, 1985; gray arrow shows locomotion direction of tracemaker)

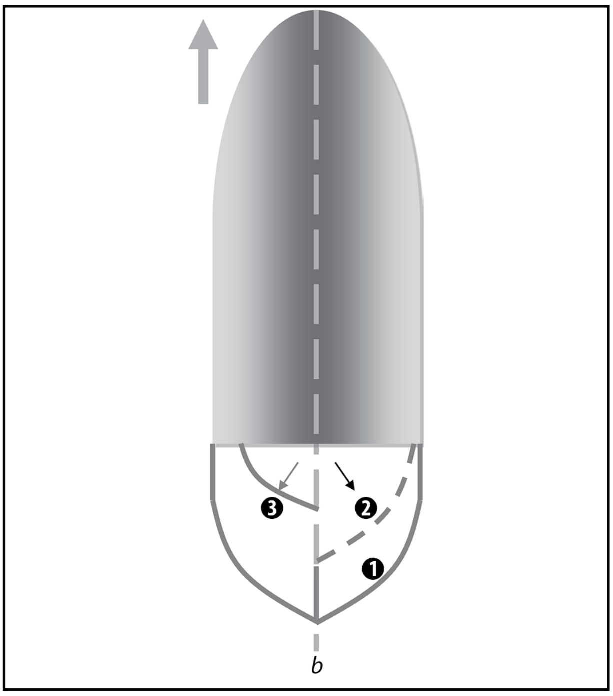

Fig. 4. The production hypothetical model of the *Rapana venosa* trace (adapted after Miller, 1974a). **1** - Pedal muscular at rest; **2** - Arched transverse ridge produced by retrograde-diagonal muscle wave (from tail to head) transmitted along the median of the foot on the right side; **3** - Arched transverse crest produced by the retrograde-diagonal wave transmitted along the median of the foot on the left side; ***b*** - Central ridge marking the median of the foot; small arrows show wave direction; big arrow show animal moving direction).

According to Rindsberg (2012), the trails is a continuous trace of locomotion left on a surface by the body of a producing animal.

Although the trails represent only 4% of the total of 585 ichnogenera reported to burrows (60%), bioerosions (17%), trackways (14%), and impressions (5%) (Knaust, 2012, p. 96, fig. 8), they are distinguished by the general morphology (straight, meandering, wrapped) and the number of lateral elements (lobes, grooves etc.) (Knaust, 2012, p. 90). At present, the morphological classification of the tracks holds 23 valid ichnogenera (Knaust, 2012, p. 93, fig. 6; *see* Supplemental Material: http://booksite.elsevier.com/978044438130). Buatois *et al.* (2017) discusses and figures in an admirable synthesis work 5 types of trails (simple horizontal trails, trilobate flattened trails, chevronate trails, trails with undulating transverse bars and furrows, bilobate trails and parired grooves).

The analysis of the phylogeny and ecological evolution of the subfamily Rapaninae (Vermeij & Carlson, 2000) highlights, among others, the following essential paleontological aspects: **a**) the chronostratigraphic gap of the Rapaninae is between the Lower Eocene-Recent; **b**) the Lower Eocene species are cited in France, Peru, Panama and Indonesia (Java), the Upper Oligocene-Lower Miocene in southern Europe, Florida, Venezuela, New Zealand and Japan, and the Pliocene-Pleistocene elsewhere (Fig. 5); **c**) the adaptation of some species to the upper shore domain was limited to the Indo-Western Pacific region, where the ecological diversification of Rapaninae occurred after the Lower Miocene; **d**) the oldest representative of the genus Rapana is represented by the *Rapana niuensis* species, from the lower part of the Upper Miocene in Japan (Fig. 5).

In contemporary historical times, after the conquest of the Black Sea and the Mediterranean, the invasive gastropod *Rapana*, either through native migration or Lessepsian "migration" (through the Red Sea and the Suez Canal) seen as a natural biological phenomenon (see Oliverio, 2003), or through non-native migration (cf. Mann *et al.*, 2004), conquered new marine territories, in Portugal and the North Sea (Kerckhof *et al.*, 2006) or in the western Atlantic Ocean, in the USA, Uruguay and Argentina (Mann *et al.*, 2004; Giberto *et al.*, 2006, 2014; Carranza *et al.*, 2011; Harding *et al.*, 2011) (Fig. 5).

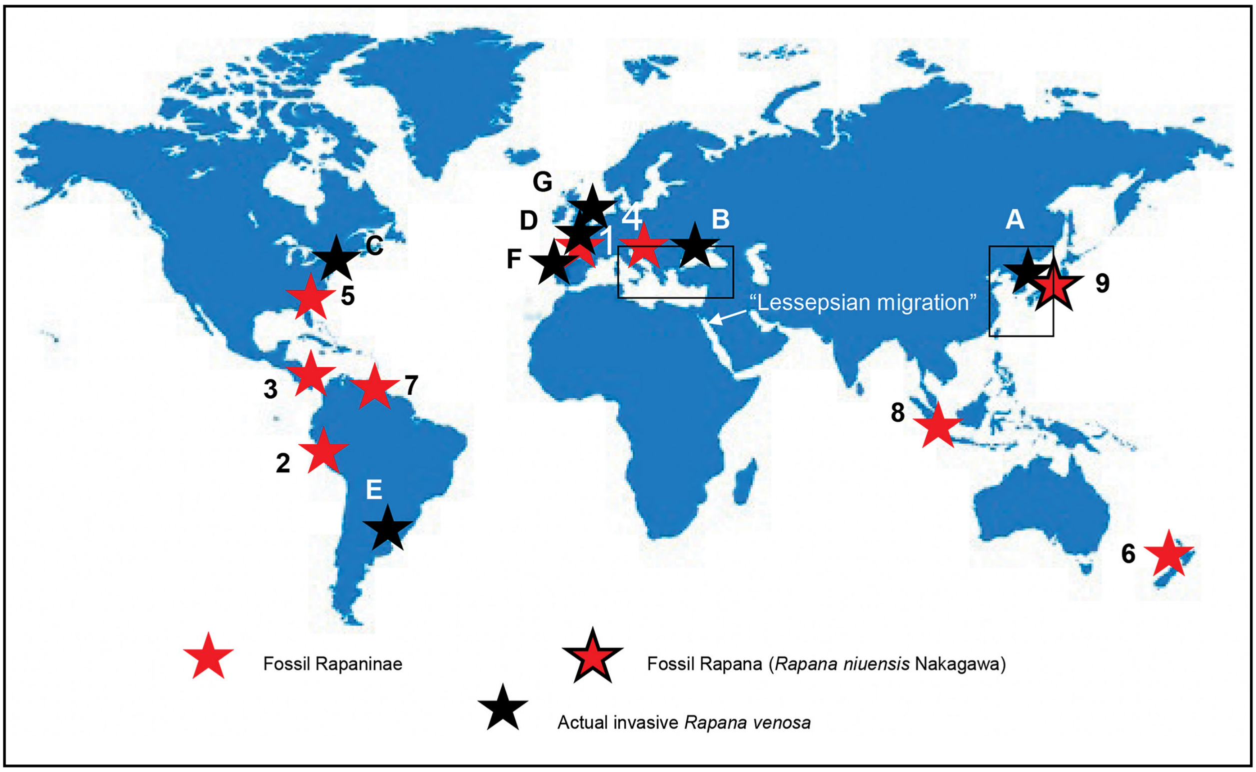

Fig. 5. Occurrences of the fossils Rapaninae (1-8, red stars) and *Rapana niuensis* Nakagawa (9, red star with black outline): **1** – France, early Eocene; **2** – Peru, late Eocene; **3** – Panama, late Eocene; **4** – South Europe, Oligocene-middle Miocene; **5** – Florida, early-late Miocene; **6** – New Zeeland, early-late Miocene; **7** – Venezuela, early Miocene; **8** – Java, early Miocene; **9** – Japan, early middle Miocene – after Vermeij & Carlson, 2000) and the actual spreading of invasive *Rapana venosa* (black stars): **A** – Native populations of *Rapana* in Korean, Japanese & Chinese seas; **B** – Non-native populations of *Rapana* in Black Sea and Mediterranean region; **C** – Chesapeake Bay – USA; **D** – the Brittany coast of France; and **E** – Rio de la Plata, Uruguay and Argentina – after Mann *et al.*, 2004; Carranza *et al.*, 2011; Giberto *et al.*, 2006; Harding *et al.*, 2011; Giberto & Bruno, 2014); **F** – Portugal; **G** – North Sea – after Kerckhof *et al.*, 2006. "Lessepsian migration" – after Oliverio, 2003 (Global map – after https://www.freepik.com/free-vector/illustration-global-icon_2687446.htm)

Interestingly, besides the humans, a unique vector of migration is the turtles (e.g., *Caretta caretta*, *Chelonia nydas*) that feed on *Rapana* (Carranza *et al.*, 2011; Lezama *et al.*, 2013), but also transports it (Harding *et al.*, 2011; Lezama *et al.*, 2013a).

In summary, the study of the *Rapana* tracks from the inner shelf of the Romanian Black Sea may serve to identify possible traces of this species in deposits newer than the Upper Miocene. Trails of this type betray the presence of the invasive gastropod *Rapana*, when the animal cannot be observed and identified. In this way, it is the indirect testimony (*sensu* Moore *et al.*, 1952) of the intruder's presence in new marine domains, conquered by active or inactive migration.

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