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The Sediment-Water Interface Increment due to the Complex Burrows of Macrofauna in a Tidal Flat

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Abstract – The architecture of macrofaunal burrows and the total area of the sediment-water interface created by biogenic structure were investigated in the Donggeomdo tidal flat on the west coast of Korea. Resin casting methods were applied to recover burrows of four dominant species, *Macrophthalmus japonicus, Cleistostoma dilatatum, Perinereis aibuhitensis*, and *Periserrula leucophryna,* and whole burrows within the casting area at three sites in different tidal levels. *P. leucophryna* excavated the largest burrow in terms of a surface area among them. In the case of whole burrow casting, the space occupied by the biogenic structure was extended into deeper and expanded more greatly at the higher tidal level. In the uppermost flat, the burrow wall surface area within sediment was more extensive than the sediment surface area. Increased oxygen supply through the extended interface could enhance the degradation rates of organic carbon and also change the pathways of degradation. Quantifying the relationship between the extended interface and mineralization rate and pathway requires more extensive study.

Key words – burrow, macrofauna, sediment-water interface, tidal flat

1. Introduction

The biogeochemical processes and associated microbial communities in the sediment are stratified and dependent on vertical transport mechanisms (Ziebis *et al.* 1996). Usually, oxygen is restricted to the upper few millimeters of the sediment in coastal environments (Jørgensen 2000; Furukawa *et al.* 2004) and the oxygen penetration is regulated by the dynamic balance between diffusion from the overlying water or air and consumption within the sediment. In sediments without bioturbating fauna, mineralization of organic matter occurs according to the vertically stratified reaction sequence characterized by an upper oxic layer, an underlying suboxic layer where nitrate, manganese (IV), and iron (III) are used as electron acceptors, and finally an anoxic layer where sulfate reduction and methanogenesis occur (Kristensen 2000). The presence of infauna and their bioturbation alter this simplified picture in sediment (Rhoads 1974); because the benthic infauna affects the physical structure of the sediment, its chemical zonations and the exchange processes across the sediment-water interface (Ziebis *et al.* 1996).

The tidal flat contains abundant burrows produced by crabs, polychaetes and other organisms that build burrows with a species-specific architecture (Fig. 1). By their burrowing activity, oxic microniches are created in the otherwise anoxic sediment, resulting in a multi-dimensional diffusion pattern of oxidizing agents and reduced compounds (Rosenberg and Ringdahl 2005). This mix of redox conditions has been shown to stimulate oxic as well as suboxic and anoxic mineralization of organic materials (Aller and Aller 1998). The burrows are generally kept oxygenated by both the irrigating and burrow-maintaining activities. These biogenic structures can thus be viewed as extensions of the sediment-water interface increasing the amount of oxic and oxidized sediment as well as the oxic-anoxic interface (Rosenberg and Ringdahl 2005).

Despite the established understanding of burrows as

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Fig. 1. Complex burrows created by a number of macrobenthos within tidal sediment. The burrow can be viewed as extensions of the sediment-water interface.

micro-environments of chemical significance to sediment-water exchange processes, reports about measurements of burrows and their extension in the field were limited. Since the development of resin-casting techniques, the description of macrobenthic fauna burrows has become more widespread (Atkinson *et al.* 1982; Swinbanks and Luternauer 1987; Griffis and Suchanek 1991; Nickell and Atkinson 1995; Stamhuis *et al.* 1997; Bird and Poore 1999; Dworschak 2002). The burrow morphology of macrofauna living in coastal sediment, especially deep burrowing decapods, has been revealed by these methods. Pemberton *et al.* (1976), for example, found that a Thalassinidean mud-shrimp burrows as deep as 2.5 m of sediment. Extensive burrowing of other mud-shrimp *Callianassa truncata* can increase the total area of the sediment-water interface by roughly 400% in a shallow bay off the Italian coast of the Mediterranean Sea (Ziebis *et al.* 1996). With the resin cast technique, it is possible to measure the space occupied by the biogenic structure in the sediment. However, little in the way of scientific studies have previously been undertaken with respect to dimensions for all burrows within the sediment, especially in the tidal flat.

On the upper tidal flat of Donggeomdo, off the west coast of Korea, where vegetation known as *Suaeda japonica* is extended to small tidal channels, a number of crabs and polychaetes construct complex burrows including the decapods, *Cleistostoma dilatatum* and *Macrophthalmus japonicus,* and the polychaetes, *Periserrula leucophryna* and *Perinereis aibuhitensis*. These species have conspicuous mounds or openings on tidal flats that are easily distinguished from each other. In the present study, the burrow architecture of four dominant species and the increment of the sediment-water interface by complex burrow systems of tidal flat macrofauna were examined. It was part of the baseline study for understanding material fluxes in sediment-water interface within tidal sediments.

2. Materials and Methods

This study was carried out on the upper tidal flat of Donggeomdo during the spring tide in April 2005. Three sites were selected according to tidal elevation and vegetation. Sites 1A and 1B were established on a vegetated area and a site 2 on the mud flat (Fig. 2). Site 1B was located at the highest position from MSL and site 2 at the lowest. The burrows of macrofauna were cast using a very fluid polyester resin *in situ*. The replicate

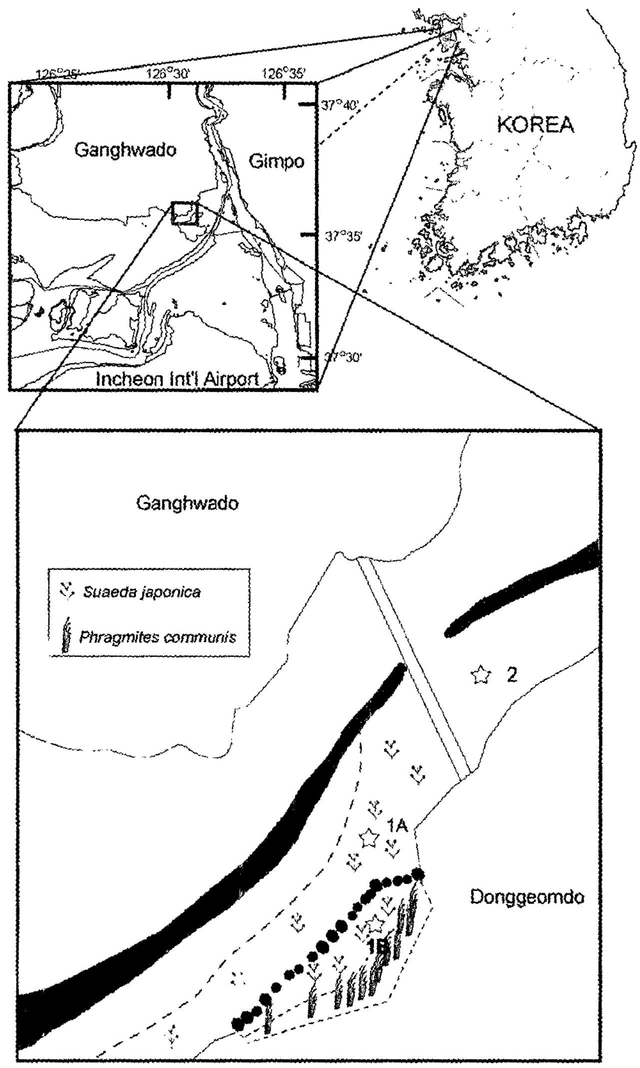

Fig. 2. Location and layout of the study site in the Donggeomdo tidal flat on the west coast of Korea. Site 1B is surrounded by a stone bank and is located at the highest level among the sites.

casting area (0.25 m^2) at site 1B and replicate casting area (0.09 m^2) at sites 1A and 2 were selected and all burrow openings within these areas were filled with resin. The resin was mixed with hardener, and poured into burrow openings at low tide. Burrows of four major species, such as *P. leucophryna*, *P. aibuhitensis*, *C. dilatatum* and *M. japonicus*, were also cast, respectively. After 3 days, the resin casts were carefully dug out so as not to break the tiny branches and were washed to remove attached sediment.

Burrow dimensions were measured with calipers and a measuring tape. The number of openings per burrow was recorded and the depth of the burrows was measured as the straight-line vertical distance from the top of the cast to the bottom. The burrow surface area was estimated by wrapping a single layer of aluminum foil of known weight per unit area around the cast, as described by Atkinson and Nash (1990). Each cast was wrapped twice, and an average was calculated. The volume of the casts was measured by displacement of water. The increment of sediment-water interface created by biogenic structure within sediments was calculated by comparing the burrow wall surface area to the unit sediment surface area.

3. Results and Discussion

The casts of burrows of four major species were recovered and analyzed. The burrow architecture of these species was shown in Fig. 3. Table 1 represents morphometric data for the burrows of four species. The burrows of two crab species, *C. dilatatum* and *M. japonicus*, had one or two openings, but few casts having 3 openings. The domicile of *M. japonicus* was an oblique U-shaped burrow with a short, inclined shaft extending from the base of the U (Fig. 3A), whereas *C. dilatatum* built a vertically straight or slightly sinuous, unbranched burrow ranging in depth from 16 to 36 cm (mean: 25.6±8.7 cm, Fig. 3B, Table 1). Although the mean burrow depth of *M. japonicus* was shorter than that of *C. dilatatum*, the total length and surface area were much longer and more extensive (Table 1). The burrow of *P. aibuhitensis* was very slender and sinuous, extending vertically and branched (Fig. 3C). Some of the burrows were extended about 100 cm in total length (mean: 60.7±19.5 cm). *P. leucophryna* constructed a burrow consisting of a main vertical shaft and several bulges (Fig. 3D). The vertical shaft was slightly sinuous and unbranched. The bulges were found along the shaft, which seemed to serve for turnabout (Lee and Koh 1994). The whole burrow had an average of 45.9 cm in depth and 91.5 cm in total length, respectively (Table 1). This species excavated the largest burrow in terms of surface area, followed by *M. japonicus*, *C. dilatatum*, and *P. aibuhitensis*. The largest *Periserrula* burrow was 128 cm in total length and was 1,133 cm^2 in surface area.

Conspicuous burrows within casts of each site were identified and counted according to species (Fig. 4). The casts were nearly occupied by four species, *M. japonicus*, *C. dilatatum*, *P. aibuhitensis* and *P. leucophryna*. The number of

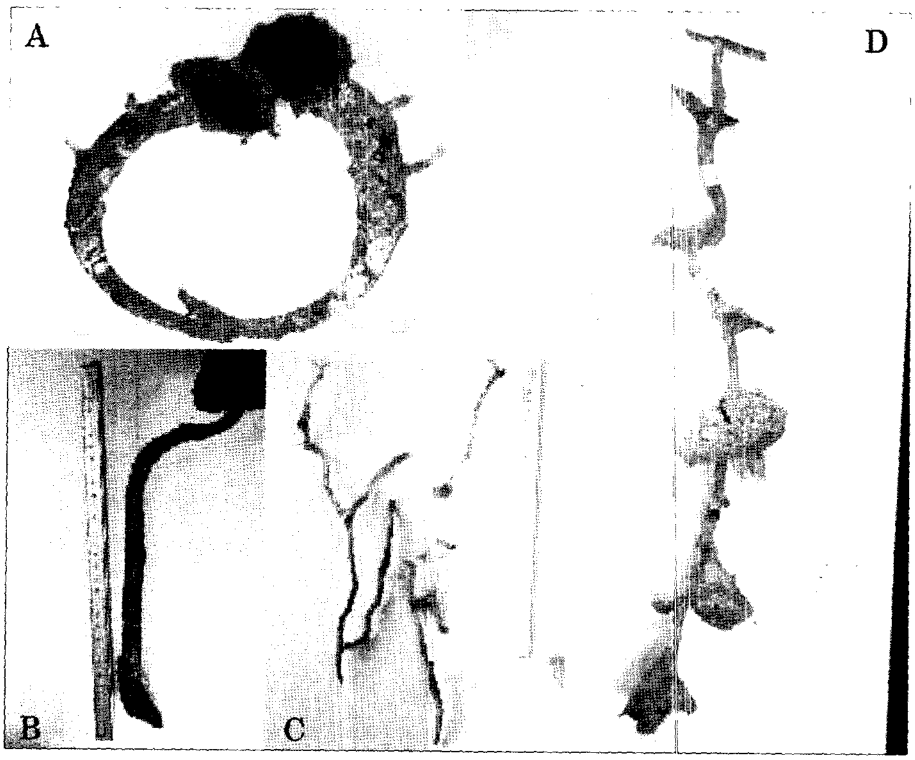

Fig. 3. Representatives of burrow architecture for four major species, *Macrophthalmus japonicus* (A), *Cleistostoma dilatatum* (B), *Perinereis aibuhitensis* (C) and *Periserrula leucophryna* (D). Each scale represents 30 cm.

Table 1. Morphometric data on the burrows of four dominant species in the Donggeomdo tidal flat.

Species	N	No. of opening	Burrow length (cm)	Burrow depth (cm)	Burrow wall surface area (cm^2)
Cleistostoma dilatatum	17	1.5±0.8	37.0±15.1	25.6±8.7	187.0±77.9
Macrophthalmus japonicus	7	1.7±0.7	61.3±40.2	14.2±5.3	503.6±223.9
Perinereis aibuhitensis	12	2.8±1.9	60.7±19.5	18.4±10.2	137.9±45.6
Periserrula leucophryna	4	1±0	91.5±26.1	45.9±10.2	695.8±392.9

burrows ranged from 10 to 30 per cast. The dominant species was *C. dilatatum* at site 1B and *P. aibuhitensis* at sites 1A and 2 (Fig. 5). Burrow depth showed an increasing tendency towards higher tidal levels (Fig. 6). The mean burrow depth of total species within a cast was deepest at site 1B (Table 2). When comparing the burrows of two polychaetes, *P. leucophryna* and *P. aibuhitensis* occurring in all sites, it was found that the dwellers built domiciles more deeply in the higher tidal levels (Fig. 6).

Mean values of the burrow wall surface area within sediments ranged from 5,322 cm^2 to 12,964 cm^2, and burrow volume ranged from 2,556 cm^3 to 6,680 cm^3 per square meter according to site (Table 2). These spaces occupied by biogenic structures increased with an increase in tidal level. At site 1B, the extensive burrows increased the total area of the sediment-water interface within the sediments by 129.6%.

The root density of halophytes affects salt marsh infauna (Daiber 1982). The thick roots in marsh plants limit the distribution of infauna by hampering movements such as burrowing and feeding activities (Capehart and Hackney 1989). The effect of halophytes, however, was not apparent in terms of mean depth and total burrow area, compared at vegetated site 1A and non-vegetated site 2, in which tidal elevation was slightly low compared to site 1A. The burrow was larger and deeper in the vegetated area (Table 2). At site 1A, the density of *Suaeda japonica* was below 100roots/m^2 and vegetation was composed mostly of buds with an average height of 5cm. It was believed that the plant density, mainly composed of buds, was not enough

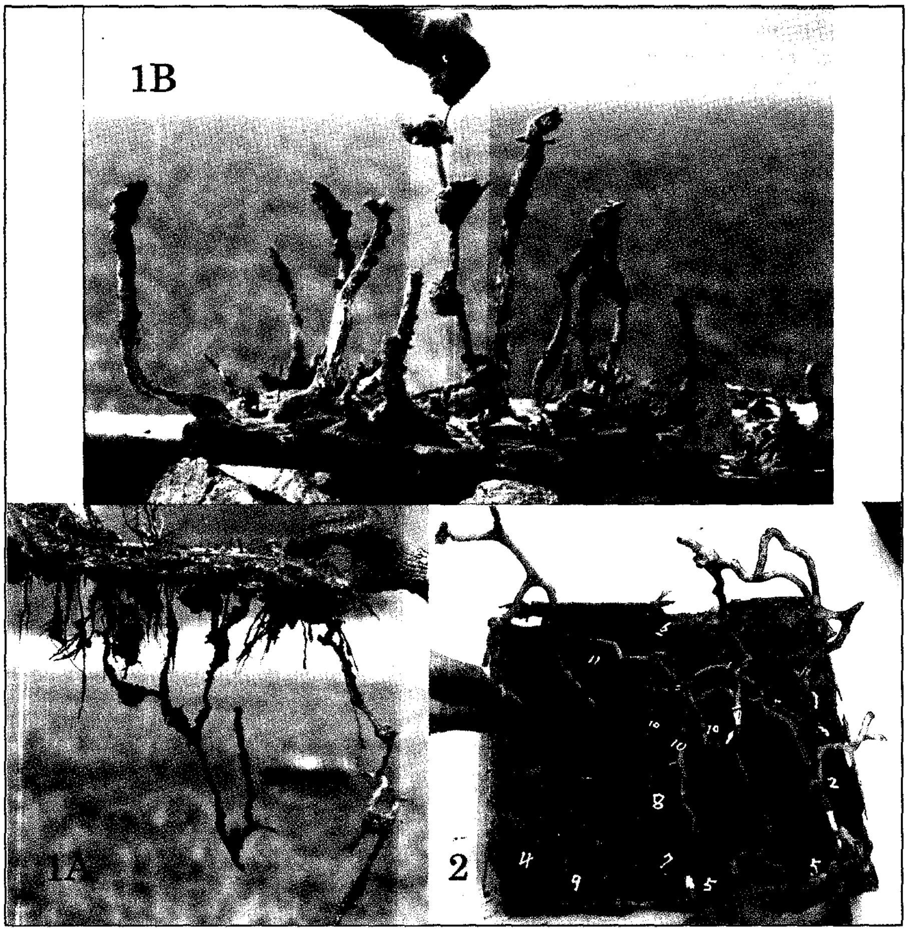

Fig. 4. Resin casts removed from each casting area at three sites. Each casting area was 0.25 m^2 at site 1B and 0.09 m^2 at sites 1A and 2.

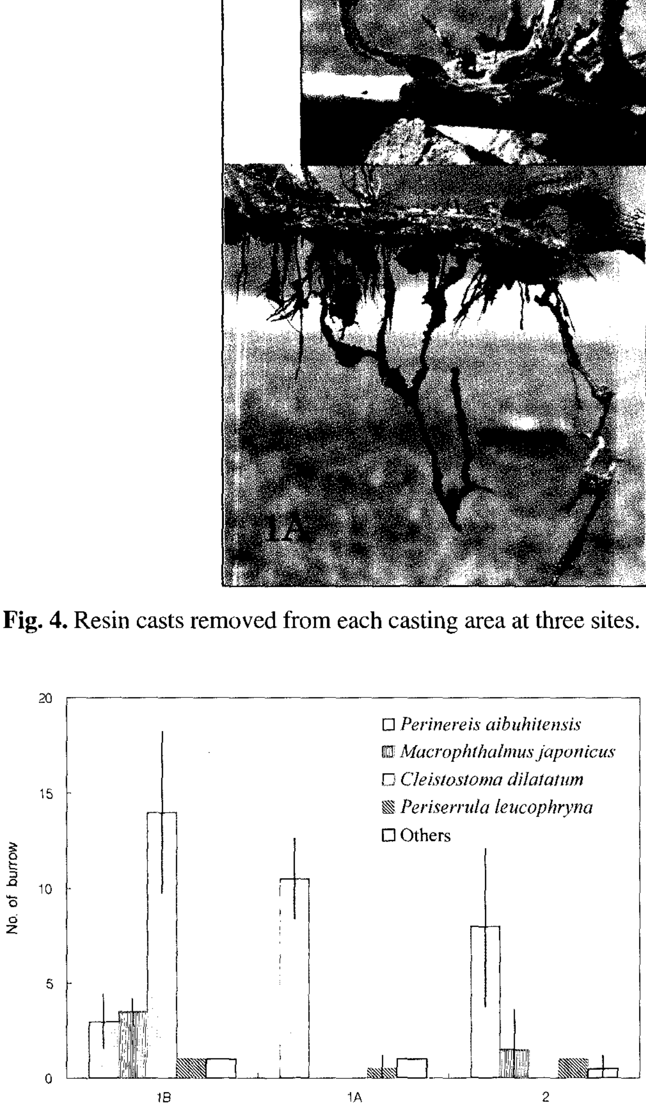

Fig. 5. The number of burrows of dominant species within the resin casts at each site. Each casting area was 0.25 m^2 at site 1B and 0.09 m^2 at sites 1A and 2.

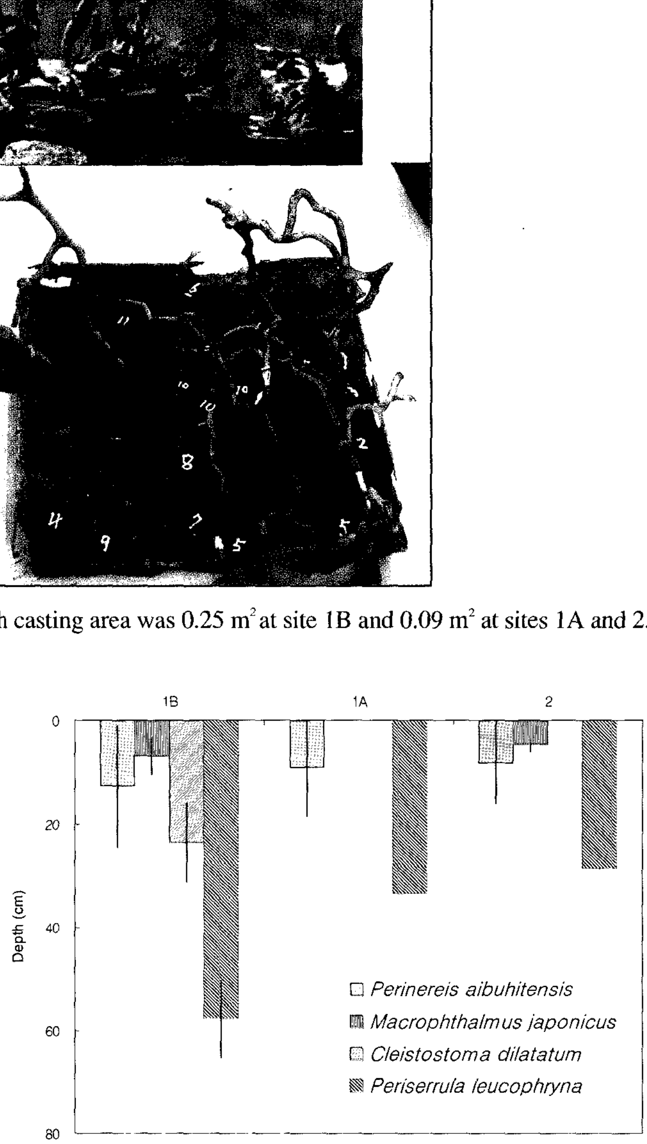

Fig. 6. Burrow depth of major species observed within the resin casts at each site.

to limit the burrowing activity of macrofauna.

The burrow was extended into deeper strata and expanded more greatly in higher tidal level. Through an evolutional process, tidal flat macrobenthos were adapted to a fossorial mode of life. The burrows provide them with a refuge from extreme environmental conditions. The most

Table 2. Morphometric data on all burrows in resin casts and the ratio of burrow wall surface area to unit sediment surface area at each site in the Donggeomdo tidal flat.

Site	Mean depth (cm)	Burrow wall surface area ($cm^2 m^{-2}$)	Burrow volume ($cm^3 m^{-2}$)	Increase rate of sediment-water interface (%)
1B	18.4±1.4	12,964±3,624	6,680±3,112	129.6
1A	9.8±4.8	8,778±4,044	3,500±78	87.7
2	6.0±4.9	5,322±2,689	2,556±1,089	53.2

extreme might be temperature. The animal burrows are known to serve as a cooling space as well as a water reservoir. The temperature inside the burrow is dependent not only on the depth and shape of the burrow, but also on the water content of the surrounding sediment (Powers and Cole 1976). The upper tidal sediment is subjected to the frequent exposure usually lasting for more than 24h and occasionally for as long as a few days. To cope with these severe harsh conditions, the upper tidal flat macrofauna construct deep, vertical burrows (Lee and Koh 1994). Thus, the total area between the sediment and water in the upper tidal flat increased more extensively compared to that in the lower tidal flat zone.

In the uppermost flat, the sediment-water interface created by the biogenic structure within sediment was more extensive than the surface area on tidal flat. A consequent increase of oxygen supply through the burrow walls could enhance the reoxidation of reduced metal ions and result in an increase of the organic carbon mineralization rate via a metal reduction process. This phenomenon has been observed from diverse marine sediment environments (Bird *et al.* 2000; Fossing *et al.* 2000; Kostka *et al.* 2002; Nielsen *et al.* 2003; Mok *et al.* 2005). However, only limited data was available for quantifying the relationship between the extended surface area and organic carbon mineralization rate and process. This requires more extensive study.

This study was limited to relating the burrow structure to diverse environmental factors affecting temperature inside the burrow, such as exposure duration, seasonality, tidal cycle and water content of surrounding sediment. These aspects might be included in future studies with more data related to burrow architecture for understanding robust estimates of sediment-water interface within tidal sediment.

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