Article

Granulometric Analysis of Shallow Vents Sediments at Banderas Bay (Mexico)

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Abstract: Ocean hydrothermal activity is well known from deep-sea studies; however, few studies have been reported at shallow depth. A shallow submarine hydrothermal system at Punta Mita described in 2000 was studied to determine the grain size classification of the marine sediments of this hydrothermal system. Three sites with hydrothermal activity were included. Each one was divided into three areas: with hydrothermal activity, intermediate, and out of hydrothermal activity. In each area, two sediment cores were randomly collected by scuba diving (number of sediment cores = 18). All sediment samples were subjected to a previous treatment, to eliminate salts and organic matter. The grain sizes were sieved and then classified following the Udden–Wentworth scale. A principal coordinate analysis was performed to determine if there was any association of the statistical moments with the areas and sites of study. The textural composition of the sediments in the hydrothermal influence areas is sand, where the very fine sand is the dominant grain size, which was confirmed with the mean moment. The sediments are characteristic of the tidal areas, except for those sediments in the areas with hydrothermal activity.

Keywords: marine sediments; hydrothermal system; vents; texture; very fine sand; Punta Mita

1. Introduction

The hydrothermal activity in the shallow submarine hydrothermal system at Punta Mita (SSHSPM), located in Las Coronas fissure [1] in Banderas Bay, can be appreciated from the sea surface, due to the presence of gas bubbles rising from the seabed and bursting in contact with the surface. It is located in continental margins affected by tectonic extension processes with a high geothermal gradient [2], and it is not related to volcanic activity, as with most shallow submarine hydrothermal systems on the planet [3]. Hydrothermal activity takes place on basaltic rock fissures partially covered by uncemented sediments, and the discharges consist of gas and water, which reach temperatures of up to 85 °C [2]. According to Canet and Prol-Ledesma [2], this hydrothermal activity affects an area greater than 1 km² at a depth of approximately 10 m. The oceanic environment of SSHSPM is influenced by four main currents: the California current, reflux from the Gulf of California, the north equatorial current, and the coastal current from Costa Rica [4]. Moreover, the bottom is subject to the action of waves, storms, and bottom currents [5]. The aforementioned prevents well-formed and large mounds on the vents, and only mounds with little vertical development are formed [5]. Canet and Prol-Ledesma [2]

identified a mound up to 0.75 m high, but also reported that the currents and waves to which the seabed of SSHSPM is continually subjected have a high erosive power.

Since 2000, the scientific interest in SSHSPM has arisen, which focused on the geochemistry of liquids and gases discharged by these shallow vents [6]. Prol-Ledesma et al. [7] reported geological aspects of the area surrounding SSHSPM and de la Vega-Márquez and Prol-Ledesma [8] reported the main lineaments in which this hydrothermal activity takes place. SSHSPM was proposed as a potential source of geothermal energy [2], which could be used by tourist resorts built in front of the beaches of the states of Jalisco and Nayarit, in Banderas Bay. Despite the above, little has been studied and published regarding SSHSPM.

Recently, Rodríguez-Urbe et al. [9] reported for the first time the presence of the amphioxus *Branchiostoma californiense* in the marine sediments within the influence area of SSHSPM. While Prol-Ledesma et al. [10] descriptively reported that small concentrations of macrofauna were observed in sediment samples collected in SSHSPM, nematodes and amphipods were the most abundant. They also concluded that these organisms are characteristic of those found in the sediments of the shallow-water vents in the Aegean Sea [11]. In their review, Tarasov et al. [3] highlighted that benthic meiofauna in shallow-water vents is better known than in deep-sea vents. All this led us to wonder about the distribution of grain size in the marine sediments in the active vents of SSHSPM and its influence area, since there is no scientific study that reports the granulometric classification of the sediments of this hydrothermal system. Related to this, Melwani and Kim [12] studied the distribution of the benthic infauna that inhabits the sediments of two shallow submarine hydrothermal systems, one in Bahia Concepcion (12 m depth), Mexico, and the other in White Point (8 m depth), California, USA. They included a granulometric analysis to characterize the grain sizes of the sediments in their study areas, and to determine the relationship between the benthic infauna concerned the grain size. Knowing the characteristics of marine sediments can help to understand the interactions between the marine environment and sedimentary deposits [13].

Blott and Pye [14] emphasized that grain size is the most fundamental property of sediment particles, since it affects its drag, transport, and deposition; similarly, an adequate granulometric analysis provides information on its origin, transport history and deposition conditions [15–17]. Whereas Sánchez et al. [18] emphasized that the granulometric tendencies of the sediments have been widely used to infer the possible trajectories of the clastic material in diverse coastal environments. This research aimed to determine the grain size classification of the marine sediments in SSHSPM and in its influence area, in order to leave a preliminary frame of reference for future studies related to the sediments of this hydrothermal system.

2. Materials and Methods

SSHSPM is located 300 m from the beaches of Punta Pantoque in Banderas Bay, Mexico (Figure 1). Three sites with hydrothermal venting were selected: Site 1 (S1) (20°44′54.7″ N, 105°28′40.6″ W), Site 2 (S2) (20°44′54.8″ N, 105°28′40.4″ W) and Site 3 (S3) (20°44′54.9″ N, 105°28′38.4″ W). The three sites were at 9 m depth.

Each study site was stratified into square areas, taking a hydrothermal vent as the center, with a total of three areas per site. They were identified as: area with hydrothermal activity (WHA), intermediate area (I), and out of hydrothermal activity area (OHA), with areas of 0.16, 9, and 36 m², respectively (Figure 2). In each area, two surface sediment cores were collected by SCUBA diving (number of sediment cores=18), using PVC plastic cores with 10 cm length and 10 cm diameter. A PVC quadrant was used to delimit the areas at each study site. In each area, the diver collected two sediment cores, randomly, but ensuring that there was sufficient distance between one sample and the other, within the same area. The diver took the sediment sample with one hand, inserting the plastic core the first 5 cm, and with the other hand, placed the cap. The sediment cores were collected on 13 December 2017, which is the first time that marine sediment samples have been collected in SSHSPM to make a granulometric analysis.

Figure 1. Study zone: location of the shallow hydrothermal vents at Punta Mita. The red oval indicates the study sites.

Figure 2. Diagram of the three areas in which each study site was stratified. WHA, area with hydrothermal activity; I, intermediate area; OHA, out of hydrothermal activity area. The red circle indicates the hydrothermal vent.

The granulometric analysis of each area in each study site was performed in duplicate, using the method of sieves [19]. Eight ALCON™ brass sieves were used. These were arranged in decreasing order, based on the mesh size, and at the bottom a collector. The mesh sizes of the eight sieves were 3.200, 2.000, 0.850, 0.600, 0.425, 0.300, 0.250, 0.150, and 0.075 mm. The grain size was classified according to the Udden–Wentworth scale [20,21]. Sediment samples received prior treatment [19] to eliminate salts and organic matter.

The structural parameters that describe the grain size distribution were calculated using the method of moments [14,22,23]. This statistical method consists of four moments (mean ($\bar{x}_0$), standard deviation (σ_0), skewness Sk_0 , and kurtosis (K_0)) determined by the formulas shown in Table 1. According to Blott and Pye [14], $\bar{x}_0$ determines the average grain size; σ_0 indicates how similar are the sizes of all the particles that make up the sample; Sk_0 measures the tendency of the particles towards a certain size; and K_0 measures the concentration of the grains in relation to the average.

Table 1. Statistical formulae of the logarithmic method of moments [14]. $\bar{x}_\phi$ = mean; σ_ϕ = standard deviation; Sk_ϕ = skewness, K_ϕ = kurtosis; f = the frequency in percent; and m_ϕ = the mid-point of each class interval in phi (ϕ) units.

Statistical Moment	Formulae
Mean ($\bar{x}_\phi$)	$\bar{x}_\phi = \frac{\sum f m_\phi}{100}$
Standard deviation (σ_ϕ)	$\sigma_\phi = \sqrt{\left(\frac{\sum f (m_\phi - \bar{x}_\phi)^2}{100} \right)}$
Skewness (Sk_ϕ)	$Sk_\phi = \frac{\sum f (m_\phi - \bar{x}_\phi)^3}{100 \sigma_\phi^3}$
Kurtosis (K_ϕ)	$K_\phi = \frac{\sum f (m_\phi - \bar{x}_\phi)^4}{100 \sigma_\phi^4}$

To look for some association of the structural moments with the areas and sites of study, a principal coordinate analysis was performed (PCO) [24] using PRIMER®+PERMANOVA version 6 software [25].

3. Results

The results of the grain size show the sediments were homogeneous (Figure 3) with a textural composition of sands. The dominant grain size was very fine sand, in the three areas of the three study sites (number of total areas=9).

Figure 3. Textural composition of the sediments in the Shallow Submarine Hydrothermal System at Punta Mita. The x-axis indicates the area of each study site, and the y-axis indicates the cumulative percent of each grain size. S1, Site 1; S2, Site 2; S3, Site 3; WHA, area with hydrothermal activity; I, intermediate area; OHA, out of hydrothermal activity area.

Table 2 shows the grain sizes of each area at each study site, in percent. Table 3 shows the structural moments of each area at each study site.

Table 2. Grain size of sediments collected on 13 December, 2017, classified according to the Udden–Wentworth [20,21], of each area in each study site. The average cumulative weight in percent in each class and the standard error are shown. WHA, area with hydrothermal activity; I, intermediate area; OHA, out of hydrothermal activity area.

Site	Area	Gravel		Sand			Silt	
		Very fine [−2,−1] phi	Very Coarse [−1,0] phi	Coarse [0,1] phi	Medium [1,2] phi	Fine [2,3] phi	Very Fine [3,4] phi	Very Coarse >4 phi
S1	WHA	0 ± 0	0.38 ± 0.009	2.26 ± 0.013	2.79 ± 0.061	22.76 ± 0.8	70.66 ± 0.164	1.15 ± 0.45
	I	0 ± 0	0.18 ± 0.05	0.97 ± 0.03	1.8 ± 0.15	24.24 ± 1.08	72.02 ± 0.94	0.8 ± 0.01
	OHA	0 ± 0	0.11 ± 0.01	1.26 ± 0.01	1.56 ± 0.02	18.9 ± 1.4	76.86 ± 1.3	1.3 ± 0.13
S2	WHA	9 ± 0.13	7.66 ± 0.62	14.79 ± 1.04	4.45 ± 0.17	20.24 ± 0.51	42.77 ± 1.2	1.28 ± 0.01
	I	0 ± 0	0.03 ± 0.01	0.17 ± 0.00	0.71 ± 0.02	23.82 ± 2.31	74.61 ± 2.23	0.67 ± 0.04
	OHA	0 ± 0	0.11 ± 0.11	0.37 ± 0.01	1.39 ± 0.01	27.87 ± 0.74	69.32 ± 0.60	0.94 ± 0.03
S3	WHA	14 ± 1.21	13.52 ± 2.89	20.93 ± 0.94	5.68 ± 0.42	11.08 ± 1.15	33.44 ± 1.49	1.36 ± 0.10
	I	0 ± 0	0.00 ± 0.00	0.11 ± 0.01	0.27 ± 0.03	17.40 ± 0.58	81.18 ± 0.62	1.04 ± 0.08
	OHA	0 ± 0	0.01 ± 0.01	0.15 ± 0.03	0.33 ± 0.01	15.88 ± 0.84	81.79 ± 0.62	1.83 ± 0.17

Table 3. Average values of the statistical moments of each area in each study site with its standard error, of the sediments collected on 13 December, 2017. WHA, area with hydrothermal activity; I, intermediate area; OHA, out of hydrothermal activity area.

Site	Area	Statistical Moments			
		Mean ($\bar{x}_0$)	Standard Deviation (σ_0)	Skewness (Sk_0)	Kurtosis (K_0)
S1	WHA	3.14 ± 0.001	0.69 ± 0.000	−2.25 ± 0.017	8.91 ± 0.09
	I	3.19 ± 0.009	0.58 ± 0.004	−2.15 ± 0.005	9.29 ± 0.24
	OHA	3.24 ± 0.015	0.57 ± 0.005	−2.55 ± 0.128	11.18 ± 0.781
S2	WHA	2.02 ± 0.048	1.72 ± 0.006	−0.81 ± 0.069	2.25 ± 0.116
	I	3.24 ± 0.022	0.47 ± 0.009	−1.64 ± 0.209	6.15 ± 1.124
	OHA	3.18 ± 0.003	0.53 ± 0.010	−1.63 ± 0.240	6.81 ± 1.804
S3	WHA	1.41 ± 0.128	1.88 ± 0.031	−0.17 ± 0.114	1.55 ± 0.075
	I	3.32 ± 0.004	0.41 ± 0.003	−1.93 ± 0.089	6.65 ± 0.519
	OHA	3.34 ± 0.008	0.41 ± 0.001	−2.16 ± 0.189	8.78 ± 1.673

In general, the mean, $\bar{x}_0$, indicates a very fine sand grain size in all samples. The standard deviation, σ_0 , of most samples was moderately well sorted, while the WHA areas of S2 and S3 were poorly sorted. The skewness, Sk_0 , was systematically negative. The kurtosis, K_0 , indicates a leptokurtic to very leptokurtic distribution, except for the WHA areas of S2 and S3, which resulted platykurtic and very platykurtic, respectively. These results are presented as histograms in Figure 4.

Figure 4. Histograms of the three areas at each study site. The x-axis represents the grain size in phi (ϕ) units, while the y-axis represents the percent of sediments retained in each class. The red dotted line represents the frequency polygon. The rows indicate the study sites and the columns the areas. S1, Site 1; S2, Site 2; S3, Site 3; WHA, area with hydrothermal activity; I, intermediate area; OHA, out of hydrothermal activity area

Granulometric results of the WHA areas of S2 and S3 were very different from the rest, as shown in Figure 4 as well as in the dispersion diagram of Figure 5, since they presented very fine gravels and coarse and very coarse sands. The grain size of these sediments was poorly homogeneous with coarse skewed and platykurtic and very platykurtic graphs (see Figure 4).

The PCO in Figure 6 shows an explained variation of 99.2%, in the first two axes. The first axis (PCO1) explains 93% of this variation and the second axis (PCO2) explains 6.2%. The explained variation in this PCO suggests the analogy between the structural moments and the study sites. Most areas of the three study sites were grouped towards large values of means and kurtosis, and low values of skewness and standard deviation. However, the WHA areas of S2 and S3 showed an inverse relationship, i.e. smaller means and kurtosis, but larger skewness and standard deviation, separating from the rest, as shown in Figures 4–6.

Figure 5. Dispersion diagram that relates moments $\bar{x}_0$ and σ_0 (mean and standard deviation). The black oval encloses the two areas that separate from the rest. S1, Site 1; S2, Site 2; S3, Site 3.

Figure 6. Graph of the principal coordinate analysis. Green triangles indicate the area with hydrothermal activity (WHA), blue triangles the intermediate area (I), and turquoise squares, the out of hydrothermal activity area (OHA). The x-axis explains 93% of the total variation and the y-axis explains 6.2%. S1, Site 1; S2, Site 2; S3, Site 3.

Figure 7 shows a photograph taken of the WHA area of S2, where altered basalt by hydrothermal activity is observed. This was reflected in the granulometric analysis with very fine gravel and very coarse and coarse sand (Table 2). The WHA area of S3 presented similar characteristics.

Figure 7. Photograph of the active hydrothermal vent of the area with hydrothermal activity (WHA) at Site 2 (S2).

4. Discussion

The marine sediments in the influence area of SSHSPM are composed of very fine sands with moderate sorting. The mounds that form in the active hydrothermal vents are a combination of very fine gravel (mainly from degraded basalt by hydrothermal activity) and sands, which range from very fine to very coarse, with poor sorting. Besides, we observed these mounds accumulate fragments of marine debris, such as sea urchin spines, shells, and corals, among others, which were not included in the analysis. Melwani and Kim [12] reported the grain size of two shallow submarine hydrothermal vent areas: Bahía Concepción (12 m), Mexico, and White Point (8 m), USA. In the area of Bahía Concepción, they divided their study sites into three zones, vent, transition, and outside, whereas White Point was stratified into two zones, vent and outside. They did not find significant differences in grain size between the zones of each shallow hydrothermal vent area. In both shallow hydrothermal vent areas, the grain size was fine to medium sands with moderate sorting. In the two hydrothermal systems studied by Melwani and Kim [12], as in the influence area of SSHSPM studied by us, the grain size was sand, which, according to Fuentes-Hernández [26], is the appropriate

grain size in tidal environments. However, our results indicate that the grain size in the sediments of the active vent areas present a combination of very fine sands to very fine gravels, as well as the accumulation of marine debris.

SSHSPM is low depth (10 m), which limits the shape, size, and existence of the mounds in the vents. During the year, several waves are presented in the study zone. Moreover, Canet et al. [5] reported that the sea bottom is brought under the action of waves, storms, and background currents, which condition the transport and deposition of the sediments both in mounds of these hydrothermal vents and in sea bottom adjacent to them.

Núñez-Cornú et al. [1] pointed out that the sediments that they observed on the sea bottom around various vents of SSHSPM were at first sight sands, mainly, since they did not do a granulometric study. They emphasized that their observations were made in September 1997, and they returned in January 1998, after passage of Hurricane Paulina. They observed drastic changes, such as the destruction of prominent mounds in some vents and the removal of surface sediments from the sea bottom, which partially unveiled basaltic structure that lies beneath the sediments. What was observed by Núñez-Cornú et al. [1] coincides with what we observed when returning to the study site, six months later, since some mounds were modified, some smaller but others larger, and new mounds had formed. We also observed that the mounds had marine debris and fragments of altered basalt, while the surrounding area was mostly composed of sand. This confirmed that the sediments in the influence area of SSHSPM are sands. According to our results, it would be very fine sands, while the mounds present, in addition to sands, very fine gravels due to the alteration of the basalt by hydrothermal discharges. The findings of this study possibly represent a dynamical equilibrium condition in the system between particle transport, erosion, and deposition, as proposed by Baux et al. [27], but that relation should be studied in greater detail.

We inferred that the marine sediments in the hydrothermal activity areas come from recurring explosive events, during the hydrothermal discharges. As shown in Figure 4, the kurtosis of the WHA areas was platykurtic to very platykurtic. Fuentes-Hernández [26] reported that this type of graphs reveals a process of forced sedimentation that shows a sudden deposition of material, and that leads to poor and very poor sorting.

As shown in Table 3 and Figure 5, we observed that the sediment samples with high mean values showed lower standard deviation values. This inverse relationship between the mean and standard deviation was also reported by Griffiths [28] and means that, at increasingly fine grain sizes, the samples have better sorting.

5. Conclusions

The marine sediments in the influence areas of SSHSPM are characteristics of those marine sediments in tidal areas where sediment accumulation occurs freely. These sediments are fine, sandy texture, and well sorted. The marine sediments of the areas with hydrothermal activity present grains ranging from very fine sand to very fine gravel, in addition to marine debris. The hydrothermal activity gives rise to the formation of mounds, whose sediments are composed of very fine gravels (mainly remains of altered basalt by the hydrothermal discharges) and very coarse to very fine sands, being these poorly sorted sediments. Waves, bottom currents, and meteorological phenomena condition the existence of these mounds. The results presented here are intended to be used as a preliminary reference framework for future studies related to the marine sediments of SSHSPM. Further research is recommended to determine the timing and distribution patterns of the sediments in this shallow hydrothermal system.

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