

Periodic Behavior of the Bubble Jet (Geyser) in the Taketomi Submarine Hot Springs of the Southern Part of Yaeyama Archipelago, Japan

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Introduction

The Taketomi submarine hot spring is a hydrothermal vent in the eastern Taketomi Island in Yaeyama archipelago, Japan (Figure 1). Photosynthesis biotas, such as Acroporid coral etc., inhabit the area surrounding the hot spring (Nakamura et al., 2006). However chemosynthetic organisms live near the hydrothermal vent and use chemicals, such as methane and hydrogen sulfide, for energy.

Thus, a different ecosystem exists in this unique shallow water region near the Taketomi submarine hot spring. Since coral is flourishing in the shallow water region where methane

ABSTRACT

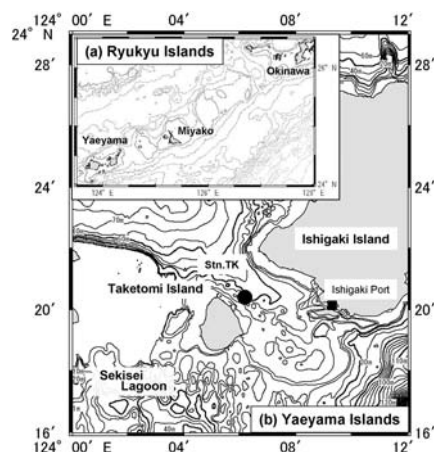
The periodicity of the bubble jet that spouts intermittently from the Taketomi submarine hot spring in Yaeyama archipelago, Japan, was measured for the first time using an acoustic current meter. The time series analysis of the upward velocity for the data, without a spiky signal, indicates that the cycle fluctuates between 38 and 85 s. Focusing on the period of high and low tide, the dominant time cycles were 66 and 41 s, respectively. These results show that the fluctuation of pressure with tide affected the eruption period of the bubble jet. In accordance with the vertical tube theory, estimations of thermal source and recharge water temperatures were carried out by taking into account the boiling point change due to the tidal variation in hydrostatic pressure. The result indicated that if the heat source temperature was higher than 200.0 °C and recharge water temperature was preheated to 117.96 °C, the observed eruption time cycles at high and low tide were stable.

Keywords: Taketomi Submarine Hot Spring, undersea geyser, periodic analysis, tide, boiling-point elevation

is blowing off, we expect that the Taketomi submarine hot spring has a definite influence on the coral reef ecosystem.

FIGURE 1

Taketomi Island and its surrounding ocean area. (a) Ryukyu archipelago, Japan. (b) Observation point of the submarine hot spring at Taketomi Island (Stn.TK).



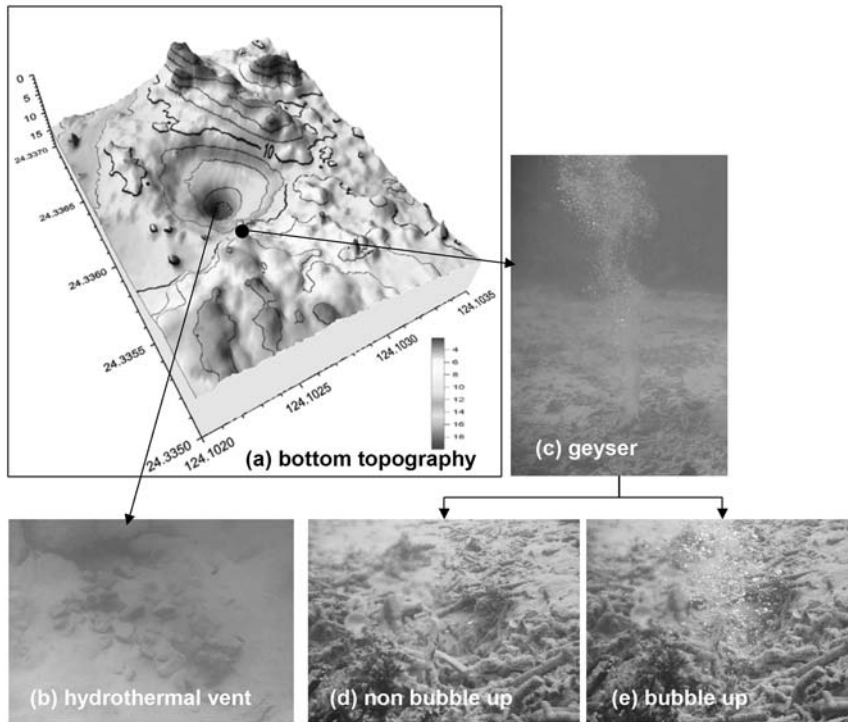
Geographically the submarine hot spring has the form of a mortar (Figure 2). Many small-scale bubble jets, like a curtain of fine bubbles, can be intermittently seen coming from the main hydrothermal vent on the south-southwest slope. A geyser with a diameter of about 30 cm, located 35 m south-southwest of the main vent intermittently releases a bubble jet. The Taketomi submarine hot spring is the only geyser in Japan's coral reef region and is famous as a scuba diving spot and tourist attraction.

The geochemical observations of blowing gas (Kaneshima et al., 1983), hot spring water and sediment (e.g., Oomori, 1987, Oomori et al, 1991) that were conducted at the Taketomi submarine hot spring suggest that the gas is volcanic (Kaneshima et al., 1983). Analysis of the blow off gas ingredients pointed to this conclusion.

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FIGURE 2

Observation site in Taketomi submarine hot spring. (a) Bottom topography map using multi-beam echo sounder, (b) main hydrothermal vent, (c) geyser at a point 35 m south-southwest, (d) non-bubble jet eruption, (e) bubble jet eruption. Diameter of geyser blowhole is about 30 cm.



Moreover, Omori (1987) suggested that the Taketomi submarine hot spring originated in hydrothermal activity in the Ryukyu archipelago since many heavy metals are contained in the sediment. Though geochemical observations were conducted near the Taketomi submarine hot spring, there has been no study of the fluctuations in the physical oceanographic environment. Therefore, we studied the Taketomi submarine hot spring with a view toward understanding the influence of the gas spout and hot spring water on the coral reef ecosystem.

Most of the research on geysers has been done in hot spring regions on land (e.g., Yuhara and Seno, 1969; Bryan, 1995). Nomura et al. (1995) investigated the temperature and tremor of erupting fluids in the Sewatashi

geyser of Oita Prefecture in order to clarify the action and physical processes of periodic geysers. This work showed the different periodicities of 30 minutes, 1 hour, and 4 hours in active geysers. Imura et al. (1999) describe geyser boiling which arises at low heat flux and low pressure in two-phase thermosyphons. In addition, Ingebritsen and Rojstaczer (1993) pointed out that seismic events, atmospheric loading, and Earth tides could be affected by the periodic fluctuation of geyser on land. Thus, research about periodicity of geyser on land has been performed, but not the research required for the continuous measurement of current velocities associated with oceanic geysers. The environmental factor causing the periodicity of oceanic geysers and the fluctuation of their

eruption periods have not yet been elucidated.

The purpose of this study was to clarify the periodic behavior of the bubble spouted from the geyser on the south of the Taketomi submarine hot spring, and to obtain a primary approximation of both heat source and recharge water temperature as basic data on the physical environment of the spring.

Method of Field Observation

Study Site

Figure 2 shows the research sites at Taketomi submarine hot springs as it was from 28 to 29 September 2005. The geographical feature of the submarine hot spring has the form of a mortar (Figure 2(a)), and the depth of the main hydrothermal vent (Figure 2(b)) is about 20 m. There are many small-scale bubble jets that form a curtain of fine bubbles that can be seen coming from the main hydrothermal vent on the south-southwest slope. A geyser with a diameter of about 30 cm, producing an intermittent bubble jet, is located at a point 35 m south-southwest of the main vent and its average depth is 10.1 m (Figure 2(c)). Hydrothermal activity of the Taketomi submarine hot spring is similar to the hydrothermal activity of the Okinawa Trough where hydrogen sulfide, methane, heavy metals, etc. are contained in the spouting gas. When there is a large bubble, which blows off intermittently, the bubble can be easily observed on the sea surface.

Observation of Velocity at Geyser

The geyser at the Taketomi submarine hot spring blows off or vents a

bubble jet periodically (Figure 2(d) and (e)). Current direction, velocity, water pressure and water temperature were observed in the geyser. The acoustic current meter that we used is Aquadopp (Model: Aquadopp2000) made by Nortek AS. Aquadopp was placed near the geyser (Figure 3) in order to measure the upward flow velocity of the bubble jet. Extrapolating from the pressure sensor signal of our Aquadopp, the average depth of observation was 10 m.

Aquadopp consists of three transducers, two of which are oriented 90 degrees horizontally, and one that provides an oscillating acoustic wave pulse at a 45° slant angle. The Aquadopp current meter has special functions other than those of the standard model: (1) Echo frequency of 2 MHz, (2) Internal sampling rate (the maxi-

imum number of pings) of 23 Hz, (3) Measurement cell size (thickness of a setting layer) of 0.75 m, (4) Measurement distance along the beam is from 0.35 to 5.00 m. The Aquadopp was installed 1.25 m away from the center of the geyser (Figure 3), and measurement accuracy is assumed to be high. The measurement accuracy of Aquadopp is ± 1%, corresponding to ± 0.5 cm/sec of measured value.

Aquadopp can collect data for upward velocity (V_U), northward velocity (V_N), eastward velocity (V_E), beam intensities for the three components, water temperature, pressure, heading angle, pitch angle and roll angle. From the data for the last three angles we can determine whether our Aquadopp was anchored firmly in position. Takasugi (1998) gives a clear summary of the measurement principle for

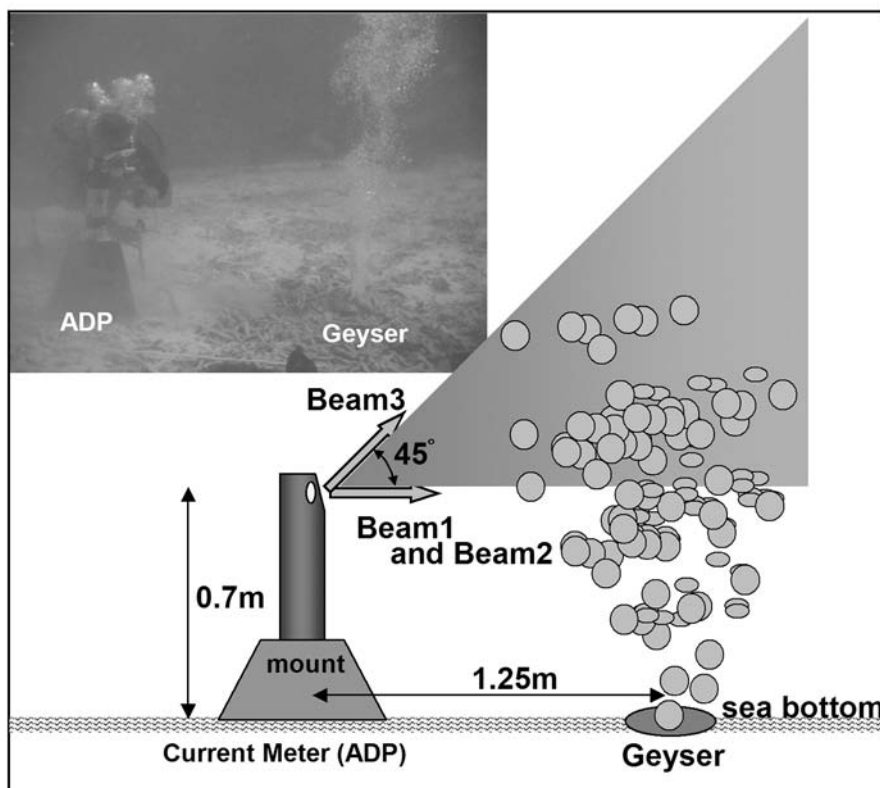
an acoustic current meter such as Aquadopp. When transducers (our Aquadopp has three) transmit an acoustic pulse in sea water, this pulse reflects off of, i.e. backscatters (BS) from, material such as marine plankton, etc, and returns to the transducers. If the backscattering material moves in the seawater, there is a difference in frequency between the reflected and the original pulse that is proportional to the velocity of the backscattering material. Assuming that the backscattering material and the seawater have the same velocity, that is, they all move together, we can measure the water velocity from this acoustic frequency difference which is based on the Doppler Effect. Practically, when we observe the thermal jet from the periodic spring using the acoustic current meter, the main contribution to backscatter seems to be bubbles of volcanic gas or suspended material originating from the seabed. If most scattering sites are bubbles, we have to determine whether the bubbles have the same upward velocities as the surrounding seawater. In this report, however, assuming that the upward velocity of the bubbles is the same as that of the surrounding seawater, we decided to take the data of upward velocity (V_U) measured by Aquadopp as the upward velocity of the surrounding water.

Measurement parameters for Aquadopp are as follows: time interval per one burst was one second, number of pings per burst was 23, because the internal sampling rate is 23 Hz. Because of the measurement technique, the resultant velocities for V_U , V_N , and V_E are averages for each burst.

We deployed our Aquadopp near the periodic spring near Taketomi Island from 21:00 on September 28, 2005 to 15:00 on September 29,

FIGURE 3

Positional relationship between our Nortek Aquadopp 2000 current meter and the undersea geyser. Beams 1, 2 and 3 and their arrows show the beam number and their transmitting direction.



2005. The predicted high and low water levels at Ishigaki port from the Japan Metrological Agency for this period are depicted in Figure 4(a).

Result and Discussion

Observations of the Physical Environment at Taketomi Undersea Geyser

Figure 4 shows the time series of sea level and all Aquadopp observation data. The sea level was monitored at Ishigaki Port (Figure 1) by the Japan Meteorological Agency. This sea level data was recorded as a height above a standard reference level for Ishigaki Island. The Aquadopp data shown are as follows: upward velocity (V_U), northward velocity (V_N), eastward velocity (V_E), average intensities of the three beams, pressure, water temperature, angles of sensor's heading, pitching and rolling.

Velocities (V_U , V_N and V_E), average beam intensity (Figure 4-1(b), (c), (d), (e)) show high frequency fluctuations. High frequency elements in the pressure data are most likely caused by small fluctuations of the seawater surface, induced by the thermal jet from the periodic spring. Since it is hard to grasp the trend of this data, we include a trend curve using a moving average with averaging length of 3600 second. Using these trend curves, the variance for V_U is from +0.1 m/s to +0.38 m/s (Vertical component); V_N is from -0.03 m/s to +0.07 m/s (North-South component); and for V_E is from -0.03 m/s to +0.08 m/s (East-West component).

The reason that the signs for the trend of V_U are always positive is that the upward velocity results from the thermal jet discharging from the blow-hole. Moreover, Figure 4-1(a) and (b)

show that the upward flow velocity increases a little at low tide.

Sea level fluctuation at the Ishigaki Island agrees with water depth change measurements obtained by Aquadopp at Taketomi undersea geyser. Water temperature varied from 31.2 °C to 30.3 °C.

The Taketomi submarine hot spring area is well known as a scuba diving spot. Therefore, the apparatus may have been moved because of diver interference during the measurement. This may account for the unusual measurement error for the data of Heading, Pitch, and Roll, which was obtained during the observation.

Difference in Time Series of V_U between High and Low Tide

We compared the time between eruptions for high and low tide. Figure 5-1 shows the contrast in the time series for V_U between high tide (04:00 - 06:00 on September 29, 2005) and low tide (11:00 - 13:00 on September 29, 2005). Comparing the fluctuation of V_U during high tide (Figure 5-1(a)) and low tide (Figure 5-1(b)) indicates a more rapidly changing V_U during low tide. In addition, the fluctuating range of V_U during high tide was between 0.6m/s and -0.2m/s, and low tide was between 0.8m/s and -0.1m/s (Figure 5-1).

In Figure 5-2 the contrast in the time series of V_U is enlarged between high tide (05:00-05:10 on September 29, 2005) and low tide (12:00-12:10 on September 29, 2005). As shown in Figures 5-1 and 5-2, the variable time cycle of V_U at high tide seems to be longer than that at low tide.

Characteristics of Dominant Time Cycle

A power spectrum density of the data in Figure 5-1 was carried out in

FIGURE 4

Time series of sea level at Ishigaki Island and data collected by our Aquadopp current meter. (a) Sea level at Ishigaki Island recorded as a height above its reference, (b) upward velocity (V_U), (c) north-south horizontal velocity (V_N), (d) east-west horizontal velocity (V_E), (e) average beam intensity. V_U in hatching regions are enlarged in Figure 5-1 and 5-2. The sea level at Ishigaki Island was monitored by Japan Meteorological Agency.

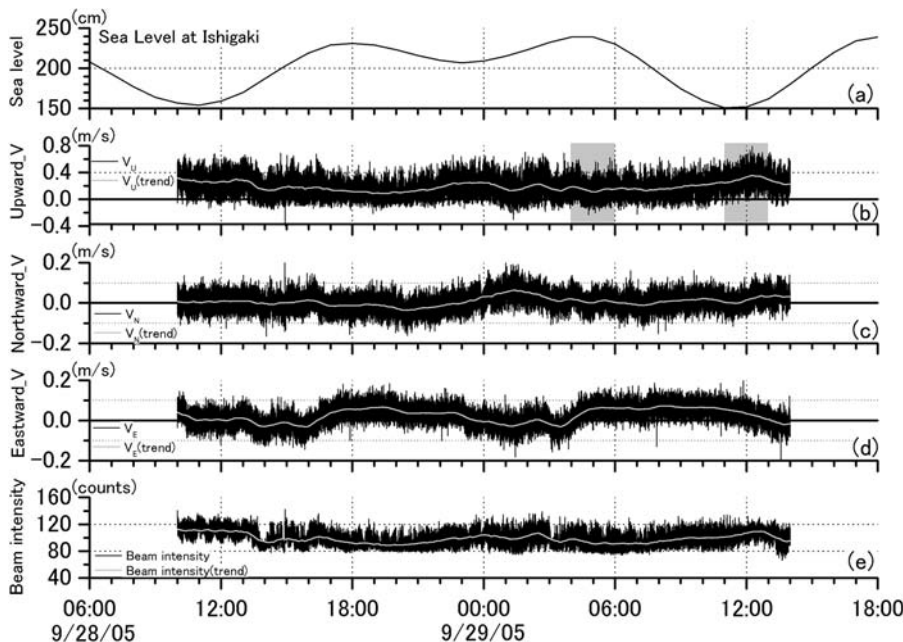
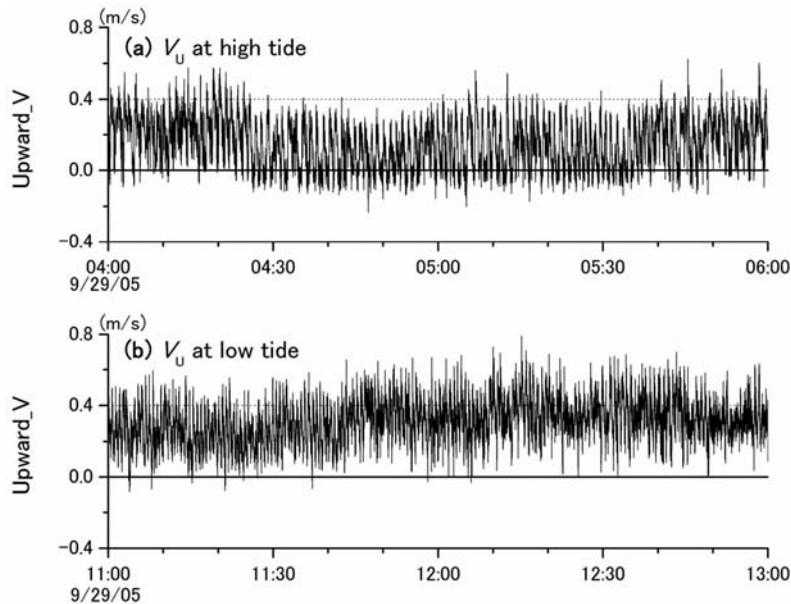
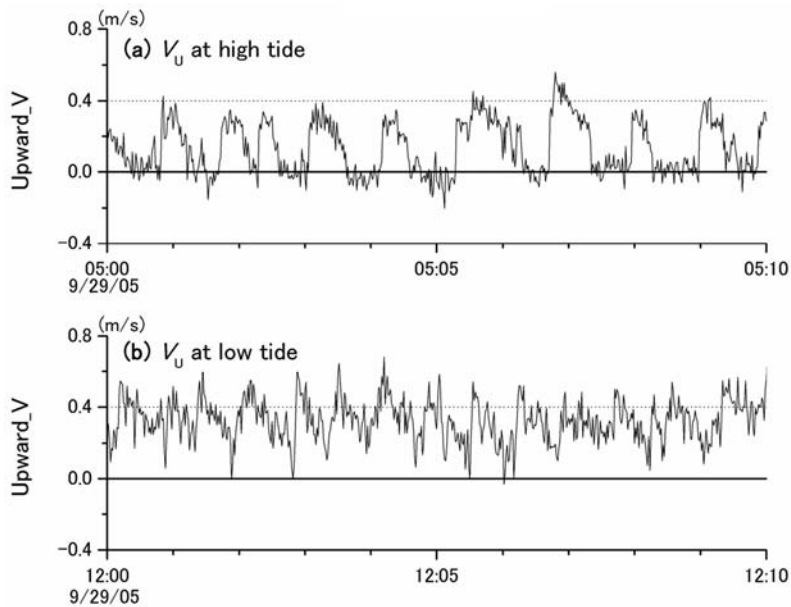


FIGURE 5

5-1. Contrast of time series of V_U between (a) high tide (04:00- 06:00 On September 29, 2005) and (b) low tide (11:00-13:00 on September 29, 2005).



5-2. Contrast of time series of V_U between (a) high tide (05:00-05:10 on September 29, 2005) and (b) low tide (12:00-12:10 on September 29, 2005).



order to examine the dominant time cycle of eruption (Figure 6-1). Because the dominant frequency of eruption seems to exist only from 10 s to 180 s, we looked for the dominant time cycle in this range with high power spectrum

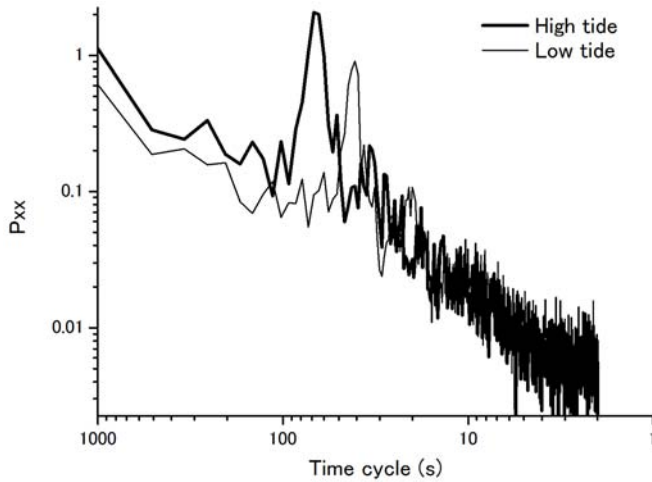
density. The dominant time cycle at high tide is 66 s and 34 s, and at low tide 41 s and 20 s. It appears that at high tide the time cycle of eruption is longer; while at low tide the time cycle is shorter.

Time Cycle Fluctuation of Eruption

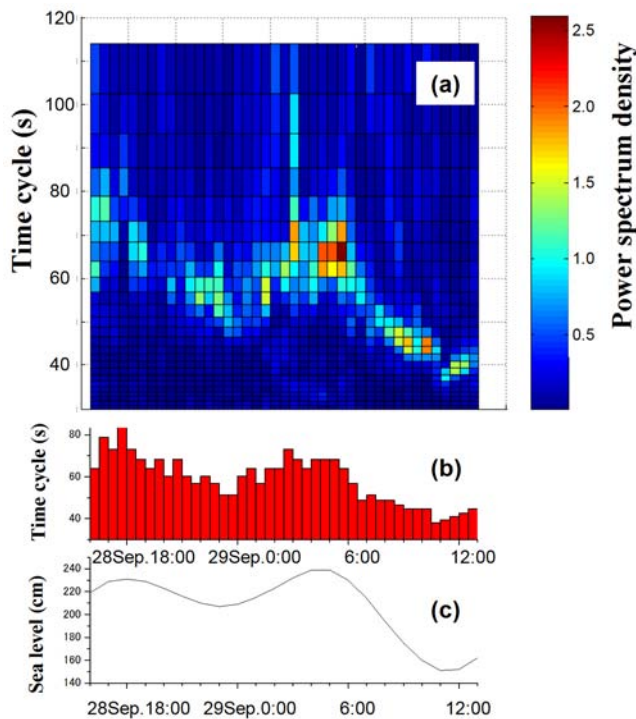
Encouraged by the result shown in Figure 6-1, we examined the trend of the time cycle for the periodic spring. Data corresponding to 21 hours from 16:00 on September 28 to 13:00 on September 29 was used for analysis. We separated the time series of V_U every 30 minutes and power spectrum densities were computed for each of these 30 minute intervals. In Figure 6-2(a) the range of the time cycle (X-axis) changes from 30 s to 120 s, because this is the range for the dominant time cycle of eruption. Figure 6-2(b) shows the dominant time cycle of the eruption. Figure 6-2(c) is the time series of sea level at Ishigaki Island. To find the dominant time cycle, we scanned the time series of the power spectrum densities shown in Figure 6-2(a). From these results, as shown in Figure 6-2(b), the longest time cycle of 85 s was observed during the high tide at 17:30-18:00 on September 28, which is a lower high tide than the high tide on September 29. In contrast, the shortest time cycle of 38 s was observed during the low tide at 10:30-11:00 on September 29, which is the lower of the two low tides that occurred during our observation period. From the higher high water to the lower low water, the longest time cycle of 68 s as observed during 05:00-05:30; which is the higher of the two high tides. From 05:00 through 11:00, the time cycle diminishes and after 12:00, the dominant time cycle tendency increases. Figure 7 shows the correlation between the sea level and the time cycle of the eruption. The solid line in the Figure 7 is the result of a simple linear regression model. Its correlation coefficient (R) is about 0.87 (rate of rejection, $P < 0.0001$), which means that the time cycle of the eruption is

FIGURE 6

6-1. Contrast of power spectrum density of V_U between high tide and low tide. Analyzed data are shown in Figure 5-2.



6-2. Time series of (a) power spectrum density, (b) dominant time cycle and (c) the sea level at Ishigaki Island. Power spectrum density of V_U in Figure 6-2(a) is depicted from 16:00 on September 28, 2005 through 13:00 on September 29, 2005. Range of time cycle (Y-axis of the top figure) is from 30 second to 120 second, because this is the range for the dominant time cycle.



strongly associated with the sea level. This result shows that the sea level (tide level) seems to control the time cycle of the periodic spring.

Mass Flux of Eruption of Geyser

The upward mass flux, dominant time cycles of eruption and sea level at Ishigaki Island from 04:00 to

13:00 on September 29, 2005 are shown in Figure 8. The upward mass flux was integrated over the upward flow velocity for 10 minutes, and calculated as mass per unit area. The upward mass flux tended to increase, when the sea level dropped. This difference of mass flux was explained as resulting from the difference of quiescent time of the geyser between at high and low tide. If unit upward mass flux for one blowout is steady, the amount of the upward mass flux per unit time depends on the number of blowouts per unit time. Thus, the upward flux at low tide is larger than at high tide, because the dominant time cycle (quiescent time) of the geyser at low tide is shorter than at high tide.

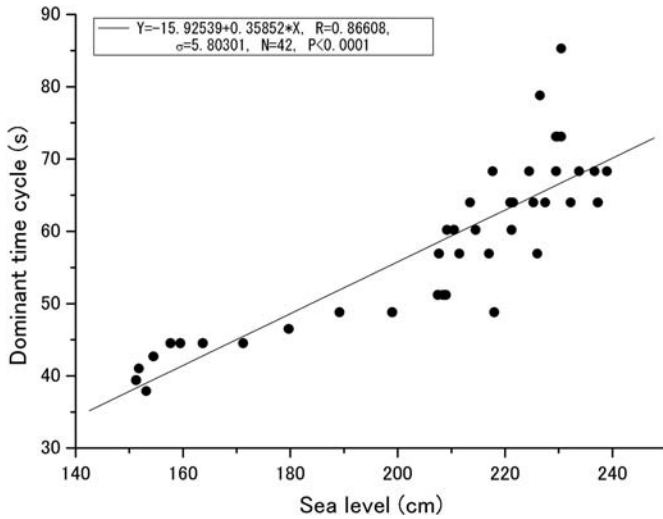
If the flux of a geyser is known, the methane or heavy metal loads can be determined. Acroporid coral, and like species, inhabit the area surrounding the hot spring (Nakamura et al., 2006). Therefore, these results will serve as basic data to assist in our understanding of the influence of the geyser on the photosynthetic activity around the Taketomi submarine hot spring. Furthermore, it can contribute to the understanding of the coral reef ecosystem by comparing the physical environment of the Sekisei lagoon (Furushima et al., 2002, Furushima and Okamoto, 2002) to the Taketomi submarine hot spring.

Application of Vertical Tube Theory of the Taketomi Submarine Hot Spring Geyser

Here we consider a qualitative mechanism for the Taketomi submarine hot spring geyser. There are two different mechanical theories for the production of a geyser. One is the cavity theory, and the other is the vertical tube theory (Yuhara and

FIGURE 7

Correlation between the sea level and the time cycle of the eruption. The solid line is the result of a simple linear regression model. Its correlation coefficient (R) is about 0.87 and its rate of rejection is less than 0.0001 ($P < 0.0001$).



Seno, 1969). In the cavity theory, the existence of a cavity is assumed. The vertical tube theory does not require the existence of a cavity to explain the periodic behavior of the geyser. The vertical tube theory is well-suited to explain the mechanism of a geyser whose upwelling flux for each eruption is small and the time cycle is short. Therefore, we assume that the geyser in the Taketomi submarine hot spring is controlled according to the vertical tube theory (Figure 9).

The vertical tube theory is as follows:

- Consider a vertical tube.
- There is water of temperature θ in area A (effective volume M) of the middle of a vertical tube and receives heat from a heat source having temperature Θ (domain of upper and under sides of area A are not heated).
- When the water temperature of area A reaches the boiling point (water temperature θ_1), the water of area A boils, and pushes the water in the upper part of the vertical tube out, creating the spout.

- After the blowout, recharge water (water temperature θ_0) of the posterior part of the vertical tube intrudes into area A, and stops the boiling.
 - This new water in area A is reheated, boils, and blows out again.
- Yuhara and Seno (1969) proposed equation (1) as the geyser time cycle in vertical tube theory.

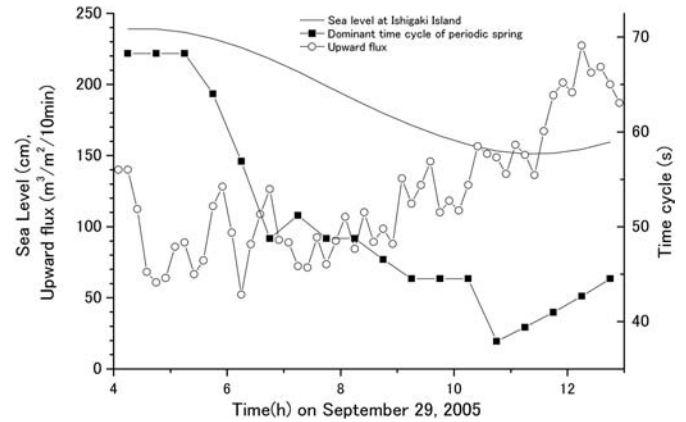
$$t_1 = \frac{M}{c} \ln \left(\frac{\Theta - \theta_0}{\Theta - \theta_1} \right) \quad (1)$$

Where c is a constant related to specific heat and transfer of seawater, M is the effective volume of the heated domain, and Θ and θ are temperatures of the thermal source and the water in the heated domain respectively. Furthermore, θ_0 and θ_1 are the initial and boiling temperatures of the recharge water, respectively.

Now we consider the pressure-dependent time cycle of the geyser at Taketomi submarine hot spring which has the mechanism described by Eq.b(1) (Yuhara and Seno, 1969) as follows.

FIGURE 8

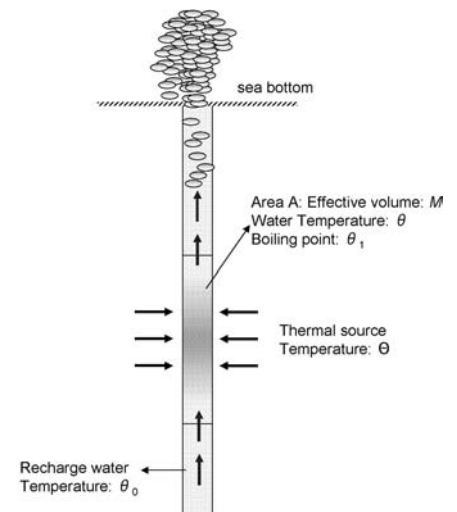
Time series of upward mass flux, dominant time cycle and sea level at Ishigaki Island from 04:00 on September 29, 2005 through 13:00 on September 29, 2005. Mass flux was integrated with the upward flow velocity for each 10-minute interval.



- Large M of domain A means a longer t_1 .
- High θ_0 means a shorter t_1 . $\theta_0 \rightarrow \theta_1$ produces a continuous discharge instead of a periodic blowout.
- High θ_1 means a longer t_1 .

FIGURE 9

Schematic view of the vertical tube theory. M is effective volume of the heated domain, and Θ and θ are temperatures of the thermal source and the seawater in the heated domain, respectively. θ_0 and θ_1 are initial and boiling temperature of the recharge water, respectively.



In the case of the Taketomi submarine hot spring, when the tidal level is high, hydrostatic pressure at the sea bottom is high. Therefore, we thought that the boiling point of recharge water (θ_1) would also increase. As a result, high tide will cause a longer t_1 and low tide will cause a shorter t_1 . From the spectrum analysis of our data, t_1 is 66 s at high tide and 41 s at low tide. This result qualitatively is consistent with iii) above.

Therefore, we examined the relationship between the thermal source temperature (Θ) and the recharge water temperature (θ_0), which should satisfy the observed conditions. This relationship was examined after taking into account the boiling point change inside the vertical tube which is dependent on the exterior hydrostatic pressure. If Θ and θ_0 are constant then from Eq. (1), the ratio of the dominant time cycles of high tide (t_{1h}) and the low tide (t_{1l}) are shown in Eq. (2).

$$\frac{t_{1h}}{t_{1l}} = \frac{A_0 - \ln(\Theta - \theta_{1h})}{A_0 - \ln(\Theta - \theta_{1l})} \quad (2)$$

Where θ_{1h} and θ_{1l} are boiling points of recharge water in the vertical tube at high and low tides respectively, A_0 is defined as $A_0 = \ln(\Theta - \theta_0)$ respectively, and we define $k = t_{1h}/t_{1l}$, Eq. (2) is solved on θ_0 for Eq. (3).

$$\theta_0 = \Theta - \exp\left(\frac{k \cdot \ln(\Theta - \theta_{1l}) - \ln(\Theta - \theta_{1h})}{k - 1}\right) \quad (3)$$

After assigning observed and estimated values from Table 1 to variables in Eq. (3), Figure 10 indicates the relationship between Θ and θ_0 . As a result, if the temperature of the thermal source (Θ) was higher than 200 °C, and recharge water temperature (θ_0) was an asymptotic temperature of $\theta_0 (= \theta_{0s} = 117.96$ °C), the

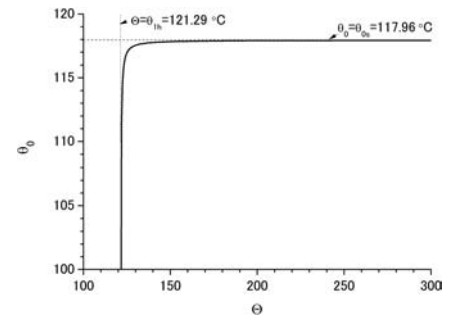
TABLE 1

Applied the value to calculate heat source temperature (Θ) and recharge water temperature (θ_0). Boiling point of the recharge water (θ_1) as a function of pressure and salinity was quoted from "Data book for seawater science and salt production" (The Salt Industry Center of Japan, 2006).

Dominant time cycle(t_1)	At high tide (t_{1h})	66 s
	At low tide (t_{1l})	41 s
	$k = t_{1h}/t_{1l}$	1.6
Average Depth	D	10 m
Sea level difference	$\Delta = \text{high tide} - \text{low tide}$	1.0 m
Depth	At high tide ($D + \Delta/2$)	10.5 m
	At low tide ($D - \Delta/2$)	9.5 m
Air pressure	P_0	10 dbar
Pressure of the sea bottom	At high tide	20.5 dbar
	At low tide	19.5 dbar
Salinity of recharge water	S	35
Boiling point of recharge water inside vertical tube	At high tide (θ_{1h})	121.29 °C
	At low tide (θ_{1l})	120.24 °C

FIGURE 10

Relationship between thermal source temperature (Θ) and recharge water temperature (θ_0) after considering the observed and estimated values in Table 1. θ_{0s} is an asymptotic value of θ_0 when Θ becomes infinity.



observed eruption period of geyser was satisfied.

Note that the recharge water must be preheated to θ_{0s} before it reaches the vertical tube, which is far hotter than the temperature of the seawater which ranged from 30.3 °C to 31.2 °C. Even if the seawater temperature is far lower than θ_{0s} , the observed time cycle can be measured if the seawater subsident is preheated to θ_{0s} through heat exchange with the thermal source. If $\Theta > 200$ °C was satisfied in all parts of the underground of the geyser, this condition could be satisfied.

There are some estimation values of temperature of "deep underground water" at the Taketomi hot spring (Oomori et al., 1993). Kaneshima et al. (1983) estimated the temperature at about 200 °C after considering mixing ratios between the seawater and the deep underground water. Kimura et al. (1985) estimated the temperature at about 200 °C using a silica thermometer that is used in geothermal areas. Oomori (1987) estimated the temperature at about 160 °C after considering that Mg^{2+} concentration must be zero in original "pure" hydrothermal solutions under high temperatures.

On the other hand, we concluded that the thermal source temperature (Θ) should be over 200 °C and the recharge water temperature (θ_0) 117.96 °C by using the observed time cycle of the geyser and the vertical tube theory. The reported values of the temperatures of “deep underground water” can be equated to the thermal source temperature (Θ) in this study. Therefore, our estimated $\Theta > 200$ °C is consistent with those reported temperature ranged from 160 to 200 °C.

Unfortunately, we don't have any data that can confirm the origin of the recharge water because we didn't measure temperature and chemical quantity of discharge from the geyser. However, we can introduce a simple estimation conducted by Kaneshima et al. (1983). They implied that the discharge water at the Taketomi Submarine Hot Springs is mainly composed of the seawater. They estimated that ratio of the seawater among all discharge from the main hydrothermal vent (Figure 2) was 93%. For this calculation, they assumed that concentrations of Cl^- and Na^+ in the seawater and the spring water had fixed values. Then they calculated the mix ratio that was accountable for the Cl^- and Na^+ concentrations in the discharge from the main hydrothermal vent.

Summary

In this study we have observed periodicity of the bubble jet that spouts intermittently near the Taketomi submarine hot spring in the Yaeyama archipelago. The geyser at the Taketomi submarine hot spring is located at a point 35 m south-southwest of the main vent, which is a geyser with a diameter of about 30 cm. An acoustic current meter was placed near the geyser from 28 to 29 September 2005 in

order to measure the upward flow velocity of the bubble jet.

As a result of our time series analysis, the upward velocity for the data, with no spiky signal, indicates that the cycle fluctuates between 38 s and 85 s. Furthermore, when we focus on it at high and low tides, the dominant time cycles were 66 and 41 s, respectively. This result indicated that fluctuation of pressure, due to tide level change, affected the eruption period. The vertical tube theory was able to explain the difference of a predominant period of bubble blowout from the geyser after taking into account the change in boiling point due to tidal static pressure fluctuation. In addition, if the heat source temperature in the vertical tube was higher than 200.0 °C and the recharge water temperature was at its asymptotic temperature (117.96 °C), the observed eruption period of geyser was satisfied.

In the future, we expect that it will be necessary to carry out research to evaluate the quantity of geyser spout and the mechanism of blowout. And further comprehensive field experiments, to obtain the unknown parameters (M , c , Θ , θ_0 , θ_1), will be needed to fully understand the difference in t_1 at high and low tides. Additionally we would like to carry out ecosystem research in the area surrounding the Taketomi submarine hot spring and also research to clarify the details of the geyser's spouting mechanism.

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