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Recent Developments of Exploration and Detection of Shallow-Water Hydrothermal Systems

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Abstract: A hydrothermal vent system is one of the most unique marine environments on Earth. The cycling hydrothermal fluid hosts favorable conditions for unique life forms and novel mineralization mechanisms, which have attracted the interests of researchers in fields of biological, chemical and geological studies. Shallow-water hydrothermal vents located in coastal areas are suitable for hydrothermal studies due to their close relationship with human activities. This paper presents a summary of the developments in exploration and detection methods for shallow-water hydrothermal systems. Mapping and measuring approaches of vents, together with newly developed equipment, including sensors, measuring systems and water samplers, are included. These techniques provide scientists with improved accuracy, efficiency or even extended data types while studying shallow-water hydrothermal systems. Further development of these techniques may provide new potential for hydrothermal studies and relevant studies in fields of geology, origins of life and astrobiology.

Keywords: hydrothermal fields; shallow water; vent mapping; in-situ observation; water sampler

1. Introduction

About forty years ago, the earliest submarine hydrothermal (HT) vent was found on the East Pacific Rise [1], which marks the beginning of HT research. In past decades, detailed studies on HT vent systems have greatly changed our ideas on submarine biological, chemical and geological processes. The extremely hot, acidic and anoxic environment around HT vents gives birth to various novel life forms [2,3]. Such environments provide constant energy, abundant organic elements and large temperature gradients that enable the polymerization of long-chain molecules. This was believed to be one of the possible conditions for the origins of life [4–6]. Massive seafloor sulfides and manganese near active or inactive HT fields were also presumed to be the result of HT activities [7–9]. These minerals not only brought new insight into seabed mineralization mechanisms, but also provided potential resources for commercial mining [9]. Besides, the hot, metal-rich plume discharges from the vents form an important part of the heat and chemical exchange between the lithosphere and the ocean [10], which is essential for global environmental studies. These particular features provide unique research conditions for the specified science fields, and thus have attracted the attention of a growing number of researchers.

In past decades, many scientists have reported their work on HT activities and their surrounding environments. But early studies mainly concentrated on HT systems located at deep ocean, e.g., the East Pacific Rise or the Central Indian Ridge [11,12]. Research on shallow-water hydrothermal

(SHT) systems were seldom found until the end of the 20th century [13]. Tarasov defines shallow-water hydrothermal (SHT) vents as vents located at a depth of 200 m or less considering the degree of obligacy of fauna [14]. According to this definition, 22 SHT zones have been found on Earth (Table 1) [14]. Their brief locations were indicated in Figure 1.

Table 1. The location and depth of known hydrothermal (HT) vent fields [14,15].

Index	Depth/m	Area	References
1	0~?	Capo Misseno Golfo di Napoli	Gimenez and Marin, 1991 [16]
2	0~10	Santorini Island, Greece, Aegean Sea	Dando et al., 1995 [17]
3	0~10	White Point Palos Verdes, California	Stein, 1984 [18]
4	0~27	Matupi Harbour, New Britain Island, Papua New Guinea	Tarasov et al., 1999; Tarasov, 1999, 2002 [19–21]
5	0~30	Kratemaya Bight Ushishir Voclcano, Kurile Islands	Buzhinskaya, 1990; Turpaeva, 2000 [22,23]
6	0~30	Cape Palinur, Italy	Southward et al., 1996 [24]
7	0~30	Punta Mita and Punta Banda, Baja California	Prol-Ledesma, 2003; Prol-Ledesma et al., 2004 [25,26]
8	0~167	Bay of Plenty, New Zealand	Kamenev et al., 1993 [27]
9	1.2~1.5	Kunashir Island, Kurile Islands	Kostina, 1991 [28]
10	3~115	Milos Island Greece, Aegean Sea	Gamenick et al., 1998 [29]
11	5	Nishino-shina Shintoh, Ogasawara Islands, Japan	Takeda and Kubata, 1977; Takeda et al., 1993 [30,31]
12	5	Kita-Iwojina Iwo Islands, Japan	Takeda et al., 1993 [31]
13	5~10	Tutum Bay, Ambitle Island, Tabar-Feni chain, Papua New Guinea	Pichler et al., 1999a, 1999b, 2000 [32–34]
14	8~20	Kueishan Is. China Taiwan	Jeng, 2000; Ng et al., 2000 [35,36]
15	9~13	Bahinde Pozzuoli Gulf of Naples, Italy	Gimenez and Marin, 1991 [16]
16	10~30	Panarea Eolian Island, Italy	Acunto et al., 1995; Colangelo et al., 1996; Lucila et al., 1996 [37–39]
17	16~45	D. Joao de Castro Bank, Azores	Avila et al., 2004 [40]
18	23~26	Akusekijina, Tokara Islands, Japan	Takeda et al., 1993 [31]
19	63~114	Esmeralda Bank, W Pacific	Turkay and Sakai, 1995 [41]
20	82~110	Kagoshima Bay, Japan	Miura et al., 1997; Miura, 1997 [42,43]
21	100~106	Kolbeinsey, north of Iceland	Fricke et al., 1989 [44]
22	200	Macauley Caldera, Northern Kermadec Ridge	Von Cosel and Marshall, 2003; Smith et al., 2004 [45,46]

Figure 1. The brief location of the known shallow-water hydrothermal (SHT) vent areas. The index in the figure is listed in Table 1 in detail. Multiple indexes on one symbol show the existence of several closely distributed vent areas [14].

Although SHT systems have similar inner structures and fluid formations with vents in deep-seas, distinct differences still exist in various aspects such as biomass, temperature, pH levels and derivatives. Due to its limited depth, the SHT plume may reach not only the surrounding region but also the surface layer of the water body, which gives rise to a close interaction with human activities and neighboring ecological systems. These factors emphasize the necessity of SHT studies.

Scientists and engineers have dedicated great efforts to the detecting, observing and sampling techniques on HT studies. Various equipment, including sensors, in-situ measurement systems or water/core samplers, was developed. Most of them were successfully applied in sea trials, and the others were tested under simulated conditions. However, most existing studies focus on deep-sea

HT systems, since the extreme pressure, temperature and depth made it a more challenging mission. This complicated, well-designed equipment was usually designed to be operated on a Remote Operated Vehicle (ROV), not by divers, and thus is not suitable for shallow-water operations. Furthermore, the difference in physical and chemical features makes some of the existing techniques developed for deep-sea HT observations unavailable in shallow-water applications. For example, the yttrium-stabilized zirconia (YSZ) electrode developed by Ding [47–49], which provides excellent performance in researching black smokers, was not suitable for direct use in shallow-waters due to its lower temperature limitation of 150 °C since the temperature of fluids in shallow depth is between 10 and 119 °C. On the other hand, the shallow depth and relatively low pressure made the SHT environment more accessible, which gave birth to novel approaches that cannot be used in deep-sea environments.

In this paper, the exploring techniques including detecting, observing and sampling techniques specified for SHT systems are addressed. Most of them have been tested in sea trials or under equivalent environments. The others have showed their potential for the application in shallow-water environments. Finally, the developing status of SHT exploring techniques concludes the paper and possible future works are discussed.

2. Detecting and Mapping Techniques for SHT Vent Fields

2.1. Surveying HT Plume with Multi-Sensors

Active HT vent fields continuously discharge hot vent fluids, which have been gradually diluted by the ambient seawater and form the mixing, buoyant turbulence known as HT plumes. HT plumes can spread from tens to thousands of kilometers under the influence of the ocean current [50,51]. The signature of the vent fluid in temperature, turbidity and chemical ingredients causes anomalies in the water column that can be used to detect the existence of HT plumes. By tracing and mapping HT plumes, the position of the HT vents can be further located.

One traditional way of searching for HT plumes in vast waters is surveying with vessels or ROVs equipped with towed multi-sensor systems (Figure 2). Usually a combination of physical and/or chemical sensors integrated in a protective shell is deployed to the depth where the HT plume may occur. The sensor bundle is connected to the vessel with cables to ensure real-time communication. Thus, when the sensors get in touch with the HT plume during navigation, the feature anomalies can be instantly recognized. To further improve the chance of encountering an HT plume, sometimes the deployment depth of the towed sensors is continuously adjusted to forms a "w" shaped trace, or a chain of sensors deployed discretely at different depths is applied (Figure 1). When the existence of an HT plume is confirmed, a refined survey at a lower depth or an up close survey such as optical observation will be performed to further locate the position of HT vents.

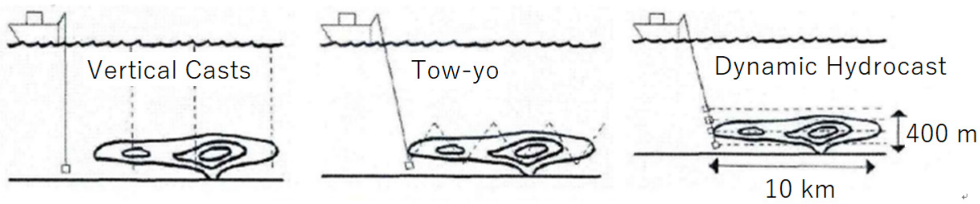


Figure 2. Vessels search HT plume using integrated multi-sensors [52]. The chance of encountering the HT plume can be enlarged by adjusting the depth of the towed sensors during the survey, or by using a vertical array of sensors.

Various physical and chemical features have been used to confirm the existence of HT plumes. These features can be roughly divided into three aspects: physical characteristics (temperature and turbidity), chemical characteristics (^3He, H_2, CO_2, CH_4, H_2S, Fe, Mn and Oxidation-reduction) and movement characteristics (rise height, advection of the non-buoyant layer) [10,53,54].

However, the sensitivity of these features in detecting HT vents differs. For example, turbidity anomalies can be detected tens of kilometers away, but the precision in locating the source is less than a few kilometers. Temperature anomalies can provide a location precision of a few hundred meters, but are difficult to detect. Oxidation-reduction has similar location precision to temperature and is sensitive to both high temperature vents and low temperature vents, which makes it a good choice for real-time surveys. Tao et al. compared the efficiency of the present vessel exploration methods and concluded that a combination of turbidity and oxidation-reduction potential sensors offers the best efficiency [53]. In recent years, researchers tend to use multiple sensors to search HT plumes to avoid false alarms. The existence of HT plumes is confirmed only when the potentials of different features coincide.

Surveying HT plumes with towed multi-sensors has led to the discovery of many deep-sea HT vents [53,55]. However, detailed reports on SHT detecting remain scarce. Nakatani et al. Nakatani et al. discovered an SHT vent area at a depth of approximately 200 m in Kagoshima Bay, Japan using a newly developed ROV TUNA-SAND (Figure 3) [56]. The vent was further observed by video camera. Liu et al. Liu surveyed the HT vent area south-east of the Kueishan Island on a vessel equipped with a sensor chain containing 4 chemical sensors, 1 turbidity sensor and 1 hydrophone [57]. Figure 4 shows the navigation track of the vessel. The survey indicated several HT vents that had not been reported.

Figure 3. TUNA-SAND and its survey in Kagoshima Bay, Japan. The ROV was released from the vessel and surveyed at a depth of approximately 200 m, searching for evidence of undiscovered HT vents [56].

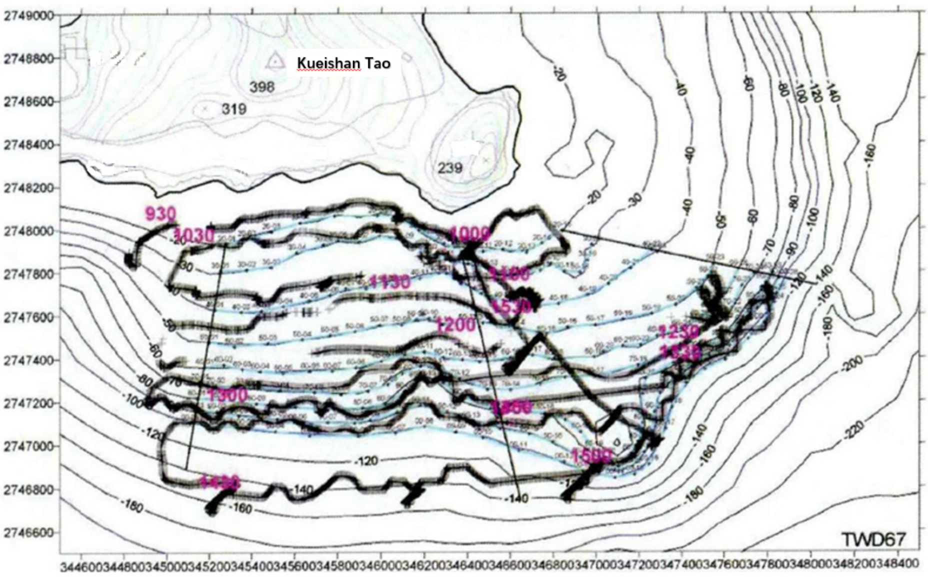


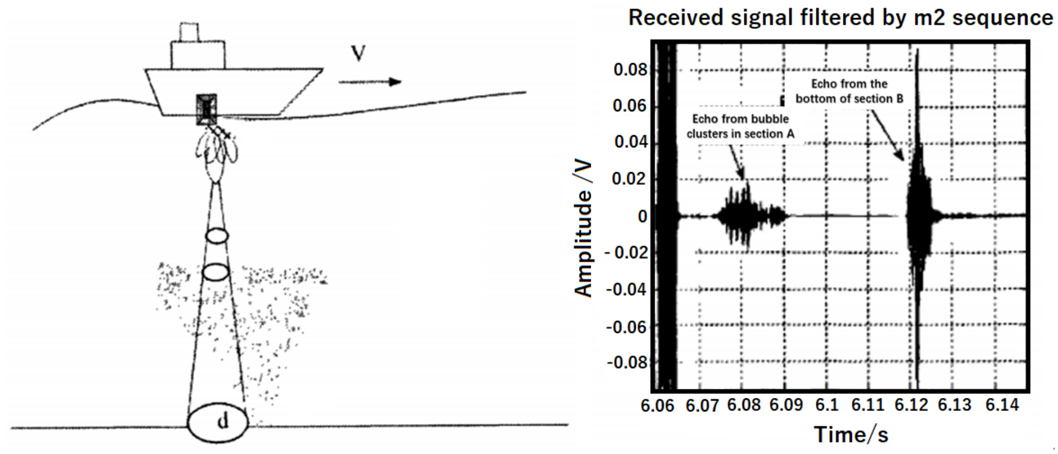
Figure 4. The navigation track of the survey south-east of Kueishan Island [57]. The sensor chain containing 6 sensors was released and towed during the survey. Data suggests the existence of undiscovered SHT vents in the surveying area.

In some other studies, though conducted in deep-sea HT areas, the navigation height of the towed sensors is in the scope of 5 to 250 m above the seafloor [58–60]. These studies somehow indicated the potential of applying similar detecting methods in SHT research.

2.2. SHT Vents Exploration with Bubble Cluster Detection

The gas (such as methane) that discharges from HT vents forms bubble clusters in the upper water column. The acoustic signature in reflection and scattering make it possible for the recognition of bubble clusters and their sources. Gas discharging is much more common in SHT vents compared to deep-sea HT vents [61]. The gas mixed with HT fluids can originate from the atmosphere or volcanic activities [62], and thus provides potential feasibility for bubble cluster detection.

Lin proposed an acoustic method for the remote detection of HT vents (Figure 5a) [63]. In his study, a transducer was fixed to the bottom of a vessel which cruised around HT areas. Sound waves were directly emitted downward to the seafloor. The anomalies in reflection tells the existence of possible HT vents and their positions. An acoustic HT detection system based on the abovementioned scheme was developed and tested in Song Hua Lake, Jilin Province, China. A fenestrated hose with one end connected to an air pump was deployed to the bottom of the lake to generate bubble clusters. A vessel equipped with the transmitter surveyed in an eight shaped track on the surface while emitting sound waves straightly downward at a carrier frequency of 20/200 Hz. The depth of the experimental area was about 40 m. Through analysis of the received signal, the depth and spreading range of bubble clusters were obtained (Figure 5b).



(**a**) (**b**)

Figure 5. Acoustic detection of bubble clusters associated with HT vents. (**a**) The sketch map of detecting bubble clusters; (**b**) the reflection signal received after filtering. The smaller peak indicates the position of bubble clusters. The larger peak indicates the depth of the lake [63].

Compared with HT plume tracking, the method of acoustic bubble cluster detection has obvious advantages in sensitivity and mapping accuracy. It responds immediately to the bubble clusters encountered and is applicable to all kinds of HT vents that discharge gases. Since bubbles are less affected by ocean currents while rising to the surface, the precision in mapping the corresponding HT vent is generally tens of meters to hundreds of meters, which can be further improved while conducted in extremely shallow waters.

So far, research on field experiments of HT exploration in shallow-waters by bubble cluster detection remains scarce. However, some sea trials conducted in deep-sea HT vent fields demonstrate encouraging results. Michio et al. reported acoustic water column anomalies (AWA) revealed by a two frequency Multi Beam Sounder (MBES) rising from HT vent fields in the mid-Okinawa Trough [64]. The AWA detected was attributed to the existence of droplets of carbon dioxide and HT plume. Kasaya et al. further applied a survey method using a hull-mounted MBES and a high-frequency MBES mounted on AUV to the HT exploration conducted at the North Iheya Knoll [65]. The existence of two unidentified HT activity zones was first discovered by the hull-mounted MBES. Later the detailed positions of the newly discovered HT activity zones were further obtained using the AUV-mounted MBES. These achievements demonstrated that the acoustic survey of HT activity related bubble clusters is one useful approach for HT exploration, especially in deep waters. However, considering the complexity of acoustic channels in shallow waters, further studies are needed to verify the effectiveness of acoustic survey for HT exploration in shallow waters.

2.3. Mapping SHT Vents Using Satellite Imagery

The limited depth of SHT vents makes it possible for the application of some remote sensing techniques, such as satellite imagery, which is not available for deep-sea HT studies. The potential of mapping and monitoring active HT systems with satellite images was reported by Martelat and his colleagues [66]. Satellite data spanning several years were involved in their study, some of them were proprietary WorldView-2 images which were taken with spectral bands that can penetrate water depths of up to 30 m. Fifteen SHT vent fields worldwide were identified in the available data, and two of them (Milos at Greece and Kueishantao at Taiwan) were further analyzed in detail. Figure 6 shows the satellite data image of HT outflow zones at Milos, Greece, at depths of up to 30 m (Figure 6a) and the image of turbidity due to HT plumes viewed at the sea surface at Kueishan Island, Taiwan (Figure 6b) [66].

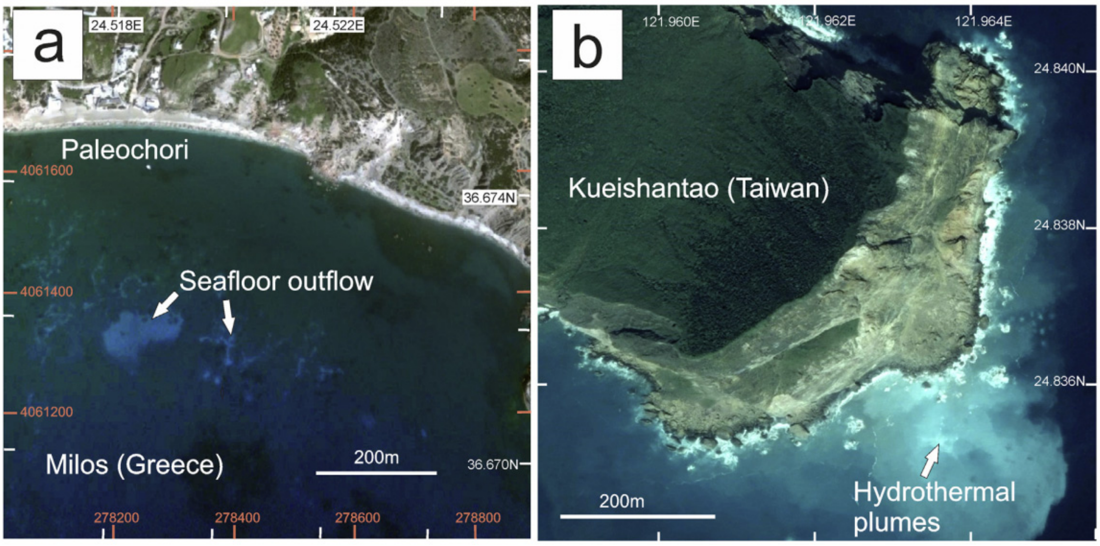


Figure 6. Satellite imagery of SHT vents. (**a**) Seafloor outflow observed in Milos associated with HT activities; (**b**) high turbidity HT plumes observed in Kueishan Tao [66].

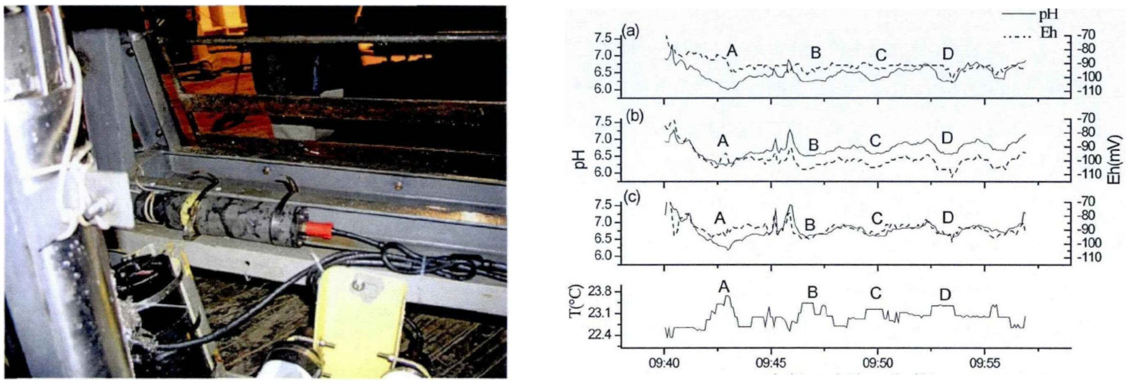
The result of their study shows that satellite imagery can not only be used to discover unknown SHT vents, but that it is also effective in analyzing the spatial-temporal change of the vent activities and its corresponding features, such as HT plumes, micro-bacterial mats and discharged particles. Compared to traditional field surveys, the approach of satellite imagery is more efficient and economical. It is especially suitable for large scale observations such as distribution of discrete vents, HT plume activities and turbidity variation associated with HT activities. The method is widely applicable since most of the satellite data involved in this pilot study are publicly available. The limitation of the approach generally lies in the quality of images and the nature of the HT vents. The former was easily affected by various factors such as light illumination, weather conditions or clouds, which might reduce the resolution of the satellite images or even make them unavailable. The later generally determines the visibility of an HT vent in the satellite image. HT vents that discharge reflective particles or exhibit visible HT features such as HT precipitates or large-scale micro bacterial mats are easier to identify.

3. In-Situ Observation Techniques for SHT Fluid

3.1. Direct Measurement Techniques

Direct measurement techniques include all kinds of chemical and physical sensors or probes that come into touch with the HT plume during observation. With the development of sensor technology, most of the sensors or measuring instruments needed for HT observation have been commercialized and can be directly applied in field surveys. However, the developing of new types of sensors is still of great significance to overcome the extreme acid, heat and corrosive environment in an HT flow.

Until now, few studies were found reporting sensors specially designed for SHT applications. But some studies have verified the performance of their newly developed sensors in SHT environments. Pan et al. developed an improved IrO_2 electrode for pH measurement with various promising properties including satisfying reproducibility and sensitivity, small open circuit potential drift, long life time and remarkable agreement with respect to potential/pH slopes and apparent standard electrode potentials of electrodes from the same batch [67,68]. The electrode can work steadily at pressures of up to 50 MPa and temperatures of up to 90 °C, and could be potentially used at temperatures of up to 150 °C. Such range perfectly covers the need for SHT measurement. The developed IrO_2 electrode, integrated with one Eh electrode and one Ag/Ag_2S, was tested in the lab and later applied in several marine investigations conducted in Kueishan Tao HT vent areas, including HT vents mapping and 3D HT plume structure detection (Figure 7).



(**a**) (**b**)

Figure 7. The IrO2 electrode applied in SHT studies in Kueishan Tao HT vent areas. (**a**) The integrated sensors; (**b**) pH and temperature measured in the HT plume of a yellow vent. The three pH curves refer to the pH measured at depths of 3, 5 and 7 m, respectively. The letters A, B, C and D mark the variation cycle of the temperature. When the temperature rises, the values of pH and Eh drop, indicating that the area is under the influence of HT fluids [68].

Ding proposed an all-solid type dissolved H_2S microelectrode optimized for its measurement range. The lower limit of detection was extended from 10^{-4} mol/L to 10^{-7} mol/L by direct current carrier electroplating. The sensor was also successfully tested in the HT vent field in Kueishan Tao (Figure 8) [69].

Figure 8. The H_2S microelectrode integrated in a multi-parameter chemical sensor [69].

Frank and his colleagues studied the micro-profiles of O_2, pH, H_2S and temperature of a shallow water HT vent system at Milos, Greece using a miniaturized version of a profiling instrument. Data obtained were used to analyze the microenvironment and microcirculation of the vent [70].

In summary, though not much isolated research was reported, the development of SHT direct measuring technique continues with the development of sensor techniques. The trend of future development may lie in the measurement range for higher measurement accuracy under extreme conditions, or in the stability and durability of the sensors to obtain a better performance in long-term observation.

3.2. Remote Sensing Techniques

Direct measurement techniques offer reliable, accurate data for HT studies. But the data collected are usually discrete, which provides only limited information when studying the continuous distribution of a certain parameter, e.g., temperature field or flow velocity field. A sensor array might extend the information collected [71], but the blocking effect of sensors to the HT fluid also prevents scientists from obtaining the original distribution of the desired parameter. Furthermore, the measurement error caused by sulfur deposition and the drifting effect during long-term measurement has long been a problem in the in-situ measurement of HT fluid [72].

To overcome the above shortcomings, a series of remote sensing approaches were developed to study the 3D structure, temperature distribution, flow field or heat flux field of the HT fluid. Taking photos or videos using underwater cameras is a traditional remote sensing approach. It intuitively records the appearance of the HT plume and the surrounding terrain or biological features, which is important in further analysis. It was widely used in the exploration of both deep-sea HT vents and SHT vents in past decades [69,73]. In recent years, the high-resolution photography and advanced algorithms provided by modern photogrammetry makes it possible to obtain even more information through photos. Gerdes et al. proposed their study on the 3D reconstruction approach of HT vent fauna based on video imagery. The vent was located at the southeastern Indian Ridge in the Indian Ocean. They used a motion photogrammetry structure to build a high-resolution 3D reconstruction model of one side of a newly discovered active HT chimney complex (Figure 9) [74]. Based on the random forest model, they predicted that accuracy on faunal assemblage distribution of the model has reached 84.97%. This technique provides scientists with the possibility to identify ecological distributions and terrain features on a larger scale. Though the data were collected in a deep-sea HT vent, the technique has the potential to work in various situations in marine monitoring, including SHT observations.

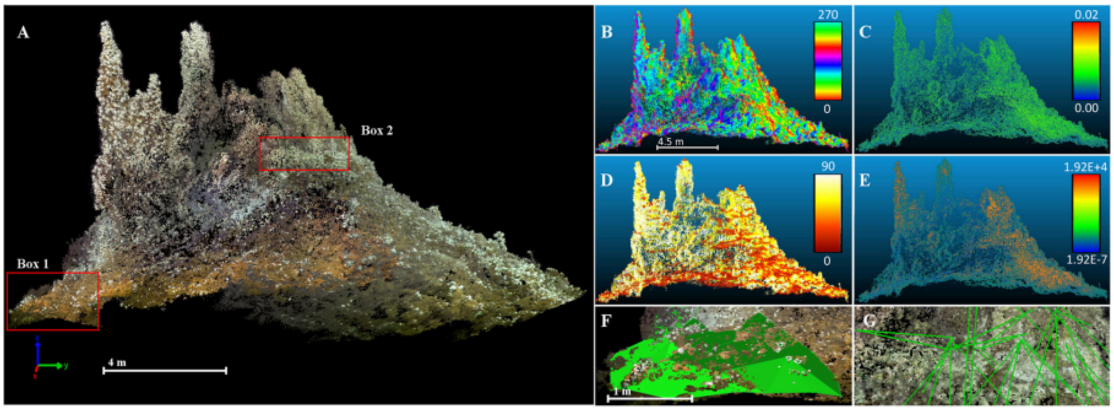
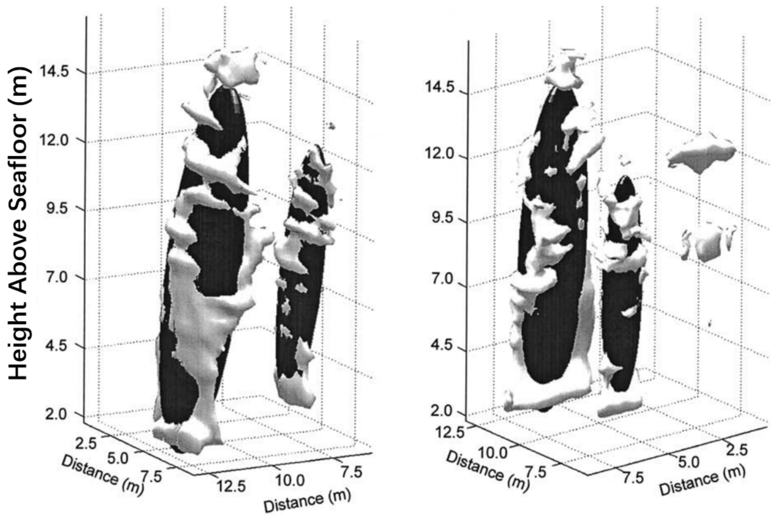


Figure 9. South side of reconstructed 3D textured dense point cloud and derived terrain variables [74]. (**B**) shows the aspect of chimney; colors on (**C**) show the different roughness; (**D**) shows the inclination of slope, with a maximum value of 90 degrees. (**E**) shows the Gaussian surface curvature. (**F**,**G**) are detailed views of box 1 and box 2 in figure (**A**), respectively.

Although photogrammetry provides us with abundant information on plume appearance, terrain signature and biological distribution, some invisible features, such as temperature and flow velocity, cannot be obtained. Besides, the high turbidity of water around HT vents often exerts a negative influence on photo quality. Thus, approaches based on acoustic methods were raised. Rona and his colleagues were among the earliest to research HT vents using acoustic methods [75–77]. During the dive in November 1990, they scanned an HT plume in arcuate sectors at increasing angular increments from the vent orifices up to 90° using a sonar system mounted on the submersible. Using the data collected, the 3D structure of the HT plume with a height of up to 100 m above the seafloor was successfully reconstructed (Figure 10).



(**a**) (**b**)

Figure 10. The front (**a**) and back (**b**) views of the reconstructed 3D image of two adjacent HT plumes [76]. The grey part in the figure shows the patterns of the HT plumes. The black part is the ellipsoids fitted to show the roughness of a plume.

The 3D imaging approach proposed by Rona was based on the scattering feature of sound beams on suspended particles that focused on the visualization of the plume structure. Fan et al. proposed an acoustic tomography method to measure the 2D temperature distribution around seafloor HT vents [72,78,79]. The measurement plain was covered by 96 acoustic paths generated by 16 hydrophones distributed on the edge of the plane (Figure 11a). Each hydrophone was used as the transmitter and the receiver at the same time. Signal correlation analysis was performed to obtain the time of flight (ToF) between two hydrophones, which reflects the average value of temperature distributed along the corresponding acoustic path. Based on all the ToFs collected, the reconstruction of the 2D temperature field was performed by the total least-squares method (Figure 11b). They tested their proposed method both in a swimming pool and around a hot spring beneath the Lake Qiezishan, Yunnan Province, China (Figure 12a,b). Satisfying results were obtained in both trials. The reconstructed temperature field (Figure 12c) in the Lake Qiezishan trial showed good accuracy with a maximum error of approximately 3.5 °C compared with the measurement results obtained by thermocouples. The Lake Qiezishan trial revealed its potential for the application in SHT observation.

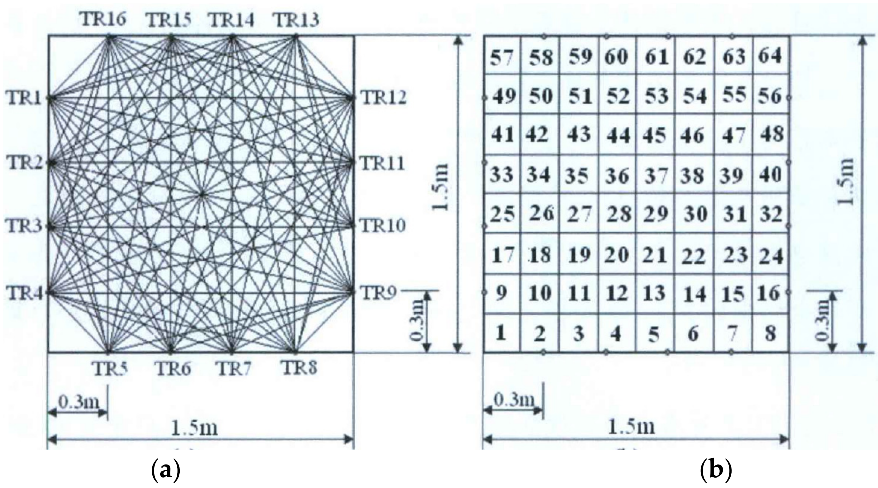
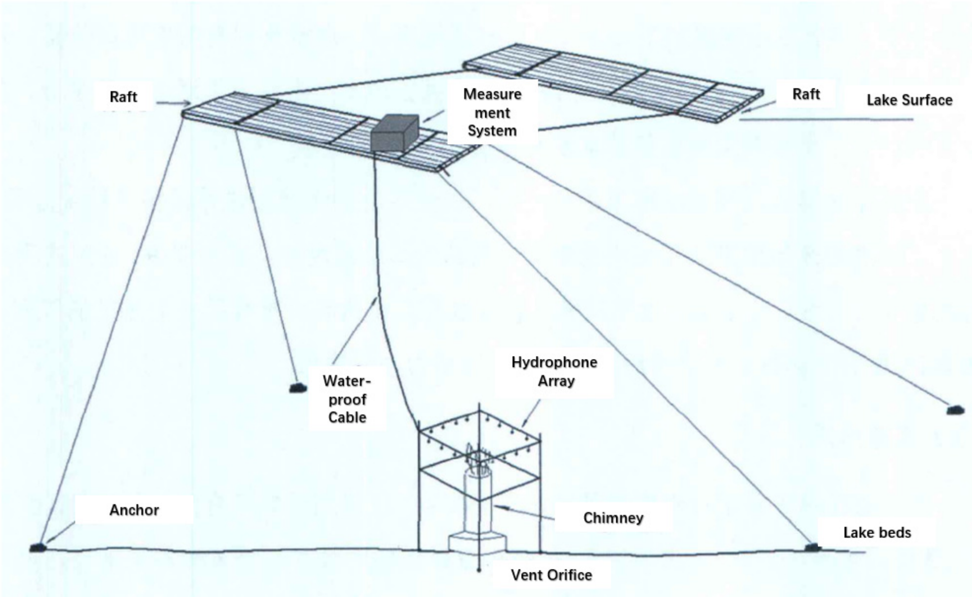


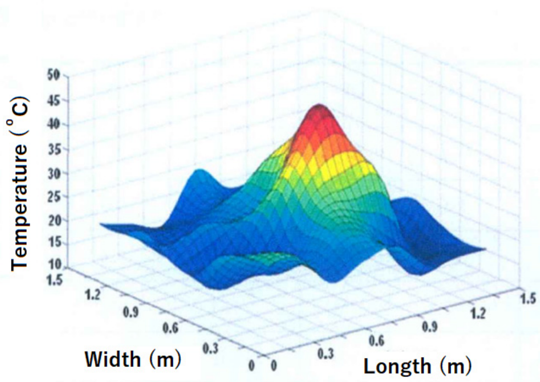
Figure 11. The reconstruction of 2D temperature field using acoustic tomography. (**a**) The distribution of hydrophones and corresponding acoustic paths on the measuring plane; (**b**) the meshed plane for the reconstruction of 2D temperature distribution using the total least-squares method [72].

Based on similar principles, Pan et al. developed a device for measuring the heat flux rising from an HT vent. Multiple layers of measurement planes were included in the approach to obtain temperature distribution at different heights [80]. The distribution of velocity field inside the measurement plane was estimated by the measurement of ToFs among the hydrophone in different layers. Using both the temperature field and velocity field reconstructed, the heat flux inside the measuring plane can be estimated.

The remote sensing techniques have the ability to observe continuous distribution of parameters around the HT vents. The remote sensing keeps them free from corrosion and sulfur deposition, thus it is ideally suitable for long-term in-situ observation. However, most of the existing approaches require complex algorithms to reconstruct the observing target from the measured data, which made the approaches less robust and sensitive. Though most of the remote sensing techniques reported were suitable for SHT studies, the wide application was believed to be limited by the complexity and cost of the measurement systems. More engineering practice is still needed to evaluate the performance of remote sensing methods in SHT observations.



(a)



(b) (c)

Figure 12. The Lake Qiezishan trial of the acoustic tomography to reconstruct the 2D temperature field around a hot spring located at the floor of Lake Qiezishan, Yunnan Province, China. (**a**) The schematic diagram of the experimental set-up. The vent orifice was covered by a chimney to form a sharp temperature gradient. The hydrophone array was deployed from two rafts that work collaboratively. (**b**) The deployment of the hydrophone array; (**c**) the reconstructed 2D temperature field. The red area near the center indicates the highest temperature in the measurement plane [72].

4. Water Samplers for SHT Vents

Although the fast development of in-situ measurement techniques provides scientists with instant and convenient ways of investigating HT features, limitations still exist when measuring organic parameters or biomass due to the lack of effective sensors. The analysis of water samples is still an important approach in HT studies. Various advanced tools have been developed to collect water samples, microbial mats or cores from deep-sea HT vents and keep them unaltered during their transportation to the laboratory [81]. These tools significantly accelerate the progress of deep-sea HT studies.

Compared with deep-sea HT studies, the development of sampling tools for SHT exploration lags far behind. One reason may be that the SHT vents are easier to explore. When samples can be easily obtained by scuba divers using glass syringes, plastic bags or bottles, which are actually the most commonly used methods even in recent years [10], the expensive, specially designed sampling tools seem unnecessary. Furthermore, most of the complex, heavy tools designed for accurate, automatic sampling were not suitable for scuba divers to operate. However, with the increasing demand in sampling accuracy and efficiency, sampling techniques targeted at SHT studies have begun to attract the attention of researchers.

Wu and his colleagues developed a handheld sampler for collecting organic samples from SHT vents (Figure 13a) [82]. The sampler utilizes a syringe-like sampling bottle made of titanium to collect organic samples. The bottle was sealed with a Teflon fluorinated ethylene propylene encapsulated O-ring to achieve perfect gas-tight performance. Two major improvements were made to ensure its performance in SHT sampling. First, a temperature logger was integrated into the sampler, which measures the temperature at the inlet of the snorkel using a thermocouple and displays the result on an LED display in real-time. The reading displayed by a red LED half hidden in a titanium housing can be clearly recognized even in high turbidity waters (Figure 12c). The real-time temperature measurement helps the diver to find the point with the highest temperature in the HT plume where the mixing of HT fluid and surrounding seawater were believed to be the weakest [83]. This feature helps in improving the purity of the HT samples collected. Second, an orifice or an annular gap between the piston rod and the end cap was used to regulate the flow rate of the sampler. A properly regulated flow rate will balance the purity of samples with the sampling efficiency. The sampler was tested in the Kueishan Tao HT vent field. The comparative test based on DOC concentration and salinity analysis shows that water samples with higher purity compared with glass-bottle-collected samples were successfully obtained.

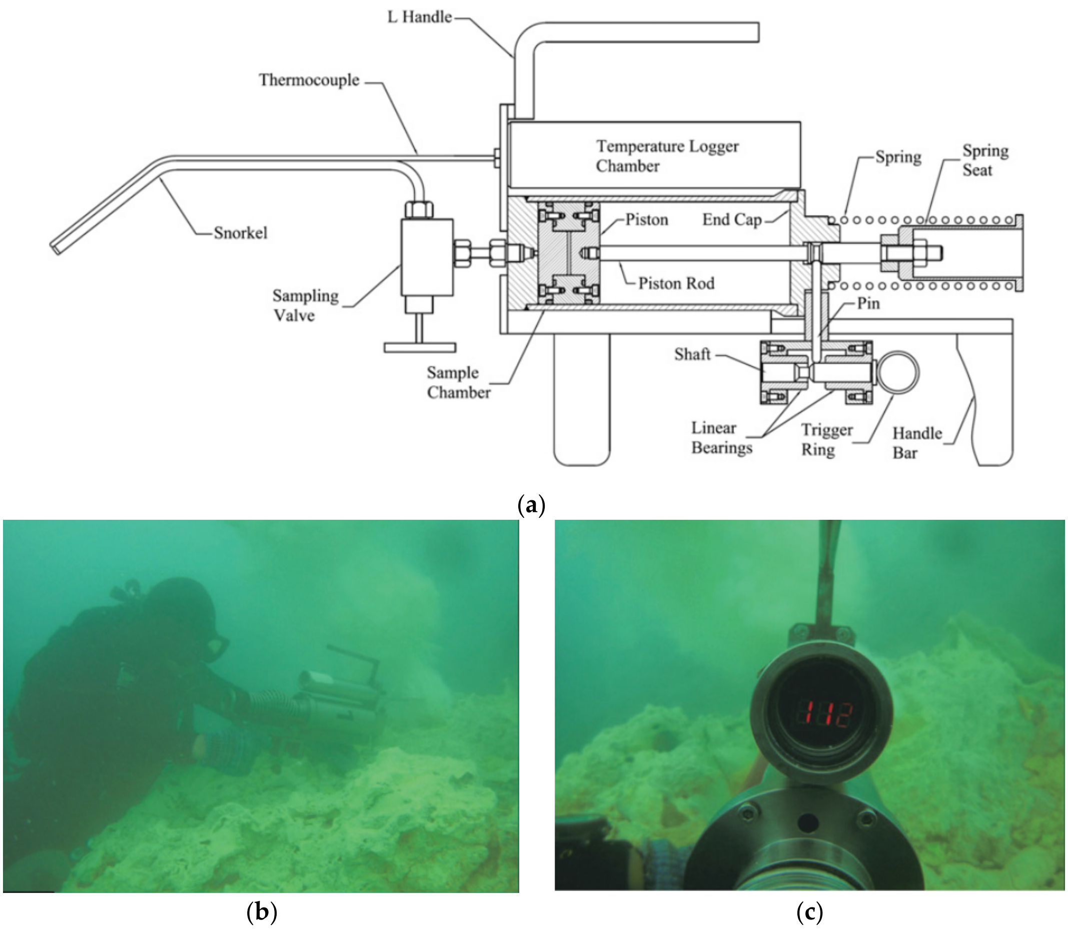


Figure 13. The handheld sampler developed for SHT sampling. (**a**) The structure diagram of the sampler; (**b**) collecting organic samples from the orifice of a yellow vent in the Kueishan Tao vent field; (**c**) the real-time measurement while sampling [82].

5. Discussion and Conclusions

Studies focused on SHT systems have been gradually given attention since the end of the last century. Being motivated by the increasing demand in scientific research, techniques that focus on SHT exploration are experiencing a gradual increase. Some of the detecting, observing and sampling methods are mentioned in this paper. Most of them have been successfully conducted at selected sites, such as the acoustic imaging of temperature fields and the satellite imagery of SHT vents. The others were tested in similar environments, such as the bubble cluster detection method, which showed the potential of engineering applications.

Although most of the newly developed HT vent exploring techniques were still in the experimental stage, the impact that they might bring to the fundamental science can be seen. With the specially designed sensors and samplers, the measurement data and samples collected will be more dependable. Remote sensing techniques, such as satellite imagery, provides scientists with a fast and economic way of studying SHT activities, which might greatly reduce labor and time on field tests. The acoustic tomography method provides scientists with means of measuring temperature fields and heat flux, as well as the 3D structure of the flume, data which has hardly been obtained before. These new tools bring more possibilities in the fundamental science on HT studies, and thus might reveal new research fields in the near future.

However, the development of exploring techniques for SHT vents was still in its infant stage. But the techniques are evolving at an increasing rate. Researchers have begun to put their eyes on the diversity that lies between SHT systems and deep-sea HT systems when developing new exploring techniques. Some research fields are raising increasing demand on the development of new techniques. For example, the need in studying HT vent microbiology is demanding a sampling method with higher sample densities in order to study the activity of micro-organisms in sharp temperature and chemical gradients. The same demand might also be raised by the origins of life studies. Future work in SHT exploring techniques may involve measuring techniques with higher reliability and accuracy, or with totally new measuring parameters.

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