ACOUSTIC IMAGING OF BLACK SMOKER PLUMES AND DIFFUSE FLOW: A NEW METHOD TO STUDY AND MONITOR HYDROTHERMAL FLOW REGIMES

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ABSTRACT. We report development, preliminary results, and future plans for a sonar system designed to image hydrothermal plumes and diffuse flow as a basis for their analysis and monitoring as major agents of dispersal of heat and chemicals into the ocean. The feasibility of the sonar system, including specifications and detection ranges for acoustic imaging of hydrothermal plumes by Rayleigh backscattering from particulate matter suspended in the plumes, was determined from theoretical calculations (Palmer et al., 1986). The system feasibility for imaging of diffuse flow is derived from phase information of the Acoustic signal (Jackson and Dworski, 1992).

A sonar system was modified to calculated specifications (pencil beam; 330 kHz). An initial experiment was performed at a hydrothermal field at 21°N on the East Pacific Rise with the sonar system installed in a submersible with the head mounted externally on the front of the sail. The system transmitted pulses and recorded volume backscattering from the buoyant plumes of black smokers which was used to reconstruct the buoyant plumes in three dimensions (Rona et al., 1991). The sonar system was further modified to record acoustic phase information and mounted on DSV SEA CLIFF in a recent (September 1996) dive series to image the buoyant plume and diffuse flow associated with Monolith vent, a black smoker complex at the northern end of the Cleft segment of the Juan de Fuca Ridge. Preliminary processing of the data and ground-truthing by direct observation suggest that the sonar system apparently delineated areas of diffuse flow around the base of Monolith chimney using phase comparison techniques and imaged the black smoker plume.

The East Pacific Rise and the Juan de Fuca data sets are being analyzed to determine the dynamics of plume and diffuse flow discharge and mixing into the surrounding ocean. Future plans include conversion of the plume imaging sonar system for incorporation into a Long-Term Hydrothermal Observation Station (LHOS) mode for daily monitoring of the activity of individual vents and entire seafloor hydrothermal fields for periods of a year or longer. The monitoring planned at selected hydrothermal sites in backarc basins of the western Pacific and ocean ridges in the eastern Pacific and Atlantic will provide a temporal record of variation in intensity of hydrothermal activity which may be a sensitive indicator of earthquake activity.

INTRODUCTION

Characterization of the behavior of hydrothermal plumes and associated diffuse flow is important as these two flow regimes are major agents of dispersal of quantitatively significant amounts of chemicals and heat derived from exchange between circulating seawater and the lithosphere in subseafloor hydrothermal convection systems at seafloor spreading centers (Wolery and Sleep, 1976; Edmond et al., 1979; Lupton, 1995; RIDGE, 1992). Plumes discharging from black smoker-type vents rise buoyantly through the overlying
water column to a level of neutral buoyancy determined by initial density deficit relative to surrounding seawater, ambient ocean stratification, and entrainment of surrounding seawater (Morton et al., 1956; Speer and Rona, 1989). A limited number of studies suggest that diffuse flow may be treated as multiple microplumes seeping from large areas of the seafloor concentrated around black smoker-type vents and may account for an order of magnitude greater heat flux than black smokers in a hydrothermal field (Rona and Trivett, 1994; Schultz et al., 1994) accompanied by an as yet undetermined flux of chemicals.

Prior investigations of hydrothermal plumes and diffuse flow have employed video and photo imagery which is limited to small volumes adjacent to a vent (Macdonald et al., 1980; Converse et al., 1984); asynchronous individual profiles of temperature, salinity, and optical light attenuation or scattering properties (conductivity-temperature-depth (CTD) profiles; Lupton, 1995); records made with standard sonar instruments (Orr and Hess, 1978; Hay, 1984; Palmer et al., 1986; Thomson et al., 1989); and laboratory tank simulations (Turner and Gustfson, 1978; Armishev and Berezutskii, 1988). The acoustic imaging of hydrothermal plumes and diffuse flow reported here are each based on a different physical mechanism and offer the potential for synoptic characterization and monitoring of large volume hydrothermal flow regimes.

Our imaging of hydrothermal plumes is based on acoustic backscattering from particulate matter in the form of metallic mineral particles precipitated and suspended in the plume. Sizes of particulate matter suspended in hydrothermal plumes (microns; Feely et al., 1987) are orders of magnitude smaller than the wavelength of the acoustic sources used in our experiments (330 kHz; 0.5 cm). Rayleigh scattering from targets very small relative to the wavelength of impinging radiation is the primary mechanism for the imaging. The suspended metallic mineral particle content of the buoyant portion of black smoker-type hydrothermal plumes generally is sufficient to account for acoustic detection (Palmer et al., 1986; Palmer and Rona, 1990). At present it is not feasible to estimate backscatter from inhomogeneities in the index of refraction due to turbulent temperature and velocity fluctuations in the plume. Our imaging of diffuse flow is based on phase shifts of the acoustic signal related to associated water temperature anomalies (Jackson and Dworski, 1992).

In this paper we briefly review results of our initial experiment in which we imaged plumes of black smokers in a hydrothermal field at latitude 21°N on the East Pacific Rise (Rona et al., 1991), and report preliminary results of our recent experiment (September 1996) that imaged a black smoker-type plume and associated diffuse flow at Monolith vent at 44°59.4'N, 130°12.1'W on the Juan de Fuca Ridge. Finally, we propose a plan for collaborative development of the sonar system for long-term monitoring of seafloor hydrothermal vents and fields.

**Method**

An existing sonar system (Mesotech model 971) with a frequency of 330 kHz, pulse duration of 100 microseconds, and transmit power level of 220 dB was modified in two stages, as follows:

1) **Imaging:** Replacement of fan-shaped sonar beam head with a conical beam (1.7° beam width); change of time-varying gain EPROM in the sonar head to increase sensitivity; addition of a second axis gimbaling module to train the sonar head in 1.7° elevation steps in addition to 0.9° azimuthal increments; addition of an analog output module and trigger pulse.

2) **Doppler:** Addition of capability to measure phase shift relative to a reference signal to measure flow rates within buoyant plumes and to image and measure temperature fluctuations in diffuse flow.

The conical sonar head with dual axis drives was mounted on the unobstructed forward part of the sail of a submersible. During data acquisition the submersible was stationary on the seafloor at various horizontal ranges up to 70 m from a target vent. A data acquisition system in the submersible recorded temperature information of the return sonar signal as decimal level of voltage (0-10 VDC). The system digitized information at frequencies of 10 or 20 kHz with 16 bits of resolution equivalent to range resolution of 0.15 and 0.075 m, respectively.

The transducer element orientation is spatially defined in a spherical coordinate system by azimuth and elevation angles of the sonar beam and range relative to the submersible (Figure 1; Rona et al. 1991). Three-dimensional sonar
images are generated by recording pings as the transducer element steps through a series of azimuth and elevation angles that define a volume ("frame") built by stacking successive individual slices ("sectors") through a plume. The duration of data acquisition for a typical frame was about 30 minutes.

Fig. 1. Data acquisition components of the hydrothermal plume imaging sonar system (top) and definition of the transducer element orientation in a spherical coordinate system relative to the submersible (bottom).

Results

The initial hydrothermal plume imaging experiment was performed at the Clam Acres site in the Southwest vent field at a depth of 2635 m at 20°49.8'N, 109°06.2' on the East Pacific Rise (Rona et al., 1991), where black smokers were first discovered (RISE Project Group, 1980). The DSV TURTLE with the plume imaging sonar system occupied positions on a horizontal surface of pillow lava flows at ranges between 5 and 70 m from two active black smoker chimneys each about 5 m high and 5 m apart and discharging a dense cloud of black smoke at rates of about 1 m/s (Rona et al., 1991). A three-dimensional reconstruction of one of the data frames recorded exhibits features of the flow regime in the lower 40 m of the buoyant plumes venting from the tops of the two adjacent chimneys (Figure 2). These features include high-intensity backscatter in two coherent columns rising about 10 m above the two chimney tops; coalescence of the the two plumes at altitudes from 15 to 20 m; progressive decrease in overall backscatter intensity with altitude as the rising plume entrains surrounding seawater; presence of distinct blobs of high-intensity backscatter with dimensions of meters within the low-intensity background; and bending of the plume in the direction of the prevailing current flow.

The recent hydrothermal imaging experiment (September 1996), with the additional capability of recording phase information was performed at Monolith vent at a depth of 2249 m at 44°59.4'N, 130°12.1'W at the northern end of the Cleft segment of the Juan de Fuca Ridge. Monolith vent is a chimney complex about 5 m in diameter and 5 m high. At least 10 black smoker-type vents irregularly distributed on the sides and top of the chimney complex discharge wispy black smoke at rates less than 1 m/s. Preliminary results at this early stage of data processing are, as follows:

1) Plume: Backscatter intensity of the plume is patchy reflecting the input from multiple vents; the prevailing current bends the weak compound plume eastward within 25 m of the top of Monolith chimney.

2) Diffuse flow: Several patchy areas of phase-shifted sonar returns appear to correspond with areas of diffuse flow up to 10 m in diameter independently mapped with the ROV ATV (Advanced Tethered Vehicle). Additional analysis is needed to confirm this apparent correspondence.

The entire data set is being processed and software is being developed for analysis of turbulent mixing processes and flow rates in the plume and of temperature fluctuations in the diffuse flow.

Adaptation of Sonar System To Seafloor Observatory

Long-term seafloor observatories are becoming increasingly important to monitor a wide spectrum of time-varying physical, chemical, and biological processes in the ocean. An association between earthquake activity, dike intrusion, lava flows and changes in hydrothermal activity has been documented for such events at 9°N on the East Pacific Rise (Haymon et al., 1993), the Coaxial segment of the Juan de Fuca Ridge (Fox et al., 1995), and the northern segment of the Gorda Ridge in the eastern Pacific (Fox and Dziak, 1996). Adaptation of the hydrothermal plume imaging system to long-term seafloor operation and incorporation into a seafloor observatory at selected seafloor hydrothermal sites will provide
Fig. 2. Three-dimensional reconstruction of an acoustic image of the lower 40 m of two buoyant plumes discharging from adjacent black smoker vents at a depth of 2635 m on the East Pacific Rise near 21°N, 109°W (5 x 5 x 5 m rectilinear grid). The image was made from a digital data set of acoustic backscattering information recorded with a specially modified submersible-mounted sonar system. The reconstructed image shows multiple zones of flow organization, coalescence of the two plumes, and bending of the coalesced plumes in the direction of the prevailing oceanic current (north). The newly developed acoustic imaging technique is providing information on the volume and structure of hydrothermal plumes on a time scale suitable for determination of plume dynamics and monitoring.
the capability to monitor the intensity of venting at individual vents and at the entire hydrothermal field including both plumes from chimneys and diffuse flow. Adaptation of the hydrothermal plume imaging system will involve selecting a suitable commercial sonar system, modifying the system along the lines of our present system, incorporating data acquisition/storage components and a power supply, and packaging the system for operation at oceanic depths. As discussed, this would be best done as a collaborative program sharing technical and scientific resources. Operation of such a sonar system in selected geologic settings including hydrothermal fields in backarc basins of the western Pacific and ocean ridges of the eastern Pacific and Atlantic will provide invaluable information on the temporal variability of hydrothermal flow regimes (venting from chimneys and diffuse flow) leading to a new understanding of relations between volcanic, tectonic and hydrothermal processes. In particular, temporal variations in hydrothermal flow regimes may be sensitive indicators of crustal movements that disrupt the subseafloor circulation cells and either precede or accompany large earthquakes.

Conclusions

The plume imaging sonar system provides a valuable new tool to study the dynamics of discharge of black smoker plumes and associated diffuse flow as major agents of dispersal of heat and chemicals from the lithosphere into the ocean. The next step in development and application is to adapt the plume imaging sonar system to a long-term seafloor monitoring mode and to incorporate the system into selected seafloor observatories at hydrothermal fields in backarc basins of the western Pacific and ocean ridges of the eastern Pacific and Atlantic. The time-series data of the distribution, form and intensity of venting from individual chimneys, areas of diffuse flow, and whole hydrothermal fields will open new possibilities for understanding relations between volcanic, tectonic and hydrothermal processes in ocean basins.

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References


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