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Research paper

Simulation of hydrothermal vents in the Izena Cauldron, Mid Okinawa trough, Japan and other Pacific locations

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Abstract

Simulation results of Jade hydrothermal vent in Okinawa trough, Japan and Dante hydrothermal vent in Endeavour ridge in the north east Pacific are presented using an improved version of MOHTV model. The results are presented along with some limited field comparisons. A limited study on the sensitivity of model results to key model parameters is also presented. The model used is capable of simulating the hydrodynamics, thermodynamics, and mineral formations in underwater hydrothermal vents. The transport and spread of the plume fluid and minerals formed are simulated in three stages: plume dynamics stage that is momentum and buoyancy driven; transition to far field conditions as a gravity current; and far field conditions where the mineral particles move according to advection diffusion governed by the ambient currents and mineral particle settling velocities that eventually lead to their bed deposition. Thermodynamics include the changes in plume temperature and its related properties such as the vent fluid density. Physico-chemical processes are the chemical reactions that occur in the plume due to the hot vent fluid mixing with cold ambient water. Chemical reactions form new compounds (mostly minerals), which change the plume properties and therefore its behavior. Model simulates the formation of minerals namely FeS, FeS_2, ZnS, $CuFeS_2$, CuS, PbS, $CaSO_4$, $BaSO_4$, and Particulate Manganese − PMn. This improved version of MOHTV considers a user defined particles size distribution, the bathymetry of the ocean bottom, and can be used to run long-term simulations. The model results compare reasonably well with the field data. The parametric analyses show, which input and/or ambient conditions most affect the distribution of particles.

Keywords: Dante; Endeavour ridge; Hydrothermal vents; Izena; Jade; Mineral distribution

1. Introduction

Hydrothermal vent plumes are releases of geo-thermally modified seawater (vent fluid) into the ocean through fissures close to the mid ocean ridges. Vent fluids are rich in dissolved minerals. They are released at temperatures and velocities ranging from approximately 10 to 400 °C and 0.01−6.2 m/s respectively (Ginster et al., 1994). When vent fluid is released at the seabed, it mixes with cold seawater triggering many chemical reactions forming precipitates (mineral sulfides, anhydrite, sulfates) due to the sudden changes in temperatures. Behavior of the vent fluid varies depending on the fluid composition, temperature and velocity at release, and the types of precipitates formed. Slow releases with low temperatures are known as diffused vents and the amount of precipitates formed in these vents is minimal. High temperature vents with high velocities form plumes are

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clouded with many mineral precipitates (black, gray, or white in color) and can even rise a few hundred meters in the ambient water. The ocean currents carry these mineral precipitates along. They get distributed and deposited in different locations, sometimes very far away from their source.

Examples of mineral precipitates found in hydrothermal vent fields are pyrite (FeS_2), iron sulphide (FeS), chalcopyrite ($CuFeS_2$), sphalerite (ZnS), covellite (CuS), anhydrite ($CaSO_4$), barite ($BaSO_4$), galena (PbS), Mn, Au, and Ag (Tivey, 2007). Some of these minerals are found in abundance in vent fields while others are rare and found only in specific sites. Many mineral deposits are formed in and around the vent fields over millions of years, which are the origins of deposits found on land (Tivey, 2007; Glasby and Notsu, 2003). Many countries are interested in harvesting these deposits, which are of high economic value. Economic grade minerals such as CuS, ZnS, PbS, Ag, and Au based minerals are reported to be common in deposits found in the Okinawa trough near Japan, and the Manus Basin and Conical Seamount near Papua New Guinea (Glasby and Notsu, 2003).

Tao et al. (2013) developed a model to simulate hydrothermal plumes and compared their simulations with analytical results. They present short-term simulation results of the plume in high resolution. Their model however, did not include the formation of chemicals, their transport and distribution at the seabed. No comparisons with experimental data were presented. Dissanayake et al. (2014) developed a new model named MOHTV (MOdel for HydroThemal Vents) to simulate hydrothermal vent plumes using integral lagrangian control volume method, which included near field, far field, and re-circulation of particles. The model included a limited number of chemical formations within the plume. In this paper MOHTV is improved by adding more chemicals, and tested by comparing simulation results with experimental data. In addition, this paper simulates the mineral transport and deposition in the Okinawa trough, and the Dante hydrothermal vent in Endeavour ridge in the Pacific. The model algorithms are significantly improved to run much longer term (3 months) simulations compared to the earlier version of the model taking into account the bathymetry of the ocean bottom as well. While the previous paper (Dissanayake et al., 2014) presented the model formulation and some preliminary results, this paper details the model testing with available experimental data, application to real field conditions, and a parametric study of key model parameters.

2. Model for hydrothermal vent plumes (MOHTV)

MOHTV model's detailed formulation can be found in Dissanayake et al. (2014). Here, we briefly outline the model along with the improvements made.

2.1. Plume dynamic stage (PDS)

During the PDS the plume is driven by the momentum of the fluid released at the vent and buoyancy force due to the density difference between the ambient seawater and the plume fluid which consists of a mixture of vent fluid, seawater, and particles. The effect of the particles on the composite density is negligible for most common thermal vent conditions because the particles are so small and the concentrations are low. The currents force the ambient water into the plume and change its momentum, which is a dominant factor that determines its path. The shear due to the difference in plume velocity and ambient velocity also causes the plume to entrain ambient water. Details of how entrainment is modeled are the same as given by Lee and Cheung (1990) and Yapa and Zheng (1997). As the plume rises, the dominating force changes from momentum to buoyancy mainly as a result of entrainment. Termination of the PDS is assumed to occur when the plume reaches a neutral buoyancy level (NBL). NBL is the level at which the density of the plume is equal to the ambient water density (Dasanayaka and Yapa, 2009). The plume dynamics are modeled using integral Lagrangian control volumes (CV) similar to that of Zheng et al. (2003). In a CV, properties such as velocity, salinity, and temperature are averaged across the cross section. CVs travel along the three dimensional path of the plume. The plume temperature changes due to the entrained ambient water. The effects of the Coriolis force, and mineral precipitation calculations are accounted for during the PDS. Concentrations of dissolved metals are high closer to the release point. Therefore, most of the mineral precipitation reactions occur near the vent orifice. MOHTV assumes that the vent fluid is released into the seawater through a circular orifice in the vertical direction. Mass and momentum conservation of a CV are the key equations of the plume model and are given in Eqs. (1) and (2) respectively

$$\frac{\mathrm{d}m}{\mathrm{d}t} = \rho_a Q_e \pm \frac{\mathrm{d}m_{\mathrm{sep}}}{\mathrm{d}t} \tag{1}$$

$$\underbrace{\frac{\mathrm{d}(m\vec{V})}{\mathrm{d}t}}_{\text{Rate of change of total momentum of the CV}} = \underbrace{\vec{V}_a \rho_a Q_e}_{\text{Entrained momentum into the CV due to ambient water}} + \underbrace{\frac{\rho_a - \rho}{\rho} mg\vec{k}}_{\text{Buoyant upward thrust on the CV}} \pm \underbrace{\frac{\mathrm{d}m_{\mathrm{sep}}}{\mathrm{d}t}\vec{V}}_{\text{Momentum of the separated mass from the CV}} - \underbrace{2\pi r_{cv} h \rho_a C_D \left(\left|\vec{V}\right| - \vec{V}_a'\right)^2 \frac{\vec{V}}{\left|\vec{V}\right|}}_{\text{Drag force acting on The CV due to velocity difference between plume and ambient liquids}} - \underbrace{2m\vec{\Omega} \times \vec{V}}_{\text{Coriolis force acting on the CV}} \tag{2}$$