論文内容の要旨

Magnetic study of seafloor hydrothermal systems in various tectonic settings

（多様な地質学的背景を持つ海底熱水系の磁気的研究）

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An understanding of the seafloor hydrothermal system is essential for discussing the cooling of the oceanic lithosphere, geochemical cycles of many elements, submarine mineral deposits, and specific chemosynthetic ecosystems. Near-seafloor magnetic anomalies can provide vital information such as the location, spatial extent, and mineralization of hydrothermal systems because magnetic minerals are oxidized, transformed, and created during the hydrothermal processes. However, previous magnetic studies are limited on basalt-hosted hydrothermal systems developed in axial areas of mid-ocean ridges (MORs), where hydrothermal fields are typically associated with reduced magnetization. Moreover, there has been limited discussion on the geological controls of hydrothermal systems in volcanic arc, back-arc, and ultramafic-hosted hydrothermal systems. Because seafloor hydrothermal circulation, fluids, and deposits are strongly controlled by tectonic processes, further study in these areas is needed to understand the geological and geophysical frameworks of seafloor hydrothermal systems.

In the present study, therefore, I analyzed near-seafloor magnetic data to discuss the magnetization structures of hydrothermal systems in various tectonic settings of three regions: (i) on- and off-axis hydrothermal fields hosted in andesite in back-arc region of the southern

Mariana Trough (SMT), (ii) basalt- to rhyolite-hosted Tarama and Irabu hydrothermal fields (THF and IHF, respectively) in arc and back-arc regions of the Okinawa Trough, and (iii) an ultramafic-hosted hydrothermal field in a non-transform offset massif of the Central Indian Ridge (CIR). In addition, I measured the rock magnetic properties of host rocks from the seafloor near those subjected hydrothermal fields in order to construct an appropriate geologic interpretation of magnetic contrast.

In Chapter 2, I investigate five hydrothermal vent fields of the back-arc spreading region on the SMT. Near-seafloor magnetic data were collected using the *SHINKAI 6500*, a deep-sea human occupied vehicle (HOV). A new three-dimensional (3-D) method is applied to exploit the surrounding bathymetry and varying altitudes of the submersible for estimating the absolute crustal magnetization. The results reveal that magnetic-anomaly-derived absolute magnetizations (MADAMs) show a reasonable correlation with the natural remanent magnetizations (NRMs) of rock samples collected from the seafloor of the same region. The distribution of MADAM suggests that all five andesite-hosted hydrothermal fields are associated with a lack of magnetization, as is generally observed at basalt-hosted hydrothermal sites of the MORs. The spatial extent of the resulting low magnetization is approximately ten times wider at off-axis sites than that at on-axis sites, possibly reflecting larger accumulations of nonmagnetic sulfides, stockwork zones, and alteration zones at the off-axis sites. Furthermore, I succeeded in distinguishing contiguous low magnetization zones (LMZs) located on the same seafloor volcano, which could not be separated in magnetic anomaly data collected at higher altitudes by an autonomous underwater vehicle (AUV).

In Chapter 3, I show the results of detailed analyses of high-resolution vector magnetic anomalies on arc and back-arc hydrothermal vent fields in the Okinawa Trough, by using the AUV *URASHIMA*. The IHF is developed on the axial area of the back-arc rift and consist of basaltic lavas. The THF is developed between a back-arc rift and arc along with dacite to rhyolite. Active hydrothermal venting was reported in both fields. The obtained magnetizations from both ship-underway and near-seafloor magnetic data are consistent with the values of NRM measured on rock samples. The distribution of crustal magnetization deduced from the magnetic anomaly revealed that both IHF and THF are associated with reduced magnetization. The spatial scale of low magnetization reflecting the extent of the discharge zone is large compared with that found at MORs. Comparisons of detailed bathymetry and magnetization distribution of the Irabu knolls reveal that the magnetization lows are located along the rim of the cauldron structure, indicating that hydrothermal fluids rise from deep areas along the caldera fault. The results show that reduced magnetization related to hydrothermal activity occurs in rhyolite-hosted systems as well as basalt-hosted systems, and that caldera faults are important pathways for forming large discharge zones of hydrothermal systems.

In Chapter 4, I investigate the Yokoniwa hydrothermal field (YHF), an inactive ultramafic-hosted hydrothermal vent field, by using high-resolution vector magnetic anomalies from the HOV *SHINKAI 6500* and the AUV *r2D4*. The YHF is developed at a non-transform offset massif of the CIR. Dead chimneys are widely observed around the YHF along with a very weak venting of low-temperature fluids. This indicates that the hydrothermal activity of the YHF is almost finished. The distribution of crustal magnetization from the magnetic anomaly revealed that the YHF is associated with enhanced magnetization, which also occurs at the ultramafic-hosted Rainbow and Ashadze-1 hydrothermal sites of the Mid-Atlantic Ridge (MAR). The results of rock magnetic analysis on the seafloor rock samples including basalt, dolerite, gabbro, serpentinized peridotite, and hydrothermal sulfide show that only highly serpentinized peridotite carries high magnetic susceptibility and NRM intensity that can explain the high magnetization of the YHF. These observations reflect abundant and strongly magnetized magnetite grains within the highly serpentinized peridotite.

In Chapter 5, I discuss three topics on the basis of these near-seafloor magnetic anomaly surveys and rock magnetic analyses with previous studies: (i) the magnetic signature of volcanic lava-hosted hydrothermal systems, (ii) magnetic mineral formation at ultramafic-hosted hydrothermal systems, and (iii) the locations and spatial scales of seafloor hydrothermal systems. I draw the following conclusions about the general magnetic characteristics reflecting the hydrothermal alteration and evolution of hydrothermal systems.

1. Volcanic lava-hosted hydrothermal fields in various tectonic settings, including volcanic arcs and back-arc regions as well as MORs, are generally characterized by reduced magnetization, reflecting primarily the alteration of titanomagnetite within volcanic rocks, with accumulation of nonmagnetic hydrothermal deposits as a secondary source. This signature is generally common even if the type of basement rock differs from basalt to rhyolite.
2. Ultramafic-hosted hydrothermal systems developed in non-transform offset massifs of slow-spreading ridges are characterized by enhanced magnetization. I propose the following three-stage model for magnetic mineral formation in ultramafic-hosted hydrothermal fields: During the initial stage of an ultramafic-hosted hydrothermal system, magnetite forms with

serpentine and H_2 through hydrothermal alteration of peridotites, and pyrrhotite mineralization occurs under reductive conditions. Once the serpentinization reaction has progressed, the amount of magnetite creation increases dramatically, strengthening the magnetization. Pyrrhotite creation continues as long as the H_2 content of the hydrothermal fluids continues to create a reducing environment in this developing stage. Hot and reduced hydrothermal fluids maintain the stability of magnetite and pyrrhotite with no low-temperature oxidation. Finally, once the reaction of the ultramafic rock ceases, H_2 is no longer formed in the system. The conditions then become oxidative, which allows pyrrhotite to be converted into nonmagnetic iron sulfide or oxide, reducing considerably their magnetization considerably.

3. The hydrothermal process involves complex interplay between the dynamics of heat supply and the evolution of crustal permeability to allow seawater to access the source. As a result, the locations and spatial scales of hydrothermal systems are controlled by the tectonic background of each vent field. Off-axis hydrothermal vent sites in seafloor spreading regions are larger than on-axis sites, reflecting the longevity of the hydrothermal activity. On-axis sites located in neo-volcanic zones are likely controlled by dike intrusions over decadal timescales, whereas off-axis sites are controlled by off-axis magmatic activity over thousands of years. Hydrothermal fields related to volcanic arc and back-arc volcanism with summit calderas have horizontal spatial scales equal to or larger than detachment-controlled large hydrothermal fields at slow-spreading ridges. It is implied that the permeability structure and style of hydrothermal circulation may play important roles in the formation of larger demagnetized hydrothermal fluid pathways in caldera-controlled systems.

A major finding is that the presence of hydrothermal sulfides and the oxidation, transformation, and creation of magnetic minerals produce specific magnetic signatures at hydrothermal vent sites in various tectonic settings. These signatures can be used to detect and characterize both active and inactive hydrothermal sites. Near-seafloor magnetic survey using underwater vehicles such as HOVs or AUVs can therefore be an important component of deep-sea exploration of seafloor hydrothermal systems.