学 位 論 文 内 容 の 要 旨/Dissertation Abstract

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学 位 論 文 題 名/Title of Dissertation

Iron supply and transport processes in the southern Sea of Okhotsk and the Coastal Oyashio region and their contribution to spring bloom development

（南部オホーツク海および沿岸親潮域における鉄供給・輸送過程と春季ブルーム発達への寄与）

Iron (Fe) is an essential element for marine microorganisms that sustain ocean primary production. However, because Fe occurs only in trace amounts in seawater, primary production is Fe-limited across ~30% of the global ocean, including the Southern Ocean, eastern equatorial Pacific, and the subarctic North Pacific. Measuring low Fe concentrations requires contamination-free environments and techniques, and consequently observational data remain sparse compared with other key parameters. Elucidating the distribution and biogeochemical cycling of Fe in the ocean is therefore critical for understanding marine primary productivity and the global carbon cycle. The southern Sea of Okhotsk and the Coastal Oyashio region, the focus of this study, are highly productive areas where large spring phytoplankton blooms develop as sea-ice retreats. Although high Fe concentrations relative to surrounding regions are presumed to support these blooms, Fe distributions, sources, transport pathways, and biological utilization in this area remain unclear and have not been quantitatively evaluated. In this study, macronutrient concentration distributions and Fe supply processes during the spring bloom period were examined using shipboard observations collected during the spring bloom following sea-ice retreat in the southern Sea of Okhotsk. The contribution of sea-ice meltwater (SIMW) to the surface layer and the supply of sea-ice–derived Fe were also quantitatively evaluated, and freshwater origins and Fe supply and transport processes in the highly productive Coastal Oyashio region influenced by Okhotsk Sea Water were investigated. Furthermore, to assess how sea-ice–derived Fe affects the development of the spring bloom, incubation experiments were conducted and the relationship between the supply of sea-ice–derived Fe and phytoplankton growth was discussed.

In this study, observational data from the KS-21-6 cruise of the R/V *Shinsei-maru* in the southern Sea of Okhotsk in April 2021 and from the KH-15-1 cruise of the R/V *Hakuho-maru* in the coastal Oyashio region and along the A-Line in March 2015 were used for sample analysis and data processing. The datasets used included salinity and temperature (sensor measurements; SBE9plus and SB45, Seabird), $\delta^{18}O$ (WS-CRDS; L2120-i, Picarro), total dissolvable Fe (TD-Fe) and dissolved Fe (D-Fe) (flow injection analysis; EN-701, Kimoto Electric), macronutrients (continuous flow analysis; QuAAtro2-HR, BL-Tec), and chlorophyll-a (Chl-a) (fluorescence method; 10AU, Turner Designs). For the collection and measurement of samples for Fe analysis, acid-cleaned plastic sampling and laboratory ware were used, and all work was conducted under clean conditions. In this study, labile particulate Fe (LP-Fe) concentrations were calculated by subtracting D-Fe concentrations from TD-Fe concentrations.

During the KS-21-6 cruise, we captured, for the first time, a spring bloom in surface waters of the southern Sea of Okhotsk following sea-ice retreat. Within the surface low-salinity water, very high Chl-a concentrations were observed, with nitrogen depleted

and Fe relatively low. Salinity–$\delta^{18}O$ analysis showed that 2.4 ± 0.5% of the surface mixed layer consisted of SIMW, and most Fe supplied by melting sea-ice was particulate, with only a small dissolved fraction. Sea-ice–derived LP-Fe accounted for ~40% of LP-Fe in the surface mixed layer, indicating that sea-ice is a major LP-Fe source. Below the surface mixed layer in the southern Sea of Okhotsk, Fe concentrations were especially high over the shelf and slope, while D-Fe exhibited a nutrient-type vertical profile in the basin. A strong positive correlation between LP-Fe and turbidity indicated that LP-Fe distributions were controlled by resuspension of shelf sediments. In the basin, a positive relationship between apparent oxygen utilization (AOU) and D-Fe suggested a supply of D-Fe via remineralization of suspended particles. Moreover, the N* value that takes redox conditions into account implied that Fe supplied from the Hokkaido shelf can be transported to the basin and that D-Fe originating from Okhotsk Sea Intermediate Water may be advected from the north.

Coastal Oyashio Water—cold, low-salinity water formed by mixing of Okhotsk Sea Water and Oyashio Water—was distributed along the southeastern Hokkaido coast and exhibited high Fe concentrations. Salinity–$\delta^{18}O$ analysis indicated that this water mass contained ~2–3% SIMW, with higher fractions nearshore. Sea-ice–derived Fe concentrations, calculated from observed Fe concentrations in sea-ice and SIMW fractions, were positively correlated with SIMW fractions. However, the proportion of sea-ice–derived Fe to observed total Fe was small; at stations with the highest Fe, most Fe originated from sources other than sea-ice. These non-sea-ice Fe concentrations were positively correlated with SIMW fractions, suggesting transport to Coastal Oyashio Water along the same pathway as SIMW. Among potential sources in the southern Sea of Okhotsk, only resuspension of shelf sediments can account for the very high Fe observed in Coastal Oyashio Water. Consistent with this, a time series at a Coastal Oyashio site recorded peak Fe concentrations after the passage of an intense low-pressure system, followed by a decline, supporting an event-driven resuspension mechanism. Together, these results outline a scenario in which sediment-derived Fe mixed with SIMW is advected across the straits into the coastal Oyashio, alongside sea-ice–derived Fe.

Incubation experiments, designed in light of these findings, were conducted to assess how the presence of sea-ice affects bloom development via its impact on Fe concentrations and stratification in the surface mixed layer. Winter mixed-layer water from the southern Sea of Okhotsk without SIMW served as the control, and treatments included sea-ice addition, Fe addition, and two light-limited conditions (50% and 10% of incident light). All treatments were incubated for 12 days to simulate spring bloom environments. The results showed that Fe supplied by sea-ice and improved light conditions enhanced phytoplankton growth rates and promoted the development of a spring bloom dominated by large diatoms. Monitoring of Fe concentrations during the incubations further suggested that substantial LP-Fe inputs from sea-ice helped stabilize D-Fe concentrations, implying that sea-ice–derived Fe can support the persistence of the spring bloom.

Overall, through comparative analysis of Fe concentration distributions and other chemical properties in a region where observational data have been limited, this study demonstrates the importance of sea-ice–derived Fe supply in coastal portions of seasonal sea-ice regions and suggests that Fe supplied from the Hokkaido shelf may contribute to Fe inputs in this region to a greater extent than previously recognized. Furthermore, in coastal areas of seasonal sea-ice regions characterized by high Fe concentrations and high primary productivity, the results indicate that sea-ice–derived Fe contributes to the development of the spring bloom and likely influences bloom magnitude and duration as well as phytoplankton community composition. These findings are expected to enhance understanding and future predictions of Fe supply and transport processes and of the mechanisms driving variability in primary productivity in seasonal sea-ice regions and adjacent waters that are highly sensitive to ongoing warming.