学 位 論 文 内 容 の 要 約/Dissertation Summary

博士（環境科学）　　氏　名/Applicant　今井 望百花

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 concentrations in seawater are extremely low, primary production is Fe-limited across ~30% of the global ocean, including the Southern Ocean, the eastern equatorial Pacific, and the subarctic North Pacific. Measuring trace Fe concentrations requires contamination-free environments and specialized techniques. Consequently observational data remain sparse compared with other key biogeochemical 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 following sea-ice retreats. Although relatively high Fe concentrations compared with surrounding regions are presumed to support these blooms, Fe distributions, sources, transport pathways, and biological utilization in this area remain poorly understood and have not been quantified. In this study, nutrient distributions and Fe supply processes during the spring bloom were examined using shipboard observations conducted in the southern Sea of Okhotsk after sea-ice retreat. The contribution of sea-ice meltwater (SIMW) to the surface layer and the supply of sea-ice-derived Fe were also quantified. In addition, the freshwater sources and Fe supply and transport processes were investigated in the highly productive Coastal Oyashio region influenced by Okhotsk Sea waters. Furthermore, to assess how sea-ice-derived Fe influences the development of the spring bloom, incubation experiments were conducted to examine the relationship between sea-ice-derived Fe supply and phytoplankton growth.

This study used 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. The datasets included salinity and temperature (determined by a conductivity-temperature-depth (CTD) device; SBE9plus and SB45, Seabird), $\delta^{18}O$ (by wavelength-scanned cavity ring-down spectroscopy (WS-CRDS); L2120-i, Picarro), total dissolvable Fe (TD-Fe) and dissolved Fe (D-Fe) (by flow injection analysis; EN-701, Kimoto Electric), macronutrients (continuous segmented flow analysis; QuAAtro2-HR, BL-Tec), and chlorophyll-a (Chl-a) (by fluorometry; 10AU, Turner Designs). For Fe sample collection and measurement, 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 from TD-Fe.

During the KS-21-6 cruise, shipboard observations captured a spring phytoplankton bloom in the surface waters of the southern Sea of Okhotsk after sea-ice retreat. Within the surface low-salinity water, very high Chl-*a* concentrations were observed, with nitrate depleted and Fe concentration relatively low. Salinity–$\delta^{18}O$ mass-balance calculation showed that 2.4 ± 0.5% of the surface mixed layer consisted of SIMW, and most Fe supplied by melting sea-ice was in particulate form, 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, LP-Fe and D-Fe concentrations were especially high over the shelf and slope. In contrast, in the basin, D-Fe increased with depth, showing a nutrient-type vertical profile with low values near the surface and higher values at depth. 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 that D-Fe was regenerated during the cumulative remineralization of organic matter in the water mass. Moreover, the N* value that takes redox conditions into account implied that LP-Fe and D-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.

During the KH-15-1 cruise, Coastal Oyashio Water (COW), cold and low-salinity water with temperature < 2 °C and salinity < 33.0, was distributed along the southeastern Hokkaido coast and exhibited high Fe concentrations. Fe concentrations in COW varied markedly before and after the passage of a low-pressure system. The highest D-Fe and LP-Fe concentrations were observed at the sea surface immediately after the passage, followed by a subsequent decline. To elucidate the origin of COW, salinity–$\delta^{18}O$ mass-balance approach was applied to estimate the sea-ice meltwater fraction. The results indicated that this water mass contained ~2–3% SIMW and it accounts for ~40% of the freshwater component in COW, indicating that SIMW is a major freshwater source. In COW, a positive relationship between the SIMW fraction and observed LP-Fe and D-Fe concentrations suggests that Fe and SIMW were transported together into the Coastal Oyashio region. Based on the estimated SIMW fractions, sea-ice-derived Fe could contribute to the observed Fe concentrations. However, the observed Fe concentrations exceed those that can be explained solely by sea-ice-derived Fe, indicating other Fe inputs. Resuspended sedimentary Fe from the shelf region is the most plausible source for generating the elevated Fe concentrations in COW. The pronounced change in Fe concentrations before and after the low-pressure passage suggests that episodic inputs of sedimentary Fe from the shelf may influence both LP-Fe and D-Fe levels in COW. Overall, these results indicate that COW contains SIMW as a major freshwater component and that seasonal inputs of sea-ice-derived LP-Fe and event-driven sedimentary LP-Fe and D-Fe supply contribute to the elevated Fe concentrations in COW.

Based on the observed contribution of sea-ice-derived Fe in the study area, incubation experiments were conducted to evaluate how sea ice influences the development of the spring bloom in Fe-replete, highly productive coastal waters. Winter mixed-layer water from the southern Sea of Okhotsk without SIMW, collected during the P/V *Soya* cruise in February 2025, served as the control, and treatments included sea-ice addition, Fe addition, and

two light-limited conditions (50% and 10% of the 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 and promoted the development of a spring bloom dominated by large diatoms as estimated from algal pigment signatures. 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 distributions and other chemical properties in a region where observational data have been limited, this study demonstrates the importance of sea-ice-derived LP-Fe supply in coastal portions of seasonal sea-ice regions and suggests that LP-Fe and D-Fe supplied from the Hokkaido shelf may contribute to LP-Fe and D-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 LP-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.