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PREFACE

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Preface for article collection "10 years after the 2011 Tohoku earthquake: a milestone of solid earth science"

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1 Preface

Many scientific discoveries have been made since the 2011 Tohoku earthquake (or Tohoku-Oki earthquake in many papers including those in this SPEPS, occurred on March 11, 2011, M 9.0), thanks in large part to the enormous amount and quality near-field observations and the existing scientific knowledge about the northeastern Japan arc that had already accumulated before the earthquake (e.g., Lay 2018; Goto et al. 2021; Uchida and Burgmann 2021). The earthquake highlighted dynamic frictional behaviors of the shallowest parts of the subduction interface, which had previously been regarded as mostly aseismic. An increasing amount of evidence for spatial correlation between the distribution of interplate faulting events of various sizes and time scales and the structural heterogeneity of the plate boundary have been presented. Several stress re-distribution processes were activated after the earthquake, including viscoelastic relaxation, aseismic afterslip and fluid remobilization. These transients occurred in both the overriding and incoming plates and the underlying mantle asthenosphere, and insights gained from studying these postseismic processes have greatly improved our overall understanding of subduction zone dynamics. Abundant records of the associated tsunami provided new insights into various processes during the generation, propagation, and inundation of tsunamis. The earthquake also provided a unique opportunity to compare the fault rupture models obtained from modern observations with those of past earthquakes based on geological records, allowing for improvements in the reconstructed recurrence history of massive earthquakes in the region. A collection of research regarding the Tohoku earthquake is expected to benefit our general understanding of infrequent gigantic (M > 9) subduction earthquakes around the world. For this special issue of SPEPS, we invited authors to contribute their own latest research as well as reviews on the seismotectonics along the northeastern Japan margin from various aspects related to the Tohoku earthquake.

Through the application of novel analysis methods to various geophysical observation data, new insights into the generation process of the Tohoku earthquake have been gained. Kubota et al. (2022) estimate the distribution of coseismic stress drop through the reanalysis of tsunami waveforms and coseismic crustal deformation. Tanaka et al. (2022) successfully elucidate the spatiotemporal development of early afterslip that occurred within ~ 1 h after the Tohoku earthquake from carrier phase data obtained from GNSS observations. Inazu et al. (2023) report on temperature variations in the deep seafloor at the source region and speculated that these might

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be caused by groundwater discharge from beneath the seafloor triggered by the earthquake.

Seafloor observations significantly contributed to improved understanding of the characteristics of the crustal structure around the Tohoku earthquake source region. Fujie et al. (2023) demonstrate a strong correlation between spatial variations in the crust and mantle structure of the subducting Pacific Plate and seismic activity at the plate boundary by compiling results from past seafloor seismic surveys around the Japan Trench and Kuril Trench. Nakamura et al. (2023) highlight that the dominant fault dipping direction of bending normal faults developed on the upper surface of the Pacific Plate near the trench axis varies along the Japan Trench. Eastward dipping normal faults were dominant in the northern and southern parts of the Japan Trench, whereas westward dipping normal faults were more numerous in the central part, corresponding to the rupture zone of the Tohoku earthquake. Seismicity in the outer rise region was activated over a wide area after the Tohoku earthquake. The activity, occurring along multiple bending normal faults, was complex, but Obana et al. (2023) attempt to understand its details through seafloor seismic observations.

The presence of slow earthquake activity prior to the Tohoku-Oki earthquake was reported, drawing attention to slow earthquake activity along the Japan Trench, leading to numerous observational reports. Nishikawa et al. (2023) review slow earthquake activity along the Japan Trench based on these new observational discoveries. Takahashi et al. (2022) report on the activity of shallow tectonic tremors north of the Tohoku earthquake source region immediately after its occurrence. Detection of slow earthquake activity without seismic wave radiation relies on geodetic methods. Hino et al. (2022) analyze the detection capabilities of seafloor pressure gauges in the S-net, a cabled seafloor monitoring network deployed in 2016. With appropriate noise mitigation strategies vertical seafloor motions associated with nearby slow earthquakes should be captured by the network. The tsunami generated by the Tohoku earthquake was detected across the Pacific Ocean, significantly advancing the understanding of long-distance tsunami propagation. Watada (2023) provide an explanation of the theory taking the coupling of solid Earth and ocean into account to accurately describe long-distance tsunami waveforms and arrival times.

The 2011 Tohoku earthquake emphasized the usefulness of tsunami deposits in investigating earthquake history, accelerating research in this area. Detailed field investigations and subsequent analyses of the 2011 Tohoku earthquake tsunami deposits were crucial for reconstructing the tsunami behavior and understanding its general characteristics. Many papers on the 2011 Tohoku earthquake tsunami deposits have been published in the past decade, and this special issue also includes two new research papers. Matsumoto et al. (2023) compile the results of surveys and sedimentological analyses of the 2011 Tohoku earthquake tsunami deposits over a wide area, mainly in Sendai Plain. The large dataset of the thickness and grain size of the tsunami deposits, together with the tsunami inundation depth, will be useful for reconstructing the hydraulic conditions of past tsunamis. Shinozaki et al. (2022) focus on traces of the tsunami inundation other than sandy materials to correctly evaluate the tsunami inundation limit, as the distribution of sandy tsunami deposits is systematically narrower than actual inundation areas. They succeed in accurately determining the tsunami inundation limit by examining the terrigenous biomarkers. Tsunami deposits data are also crucial for reconstructing past earthquake source images. Masuda et al. (2022) demonstrated that effectively combining tsunami deposit data with sediment transport simulations could improve the accuracy of estimating source models of past tsunamigenic events.

Research on the paleoseismology along the Japan and Kuril trenches based on tsunami deposits faces the major challenge of elucidating the true nature of earthquakes that occurred in the fifteenth to seventeenth centuries. Yamanaka and Tanioka (2022) suggest that the 1611 Keicho earthquake, which has posed many mysteries regarding its source, might have been a tsunami earthquake with significant slip along the Japan Trench and composed of multiple patches of large shallow coseismic slip. Separating the traces of the seventeenth century Kuril Trench giant earthquake, which occurred around the same time as the Keicho earthquake, is important but challenging. Aware of this issue, Ishimura et al. (2022) conduct tsunami deposit surveys at a coastal lowland on the north coast of the Shimokita Peninsula, where tsunamis associated with both the Japan and Kuril trenches earthquakes could strike. They identify five tsunami deposits, including the fifteenth–seventeenth century tsunami deposit, during the past 6000 years. Based on this geological data, Sato et al. (2022) conduct the numerical tsunami calculations and indicated the possibility of a giant earthquake with a significant slip on the plate interface in the junction zone.

Research on the earthquake history through tsunami deposits is being actively conducted not only off the coast of Tohoku but also along the Nankai Trough. Shimada et al. (2023) contribute the results of such research to this special issue. They collect sediment cores at a coastal lake in Mie Prefecture and identified several event layers formed by past Nankai Trough tsunamis and extraordinary storms. More such studies in the future are essential to elucidate the history of tsunamis and to assess future risks.

Records of past massive earthquakes also remain on the deep seafloor as turbidites. Kanamatsu et al. (2023) identify traces of past great earthquakes comparable to the Tohoku earthquake through age determination using paleomagnetic analyses. Ikehara et al. (2023) examine the causal relationship between the peak ground acceleration of great earthquakes and turbidite deposition by focusing on estimates of strong ground motion from historical earthquakes on the deep seafloor.

Along with the results of historical research based on preserved records of past great earthquakes, numerical modeling of the earthquake cycle has also progressed. The overview of these results is summarized in the review paper by Shibazaki (2023), which explains new concepts about the frictional properties of plate boundaries and highlights the importance of viscoelasticity in modeling long-term crustal deformation during the interseismic periods. Nakata et al. (2023) conduct simulations to reproduce interacting earthquake cycles, where frequent M7-class and infrequent M9-class earthquakes coexist, in the central Japan Trench where the Tohoku earthquake occurred, and attempted to verify the results with actual observational data. Regarding the importance of the lithosphere's viscoelasticity pointed out by Shibazaki (2023), Dhar et al. (2023) discuss evidence for the spatial heterogeneity of the viscoelastic earth structure along the northeastern Japan arc based on post-earthquake crustal deformation observation results.

While research on the Tohoku earthquake is showing steady progress, the significant postseismic deformation triggered by the Tohoku earthquake continues. In this sense, the full picture of the infrequent great Tohoku earthquake has not yet been revealed. Ongoing research on various tectonic phenomena in the postseismic period will contribute to constructing more realistic earthquake cycle models and elucidating the rheological structure of the subduction zone. Historical research on earthquake occurrence suggests the possibility of more unknown great earthquakes in the past, in addition to the great earthquake accompanied by a massive tsunami that occurred in the seventeenth century in the Kuril Trench. We expect that the integration of research on earthquake mechanisms and historical research will be especially important to allow for construction of a model describing earthquake cycles comprising multiple infrequent and gigantic events occurring over a wide area from the Japan Trench to the Kuril Trench, an important theme in future research on the Tohoku earthquake. All the research results of the 10 years after the 2011 Tohoku earthquake, including the papers collected in this special issue, will form a strong foundation for such next-generation research.

Abbreviations

GNSS Global navigation satellite system

S-net Seafloor observation network for earthquakes and tsunamis along the Japan Trench

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