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Using Late and Middle Pleistocene tephrostratigraphy and cryptotephrostratigraphy to refine age models of Holes ODP1150A and ODP1151C, NW Pacific Ocean: A cross-check between tephrostratigraphy and biostratigraphy

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ABSTRACT

We investigated the deep-sea sedimentary sequences of Holes ODP1150A and ODP1151C and refined the Late and Middle Pleistocene tephrostratigraphy and cryptotephrostratigraphy in the NW Pacific Ocean. Further, we correlated tephras in these sequences with marine isotope stage (MIS)-correlated tephras of Hole Chikyu C9001C and created robust age models for the ODP holes. We first counted glass shards and heavy mineral grains in marine sediment samples from the ODP holes and analyzed the major-element chemistry of glass shards and of cummingtonite grains associated with shard spikes. Then, using these major-element compositions, we correlated some glass shard spikes of Hole ODP1150A with known dated tephras for the first time: G5 with Towada-Ofudo (late MIS 3); G8 with Numazawa-Kanayama (MIS 3–4); G12.3 with Naruko-Nisaka (MIS 5b–c); G12.4 with Dokusawa (MIS 5b–c); G12.5 with C9001C G3.1 (MIS 5b–c); G13.1 with Sambe-Kisuki (MIS 5c); G13.2 with Toya (MIS 5d); G16 with C9001C G7 and G8 (MIS 7a–b); either G16.2 or G17 with C9001C G10 (MIS 7b–c); G19.5 with Shiobara-Otawara (mid MIS 8); and G21.1 with Naruohama-IV (MIS 10d). We also confirmed previously reported tephra correlations: G1 with Towada-Hachinohe (MIS 1/2 boundary); G6 with Shikotsu-1 (MIS 3); and G12 with Aso-4 (MIS 5b). Similarly, we correlated some spikes of Hole ODP1151C with known dated tephras for the first time: G0.2 with C9001C G10 (MIS 7c); G1 with ODP1150A G18; G2 with ODP1150A G19.3; G3 with Shiobara-Otawara (mid MIS 8); G3.4 with ODP1150A G20; G4.4 with C9001C G19.3 (MIS 13 or 13/14 boundary); G9 with Kaisho-Kamitakara (MIS 15–16); and G10.8 with C9001C G25.2, 25.3, 25.4, or 25.6 (MIS 18). The tephrostratigraphy results indicate that sediments corresponding to 400–770 ka (from slightly older than the Naruohama-IV tephra to the base of the Brunhes chron) are not preserved in the sediments of Hole ODP1150A. We suggest that our tephra-based age models for Holes ODP1150A and ODP1151C are more reliable than the previously reported Middle Pleistocene biohorizon-based model, which was constructed on the basis of a poorly preserved fossil record.

1. Introduction

Deep-sea sediments constitute a continuous archive of stratigraphic information, including tephrostratigraphy, microbiostratigraphy, and magnetostratigraphy. Some of this information has been globally correlated or astronomically tuned via $\delta^{18}O$ stratigraphy and therefore can provide reliable tie-points for creating age models of deep-sea sedimentary sequences (e.g. Thierstein et al., 1977; Paterne et al., 1988; Farrell and Janecek, 1991; Gradstein et al., 2012; Balestra et al., 2015; Petrosino et al., 2016). Further, via such age models, a tephra that is associated with a reliable numerical age can potentially be used to link the marine record to terrestrial and continental ice records (Pillans et al., 2005; Blockley et al., 2014; Davies et al., 2014; Matsu'ura et al., 2014).

In deep-sea sediments, biostratigraphic events (e.g. first and last appearance datums, FAD and LAD, respectively) can provide useful datum planes. For example, calcareous nannofossil biohorizons have been widely recognized in the NW Pacific Ocean area. Among them, the FAD of *Emiliania huxleyi* is a globally correlated age indicator of the marine isotope stage (MIS) 8 horizon in the $\delta^{18}O$ stratigraphy

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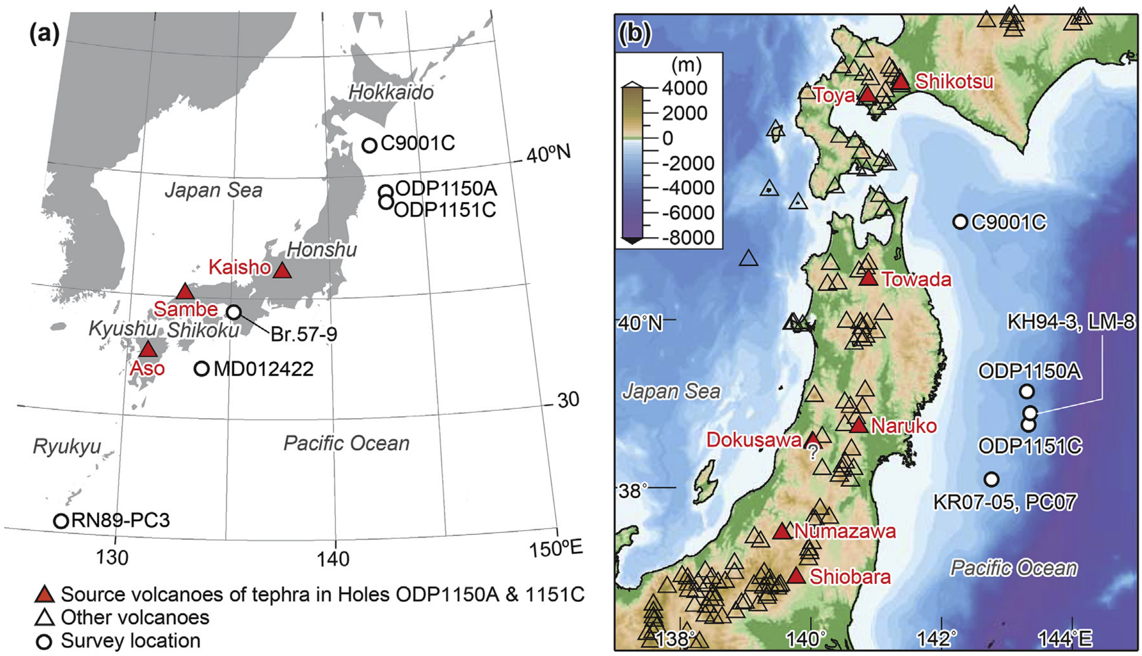

Fig. 1. Locations of ocean drilling sites in (a) the northwestern Pacific Ocean and (b) off NE Japan, where first appearance datum (FAD) planes of *Emiliania huxleyi* have been identified in Middle Pleistocene sequences. The source volcano of the Dokusawa tephra is unknown.

(Thierstein et al., 1977). This datum plane is consistent with the tephrostratigraphy in cores RN89-PC3 (Ahagon et al., 1993), MD012422 (Ikehara et al., 2006), and Br.57-9 (Nishida, 1996) off Ryukyu, Shikoku, and western Honshu, respectively (Fig. 1). However, it is inconsistent with other biostratigraphic datum planes and with the tephrostratigraphy in Holes ODP1150A and C9001C off northern Honshu (Fig. 1): In Hole ODP1150A, the MIS 8 datum plane (i.e. the FAD of *E. huxleyi*; Thierstein et al., 1977) occurs above the Aso-4 tephra (MIS 5b) (Motoyama et al., 2004); moreover, when this datum plane was used to create an age model for Hole C9001C, the inferred sedimentation rate was unusually higher during MIS 7 than during other MISs (Domitsu et al., 2011; Matsu'ura et al., 2014, 2017). Further, also in Hole ODP1150A, another calcareous nannofossil biohorizon, the LAD of *Pseudoemiliania lacunosa* (408 ka), is in a younger stratigraphic position than a diatom biohorizon, the LAD of *Proboscia curvirostris* (300 ka) (Motoyama et al., 2004). Although the calcareous nannofossil datum planes in Hole ODP1151C, which is also off northern Honshu, are clearly above the base of the Brunhes chron (770.2 ± 7.3 ka, Suganuma et al., 2015; 783 ± 0.6 ka, Mark et al., 2017), their stratigraphic positions have not yet been cross-checked against other age indicators (Fig. 2). The apparent stratigraphic inconsistencies indicate that the use of calcareous nannofossil stratigraphy can be problematic when used in combination with other datum planes to create an age model; in fact, it allows quite different age models to be constructed. Thus, the calcareous nannofossil stratigraphy of marine sedimentary sequences of Middle Pleistocene age, in particular, should be checked against other types of stratigraphic data, such as tephrostratigraphy (Matsu'ura et al., 2017). In addition, the detection of more tephras in the sediments of Hole ODP1150A is necessary to refine its Late Pleistocene tephrostratigraphy and confirm the position of the Aso-4 horizon used as a cross-check against the FAD of *E. huxleyi*. Further, Middle Pleistocene tephras in Holes ODP1150A and ODP1151C have not yet been correlated with known tephras. Thus, the tephrostratigraphy and cryptotephrostratigraphy of their sediments need to be established to determine precisely the position of the MIS 8 horizon (i.e. the true FAD of *E. huxleyi*).

In this study, we investigated the deep-sea sediments of Holes C9001C, ODP1150A, and ODP1151C to refine their Late and Middle Pleistocene tephrostratigraphy and cryptotephrostratigraphy. We identified tephra and cryptotephra horizons by examining concentrations of glass shards and heavy mineral grains in the sediments of the ODP holes. Then we analyzed the chemistries of the glass shards and cummingtonite, which have already been used to establish the terrestrial tephrostratigraphy of northern Honshu (Matsu'ura et al., 2011, 2012; Matsu'ura and Sugaya, 2017). Subsequently, we correlated tephras and cryptotephras of Holes ODP1150A and ODP1151C with MIS-correlated tephras in Hole C9001C (Matsu'ura et al., 2017; Matsu'ura and Komatsubara, 2018). Further, we cross-checked the tephrostratigraphy against the reported biostratigraphy, especially calcareous nannofossil datum planes, and examined inconsistencies between them. The techniques presented in this paper for the identification, correlation, and dating of tephras and cryptotephras are also applicable to deep-sea sequences in other regions of the world where tephras are common.

2. Regional setting of the study area

Holes C9001C, ODP1150A, and ODP1151C (Table 1) lie in the nonvolcanic forearc, but they are also within the westerly wind belt and many volcanoes are upwind of the sites. Therefore, they have received tephras from both nearby and distant volcanoes during the Quaternary (Sacks et al., 2000; Matsu'ura et al., 2014). Tephra-derived volcanic shards are obviously more abundant in the sediments of Holes ODP1150A and ODP1151C than in those of Hole C9001C (Fig. 3). The higher background level in the ODP holes may be due to a more frequent supply of tephra-derived glass shards to those sites from volcanoes in southern NE Japan and Honshu or to more effective transport by ocean currents of tephras drifting on the sea surface.

Hole C9001C is located within the central, gently sloping part of the continental shelf (Aoike, 2007), but Holes ODP115A and 1151C are located within a deep-sea terrace between the continental slope and the trench slope (Sacks et al., 2000). The different setting of the ODP holes