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Use of amphibole chemistry for detecting tephras in deep-sea sequences (Chikyu C9001C cores) and developing a middle Pleistocene tephrochronology for NE Japan

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ABSTRACT

Using amphibole crystals, we detected tephras in deep-sea sequences (Chikyu C9001C cores) and correlated marine and terrestrial tephras in NE Japan; then we reconsidered some previously reported tephra ages by using the age model of the cores. We identified 50 spikes in amphibole grains (numbered A1–A50 from top to bottom). Among these, 12 spikes (A38–49) corresponded to a thick, non-tephric sand layer. We selected 20 spikes containing amphibole grains with glass coatings as likely primary tephras and analyzed their chemistry for tephra characterization. On the basis of its amphibole chemistry, we correlated spike A34 with the Tn-Cii–Ciii layers of the Tanabu-C tephra (Tn-C), which erupted from Osore volcano on Shimokita Peninsula. We then showed that spike A34 represents primary tephra deposition, not secondary deposition through bioturbation or bottom current reworking, because amphibole grains with homogeneous chemistry were accumulated only in sediment near the spike (within 10 cm). We also showed that the chemical variation within each amphibole grain was not as great as the variation between grains, which further supports the correlation between spike A34 and Tn-Cii–Ciii. These findings show that amphibole grains, which are resistant to weathering, can be used for characterization and correlation of weathered tephras from which glass shards have been removed by dissolution. The glass shard chemistry of the 16H6A 60–80 tephra at 4.58 m below spike A34 (which does not correspond to an amphibole spike) suggests that this tephra likely correlates with the amphibole-free Tn-Ci layer. In the terrestrial sequences, non-tephric sediments (marine sand and lahar deposits) occur between Tn-Ci and Tn-Cii–Ciii, suggesting that some time elapsed after the deposition of Tn-Ci before Tn-Cii–Ciii were deposited. By using the stratigraphic information of the 16H6A 60–80 tephra and spike A34 together with the $\delta^{18}O$ stratigraphy of the deep-sea sequence, we re-assigned the eruptive age of Tn-C from the previously reported zircon fission-track age of 180 ± 40 ka to MIS 8 (257–263 ka).

1. Introduction

Marine tephrochronology is based on stratigraphic information of tephras identified within deep-sea sequences that also contain microbiostratigraphic and marine oxygen isotopic records. Therefore, well-dated tephras within such sequences are useful tools for correlating and dating sediments across long distances (e.g., Lowe, 2014). Tephras are usually detected as glass shard concentrations within deep-sea sediments, where shards are not usually dissolved by weathering and where their original chemical properties are generally preserved. Therefore, marine tephrostratigraphy and cryptotephrostratigraphy have been established on the basis of glass shard chemistry (e.g., Westgate et al., 1998; Buhring and Sarnthein, 2000; Shane, 2000; Song et al., 2000; Shane et al., 2006; Aoki, 2008; Brendryen et al., 2010; Abbott et al., 2011; Lowe et al., 2012; Albert et al., 2012; Davies et al., 2012; Gorbarenko et al., 2014; Insinga et al., 2014; Satow et al., 2015). Tephras have also been used for linking deep-sea sediments with

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ice cores containing high-time-resolution records of $\delta^{18}O$ stratigraphy (Davies et al., 2014), and they have been further applied to establish the chronologies of late Quaternary marine terrace deposits, which are deposits corresponding to past interglacial periods (Koike and Machida, 2001; Machida and Arai, 2003; Matsu'ura et al., 2014a). However, because in NE (Matsu'ura et al., 2011) and SW Japan (Matsu'ura, 2015) the constituent glass shards of tephras within terrestrial loess sequences that date to marine isotope stage (MIS) 5 or older have often been dissolved by weathering, widespread glassy tephras and cryptotephras are seldom detected in such deposits. Therefore, an alternative to glass shards is required to establish correlations between marine tephras and (weathered) terrestrial tephras on late Quaternary marine terrace deposits.

Olivine, pyroxenes, amphiboles, biotite, and Fe–Ti oxides are common minerals in tephras, and the chemical compositions of some of these minerals have been used to supplement the chemical composition of glass shards for robust tephra characterization (Cronin et al., 1996; Shane, 1998; Shane et al., 2003; Jensen et al., 2008, 2011; Smith et al., 2011; Rawson et al., 2015). Further, some of these minerals that are resistant to dissolution during long-term weathering have been used to correlate weathered tephras lacking preserved glass shards (amphiboles: Takeshita et al., 2005; Kotaki et al., 2011; Matsu'ura et al., 2011, 2012; Fe-Ti oxides: Suzuki, 2008). Therefore, tephra correlation methodologies based on mineral chemistries should be developed and applied to the correlation of marine and terrestrial tephras. Recently, Matsu'ura et al. (2014a) identified relatively high concentrations of orthopyroxene and amphibole grains, forming spikes, in some horizons of deep-sea core sequences (C9001C cores: see below) as possible tephra or cryptotephra horizons. The chemical compositions of the grains within these concentrations may be useful for linking marine and terrestrial (weathered) tephras. In view of these previous studies, in this study we focused on amphibole chemistry for correlating between marine and terrestrial tephras.

Cores were obtained at site C9001C, on the continental slope off Shimokita Peninsula, by D/V *Chikyu* in 2006, during its shakedown cruise for the Integrated Ocean Drilling Project (Fig. 1b) (Aoike, 2007; Kobayashi et al., 2009). Together, the cores contain a continuous, 365-m-long marine sequence that has been correlated with MISs by benthic $\delta^{18}O$ analyses, biostratigraphy, magnetostratigraphy, and tephrostratigraphy, and which extends from MIS 18 to the present (Domitsu et al., 2011). In particular, tephrostratigraphy (including cryptotephrostratigraphy: Lowe, 2011; Nagahashi and Kataoka, 2015) based on glass shard chemistry has provided useful time markers for refining the age model of the cores (Matsu'ura et al., 2014a, 2016). To establish links between marine and weathered terrestrial tephras, however, the chemical compositions of mineral grains resistant to weathering need to be investigated (Matsu'ura et al., 2014a).

To be useful for correlation, the mineral grains should be phenocrysts; however, abundant mineral grains in a tephra may consist of xenocrysts from multiple sources (Gardner et al., 2002; Liu et al., 2006). In that case, although the grain abundance of a mineral might still indicate a tephra horizon, its chemical composition is likely to display considerable variation. The presence of glass coatings on mineral grains is a useful indication that the grains are phenocrysts rather than xenocrysts (Wilcox and Naeser, 1992), especially in deep-sea cores where the tephras are unweathered. Another consideration when comparing mineral grain chemical compositions between tephras for tephra correlation is the range of chemical variation (due to zonation) within individual mineral grains.

Tephrostratigraphy has been used as a dating tool for late Quaternary marine and terrestrial sediments (Pillans, 1990; Ota and Omura, 1991; Machida, 1999; Litchfield and Berryman, 2005), but some identified terrestrial tephras have fission-track (FT) ages that are inconsistent with their stratigraphic position (Pillans et al., 1996; Alloway et al., 2013), and some have not yet been assigned to a MIS because of a paucity of stratigraphic information from late Quaternary deep-sea sediments (Koike and Machida, 2001). Therefore, the tephras in the C9001C cores hold promise for advancing the late Quaternary chronology of terrestrial sequences such as those of marine terraces in NE Japan. Further, a method for characterizing and distinguishing tephras using resistant minerals would have global applicability to late Quaternary marine and terrestrial tephrostratigraphic investigations in the island or continental arcs of subduction zones, such as along the rims of the Pacific Ocean, Indian Ocean, Mediterranean Sea, and Caribbean Sea, where marine terraces are common (e.g., Murray-Wallace and

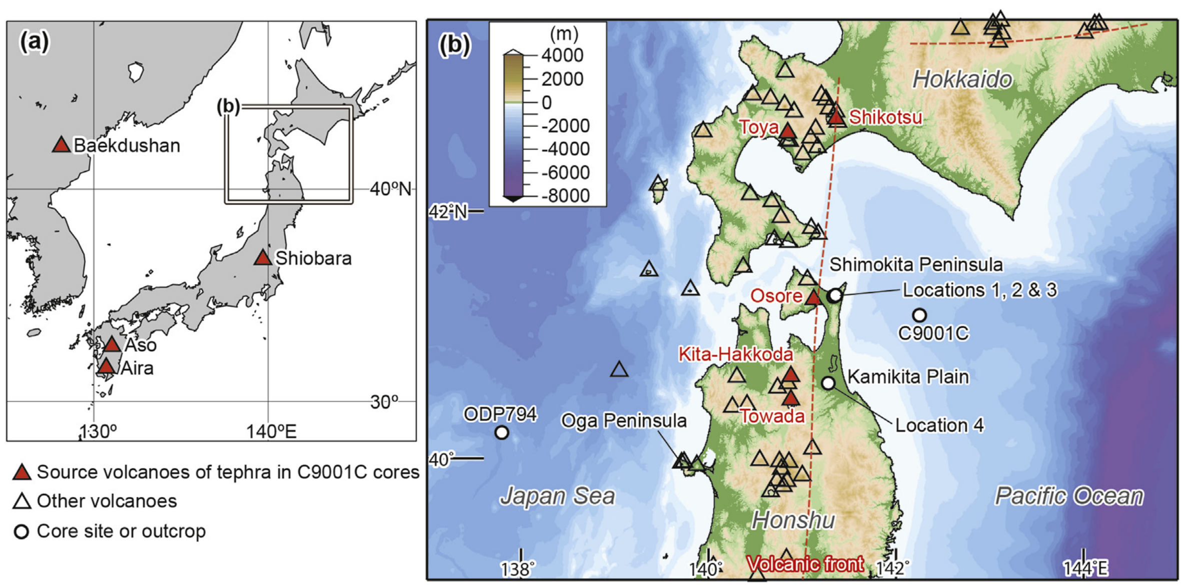

Fig. 1. Locations of volcanoes, ocean drilling sites, and terrestrial tephra sites on (a) a map of Japan and the coast of the Asian continent and (b) a map of northern Honshu and southern Hokkaido.