Paleomagnetic data as a test of correlations of the Pliocene Wakebe tephra in the Tokai Group, central Japan

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Abstract: This paper presents a paleomagnetic test for the correlation of tephra over large areas. A recent preliminary investigation suggests the possibility, based mainly on geochemical data, that the Pliocene Wakebe tephra in the lower Kameyama Formation of the Tokai Group is correlative with a widespread tephra in central Japan that was deposited in a normal polarity subchron of the Gauss Chron (C2An). Here, new paleomagnetic data are presented to show that reverse polarity remanent magnetizations are recorded in the Wakebe tephra and in siltstones located immediately above and below the tephra. The results do not support the preliminary correlation of the Wakebe tephra with the widespread tephra of normal polarity, and correlation with this tephra needs to be reconsidered. The Wakebe tephra was deposited between ~3.95 Ma (age of the underlying Akogi tephra) and 3.596 Ma (Gauss–Gilbert boundary age) in the late Gilbert Chron (C2Ar).

Keywords: paleomagnetism, Pliocene, tephra correlation, tephrochronology, Tokai Group, Wakebe tephra

Introduction

Paleomagnetic analysis can be an important tool for tephra correlation. Tephras can preserve a geologically instantaneous record of the time-varying geomagnetic field as a remanent magnetization at the time of deposition or shortly after. Thus, deposits of a widespread, correlative tephra at different places should have a similar remanent magnetization direction of the same magnetic polarity. Based on this premise, widespread tephra correlations can be tested by comparison of remanent magnetization directions (e.g., Hayashida et al., 1996; Fujii et al., 2001).

This paper reports paleomagnetic data obtained from the Wakebe tephra (Mori et al., 2015; Tamura et al., 2015) intercalated within the lower Kameyama Formation (early to middle Pliocene) of the Tokai Group in Mie Prefecture, central Japan. Preliminary descriptions of this tephra were given by Mori et al. (2015) and Tamura et al. (2015). The Wakebe tephra consists mainly of fine glass fragments and could be a widespread tephra (Tamura et al., 2015). Based on geochemical analysis of volcanic glass, Tamura et al. (2015) suggested that the Wakebe tephra is correlative with deposits of a widespread tephra intercalated within the Kakegawa, Miura, and Inubo groups in central Japan (Tamura et al., 2014). Importantly, one of these deposits, the Ikg1 tephra (Tamura et al., 2014) in the upper Ikego Formation of the Miura Group, is present within a normal polarity magnetostratigraphic zone, which chronologically corresponds to Chron C2An.2n of the Gauss Chron (Utsunomiya et al., 2017; I. Tamura and M. Utsunomiya, personal communication, 2019). Therefore, if this correlation is correct, the Wakebe tephra must have a normal polarity remanent magnetization. To verify this, a paleomagnetic study of samples from the Wakebe tephra and siltstones above and below the tephra was undertaken.

Materials and methods

Numerous tephra layers are intercalated within the Tokai Group, and their lithologies, mineral compositions, radiometric ages, and paleomagnetic directions have been described elsewhere (e.g., Yoshida, 1990; Nakayama and Yoshikawa, 1990; Yoshikawa et al., 1991; Nakayama et al., 1995; Yoshikawa, 2001).

The Wakebe tephra is located stratigraphically between the Akogi and Otani-ike tephras in the lower Kameyama Formation of the Tokai Group (Fig. 1a; Mori et al., 2015; Tamura et al., 2015). At its type locality ~5 km west of the center of Tsu City (34°44′01.2″N, 136°27′08.8″E), it is 4–6 cm thick, consists of fine tuff with no visible sedimentary structures, and has a local strike and dip of N31°E/11°E. According to the preliminary description by Tamura et al. (2015), this tephra is largely composed of glass shards, along with scarce hornblende and orthopyroxene crystals. Radiometric ages and paleomagnetic data have not yet been reported for this tephra.

For paleomagnetic analysis, rock cores of 2.5 cm in...
diameter were collected with a battery-powered drill at the type locality of the Wakebe tephra. The cores were oriented with a magnetic compass, and were taken from three stratigraphic sites (Fig. 1b): (1) 10 fine-grained tuff cores from the Wakebe tephra (cores W1–W10); (2) 4 cores from the siltstone immediately below the Wakebe tephra (cores W11–W14; within 5 cm of its basal contact; site “SBW”); and (3) 4 cores from the tuffaceous siltstone above the Wakebe tephra (cores W15–W18; 23–28 cm above its top surface; site “SAW”). Between one and three 2.2-cm-high cylindrical specimens were cut from each core for paleomagnetic measurements.

Paleomagnetic measurements and demagnetization were carried out in the magnetically shielded paleomagnetic laboratory at the Center for Advanced Marine Core Research of Kochi University, Japan. Data acquisition and analysis methods used in this study are essentially the same as those described in detail by Hoshi et al. (2015). A total of 34 specimens were subjected to stepwise thermal demagnetization (ThD) or alternating field demagnetization (AFD). Mean remanent magnetization directions and Fisherian statistical quantities were calculated for each of the three sites by applying the great circle method of McFadden and McElhinny (1988). The PuffinPlot v.1.03 software (Lurcock and Wilson, 2012) was used for data analysis and visualization.

**Results and interpretations**

Characteristic remanent magnetization (ChRM) directions were determined for five specimens (four by ThD and one by AFD). Viscous components having a northerly and down direction were commonly present in these specimens (Fig. 2a, b), and were removed by ThD at 200°C or by AFD at 25 mT.

Best-fit demagnetization great circles were obtained for 21 specimens (4 by ThD and 17 by AFD). An example from the Wakebe tephra is presented in Fig. 2c and f, where the magnetization vector direction sequentially changes on a plane in the equal-area plot throughout AFD, although there is only a northerly and down component (most likely a viscous magnetization) that does not pass through the origin in the orthogonal diagram. A best-fit great circle was determined by principal component analysis (PCA; Kirschvink, 1980), as illustrated in Fig. 2f.

Site-mean directions of the three sites are listed in Table 1, and plotted in geographic coordinates (i.e., uncorrected for tilt) on equal-area projections in Fig. 3.

**Wakebe tephra:** Only one specimen yielded a reverse polarity ChRM direction through ThD (Fig. 2a), which was obtained in a temperature range between 200 and 275°C by PCA. In the PCA, data at 300°C and higher temperatures were not included, because these were likely influenced by thermal alteration, as suggested by a rapid increase in both initial magnetic susceptibility and magnetization intensity (Fig. 2d). The main magnetic mineral carrier is possibly magnetic iron sulfide (e.g., greigite), on the basis of the following observations: (1) severe thermal alteration occurred above 275–300°C; and (2) the ChRM appeared to be mostly lost below 300°C, although the unblocking temperature was not constrained due to the thermal alteration. If this inference regarding the magnetic carrier is correct, then the reverse polarity would be a chemical/crystallization remanent magnetization (CRM) acquired after deposition.

A reverse polarity site-mean direction was determined by combining one ChRM direction and nine best-fit great circles (Fig. 3a). This mean direction is considered to be reasonably reliable for the following reasons: (1) the presence of a ChRM direction; and (2) the intersection of most of the nine great circles at relatively large angles. After tilt correction, the mean direction is indistinguishable from the geocentric axial dipole field direction of reverse polarity.

**SAW:** Reverse polarity ChRM directions were determined for four specimens. In an example shown in Fig.
A ChRM direction was obtained between 200 and 400°C, and there was no rapid increase in initial magnetic susceptibility or magnetization intensity through-out ThD (Fig. 2e), which is in contrast to the Wakebe tephra results. The ThD results may suggest that the main magnetic carrier is titanomagnetite, and it is reasonable to assume that the ChRM is depositional remanent magnetization (DRM) acquired by the sediments at or soon after deposition. A reverse polarity site-mean direction was obtained by combining four ChRM directions and eight best-fit great circles (Fig. 3b). The mean direction is reliable because the ChRM directions are clustered around the mean direction, although the best-fit great circles are subparallel to each other. The tilt-corrected mean direction has a SSE declination and shallow negative inclination, and is significantly different from that of the Wakebe tephra direction and the geocentric axial dipole field direction of reverse polarity.

SBW: During ThD of specimens, the magnetization was mostly eliminated by 200–250°C, and no significant increase was observed in initial magnetic susceptibility or magnetization intensity at higher temperatures up to 350°C (thermal treatment was stopped at this point due to...
to specimen degradation). Magnetic iron sulfide (e.g., greigite) or titanomagnetite may be the magnetic carrier. Only four best-fit great circles were derived for this site and were used to estimate a reverse polarity site-mean direction (Fig. 3c). As such, the reliability of this direction is poor. However, the close similarity of this direction with that of the Wakebe tephra is compatible with the fact that this site is located only 5 cm below the base of the Wakebe tephra.

The paleomagnetic direction of the Wakebe tephra is of reverse polarity. Strong support for this is provided by the observation that both the SAW and SBW specimens are also reversely magnetized. Although the reverse polarity of the Wakebe tephra may be of CRM origin, its deposition during a reverse polarity period is suggested from the reverse polarity of the SAW that is interpreted to be a DRM. Thus, the hypothesis of Tamura et al. (2015) that the Wakebe tephra is correlative with a widespread tephra deposited in a normal polarity chron is not supported by the present results, and the widespread correlation of the Wakebe tephra needs to be reconsidered.

The Akogi tephra below the Wakebe tephra has a reverse polarity (Fig. 1a; Nakayama and Yoshikawa, 1990) and was deposited within Chron C2Ar in the late Gilbert Chron (Satoguchi et al., 2005). In contrast, the Otani-ike tephra above the Wakebe tephra is normally magnetized (Fig. 1a; Nakayama and Yoshikawa, 1990) and corresponds to Chron C2An.3n in the early Gauss Chron (Hoshi, 2016, 2017). Therefore, the reverse polarity of the Wakebe tephra corresponds to Chron C2Ar in the late Gilbert Chron, and its depositional age is between ~3.95 Ma (i.e., the age of the Akogi tephra and its correlative ash beds; e.g., Ueki et al., 2019) and 3.596 Ma (age of the Gauss–Gilbert boundary; Gradstein et al., 2004).

Trace element analyses indicate that the volcanic glass of the Wakebe tephra has relatively high Ba/La and low La/Y values (Tamura et al., 2015), which are characteristic of a tephra sourced from the Tohoku (northern Honshu) region (Tamura et al., 2008). Tamura et al. (2015) suggested that the source volcano is located in the Tohoku region. If this is correct, then the Wakebe tephra should be able to be correlated with a high-Ba/La and low-La/Y, reverse polarity tephra (possibly a pyroclastic flow deposit) deposited between ~3.95 and 3.596 Ma in Tohoku and surrounding regions.

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