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Reliable paleointensity determinations from Late Cretaceous volcanic rocks in Korea with constraint of thermochemical alteration

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ABSTRACT

Paleointensity determinations were carried out from Late Cretaceous (~77 Ma) volcanic rocks in Korea using a Thellier-type IZZI experimental protocol with systematic partial thermal remanent magnetization (pTRM) checks. Various data selection criteria were used to estimate reliable paleointensities. We set stringent threshold values for each parameter to ensure that there was: (1) a linear relationship between natural remanent magnetization (NRM) lost and TRM gained; (2) negligible thermal alteration of magnetic minerals; and (3) univectorial decay of NRM towards the origin. From the 336 samples, ~88% were rejected because of an insufficient extrapolated NRM fraction in the best-fit line ($f_{\text{vds}} < 0.6$), highlighting that f_{vds} is the most stringent selection criterion in this study. For the 31 accepted samples, paleointensities range from 6.4 to 30.4 μT. Among the 31 samples, eight samples yielded extremely low paleointensities. Although single-domain (titano)magnetite was identified as the stable paleointensity recorder, oxidation of superparamagnetic fractions upon repeated heating probably caused enhancement of pTRM acquisition and yielded a low paleointensity estimate. Apart from these low paleointensities (n = 8) as screened by a newly proposed data selection criterion of $\Delta k < 0.2$, the remaining 23 samples have a mean paleointensity of 23.1 ± 4.8 μT, corresponding to a virtual axial dipole moment (VADM) of 40.8 ± 8.5 ZAm^2, which is ~50% of the present-day VADM.

1. Introduction

Absolute paleointensity data can constrain the past behavior of Earth's magnetic field and dynamics of its deep interior, including the growth of the inner core and evolution of the geodynamo (e.g., Kono and Roberts, 2002; Tauxe, 2006; Biggin et al., 2015). Paleointensity determination is also useful to relate geomagnetic contribution to the geochronology (e.g., Tauxe and Yamazaki, 2007; Bowles et al., 2014; Cai et al., 2014) and to the atmospheric variation (e.g., Sinnhuber et al., 2003; Courtillot et al., 2007; Tarduno et al., 2010). In general, a stepwise double-heating method (Thellier and Thellier, 1959) is favored for recovering absolute geomagnetic field intensities from baked bricks, tiles, pottery, and volcanic rocks (e.g., Perrin and Schnepp, 2004; Tauxe and Yamazaki, 2007; Biggin et al., 2010; Korte and Constable, 2011). One inherent ambiguity in paleointensity determinations is that the data are acquired by different experimental protocols, as well as various sample selection criteria.

To date, more than 40 relevant sample selection criteria have been suggested to quantify the quality of paleointensity determinations (e.g., Selkin and Tauxe, 2000; Kissel and Laj, 2004; Leonhardt et al., 2004; Tauxe and Staudigel, 2004; Yu and Tauxe, 2005; Shaar and Tauxe, 2013; Paterson et al., 2014). Most of these criteria are designed on the basis of geometric patterns of data points on Arai plots (i.e., a plot of natural remanent magnetization (NRM) lost versus thermal remanent magnetization (TRM) gained) (Nagata et al., 1963), focusing mainly on how the data points are arranged in a straight line (e.g., Coe et al., 1978; Yu and Tauxe, 2005) and on how the partial TRMs (pTRMs) are influenced by thermal alteration (e.g., Selkin and Tauxe, 2000; Leonhardt et al., 2004). In addition to these Arai plot-relevant sample selection criteria, qualitative approaches based on rock magnetic characteristics became an important facet of paleointensity determinations, given that magnetic alteration can induce non-linearity on an Arai plot (Calvo et al., 2002; Yamamoto et al., 2003; Fabian, 2009; Zhao et al., 2014). For example, Fabian (2009) demonstrated with a numerical simulation that the acquisition of thermochemical remanent magnetization produces a perfectly linear, but inaccurate, Arai plot. According to Calvo et al. (2002) and Yamamoto et al. (2003), paleointensity determinations from historic lava flows in Italy and Hawaii are ~25–35% overestimated relative to the true values, probably due to thermochemical alteration. In contrast, Zhao et al. (2014) showed

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that paleointensity is underestimated as newly formed magnetic minerals preferentially enhance pTRMs. In either case, growth of new magnetic minerals or fractionation of existing crystals systematically affects both pTRM and NRM, yielding a linear yet unreliable outcome. In particular, when a newly formed magnetic mineral acquires TRM at low temperatures and unblocks at high temperatures, pTRM checks cannot detect the neo-formation as a result of thermal alteration. Thus, linearity of paleointensity data does not necessarily guarantee reliable paleointensity determinations.

In this study, Thellier-type IZZI paleointensity determinations (Tauxe and Staudigel, 2004; Yu et al., 2004) were carried out on Late Cretaceous volcanic rocks from Korea. The Thellier-type IZZI experimental protocol has the advantage of checking for subtle pTRM tails without incorporating additional heatings (e.g., pTRM tail check). To increase the reliability of paleointensity determinations, we utilized several screening parameters with stringent threshold values. More importantly, we propose a simple screening parameter that can identify the growth or decay of magnetic minerals during heating. We then further checked the fidelity of statistically screened paleointensity data using thermal demagnetization behavior, as initially proposed by Valet et al. (2010).

2. Samples and experiments

Late Cretaceous volcanic rocks in Korea were mostly erupted in the latter stages of basin formation (Won et al., 1990; Lee et al., 1992; Kim et al., 2000) and are exposed along faulted basin boundaries (Fig. 1a). Volcanic rocks covering sedimentary units in the Gongju Basin (Fig. 1b) are basalts to basaltic andesites and have K–Ar ages of ~77 Ma (73.51 ± 2.16, 76.77 ± 2.26, and 80.32 ± 2.36 Ma) (Cheong, 2002; Doh et al., 2002). A paleomagnetic study of these volcanic rocks (Doh et al., 2002) identified a primary polarity reversal of the Campanian stage. In particular, NRMs of Gongju volcanics are mainly carried by single-domain (SD) magnetic minerals, satisfying a pre-requisite for successful paleointensity determinations (e.g., Thellier, 1938; Néel, 1949).

A total of 336 samples of fresh volcanic rocks were collected from 13 different outcrops (Fig. 1b). In the laboratory, samples of 25 mm in diameter and 22 mm in height were prepared for paleointensity experiments and stored in a near-zero field environment (< 50 nT) to avoid magnetic viscosity effects caused by the ambient geomagnetic field. These 336 samples were then treated as follows. At each temperature step of T_i, the samples were heated and cooled both in the presence (in-field stage) and absence (zero-field stage) of a laboratory field (B_{lab} = 25 μT; directed along the z-axis of the sample). After each heating/cooling stage, the remanence was measured. To detect magneto-mineralogical changes produced by repeated laboratory heating treatments, pTRM checks were performed after every zero-field stage preceding an in-field stage.

Throughout the experiments, a weak-field bulk magnetic susceptibility (k) at room temperature was also monitored after each heating/cooling cycle. The optimized temperature steps for the experiments were determined based on preliminary investigations of stepwise thermal demagnetization data and were set to 200, 300, 350, 400, 450, 500, 520, 540, 550, 560, 570, 580, 590, and 600 °C. In some cases, additional temperature steps of 573 °C and 576 °C were used because NRM unblocks in a narrow temperature interval from 570 °C to 580 °C. During heating with a Magnetic Measurements MMTD-80 thermal demagnetizer, the temperatures were reproducible to ± 2 °C. Following the paleointensity experiments, the anisotropy of anhysteretic remanent magnetization (AARM) tensor was acquired (Selkin et al., 2000) for selected samples, and the possible effect of remanence anisotropy was checked using the AARM tensor.

To identify magnetic carriers and their thermal stability, thermal demagnetization of the three-axis isothermal remanent magnetization (IRM) (Lowrie, 1990) and temperature dependence of bulk magnetic susceptibility (k–T) were measured on representative samples. For 47 selected samples, DC fields of 2.5, 0.6, and 0.12 T along the Z-, Y-, and X-axes, respectively, were measured using an ASC Scientific IM-10-30 impulse magnetizer. The samples were then thermally demagnetized up

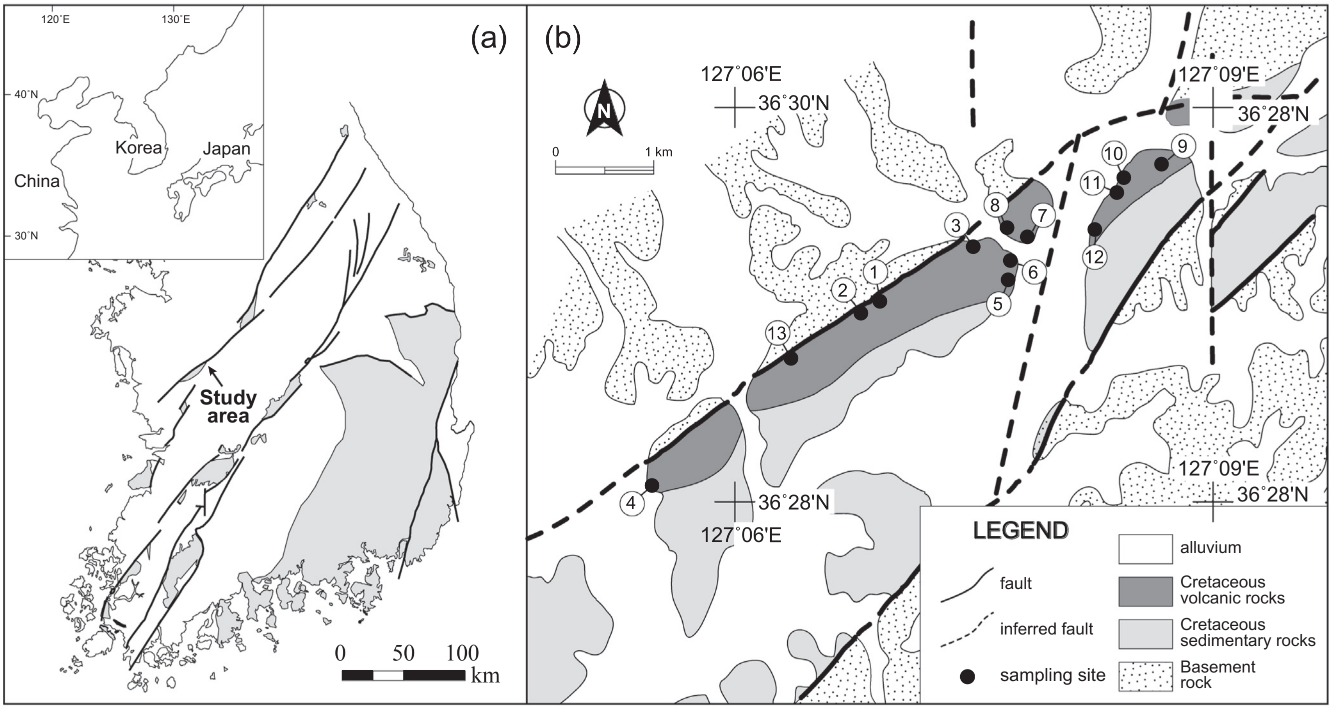

Fig. 1. (a) Distribution of Cretaceous basins (grey areas) and major faults in South Korea. Most of the Cretaceous volcanic rocks were erupted along basin-bounding faults. The study area (Gongju Basin) is indicated by an arrow. (b) Geological map of the Gongju Basin (modified from Kim et al. (1976)). The sampling locations are shown as solid circles annotated with site numbers.