Journal of Volcanology and Geothermal Research 336 (2017) 68–80

Contents lists available at ScienceDirect

Journal of Volcanology and Geothermal Research

journal homepage: www.elsevier.com/locate/jvolgeores

Complex remanent magnetization in the Kızılkaya ignimbrite (central Anatolia): Implication for paleomagnetic directions

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ARTICLE INFO

Article history:
Received 22 March 2016
Received in revised form 6 February 2017
Accepted 6 February 2017
Available online 20 February 2017

Keywords:
Ignimbrite
Magnetic remanence
Kızılkaya
Cappadocia

ABSTRACT

Pyroclastic flow deposits, known as ash-flow tuffs or ignimbrites, are invaluable materials for paleomagnetic studies, with many applications for geological and tectonic purposes. However, little attention has been paid to evaluating the consistency and reliability of the paleomagnetic data when results are obtained on a single volcanic unit with uneven magnetic mineralogy. In this work we investigate this issue by concentrating on the Kızılkaya ignimbrite, the youngest large-volume unit of the Neogene ignimbrite sequence of the Central Anatolian Volcanic Province in Turkey, bringing evidence of significant magnetic heterogeneities in ignimbrite deposits (magnetic mineralogy, susceptibility, magnetic remanence, coercivity, etc.) and emphasizing the importance of a stratigraphic sampling strategy for this type of volcanic rocks in order to obtain reliable paleomagnetic data. Six sections were sampled at different stratigraphic heights within the devitrified portion of the ignimbrite. Isothermal remanence measurements point to low-Ti titanomagnetite as the main magnetic carrier at all sites; at some sites, the occurrence of oxidized Ti-magnetite and hematite is disclosed. The bulk susceptibility (k_m) decreases vertically at two out of six sections: its value for the topmost samples is commonly one order of magnitude lower than that of the samples at the base. In most cases, low k_m values relate to high coercivity of remanence (B_{CR}) values, which range from 25 to >400 mT, and to low S-ratios (measured at 0.3 T) between 0.28 and 0.99. These data point to the occurrence of oxidized magnetic phases. We therefore consider the k_m parameter as a reliable proxy to check the ignimbrite oxidation stage and to detect the presence of oxidized Ti-magnetite and hematite within the deposit. The characteristic remanent magnetization is determined after stepwise thermal and AF demagnetization and clearly isolated by principal component analysis at most sites. For these sites, the site-mean paleomagnetic direction is consistent with data from the literature. At a few other sites, the remanence is more complex: the direction moves along a great circle during demagnetization and no stable end-point is reached. The occurrence of oxidized Ti-magnetite or hematite as well as two remanence components with overlapping coercivity and blocking temperature spectra suggest that the Kızılkaya ignimbrite acquired first a thermal remanent magnetization and then, during the final cooling or a short time later, a secondary remanent magnetization component which is interpreted as a CRM acquired during post-emplacement devitrification processes. Notwithstanding the Kızılkaya ignimbrite is a single cooling unit, its magnetic properties suffered substantial variations laterally and vertically within the deposit. The Kızılkaya case shows that thick pyroclastic deposits should be sampled using a stratigraphic approach, at different sites and different stratigraphic heights at each individual sampling location, otherwise, under-sampling may significantly affect the paleomagnetic results. When sampling is performed on a short duration or on very poorly preserved deposits we recommend drilling the lower-central portion in the most strongly welded and devitrified facies. Such sampling strategy avoids complications arising from the potential presence of a pervasive secondary CRM masking the original ChRM.

1. Introduction

Most volcanic rocks contain ferro-magnetic minerals that record past geomagnetic field in both direction and intensity. Lavas and indurated or welded pyroclastic rocks thus represent an invaluable material to obtain paleomagnetic information of utmost relevancy for volcanological and

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http://dx.doi.org/10.1016/j.jvolgeores.2017.02.007
0377-0273/

tectonic works. A significant literature based on such studies has arisen in past decades, resulting in major advances in many fields of geosciences, and applications have especially focused on stratigraphic correlations, paleogeographic reconstructions and deformation quantification at plate boundaries and orogenic belts (e.g. Eldredge et al., 1985; Johnston, 2001; Kent and Olsen, 1997; Nourgaliev et al., 2007). In volcanology, the relevance of paleomagnetic analyses of pyroclastic rocks has long been recognized, notably for paleo-directions (Lanza and Zanella, 2003; Alva-Valdivia et al., 2005; Paquereau-Lebti et al., 2008; Lesti et al., 2011; Cicchino et al., 2011; Zanella et al., 2012), and recently for paleo-intensity determinations (Gee et al., 2010; Perrin et al., 2013). While the input of paleomagnetic results based on the analysis of volcanic rocks is undisputed, little attention has been paid to sampling strategies and notably to the evaluation of the reliability of the paleomagnetic data when results are obtained on a single volcanic unit with uneven magnetic mineralogy (McIntosh, 1991; Palmer et al., 1996; Paquereau-Lebti et al., 2008; Caballero-Miranda et al., 2016). The aim of the present study is to take a closer look at this issue by focusing on magnetic properties of ignimbrites (volcanic ash-flow tuffs), which have been widely used in previous paleomagnetic works (e.g. Black et al., 1996; Urrutia-Fucugauchi et al., 2000; Urrutia-Fucugauchi and Ferrusquìa-Villafranca, 2001) and for the evaluation of ignimbrite flow directions and vent location (e.g. Rosenbaum, 1986; Schlinger et al., 1991; Ort et al., 1999; Palmer and MacDonald, 1999; Le Pennec, 2000; Reynolds, 1977; Alva-Valdivia et al., 2005). We particularly concentrate on the magnetic inhomogeneity of the deposit through examining the vertical variation of its magnetic properties (magnetic susceptibility, coercivity and remanent magnetization) to infer the chemical and physical processes that occurred at specific levels in the deposit. We refer to a companion paper (Agrò et al., 2015) for a deeper discussion of the Kızılkaya magnetic fabric and magnetic mineralogy.

The perspective of reliable magnetic results from this rock type is supported by the fact that many Neogene and Quaternary ignimbrites are well exposed over wide areas, where pre-flow paleotopography is well known; in these cases geological constraints can help reconstruct flow directions and locate the vent position. Besides, welded ignimbrites are mostly characterized by a stable thermal remanent magnetization (TRM), which provides an accurate paleomagnetic record in most cases (Lanza and Meloni, 2006; Zanella et al., 2015).

Pioneering works on Köenigsberger ratio showed that the variation of the crystal properties with cooling rate significantly affects the TRM acquired in a rhyolitic ignimbrite in New Zealand (Hatherton, 1954). Later, Reynolds (1977) documented lateral and vertical variations of paleomagnetic directions recorded in a welded tuff of the Yellowstone Caldera Complex, and Rosenbaum (1986) highlighted the effect of viscous deformation on remanence in some ignimbrite sheets of the Paintbrush tuff, Nevada. Sedimentation, cooling, viscous compaction (welding), possible rheomorphic creep, and other post-emplacement processes within a temperature range colder than the magnetic blocking temperature can complicate the paleomagnetic record, resulting in directional variations both laterally and vertically within a single ignimbrite deposit (Gose, 1970; Schlinger et al., 1991; Black et al., 1996). Understanding the origin of paleomagnetic complexities in ignimbrites is thus important to obtain improved usage of paleomagnetic directions in such deposits, and to gain insight into the processes that affect the magnetic signal.

In this work we perform a detailed analysis of the paleomagnetic signal in an ignimbrite unit of Cappadocia (Central Anatolia, Turkey). Earlier paleomagnetic research in the area aimed at estimating tectonic rotation rates at a regional scale to infer the recent geodynamic evolution of Anatolia (Piper et al., 2002), but did not address intrinsic paleomagnetic variability of the ignimbrite units. On the other hand, the stratigraphy and correlation pattern of the Cappadocia ignimbrites have been debated in past decades because of inconsistencies among early chronostratigraphic schemes (e.g. Pasquarè et al., 1988; Le Pennec et al., 1994; Schumacher and Mues-Schumacher, 1996; Temel et al., 1998; Le Pennec et al., 2005; Viereck-Goette et al., 2010; Aydar et al., 2012; Lepetit et al., 2014). Here we focus on a single well-defined and well-dated unit, the Kızılkaya ignimbrite, which is widely exposed at the top of the continental Neogene Cappadocia succession, and we investigate the magnetic mineralogy and remanence patterns along selected sub-vertical profiles. The Kızılkaya ignimbrite offers favorable conditions to address the issue presented above: firstly, recent analyses of zircon populations from pumice and whole rock samples indicate reliable correlation of this conspicuous 5.4 Ma-old unit (Aydar et al., 2012; Paquette and Le Pennec, 2012). Secondly, the partly welded Kızılkaya ignimbrite displays both lateral and vertical lithological diversity, with uneven degree of mechanical and viscous compaction, and a range of alteration and weathering facies. Thirdly, previous magnetic data on the Kızılkaya unit have concentrate on anisotropy of magnetic susceptibility (Le Pennec et al., 1998; Le Pennec, 2000; Agrò et al., 2015), and paleomagnetic directions (Piper et al., 2002), but none have focused on deciphering the diversity and origin of magnetic mineralogy and remanence within the deposits. Recently, Çubukçu (2015) investigated the vertical variation of the deuteric oxidation in the Kızılkaya ignimbrite deposit and discussed its relation to emplacement temperatures and its potential impact on the magnetic properties. He documented a systematic vertical variation pattern of Ti-magnetite oxidation state throughout the ignimbrite. Mineralogic and petrographical analyses revealed that the basal zone of the Kızılkaya ignimbrite contains unoxidized and homogeneous Ti-magnetite grains, while both deuteric oxidation and devitrification increase upward leading to the crystallization of paramagnetic oxyexsolved Ti-rich lamellae surrounding the ferromagnetic Ti-magnetite grains. He interpreted these features in terms of relative differences in cooling rates from the base to the top of the deposit and stronger degassing promoted by devitrification toward the top of the deposit. In this work we expand these previous investigations by focusing on the variability and origin of the magnetic mineralogy and remanence within the deposits and their paleomagnetic significance.

2. Geological setting

The Central Anatolian Volcanic Province (CAVP), a NE-SW trending Neogene-Quaternary volcanic field in the Anatolian microplate, developed upon the pre-Oligocene metamorphic and granitic basement (Toprak et al., 1994) (Fig. 1). The CAVP, bordered by the transtensional conjugate Tüzgölü-Ecemiş fault system, is characterized by a compositional trend from initial calc-alkaline signatures to quaternary alkaline affinities, and has been correlated to the extensional deformation of the Central Anatolian block, which developed through second-order dextral and sinistral strike-slip faults playing from the North Anatolian Fault Zone (NAFZ), in a context of regional convergence between Eurasia and Afro-Arabia since the latest Mesozoic (Facenna et al., 2003; Dilek, 2010).

The CAVP consists of many Quaternary monogenetic edifices and a few elevated Miocene to Quaternary strato-volcanoes (e.g. Melendiz Dağ, Hasan Dağ and Erciyes Dağ, Fig. 1), and exposes a succession of widespread Neogene ignimbrite units intercalated with continental sedimentary deposits. The late Miocene Kızılkaya ignimbrite is the youngest large-volume unit of the Cappadocia Plateau sequence; recent ^{39}Ar-^{40}Ar and U-Pb determinations on whole rock and minerals yield an eruption age of ~5.4 Ma (Aydar et al., 2012; Paquette and Le Pennec, 2012), and widespread sampling argues for robust correlation across the whole Cappadocia Plateau. The low aspect-ratio Kızılkaya ignimbrite defines flat structural surfaces on the plateau and usually occurs as a 10–30 m-thick (locally >80 m) red-tinted and columnar-jointed unit (Pasquarè et al., 1988). In the eastern part of the Plateau, the >180 km^3 ignimbrite is underlain by a plinian pumice fall deposit (Le Pennec et al., 1994; Schumacher and Mues-Schumacher, 1996). The ignimbrite is commonly welded and sintered, and the degree of welding varies both vertically and laterally, with eutaxitic textures observed in some valley-ponded facies (e.g. Ihlara, Soğanlı, Fig. 1). The jointing