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Reliable absolute palaeointensities independent of magnetic domain state

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Abstract

Knowledge of palaeointensity variation is required for determining the full vector variation of the geomagnetic field as a function of geological time. This provides essential constraints for numerical geodynamo models. To date, most palaeointensity determination methods are laborious, characterised by rather low success rates, and demand substantial processing time. The rocks under investigation must obey stringent criteria to yield faithful palaeointensities: the magnetic particles must be single domain, the natural remanent magnetisation must be a thermoremanent magnetisation, and during the successive heating steps in the laboratory no chemical alteration should occur. Here, we describe a new method that allows all magnetic domain states to be processed, i.e. it does not require single domain particles. The method makes use of the linearity of partial thermoremanent magnetisation (pTRM) with the applied laboratory field. Multiple specimens are used so that every sample is exposed only once to a laboratory field, warranting that all samples experienced the same magnetic history. Through the limited number of thermal steps alteration effects are reduced as well. The laboratory pTRM and natural remanent magnetisation (NRM) of the specimens are oriented parallel to minimise the effects of high-temperature tails that affect multidomain minerals. The pTRM acquisition temperature is selected below the temperature at which chemical alteration sets in and above the temperature trajectory where secondary viscous NRM components occur. The procedure requires a lower number of steps than any other palaeointensity method, reducing significantly the total time needed per rock unit. We propose to name the new protocol 'multispecimen parallel differential pTRM method'. It provides the correct answer to ~5% for artificial samples and natural rocks containing multidomain magnetic particles that were given a laboratory TRM of known intensity. Application to the Paricutin September–December 1943 lava flow (three sites, 7 specimens per site) yields a weighted mean of 45.9 ± 1.25 μT, within uncertainty margin of the expected value of 45.0 μT.

Keywords: absolute palaeointensity; magnetic domain state; Paricutin

1. Introduction

The Earth's magnetic field is generated in the liquid outer core of the Earth by magnetohydrodynamic processes referred to as the geodynamo [1]. The intensity of the geomagnetic field as a function of historical and geological time is known to be quite variable. For

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example, the present-day Earth's magnetic field declines rapidly in strength [2] resulting in a higher exposure to hazardous incoming cosmic radiation because the shielding capacity of the geomagnetic field is reduced. There is little consensus, however, on how far the intensity can drop during periods of stable polarity or what the field-strength range is during the reversal process itself [3]. The geodynamo is characterised by two fundamental modes: the so called mixed-polarity status during which the field reverses polarity up to a few times per Ma, alternated by long periods (>20 Ma) during which no polarity changes occur, referred to as superchrons. It is debated whether a relation would exist between reversal frequency and the strength of the geomagnetic field. If so, during superchrons high field intensity would be expected as indeed shown by [4–6]. Other workers [7–10] argue that such relation cannot yet be conclusively discerned.

The prime reason for these different, occasionally opposing, views is that it is very difficult to acquire good-quality absolute palaeointensity estimates. All studies are based on various versions of the so called Thellier–Thellier technique [11] and involve data selection, usually severe: a large number of determinations must be discarded because they are technically incorrect. For the Thellier–Thellier technique to work the magnectic particles must be single domain and must not alter during the experiment. Moreover, the natural remanent magnetisation (NRM) should be a pure thermoremanent magnetisation (TRM). Though simple, these criteria pose heavy restrictions in practice: most rocks appear to be unsuited.

The thermoremanent magnetisation (TRM) in single domain particles is the sum of partial TRMs (pTRMs) produced between successive temperature segments. Each pTRM segment is independent from one another. In a Thellier–Thellier experiment, the rock's original TRM, i.e. its natural remanent magnetisation (NRM), is progressively replaced by a set of laboratory pTRMs to successively elevated temperatures in a known field. In a 'pTRM gained' versus 'NRM left' plot (referred to as an Arai plot [12]) samples with single domain grains define a straight line from which the palaeofield wherein the TRM was acquired can be calculated straightforwardly, since TRM and therefore pTRM are proportional to the inducing field. Deviations from linearity in the Arai plot are due to multidomain behaviour and/or alteration that preclude a meaningful experiment. Various versions of the Thellier technique have been developed to detect alteration and multidomain behaviour involving zero-field heatings followed by in-field heatings for each temperature step [13], the inverted sequence per temperature step [14], or alternating the zero-field and in-field steps [6]. pTRM checks the test for alteration, while pTRM tail checks [15] and additivity checks [16] the test for multidomain behaviour that shows up as convex-down in Arai plots. This 'sagging' in Arai plots is due to non-reversibility of the magnetic starting state characteristic of multidomain grains [17,18]. Changing starting states are unavoidable in a Thellier–Thellier experiment. To arrive at more linear Arai plots, a multispecimen approach was proposed recently [19] in which individual specimens are processed for one temperature only; the behaviour for that temperature is evaluated by performing five thermal cycles, including removal of the viscous NRM component (cycle 1 to temperature T_0). Subsequently two zero-field cycles to T_1 and T_2 are performed (with $T_2 > T_1 > T_0$) and thereafter the laboratory pTRM is induced with the field switched on only during cooling from T_2 to T_0. The final cycle involves demagnetization at T_1 to ascertain the behaviour of laboratory TRM between T_1 and T_0. All is normalized to T_0 for individual specimens and a composite Arai-style plot allows the determination of the palaeointensity by making use of the inherent within flow variability in magnetic properties. A historic lava flow from Hawaii analysed with this procedure yields the expected intensity within measurement uncertainty [19]. Also recently an entirely new palaeointensity processing method has been developed, based on the ferromagnetic resonance using microwave fields [20,21]. This significantly reduces the thermal alteration and increases the success rate. Microwave palaeointensity determination is also faster than a Thellier type, thermal, experiment. However, due to the complex technology only two laboratories are using it at this moment.

Rather than focussing on optimising the laboratory palaeointensity determination procedure, the alternative approach of searching for rock samples that only contain single domain particles was also adopted, proposing to use submarine basaltic glass [22] to this end, or single plagioclase crystals with magnetite inclusions that are mostly single domain [23,24,4]. The latter are armoured by the surrounding plagioclase [see also [18]] against geological alteration and alteration induced by the laboratory processing. With the exception of the youngest extrusive rocks, weathering induced clay formation is the rule and even seemingly fresh rock samples may bear subtle signs of incipient weathering that only emerge when alteration sets in at temperatures higher than ~450 °C. It should be kept in mind, however, that submarine basaltic glass is relatively rare. Plagioclase crystals are common but the requirement of clear crystals free of groundmass forces the user to small fragments of up to a few mm in size. Meaningful measurement of the accompanying low intensities requires high-resolution superconducting magnetometers whereas the use of standard superconducting magnetometer systems may yield