Quaternary Science Reviews 61 (2013) 1–16

Contents lists available at SciVerse ScienceDirect

Quaternary Science Reviews

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

Invited review

Magnetic paleointensity stratigraphy and high-resolution Quaternary geochronology: successes and future challenges

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ARTICLE INFO

Article history:
Received 12 September 2012
Received in revised form
25 October 2012
Accepted 29 October 2012
Available online 12 December 2012

Keywords:
Geomagnetic field
Paleointensity
Quaternary
Geochronology
Depositional remanent magnetization
Post-depositional remanent magnetization

ABSTRACT

Magnetic paleointensity stratigraphy is used to detect variations in the strength of Earth's ancient magnetic field. Paleointensity studies have demonstrated that a dominantly dipolar geomagnetic signal can be recorded in a globally coherent manner in different types of sediments and in non-sedimentary archives, including ice core records and marine magnetic anomaly profiles. The dominantly dipolar nature of geomagnetic paleointensity variations provides a global geophysical signal that has come to be widely used to date Quaternary sediments. Despite the many successful applications of paleointensity-assisted chronology, the mechanisms by which sediments become magnetized remain poorly understood and there is no satisfactory theoretical foundation for paleointensity estimation. In this paper, we outline past successes of sedimentary paleointensity analysis as well as remaining challenges that need to be addressed to place such work on a more secure theoretical and empirical foundation. We illustrate how common concepts for explaining sedimentary remanence acquisition can give rise to centennial to millennial offsets between paleomagnetic and other signals, which is a key limitation for using paleointensity signals for geochronology. Our approach is intended to help non-specialists to better understand the legitimate uses and limitations of paleointensity stratigraphy, while pointing to outstanding problems that require concerted specialist efforts to resolve.

1. Introduction

Geomagnetic polarity reversals have been used widely in Quaternary geochronology (Fig. 1) because they result from a virtually synchronous global change in sign of the geomagnetic dipole. The geomagnetic polarity timescale (GPTS; e.g. Cande and Kent, 1995) serves as the backbone for the geological timescale for the last 200 Myr, and is based on temporally calibrated records of Earth's polarity history. Polarity reversals are accompanied by dramatic decreases in geomagnetic paleointensity (Fig. 1). Along with higher-frequency paleointensity variations within periods of stable polarity (Fig. 1), these major intensity changes can also provide a timescale that has come to be used widely in geochronology (e.g. Guyodo and Valet, 1996, 1999; Laj et al., 2000; Kiefer et al., 2001; Stoner et al., 2002; Stott et al., 2002; Valet et al., 2005; Yamazaki and Oda, 2005; Channell et al., 2009; Ziegler et al., 2011). The geomagnetic field is generated in Earth's fluid outer core, and is dominated by the dipole component, so that variations in field intensity have a strong global signal that can potentially be used to provide a high-resolution (millennial scale) timescale for chronostratigraphy. This temporal resolution contrasts with geomagnetic reversals (Fig. 1), which occurred only ~4–5 times per million years over the last ~31 Myr (Lowrie and Kent, 2004).

Determining the magnetic polarity of a given geological unit is straightforward, whereas, as argued below, determining the ancient geomagnetic field strength is not so simple. Given the increasing use of paleointensity estimation in Quaternary geochronology, we provide an overview for a general audience of how geomagnetic paleointensities are estimated. We then summarize the strongest lines of evidence for why such estimations appear to be robust, followed by discussion of some of the uses of geomagnetic paleointensity analysis in high-resolution Quaternary geochronology. This treatment is representative of the successes of paleointensity analyses of Quaternary sediments. However, despite these outstanding successes, challenges remain. The remainder of the paper is devoted to summarizing these challenges. Our overall aim is to help Quaternary scientists to understand better how sedimentary paleointensities are estimated, their potential chronostratigraphic value, and their limitations. We also point out problems that require concerted paleomagnetic

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http://dx.doi.org/10.1016/j.quascirev.2012.10.036

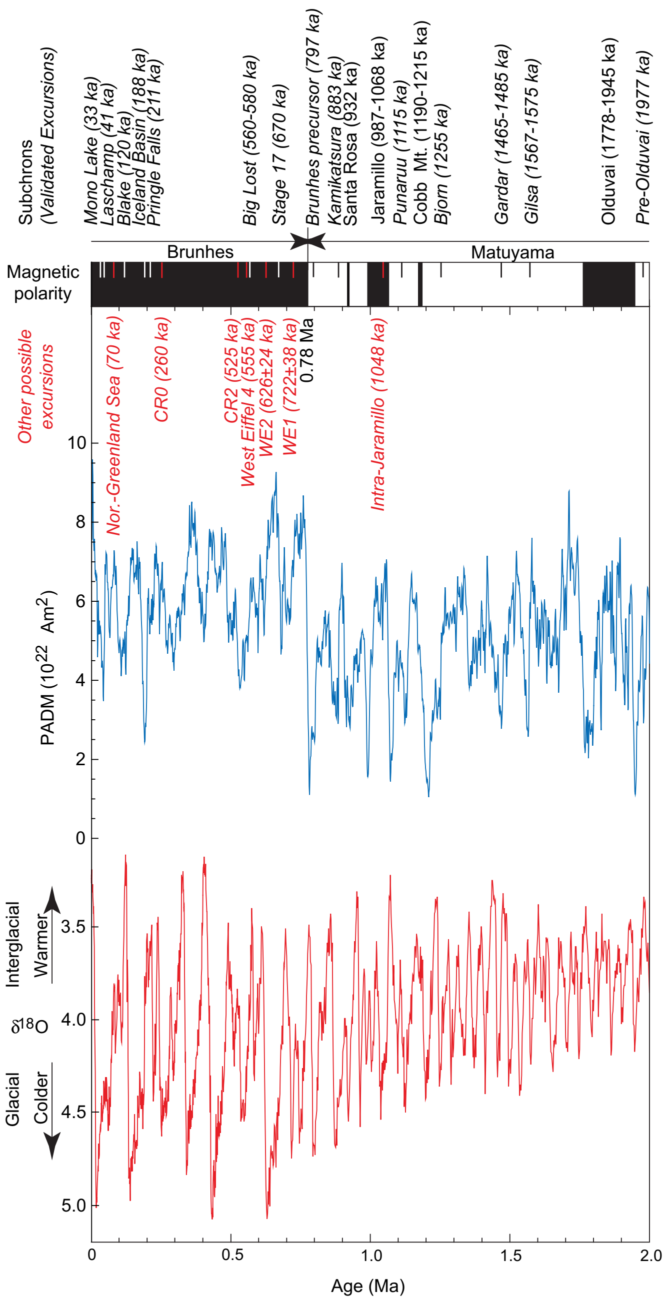

Fig. 1. Geomagnetic polarity timescale for the last 2 million years, with geomagnetic excursions, relative paleointensity variations and benthic $\delta^{18}O$ variations. Geomagnetic polarity is indicated at the top of the figure (black = normal; white = reversed polarity). Validated excursions (white) are indicated along with their respective ages above the polarity log in italics, with "possible" excursions (red) that have yet to be fully validated are indicated in red below the polarity log (Laj and Channell, 2007; Roberts, 2008). Each polarity reversal and excursion coincides with a paleointensity minimum. The paleomagnetic axial dipole moment (PADM) model (Ziegler et al., 2011) is used to represent paleointensity (blue). The climatic context of the geomagnetic variations is illustrated using the global stacked benthic $\delta^{18}O$ record (red) of Lisiecki and Raymo (2005).

effort to resolve. Such efforts will be valuable for improving our understanding of the geodynamo as well as aiding geochronological applications.

2. How does paleointensity determination work?

Reliable contemporary measurement of the intensity of the geomagnetic field has only been possible since the first measurements made by Gauss in 1835. Determination of geomagnetic field intensities for time periods preceding the 19th Century, therefore, requires paleomagnetic analysis of rocks or archaeological artefacts. Estimating the intensity of an ancient magnetic field is based on the assumption that the magnetization of a rock will be related linearly to the geomagnetic field strength. It is, therefore, expected that the natural remanent magnetization (NRM) of a sample will be related to the ancient field intensity (B_{anc}) as follows:

$$\mathrm{NRM} \cong \alpha_{anc} B_{anc},$$

where α_{anc} is a constant of proportionality. For certain igneous rocks, archaeological artefacts or other materials that have cooled from high temperatures, there is a robust physical theory and experimental protocol that enables determination of the absolute paleointensity from the recorded thermal remanent magnetization (TRM) (Thellier, 1938; Néel, 1955; Thellier and Thellier, 1959). Laboratory experiments are aimed at determining the proportionality of the TRM intensity to the geomagnetic field strength (Thellier and Thellier, 1959). After measuring the ancient TRM (TRM_{anc}) at a given temperature, a TRM can be imparted in the laboratory by heating the sample to the same temperature in a known applied laboratory field (B_{lab}). This enables determination of the laboratory constant of proportionality (α_{lab}). Assuming that α_{lab} is identical to α_{anc}, which can be tested with carefully designed experiments, the paleofield intensity can be determined from:

$$B_{anc} = (\mathrm{TRM}_{anc}/\mathrm{TRM}_{lab}) B_{lab}.$$

While the laboratory normalization technique provides a theoretically grounded means of determining absolute ancient field intensities, suitable materials with thermal remanences are neither temporally continuous nor are they globally available. Young volcanic rocks are also notoriously difficult to date and only a small fraction of available material yields useful paleointensity data. Sedimentary sequences are, therefore, an attractive target for obtaining continuous records of geomagnetic paleointensity variations. However, identification of a robust procedure for laboratory normalization of a sedimentary NRM that is analogous to that for a TRM has proved elusive. The problem is that there is no simple means of determining α_{anc} to calibrate the relationship between the NRM of a sample and the strength of the magnetizing field. The magnetization of sediments is affected by the strength of the ambient magnetic field, the magnetic mineral that records the paleomagnetic signal, the concentration of this magnetic mineral fraction, its grain size and the mechanism by which the magnetization was acquired. An empirical approach has been developed for estimating paleointensities from sediments in which the NRM is normalized by an artificial laboratory-induced magnetization (Levi and Banerjee, 1976). The goal is to remove the influence of rock magnetic variations with non-geomagnetic origins, and to validate the record by imposing strict rock magnetic selection criteria. These criteria traditionally require magnetite to be the only magnetic mineral present and that it occurs within a narrow grain size and concentration range (King et al., 1983; Tauxe, 1993). While this empirical approach appears to work (see discussion below), its theoretical underpinning is complicated (e.g. Tauxe et al., 2006). The result is that, because we cannot determine absolute paleointensities from sediments, we seek to estimate relative paleointensity variations by minimizing the number of variables that contribute to the magnetization of the sediment under investigation.

Despite the lack of a first-principles theory for how sediments become magnetized, we can outline general principles by which