Earth and Planetary Science Letters 441 (2016) 103–112

Contents lists available at ScienceDirect

Earth and Planetary Science Letters

www.elsevier.com/locate/epsl

Pallasite paleomagnetism: Quiescence of a core dynamo

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ARTICLE INFO

Article history:
Received 26 September 2015
Received in revised form 18 January 2016
Accepted 17 February 2016
Editor: B. Buffett

Keywords:
extraterrestrial magnetism
cloudy zone
pallasite meteorites
X-ray photoemission electron microscopy
core dynamo activity

ABSTRACT

Recent paleomagnetic studies of two Main Group pallasites, the Imilac and Esquel, have found evidence for a strong, late-stage magnetic field on the parent body. It has been hypothesized that this magnetic field was generated by a core dynamo, driven by compositional convection during core solidification. Cooling models suggest that the onset of core solidification occurred ∼200 Ma after planetary accretion. Prior to core solidification, a core dynamo may have been generated by thermal convection; however a thermal dynamo is predicted to be short-lived, with a duration of ∼10 Ma to ∼40 Ma after planetary accretion. These models predict, therefore, a period of quiescence between the thermally driven dynamo and the compositionally driven dynamo, when no core dynamo should be active. To test this hypothesis, we have measured the magnetic remanence recorded by the Marjalahti and Brenham pallasites, which based on cooling-rate data locked in any magnetic field signals present ∼95 Ma to ∼135 Ma after planetary accretion, before core solidification began. The cloudy zone, a region of nanoscale tetrataenite islands within a Fe-rich matrix was imaged using X-ray photoemission electron microscopy. The recovered distribution of magnetisation within the cloudy zone suggests that the Marjalahti and Brenham experienced a very weak magnetic field, which may have been induced by a crustal remanence, consistent with the predicted lack of an active core dynamo at this time. We show that the transition from a quiescent period to an active, compositionally driven dynamo has a distinctive paleomagnetic signature, which may be a crucial tool for constraining the time of core solidification on differentiated bodies, including Earth.

1. Introduction

Paleomagnetic studies of meteorites provide evidence that core dynamos were a widespread feature of planetesimals during the early solar system (Weiss and Elkins-Tanton, 2013; Scheinberg et al., in press). Two recent studies (Tarduno et al., 2012; Bryson et al., 2015) have shed light on the nature of magnetic fields on the Main Group (MG) pallasite parent body. Time-resolved paleomagnetic records suggest the MG parent body experienced an intense, late-stage magnetic field, which is attributed to an active core dynamo driven by compositional convection during inner core solidification (Nimmo, 2009). The onset of core solidification is predicted to have started ∼190 Ma after planetary accretion, based on the planetary cooling model proposed by Bryson et al. (2015) for a 200-km-radius body. Prior to this time, any long-term dynamo would have been driven by thermal convection. Thermal modelling suggests an active thermal dynamo would require a magma ocean to generate the required heat flux out of the core. This is predicted to have acted at most for 10–40 Ma after accretion (Elkins-Tanton et al., 2011), leading to a quiescent period after the shut down of the thermal dynamo and before the onset of core solidification. A thermal dynamo requires a high heat flux to operate and therefore tends to be of limited duration. Numerical modelling and simple energy balance arguments suggest that a small planetary body with radius <500 km cannot be sustained for more than 10 Ma (Sterenborg and Crowley, 2013). These authors demonstrate that the lifetime of a thermal dynamo is highly dependent on the radius of the planet, $t_{dyn} \propto r^4$, therefore other physical parameters (such as convection of a magma ocean) have an insignificant effect on dynamo duration compared to planetary radius. Likewise, a compositionally driven dynamo can only become active after suf-

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http://dx.doi.org/10.1016/j.epsl.2016.02.037

ficient cooling of the planetary body has taken place for the core to reach its liquidus temperature. Here we investigate if any magnetic field was generated by, or acting on, the MG parent body between these predicted periods of dynamo activity.

In the following, we follow Tarduno et al. (2012) in assuming that the metallic component of the MG pallasites was delivered to the pallasite parent body during a collision with another differentiated body. The metal will have rapidly solidified and thermally equilibrated with the surrounding silicates; the cooling rates thereafter would have been controlled by the depth of metal within the parent body. Pallasites with different cooling rates are assumed to have experienced different long-term thermal evolution, owing to their differing depths within the parent body. For consistency with prior work, we assume the same pallasite parent body radius (200 km) to derive original depths based on the observed metallographic cooling rates. Small variations in the size of the parent body do not significantly affect the timing of magnetisation for the pallasites, so do not change our results (see Supplementary Table 1).

Two MG pallasites, the Brenham and Marjalahti, have been measured to study the possible presence of magnetic fields during the predicted quiescent period. Both pallasites were examined for paleomagnetic signals recorded by microstructures within the FeNi matrix. New experimental techniques such as electron holography (Bryson et al., 2014a) and X-ray photoemission electron microscopy (X-PEEM) (Bryson et al., 2014b), have revealed the capability of meteoritic FeNi metal to record information about these ancient paleomagnetic fields. The FeNi metal contains a range of microstructures depending on its local Ni content. During slow cooling, nucleation of kamacite lamellae within the parent taenite leads to the characteristic Widmanstätten pattern and distinctive M-shaped diffusion profiles (Yang et al., 1996). Local Ni composition within the M-shaped profile varies from ~50% bulk Ni content immediately adjacent to the kamacite lamellae to ~10% further away from the kamacite interfaces. The most Fe-rich phase is kamacite, which forms intersecting µm-scale lamellae. These lamellae contain multiple magnetic domains and are magnetically soft, making them poor paleomagnetic recorders (Garrick-Bethell and Weiss, 2010). Adjacent to the kamacite is the tetrataenite rim ($Fe_{0.5}Ni_{0.5}$), a 1–2 µm-wide region which also exhibits multidomain magnetic behaviour. Next to the tetrataenite rim is the 'cloudy zone', which is followed by plessite; a mixture of kamacite, taenite and ordered tetrataenite (Goldstein and Michael, 2006).

The 'cloudy zone', a region of $Fe_{0.5}Ni_{0.5}$ 'islands' in a Fe-rich matrix, forms by spinodal decomposition during slow cooling of FeNi metal with composition ~25–45% Ni (Yang et al., 2010). The size of the islands correlates inversely with cooling rate (Yang et al., 2010); once islands form they then continue to coarsen and their volume increases linearly over time (at constant temperature) (Weinbruch et al., 2003). The islands are formed of ordered tetrataenite with the tetragonal $L1_0$ superstructure (Yang et al., 1996). This structure means that they are excellent paleomagnetic recorders, with an intrinsic coercivity of ~2 T (Uehara et al., 2011). The c-axis is perpendicular to one of the three {100} orientations of FeNi layering (Lewis et al., 2014) providing three orthogonal easy axes along which the islands can be magnetised. As the cloudy zone forms, the atomic structure adopted by each island will be influenced by the presence of any magnetic field, locking in a chemical transformation remanent magnetisation (CTRM). If the cloudy zone forms in the absence of an external field, the islands within the cloudy zone will be magnetised along each of six possible directions (± directions along each of the three easy axes); however in the presence of an external field, a bias in the direction of magnetisation can be detected. This bias can be used to quantify the magnetic field intensity experienced by the cloudy zone at the time when magnetisation became locked in. The islands lock in a magnetic field signal when they reach their blocking volume (the volume at which the magnetisation of the island becomes stable), so the largest islands lock in paleomagnetic signals earlier than the smaller islands (they have coarsened more since growing through their blocking volume). The blocking volume is reached when the island size exceeds the diffusion length, preventing reorganisation of easy axes and hence magnetisation across the entire island. The island may continue to grow and coarsen after this time, but the magnetisation of each island is expected to remain constant.

We chose the Brenham and Marjalahti based on the size of the islands in the cloudy zone, which at their coarsest are 123 ± 3 nm and 118 ± 3 nm in diameter, respectively (Yang et al., 2010). The coarsest islands in the Imilac and Esquel, which revealed evidence for a compositionally driven dynamo (Bryson et al., 2015; Tarduno et al., 2012) are 143 ± 4 nm and 157 ± 11 nm; since these two pallasites cooled slower, they are predicted to have reached the cloudy zone formation temperature later and hence have recorded a later period of dynamo activity than the Brenham and Marjalahti. According to the thermal model for the MG pallasite parent body, the Brenham and Marjalahti formed their cloudy zones and acquired a CTRM prior to the onset of inner core solidification. Constraining paleomagnetic signals in this potentially quiescent period is essential for characterising core dynamo behaviour over long timescales, and may help with identifying signals that indicate the onset of core solidification.

2. Methods

2.1. Experimental methods

Samples of the Brenham (BM 68725) and Marjalahti (BM 1920,318) were obtained from the Natural History Museum, London, UK. The samples were initially polished and etched using nital (2% nitric acid in ethanol) and examined using a reflected light microscope to check for signs of alteration or shock. Samples were then repolished to reveal a fresh surface prior to X-PEEM measurements. X-PEEM was performed at the SPEEM UE49 beamline, BESSY II, Berlin (Kronast et al., 2010). Firstly, the samples were sputtered using a focused Ar-ion beam under vacuum (pressure $<1.5 \times 10^{-5}$ mbar) to remove any oxidation or surface magnetisation induced by polishing. The Marjalahti was sputtered for 20.5 h and the Brenham for 19 h whilst reducing the voltage from 1.2 keV to 0.4 keV to minimise surface topography due to differential etching. The samples were kept in vacuum after sputtering and prior to measuring (measuring pressure $<1 \times 10^{-8}$ mbar). X-PEEM images with a 5 µm field of view were taken at multiple locations around the Marjalahti and Brenham. The maximum possible resolution achievable with this technique is 30 nm (Locatelli and Bauer, 2008), although resolution varies depending on several factors. An intense beam of monochromatic X-rays was focused at an angle of 16° to the sample surface. Secondary photoelectrons were excited from the top ~5 nm of the sample surface by the X-rays. Photoelectrons are preferentially excited from particular elements and spin states, according to the energy and polarisation of the X-ray beam, respectively. Excited photoelectrons were accelerated and focused using electron lenses, forming an image of the sample surface (Ohldag et al., 2001; Nolting et al., 2000). This technique allows compositional and magnetic imaging to be carried out in the same location in quick succession by changing the energy and polarisation of the X-ray beam, meaning a direct comparison can be made between composition and magnetisation for each region. Each image is individually assessed for light drift and charging artefacts, and only the highest quality data are selected for further analysis.