A time-series record of magnetic activity on the pallasite parent body

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Paleomagnetic measurements of meteorites[1-5] suggest that, shortly after the birth of the solar system, the molten metallic cores of many small planetary bodies convected vigorously and were capable of generating magnetic fields[6]. Convection on these bodies is

currently thought to have been thermally driven[7,8], implying that magnetic activity would have been short-lived[9]. Here we present a time-series paleomagnetic record of the field recorded by the Imilac and Esquel pallasite meteorites, derived from nanomagnetic images[10] of their metallic matrices. The results reveal a history of long-lived magnetic activity on the pallasite parent body, capturing the decay and eventual shut down of the magnetic field. We demonstrate that magnetic activity driven by progressive solidification of an inner core[11-13] is consistent with our measured magnetic field characteristics and cooling rates[14]. Solidification-driven convection was likely common among small body cores[15], and, in contrast to thermally driven convection, will have led to a relatively late (hundreds of millions of years after accretion), long-lasting, intense and widespread epoch of magnetic activity among these bodies in the early solar system.

The pallasites are slowly cooled (2 - 9 K Myr^{-1})[14] stony-iron meteorites[16], which originated from the mid- to upper-mantle of a ~200-km-radius body[1]. The slow cooling rate of these meteorites allowed for characteristic microstructures to form in their metal matrix[17], a key feature of which are regions of intergrown nanoscale islands of tetrataenite (ordered FeNi)[18,19] and an ordered Fe_3Ni matrix[20], collectively known as cloudy zones (CZ)[21]. During parent body cooling, these tetrataenite islands exsolved and subsequently coarsened over tens of millions of years[22]. The island diameter decreases systematically across the CZ, reflecting a decrease in the local formation age of the islands[20]. Each island adopted one of three orthogonal magnetic easy axes as it formed[18,23], thus could display any one of six magnetisation directions. Variations in the intensity and direction of an external magnetic field led to measurable differences in the populations of each magnetisation direction[20]. Crucially, the temporal evolution of an external field is recorded by the variations in the relative proportions of these directions across the CZ[10], which can be quantified using high-resolution nanomagnetic imaging. These images were captured for the Imilac and Esquel pallasites, utilising X-ray magnetic circular dichroism[24,25] at the X-ray photoemission electron microscope (XPEEM)[26] at the BESSY II synchrotron, Berlin, which provides the spatially resolved magnetisation of a sample surface with a resolution down to 40 nm over a 5 μm field-of-view[10].

Four and six non-overlapping, 450-nm-wide regions across the CZ (decreasing age) were extracted from the XPEEM images of Imilac and Esquel meteorites, respectively (Fig. 1). The field recorded by each region was deduced by comparing the experimental XPEEM signal to that of simulated CZ nanostructures magnetised by variable field components[10] (see Methods).

The field components that created the five best fits to the experimental data for all regions in the Imilac meteorite and regions 1 - 5 in the Esquel meteorite are self-consistent, while those of region 6 in the Esquel meteorite display a large degree of scatter (Fig. 2). These observations imply the time-averaged field experienced by each region is unidirectional. The Imilac meteorite recorded a roughly constant intensity between 119(±12) - 131(±13) μT across all regions (Fig. 3a). The Esquel meteorite recorded a very different trend, with an initial intensity of 84±14 μT, which decreases down to a plateau at a value of 31(±10) - 35(±7) μT. Due to the limitations of the fitting, the field recorded by region 6 could only be constrained to ≤10 μT (Fig. 3b), which, coupled with the large degree of scatter, suggests this region potentially did not experience a field. These intensity values are consistent with those reported independently[1], deduced by a different method. The main uncertainty in our intensity values is the island volume when they recorded the field (see Supplementary Information). With the largest possible (present day) island volume, the intensity of the first region of the Imilac and Esquel meteorites is 4±0.4 μT and 2±0.7 μT respectively. Our main result, however, is the inferred time-variation in relative field strength and orientation, which is unaffected by the absolute recording volume.

In order to estimate when each meteorite recorded the field, we modelled the cooling of a 200-km-radius[1] conductive body during the ~250 million years following accretion (Fig. 4). Depths were assigned to the Imilac and Esquel meteorites based on their cooling rates at 800 K (Extended Data Fig. 6), calculated using the observed island sizes of 147±4 nm and 158±6 nm, respectively (Extended Data Fig. 2), and the empirical relationship between island size and cooling rate[14]. The Imilac and Esquel meteorites resided at depths of 38±2.5 km and 45±4 km, respectively. The CZ started recording the field once tetrataenite formation commenced (593 K), which we predict occurred at these depths during the period of core solidification (Fig. 4).

At this time, dynamo activity could have been driven by compositional convection resulting from the preferential fractionation of light elements (e.g. S) into the liquid outer core as the inner core solidified[11], as is the case for the present-day geodynamo[6,12]. To assess this hypothesis, the magnetic moment, magnetic Reynolds number and local Rossby number (Extended Data Figure 7) were calculated[13] for a compositionally driven dynamo throughout the period of core solidification (Fig 3c). In our model (see Supplementary Information), the thermal structure of the mantle governs the core-mantle boundary heat flux, which in turn dictates the rates of inner core growth and light element rejection that ultimately control convection[15]. Across the majority of core solidification, the core magnetic moment is predicted to decrease smoothly down to zero. The magnetic Reynolds number governs whether the convective motion generates a field, and, for a four-hour rotation period, dynamo activity is predicted to have ceased at the latest stages of core solidification. The local Rossby number governs the polarity of the moment, and, for the same rotation period, a dipolar to multipolar transition is predicted slightly before dynamo cessation. This transition is accompanied by a decrease of up to a factor of 20 in the field intensity[13].

The conductive cooling model predicts that the Imilac and Esquel meteorites started recording the dynamo field during the early (sometime between 0 - 33% of the core volume solidified) and late (43 - 100% of the core volume solidified) stages of inner core growth, respectively (Fig. 4). In each case, recording is estimated to have continued while a further 10 - 20% of core volume solidified. The Imilac meteorite is therefore predicted to have experienced a smoothly decreasing dipolar dynamo field (corresponding to the early decreasing core moment), whereas the Esquel meteorite is predicted to have captured a decrease in the field intensity (dipolar-multipolar transition), a constant weak intensity (multipolar regime), and finally zero intensity (dynamo cessation). Both trends agree, within uncertainty, with the results inferred from their respective meteorite (Fig. 3), indicating that the recorded fields were generated by compositional convection.

The model dynamo field intensity midway through the mantle (corresponding roughly to the depths of the two meteorites) (Fig. 3c) is about an order of magnitude less than the nominal values extracted from the CZ. This discrepancy may be explained through the amplification of the dynamo field by the mantle-hosted metal that constitutes the pallasites. At the CZ magnetisation acquisition temperatures, this metal will have consisted predominantly of the magnetically soft phases kamacite and taenite[27]. By considering the extremes in feasible metal morphologies (see Supplementary Information), the field within the metal will be amplified by a factor of 3 - 200 (Fig. 3c), generating intensities well within the range of our measured values.

The values of many of the parameters in the cooling and dynamo scaling models are uncertain (e.g. the light element content of the core liquid and variation in this parameter during solidification). Also, the scaling model is derived empirically from numerical models with parameters different to those relevant to the interior of small bodies, and not all small body cores are expected to have solidified from the bottom-up[28]. Despite these caveats, the field intensity trends inferred from the CZ of the pallasites agree with our model predictions. The thermally driven dynamo activity that is widely believed to have acted on small bodies[7-9] is inefficient[15] (hence was likely uncommon) and could only have generated fields for the first 10 - 50 million years (depending on the body's radius) after CAI formation[7, 29]. Our results suggest that compositionally driven dynamo activity was generated in outwardly solidifying small body cores from ~60 - 250 million after CAI formation, and lasted for the majority of core solidification (a further ~25 - 150 million years depending on the body's radius)[1]. These later fields were extremely easy to generate[15] (so would have been widespread), relatively constant in both direction and intensity, and were capable of displaying both dipolar and multipolar morphologies. These conclusions imply a second epoch of dynamo activity across a potentially large fraction of small bodies in the early solar system, and can help explain the long-lived magnetic activity observed for other bodies, e.g. the Moon[30].

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Author Information Reprints and permissions information is available at www.nature.com/reprints. The authors declare no competing financial interests. Readers are welcome to comment on the online version of the paper. Correspondence and requests for materials should be addressed to J.F.J.B (jfjb2@cam.ac.uk).

Figure 1. Representative XPEEM images of the kamacite, tetrataenite rim and CZ in the Imilac and Esquel pallasites. Blue and red signals correspond to positive and negative projections of the magnetisation along the X-ray beam direction (Extended Data Figure 1) in the **a** Imilac and **b** Esquel meteorite. Each image is one of four used in the paleomagnetic analysis (Extended Data Figs. 3 and 4). The CZ displays a complex interlocking pattern of positive and negative domains. The CZ regions are labelled. The age of the CZ decreases with distance from the tetrataenite rim. TT: tetrataenite.

Figure 2. The five best-fitting and average field components for each CZ region of the Imilac and Esquel pallasites. Equal-area stereographic projection of the field components in the **a** Imilac and **b** Esquel meteorite. Empty points and dashed lines represent the lower hemisphere of the stereoplot, and filled circles and solid lines represent the upper hemisphere. The 95% confidence interval assuming a Fisher distribution is included as an ellipse around each of the average directions. This ellipse is not included for region 6 of the Esquel meteorite due to the large degree of scatter.

Figure 3. Measured and simulated dynamo field intensity trends. Measured intensities for **a** Imilac and **b** Esquel meteorites. Points and error bars are the mean and standard deviation, respectively, of the five best-fitting field components. The ≤10 μT field for region 6 of the Esquel meteorite is depicted as a black rectangle. Each region corresponds to a maximum time period of ~1 - 2 Myr. **c** Simulated mid-mantle intensities. Dipolar amplification: 10x dipolar field. Multipolar amplification: 0.05x amplified dipolar field. Im and Esq mark the recording periods of the Imilac and Esquel meteorites, respectively (from Fig. 4).

Figure 4. Cooling of a 200-km-radius body, consisting of a core, mantle and regolith. Evolution of the temperature (colour and contours) at a given radius and time. The red contour depicts the initial tetrataenite formation temperature (593 K), corresponding to the earliest CZ remanence. Black horizontal lines mark the inferred depths of the Imilac and Esquel meteorites, calculated[14] from the average largest island size (Extended Data Figure 2). Dashed grey vertical lines mark the likely recording period for each meteorite, inferred from the size range of largest CZ islands. During solidification (grey region), the core was isothermal at 1200 K.

Online-only Methods

Sample characterisation and experimental details. The Imilac meteorite sample was provided by the Sedgwick Museum of Earth Sciences, University of Cambridge, sample number 11587. The Esquel meteorite sample was provided by the Natural History Museum, London, sample number BM.1964,65. Both samples were cut and polished to generate the flat, clean surface required XPEEM measurements. Both samples contained multiple, large (cm-sized) olivine crystals, which were surrounded by swathing kamacite. The CZ bordering swathing kamacite was studied in both meteorites. Care was taken at all stages that the experimental team were in possession of the samples to limit their exposure to both natural and artificial magnetic fields.

The XPEEM measurements were performed at the SPEEM UE49 end station at the BESSY II synchrotron. The sample surfaces were illuminated with a monochromatic, circularly polarised X-rays beam tuned to the Fe $L_{2,3}$ edge. A 10 kV or 15 kV high voltage was used to produce images with a high spatial resolution, which varied between 100 - 200 nm. We believe this relatively poor resolution (XPEEM can achieve at best 30 - 40 nm resolution) is sample-specific and due to strong stray fields emanating from the sample surface as well as surface roughness. The XPEEM signal is enhanced by capturing and subtracting images with opposite circular polarisations[10]. Secondary electrons can only escape from the top ~5 nm of the sample[31], so XPEEM is only capable of probing the surface magnetisation of the sample. The beam was orientated 16° out of the plane of the sample, and 16° clockwise from the vertical edge of the image (Extended Data Fig. 1). The analysed images have a 5 μm field-of-view and a pixel resolution of ~10 nm/pixel. During polishing, the top 80 - 100 nm of the sample was physically altered such that the magnetisation was unrepresentative of the underlying natural signal[10,20]. To remove this layer, the meteorites were Ar ion sputtered under ultra-high vacuum (Esquel meteorite: 12 hours at 0.8 keV, followed by 3 hours at 0.4 keV; Imilac meteorite was sputtered for 16.5 hours at 0.8 keV followed by 1 hour at 0.4 keV).

Scanning electron microscopy (SEM) backscattered electron images were captured at the Center for Electron Nanoscopy, Technical University of Denmark, on a FEI Helios NanoLab 600. The images were acquired at an electron probe current of 5.5 nA and an acceleration voltage of 3 kV. SEM was used to measure the diameter of the tetrataenite islands across the CZ in both meteorites (Extended Data Fig. 2). The island diameter was used to calculate the size of the blurring function during paleomagnetic analysis. The average island size for each region is presented in Extended Data Table 1.

Paleomagnetic analysis. 5 μm field-of-view XPEEM images were captured at multiple locations across both samples. The quality and orientation of each image was assessed and only those of high quality (i.e. showing no beam drift, oxidation or charging) and those with features at a constant orientation to the X-ray beam were further analysed. These selection criteria resulted in four images for each meteorite. Pixel-intensity histograms were extracted from adjacent, non-overlapping, 450-nm-wide regions of all four XPEEM images of each meteorite. Histograms of the same region from all four images of the same meteorite were averaged to generate a representative data set for each region (Extended Data Figs. 3 and 4).

The strength and direction of the field recorded by each region were deduced by comparing the measured XPEEM signal to that of a simulated nanostructure magnetised by variable field components[10]. Firstly, the XPEEM intensities corresponding to each of the six possible magnetisation directions were extracted from the tetrataenite rim (positive and negative values of the three distinct twin domain intensities). These intensities were used to populate the islands in a simulated CZ nanostructure. This nanostructure consisted of 800 islands, created by eroding Voronoi cells[10]. The matrix is modeled as a soft magnet[20], and its XPEEM signal is calculated assuming strong exchange coupling to the tetrataenite islands[10]. The combined island and matrix signal was then convoluted with an approximation to the experimental point spread function (calculated from the width of the domain boundaries in the tetrataenite rim and the measured CZ island size, Extended Data Figure 2), and noise was added.

To identify the properties of the field recorded by each region, the XPEEM signals expected for a range of field intensities and directions were simulated and compared to the experimental data, according to the procedure outlined in Extended Data Fig. 5. Firstly, an approximate field intensity was identified for each region using a trial-and-error method, where the field components were altered manually until the simulated pixel-intensity histogram was at least in partial agreement with the average experimental histogram. A direction was then chosen at random from a Gaussian distribution. This direction was scaled to the approximate intensity value, and the proportions of the magnetisation directions expected for this field were calculated[20] for a 45 nm island radius (see Supplementary Information). The simulated nanostructure was populated with these proportions and the corresponding pixel-intensity histogram calculated. This process was repeated three times, and the individual histograms were used to create an average histogram representative of the field components. The squared difference (χ^2) between the average simulated histogram and the experimental histogram was then calculated. This whole procedure was repeated to generate χ^2 values corresponding to 150 randomly selected directions. The five directions with lowest χ^2 values were identified, which correspond roughly to that of the field recorded by each region. These five field components were then used as the inputs for full least-squares fits to the experimental pixel-intensity histogram for each region. In this fitting procedure, the values of all three components were varied systematically (allowing both the field intensity and direction to vary) to create simulated nanostructures that minimised the χ^2 value between the simulated and experimental pixel intensity histograms. Again, the simulated nanostructures were populated three times for each set of field components. This process resulted in five sets of field components that all produced very high-quality fits to the experimental data (Fig 2).

Planetary cooling model. The planetary cooling model employs multiple simplifications and there are large uncertainties in many of the values of the variable used, hence we adopt a very simple approach[1]. The equations are all included in the Supplementary Information.

Initially, the entire body is isothermal at 1600 K, which is the approximate silicate solidus. The parent body is assumed to cool rapidly to this temperature via advection of melt to the surface. Once this advective phase has ended, subsequent cooling will be much slower since it is controlled by conduction rather than melt advection. We further assume that no extra sources of heat were present (e.g. long-lived nuclides, heating from impacts). The temperature at the surface is kept at a constant value of T_S = 250 K (ref 32). The radius of the body is taken as 200 km (ref 1), which places the pallasites in the mid- to upper-mantle based on their measured cooling rates at 800 K (ref 10). We also assumed an 8 km thick megaregolith at the asteroid surface with an order of magnitude lower thermal diffusivity than the mantle[33,34]. The upper half of the asteroid radius was modelled as the mantle, and the lower half as the core. Our cooling model captures the periods before and during core solidification. The core liquid is assumed to convect, so at any given time step is modelled as isothermal. Before solidification, the core temperature was modified from the value at the previous timestep based on the heat extracted across the core mantle boundary during that timestep. The core started to solidify when it first reached 1200 K (ref 1). Beyond this time, the core temperature was manually held at 1200 K to approximate the fact that the core temperature barely changes during solidification, owing to the small slope of the melting curve. Once the total heat extracted across the core mantle boundary exceeded the entire latent heat of the completely solidified and the simulation ended. The values of the parameters used in the model are presented in Extended Data Table 2.

The cooling rate was found by differentiating the cooling model results with respect to time (Extended Data Fig. 6). Original depths in the parent body were determined for the pallasites by comparing their inferred cooling rates at 800 K with those calculated from Fig 4. The experimental cooling rates were calculated using islands sizes of 147 ± 4 nm and 158 ± 6 nm for the Imilac and Esquel meteorites respectively (Extended Data Fig. 2) and the relationship between island size and cooling rate[14].

Cooling models were also performed for 100-km and 300-km-radius parent bodies, to confirm that the value of 200 km used in this study is realistic (Extended Data Figure 8).

Dynamo generation model. To investigate the possibility of thermally driven dynamo activity, the cooling rate of the core liquid during solidification was calculated[15] from the heat flux across the core mantle boundary (using temperature values from Fig 4). All details and equations are outlined in the Supplementary Information.

To investigate compositional convection, the rate of inner core growth was calculated from the liquid cooling rate. This was performed iteratively with a 2 x 10^{10} s timestep from an initial core radius of 5 km up to the entire radius of the core (100 km). The growth rate was in turn used to calculate the buoyancy flux generated by the ejection of light elements during solidification (using a fluid density contrast of 195 kg m^{-3}). This parameter was then used to calculate the flux-based Rayleigh number[13]. From this parameter, the local Rossby number, magnetic Reynolds number and dipolar Lorentz number were all calculated (Extended Data Fig. 7). All equations are presented in the Supplementary Information.

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Extended data legends

Extended Data Table 1: **Average island sizes for each region of the Imilac and Esquel meteorite studied.** Values extracted from Extended Data Fig. 2.

Extended Data Table 2: **Values of the parameters used in the planetary cooling and dynamo generation models.** All values are supported by experimental and/or theoretical work[1,7,56].

Extended Data 1. 15 μm field-of-view XPEEM image of the kamacite, tetrataenite rim, CZ and aligned CZ in the Imilac meteorite. The boundaries between the kamacite and tetrataenite rim and the tetrataenite rim and CZ are marked as solid black lines, and the boundary between the CZ and aligned CZ is marked as a dashed line. Note that the interface between the CZ and fine aligned CZ is abrupt and parallel to the tetrataenite rim. The in-plane orientation of the X-ray beam is included as an arrow; the beam was 16° out-of-plane. This orientation applies to all images.

Extended Data Figure 2. Representative SEM images of the CZ in the pallasites. Coarser tetrataenite islands in the **a** Imilac and **b** Esquel meteorite. The regions corresponding to Fig. 1. are included (red boxes). The CZ is unclear and island sizes could not be extracted beyond four and six regions of the Imilac and Esquel meteorites, respectively. The average island size of each region is included in Extended Data Table 1.

Extended Data Figure 3. Additional XPEEM images and pixel intensity histograms for the Imilac meteorite. **a**, **b**, **c** 5 μm field-of-view XPEEM images from three areas of the Imilac meteorite. These areas, along with Fig. 1a, passed the selection criteria outlined in the Experimental Analysis section. Note that the magnetic patterns vary between images. **d** Average pixel intensity histograms calculated from the four images of the Imilac meteorite. The dashed line is the optimised fit curve for the best fit for region 1; the fits for other regions were not included (to reduce clutter), but all displayed similar agreement to their experimental counterpart.

Extended Data Figure 4. Equivalent to Extended Data Fig. 3 for the Esquel meteorite.

Extended Data Figure 5. Flow diagram of the procedure used to identify the intensity and orientation of the field recorded by each region, described in the Methods section. The blue box represents the input to the procedure (approximate field intensity). The orange boxes represent the parts of the procedure used to deduce the approximate direction of the recorded field. The red boxes represent the part of the procedure used to optimise the direction and intensity estimates. The green box represents the final outputs.

Extended Data Figure 6. 200-km-radius body cooling rate. Values derived from Fig. 4. Cooling rates between 0 and 10 K Myr^{-1} are depicted by the colour scale; any value greater than 10 K Myr^{-1} is depicted by the dark red colour. The green line is the 800 K contour from Fig 4, which corresponds to the temperature of the cooling rates inferred from the relationship to island size[14]. The core cools between 0 and 3.6 K Myr^{-1}.

Extended Data Figure 7. Additional planetary cooling models. a Temperatures and **b** cooling rates from the conductive cooling model with a 100 km radius. The cooling rate at 800 K (green line) reaches the inferred values of the Imilac or the Esquel meteorites after complete core solidification. **c** Temperatures and **d** cooling rate from the conductive cooling model with a 300 km radius. The depths (horizontal black lines) corresponding to the inferred cooling rates at 800 K (green line) for the Imilac and Esquel meteorites reach the tetrataenite formation temperature (593 K, red line) before the core solidification starts.

Extended Data Figure 8. Planetary magnetic parameters calculated from the dynamo generation model. **a** Local Rossby number, Ro_l, showing the combination of parameters resulting in predominantly dipolar (red region) to multipolar (blue region) fields. **b** Magnetic Reynolds number, R_m, showing the combination of parameters that do (blue region) and do not (red region) results in dynamo activity. **c** Dipolar Lorentz number, Lo_{dip}, showing the combination of parameters that do (blue region) and do not (red region) produce and $Lo_{dip} > 10^{-5}$. A four-hour rotation period is highlighted in each figure.