THE THERMAL EVOLUTION OF PLANETESIMALS DURING ACCRETION AND DIFFERENTIATION: CONSEQUENCES FOR DYNAMO GENERATION BY THERMALLY-DRIVEN CONVECTION. K. H. Dodds[1], J. F. J. Bryson[2], J. A. Neufeld[1,3,4] and R. J. Harrison[1], [1]Department of Earth Sciences, University of Cambridge, Cambridge, UK, [2]Department of Earth Sciences, University of Oxford, Oxford, UK, [3]BP Institute, University of Cambridge, Cambridge, UK, [4]Department of Applied Mathematics and Theoretical Physics, University of Cambridge, Cambridge, UK.

Introduction: The meteorite paleomagnetic record reveals widespread magnetic field generation in the first few 100 Myr of the solar system [1,2]. The period of magnetic field generation from 5-40 Myr after the formation of calcium-aluminium-rich inclusions (CAIs) has been attributed to planetary dynamo fields generated by thermal convection alone in the fully fluid cores of some meteorites' parent bodies [2-5]. Specifically, these fields have been invoked to explain the remanence of the Angra dos Reis angrite at ~11 Myr after CAI formation [3] as well as some CV chondrites at >5 Myr after CAI formation. This latter result has been used to argue that the CV parent body was partially differentiated [4,5].

Dynamo generation driven by thermal convection alone requires fast (>5 K Myr^{-1}) core cooling rates due to the small density differences generated by cooling [6]. Such rapid core cooling was likely only possible during an early period of magma ocean convection in the planetesimals' silicate portion that lasted for less than ~ 35 Myr after CAI formation [1,2]. However the partitioning of the lithophilic heat source ^{26}Al into the silicate portion of a planetesimal during differentiation and core formation could hinder early core convection during this period of rapid cooling. The silicate mantle will continue to heat up after core formation and pass heat into the top of the core, leading to the growth of a stable thermal stratification at the top of the core. This stratification must then be eroded before whole core convection can start and potentially generate a thermally-driven dynamo field.

Previous models of thermal dynamo generation in planetesimals [1,8,9] have not included the build-up and erosion of this thermal stratification in the core. We build on these models by including this thermal stratification as well as modelling gradual accretion and differentiation of planetesimals to investigate the effect of these processes on the ability of planetesimals to generate thermal dynamos. We ran 10,000 model simulations with randomly selected accretion start time t_0, and duration as well as initial (R_0) and final (R_p) body radii to cover parameter space. We then compared the results of our model to the paleomagnetic record of the angrites to constrain the accretionary history and physical properties of the angrite parent body (APB).

Model description: We created a 1D model of planetesimal thermal evolution from accretion, through differentiation, the introduction and subsequent erosion of a core thermal stratification, and the onset of core convection until the cessation of magma ocean convection in the silicate mantle (Fig. 1). Scaling laws from magnetohydrodynamics simulations [7] are used to convert the CMB heat flux to a magnetic Reynolds number, Re_m, which is used to predict whether the planetesimal was capable of generating a dynamo field and the timing of this field. For dynamo generation we require Re_m >10.

Constraints on parent body size and accretionary history: We find that we require an accretion start time of <1.8 Myr after CAI formation (Fig. 2a) and a minimum core radius size of 205 km (or body radius of >410 km) for thermal dynamo generation. These results are similar to those found by previous models [1,8,9]. We also find that planetesimals that accrete rapidly in <100 kyr are not capable of generating a thermal dynamo at any time regardless of core size (Fig. 2b) whereas those that accrete over >100 kyr are. This is due to the differences in the timescales and mechanisms of core formation. In a rapidly accreting planetesimal, differentiation occurs quasi-instantaneously over the entire body at a temperature of ~1520 K, producing a fully formed core. ^{26}Al then rapidly heats up the silicate magma ocean to >1600 K and heat is passed diffusively across the CMB to the top of the core. A strongly stratified thermal layer develops below the CMB, which takes >10-20 Myr to be eroded, after which whole core convection can start.

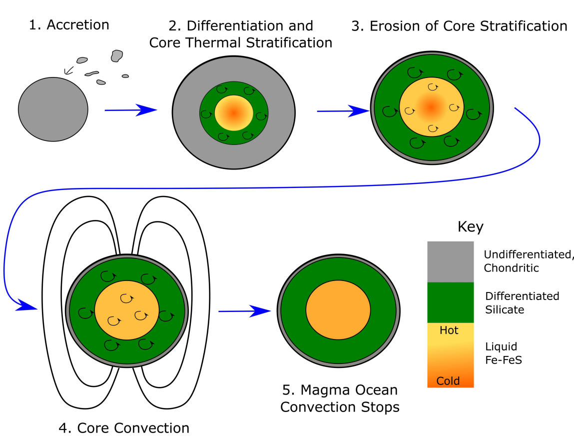

Fig. 1. Schematic of planetesimal thermal evolution.

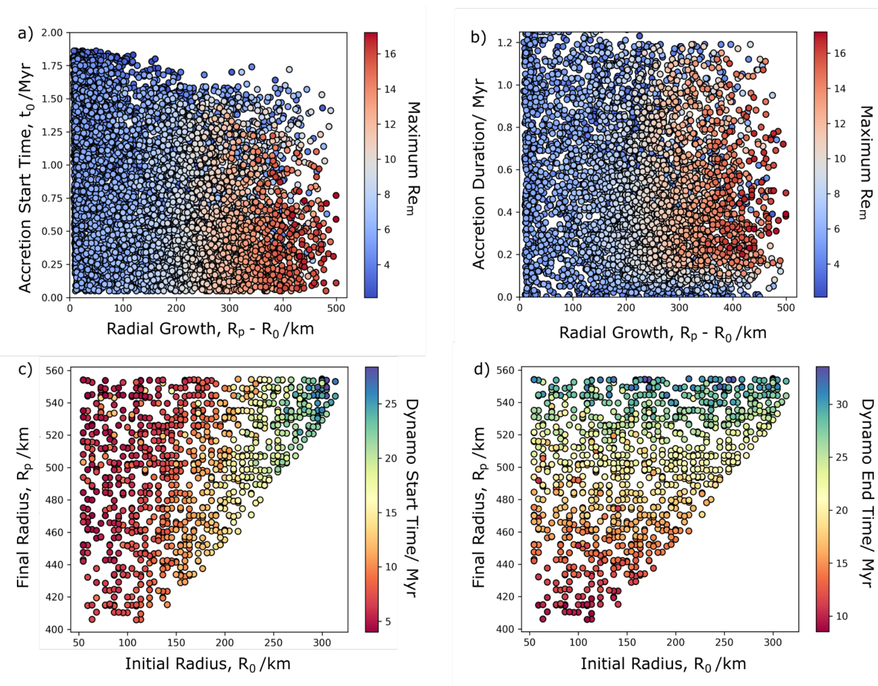

Fig. 2. Dependence of magnetic Reynolds number on a) accretion start time and b) accretion duration in planetesimals with core radii >205 km. c) Start and d) end times of thermal dynamo generation as a function of planetesimal initial and final radius.

By this late time, the magma ocean is viscous and cools slowly. This results in subcritical CMB heat fluxes and no thermal dynamo generation.

Conversely, if a planetesimal accretes over a duration of >100 kyr, differentiation and core formation is a more gradual process. An initial episode of differentiation occurs at a temperature of ~1550 K across a small interior portion at the centre of the body. The ^{26}Al in the magma ocean then quickly heats the convecting silicates up to >1600 K. Molten metal that is then added to the core during subsequent episodes of differentiation from the shallower surface layers of the body passes through this superheated magma ocean and thermally equilibrates. This hot metal is then added to the top of the colder proto-core. This results in a thick hot isothermal layer below the CMB that, once the core starts to cool, can readily convect. Any deep-seated stratification is then rapidly eroded. This enables core convection over much of its radius during the period of fast body cooling and results in supercritical CMB heat fluxes and dynamo generation.

Timings of planetesimal thermal dynamo fields: These fields can start at any time from 5-28 Myr and end from 8-35 Myr after CAI formation (Figure 2c-d) depending on parent body accretionary history. The start time is controlled by the initial seed radius of the planetesimal as this (along with accretion duration) controls the rate of differentiation and core formation, which in turn dictates the extent and location of any thermal stratification that may develop. The end time of the dynamo field depends solely on the final radius of the planetesimal as this controls how quickly the body cooled.

The predicted timings of these thermal fields make them possible source candidates for the magnetization of both the angrites and CV chondrites at 5 - <40 Myr after CAI formation [3-5]. However it is possible that these early fields were instead driven by compositional convection generated during the crystallization of a sulfur-poor core. The exact mechanism and direction of core solidification in planetesimals is uncertain [10] but is a far more efficient method for generating a planetary dynamo [6]. Additionally, none of the model runs that produced a thermal dynamo field in this study had any appreciable undifferentiated crust. Therefore a different accretionary regime is required to explain the magnetization of CV chondrites.

Properties of the Angrite Parent Body (APB): The angrites are unmagnetized at ~4 Myr then magnetized at ~11 Myr after CAI formation [3]. Assuming a start time between 4-11 Myr and end time of >11 Myr for the APB thermal dynamo field requires the APB to have grown from an initial radius of <225 km to a final radius of >420 km over a duration of 100-1000 kyr. This final radius constraint is similar to that obtained by [1] and from analysis of melt inclusions by [11].

Conclusions: The partitioning of ^{26}Al into the mantle of planetesimals during differentiation and core formation can lead to the development of a strong thermal stratification below the CMB that hinders core convection and thermal dynamo activity. Gradual accretion of planetesimals over >100 kyr timescales promotes core formation that prevents the build-up of this stratification below the CMB and enables early whole core convection and thermal dynamo generation from as early as ~4 Myr after CAI formation. These results potentially provide a way of constraining planetesimal accretion durations and final radii from the timings of thermally driven dynamo fields recovered from paleomagnetic studies of meteorites.

References: [1] Bryson et al. (2019) *EPSL* 521, 68-78. [2] Dodds et al. (2020), submitted. [3] Wang et al. (2017) *Science* 355(6325), 623-7. [4] Gattacceca et al. (2016) *EPSL* 455, 166-75. [5] Carpozen et al. (2011) *PNAS* 108(16), 6386-89. [6] Nimmo (2009) *GRL* 36, 10. [7] Olson & Christensen (2006) *EPSL* 250(3-4), 561-71. [8] Elkins-Tanton et al. (2011) *EPSL* 305, 1-10. [9] Sterenborg & Crowley (2013) *PEPI* 214, 53-73. [10] Willliams (2009) *EPSL* 284, 564-69. [11] Sarafian et al. (2017) *Philos. Trans. R. Soc. A* 375:20160209.