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Collisional stripping of planetary crusts

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ABSTRACT

Geochemical studies of planetary accretion and evolution have invoked various degrees of collisional erosion to explain differences in bulk composition between planets and chondrites. Here we undertake a full, dynamical evaluation of 'crustal stripping' during accretion and its key geochemical consequences. Crusts are expected to contain a significant fraction of planetary budgets of incompatible elements, which include the major heat producing nuclides. We present smoothed particle hydrodynamics simulations of collisions between differentiated rocky planetesimals and planetary embryos. We find that the crust is preferentially lost relative to the mantle during impacts, and we have developed a scaling law based on these simulations that approximates the mass of crust that remains in the largest remnant. Using this scaling law and a recent set of *N*-body simulations of terrestrial planet formation, we have estimated the maximum effect of crustal stripping on incompatible element abundances during the accretion of planetary embryos. We find that on average approximately one third of the initial crust is stripped from embryos as they accrete, which leads to a reduction of ∼20% in the budgets of the heat producing elements if the stripped crust does not reaccrete. Erosion of crusts can lead to non-chondritic ratios of incompatible elements, but the magnitude of this effect depends sensitively on the details of the crust-forming melting process on the planetesimals. The Lu/Hf system is fractionated for a wide range of crustal formation scenarios. Using eucrites (the products of planetesimal silicate melting, thought to represent the crust of Vesta) as a guide to the Lu/Hf of planetesimal crust partially lost during accretion, we predict the Earth could evolve to a superchondritic $^{176}Hf/^{177}Hf$ (3–5 parts per ten thousand) at present day. Such values are in keeping with compositional estimates of the bulk Earth. Stripping of planetary crusts during accretion can lead to detectable changes in bulk composition of lithophile elements, but the fractionation is relatively subtle, and sensitive to the efficiency of reaccretion.

1. Introduction

Terrestrial planets are thought to form from the accumulation of planetesimals into planetary embryos, followed by a period in which these embryos undergo giant impacts to form a final system of planets (e.g. Morbidelli et al., 2012). Accretion of planetesimals onto larger bodies is a key process during both intermediate and late stages of planet formation, but this process is not one of monotonic growth. The collisions experienced by the planets as they grow can also lead to loss of material and the final composition of a planetary body can be influenced by preferential erosion of chemically distinct layers (e.g. Carter et al., 2015).

Crusts are expected to contain a significant fraction of planetary incompatible element budgets (elements that are concentrated during magmatic processes because they more strongly partition into the melt than residual solid during partial melting), and it has previously been suggested that preferential removal of the outer crustal layers of planetary building blocks alter bulk compositions (e.g. Greenwood et al., 2005; O'Neill and Palme, 2008; Boujibar et al., 2015; Jellinek and Jackson, 2015). Since there is ample evidence of the early differentiation of planetesimals (e.g. Lugmair and Shukolyukov, 1998; Srinivasan et al., 1999; Bizzarro et al., 2005; Amelin, 2008; Kruijer et al., 2014), collisional erosion is an obvious means of removing the chemically distinct outer layers of growing planets. Several studies have previously demonstrated that collisions during accretion can influence the major element compositions of the resulting objects (e.g. Marcus et al., 2009, 2010; Bonsor et al., 2015; Carter et al., 2015; Dwyer et al., 2015), but most of the work on individual collision outcomes has

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not focused on heterogeneous colliders (e.g. Leinhardt and Stewart, 2012), or has considered only giant impacts (Marcus et al., 2009, 2010). Moreover these studies have not quantified the budgets of important trace elements[1] used to characterise planetary bodies.

The modification of planetary compositions during growth has consequences for the long-standing paradigm that primitive meteorites, chondrites, represent the building blocks of planets. Chondritic ratios of cosmochemically refractory elements (elements with high condensation temperatures in a hydrogen-rich environment), such as the rare earth elements, have been taken to provide a robust bulk planetary reference. Yet, some doubt has been cast on the reliability of this approach given the possibility that the Earth has non-chondritic $^{142}Nd/^{144}Nd$ (Boyet and Carlson, 2005). Proposed means to account for the terrestrial $^{142}Nd/^{144}Nd$ include: the Earth is made from chondrites different to those in our current collection (e.g. Huang et al., 2013; Burkhardt et al., 2016), the Earth's mantle is incompletely sampled (e.g. Boyet and Carlson, 2005; Labrosse et al., 2007), or the Earth accreted from differentiated bodies that had experienced prior collisional erosion (e.g. Bourdon et al., 2008; O'Neill and Palme, 2008). Since ^{142}Nd is the daughter of the extinct radioisotope ^{146}Sm (half life ∼100 Myr, Meissner et al., 1987), a reservoir enriched in Sm relative to Nd (i.e. incompatible element depleted) early in the evolution of the solar system (within the first 100 Myr) would evolve into a reservoir with elevated $^{142}Nd/^{144}Nd$. Whilst the idea that the Earth accreted from distinct material has recently gained significant traction (see also Bouvier and Boyet, 2016) as a preferred explanation for superchondritic terrestrial $^{142}Nd/^{144}Nd$, recent dynamical models have underscored the potential for collisional modification of bulk planetary compositions during accretion (e.g. Bonsor et al., 2015; Carter et al., 2015), at least for readily fractionated materials. Here we specifically investigate the importance of such collisional losses from differentiated bodies for the ratios of key refractory, lithophile element isotopes (Sm–Nd, Lu–Hf).

1.1. Previous work

Marcus et al. (2009) presented simulations of giant impacts onto Earth and super-Earth sized bodies using differentiated impactors with Earth-like composition and masses in the range 0.25–10$M_\oplus$ (where $M_\oplus$ is the mass of the Earth). As well as examining the catastrophic disruption criteria, they derived a scaling law for the change in bulk composition due to mantle stripping, demonstrating that the iron-to-silicate ratio of the largest remnant increases with increasing impact energy. That work was extended to ice-rock planets in Marcus et al. (2010).

Leinhardt and Stewart (2012) used the results of a variety of previous impact simulations (including Marcus et al., 2009) and conducted new N-body simulations of smaller (homogeneous) planetesimal collisions, using 10 km radius targets, to determine the effects of collision parameters on collision outcome. They derived scaling laws to describe the size and velocity distribution of the collision remnants (see also Leinhardt et al., 2015). This work demonstrated that the collision outcome is velocity dependent, allowing correction for the impact angle and mass ratio.

We have previously applied the Marcus et al. (2009) mantle stripping law and the state-of-the-art collision model from Leinhardt and Stewart (2012) and Leinhardt et al. (2015) to examine the changes in bulk composition during accretion of planetary embryos using high resolution N-body simulations (Bonsor et al., 2015; Carter et al., 2015). These simulations of the intermediate stages of planet formation, from ∼100 km planetesimals to planetary embryos, explored two contrasting dynamical scenarios: a calm disc unperturbed by giant planets, and the dynamically hot Grand Tack model (Walsh et al., 2011). We found that significant compositional change can occur, in terms of core/mantle ratio, in growing planetesimals, especially in dynamically hot protoplanetary discs (Carter et al., 2015).

Here we explore the effects of collisions on the crusts of planetesimals by conducting a new set of impact simulations, and explore the implications for planetary compositions by applying scaling laws to previous N-body simulations of planet formation. We begin by describing the impact simulations, and the post-processing of N-body simulations to examine crust stripping during accretion (section 2). We present the results of the impact simulations in section 3.1 and the results of the post-processing in section 3.2, then discuss these results in section 4.

2. Numerical methods

2.1. Hydrodynamic modelling

We simulated collisions between planetesimals and embryos using a version of the GADGET-2 smoothed particle hydrodynamics (SPH) code (Springel, 2005) modified for planetary collision calculations. This modified version of GADGET-2 calculates thermodynamic quantities by interpolating tabulated equations of state, for details see Marcus et al. (2009, 2010), and Ćuk and Stewart (2012). As in previous studies (Marcus et al., 2009; Ćuk and Stewart, 2012; Lock and Stewart, 2017), we modelled the silicate layers and metallic cores of terrestrial planet embryos as pure forsterite and pure iron using tabulated equations of state obtained from the M-ANEOS model (Melosh, 2007; these tables are available in the online supplement to Ćuk and Stewart, 2012).

The initial differentiated planetesimals were comprised of 22 wt% iron and 78 wt% forsterite (this smaller iron core compared to Marcus et al., 2009, is consistent with chondritic building blocks). The bodies were initialised with a simple temperature profile approximating the state of planetesimals in the first few million years of evolution. Since the planetesimals are differentiated they should have undergone large-scale melting, and so, based on the melting model from Hevey and Sanders (2006), we set the temperature to 1850 K from the centre to 0.8R (where R is the radius of the body), dropping linearly to 300 K at the surface.

The bodies were then evolved through two equilibration steps each lasting 10 h. Because the initial density and temperature distribution are not perfectly in gravitational equilibrium, large particle motions are induced as the body evolves under self-gravity. Thus, to accelerate convergence to equilibrium, particle velocities are damped by a factor of 50% per time step during the first 10 h period. Without damping, these particle velocity perturbations can generate strong shocks that disturb the desired thermal profile (sometimes in a dramatic fashion). In the second equilibration phase the body evolves under self-gravitational forces (without additional damping) towards a hydrostatic profile. In many cases particle motions during equilibration led to a single particle reaching escape velocity. The state of a planetesimal of mass $1 \times 10^{-5} M_\oplus$ after equilibration is shown in Fig. 1. This equilibration procedure does not significantly alter the temperature profile of the body.

We used target masses of $1 \times 10^{-5} M_\oplus$, $5 \times 10^{-5} M_\oplus$, $1 \times 10^{-3} M_\oplus$, and $1 \times 10^{-1} M_\oplus$, mostly comprised of 2×10^4 particles; more extreme mass ratios require higher resolution in order for the projectile to be well resolved. For projectile/target mass ratios smaller than 0.1 we used targets comprised of 2×10^5 particles. A subset of collisions were run with ten times as many particles to check sensitivity to resolution, producing equivalent results.

We explored mass ratios of 0.01, 0.02, 0.05, 0.1, 0.2, 0.3, 0.4, 0.5 and 1.0, with the projectile having the same mass per parti-

[1] Trace elements are defined as having concentrations <1000 ppm