MIXING OF IRON AND SILICATE DURING COLLISIONS ON DIFFERENTIATED PLANETESIMALS.

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Introduction: Stony-iron meteorites, mixtures of silicate and metal thought to have formed during collisions between differentiated planetesimals, are the least common subset in the terrestrial collection. The canonical theory of stony-iron meteorite formation requires low velocity, glancing ('hit and run') collisions between relatively large planetary embryos [1-2]. However, such collisions within a terrestrial planet forming region dynamically excited by Jupiter [3] were likely quite rare. Because there are several distinct genetic groupings of stony-irons [2], implying different parent bodies and hence multiple rare hit-and-run collisions, it is worthwhile to quantify the ability of smaller, more common impacts to produce silicate-iron mixtures within differentiated planetesimals.

Collision Models: Using the iSALE-2D [4-6] shock physics code, we modeled 10 km radius dunite impactors colliding head-on into a 100 km radius differentiated target planetesimal at 3 and 6 km/s at various points in their evolution (10, 50, and 88 Myr after formation). Pre-impact target temperature profiles are determined using an internal differentiation and cooling model [7]. All impact models assume a cylindrically symmetric geometry, have a spatial resolution of 666 m, and use self gravity. Material thermodynamics are addressed using the ANEOS equation of state package [8]. The mantle is treated as a visco-elastic-plastic solid [9], with flow laws appropriate for the terrestrial mantle [10], and a temperature dependent yield strength with a melting point of 1436 K. In the 10 Myr scenario, the entire core is above the melt temperature of most iron alloys and is assumed to be a fluid with viscosity η=100 Pa s. For the 50 Myr scenario the core has an initial temperature of ~1200 K, and depending on composition, could reasonably be either entirely molten or entirely crystallized before impact. As such, we consider both liquid (η=100 Pa s) and solid cores; in the latter case assuming a strain- and temperature-dependent yield strength [11] appropriate for metals and a melt temperature of 1300 K. For the 88 Myr scenario, the temperature of the core is ~750 K and is treated as a solid for all impact scenarios.

Turbulent Mixing of Iron and Silicate: A Lagrangian tracer, which tracks the motion of material through iSALE's fixed Eulerian computational mesh, is embedded within each cell of the pre-impact target. Each tracer is initially composed of 100% iron or 100% silicate. At each post-impact timestep, tracer pairs in close proximity with large differences in composition are identified. For each such tracer pair, we find a second set of nearby, orthogonally oriented tracers in order to build a quadrilateral set. The deformation of this quadrilateral allows us to calculate a shear strain rate for each tracer pair [12]. We then allow material to flux from one tracer into another assuming a Prandtl [13] turbulent mixing velocity that is proportional in scale to this shear, such that the rate at which material is exchanged is highest for tracer pairs in close proximity and with high shear rates. Because each tracer may form more than one pair in a given timestep, concentrations are updated in such a way as to conserve total system mass. To avoid rapid diffusion of material across the target, we only allow tracers to exchange material if they have a difference of composition greater than 10%.

Results: Immediately after passage of the shock wave, a small amount of material interchange takes place at the core mantle boundary of the target, but the degree of mixing is relatively minor. In simulations where the transient crater is deep enough to significantly deform the core, crater collapse induces large shear strains at the core mantle boundary, rapidly mixing silicate and metal. The amount of mixing can be considerable: in the 10 Myr scenario [Fig. 1 a-d] where the majority of the target's interior is molten, ~35 impactor masses worth of material are >50% mixed at the end of the simulation [Fig. 1 d]. While most tracers that become heavily mixed are ultimately emplaced near the core mantle boundary, a considerable amount of mixed material is advected into both the mantle and the interior of the core. Mixtures which end up in the planetesimal's upper mantle may record vastly different post-impact cooling rates than mixtures in the deep interior of the body. This may help to explain the diverse cooling rates reported for stony iron meteorites [13], depending on whether or not these metal rich plumes reach closure temperature before being gravitationally driven back deeper into the interior of the body.

While some mixing does occur in late (50 and 88 Myr post-accretion) impact scenarios, the total mass of thoroughly mixed material produced is considerably lower than for early (10 Myr) impacts [Fig. 1 d-f]. This is because the elastic strength of the cooler targets greatly suppresses the amount of shear that can occur during crater collapse. In these cases, the majority of thoroughly mixed material ends up near the target's final core mantle boundary, and as such, the cooling rates recorded by these mixtures should be fairly uniform. The exception to this rule is very energetic [Fig. 1 e-f] late collisions in which part of the core is melted by the impact shockwave, allowing for an enhanced degree of mixing, but the strength of the unmelted mantle prevents the planetesimal from completely collapsing back into a spherical, isostatic shape.

Discussion: There are several limitations to the mixing model as implemented in this work. First, the parameterization of sub-grid scale turbulent advection is quite simple, with a linear dependence on shear rates, and relies on tuneable free parameters that can alter the total amount of mixing induced by a given impact. Secondly, because the mixing analysis is done as a post-processing step, silicate-iron mixture thermodynamics and rheologies do not influence the bulk advection of material within the impact simulations. Nonetheless, our results are sufficient a) to demonstrate the efficacy of small impacts in producing silicate-iron mixtures within differentiated planetesimals; and b) for quantifying how the magnitude of mixing depends on how long after accretion an impact occurs.

Conclusions: Relatively small impacts into differentiated planetesimals are capable of producing large quantities of iron-silicate mixtures. The degree of mixing that occurs is a function of both impact energy and epoch of impact (with early impacts producing several orders of magnitude more mixed mass than late impacts).

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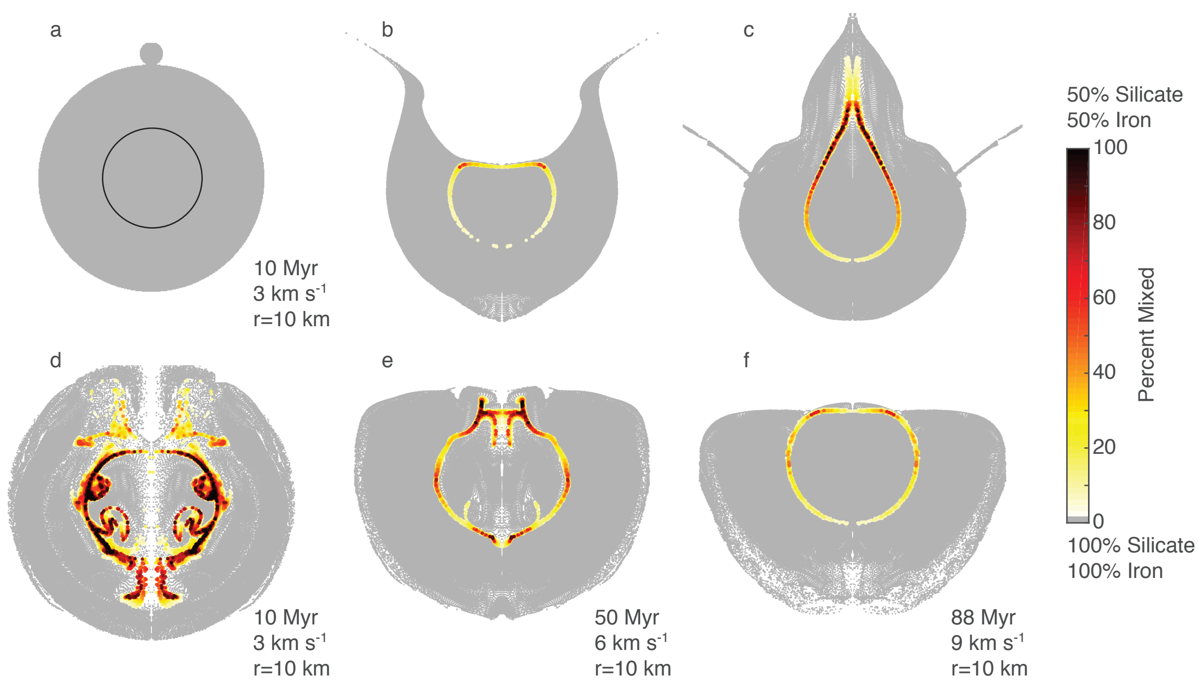

Figure 1: [a-c] Time series showing (a) pre impact state (b) mixing at the onset of transient crater collapse and (c) mixing at the onset of central uplift collapse. [d-f] Final states for impacts into targets 10 (d), 50 (e), and 88 (f) Myr after formation. The color scale represents the degree of mixing, with 0 corresponding to pure metal or pure silicate, and 100 corresponding to a fully mixed, 50% silicate/50% iron material. Completely unmixed tracers are plotted in grey. All targets have initial radius of 100 km.