HYSTERETIC EVOLUTION OF ACCRETING PLANETARY INTERIORS. Erik Asphaug, Lunar and Planetary Laboratory, University of Arizona, Tucson, AZ 85721 (asphaug@arizona.edu)

Summary. As primary accretion advances, the majority of matter ends up in a set of largest and next-largest bodies. Further growth is then mostly through binary collisions, but these are inefficient at merging, even at relatively low velocity. This regulates continued growth and generates myriads of outcomes as bodies experience a hierarchy of pathways to accretion.

Early Formation. In early growth [1] matter adds to more matter at a rate τ_M calculated from efficiencies of accumulation that start out of order unity. Growth of a mass M is governed by its gravitational cross-section relative to a flux of much smaller bodies; if they hit, they stick. Gravitation increases with mass, so like a net that grows larger with every catch, a growing body reaches further while stirring up and depleting the remaining population. Accretion efficiency $\xi\sim 1$ applies to early growth, $\xi = (M_f - M)/m$ defined [2] to be 1 when all of m is acquired by M to make a final mass M_f. Missions to primitive bodies suggest that they are weak, porous aggregates [3, 4], which indicates that accreting planetesimals might dissipate collisional kinetic energy effectively through compaction and friction [5]. It is thus likely that ξ~1 even for $v_{rel} \gg v_{esc}\sim\sqrt{2GM/R}$, the escape velocity, which is ~1 m/s per km of target radius $R\sim(M/\rho)^{1/3}$, especially for impacting masses $m \ll M$ for geometric reasons.

Early accretion thus causes a monotonic ramp-up of geologically significant processes and irreversible transformations inside of growing planetesimals: compaction, alteration, metamorphism, and potentially melting and differentiation [6] and loss of volatiles to space. Mass creates hydrostatic pressure of order $P_s\sim G\rho^2 R^2$, while heat is converted from gravitational potential and kinetic energies $\propto v_{esc}^2$, and from radioactive decay (when τ_M < a few Ma, a few half-lives of ^{26}Al). Pressure and temperature grow deep inside, while outer regions are increasingly subject to collisional crushing, friction, and among the near-final bodies, interfacial jetting and shocks.

Eventually, at some large-enough v_{rel}, the same impactors that would add to M cause mass loss, leading to the simple notion that early accretion formed the bodies, and then erosion and disruption happened.

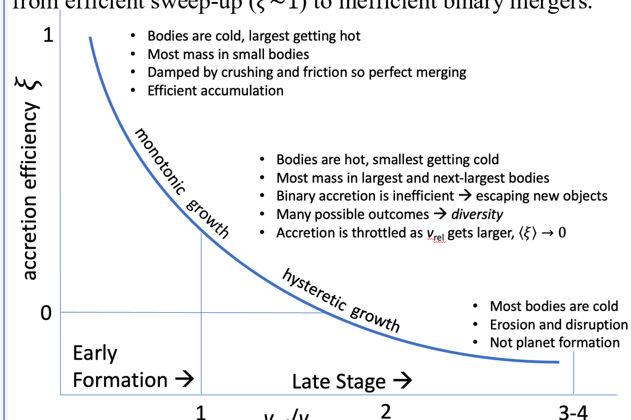
Late Stage. While these processes collectively provide a big picture understanding of meteorites as samples of planetesimals [e.g., 7], there remain stubborn problems (e.g., stony-iron and ureilite formation, the origin of chondrules, the compaction of breccias, the causes of early aqueous alteration) that could be related to the far more convoluted post-planetesimal epoch, which begins when most of the mass is in a relatively few largest and next-largest bodies. Further growth would have to occur mostly through binary collisions, where impactor radii $r\sim R$. Examples include giant impacts at the end of terrestrial planet formation [8] and satellite formation [9], and also planetesimal formation during various stages of evolution [10, 11].

Binary collisions span various physical regimes [2] and have complicated relationships between inputs and outcomes. How much mass ends up gravitationally bound (ξ) depends sensitively on v_{rel}, M, m/M, and impact angle θ. For parameters ranging around typical expected values (e.g., $\theta\sim 45°, \frac{m}{M}\sim 0.3, v_{rel}\sim v_{esc}$) outcomes of many kinds are generated in numerical simulations [e.g., 12, 13]. Two bodies might be accreted (ξ>0), eroded (ξ<0), or neither (a hit-and-run collision, ξ~0), or both (accretion and disruption happening in one event, a spiral arm escaping from a graze-and-merge collision [10]). These are extraordinary geophysical phenomena, where mass is exchanged, internal pressures loaded and unloaded [14], outer layers removed, and temperature structures overturned. Yet the *net* accretion efficiency $\langle\xi\rangle$ can be small, or even stagnate, depending sensitively on the random velocities, signifying the importance of relatively modest external perturbers on planet formation.

Hysteretic Growth. In early formation, the outcome of each accretion is more or less the same: a mass added near the surface. This moves the system to the right in **Fig. 1** as bodies grow incrementally to geologically significant sizes. Further accretion must proceed via a hierarchy of binary mergers and attempted mergers, during which time bodies transform and mature, although net growth may be slow.

To characterize how many mergers must occur, consider N bodies accreting pairwise to form N_{final}. This requires $a_h\sim\log_2(N/N_{final})$ hierarchies of growth per final body, in which a body's further collisional growth – and evolving geology and material properties –

Figure 1. Schematic of the evolving character of accretion, from efficient sweep-up ($\xi\sim 1$) to inefficient binary mergers.



depend increasingly on the collisions that came before. For every successful merger there are about as many unsuccessful attempts [2, 12, 13], even under modest gravitational stirring, so a_h represents the depth and complexity of an *accretion network* that can take many paths, some more fruitful than others – a sequence of multiscale global material interactions causing hysteretic geophysical and chemical transformations that accumulate uniquely within each growing body.

Examples. The hypothesis of hysteretic growth essentially states that each late stage collision has a memory of the collisions that came before. Given that binary accretion moves forward in discrete events, bodies will undergo cycles of processing that advance upon the prior state. Here are some examples:

Shear and mixing. Global-scale deformations accumulate multiple times for materials inside of bodies experiencing late stage accretion. Global-scale deformations (strains ε>1) are observed in simulations to accrue on the gravitational timescale [2], or stain rates $\dot{\varepsilon}_{ij}{\sim}10^{-3}$ s^{-1} accumulating for hours to days, under significant starting hydrostatic pressures (P_s is around 1 MPa inside of r=30 km planetesimals, and 100 MPa for 300 km radius). Such deformations would occur, under increasing stress conditions, during each subsequent accretion and attempted accretion. Bodies would undergo layered intra-body mixing, and if in a mostly-solid state would obtain an increasingly significant geologic record of shear under time-varying pressures.

*Porosity and fluids***.** In binary collisions, interior pressures can drop and rise by factors of several on timescales of hours, regionally and globally in the colliding bodies [14, 11]. In a hit-and-run collision the pressure drop is partial, and permanent, until the next collision. Dispersed smaller bodies that start out deep inside an impactor or target can be substantially unloaded. A partial or more significant pressure release in hydrated materials can lead to exsolution and mobilization of fluids, without input of heat. Mobilized fluids require permeability, which may be reduced as accretion proceeds, once the static pressure exceeds the crushing strength, limiting porosity.

Chondrule production. There is evidence for chondrule formation in the presence of planetesimals [e.g., 16], and the relatively late formation ages of most chondrules ≳0.5-2 Ma overlap the formation ages of planetesimals [e.g., 7, 10]. If most of the mass is in sizable planetesimals, further accumulation would not be incremental but via hierarchic growth. It has been proposed [11] that chondrules formed as droplet-rich plumes from exhumed depressurized interiors, when magmatic progenitors of order ~30-100-km diameter underwent inefficient binary accretion. Unloading from P_s produces sub-mm droplets from the melt, diameter $\sim\gamma/P_s$ where γ is surface tension. The process would occur throughout early binary accretion as long as melts or partial melts persist, each collision releasing substantial internal heat. Binary accretion of 30-km progenitors into one 300-km body (say) would indicate $a_h{\sim}3\log_2(300/30)\sim10$ stages of growth, with an evolving internal composition and melt fraction with time. If each stage transformed (say) 5% of the colliding material into chondrules the process would be ~50% efficient overall. But the efficiency percentage depends on the parameters of the collision [11]. Subsequent collisions would be between colder and less melt-rich bodies, transforming chondrule formation and then shutting down this mechanism.

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