# Theoretical models for terrestrial planet formation

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Our understanding of terrestrial planet formation is based on observations of protoplanetary disks and objects in the Solar System, together with cosmochemical analysis of Solar System materials, and basic physics. Here I describe current models of terrestrial planet formation paying particular attention to factors that affect planetary compositions.

Protoplanetary disks contain large amounts of micron-sized dust. Laboratory experiments show dust grains stick to form mm-to-cm sized aggregates. In the inner disk, many dust aggregates are thermally processed to form chondrules and refractory inclusions, leading to substantial chemical fractionation. These processes continue for the most of the lifetime of the disk, during which time the temperature, pressure and redox state of the disk vary substantially at a given location, leading to a range of particle properties.

Disks are likely to be turbulent, preventing further growth via sticking or gravitational instabilities. Planetesimals probably form via turbulent concentration of mm-sized particles into gravitationally bound clumps, which shrink to form solid objects. Formation is inefficient, so planetesimals have a wide range of ages. Early planetesimals are heated by shortlived isotopes, undergoing melting, differentiation and loss of volatiles. Late forming planetesimals resemble the parent bodies of chondritic meteorites.

Once planetesimals appear in large numbers, dynamical interactions give the largest objects the most favourable orbits for further accretion, leading to oligarchic growth. Each radial location in the disk becomes dominated by a single planetary embryo that grows from a localized feeding zone. Embryos acquire different compositions as a result.

Oligarchic growth ceases when the supply of planetesimals dwindles. The last stage of growth is marked by giant impacts between planetary embryos. Near misses cause radial scattering, partially erasing chemical gradients established during the oligarchic growth phase. Giant impacts cause melting and differentiation, possibly associated with further volatile loss. Non-accretionary collisions also lead to preferential removal of mantle material from some objects.

The combination of proceses involved in planet formation means that terrestrial planets inevitably have very different compositions than protoplanetary dust grains.

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# Deciphering microbial roles in mineral formation: An interdisciplinary, microscopy-based approach

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Microorganisms are small, abundant, and ubiquitous. All have relatively high surface area over which they interact with solutes and many are chemolithotrophs, with a high potential for affecting mineral formation. Microbes influence precipitation through a combination of interactions with their surfaces, enzymatic reactions, and binding by exudates. Microbial roles in mineralization are often not straightforward to determine, especially when precipitation occurs extracellularly. In order to understand microbial roles and effects we must take a whole-system approach, studying not only mineralogical distribution and properties, but also biological aspects, including physiology, the genetics and biochemistry of transformations, and cell surface and extracellular polymer chemistry. Connections to field-based studies ensure the relevance of laboratory systems, and allow us to link nano- and micro-scale processes to field (and hopefully global) scales.

Essential to our understanding of biomineralization is accurate imaging of cell-mineral spatial relationships over the course of mineral nucleation and growth. Thus, we aim to use microscopy-based methods that either visualize live cells or minimize sample fixation artifacts (e.g. cryo-electron microscopy). Especially useful is microscopy in combination with a method that gives chemical information—spectroscopy (e.g. X-ray absorbance), selected area electron diffraction, *in situ* labeling (e.g. lectins, antibodies), and probing of charge and other interactions (e.g. atomic force microscopy). In this way, we not only document the association of cells and minerals, but also relationships to specific biomolecules and biomolecule properties.

In this context, I will discuss results of biomineralization studies of the iron-oxidizing, biomineralizing microorganisms *Mariprofundus ferrooxydans* PV-1 and a recently-isolated strain of *Gallionella*. By applying a combination of some of the above-mentioned methods to cultured and related environmental samples, we have shown that both microbes affect mineral formation by metabolic reactions (i.e. oxidizing iron) and by producing extracellular polymers on which minerals nucleate. The directed mineralization processes, in concert with unusual cell surface structures, appear to be adaptations to avoid encrustation.