COMPOSITIONAL RANGES FOR THE EARLIEST ATMOSPHERES DEGASSED FROM ROCKY PLANETS.
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Introduction: Terrestrial planets are likely to obtain their first planetary atmospheres through degassing during accretion. Though the first atmospheres on the Earth and Mars have been changed and depleted past recognition, they may have played important roles in determining the planets' surfaces and their habitability. Here we examine the likely range of compositions of earliest degassed atmospheres, along with what is known about compositions of volcanic degassing during subsequent planetary evolution.

Volatile contents of planetary building blocks. Whether water can survive the processes of accretion remains a contentious topic, with some researchers positing that it must be added after accretion is complete. Compositions of primitive and differentiated meteorites provide a range of reasonable starting bulk materials for planetary formation and atmospheric degassing. Chondritic meteorites can contain as much as 20 wt% water and 3 wt% carbon, while achondrites, which have been processed through a differentiation event on their parent body, can contain as much as 4 wt% water and 4 wt% carbon [1]. The processes of differentiation are widely assumed to reduce volatile content through degassing or oxidation of planetary materials. In general, meteorites from differentiated bodies contain lower volatile contents that do primitive meteorites.

Simulations of planetary accretion indicate that accretion proceeds from planetesimals with radii from tens to hundreds of km, to differentiated planetary embryos on the scale of thousands of kilometers in radius, and that these bodies move radially in the solar system during accretion and so form planets that are mixtures of material from the inner and outer disk [*e.g.*, 2-4] [Fig. 1]. The final stages of accretion consist of violently energetic impacts of embryos [*e.g.*, 4-7].

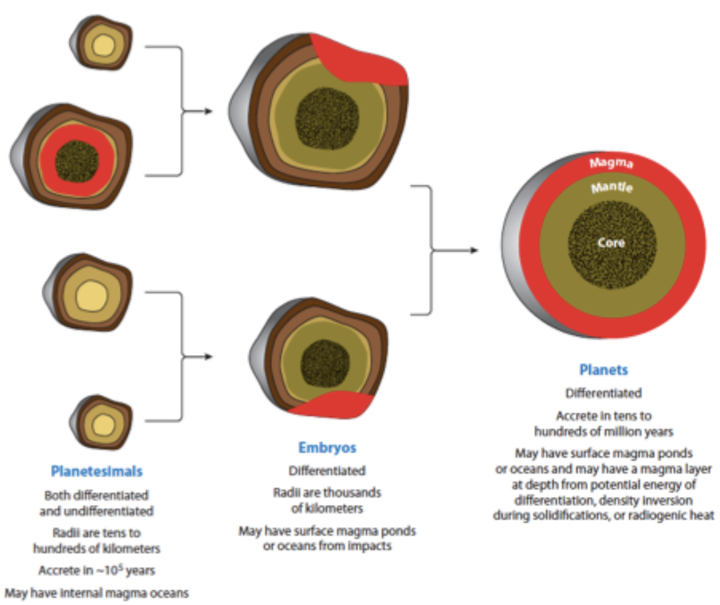

Fig 1. Schematic of planetary accretion, after Elkins-Tanton [8]. Each heating or melting event can cause depletion of volatiles but not their complete loss.

New observations, however, indicate that even giant accretionary impacts cannot remove all the volatiles from the impacted planet or its accreting material. Lavas from the lunar interior indicates that the Moon accreted with some non-zero water content [9,10]. Surface compositions from Mercury show potassium to thorium ratios co-linear with those of Earth and Mars, as well as a large supply of sulfur [11], indicating that even that planet is not fully devolatilzed.

Most planetary materials have likely been processed through at least one a magma ocean, since each of the large accretionary impacts are assumed to create magma ponds, if not global magma oceans, and because some earliest-accreting planetesimals melted internally through the radiogenic heat of the short-lived radioisotope ^{26}Al. These physical processes produce predictions for the mass and composition of degassed atmospheres as well as for the initial composition and density of the planetary silicate mantle, from which comes later degassing into the atmosphere.

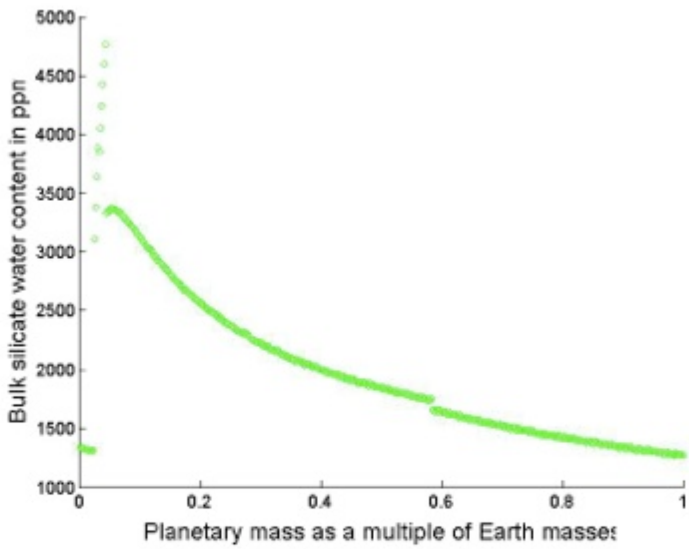

Fig. 2 Bulk silicate water content of terrestrial bodies, if all nominally anhydrous mantle phases accept hydroxyl to their saturation limits. Larger planets may hold less water in their interiors, and therefore degas relatively thicker steam atmospheres, though other volatiles may be degassed in smaller relative quantities.

Results and conclusions: When processed through a magma ocean, a small initial water content (on the order of a hundred parts per million) in the accreting Earth can produce a dense steam atmosphere, while a small change in chemistry can produce a carbon-based atmosphere, such as that on Venus. The presence of surface water may be critical in both preventing a Venusian runaway greenhouse and encouraging plate tectonics. Work by Hashimoto et al. [17] and Shaefer and Fegley [18,19] indicate a wide range of reducing and oxidizing conditions, accompanied by a similar compositional range, can be produced from plausible meteorite compositions.; see Table 1 for elemental compositions.

Table 1. Volatiles available for outgassing from bulk meteorite compositions (after [20]).

	Mass % of water	solid H	planet N	C
CI	23.08	0.00	0.19	5.13
CM	14.70	0.00	0.18	1.98
CR	2.13	0.91	0.00	1.85
CO	0.00	0.14	0.01	0.61
CV	1.38	0.27	0.01	0.62
CK	0.81	0.00	0.00	0.10
CH	0.00	0.02	0.00	0.60
H	0.00	0.00	0.00	0.10
LL	0.00	0.00	0.01	0.10
EH	0.00	0.35	0.00	0.10
EL	0.00	0.00	0.00	0.10

The molecular composition of the resulting atmosphere will depend upon temperature, oxygen fugacity, and surface composition. Following chemical reactions and atmospheric loss, then, planetary atmospheres may evolve with time from hydrogen alone to hydrogen, water, and carbon compounds, and from reducing to oxidizing conditions.

The degassed atmosphere represents between ~60 and 99% of the original volatile content of the material before impact and magma ocean processing [21]. The remaining volatiles exist in the siliate planetary interior, available for later degassing. The volatile content of the planetary interior is controlled by the partitioning and saturation limits of the minerals in the mantle, and thus is further controlled by the size and therefore pressure range of the body, which determines the stability of minerals.

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