MODELING CARBON OUTGASSING FROM ANHYDROUS PLANETESIMALS. B. Peng[1] and D. Valencia[1,2], [1]Dept. of Astronomy & Astrophysics, Univ. of Toronto (bpeng@astro.utoronto.ca), [2]Dept. of Physical & Environmental Sciences, Univ. of Toronto Scarborough.

Introduction: Characterizing the pathways of carbon delivery during the Earth's formation is significant in understanding its habitability. To explain the bulk silicate Earth's (BSE) ~2 orders of magnitude of carbon depletion [1] as compared to chondrites, previous experimental works invoked core-mantle partitioning during proto-Earth's core formation and late giant impact scenarios [2,3]. Yet meteoritic evidence suggest devolatilization may have occurred on the planetesimals, the building blocks of Earth [4], which may account for some carbon lost during the Earth's accretion. To probe this earlier stage of carbon depletion, we constructed a 1-D thermochemical model of anhydrous, porous planetesimals which simulates the production and outgassing of CO_2 in their interiors.

Model Description: Our model is based on solving the spherically symmetric 1-D heat conduction equation, modified to account for processes such as sintering, CO_2 generation and gas outflow. The thermal component of our model adopts the framework of Neumann et al. [5], while the chemical and outgassing parts utilizes a similar scheme as that of Sugiura et al. [6]. The coupled equations with time-dependent coefficients are solved numerically with a direct finite-difference scheme.

The planetesimal is heated by the decay of ^{26}Al and ^{60}Fe. We assume an isothermal initial condition and fix the outer boundary temperature to 300 K, reasonable for Earth-forming region of the protoplanetary disk. For this first attempt we ignore ice phases and assume all carbon is present as graphite. As the most refractory phase of C [7], this assumption constitutes a lower limit to carbon loss.

We set a uniform initial porosity of 40%, an upper limit given by geometric packing arguments [8]. At a prescribed temperature sintering commences. Sintering is the process where rocky grains viscously deform to occupy the pore space, thus decreasing the bulk porosity of the planetesimal. Sintering's effects are twofold: it increases the thermal conductivity of the matrix, while shuts off the outgassing pathway when it is complete.

The chemical model takes the thermal profile as input to calculate the gas pressure profile. Assuming CO_2 is the only gas species, and that it is in chemical equilibrium with graphite, in other words, assuming the CCO buffer controls C burning, gas pressure is a function of temperature and oxygen fugacity, f_{O_2}. This vital quantity is itself a function of composition and

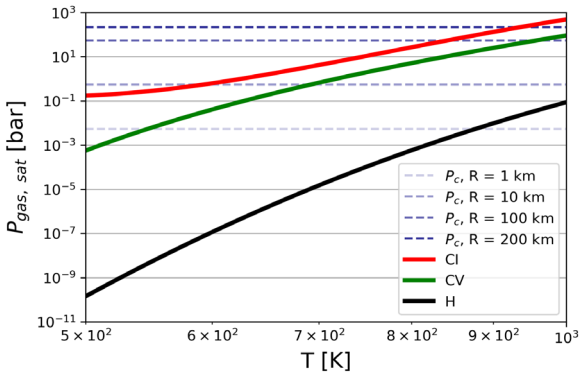

Fig. 1. Solid lines: saturation CO_2 pressure as a function of temperature for 3 chondritic f_{O_2}[9]. Dashed lines: central lithostatic pressures for spherical planetesimals of 2g/cc density, typical of

temperature. We adopt f_{O_2} fits to chemical equilibrium calculations [9] performed on different chondritic compositions. Fig. 1 shows the resultant saturation gas pressure $P_{gas,sat}$ as a function of temperature for carbonaceous ("CI" and "CV") and ordinary ("H") chondrite compositions. The carbonaceous compositions can produce ~ 200 bars of CO_2 at ~900 K, exceeding the lithostatic pressure in much of a 100-km body. Thus, P_{lith} provides an upper limit for the gas pressure profile. Since the temperature profile develops a negative gradient near the surface, so would the gas pressure profile. The consumption of solid carbon reservoir is then tracked via bookkeeping the CO_2 outflow driven by the gas pressure gradient. Given total carbon mass conservation the local divergence of gas flux is assumed to be balanced by solid carbon consumption or condensation. Thus, the model tracks the solid carbon reservoir over time.

Preliminary Results: We simulated early-accreted anhydrous CI planetesimals across a range of initial (pre-sintering) radii (10 – 200 km) and timings of accretion (1 – 3 My after CAI). We focus on CI composition for two reasons: CI has the most oxidizing redox environment; therefore, CO_2 is a better proxy for CI composition's outgassed carbon than for any other composition. CI is also the most volatile-rich of chondrites, therefore it is frequently invoked as the volatile source of the Earth.

The size of the planetesimal positively correlates with its carbon removal efficiency. This seems to stem from the relief-valve effect of the lithostatic pressure profile. To illustrate this point, Fig. 2 shows the detailed

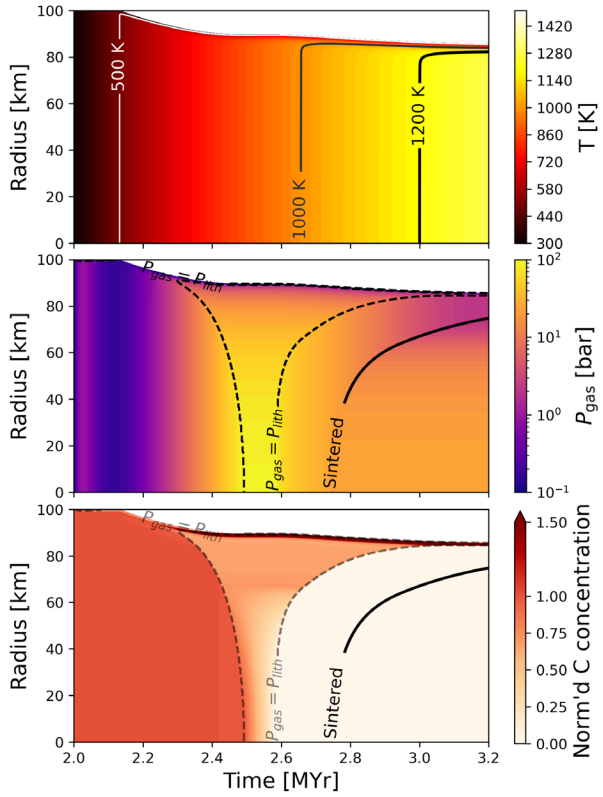

Fig. 2. The detailed evolution of a CI planetesimal with an initial radius of 100 km, accreted at 2 My. Top: temperature contour as a function of radial position and time; middle: the same plot for gas pressure; bottom: the same for graphite concentration, normalized to the initial level.

evolution of a sample case. Severe carbon consumption occurs at radial locations where $P_{gas,sat} = P_{lith}$ is satisfied, because above such locations, gas pressure follows the lithostatic pressure profile, while below it P_{gas} tends to be constant, either due to the uniform temperature profile or complete solid carbon depletion. Such a discontinuity in gas pressure gradient results in significant solid C consumption. The rate of carbon destruction at such a location is therefore determined by the local ∇P_{lith} - a steeper P_{lith} profile drives a stronger Darcy flow. The larger a planetesimal, the steeper its P_{lith} profile, thus the faster it depletes its solid carbon. A 100-km body can deplete carbon from most of its interior within 1 My.

The timing of accretion critically determines the thermal evolution of the planetesimal, consistent with the literature. Earlier accreted bodies have more radioactive heat source available and can thus reach higher peak temperature. Only planetesimals which accreted earlier than ~2.4 My after CAI could reach silicate solidus at around 1420K.

Combining the above two observations, it seems these anhydrous CI planetesimals can be classified into 4 types, with respect to the fate of their carbon reservoir (see Fig. 3):

A - Those formed small and early: their C depletion is not complete when melting occurs. The melt may thus be pressurized by CO_2 and can result in extrusive volcanism that further depletes C.

B - Those formed large and early: they tend to deplete C before melting temperature is reached. They may experience differentiation but possibly no extrusive volcanism.

C - Those formed small and late: neither C depletion nor melting occurs on them.

D - Those formed large and late: they never experience melting or core formation but become severely C depleted.

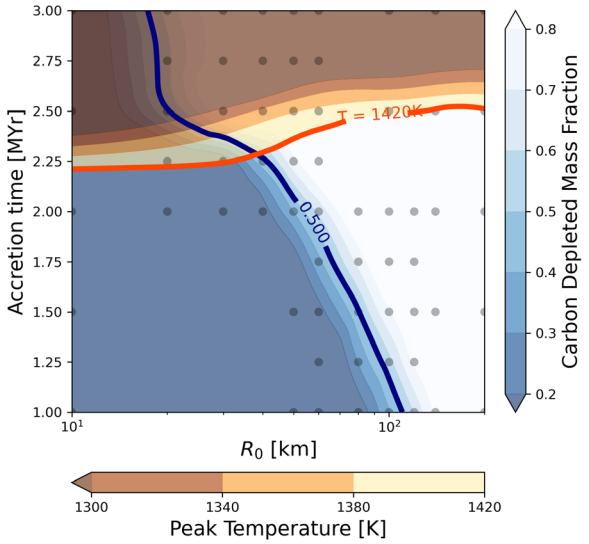

Fig. 3. The fate of carbon in planetesimals, controlled by the initial radius R_0 and the timing of accretion. Grey dots denote parameters used by the simulations.

Conclusion: Carbon may have been geochemically destructed on early-accreted planetesimals within a few million years of their accretion. If the CI planetesimals are responsible for carbon delivery to the terrestrial planets, such bodies should have formed late and small.

References:

[1] Bergin et al. (2015) PNAS, 112 (29), 8965 - 8970. [2] Fischer et al. (2020) PNAS, 117 (16), 8743–8749. [3] Grewal et al. (2019) Sci. Adv. 5: eaau3669. [4] Hirschmann et al. (2019) LPSC L, #2836. [5] Neumann et al. (2012) A&A, 543, A141. [6] Sugiura et al. (1986) Earth Planet. Sci. Lett., 78, 148 – 156. [7] Gail & Trieloff. (2017) A&A, 606, A16. [8] Neumann et al. (2014) A&A, 567, A120. [9] Schaefer & Fegley. (2017) ApJ, 843:120.