EXTENDING THE MUDBALL MODEL TO OTHER CHONDRITE GROUPS. P. A. Bland[1] and B. J. Travis[2], [1]School of Earth and Planetary Science, Curtin University, GPO Box U1987, Perth, WA 6845, Australia, p.a.bland@curtin.edu.au; [2]Planetary Science Institute, 1700 E. Ft. Lowell, Suite 106, Tucson, AZ 85719, USA.

Introduction: A wide variety of numerical models have been developed to understand the geophysical evolution of carbonaceous asteroids. Well-supported model constraints, data, and observations, are not converging on a solution. The initial state for these models involves anhydrous coherent rock reacting with water. But there is no *a priori* reason why nebular fines, ice, and chondrules would be lithified before aqueous alteration. In recent work we have explored the effect of removing the assumption of lithification – the so-called 'mudball' model. We have discussed previous iterations of the model applicable to CM chondrite parent bodies elsewhere [1-3]. Here we extend the model to allow a more detailed comparison with CM petrography; discuss scenarios that would generate CI-like materials; present simulations with CV chondrite inputs; and review case studies (Ceres).

The model: In this study we explore this concept with the MAGHNUM numerical simulator, previously used to model hydrothermal evolution of consolidated carbonaceous chondrite parent bodies [4,5]. New features include particle transport using Stokes-Rubey settling [6,7], minimum porosity from packing models, mud viscosity, serpentinisation and dehydration. Model asteroids are unconsolidated mixtures of coarse particles (chondrules) and mud (initially a uniform mix of fines and ice). The code tracks chondrules. Dimensionless tracer particles scattered throughout the mud also allow us to track movement, temperature and water/rock (WR) ratio - dimensionless mud 'grains' - as they evolve within the body over time.

Input parameters: Initial abundance of radioisotopes, bulk chemistry, and the range of plausible WR ratios for a specific chondrite group are drawn from the literature. Other inputs are detailed elsewhere [1]. We use relevant literature data to constrain accretion time and parent body diameter.

Accretion time. Constraining accretion time for a chondrite parent body is a key factor in understanding its geophysical evolution. Geochronology of components in chondritic meteorites provide that constraint: chondrule ages give an upper limit; ages for alteration products a lower limit. The youngest ages for Allende chondrules come from a multichondrule fraction [8] which yielded an age of 4564.5±0.50Myr (published age corrected using current $^{238}U/^{235}U$ values [e.g. [9]). Recent Mn-Cr dating of secondary Ca-Fe silicates in CVs obtained ages of $3.2_{-0.7}^{+08}$ Ma after CAI [10], apparently cogenetic with fayalite (and magnetite). The suggestion is that the CV parent body accreted at around 3-3.5Myr. Although not a principal focus of the study, a large Pb-Pb dataset of ages for OC and CR chondrules [11] are consistent with an accretion time for these chondrite groups of 3-4Myr. Mn-Cr ages for carbonates in CMs and CIs, supplemented with thermal modelling [12,13], indicate an accretion age for the CM and CI meteorite parent bodies of 3-4Myr. It is interesting that all these data converge on similar accretion times. We model accretion at 3-3.5Myr.

Parent body diameter. Studies of the SFD of main belt asteroids suggest that bodies >120km diameter represent an accretionary population, and that the planetesimal formation process favored the creation of bodies >100km [14]. We model 100-200km bodies.

Chondrule size frequency distribution. We include a variety of chondrule sizes in the mudball model for each simulated body. In this study that size frequency distribution is tailored to specific chondritic parent bodies based on literature data for chondrule SFD for the relevant meteorite type [15].

Results & Discussion: By definition, meteorites are derived from parent bodies that are either partially or completely fragmented. A useful test of our model is not only whether it approximates the conditions under which alteration occurred, but whether a model asteroid when fragmented could generate the variety that we see in that particular meteorite class.

CM chondrites. Almost all of these rocks appear to have experienced alteration over a narrow temperature range, and at relatively low temperatures (<150°C). Model results show a similar feature. Mud convection moderates internal temperature, and reduces variation in temperature throughout. In fact, bodies accreting at 3-3.5Myr, with 100-200km diameter, and at WR=0.6-1.0, all show similar peak T (<150°C). >95% of the asteroid beneath the ice shell experiences alteration over only a 75°C temperature range: a fragmented mudball asteroid would generate a similar CM suite to what we see in our collections.

By tracking the evolution of dimensionless tracer particles we can explore another feature of CM petrography. Large-scale homogeneity gives way to fine-scale chemical and isotopic heterogeneity in these rocks. Heterogeneity in carbonate oxygen in a rock (often between adjacent grains) suggests formation at varying temperatures and WR ratios [16]. 'Clumped' isotope and C-isotope data [17-19] and chemical data [19], also indicate formation over a range of temperatures (even in the same meteorite [17]) and under different physicochemical conditions (e.g., redox states) – this heterogeneity is observed at fine scales (100's µm [19]). This is difficult to achieve in a lithified rock where neighbouring components could be expected to witness similar conditions. But in the mud model, grains forming at different times, temperatures and WR ratios will be brought together in their final configuration only at the end of convection. To constrain the degree of heterogeneity we track the variety of dimensionless tracer particle histories for position, temperature, and WR trajectories, for particles that begin at the same level in an asteroid. We find that a single mud grain might circulate throughout the body, from core to just beneath the ice shell. Grains that might be adjacent at the end of convection experience a wide range of T and WR conditions.

CI chondrites. In our CM simulations, chondrules settle rapidly to form a chondrule-rich core, and mud ocean mantle. That mantle is CI-like: >95% fines, with minor small clasts. It is interesting to note that Mn-Cr ages of carbonates in CI chondrites [13] are essentially indistinguishable from carbonate ages in CMs. To our knowledge, there are few taxonomic discriminants that clearly separate CM matrix from CI bulk. If we envisaged a situation where initial ratios of fines to chondrules in the formation region of CMs allowed for a relatively thin mud mantle this might offer an interesting solution to a long standing (but rarely discussed) problem: why there are only 9 CI chondrite meteorites, and >550 CM chondrites. CIs would be the thin mud mantle counterpart to CMs, from the outer portion of a parent body that is volumetrically minor, and further eroded by impacts over solar system history. We encourage colleagues to look for petrographic data that might test this hypothesis.

CV chondrites. Our CV simulations begin with initial inputs drawn from the meteorite literature – for CVs this means lower mud:chondrule ratios than CMs, higher ^{26}Al abundance, and significantly lower WR (WR in CVs is less well constrained than in CMs; we ran simulations at WR=0.1 and WR=0.2).

Unlike CM chondrites where the large majority of samples experienced alteration at low T and over a narrow temperature range, peak temperatures for CV chondrites are higher, and range from 200-600°C [20-22]. Our simulations are a good match. Peak T in the interior of 100-200km asteroids, with WR of 0.1-0.2, accreting at 3Myr, is 500-600°C. Some convection occurs, but it is limited. The result is a very different T-radius profile than the CM simulations – closer to an onion-shell – spanning the complete range of temperatures that we observe in CV chondrites.

Case-study - Ceres. We also generated a mudball model simulation of Ceres. The results are discussed extensively elsewhere [23-25], but in summary, the model suggests that large scale convective processes have been active until near the present time. The model radial density profile agrees with estimates from shape analysis of Ceres. Ceres surface composition is consistent with model predictions. The model offers a possible mechanism that could have formed the bright spots at Occator and the central pit. Long wavelength Cerean topography is consistent with large upwelling plumes observed in 3D simulations early in Ceres' history. Small-scale, late time convection cells are ~50-100 km in diameter, and may be responsible for the large domes observed at Ceres (~1-5 km high and 50-100 km diameter).

Conclusions: A large number of numerical models have been proposed in an attempt to understand the geophysical evolution of carbonaceous asteroids. An unconsolidated mudball model may offer a general solution. The model is not finely tuned to generate a specific outcome. We consider a range of initial input parameters appropriate for any given chondrite group (parent body diameter, WR, accretion time etc), but across that range we observe outcomes that are a close fit to meteorite petrography. In the Ceres case study, our simulation is consistent with a range of Dawn mission observations. We are now extending the mudball model to other chondrite groups.

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