GIANT CONVECTING MUDBALLS OF THE EARLY SOLAR SYSTEM. P. A. Bland[1], B. J. Travis[2], K. A. Dyl[1] and G. Schubert[3], [1]Department of Applied Geology, Curtin University, GPO Box U1987, Perth, WA 6845, Australia, p.a.bland@curtin.edu.au, [2]Computational Earth Science Group, EES-16/MS-J535, Los Alamos National Laboratory, Los Alamos, NM 87545, USA, bjtravis@lanl.gov, [3]Department of Earth and Space Sciences, University of California, Los Angeles, CA 90095-1567, USA, schubert@ucla.edu.

Introduction: Carbonaceous chondrites (CC) are the most compositionally primitive rocks in the solar system, but the most chemically pristine (CI and CM chondrites) have experienced pervasive aqueous alteration, apparently within asteroid parent bodies (e.g. [1]). Solar elemental abundances (e.g. [2]) require that alteration was isochemical, suggesting negligible fluid flow: a closed-system at scales larger than 100s µm. However, numerical studies consistently predict large-scale (10's km) water transport in model asteroids (e.g. [3-9]). Convective heat transfer is an effective way of moderating temperatures within an asteroid parent body (e.g. [7]). For CCs this is particularly important as almost all CI and CM chondrites experienced alteration over a narrow temperature range and at <150°C. But a problem with numerical studies is that they often produce only narrow bands within model asteroids that match CC conditions (e.g. [5]). In addition, a consideration of the material properties of chondrites suggests very low permeability - a function of the extreme fine grain-size of primordial materials [10]. As a result, liquid water flow would be reduced to mm-scale distances at most, even in a high porosity, water-saturated asteroid. But in the absence of convective motion of water (a closed-system scenario) we are required to posit small (<10's km diameter) primordial parent bodies in order to moderate temperatures during alteration [10]. Carbonate grains in some CMs exhibit a large range in $\delta^{18}O$ (e.g. [11]), interpreted as suggesting open-system water-rock interaction [4]. But achieving this O-isotope heterogeneity at the thin section scale would require a dense network of channels - a feature that is not observed petrographically. Finally, reaction modelling [12] predicts abundant $CH_{4(g)}$ and $H_{2(g)}$ as a consequence of asteroidal aqueous processing, requiring an open-system with respect to gaseous species.

It is apparent that a variety of well-supported model constraints, data, and observations, are incompatible within either an open- or closed-system scenario. However, there may be an alternative that can reconcile these lines of evidence. All previous studies of water:rock interaction in asteroids - including our own - have assumed that the object is lithified: anhydrous coherent rock reacts with water. But there is no *a priori* reason why lithification should have occurred before aqueous alteration. On accretion, nebular fines, ice, and chondrules would not be lithified. On melting, chondrules might become a suspended load in a viscous mud. Water and solids would move together; the notion of open or closed-system would no longer apply.

Model: In this study we explore this concept using a numerical model for the thermal evolution of CC parent bodies similar to that previously described [7,13]. Model asteroids have 50 km radius; initial temperature is 170 K; and chondritic abundances of radiogenic elements. But they are unconsolidated mixtures of coarse particles (1 mm chondrules) and mud (initially a uniform mix of fines and ice).

Results: We consider 3 scenarios, varying the initial mix of coarse and fine particles (see Figure for 2D temperature distributions). On melting, measurements indicate that mud viscosity would be ×50 that of water at the same temperature.

Scenario1: 100% matrix. Convection is initiated by random perturbations to the initial temperature field. The system convects as the interior thaws. Navier-Stokes flow is unsteady but dynamic, despite the high viscosity, characterised by many narrow upwellings and downwellings. Strong convection lasts 3-4 Myr below an ice shell 2-4 km thick. Peak T is 124°C. Temperatures of 70-124°C are maintained for 1.5 Myr throughout the inner ~45 km of the asteroid, with T varying by only 20°C at any given time. Switching off fluid circulation illustrates the difference that convection makes to internal T. Peak T without flow rises to >500°C in the inner core region of the asteroid.

Scenario2: 50% matrix 50% chondrules. Chondrules settle out rapidly to form a coarse core out to ~33 km, with a mud mantle above. The core is partially stratified. Peak T in the inner core is >600°C, but most of the core is at 250-450°C. The fines mud ocean remains at <100°C throughout.

Scenario3: 75% matrix 25% chondrules. Chondrules settle out forming a core to ~25 km radius with a mud ocean above. The innermost core peaks at ~560°C but most of the core is <350°C (mixing and cooling occurs in the outer core). Mud ocean convects strongly; cells have ~1:1 aspect ratio; it remains at ~100°C.

Discussion: The mud asteroid model appears capable of reconciling a number of contradictory observations. Large scale convection occurs, moderating internal temperature. As a viscous mud, fines and water move together: the system is thoroughly mixed so alteration will necessarily be isochemical. Local solubility-related fractionation will tend to be reduced or removed by mud flow. Heterogeneity in carbonate oxy-

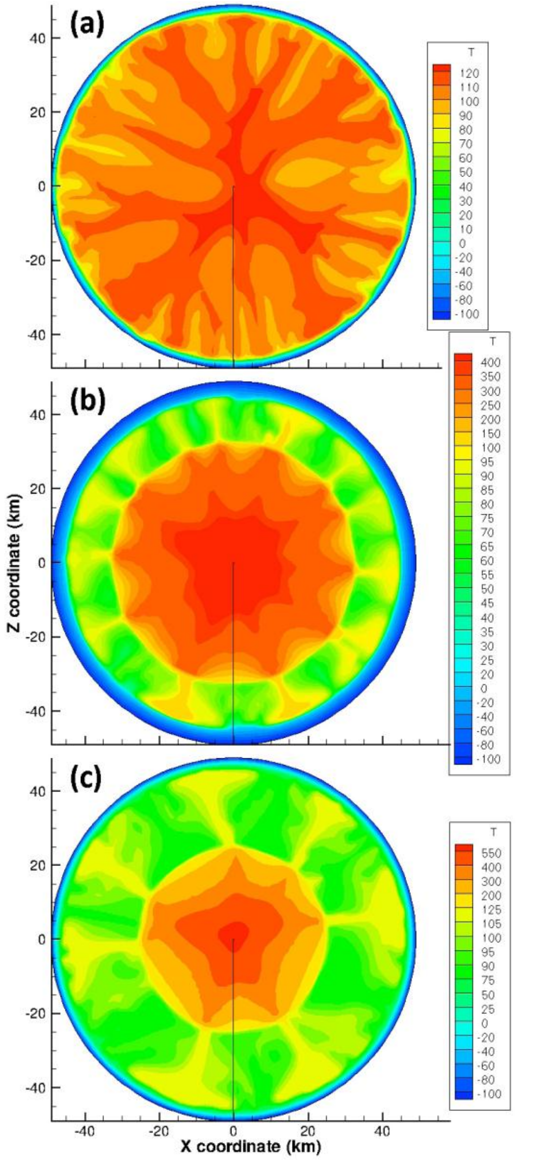

Figure: 2D temperature distribution (°C) (a) at time of max T for 100% fines; (b) for 50:50 mix; (c) for 75:25.

gen requires formation at varying temperatures and fluid compositions, interpreted as consistent with open-system flow [4,11]. But in the mud convection model carbonates will precipitate throughout the active phase of aqueous alteration. Grains forming at different times and temperatures will be brought together in their final configuration only at the end of convection. Significant isotopic heterogeneity over short lengthscales is expected, without a requirement for channel networks.

In detail, our initial modeling indicates that an asteroid composed of 100% unconsolidated fines is a good match to CI chondrite: convecting for 3-4 Myr, it maintains temperatures of 70-124°C for an extended period and is well-mixed (a large volume shows minimal T variability). In scenarios that involve a matrix:chondrule mix we observe rapid settling, with a 'hot' chondrule-dominated core beneath a cool convecting mud-dominated ocean. We are exploring whether small chondrules would be carried as suspended load (currently our coarse particles are 1 mm, while CM chondrules are ~100 µm). The mud ocean in both cases is cooler than in the 100% fines scenario - closer to CM temperatures. The majority of the core in the 75:25 scenario is at temperatures similar to CO chondrite metamorphism [14]. Rim textures may be related to movement of CM chondrules through a mud, but intriguingly, there are additional petrographic features in CMs that support the mud convection concept. Although these were interpreted as arising from compaction following impact [15], they appear to be entirely consistent with mud flow.

Finally, our work may have implications for understanding the evolution of dwarf planets such as Ceres. Ceres shape, and the absence of large topographic features, indicate that it is in hydrostatic equilibrium [16]. Modelling has suggested water:rock differentiation with a hydrosphere over a rocky core [17]. But a convecting mud ocean surrounding a high T coarse 'chondrule' core may also be consistent with observations. Future modelling will consider dwarf planet scenarios.

Conclusion: There is no requirement for multiple meteorite types to come from a single parent. But it is interesting that the mud asteroid model generates similar outcomes from a range of initial accreted mixtures. Large chondrules will separate and form a 'hot' core. Mud-dominated oceans will convect, moderating temperature. CI and CM chondrites - and possibly other chondrite groups - could derive from asteroids that were unlithified convecting mudballs during the phase of aqueous alteration.

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