What controls ooid grain size?

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Summary. Ooids are enigmatic, concentrically coated carbonate sand grains that reflect a fundamental mode of carbonate sedimentation and inorganic product of the carbon cycle—trends in their composition and size are thought to record changes in seawater chemistry over Earth history. Grainstones comprised of ooids typically make excellent reservoir rocks because the typically well-sorted, subspherical sand sized grains lend themselves to high porosity and permeability, via primary interparticle or secondary fabric-selective porosity. Substantial debate persists concerning the roles of physical, chemical, and microbial processes in their growth, including whether carbonate precipitation on ooid surfaces is driven by seawater chemistry or microbial activity, and what role—if any—sediment transport and abrasion play. To test these ideas, we developed an approach to study ooids in the laboratory employing sediment transport stages and seawater chemistry similar to natural environments. Additionally, we were able to take these experimental results and cast them into clear, testable predictions of how ooids grow in modern environments.

Ooids reflect a dynamic balance between chemical growth and abrasion during sediment transport. These experimental results have illustrated that ooid size reflects a tight balance between growth and abrasion processes. This is made most clear by our observations that ooid abrasion and precipitation rates in the experiments were four orders of magnitude faster than the net growth rates of natural ooids in the environment as measured by radiocarbon techniques. This implies that ooids approach a stable size representing a dynamic equilibrium between precipitation and abrasion. Results demonstrated that the physical environment is as important as seawater chemistry in controlling ooid growth and, more generally, that sediment transport plays a significant role in chemical sedimentary systems. These experimental results also allowed us to construct a mathematical model for ooid grain size as a function of environmental conditions that can be tested

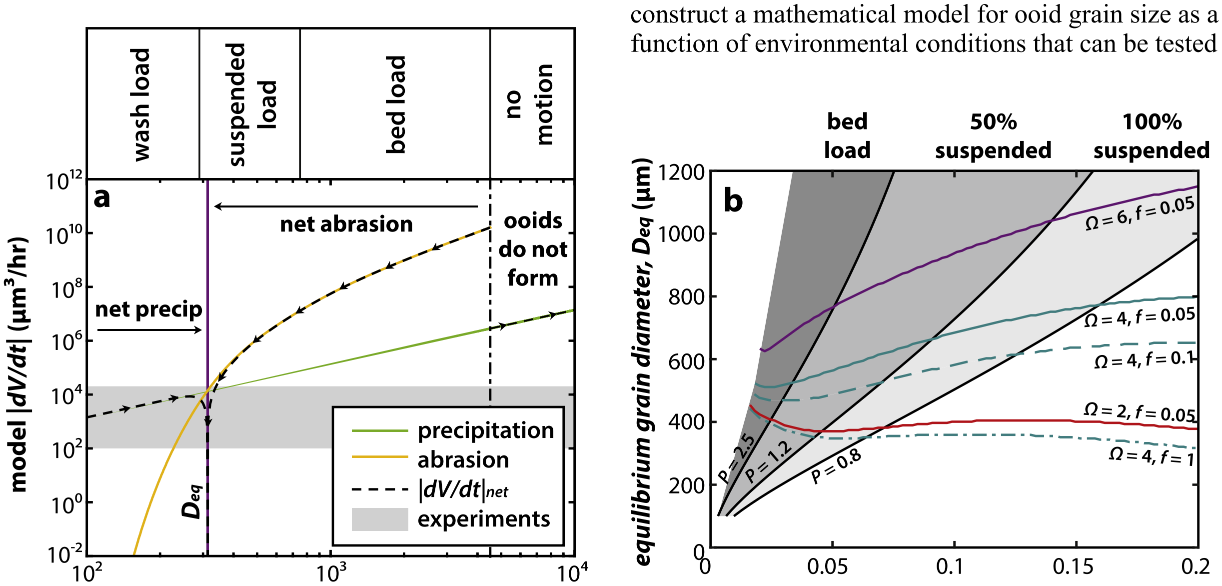

Fig. 1 Benchmarked model results show the mechanics behind the dynamic equilibrium ooid size hypothesis. (a) Modeled magnitudes of precipitation (green line), abrasion (yellow line), and net size change (dashed black line) rates ($|dV_p/dt|$) vs. grain size (D) for $u_* = 0.05$ m/s (near the threshold of suspension for medium sand-sized grains), with transport regimes indicated along the top. An equilibrium grain size (D_{eq}) is predicted where precipitation and abrasion rate are equal and $|dV_p/dt|_{net}$ goes to zero (purple line). Where grains are below the threshold of motion, abrasion rate drops to zero and ooids are not predicted to form (rightmost region). (b) Predicted equilibrium grain size, D_{eq}, vs. u_* for a range of seawater carbonate chemistry conditions ($\Omega_{aragonite}$). Transport regimes are indicated by Rouse number curves. The model predicts that the equilibrium grain size can be increased by increasing $\Omega_{aragonite}$, or by increasing shear velocity in order to transport more grains in suspension. Ooid size thereby reflects tradeoffs in abrasion rate as a function of transport stage.

with further field work. This model is a valuable data product for this project and an example is shown in **Fig. 1**. Finally, the dynamic equilibrium model generates straightforward testable predictions about ooid size that can be validated in modern systems. In particular, the model predicts that there should be a clear relationship between sediment transport mode and ooid size: zones characterized by suspended load transport should produce larger ooids than zones where sediment transport dominantly occurs in the bed load. More broadly, the dynamic equilibrium model indicates that ooid size provides a direct record of physical and chemical conditions of Earth surface environments, such that sedimentological observations of ooid grainstones can be used to quantify the carbonate chemistry of ancient seawater.

Environmental trends in ooid size and shape illustrate the importance of sediment transport and abrasion
We published the first paper describing our experimental work and sought to cast our new knowledge into tests of natural 'modern' ooids in the environment. We conducted a detailed field test of ooid-growth hypotheses on Little Ambergris Cay in the Turks and Caicos. This site is characterized by westward net sediment transport from waves driven by persistent easterly trade winds, which makes it possible to track changes in ooid properties along their transport path as a proxy for changes in time. Ooid size, shape, and radiocarbon age were compared along this path to determine in which environments ooids are growing or abrading. Ooid surface textures, petrographic fabrics, stable-isotope compositions, lipid geochemistry, and genetic data were compared to characterize mechanisms of precipitation and degradation and to determine the relative contributions of abiotic (e.g., abiotic precipitation, physical abrasion) and biologically influenced processes on ooid growth. We saw active ooid growth occurs along the transport path in a high-energy shoal environment characterized by frequent suspended-load transport. The median size increased by more than 100 microns and bulk radiocarbon ages decrease by 360 yr westward along the ~ 20 km length of the shoal crest. Stable-isotope compositions indicated abiotic precipitation of aragonite from seawater. Increases in ooid sphericity during transport illustrated that ooids experience subequal amounts of growth and abrasion—in favor of net growth—as they are transported along the shoal crest. Overall, these results demonstrated that, in the Ambergris system, the mechanism of ooid growth is dominantly abiotic and the loci of ooid growth is determined by both carbonate saturation and sediment transport mode—supporting the utility of predictions made by the dynamic equilibrium hypothesis that emerged from our laboratory ooid growth experiments. Going forward for further integration into carbonate facies models, our new understanding appears to be sufficiently accurate that we might profitably move away from classical models that exhort the existence of an 'ooid factory' in favor of approaches that combine shape and size information from ooid grainstones along with sedimentary structures to gain deeper insights into the local transport mode during the accumulation of large ooid bodies in the stratigraphic record.

Microbes play a largely destructive, rather than constructive, role in ooid size and fabric.
In our experimental work, because we were able to eliminate the effects of microbial processes in the lab, we were able to determine that microbial processes are not required for the development of ooids. But is this also true in the environment? From our Ambergris results, it is clear that diverse microbes are commonly associated with ooids. But lipid and genomic data highlighted a spatial disconnect between the environments with the most extensive biofilm colonization and environments with active ooid growth. Furthermore, electron microscopy illustrated extensive, fabric-destructive colonization by endolithic Cyanobacteria in all environments, implying that microbes play a largely destructive, rather than constructive, role in ooid size and fabric—at least in this environment.

Personnel.
To date we have employed three talented women that have worked on the project. Elizabeth Trower worked on this project with a focus on synthesis of results of laboratory experiments with field data collected from ooid forming environments. She was hired as faculty at CU Boulder last year and is running her own research lab there now. Usha Lingappa has worked on the ooid project both in the lab and the field. She was responsible for the discovery of the effect of microbes on mass loss and textures within ooid grains, from a combination of microscopy, sequencing, and incubation experiments. She is a fourth year graduate student at Caltech. Lydia Kirvak worked on this project, with much of the work focused in the summer. Her prior research was in mineralogy and field geology. Working on this project she received substantial training in both experimental approaches to understanding the mechanics of sediment transport (running the abrasion mills and annular flumes) as well as experience in analytical approaches and data reduction measuring the experimental outcomes via dynamic image analysis and particle size and shape statistics. She has taken her exams and will attend graduate school next fall (location still TBD). Finally, Tom Ulizio (manager of the flume lab) worked closely with students on this project, helping construct the flumes, and with experimental design.