Sedimentary Structures in the Upper Kingston Peak Formation: Implications for Snowball Earth Environments

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Introduction
The “Snowball Earth” events of the late Neo-Proterozoic Era were global cataclysms, in which most of the Earth was covered by ice for millions of years. Despite the implications for early Earth history, the extent of glaciation and the climate during Snowball Earth remain poorly understood. The duration of the glacial epoch, the condition of the oceans, and the erosive impact on landmasses are all largely unknown.

The Kingston Peak Formation in Death Valley, California, is a thick sequence of Neo-Proterozoic sediment that shows textures characteristic of glacial deposition. By examining the sedimentary structures in the upper-most members of the formation, we infer the local environmental conditions around the ice sheet at the end of Snowball Earth.

Methods
Our field investigation was centered on two little-studied locales to the southeast of Death Valley: the Ibex Hills and the Alexander Hills near the Kinston Range (Fig. 1).

In the Ibex Hills, we drew two measured sections through the formation. We noted changes in lithology and particle size, and took representative samples for laboratory analysis. In addition, we observed large-scale changes and sedimentary structures along the strike of the outcrop. Although we noted no significant lithologic changes at the Alexander Hills location, we collected another set of samples for analysis.

In the lab, we examined thin section slides from each of our samples under petrologic microscopes. We noted differences in grain size, composition, matrix, and the presence of small-scale structures.

Observations
The stratigraphic section in the Ibex Hills shows two lithologies. At the top and bottom of the section, the outcrop is dominated by laminated silts and thin beds of conglomerate. (Fig. 2 and 4) Distinct ripples are absent from the silt layers, suggesting that particles settled from suspension in still water.

In contrast, the clasts in the conglomerate are too large and too well-organized to have been suspended in the water column. The conglomerates show grading by size, from matrix-supported gravels at the bottom to sand and silt at the top. Upscale-fining conglomerates are commonly deposited in water-saturated debris flows.

Several meters of rock near the middle of the stratigraphic section are composed entirely of a massive conglomerate, with weakly graded clasts. The maximum clast size in the conglomerate changes dramatically along strike, with individual clasts up to 6 meters long at the west end of the outcrop. These huge boulders are solely composed of the local basement rock, and are too large for transport by water alone; they may have been moved by ice as a part of a debris flow. This massive conglomerate layer is the most notable feature of the Ibex Hills location. (Fig. 3)

Superficially, the Alexander Hills outcrop is similar to the conglomerate in the Ibex Hills, but significant differences become apparent upon close inspection. Microscopic examination reveals a wide diversity of particles (Fig. 5), indicating a large and complex source area. In addition, the largest clasts in the Alexander Hills are rarely more than a few tens of centimeters in diameter, and graded beds are rare. This massive, poorly-sorted, and heterogeneous unit has many characteristics of a glacial deposit.

Conclusions
Although these two outcrops are stratigraphically equivalent, they were formed from different sedimentary materials, moved by different transport mechanisms, and deposited in different environments. Still, we find that both lithologies are consistent with glacial or pro-glacial environments.

In the Ibex Hills, the rapid succession of silt and conglomerate indicates that both depositional processes – particle settling from the water column and subaqueous debris flows – were active at the same time. The large-scale structure of the massive conglomerate suggests to us that it is simply the largest of the submarine debris flows in the outcrop, and does not represent a change in the depositional environment, such as a glacial advance or change in water depth. Our contention is supported by the similarity of sedimentary materials in both coarse and fine layers.

The diversity of sediment sources in the Alexander Hills, and the apparent lack of sorting or structure in a very thick bed is consistent with the accumulation of glacial till, transported over relatively long distances. The Ibex Hill sediments are consistent with rapid glacial erosion and fluvial transport, but show only local transport and deposition in shallow water. With respect to the Snowball Earth scenario, we draw two conclusions: First, erosion by terrestrial glaciers was significant, and therefore the hydrologic cycle was not fully interrupted by the ice. Second, areas of shallow water must have remained unfrozen near the ice sheet, allowing interactions between the ocean and the atmosphere. We look forward to future work testing these hypotheses.

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