MODELING DISTAL IMPACT EJECTA SEDIMENTATION: THE K/T BOUNDARY DOUBLE LAYER. T. J. Goldin[1] and H. J. Melosh[2], [1]Department of Geosciences, University of Arizona, Tucson, Arizona 85721 (tgoldin@geo.arizona.edu), [2]Lunar and Planetary Lab, University of Arizona, Tucson, Arizona 85721 (jmelosh@lpl.arizona.edu).

Introduction: Impact ejecta layers not only serve as important marker beds in the stratigraphic record, but also hold information about the impacts that formed them and the environmental consequences of such events. Thus, ejecta deposits are just as important to the field of impact cratering as the crater itself. However, the mechanics of impact ejecta deposition are not well understood for planets with atmospheres, such as Earth, where complex interactions occur between the ejected particles and the surrounding atmosphere. Current models of ejecta emplacement that rely on the fact that material is ejected from craters on ballistic trajectories cannot account for multiple layers of ejecta deposited around some terrestrial craters such as Chicxulub, where a dual ejecta layer is oberved in North American localities. Studying the interactions between Chicxulub impact ejecta and the atmosphere is particularly important for understanding the environmental effects of this catastrophic impact.

Observed Chicxulub Ejecta: The global ejecta layer at the K/T boundary has been linked to the 65-Ma Chicxulub impact off the coast of the Yucatan, Mexico. The distal ejecta layer is found at sites more than 7000 km from the crater and has a fairly constant thickness of 2-3 mm [1]. In general, the distal ejecta layer, the "fireball layer", consists of ~250 µm densely packed spherules with a spherule area density of ~20,000 per square centimeter [2]. The layer is also enriched in Iridium, an impact indicator, which suggests an origin from the impact plume.

At sites of intermediate distance (2000-4000 km) from the crater in continental North America, the Chicxulub impact ejecta consists of two layers: In addition to the ~3 mm-thick upper layer containing the Iridium anomaly and relict spherules, there is a lower, thicker (i.e. ~2 cm-thick in Raton Basin, NM) layer consisting of mainly terrestrial claystone [2]. Despite local thickness variations [3], the average thickness of the lower layer decreases with increasing distance from Chicxulub [2]. It has been suggested that the upper layer is equivalent to the distal fireball layer and the lower layer represents weathered material from the ejecta curtain, but the mechanics of producing two distinct layers is unclear. The dual-layer stratigraphy has led to the argument of a second impact event, but we argue that atmospheric interactions can explain the emplacement of two distinct ejecta layers from a single impact.

Modeling: KFIX-LPL is a version of the KFIX code [4], which has been modified to suit the problem of impact sedimentation. KFIX is based on the original KACHINA code [5]. The finite-difference code models two-dimensional, two-phase fluid flow allowing us to examine the interactions between the atmosphere and ejected particles (spherules). The code can accomodate both stokes and turbulent flow.

Distal Fireball Layer: Starting with the simplest case of impact plume ejecta only, we modeled a simplified distal Chicxulub scenario of the injection of uniform sized (250-µm diameter) spherules into the atmosphere at 8 km/s, at an altidude of 200 km and with a inflow density consistent with the volume of spherules observed in outcrops. The initial mesh approximates the Earth's atmosphere and employs an exponential pressure gradient, constant temperature, and standard gravity of 9.8 m/s^2. Air is modeled using the equation of state of a perfect gas and the spherules are modeled as a simple incompressible fluid with the properties of basaltic glass.

The particles fall through the thin upper atmosphere, pushing the atmosphere downwards until the particles decelerate due to drag and increasing atmospheric pressure. The particles accumulate in dense layers at ~50-km altitude. The deceleration of spherules heats the atmosphere (>700 K) around the particles causing expansion of the atmosphere and creating a sharp boundary between hot dense atmosphere below the spherules and cool thin atmosphere above.

Double Layer: Deposits from the ejecta curtain are expected to extend to the intermediate distances where the double layer is observed. Thus, we employed an initial brief injection of terrestrial ejecta at 4.5 km/s into our model atmosphere in addition to the more prolonged flux of fireball material. The size (500 µm) and total volume of ejecta curtain material injected is again equal to that observed on the ground.

The high flux of ejecta curtain material compresses the atmosphere to below 40 km in altitude. As this brief pulse ends, the atmosphere rebounds upwards and ejecta from the fireball pulse accumulates at a higher level. Thus, the compression of the atmosphere by the terrestrial material alters the structure of the atmosphere causing the fireball material to fall separately and resulting in the deposition of two distinct layers (Fig. 1). Initially, the spherules settle through the atmosphere as individual particles, but as each layer nears the ground, density currents form. The layers are thus deposited more quickly than stokes flow settling would allow. Deposition of the lower terrestrial layer on the ground begins at ~80 minutes and that of the upper fireball layer begins at ~130 minutes.

Instability Formation: It is necessary to confirm that the instabilities produced in our KFIX-LPL simulations are real density currents and not numerical artifacts. Instead of attempting to evaluate the complex conditions of the ejecta models, we instead tested KFIX-LPL by simulating the observational results of a series of tephra fall experiments in water [6]. In these experiments, Carey [6] dropped Pinatubo tephra into a water tank at a mass flux comparable to that measured in nature and observed that the particle settling in the water column is accelerated by the formation of density currents. We modeled these experiments by dropping spherical tephra particles at various mass fluxes into a model mesh with the properties of water and observed instabilities formation. These instabilities were then evaluated using a criterion yielded by the ratio between turbulent instability growth rate and the Stokes velocity of individual particles:

$$B = \frac{\eta}{2a^2}\sqrt{\frac{N\,h}{\rho_0(\rho_p - \rho_0)\,g}}$$

where η is the viscosity of water, a is the particle radius, N is the particle volume fraction of the particle layer, h is the thickness of the particle layer, ρ_0 is the water density, ρ_p is density of the tephra particles and g is the acceleration of gravity. Large values of B ($B>1$) favor the formation of density currents and small values ($B<1$) favor Stokes flow settling.

Instabilities in our tephra fall models all agree with the instability criterion, occurring at B values exceeding 1.0. The modeled tephra layer is more stable than observed in the experiments; instabilities form at B values ranging from 10 to 15 instead of closer to 1. KFIX-LPL cannot accommodate some of the heterogeneities in the experimental setup, such as a range of tephra sizes and shapes, and so it is more difficult to initiate density currents than in nature. However, the models do consistently obey the instability criterion and thus the density currents are real and not numerical.

Summary: Results from KFIX-LPL models suggest that the influx of distal ejecta spherules into the upper atmosphere following the K/T impact event compressed the upper atmosphere, disrupted the normal pressure gradient, and heated the atmosphere at an altitude ~50 km. Such extreme changes to the atmosphere explain the deposition of the impact plume and ejecta curtain material as two distict layers and our models suggest deposition of both layers occurred over a timescale of hours. Density currents, the formation of which we have verified by modeling experiments of tephra fall in water, permit the ejecta to fall through the atmosphere much faster than individual particle settling. The double layer observed in North American localities is *expected* from a single impact at intermediated distances from Chicxulub.

References: [1] Smit, J. et al. (1992) *Proc. Lunar Planet. Sci. Conf.* 22, 87-100. [2] Smit, J. (1999) *Annu. Rev. Earth Planet. Sci.* pp. 27,75-113. [3] Izett, G. A. (1990) *GSA Special Paper* 249, 1-100.[4] Rivard, W.C. & Torrey, M.D. (1977) *Los Alamos National Laboratory Report* LA-NUREG-6623, Los Alamos, 125 pp. [5] Amsden, A.A. and Harlow F.H. (1974) *Los Alamos Scientific Laboratory Report* LA-5680, Los Alamos. [6] Carey, S. (1997) *Geology* 25(9), 839-842.

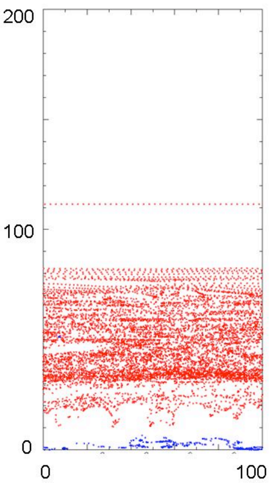

Figure 1. The position of injected spherule tracers after 90 minutes for locations ~2000 km from Chicxulub, where there is both an initial ejecta curtain pulse (blue) and the fireball pulse (red). At 90 minutes, the ejecta curtain material is being deposited to form a lower layer, distinct from the fireball material which will form the upper layer. Note the density currents forming in both types of ejecta as they approach the ground.

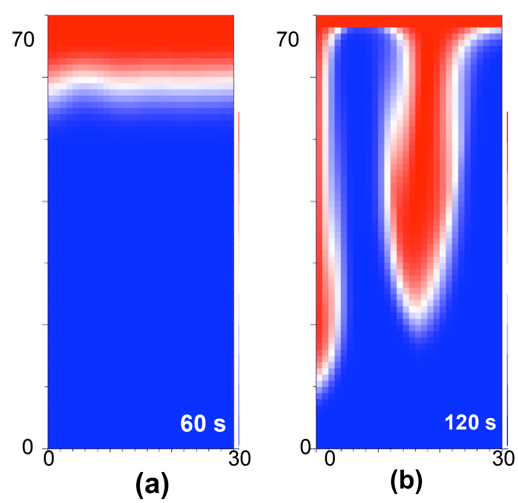

Figure 2. Macroscopic tephra density from model results for 48-µm tephra falling through a 30 x 70 cm^2 tank of water. Warm colors indicate higher densities. (a) Instabilities beginning to form after 1 minute. Tephra volume fraction is ~4% and B=14. (b) Further development of plumes after 2 minutes.