Simulating the Formation of Earth's Largest Impact Crater. N. H. Allen[1,2], M. Nakajima[1,3], S. Helhoski[1], K. Wünnemann[4,5], and D. Trail[3]. [1]Deparmtent of Physics and Astronomy, University of Rochester, Rochester, NY (nallen7@u.rochester.edu), [2]Deparmtent of Physics and Astronomy, Johns Hopkins University, Baltimore, MD, [3]Deparmtent of Earth and Environmental Sciences, University of Rochester, Rochester, NY, [4]Museum für Naturkunde, Leibniz Institute for Evolution and Biodiversity Science, Berlin, Germany, [5]Freie Universität Berlin, Berlin, Germany.

Introduction: The Vredefort crater in South Africa is Earth's largest verified impact crater, and has an age of 2.02 Gyr [1]. Previous studies indicate that erosion of ~10 km would have occurred since its formation, which leads to significant uncertainties in the original crater size. Moreover, the erosion would have erased the original complex and multi-ring structure of the crater, which makes the problem of characterizing the original structure and size of the crater even more challenging. Nonetheless, it is commonly agreed upon that the size was initially between 250-300 km, with most recent estimates leaning towards the largest value [2].

The remnant of the crater today holds a wealth of geologic information. There is a variety of features, both those that can be created from a wide array of different processes and those that must have had an impact origin. Among these are shatter cones, pseudotachylitic breccias, and planar deformation features (PDFs), as well as evidence of melt (the Vredefort Granophyre and gabbronorite, see [3] for an overview of geologic evidence). Each of these occur in a certain pressure-temperature region, and thus we are able to determine the conditions created by the impact at the locations at which this evidence can be constrained. This allows us to establish the parameters of the impact better than only from crater size.

The Vredefort crater is usually described as being formed by an impactor of 5-15 km in diameter with the impact velocity of approximately 15-20 km/s. Ivanov 2005 [4], which is the most recent numerical modeling publication, reports an impactor of ~15 km in diameter with the impact velocity of 15 km/s. In this work, the estimated crater size is approximately 200 km, which is much smaller than the current estimate of the original crater size. Additionally, the simulation did not run long enough to reach an equilibrium state, which requires a runtime of ~ 1000 seconds instead of the 400 seconds used [4]. Given that many previous studies have compared geological features with this numerical model (i.e. [3]), updating to this model is required.

In this work, we focus on creating a crater with the required size as a first step. Secondly, we will compare our simulation results with other geological features, such as the shatter cones and PDFs distributions. We simulate the impact using the iSALE2D code, which stands for impact Simplified Arbitrary Lagrangian Eulerian and has been extensively used and tested in the impact community [e.g. 5]. We then compare our result to [4], to contrast and highlight the differences obtained using our impact parameters.

Methods:

Model: In our simulations, we use a model of Earth based on detailed observations of the structure in the Vredefort region [6]. Thus, we assume the target has quartzite (15 km), granite (25 km) and dunite (below 40 km) layers. The impactor is composed of granite. The ANEOS equation of state is used for all materials. We run the simulation based on a cylindrical coordinate system, which assumes that the collisions are always head-on and thus the result is axisymmetric. However, the most probable impact angle is 45 degrees [7].To take this into account, our underlying assumption is that our simulation velocity is the vertical component of the true velocity.

We define the diameter of the crater as the distance between inflection points at which the slope of the crater changes from positive to negative on each side at the point the crater reaches equilibrium (around 1000 seconds in our simulations). Determining an exact diameter is difficult considering the resolution of the simulation and small movements that continue in the surface long after equilibrium is essentially reached. Thus, there is some small level of uncertainty (approximately ~10 km) in our listed diameters, but it is insignificant when considering the uncertainty of the original diameter (250-300 km). Our simulation runs are shown in Table 1.

Run	Impactor Diameter	Impact Speed	Final Diameter
1	15 km	15 km/s	152 km
2	15 km	30 km/s	198 km
3	15 km	40 km/s	216 km
4	15 km	50 km/s	240 km
5	15 km	60 km/s	266 km
6	25 km	15 km/s	264 km
7	30 km	15 km/s	292 km
8	20 km	25 km/s	252 km

Table 1: The simulations run for this work.

Results: Run 1 is a reproduction of the simulation from [4], whose diameter (152 km) is consistent with the previous result. We are able to approximately recreate the result from this work, although there are some differences due to it using an older version of the code than is used in this work. However, this diameter is much smaller than that agreed upon today (250-300 km). Thus, we continue to explore the parameter space.

First, we run simulations of the impact velocity required to create a crater of the correct diameter with a fixed impactor diameter of 15 km (Runs 2-5). We find that the required velocity is 60 km/s or higher. As impact velocities higher than 45 km/s are highly unlikely [8], these parameter spaces are not probable.

Second, we run simulations of the impactor diameter required to create a crater of 250-300 km in diameter with a fixed impact velocity of 15 km/s (Runs 6 and 7). We find an impactor of 25-30 km in diameter forms a crater 264-296 km in diameter. These large impactors are not common, but possible; previous studies [e.g. 8] indicate that impactors of ~20 km occur once every 300 million to 1 billion years. We use the 25 km impactor as our best result as smaller impactors are more probable.

We also run a simulation in the middle of the parameter space (Run 8) – an impactor 20 km in diameter with the impact velocity of 25 km/s. This is also able to form a crater close to the reported size, with a diameter of 252 km. This shows that there is a degeneracy in the parameter space between impactor size and impact velocity. For the comparison we will show three different results: (A) our "best case" scenario (25 km diameter and 15 km/s, Run 6), (B) our "second" choice (20 km diameter and 25 km/s, Run 8) and (C) Ivanov model (15 km diameter and 15 km/s, Run 1). Shown in Figure 1 is the equilibrium state (t = 1000 s) of each of our results, with the crater edge marked with an arrow and radius.

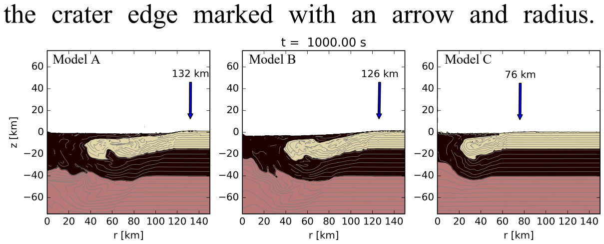

Figure 1: From left to right: Model A (Run 6), Model B (Run 8), and Model C (Run 1) shown at their equilibrium state. The radius of the crater is marked with the arrow.

Discussion - Shock Morphology and Pressure Distribution: Shown in Figure 2 is the peak pressure contours at $t = 1000$ s for each of the three models. Since the publication of [4], a significant amount of new geologic evidence has been obtained and it increased the distance from the center that specific shock morphological features are found. Thus, the shock pressures that were sufficient to explain the existence of known features are no longer high enough. Our higher energy impacts are able to reach these required pressures, however. For example, the distribution of shatter cones indicates a pressure of at least ~2-6 GPa up to ~90 km from the center of the Vredefort crater [3, 9]. Our models A and B are able to match this requirement, but model C is not able to, either in our recreation or in the original work. Our models A and B are able to match all of the shock morphology we have tested thus far while model C cannot.

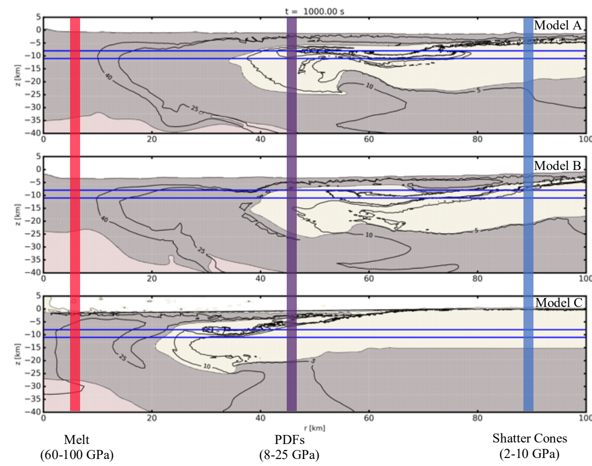

Figure 2: From top to bottom: Model A (Run 6), Model B (Run 8), and Model C (Run 1). Marked are peak pressure contours of 5, 10, 25 and 40 GPa. The blue lines mark the level of erosion today (8-11 km). The colored stripes mark the outer limits of discoveries of melt, PDFs, and shatter cones inside the crater, respectively.

Future Work: We will continue to compare the geologic evidence to the shock pressures predicted by our simulation, as well as look in to any potential remnants of a melt sheet. Additionally, we hope to look into ejecta remnants from this impact that have been found around the world (i.e. in Greenland [10]).

References:

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