The role of central peak oscillation in the formation of complex planetary craters

John D. O'Keefe and Thomas J. Ahrens
Lindhurst Laboratory of Experimental Geophysics
Seismological Laboratory, California Institute of Technology
Pasadena, California 91125

Baldwin (1) and Van Dorn (2), (3), suggested that the rings around lunar craters formed as the result of the arresting of giant fluid surface waves driven by an impact event. In the intervening 20 years, complex craters' morphologies are observed on all solid planets and major satellites in the solar system. Baldwin and Van Dorn based their arguments on an analogy to droplet impacts into water and other fluids. These experiments (4) showed the formation of a tall transient central peak that was an order of magnitude larger than the droplet size and that the oscillation of the peak drove a series of concentric surface waves. While these papers were provocative, they did not provide a quantitative description of the threshold for wave production nor a description of the assisting mechanisms for the waves in planetary materials. We have modeled large scale impacts on planets for a range of material strengths and found the development of tall transient central peaks that drive surface waves and flooding waves such as observed on Venus. In these series of calculations we varied the gravity scaling parameter \( ga/U^2 \) from 0 to 0.34, and the strength scaling parameter \( Y/ptU^2 \) from 0 to 2400, where \( a \) is the impactor radius, \( U \) the impact velocity, \( g \) is the planetary gravitational acceleration, and \( Y \) the planetary crustal strength. We have extended our previous calculations (6) (7) out to very late times so as to model the central peak-surface wave interaction.

An example of the formation and oscillation of the central peak and the production of surface waves is shown in figure 1 for the scaling parameters \( ga/U^2 = 0.0034 \) and \( Y/ptU^2 = 6.2 \times 10^{-5} \). The series of plots show the crater evolution from the time of maximum penetration to the decay of the central peak after two oscillations. The flow field and material motions are very complex. To illustrate these, we show on the left side of the figure the velocity field at a given dimensionless time \( Ut/a \), and on the right side we show the motion histories of tracer particles placed at various levels in the planet. Here, \( t \) is the actual time.

At the time of maximum penetration (\( Ut/a - 18 \)), the impactor has lined the transient cavity wall and the particle motions near the centerline are downward and at the surface are upward at about a 60 degree angle. As the crater evolves the gravitational forces come into play and the central peak starts to form (see figure 1b). The central peak reaches a maximum at \( Ut/a - 112 \) and is shown in figure 1c. The maximum peak height is \( 9 \times \) times the impactor radius. At this time the ejecta has landed on the surface. Note that the flow field has evolved from being radially outward near the centerline as shown in figure 1a to a toroidal form shown in figure 1c. The first peak collapses and drives material radially outward and creates a surface wave (see figure 1d). The material that is driven outward is shock heated and could be a source of surface flooding of melt such as observed on the surface of Venus. The first peak collapses downward and creates a transient cavity (see figure 1e) that is smaller than the initial cavity shown in figure 1a. This cavity closes and creates a second peak oscillation whose height is close to the initial height but is narrower in diameter (see figure 1f). The second oscillation of the peak collapses and decays and results in a shallow crater. Scaling laws following the approach in (5) and (7) have been developed for the central peak height and other crater dimensions and the implications of the these are presented.

ACKNOWLEDGMENTS
We appreciate the computational assistance of M. E. Lainhart. This research was supported by NASA.

REFERENCES
Figure 1. An example of formation and oscillation of central peak and the production of surface waves. Dimensionless parameters are $ga/U^2 = 0.0035$ and $Y/pU^2 = 6.2 \times 10^{-5}$.