

Computer Simulations of 10-km-Diameter Asteroid Impacts into Oceanic and Continental Sites--Preliminary Results on Atmospheric Passage, Cratering, and Ejecta Dynamics

Roddy, D.J., U.S. Geological Survey, Flagstaff, Ariz.; Schuster, S.H., Rosenblatt, Martin, Grant, L.B., Hassig, P.J., and Kreyenhagen, K.N. California Research and Technology, Chatsworth, Calif.

The effects created by large asteroids and comets impacting on the Earth have generated increasing interest in a number of scientific disciplines, ranging from cratering mechanics to biological research. An intriguing idea raised in 1980 by Alvarez and co-workers and now discussed by many others is that a number of large impacts formed giant craters on the Earth and have ejected sufficient material into the atmosphere to cause major global atmospheric and biologic changes [1]. In an effort to quantify certain aspects of such impact events, we are working on a series of analytical calculations of large-scale cratering events for both oceanic and continental sites in order to examine their effects on the target media and atmosphere.

The first of our analytical studies that have been completed consists of computer simulations of the dynamics of (a) the passage of a 10-km-diameter asteroid moving at 20 km/sec through the Earth's atmosphere, and (b) the impact-cratering events in both oceanic and continental environments. The asteroid was modeled as a spherical body moving vertically downward, and the physical properties and equations of state of the asteroid, ocean, crust, and mantle were selected to represent generalized but realistic terrestrial conditions. The asteroid composition was modeled as a single generic silicate (quartz). The geologic layering was defined on the basis of V_p and V_s seismic data, and densities and thermal gradients were modeled for the target rocks. The passage of the asteroid through the atmosphere was simulated with the multiphase DICE computer code, and the impact-cratering events were simulated with the CRALE2 computer code. Both codes were chosen because of their extensive testing and calibration against a wide range of high-explosive and nuclear-explosion data.

Calculation of the dynamics associated with the passage of the asteroid through the atmosphere showed strong effects on the surrounding air mass throughout a calculational time of 30 s. During its descent, the asteroid generated a strong shock wave of hot compressed air that initially formed a narrow, conical bow wave extending back along the trajectory. After impact, this mass of shocked air expanded rapidly for tens of kilometers as a strongly heated, low-density region behind the outward-moving shock front in the air. Peak air pressures in front of the asteroid were about 0.5 Kb at 10-km altitude and reached 200 Kb at the time of impact. A large heated mass of low-density air that had peak temperatures of nearly 20,000 K formed adjacent to the uplifting crater rim and moved rapidly out from the impact area; surface fires could be expected at greater ranges if combustible materials were present. By 10 s, the low-density air still had temperatures of several thousand degrees kelvin, and extended outward in excess of 30 km and upward more than 30 km. At ranges of 200 km, the peak air velocity was estimated to be as high as 50 m/s. Calculations to 30 s showed that the air shock fronts and most of the following shocked air mass preceded the

formation of the crater, ejecta, and rim uplift in time and location and did not interact. Uplifted rim and target material were later ejected into the shock-heated, low-density air immediately above the forming crater and would interact only in this region of the expanding atmosphere.

The calculations of the impact-cratering events showed equally dramatic effects on the oceanic and continental environments throughout a calculational interval of 120 s. Early in both impact sequences, the asteroid penetrated and compressed the ocean and sedimentary rocks to about a 2-km thickness. By 10 s in both calculations, the asteroid was largely vaporized and the transient craters were about 30 km deep and about 40 km across; the oceanic impact had penetrated into mantle material that had residual temperatures of about 400 °C. At this time, transient rim uplift of ocean and crustal material exceeded 20 km in height above the original ocean level. Peak axial overpressures were about 4 Mb at the surface, 2 Mb at a depth of 5 km, 1 Mb at a depth of 10 km, and 0.25 Mb at a depth of 40 km. Increasingly strong rebound of the deeper rocks occurred after about 30 s, and the transient craters ceased to deepen below about 40 km in mantle material at about 450 °C. The transient oceanic diameter, about 60 km across at 30 s, continued to expand at a slower rate for the next 90 s. The transient rim crest of ocean and crust rose to a maximum of about 40 km at 30 s into the event. At 60 s, the transient rim stood at least 35 km above the original ocean level and was moving outward at velocities as great as 0.5 km/s. At 120 s, the transient oceanic diameter was about 105 km and the transient continental diameter was about 85 km. The massive rebound of the subcrater floor crust and mantle that started at about 30 s continued to the end of the calculational times and exhibited major inward flow and uplift. Central uplift structures are indicated in both cratering calculations. The transient rim crests were initially above the original impact surfaces, but late-stage relaxation is expected to lower the rims and produce major slump terraces and inward-dipping layers.

At 120 s, the target materials that surrounded the crater floors and walls were responding largely to gravitational relaxation, but still had material velocities ranging from 5 to 50 m/s. The final transient-crater motions, coupled with certain explosion and impact-crater analogs, lead us to tentatively estimate that the final oceanic crater will have a diameter on the order of 120 to 150 km and a depth of less than 10 km, coupled with central uplift and/or multiring uplift structures; the final continental crater is tentatively estimated to have a diameter of about 100 to 120 km and a depth of less than 10 km. More than $7 \times 10^4 \text{ km}^3$ (10^{14} metric tons) of target material was ejected (no mantle) and would have formed a massive ejecta blanket surrounding the cratered areas. If scaling holds from other large explosion and impact-crater field data, more than 70% of the ejecta should lie within three crater diameters of the impact points. The remaining ejecta, including most of the asteroid material, would reside both at different altitudes in the atmosphere as high as the ionosphere and at extended ground ranges. The uplifted hot crustal/mantle rocks would cover about $15 \times 10^3 \text{ km}^2$ of the inner-crater floor and, depending on their volatile content, may degas violently and add ash to the atmosphere that

potentially could exceed the ejecta contributions. Other cratering processes that require additional study include such effects as late-stage crater relaxations, ejecta/atmosphere interactions, ejecta distributions in atmosphere, return flow of ocean, tsunamis, long-term induced volcanism, and numerous other late-stage effects.

Reference

- [1] Alvarez, L.W. Alvarez, W., Asaro, F., and Michel, H.V., 1980, Extraterrestrial cause for the Cretaceous-Tertiary extinction: *Science*, v. 208, p. 1095-1108.