
The origin of the one or more asymmetric ring scarps surrounding large lunar impact structures has been vigorously debated [1]. One model that has achieved substantial support proposes that rings form when the initial transient crater penetrates the lithosphere and rapid inward flow of asthenospheric fluid rafts the lithosphere inward and brings the radial stresses into tension some distance from the transient crater rim [2]. This model, however, is based on a number of analytic simplifications of the complex asthenospheric flow induced by the crater.

We have attempted to eliminate the need for these analytic approximations by constructing a finite element model of large impact crater collapse. The finite element method allows us to employ complex boundary shapes (specifically, that of a rimmed crater) and to incorporate rheological variations, such as the lithosphere-asthenosphere boundary. The one area in which this computation is still approximate is that our code lacks inertial forces: we assume that the collapse is sufficiently slow that inertia can be neglected. Although this is not a good approximation near the crater's center, where rapid rebound may result in central peaks or internal peak rings, inertia can almost certainly be neglected at the larger distances where the ring scarps form.

The finite element code we used [3] is specifically designed to treat tectonic problems. The rheology of all elements is Maxwell-viscoelastic, in which the viscous flow portion may be either newtonian or non-newtonian. We performed computations for both n=1 (newtonian) and n=3 power law flows. Axisymetric 3 and 4 node isoparametric elements were used to model the crater.

We chose to model a 200 km diameter transient crater on the moon, initially 40 km deep. The crater was underlain by a viscous layer that extended to the outer edge of the grid 1140 km from the center. The viscous layer was itself underlain by a 1000x more viscous layer at a depth of 115 km. The bottom of the grid was 355 km below the surface. A 10 km thick elastic lithosphere surrounded the crater, from the rim to the end of the grid. The grid (Fig. 1) contains 305 nodes and 303 elements. The element size is smallest in the vicinity of the crater, where stresses change most rapidly.

Immediately after the crater forms all stresses are elastic. The finite element results for these stresses agree well with an analytic solution [4]. Subsequently, viscous flow begins and after one or two Maxwell times viscous flow inward toward the crater cavity is established. Figure 2 illustrates the change in the radial stress component σr at three times, t=0 (elastic), t=140 sec (3 Maxwell times after excavation) and t=1000 sec (fully developed viscous flow) for a newtonian viscous model in which the viscosity is 10^{12} Pa-s in the asthenosphere.

The radial stresses are initially compressional from the crater rim to the end of the grid. After 3 Maxwell times the distal stresses become slightly extensional, but radial stresses near the rim remain compressional. Figure 2 shows that as the flow becomes fully established the radial stresses strongly become extensional, peaking at a radius of 200 km, about equal to the transient crater radius. These stresses reach nearly 100MPa, easily enough to cause the lithosphere to fail in extension and produce a ring-shaped normal fault surrounding the crater. The finite element computation shows that the lithosphere is tilted outward away from the crater center, so that the resulting normal fault scarp should face inward, as is observed in lunar multiring basins.

The non-newtonian computation yields nearly identical results, although the timescale for development is somewhat longer. The non-newtonian result is important because the newtonian viscosity of 10^{12} Pa-s required to explain multiring basin formation is implausibly small. Even the earth's present asthenosphere has an effective viscosity of about 10^{18} Pa-s at a shear stress of ca. 1 MPa [5]. However, for n=3 non-newtonian materials the effective viscosity scales as the inverse second power of stress, so that the several 100 MPa stresses developing beneath the crater can reduce the effective viscosity into the range required for basin formation.
Acute readers will note that the finite element model's-predicted ring diameter is almost exactly twice the transient crater diameter, whereas traditional multiring lore notes that the most common ring spacing is close to 1.5 (or \( \sqrt{2} \)). At present we are not certain of what to make of this: the factor 2 spacing seems to be a robust result of the models run so far. However, we note that most transient craters expand up to 60% of their initial diameter by rim slumping, so that the ratio of collapsed rim diameter to scarp diameter is closer to 1.5. We also plan to investigate models with thicker lithospheres and other rheological variations to see if the ring ratios depend upon factors we have not yet studied.

Nevertheless, our results do support the idea that ring fractures around large impact structures can develop by inward flow of the asthenosphere beneath the crater.