ACOUSTIC FLUIDIZATION: WHAT IT IS, AND IS NOT. H. J. Melosh¹

Acoustic Fluidization: I introduced the concept of acoustic fluidization in 1979 to explain the astonishingly low strength and viscosity exhibited by the collapse of impact craters and the formation of central peaks in lunar craters [1]. The name I gave to this process was not well chosen for the geologic community—“vibrational fluidization” might have been more apt—but that name was already in use in another context and would have proven confusing [2].

The principal motivation for introducing this process was to explain the transition from simple to complex craters on the Moon. Mechanical analysis of the collapse of simple craters indicates that the strength of the underlying material is only about 3 MPa [3]. Furthermore, the rise of central peaks in craters larger than about 15 km diameter on the Moon suggests that the post-impact debris can flow as a fluid with a viscosity in the vicinity of about $10^9$ Pa-sec [4], implying a Bingham rheology for the material surrounding the crater. How could dry, broken rock debris on the surface of a planet lacking water, air or even clay minerals flow like a liquid? My solution was to invoke the action of strong vibrations in the rock debris broken by the shock from the impact, which I proposed could briefly fluidize the debris. The reality of such strong vibrations near an impact is supported by ground motion measurements near large explosions on Earth [5], and the nonlinear dependence of strain rate on stress predicted by the theoretical model is consistent with the phenomenological Bingham rheology [6]. Moreover, the predicted relation between stress and strain rate as a function of the amplitude of vibrations was verified by measurements with a rotational viscometer [7], as shown in Figure 1.

The acoustic fluidization model has been widely applied to hydrocode modeling of impact crater collapse through the approximate scheme of the “Block Model” [8], with great success, although at the cost of introducing three empirical parameters; one that relates the amplitude of the vibrations to the strength of the initial shock wave, another that specifies an effective viscosity (it essentially chooses an effective frequency or wavelength of the vibrations) and one that specifies the decay rate of the vibrational energy.

The full acoustic fluidization model also envisions a feedback between flow and the vibrational energy field [9,10], which is not captured by the Block Model. A recent study has finally begun to lift this restriction [11] and provides a more accurate model of how craters collapse.

Tests of Acoustic Fluidization? A recent study [12] argues against the efficacy of acoustic fluidization in the formation of a well-exposed central peak of a crater on Mars on the basis of the mapped exposures’ failure to conform to the assumptions of the Block Model. In particular, it was stated that the apparent continuity of the mapped units and the lack of matrix separating observable observable discrete blocks is evidence against the process. However, I believe that this is a case of taking a simplified heuristic model too literally. The Block Model, with its discrete blocks separated by thick layers of matrix is only a conceptual model to motivate equations that are similar to those of the full acoustic fluidization model, which never postulated such a structure. Acoustic fluidization only supposes that a mass of dry rock debris, which is potentially quite homogeneous, is fluidized by the fluctuating pressures induced by strong vibrations (acoustic waves) traversing the mass. Individual clasts or larger rock units, normally pushed tightly against each other by the pressure of overlying rock debris, suddenly become free to slip during a transient fluctuation of the pressure field to low pressure. The mechanism is very similar to one proposed (and observationally verified) for the flow of rock debris in muddy debris streams [13,14], where pore pressure fluctuations relieve the overburden pressure within the normally clast-supported matrix.

Figure 1. Strain rate vs. stress in sand fluidized by strong vibrations at a frequency of about 300 Hz. $\Sigma$ is the ratio between the rms vibration amplitude and the overburden pressure, and the yield stress is measured in the absence of vibrations. The solid theoretical curves are fit to the data with no free parameters.
I have also suggested that acoustic fluidization is responsible for the low coefficients of friction observed in large-volume rock avalanches, termed long-runout slides or sturzstrom [1,9,15]. These large, rapid mass movements have much in common with crater collapse, including Bingham rheology, low coefficients of friction and laminar viscous deformation [16]. Figure 2 illustrates the debris lobe of one such avalanche that exhibits many of the characteristics of the units mapped by Johnson and Sharpton [12].

Figure 2. Debris lobe of the McGinnis Peak, AK sturzstrom that was initiated by the 2002 Denali earthquake. Note the coherent, but highly deformed, contacts of distinct debris units in the landslide lobe [17].

It has long been noted that such avalanches, in spite of speeds from 50 to 70 m/sec, flow in an apparently laminar fashion that does not mix distinct rock units, in spite of very large strains incurred as the broken rock mass flows between its source area and final debris lobe [18].

From a distance, one might infer that the rock in the slide lobe remained intact, as is suggested by geologic maps of many impact crater central peaks. However, close inspection reveals that the rock is thoroughly shattered and lacks any appreciable tensile strength. Coherent block sizes can range from centimeters to many meters and, in still larger collapses occurring in impact craters, might even approach tens or hundreds of meters, as suggested by the boreholes into the Puchezh-Katunki crater’s central peak [19]. Although the flow incorporated large (but evidently deformed) “blocks”, there is seldom evidence of a finer matrix between these units: They are typically separated only by narrow faults and fractures, consistent with the requirements of the acoustic fluidization model. Similar observations have also been reported from the well-exposed central peak of the 12 km diameter Kentland, IN (USA) impact crater [20] as well as other craters [21], in which the deformation is largely due to numerous small-scale fractures whose motion would normally be opposed by friction and thus require a temporary relief of overburden pressure to slide.

I thus believe that the Martian crater observations of Johnson and Sharpton [12] as well as the more detailed observations possible at terrestrial craters, are entirely consistent with the action of acoustic fluidization. On the other hand, the apparent absence of melt sheets bounding the deformed blocks forming the central peaks of terrestrial craters mitigates strongly against alternative weakening models that appeal to discrete planes of melting in collapsing rock units [22].