cells, such as red blood cells, and yeast—can determine their own shape by their cytoskeleton or other intrinsic signals (9). Endothelial cells, and presumably other adherent cells, clearly differ in that their shape is determined by the properties of the surrounding ECM and by adjacent cells.

The results of Chen *et al.* indicate that after the ECM controls cell shape, cell shape in turn controls survival and growth. This relation makes sense in situations such as tissue regeneration. For example, if an epithelial or endothelial cell layer is damaged, there will be fewer cells covering the damaged area, the remaining cells will be able to spread, and this would stimulate them to proliferate until the tissue gap is filled.

A highly speculative, but tantalizing, possibility raised by these and earlier results from the same laboratory is that cell shape might directly control gene regulation. The authors have shown that tugging on an integrin outside the cells can cause deformation and movement of the nucleus (10). It will be interesting to see whether such a physical connection might alter the regulation of growth and survival genes without chemical intermediates.

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PLANETARY GEOLOGY

Extreme Cratering

William B. McKinnon

In March 1995, geologists E. M. Shoemaker [U.S. Geological Survey (USGS), Flagstaff, Arizona] and J. C. Wynn (USGS, Reston, Virginia) were invited to accompany an expedition sponsored by the Zahid Corporation (a heavy equipment dealer) of Saudi Arabia. Their mission: to venture into The Empty Quarter of southern Arabia and recover the "lost" iron meteorite craters of Wabar. First described to the West by St. John Philby in 1933 (*1*), these craters had by 1961 been mostly buried by the shifting desert sands. Traveling in Humvees and through 55°C daytime heat, the geologists were simply taking the extreme measures necessary to study that most extreme of geologic events, the hypervelocity collision of planetary objects. Shoemaker described the results of his adventure at Lunar and Planetary Science Conference XXVIII, held 15 to 19 March 1997 in Houston, Texas. This meeting, although broad in scope, is the preeminent annual meeting for the presentation of new results on impact cratering: terrestrial studies, planetary observations, theoretical models, experimental tests, and simulations.

There is little doubt in the planetary community as to the importance of major impacts in the evolution of life on Earth. The best established and most studied example is, of course, the demise of the dinosaurs at the end of the Cretaceous Period (65 million years ago), which is linked by abundant trace element, isotopic, mineralogic, and microfossil evidence to the 200- to 300-km-diameter Chicxulub crater in the Yucatán (*2*). It was of some interest, then, when geochemical and petrological analyses of drill cores from a large near-circular structure near Morokweng, South Africa, were reported at the same meeting (C. Koeberl, University of Vienna). The site had already been suspected of being an impact (*3*), and the drill cores turned up a thick layer of impact melt rocks with high abundances of iridium and other platinum-group elements. The samples of impact melt rock have a remarkably uniform composition, which is characteristic of large melt bodies formed by wholesale fusion of country rock, and the platinum-group elements are sufficiently abundant to indicate mixing of 2 to 5% chondritic meteoritic component into the melt. Unannealed relics in quartz show remnants of planar deformation features, the signature indicator of shock passage. Most intriguing of all are the age dates from zircons that grew from the melt, which are, within the errors, indistinguishable from that of the Jurassic-Cretaceous (J-K) boundary (≈145 million years ago).

The size of the original Morokweng impact crater is uncertain, owing to deep erosion, but diameter estimates range from a merely devastating 70 km to a truly Chicxulubian 340 km (*3*). Stratigraphic evidence of impact debris (ejecta) at the J-K boundary has not yet been reported (*4*), but greater attention to defining and studying this boundary is clearly in order.

An ejecta horizon from a different (and much older) era, the late (or neo) Archean, has been discovered in the Transvaal of South Africa (reported by B. M. Simonson, Oberlin College). This distinctive ejecta layer, the Monteville, consists of spherules up to 1 mm in diameter that display inward-radiating fibrous quench and devitrification textures: that is, the spherules are frozen impact melt spray (or condensed vapor). Similar textures are seen in spherules from the Cretaceous-Tertiary boundary and, indeed, from even older Archean units in South Africa and Australia (*5*). What makes these spherules notable is that they are petrologically similar to impact spherules found in layers preserved in Neo-Archean strata of the Hamersley Basin of Western Australia. The Monteville and one of the Hamersley layers, the Wittenoom, are also of a very similar age (≈2.55 billion years ago), based on radiometric dating of volcanic tuffs in the stratigraphic vicinity of the layers and of carbonates within the Wittenoom, and both appear to have been deposited under high-energy wave conditions, possibly impact-induced tsunamis. Furthermore, independent geologic evidence suggests that the South African and Western Australian provinces in which the spherule layers are found were once part of a single continental landmass (*6*).

Thus, this work suggests that the Monteville and one of the Hamersley spherule layers are contemporaneous, and more significantly, that a new technique exists for establishing the stratigraphic succession of ancient terrestrial rocks. Ejecta horizons have been pressed into service as stratigraphic markers for some time on the moon and planets, more or less by default. The terrestrial spherule layers represent a new tool for establishing the intercontinental correlation of geologic time, which for early Precambrian geology would be a tremendous boon.

The author is in the Department of Earth and Planetary Sciences and McDonnell Center for Space Sciences, Washington University, Saint Louis, MO 63130, USA. E-mail: mckinnon@wunder.wustl.edu

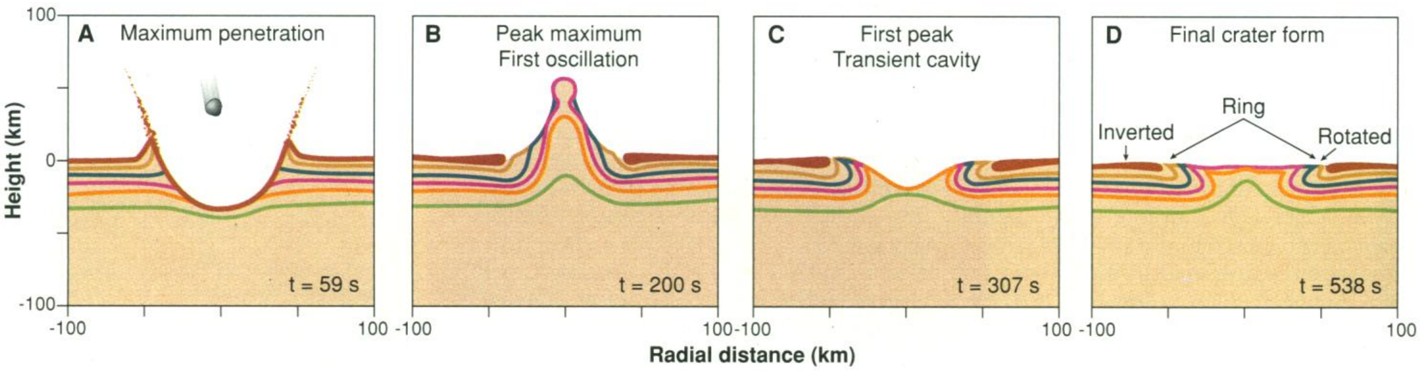

Fig. 1. Formation of a very large complex impact crater (*14*). Distances and times are given for a 5-km-radius impactor striking Earth at 25 km s^{-1} (similar to the formation conditions of Chicxulub), based on the scaling in (*7*) and assuming self-similarity holds throughout the formation sequence. The peak ring of vertically rotated strata is indicated, and the crater rim lies near the edges of Fig. 1D.

Fundamental understanding of the impact process itself is both constrained by and is necessary to interpret the observations above. Formation of small bowl-shaped craters is relatively well understood, but the larger the scale, the greater the uncertainty. The creation of larger, complex craters (that is, those with flat floors, central peaks, or mountainous inner rings) is one of the great unsolved problems of planetary geology. Numerical simulations of complex crater formation (presented by J. D. O'Keefe, California Institute of Technology) are illustrative of a new threshold in computational ability, if not realism. No longer limited by computational power or expense, this type of simulation can be carried out to the latest times, when mass motion ceases. The real scientific frontier is actually understanding and modeling the response of geological materials under extreme conditions, such as those imposed by the growth of the initial transient cavity (Fig. 1A), its gravitationally driven rebound (Fig. 1B), and ultimate collapse to a flattened form (Fig. 1, C and D).

The calculations shown have a long inheritance (*7*), but a variety of fracture and comminution, as well as pressure- and temperature-dependent, strength models can be incorporated, and stratigraphic details at least predicted. The calculations illustrated are only as good as the strength model incorporated but imply that the inner ring of peak-ring craters or basins, such as the Schrödinger Basin on the moon (*8*), bound the transient cavity. The observed, downfaulted topographic rim is generally (but not always) twice as wide as the peak ring (*9*). Of course, competing theories of ring formation exist, incorporating mechanisms not included in the present calculations (*9–11*), but detailed models of the type in Fig. 1 should prove valuable when compared to field observations. One of the best ways to preserve impact stratigraphy on this active Earth is, paradoxically, to bury it. The peak ring of Chicxulub and that of the 85-km-diameter Chesapeake Bay impact (C. W. Poag, USGS, Woods Hole, Massachusetts) are buried more or less intact and thus are available for future study.

The first moments of an impact are also rich in phenomena. Especially important is jetting, whereby the high-pressure zone between the impactor and the target planet is free to expand at high velocity into the planet's atmosphere (or into space, as the case may be). Fundamentally, jetting results from the obliquity of a collision interface, with jet velocities and pressure-temperature conditions greatly in excess of those obtained in the idealized planar impact at the same velocity (*11*). Jetting has been proposed as mechanism responsible for, among other things (i) forming chondrules during asteroid collisions, (ii) forming tektites in terrestrial impacts, (iii) entraining and accelerating meteorites off of the surface of Mars, and (iv) providing the material to form the moon in a giant collision involving Earth.

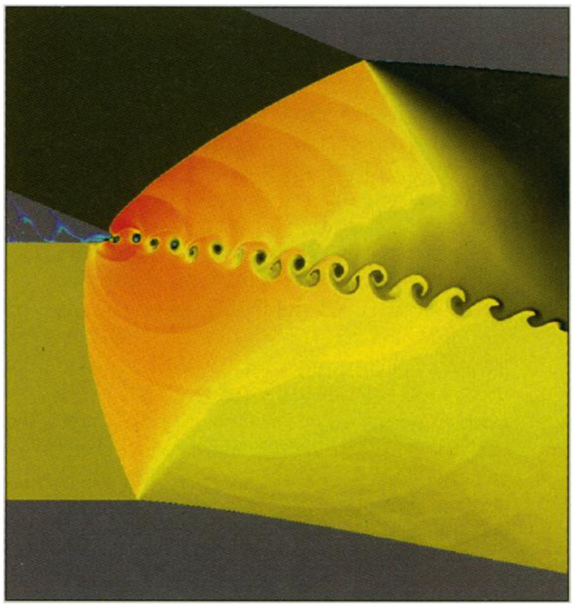

Fig. 2. A copper plate slams vertically into an inclined tin plate at 1.9 km s^{-1}, as seen in cross section 4 μs after impact. Color-coded according to density, the highest shock pressures (in red) occur near the convergence point. The convergence point moves to the left, and the velocities of shocked Cu and Sn are discontinuous across their interface (to the right), leading to Kelvin-Helmholtz instabilities and cavitation. An unsteady Sn-Cu jet (thin blue line) squirts off to the left at 8.4 km s^{-1}. [Courtesy of G. Miller]

Long the darling of the ordinance community, jetting has been called upon to do many wonderful things, but the applications above all involve rather uncertain extrapolations of the only complete and experimentally verified theory available, that of oblique collisions of thin plates of identical composition (*11*). Presentation of a comprehensive theory for the collision of dissimilar materials, along with experiments and detailed numerical hydrocode simulations (reported by G. H. Miller, University of Chicago) is therefore something of a breakthrough (Fig. 2). Depending on the geometry and the thermodynamic properties, the impactor or target, or both or neither, may contribute to the jet. A key inference is that the so-called stagnation point need not lie on the impactor-target interface. Further work and planetary applications should prove illuminating.

But what of planetary applications? The most extreme situation is when an impact blows a planetary body apart, which is an ongoing process in the asteroid belt. The impact energy necessary to accomplish this feat has for years been uncertain, as it was uncertain how to scale up the results of laboratory experiments. Great improvement in hydrocode modeling of rock fracture and breakup (*12*) and a comprehensive scaling theory based on dimensionless analysis (*13*) have completely changed this picture. Recent experiments on the breakup of rock targets, with both target and projectile size varied, demonstrate unambiguously a decrease in target strength with increasing event size, and the rate of decrease matches theoretical expectation (K. R. Housen, Boeing Corporation). Code simulations of oblique collisions among asteroids also quantified the transfer of angular momentum in larger scale collisions in the gravity regime (as opposed to the strength regime, which can be measured in the laboratory) (S. G. Love, California Institute of Technology). Angular-momentum transfer was found to be quite inefficient (compared with laboratory-scale experiments) because so much is carried away in forward-moving ejecta. The ultimate control of the spin evolution of the asteroids, as an ensemble, turns out to be their bulk densities.

It also turns out that the density, or more specifically, the porosity, of desert sand accounts for some remarkable aspects of the Wabar craters, which were indeed found and systematically surveyed by Shoemaker and company. Modest in size (the largest being ≈120 m across), the craters turn out, despite earlier reports, to have not formed in bedrock. Rather, the floors and rims are lined with chunks of black and white impact glass and hunks of shock-compressed sand metamorphosed to firm rock. These impacts were preserved in the sands of time entirely because this "instant rock" resisted erosion. Similar shock-welding no doubt occurs in the surface regolith and soil layers of the moon and other planets and satellites. Finally, preliminary thermoluminescence dating of sand buried beneath the crater rim ejecta gives a formation age for the craters, reducing a previous value of ~6500 years before present by an order of magnitude. So rather than forming in prehistory, the rain of Wabar iron could have been viewed by descendants of the Prophet. This is the real lesson of impact studies, that the extreme is neither unusual nor infrequent.

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SONOLUMINESCENCE

Shocking Revelations

Lawrence A. Crum and Thomas J. Matula

In single-bubble sonoluminescence (SBSL), a small gas bubble that has been acoustically levitated in a liquid and driven into large amplitude volume oscillations by the sound field, radiates visible light each and every acoustic cycle (*1*). These emissions are extremely short in duration (<50 ps), and the spectral content of the light suggests that the temperature of the gas that gives rise to these emissions may be much hotter than the surface of the sun (~7000°C), may even be as high as a million degrees, and could potentially lead to thermonuclear fusion. On page 1398 of this issue, Moss *et al.* (*2*) present the results of their application of the tools of fusion research—large computer simulations of inertially confined plasmas—to uncover some of the physics of sonoluminescence.

Previously, Hiller *et al.* (*3*) reported that small amounts of noble-gas doping could greatly influence the light output of SBSL, and an accompanying Perspective (*4*) described how much was still unknown about this intriguing phenomenon. Since that time, there have been several additional articles published offering more experimental data and theories about the mechanism of light emission.

Eberlein (*5*) extended the original suggestion of Schwinger (*6*) that SBSL was a modified version of the dynamic Casimir effect and proposed that it was the first macroscopic demonstration of quantum vacuum radiation. In this scenario, the rapidly decelerating dielectric interface interacts with the quantum vacuum field, and photons are emitted. This theory has been challenged by a number of investigators (*7*) but was considered one of the top 20 physics stories of 1996. Bernstein and Zakin (*8*) have proposed that the origin of sonoluminescence arises from the emissions of electrons confined in small voids within the dense fluid during the final stages of bubble collapse. Lepoint *et al.* (*9*) have explained SBSL on the basis of an electrical discharge theory in which numerous small, charged liquid jets penetrate the interior of the bubble during bubble collapse. The tips of these charged jets produce a strong enough field that electrons are emitted and produce light through collisions (bremsstrahlung). Prosperetti (*10*) suggests that this light emission occurs not by electrical discharge, but when the high-speed jet strikes the opposing wall of the bubble, light is produced by a form of fractoluminescence.

The most popular theory at the moment appears to be the one originally proposed by Jarman (*11*) in the 1960s, in which the rapidly moving bubble interface launches an imploding shock wave into the gas contained in the interior (see figure). This imploding–shock-wave model was examined by a number of investigators (*12*), who used various formulations for the bubble and shock-wave dynamics and the equation of state for the gas. Predictions of temperatures in excess of several million degrees were made. Of course, the imploding shock theory assumes that the collapsing bubble remains symmetrical long enough to launch a shock wave, a feature challenged by some researchers (*10*, *13*). There are a number of other theories besides these, and they all purport to explain at least some of the existing experimental observations.

The experimentalists have also made a number of amazing discoveries. For example, Young *et al.* (*14*) exposed a sonoluminescing bubble to a high magnetic field and found that they could double the light intensity; in addition, they were able to increase the acoustic pressure required for light emission to a factor of two higher than that required at zero magnetic field. In an experiment in which SBSL was compared with multiple-bubble sonoluminescence (MBSL) (in which a field of bubbles created by cavitation, rather than a single bubble, produces light), Matula *et al.* (*15*) demonstrated that the spectrum of MBSL contained emission bands that were characteristic of the liquid, but these bands were completely absent for

The authors are from the Applied Physics Laboratory, University of Washington, Seattle, WA 98105, USA. E-mail: lac@anchor.apl.washington.edu and matula@crosby.apl.washington.edu