Impact processes

A major conclusion resulting from U.S. and Soviet imaging and sampling missions to the Moon is that all the soils and many near-surface rocks are impact ejecta, and that even pristine rock surfaces, when examined under all resolvable scales, are covered with impact craters. New results reported, pertaining to cratering on the Moon and the other terrestrial planets, range from data on the dynamic strength of a rock to energy partitioning and crater-stability calculations. New ideas on the role of volatiles in crater formation and criteria for recognition of impact melts were presented. New constraints on the size and flow rate of impacting objects in the zones of the terrestrial planets over the last $3 \times 10^6$ years were given.

Fundamental processes, John D. O'Keefe and Thomas J. Ahrens (Cal Tech) presented calculations prescribing the partitioning of energy upon impact of projectiles with a half-space of lunar gabbroic anorthosite over a range of speeds from 3 to 45 km per second. They find that, depending on velocity, some 15 to 60% of the impactor energy results in direct shock heating of the planetary surface material, which largely resides in ejecta, whereas the portion of the kinetic energy in the primary ejecta is nearly constant, <10% of the meteoroid energy. Discontinuously, their results demonstrate that at low speeds (less than 15 km per second) some 50% of the impactor energy can reside in plastic work or rock comminution, depending on what is assumed for the presently poorly understood dynamic yielding processes that occur in rocks. The important role of volatiles such as H$_2$O and CO$_2$, both in controlling the quantity of impact melt and also the subsequent motion of impact ejecta was emphasized in papers delivered by Charles H. Simonds (Lunar Science Institute), W.C. Phinney & J.S. Warner (Johnson Space Center), and Susan W. Kieffer (UCLA). Simonds & others reported on the relative abundance of shock-induced melt in the ejecta deposits of 32 terrestrial impact craters and pointed out the strong correlation of target lithology with mass fraction of melt in the ejecta. Sedimentary terranes, with pore-water storage potential yield virtually no impact melt sheets (e.g., Barringer, Flynn Creek), whereas targets consisting of igneous or metamorphic rocks produce copious melts (such as Manicouagan). The Ries crater represents an intermediate category. Kieffer pointed out that the shock data indicated that the water, in water-bearing soils and rocks, will flash to steam upon unloading from above about 10$^6$ kilobars. She notes evidence for degassing of H$_2$O or CO$_2$ in the survive ejecta unit of the Ries crater. Such gases could result in extensive ejecta fluidization for impacts on the volatile-rich surfaces of the Earth and Mars. E.C.T. Chao (Science, v. 194, p. 615, 1976) has suggested a non-ballistic high-pressure roll-and-glide process for emplacing some of the ejecta units. K. Horn (ISC) & others reported results of core drilling within the Ries Bunte brecchia ejecta unit more than a crater diameter from the rim. They find a high proportion of unshocked clasts of the underlying sedimentary rocks and conclude, contrary to Chao, that secondary cratering accounts for the turbulent mixing process.

H. Fechtig & others (Heidelberg) reported new laboratory data on the ratio of minor- to major-crater diameter, versus impact angle of incidence. i, for 10$^{-6}$-10$^{-7}$ g/cm per second, impactors striking fused quartz which fits the relation $C_i = 0.146 + 0.000495 \times 0.000005277$, where $i$ is in degrees. They provide examples of such impacts produced by about 3 g/cm$^2$ objects on several lunar rocks. The results for micrometeoroids contrast with the conclusion of D. Gault (The Moon, v. 6, p. 32, 1973) who demonstrated that for centimeter-size craters, off-axis oblique impacts of as much as 20$^\circ$ affect crater circularity only slightly.

Particle-speed velocity field after 47 microsecond, resulting from the impact of a 10 cm-diameter iron meteorite on anorthosite half-space (at 15 km a second). VapORIZED melt from the melt zone is expanding and filling transient cavity. (Calculations by John D. O'Keefe and Thomas J. Ahrens.)
Shock metamorphism. New results described by R. Schaal and F. Hörz (15C) described shock metamorphism of a lunar basalt (75015) over the shock-pressure range of 90 to 1,000 kilobars. They quantified the range over which conversion of plagioclase to maskelynite occurs as more than 300 kilobars, and described conversion of the plagioclase into frothy glass over the range 500-1,000 kilobars. Features similar to those produced in the laboratory experiments are described by them in both immediately and heavily shocked samples from the Apollo 17 site. R. Jeanloz (Cal Tech) described a new index for shock metamorphism in plagioclase-bearing rocks, based on the volatility of Na in that mineral under an electron microprobe beam. Analyses of plagioclase shocked in the laboratory and in a suite of naturally shocked chondrites were shown to correlate with previous qualitative petrographic descriptions. Jeanloz & others also reported the discovery, via transmission electron microscopy, of amorphous olivine in a peridot shock-loaded in the laboratory to 560 kilobars and rapidly quenched. Measurements of the stresses (less than 0.5 kilobars) required to close shock-induced cracks in garnites in both

**King crater** (diameter = 71 km) exhibits deposits of impact melt, both on the floor and on the topographically low northern rim. The melt occurs as ponds, flows, and veneer draped over pre-existing topography. The large exterior pond (middle right) is adjacent to the lowest segment of the rim crest and opposite that portion of the crater wall where maximum slump ing has occurred.

This map of the King Crater region illustrates the relationship of King Crater to pre-existing topographic features.
the laboratory and by an underground explosion were found by M. Gene Simmons & others (W.L.T.) to be significantly lower and narrower than the range of stresses required to produce complete crack closure in several lunar samples (typically greater than 2 kilobars). They concluded that these differences arise from the unconfined stress environment in which multiple impacts occur on the lunar regolith.

Crater evolution. A theoretical analysis of crater morphology and possible failure modes was presented by H. Jay Melosh (Cal Tech). He defines a non-dimensional parameter k = p / H_c for describing the onset of crater slope terrace and then complete collapse in an attempt to explain the decrease in the slope of the depth, H, to diameter ratio observed for lunar and Mercian craters (e.g., Gault & others in Journal of geophysical research, v. 80, p. 2,341, 1976). From the almost constant depth (3-5 km) observed for large craters (diameter more than 15 km) and low angles of crater-wall repose, a surprisingly low strength of 20 to 25 bars is inferred. For k less than about 5.5, craters are stable; for k equal to or about 5.5 to 10, slumps and terrace failures are predicted, whereas for k greater than 10, crater failure (isostatic rebound) is predicted. Comparison of the frequency of crater-failure modes on the Moon and Mercury, by M.J. Cintala & others (Brown University), demonstrates that for a given diameter, collapse and floor-uplift features occur more frequently on Mercury than on the Moon—in agreement with this first-order theory. However, the Brown group point out that these frequencies of collapse features depend on geophysical prov. Within this framework the Mar. tian craters are highly dissipative, implying the importance of other processes or variable rock properties. J. Dvorak (Cal Tech) and R. Phillips (Jet Propulsion Laboratory) have studied these pronounced and highly localized gravity lows observed by line-of-sight tracking of low-orbiting spacecraft above young, large craters in a range of 58-132 km diameter (which all display flat floors, central peaks and terraces). Although several subsurface-density models are preferred to explain these about 10% of normal, the inferred mass deficiencies can arise from in-situ brecciation (and hence a lower density beneath the craters as well as, or by fall-back ejecta lenses. A zone of fall-back ejecta, supported by a deep zone of low-velocity rock, presumably cracked rock, has been delineated in the somewhat analogous uplifted central block of the Ries crater by J. Pohl (Proceedings of the Conference on Planetary Cratering, 1977). Cross-sections of craters and craters, high-explosive Prairie Flat crater displayed by D. Stoffler (Münster), D. Roddy (U.S. Geological Survey), and W. Ullrich (A.F.W.L.) demonstrate considerable central collapse; however, the mechanisms inducing these upward motions may well be different. Impact melt pools, originally thought to be volcanic in origin, are inferred to be present by R.B. Hawke & James W. Head (Brown) in several lunar craters having diameters greater than about 10 to 15 km. These melt pools appear to be preferentially produced in crater-wall terraces, rims, and immediately exterior to craters in the direction of lower pre-impact elevation and, possibly, domed range of oblique impacts.

Cratering ages. Papers by A. Woronow (Tucson) and D.T. Queller & others (South Carolina) discussed the lack of a theoretical crater saturation in the lunar highlands and a first-order attempt to study the roughness of crater rims via Fouier power spectra. The latter technique may prove useful in mapping the ex. of erosional processes on the heavily cratered planets. Relatively young surfaces are reported by Rich & A. Young (SUNY, Geneseo) on the basis of low crater areal densities on Mare Procellarum (about 2.4 and about 1.2 10^2 km^2) and (1.8 ± 0.3) × 10^2 km^2) on Mare Serenitatis. Contrary to previous conclusions reached by L.A. Soderblom & J.A. Boyce (NASA SP315, 1972), C. Neu- kum (Munich) inferred a wide series of ages for the light plains units on the Moon. By applying criteria stemming from the angular relations between the directions of the locus of center lines of craters and the orientation of the axis produced by intersecting vectors developed in laboratory experiments, V.C. Ober- beck and H. Aggerwul (NASA, Ames) have been eliminating secondary craters from crater populations on select. ed areas on the Moon and Mars. They provide striking evidence for the 1 common distributions of objects sticking the Moon, Mercury, Earth, Mars, and similar surface processes taking place on all 3 planets, for craters less than 50 km in diameter, as the small crat. ers appear to be distinctly depe. By taking into account the time in mean impact velocity in going from the Earth's zone to that of Mars, Neu- kum and Wise (Science, v. 194, p. 1386, 1976) have also shown that the cumulative number of craters versus cumulative size distribution for Mars and the Moon are quite similar. Buzzard (LSI) & others, and others & others (Cal Tech), pointed out how variations in regolith thick- ness and the dynamic strength prop. erties of the underlying bedrock can affect crater size versus frequency distributions.

The meteoroid flux varies time, M. Mangrall & others (Benn & R.J. Droz & others (St Louis) have re- fine the dating of the Shorty crater event (Apollo 17) at 17 ± 10^2 years, using the content of galactic cosmic ray-induced rare-gas isotopes versus depth in rocks uncovered by that event and later rolled over. Droz & others also provided refined values (10^2 ± 10^2 years) for the presumed Tycho ejecta ray which crossed the Apollo 17 site. R. Anderson & others (St Louis) on the basis of crater popu. lations on (the smooth ejecta blanket of Tycho and the 'absolute age' determination discussed above; (b) on the smooth crater interior plains of Copernicus, variously dated at 760 to 900 ± 10^2 years; and (c) the youngest radiometric of the Apollo 12 basalt, 3.3 ± 10^2 years, conclude no statistical basis exists for a change in meteoroid flux rate on the Moon for the last 3.3 × 10^2 years. B. König & others (Heidelberg) generally agree with the above results and point out that if the data from the Canadian shield are included, a cratering rate half- life of 300-1000 ± 10^2 years for the last 800 ± 10^2 years is inferred on the Moon. Dates for Arcturus (130- 180 ± 10^2 years) and Kepler (625- 950 ± 10^2 years) craters were also given by this group.

Unresolved problems. Major prob. lems that are readily identified in (a) the degree to which the larger craters on the terrestrial planets form deep transient cavities (prior to slip) and floor collapse and hence bring to the surface, by ejecta, samples of the planetary interior; (b) the degree to which crater size versus frequency data may be relied upon to give surface age, given the incom. pletely known quantitative effects of regolith thicknesses and dynamic rock strength at large scales; and (c) the degree to which shock versus thermal heating in terrestrial objects has contributed to their thermal evolu. tion during early accretion and their effect on later endogenic differentia. Thomas J. Ahrens Seismological Laboratory California Institute of Technology Pasadena, 91125