THE MANSON IMPACT CRATER: ESTIMATION OF THE ENERGY OF FORMATION, POSSIBLE SIZE OF THE IMPACTING ASTEROID OR COMET, AND EJECTA VOLUME AND MASS;

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A research program on the Manson impact structure has substantially improved our knowledge of the detailed features of this eroded crater [1]. As part of our structural studies, we have derived a value of 21 km for the diameter of the final transient cavity formed during crater excavation. With this information, we can estimate the energy of formation of the Manson crater and the possible size of the impacting asteroid or comet. In addition, we have estimated the near- and far-field ejecta volumes and masses.

High-speed impact produces a transient cavity that expands rapidly outward from the penetration path of the projectile. After the transient cavity has reached its maximum size, its uplifted rim begins to collapse inward, and the crater floor starts to rebound. In large craters, the rim collapses to form a structurally complex set of down-dropped blocks (referred to as terrace terrane in [1]). These blocks normally move downward and inward to produce a final collapsed crater substantially larger than the transient cavity. The contact between the down-dropped block nearest the crater center and the chaotic crater breccia on the crater floor marks the approximate final position of the wall of the transient cavity. The wall is transported slightly inward during collapse.

Our estimate of the present position of the transient cavity wall at Manson is based on interpretation of a seismic reflection profile provided by Amoco. This interpretation is supported by new drill core data acquired along this east-west radial. Drill holes in adjacent blocks in the terrace terrane penetrated down-dropped Upper Cretaceous strata and crater ejecta stacked in inverted stratigraphic sequence. The distance from the west edge of the westernmost downdropped block that is recognizable along the seismic profile is about 10.5 km ± 1 km east of the center of the crater. The center refers to the 35-km-diameter crater formed by collapse; the position of the lip of the collapsed crater has been established by study of cuttings from numerous water wells supplemented by two seismic reflection profiles.

Analysis of fault displacements recognized in the Amoco seismic reflection profile suggests that inward migration of the transient cavity wall during collapse was negligible. In estimating the energy of formation of the crater, we adopt 21 km as the maximum diameter of the transient cavity. This value implies enlargement of the crater during collapse by a factor of ~1.7, substantially larger than the collapse factor of 1.3 adopted as an average value by [2] but smaller than the factor suggested by formulas given in [3].

The energy of formation of the Manson crater was calculated from energy scaling by using two different approaches. In the first approach, we utilized a numerical computer simulation of the vertical impact of a 10-km-diameter asteroid into continental crust [4]. The kinetic energy of the projectile (density = 2.5 gm cm^{-3}, velocity = 20 km sec^{-1}) in this calculation was 6.2x10^{7} Mt, and the resulting transient cavity was estimated to be ~90 km (Table 1). To obtain the energy of formation of the much smaller Manson crater, the following energy scaling relation was used,

$$\frac{E_M}{E_A} = \left[\frac{D_{Mtc}}{D_{Atc}}\right]^{3.4} , \qquad (1)$$

where E_M = energy of formation of the Manson crater, E_A = kinetic energy of the 10-km asteroid in the numerical simulation, D_{Mtc} = diameter of the Manson transient cavity, and D_{Atc} = diameter of the transient cavity resulting from the 10-km asteroid impact. The energy estimated for the special case of vertical impact at Manson is 4.4x10^{5} Mt. In the general case, the impact will not be vertical, and a correction should be made for an elevation angle of impact less than 90°. This correction, given our present understanding of impact mechanics, is uncertain; moreover, the actual impact angle is unknown. For small-scale laboratory experiments, Gault [5] found the following empirical relationship,

$$D_i = D(\sin i)^{2/3}, \qquad (2)$$

where D_i is the diameter of a crater formed by impact at elevation angle i, and D is the diameter of a crater formed by a projectile of the same kinetic energy impacting at vertical incidence. Gault later suggested that the exponent in equation (2) should be reduced to 1/3 for large craters [6], but no formal treatment has been given for this relationship. As an upper bound for the most likely energy for oblique impact at Manson, we adopt equation (2) and i = 45°, the most probable impact angle for an isotropic flux of impactors. The energy estimated for oblique impact is 10x10^{5} Mt (Table 1), about twice as high as for vertical impact.

In the second energy scaling approach, we used the formula

$$E=\left[\frac{D_{Mtc}}{K}\right]^{3.4}\frac{\rho_t}{\rho_a}, \tag{3}$$

as modified from [2] where E = energy of crater formation, K = 0.56 km (Mt)$^{-1/3.4}$, ρ_a = 1.8 gm cm^{-3}, ρ_t = 2.4 gm cm^{-3}. The constant K in equation (3) is based on the 78-m diameter Jangle U nuclear crater [2]; it yields the same estimate of energy of formation for Meteor Crater, Arizona (1.2 km in diameter) as obtained by numerical computer simulations for vertical impact (i.e., ~15Mt) [7]. Solution of equation (3) for Manson gives an energy of 2.9x10^{5} Mt for vertical impact (Table 1), about 35% less than that obtained from equation (1) in the first approach. This difference is indicative of the likely errors of the estimates. Correcting for oblique impact, we find a maximum likely energy of 6.4x10^{5} Mt using equation (3) in the second approach.

The size of an asteroid or comet that could have formed Manson can be estimated from the formula for kinetic energy, with various assumptions about densities and velocities of the impacting body (Table 1). For the asteroid we used a density of 2.5 gm cm^{-3} and a velocity of 17.8 km sec^{-1}; for the comet we used a density of 1.0 gm cm^{-3} and a velocity of 57.7 km sec^{-1}. The velocities are the respective rms impact velocities weighted by probability of collision for Earth-crossing asteroids and for long-period comets [8].

Also listed in Table 1 are estimates of the masses and volumes of the near-field and far-field ejecta from Manson. These estimates have been derived by scaling of results from the numerical simulation of the 10-km-diameter asteroid impact. Materials ejected above the tropopause are taken to be "far-field" ejecta.

For purposes of comparison, we have also calculated energies, projectile sizes, and masses and volumes of ejecta for the 180-km diameter Chicxulub crater in Yucatan, by using the same scaling techniques applied here to the Manson crater (Table 1). A crater collapse factor similar to that observed at Manson was assumed for the Chicxulub crater. The far-field ejecta from Chicxulub are about 150 times greater in volume and mass than from Manson.

References: [1] Anderson, R.R. et al., 1993, this volume. [2] Shoemaker, E.M., 1983, Ann. Rev. Earth and Planet. Sci., 11, 461-494. [3] Melosh, H.J., 1989, Impact Cratering, A Geologic Process, Oxford Univ. Press, N.Y., 245 p. [4] Roddy, D.J. et al., 1987, Int. J. Impact Eng., 5, 525-541. [5] Gault, D.E., 1983, The Moon, 6, 32-44. [6] Gault, D.E., 1974, in Greeley R., and Schultz, P., eds., A Primer in Lunar Geology, Ames Research Center, NASA, Mountain View, Calif. [7] Roddy, D.J. et al., 1980, Lunar Planet. Sci. Conf. Proc., 11th, 2275-2308. [8] Shoemaker, E.M. et al., 1990, Geol. Soc. America Spec. Paper, 247, 155-170.

Table 1. Measured and estimated crater diameters and estimated energies of crater formation, asteroid and comet projectile diameters, and ejecta volumes and masses for the Manson and Chicxulub craters. Values (~) are calculated estimates. All values listed in the asteroid impact numerical simulation are calculated except for the asteroid diameter (initial parameter).

	D_{cc} km	D_{tc} km	E_v Mt (ergs)	E_o Mt (ergs)	Asteroid Diameter Vert. km	Asteroid Diameter Oblq. km	Comet Diameter Vert. km	Comet Diameter Oblq. km	Ejecta Near-fld km^3 (tons)	Ejecta Far-fld km^3 (tons)
Manson	35	21	~4.4x10^{5} ~(1.9x10^{28})	~10x10^{5} ~(4.2x10^{28})	~2.0	~2.7	~1.3	~1.7	~1040 ~(2.5x10^{12})	~166 ~(4.0x10^{11})
			~2.9x10^{5} ~(1.2x10^{28})	~6.4x10^{5} ~(2.7x10^{28})	~1.8	~2.4	~1.1	~1.5		
Chicxulub	180	~110	~12x10^{7} ~(5.2x10^{30})	~27x10^{7} ~(1.1x10^{31})	~13.6	~17.4	~8.4	~10.8	~150,000 ~(3.6x10^{14})	~24,000 ~(5.7x10^{13})
			~8.1x10^{7} ~(3.4x10^{30})	~18x10^{7} ~(7.6x10^{30})	~11.8	~15.4	~7.3	~9.6		
Asteroid Impact Numerical Simulation	~150	~90	~6.2x10^{7} ~(2.6x10^{30})	--	10.0	--	--	--	~85,000 ~(2.0x10^{14})	~13,500 ~(3.2x10^{13})

D_{cc} = diameter of collapsed crater
D_{tc} = diameter of transient cavity
E_v = energy of crater formation with vertical impact, given in megatons TNT equivalent (Mt) and (ergs)
E_o = energy of crater formation with 45° oblique impact, given in megatons TNT equivalent (Mt) and (ergs)