TSUNAMI GENERATION BY PELAGIC PLANETOID IMPACT

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The impact upon Earth of a 1.4 km diameter Apollo object with an approach speed of 24.6 km/sec and silicate density of 3.3 g/cm^3 (1) releases approximately 2.8 x 10^{28} ergs into the atmosphere and geoid, corresponding to about 10^6 megatons of TNT equivalent. This energy release may be compared to the largest earthquakes (10^{25} ergs) and the yearly earthquake budget(5 x 10^{25} ergs), which is about 0.3-percent of the total heat flow from Earth(1.8 x 10^{28} ergs)(2). Thus, an impact event of the hypothesized Apollo object is comparable to global energy processes.

Since 24.6 km/sec corresponds to a speed of about Mach Number 74, during its passage through the atmosphere an intense shock wave would be formed, wrapped tightly around the nose of the object and trail behind with an almost cylindrical geometry. The body would experience virtually no deceleration and relatively little ablation so that in contrast to the Tunguska event of 1908 when the entering object is thought to have disintegrated and effectively exploded in the atmosphere(3), most of the energy of incident motion should be imparted to the Earth's surface.

The frequency of fall for such Apollo bodies is (0) once per 10^6 years integrated over the surface of the Earth(1, 4). Since three-quarters of the Earth is covered by oceans, most of impact events should be pelagic. This incidence for kilometer-size bodies is about 100 times the renewal time for the major ocean basins due to seafloor spreading; it would seem, therefore, crater signatures recorded on the ocean floor might be seen and await indentification.

The impulse delivered by the impact to the ocean water should yield a transient, approximately hemi-spherical shaped crater(5), basically the same morphology as for the initial stages of a crater formed in rock(6, 7), since for both cases the post-shock overpressure in the materials greatly exceeds their strengths. A key difference between the two media, however, is the total lack of strength for craters formed in water; the energy to form a crater in water involves only gravity forces acting to resist the deformational process(8). Thus the energy, E to form a hemi-spherical crater in water is $E = \frac{1}{4} \pi \rho g r^4$, where ρ is the mass density, g the gravitational acceleration, and r is the crater radius; this expression for E is also the potential energy of the water displaced by the crater. For the hypothetical Apollo object, experimental results for impact craters formed in water (9) indicate that the crater could attain a maximum depth of about 13 km and a radius of about 15 km at a later time when the maximum displaced volume occurred; the corresponding energy would be about 2.3 x 10^{27} ergs or about 8-percent of the incident kinetic energy.

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The remaining 92-percent would be expended for ejection of water away from the transient cavity, shock-heating, and formation of waves. For the mean depth of the abysmal plane of 6 km(10), the projected maximum crater depth is more than twice as great and the ocean floor would be intersected so that the resultant crater would probably be a combination of a cavity in the ocean floor of unknown strength and the overlying water. However, the bulk of the crater volume would be that of the transient water cavity.

The total displaced volume of water is (0) 10^4 km^3, the potential energy of which would be available for the formation of a central peak or column of water upon collapse of the cavity. Based on experimental results(5) the potential energy in the column of water could be 3- to 4-percent of the incident kinetic energy, yielding a mean elevation at maximum height of the column of (0) 10 km above the geoid. It is the initial displacement of water during crater formation and subsequent collapse forming a large column of water that provide the forcing function for the eventual outward propagating wave fields.

The near wave field of waves has been discussed by Kranzer and Keller(11), and results for the hypothesized Apollo object and lesser events are presented in the table. In those cases for which the "crater" penetrates into the ocean floor, the coupling of water and ocean floor probably makes detailed analysis and the numerical results uncertain. The far field waves should be governed mostly by the ocean as a distance from the impact event and the total energy available for driving the waves. At large distances the wave field would convert to deep water waves with a characteristic group propagation velocity (0) $\sqrt{gh}$, where h is the ocean depth. For an initial wave amplitude equal to the ocean depth for the hypothesized Apollo event, which we assume would have the effect of evacuating the ocean to a depth of 6 km over a radial dimension of 15 km, the residual amplitude at a distance of 100 km from the impact is estimated to be (0) 1 km and the amplitude decreasing with distance R from the origin as 1/R. Thus, at 10^3 km distance the amplitude could still attain 50 meters. The deep water speed of wave propagation would be (0) 200 m/sec, and since the waves are dispersive they would spread apart and with increasing distance in accordance with standard behavior the long wave lengths outrunning the shorter wave lengths.

As the waves approach the shores of land masses the decrease in water depth will cause the wave amplitudes to grow as the propagation velocities reduce and promote the possibility of the waves breaking. The amplification factor for wave height may be as great as 10 for the run up on coastal shores(12). Thus one could expect that for the 10^3 km radial distance mentioned above, some coastal inundation by waves breaking from 500 meter heights, or even from 50 meter waves emanating from distances R = 10^4 km. Although such potentially catastrophic inundations of islands and continental margins may be rare occurrences, they represent potentially significant terrestrial events, both biologically and geologically, that have probably occurred in the past and could occur in the future. The search and recognition of such events, which may be stored in the geologic record, offers an interesting and rewarding challenge.

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TABLE

Diameter Apollo body (km)	(a) Incident kinetic energy (ergs)	(b) Pelagic frequency (10^6 yrs)	(c) Crater formed in water: Max. depth (km)	(c) Crater formed in water: Diam. at max. vol. (km)	(d) Wave run-up height at 1000 km. using (11) (m)
1.4	2.8×10^{28}	0.5	13	15	500
1.0	5.2×10^{27}	1	8.5	9.9	300
0.5	7.3×10^{26}	3	5.2	6.1	150
0.15	1.6×10^{25}	30	2.0	2.3	25
0.06	1.0×10^{24}	200	1.0	1.2	4

(a) Using rms value for velocity of Apollo objects given in (1) and silicate mass density of 3.3 g/cm^3.
(b) Using frequency given in (1) for diameters > 0.5 km and taking an exponential cumulative mass distribution with the exponent = 0.67.
(c) Estimated from experimental impact craters formed in water as reported in (9).
(d) Run-up amplification factor = 10 taken from (12).