PROCEEDINGS OF THE THIRTEENTH LUNAR AND PLANETARY SCIENCE CONFERENCE, PART 2
JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 88, SUPPLEMENT, PAGES A799-A806, FEBRUARY 15, 1983

IMPACT OF AN ASTEROID OR COMET IN THE OCEAN AND EXTINCTION OF TERRESTRIAL LIFE

Thomas J. Ahrens and John D. O'Keefe

Seismological Laboratory, California Institute of Technology Pasadena, California 91125

Abstract. Finite difference calculations describing the impact mechanics associated with a 10 to 30 km diameter silicate or water object impacting a 5 km deep ocean overlying a silicate solid planet at 30 km/sec demonstrate that from 12 to 15% of the bolide energy resides in the water. In the gravity field of the earth some 10 to 30 times the impactor mass of water is launched on trajectories which would take it to altitudes of 10 km or higher. This ejecta launched on trajectories which can achieve stratospheric heights is 10^1 to 10^2 projectile masses, similar to that resulting from impact of objects on an ocean-free silicate half-space (continent). As in the case of impact directly onto a continent, only the ejecta composed of impactor material, launched on trajectories which would carry it to stratospheric heights, matches the fraction (10^{-2} to 10^{-1}) of bolide (extraterrestrial) material found in the platinum-metal-rich Cretaceous-Tertiary and Eocene-Oligocene boundary layers. Oceanic impact results in impulsivelike giant tsunamis initially having amplitudes of ~4 km, representing the solitary waterwave stability limit in the deep ocean, and containing 10^{-2} to 10^{-1} of the energy of the impact. Using the constraint of no observed turbidites in marine sediments in the Cretaceous-Tertiary and Eocene-Oligocene boundary materials (calculated maximum water-sediment interface particle velocity ~ 10^0 m/sec) implies a maximum impactor energy of ~10^{28} to ~10^{29} erg corresponding to a maximum diameter for a silicate impactor of ~2 km (at 11 km/sec). Minimal global tsunami run-up heights on the continents corresponding to impacts of this energy are 300-400 m. We speculate that such waves would inundate all low altitude continental areas and strip and silt over virtually all vegetation. As a result, the terrestrial animal food chain would be seriously perturbed. This, in turn, could have caused extinction of large terrestrial animals including the archosaurs.

Introduction

One of the largest extraterrestrial objects (asteroid or comet) which appears to have interacted with the earth in the last 100 Ma was the 10^{16} to 10^{18} gram object which produced the worldwide enrichment in platinum-group elements in Cretaceous-Tertiary (K-T) (67 Ma) boundary material. The association of meteoritic elements at the K-T boundary has now been recognized in both marine and nonmarine rocks in Europe and North America, Africa, New Zealand, Russia, and in the Caribbean, as well as in abyssal marine sediments recovered from deep-sea piston cores from the North Pacific and South Atlantic [L. Alvarez et al., 1980; W. Alvarez et al., 1982; W. Alvarez, personal communication, 1982; Smit and Hertogen, 1980; Kyte et al., 1980; Orth et al., 1981; Ganapathy, 1980; Hsü, 1980; Nazarov et al., 1982]. Since the discovery at the K-T boundary layer, searches for other platinum-group element enriched layers have concentrated on sediment sections from deep-sea drill cores which may have recorded other large impact events associated with major extinctions. These searches have now uncovered two platinum-element-rich layers of presumably extraterrestrial origin. One is probably a local event recorded in 2.3 Ma old sediment from the Antarctic Ocean and contains both a platinum-metal-rich ejecta layer as well as what appears to be meteoritic ablation debris [Kyte et al., 1981]. A second, considerably larger event at 34.4 Ma associated with the North American tektite strewn field [Glass et al., 1973; Ganapathy, 1982; W. Alvarez et al., 1982] appears to correlate roughly with the Eocene-Oligocene boundary and the extinction of a number of species in both the marine and continental realm. A number of mechanisms have been proposed to account for the occurrence of massive extinctions of marine organisms and the collapse of the marine food chain at the K-T boundary. Proposed mechanisms causing extinction include a sharp and pronounced decrease of light due to a global ejecta layer of dust launched into the stratosphere [Alvarez et al., 1980; Toon et al., 1982], as well as global heating due to the enhancement of the terrestrial greenhouse effect [Emiliani et al., 1982]. The temporal sequence of these and the ejecta interaction heating mechanism are described by O'Keefe and Ahrens [1982a,b]. The possible effects of a large bolide on land plants and animals especially the archosaurs is still controversial, e.g., Clemens et al., 1981; Schopf, 1982.

No continental impact craters with precisely the expected age (67 Ma) and diameter ~10^2 km (and ~10^1 to 10^2 km for the 34 Ma event) have been identified. We assume that such craters may be undetected on land or on the seafloor or have existed on the seafloor and have been subducted. Some 51% of the seafloor which existed at 67 Ma has been subducted since that time [Parsons, 1982].

Previously we have described the impact of silicate, metallic, and water-bearing projectiles onto silicate planets [O'Keefe and Ahrens, 1977, 1981, 1982a,b,c]. In this present paper, we described the impact-induced flow-field resulting from the interaction of silicate (asteroidal) and water (cometary) projectiles into an ocean overlying a silicate planet. We examine the energy partitioned into the water of the ocean versus partitioning that occurs upon continental land impact. We also compare the fractions of meteoritic component in the initial high speed

Paper number 2B1627.
0148-0227/83/002B-1627$05.00

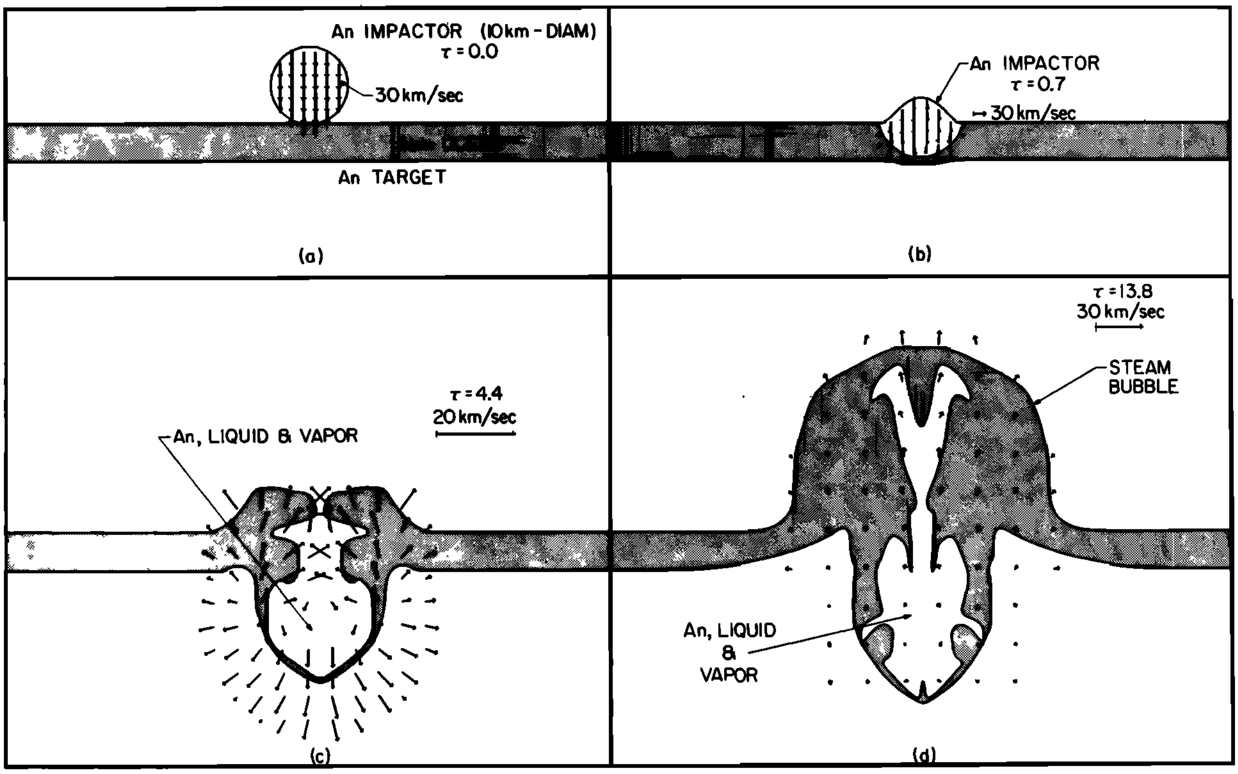

Fig. 1. Particle velocity flow-field for 10 km diameter, 30 km/sec silicate impactor impacting 5-km-deep ocean overlying a silicate half-space. Dimensionless time, τ, is real time (4.7 sec) multiplied by impact velocity, divided by projectile diameter.

ejecta launched to stratospheric altitudes for worldwide distribution. The implications of the generation and the propagation of giant tsunamis as a result of impact in the ocean is explored. Giant waves will produce, even at great distance, turbidity on the ocean floor. Since this phenomenon is notably absent in the geologic record at the K-T boundary, we use a calculated minimum bottom horizontal particle velocity to place constraints on the total energy of the K-T bolide. Finally we estimate the open ocean and run-up wave height versus energy and distance. The results of this calculation suggest that the K-T event induced a severe tidal run-up wave which may have stripped the vegetative basis of the terrestrial, especially archosaurian, food chain at low elevations.

Mechanics of Oceanic Impact

Previously, O'Keefe and Ahrens [1982b] calculated the flow-field induced from a silicate bolide impacting an infinitely deep ocean (and also an atmosphere). Using eulerian finite difference calculational methods, they found that for impact into water some 30 projectile diameters are required to stop a silicate projectile. Moreover, calculations carried out for impacts into fluids at velocities ranging from 15 to 72 km/sec demonstrate that the stopping distance is nearly independent of velocity. This is because the supersonic drag coefficient varies only slightly with velocity and the retarding force on a bolide is proportional to the square of the velocity. From the results of O'Keefe and Ahrens [1982b], we concluded that for a 5 km deep ocean, silicate projectiles with a diameter of less than ~300 m will be stopped by the ocean. Since the minimum diameters are on the order of 3 km and 10 km [Alvarez et al., 1980; Ganapathy, 1982] for the Eocene-Oligocene and K-T bolides, respectively, provided they were silicate objects, it is clear that these larger impactors will severely crater the ocean floor.

We have calculated the flow-fields and initial configuration of a large water wave resulting from the impact of a 1.5×10^{18} g silicate, water, and porous water bolides with densities 2.9, 1.0, and 0.1 g/cm^3 (shown in Figures 1, 2, and 3). The numerical methods employed are described in Dienes and Walsh [1970] and Hageman and Walsh [1970]. We used the equation of state descriptions of silicate (anorthite, An), and water given in O'Keefe and Ahrens [1982c] to calculate the flow-fields of Figures 1-3. As can be seen in these cases, the ocean is easily punctured by 30 km/sec bolides (having diameters of 10 and 31 km). Although the bolide penetration distance of ~3 to ~1 projectile diameters into a water-covered silicate half-space for the silicate and porous water impactors (depicted in Figures 1-3) is well described by the present calculations, the final crater diameter and volume are not, as transient craters continue to grow laterally after the maximum excavation depth has been achieved [Schultz et al., 1981]. Using the empirical similarity scaling parameter for impact of a 10 km diameter silicate 30 km/sec projectile into rock proposed by Schmidt and Holsapple [1982] a final crater volume, V, of 1.5×10^{19} cm^3 (ignoring the

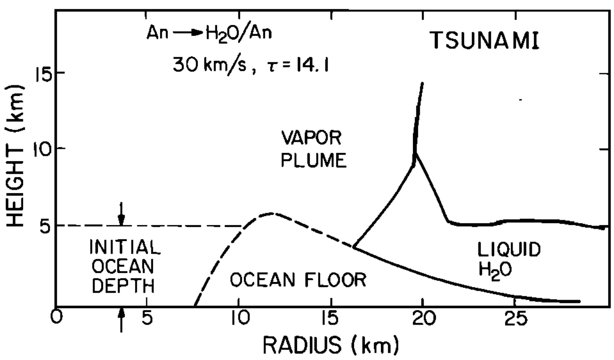

Fig. 2. Initial configuration of transient crater and water-wave for impact flow depicted in Figure 1.

ocean layer) is calculated from

$$V = [3.0\ (cm^3)\ m/\rho]\ U\ [d]^{-1/2}, \qquad (1)$$

where m(g), U(km/sec), and d(km) are projectile mass, velocity, and diameter and $\rho (g/cm^3)$ is the (silicate) target density. For a spherical bowl-shaped crater with a diameter to depth ratio of 5, a 60 km crater diameter is calculated. Assuming a water target and equation (39b) of Holsapple and Schmidt [1982], a somewhat larger crater in water is predicted, of the order of 250 km diameter.

We have carried out energy partitioning calculations at an impact velocity of 30 km/sec. O'Keefe and Ahrens [1977] have shown that the fraction of the impact energy partitioned into internal and kinetic energy of the target and projectile is relatively insensitive to impact velocity. As is seen in Figure 4, in the absence of an ocean, after the initial shock interaction, the internal energy and kinetic energy retained in the largely vaporized projectile is some 4 and 3%, respectively, of the initial kinetic energy whereas the target retains more than 80% of the impact energy. Some 12 and 14% of the impact energy, however, resides in the water ejecta, for 2.9 g/cm^3, silicate, and 0.1 g/cm^3, water impactors of equal mass (1.5 x 10^{18} g) impacting a 5 km thick ocean overlying a silicate half-space

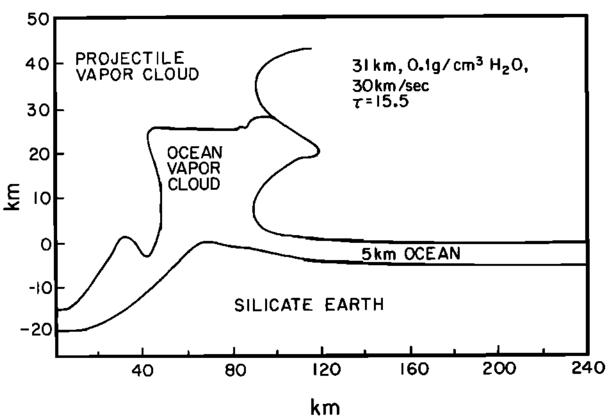

Figure 3. Initial configuration of transient crater and water-wave for impact flow induced by 31 km diameter, 0.1 g/cm^3 water bolide impacting a 5-km-deep ocean overlying silicate earth at 16 sec.

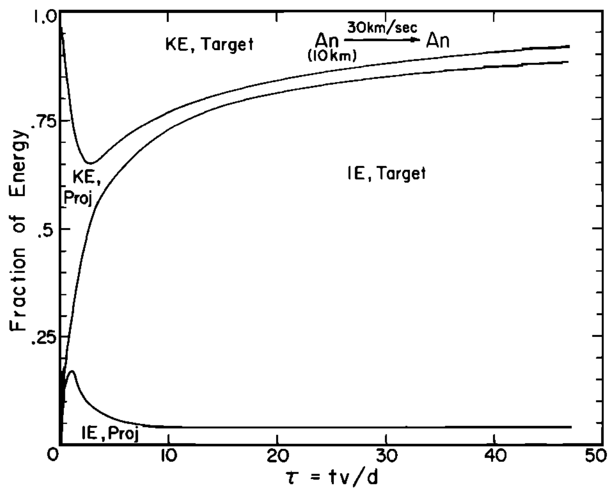

Fig. 4. Energy partitioning versus dimensionless time for impact of 10 km silicate (An) impactor upon a silicate half-space (no water layer).

(Figures 5 and 6). If the impact energy imparted to the water were distributed over the upper 10 m of the world's oceans it would give rise to ~5° C temperature increase. We doubt, however, that this distribution of water could be achieved and suggest in the actual case the shock heated water would largely be confined to within 10^3 km of the impact site.

Using the early time impact-induced flow fields, we have calculated the minimal amount of water that could be ejected to various altitudes (Figure 7). As can be seen, some 10 to 30 times the mass of the bolide of water ejecta (i.e., 1-5 x 10^{19} g) is launched into the stratosphere. As Jones and Kodis [1982] point out, this ejection process can be assisted by bouyancy forces. Although the amount of water launched into the stratosphere is only a small fraction of the 10^{24}

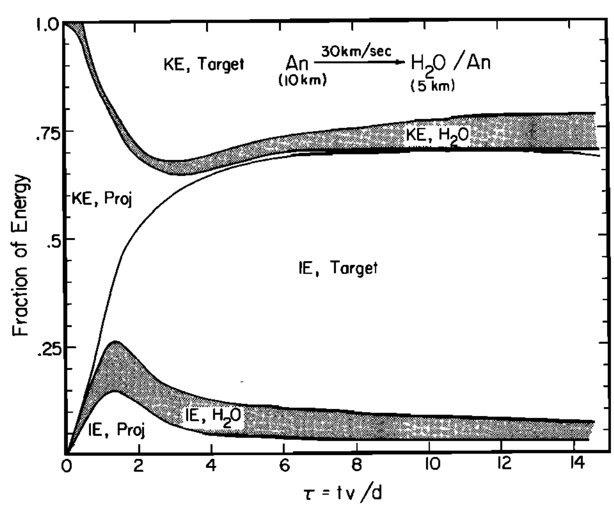

Fig. 5. Energy partitioning versus dimensionless time for impact of a 10 km diameter silicate sphere at 30 km/sec into a 5 km water ocean overlying a silicate half-space. Shaded region depicts energy delivered to water layer.

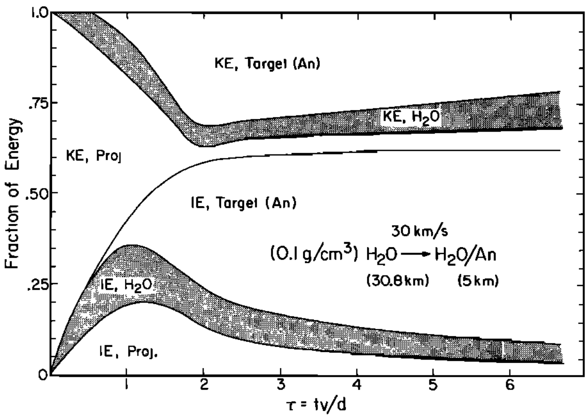

Fig. 6. Energy partitioning versus dimensionless time for impact of 30.8 km sphere of 0.1 g/cm^3 water at 30 km/sec into a 5 km water ocean overlying a silicate half-space. Shaded region depicts energy delivered to water layer.

g water budget of the earth, it is overwhelmingly greater than the 5 x 10^{11} to 10^{12} g of water, mostly in the form of H_2O_2 and HO_2 which is present in the normal stratosphere and mesosphere. The effect of injection of 10^7 to 10^9 times the normal upper atmospheric water budget is not clear. Although an enormous quantity of water must logically fall back to the earth, the question of whether the time constant for return to equilibrium is sufficiently long that the terrestrial greenhouse effect is strongly enhanced giving rise to a change of global climate, as speculated by Emiliani et al., [1982], needs further study.

Previously, O'Keefe and Ahrens [1982a,b] have proposed that the worldwide extent of the K-T boundary layer and its remarkably high, ~1 to 20%, content of extraterrestrial component (ETC) could be explained if it originated from the early (0.5 to 10 km/sec) high-speed ejecta. This is the only portion of ejecta with an ETC matching that is found in the K-T or Eocene-Oligocene boundary layers. This material is launched to stratospheric heights during the time period that the bolide imbeds itself ~3 projectile diameters into the silicate earth and is subsequently spread globally within the stratosphere. We demonstrated that the late, largely indigenous, ejecta is launched at lower velocity (< 0.5 km/sec) and inevitably is slowed down by atmospheric drag and is then deposited locally.

It was earlier suggested by Smit [1981] that impact of an asteroidal object onto an ocean might, because of the water ejecta, suppress the lofting of indigenous terrestrial solid ejecta, and explain the extraordinarily high values of ETC found in the K-T boundary layer material. Our calculations of the minimum total ejecta launched to various altitudes for the impact of a series of bolides into an ocean-covered silicate earth indicate ejecta representing some 20 to 10^2 times the bolide mass is launched into trajectories which could carry it to stratospheric heights (Figure 8). This quantity of high speed ejecta is comparable to that calculated by O'Keefe and Ahrens [1982a,b] for terrestrial impacts. Thus the total amount of ejecta (including water) which is launched into the stratosphere is comparable for oceanic and continental (terrestrial) impact.

The question is whether the relative amount of ETC is higher for oceanic versus terrestrial impact. In Figure 9, we plot the mass fraction of ETC versus minimum ejection height for a wide range of impact velocities and impactor densities. As already stated, it is only the early high speed ejecta, launched to trajectories which can loft material to the stratospheric heights for which the ETC values are comparable to those measured in the K-T boundary layer materials. This range varies from 21% in the Danish (fish clay) sections down to ~1 to 2% measured in the Appenine carbonate sections [Kyte et al., 1980]. In Figure 9, we compare the ETC observed in the silicate ejecta for the impact of a 10 km diameter, 30 km/sec silicate impactor onto a 5 km ocean overlying silicate half-space versus that for impact directly on the silicate. This figure demonstrates that the fraction of ETC, in the ejecta from an oceanic impact is similar but has a slightly lower value (50%) than that from a presumably continental impact. This is the opposite of what Smit [1981] has suggested. The reason for this is that upon impact onto silicate, and water overlying silicate, peak shock pressures in the projectile will be 9.2 and 5.0 Mbar, respectively. Therefore relatively more vaporized projectile and intensely shocked target material in a continental impact is launched to higher altitudes.

Impact-Induced Tsunamis

As is evident in Figures 1-3, a giant tsunami is expected to result from an impact of a large bolide in the deep ocean. It will contain kinetic and gravitational energy amounting to some 7 to 9% of the impact energy (Figures 5 and 6). Since tsunamigenic earthquakes partition from ~1 to 10% of their energy into water waves [Wiegel, 1970], comparable to the impact case, it follows from the surface wave magnitude (M_s) energy (E) relation [Kanamori, 1978],

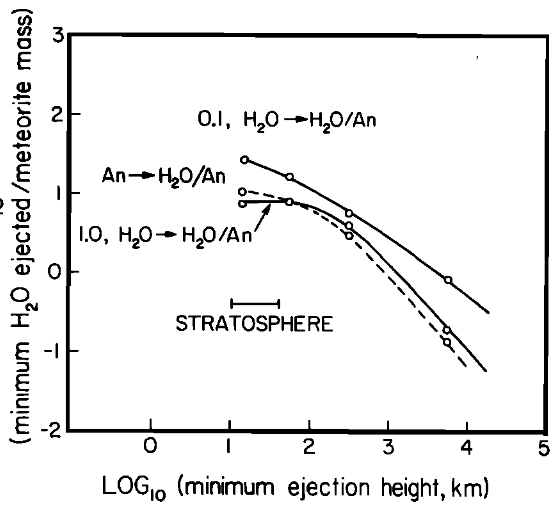

Fig. 7. $\log_{10}$ (minimum water ejected/meteorite mass) versus $\log_{10}$ (minimum ejecta height, km) for three impact conditions, silicate, water, and porous water (comet).

$$\log_{10} [E, \text{ergs}] = 1.5 M_s + 11.8, \qquad (2)$$

that for the impact energy (6.9×10^{30} erg) assumed in Figures 1-3, the equivalent value of M_s is 12.7. By comparison, the largest earthquakes have surface wave magnitudes of 9.5. This indicates that impact events of the magnitude of the K-T bolide impact are expected to lead to tsunamic effects possibly 10^3 times more intense than those of the largest earthquakes.

It has long been recognized [Heezen and Ewing, 1952] that even a moderate earthquake can trigger impressive submarine landslides and turbidite flows along the continental shelf. Thus the high intensity of tsunamis resulting from either a large impact on the continental shelf or deep ocean contrasts strikingly with quiescent water conditions which are presumed to have existed in the time of deposition of the K-T boundary layer both in the sections described by Smit [1981] in Denmark and Tunisia and those described by Alvarez et al., [1980] in Italy. Both sections contained turbidite deposits but not directly at the K-T boundary. Using the lack of evidence for a turbidite layer at the K-T boundary, we will attempt to constrain the maximum energy and hence the dimension of the K-T bolide. Using the Le Méhauté [1971] fit to empirical data from impulsive sources, the peak water wave amplitude can be inferred using the large explosion data set (up to 10^{22} ergs) from shallow water explosions given by

$$\log_{10} (H) = -0.704 \log_{10} (R) + 0.15 \log_{10} (E) - 5.061, \qquad (3)$$

where H is the initial wave height (cm), R is radius from the source (cm), and E is explosive energy (ergs). As Strelitz [1979] has pointed out, energy dissipation, via wave breaking, may occur in the deep ocean, hence (3) may overestimate the peak wave height. The wave observed propagating from explosions begins with the fastest propagating, longest period wave whose effective wavelength is given below (11). The initial largest amplitude peak propagates with only a slowly varying wave form, approximating a solitary wave. How efficiently explosives couple into shallow water waves relative to impactors is not known. It is likely, however, that from other comparisons of explosive and impact cratering [Oberbeck, 1977], the explosive data can provide an approximation to the impact case. To examine this issue further, we use (3) to calculate the tsunami height at a radius of 20 km and 90 km corresponding to the configurations presented in Figures 2 and 3. In the case of the silicate impactor (Figure 2), the value of H from (3) is 17 km compared to 5 km calculated by finite difference methods. In the case of the more efficient porous water impactor (Figure 3), equation 3 yields a 6 km wave amplitude, whereas we calculate a wave amplitude of 25 km via finite difference methods. These comparisons are both somewhat unrealistic since the finite size of the impactor is not taken into account, wave dissipative mechanism are probably poorly represented in finite difference methods, and the maximum stable height of impulsive solitary type waves is [Munk, 1949]

$$H \cong 0.8\ h, \qquad (4)$$

where h is the undisturbed water depth. Nevertheless, the impact-induced water waves appear to yield waves which have the same

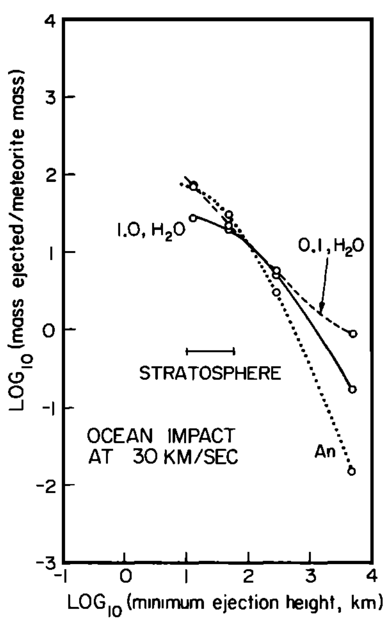

Fig. 8. Log_{10} (total mass ejected/mass of meteorite) versus $\log_{10}$ (minimum ejection height, km) for 30 km/sec impact of silicate (An), water ($1.0 g/cm^3$) and porous water ($0.1 g/cm^3$) impactors.

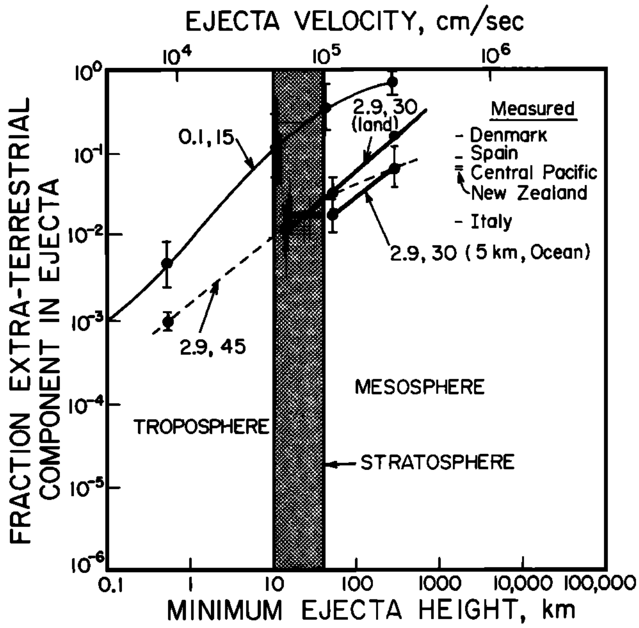

Fig. 9. Mass fraction extraterrestrial material, in ejecta versus minimum ejecta height, (km). Data for fraction ETC measured at 5 sites are comparable to composition of ejecta lofted to minimum altitudes of 10 km. Scale on upper edge is ejecta velocity (km/sec). Two figures for each curve are impactor density (g/cm^3) and impact velocity (km/sec).

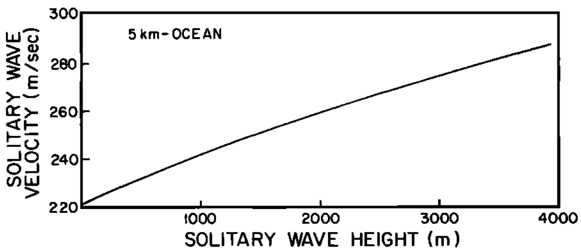

Fig. 10. Group velocity versus solitary wave height (5).

magnitude as Le Méhauté's empirical correlation.

In order to approximately calculate the values of peak horizontal velocity at the seafloor and relate these to criteria for generating sedimentary disturbances, we must first calculate the slight dependence of group velocity of an impulse wave on amplitude. This is given approximately as [Komar, 1976]

$$C = \sqrt{gh}\ [1 + 1/2\ (H/h) - 3/20\ (H/h)^3], \quad (5)$$

where g has the usual meaning. For a 5-km-deep ocean on the earth, this dependence of C on H is shown in Figure 10. The maximum horizontal particle velocity beneath an impulsive solitary wave at the base of the ocean below the velocity gradient range where Kelvin-Helmholtz instabilities occur is approximately given by

$$u \cong NC, \quad (6)$$

where N and M are approximately given as [Munk, 1949],

$$N = 0.64 \sin\ (0.4\Pi\ H/h) \text{ and} \quad (7a)$$

$$M = 0.97 \sin\ (0.4\Pi\ H/h). \quad (7b)$$

Combining (3), (5), (6), and (7a) yields values for the maximum horizontal particle velocity on the sea floor during passage of initial, solitary wave versus impact energy and radial distance from the impact site (Figure 11). Based on experiments, the threshold particle velocity, u_t, required to obtain erosion by wave-motion at the water-sediment interface is given for grain diameters of less than 0.5 mm and greater than 1 cm as [Komar, 1976]

$$u_t^2 = 0.21\ g\ D[(\rho_s - \rho)/\rho]\ (d_o/D)^{1/2} \text{ and} \quad (8)$$

$$u_t^2 = 0.46\Pi\ g\ D\ [(\rho_s - \rho)/\rho]\ (d_o/D)^{1/4}, \quad (9)$$

where D is grain diameter, ρ_s and ρ are grain and fluid density, respectively, and d_o is the bottom orbital diameter. Equation 8 is plotted as the nearly horizontal line in Figure 11. The near-bottom ocean water particle motion orbital diameter is given by

$$d_o \cong H/\sinh\ (2\Pi\ h/L_{eff}), \quad (10)$$

where stable flow is assumed and L_{eff} is the effective wave length of a solitary wave [Bagnold, 1947].

$$L_{eff} \cong 2\Pi C/M\sqrt{h/g}, \quad (11)$$

where M is given in (7b). Since u_t depends on d_o to the 1/4 and 1/8 power, respectively, in (8) and (9), its value depends only weakly on wavelength and hence, the dependence of critical particle velocity with range and energy shown for (8) in Figure 11 is not discernible.

Although we may have slightly overestimated the coupling of a 7 x 10^{30} erg impactor (corresponding to 10 km silicate asteroid, impacting at 30 km/sec), it appears that an impactor striking the deep ocean with this large an energy would cause erosion and we infer from Figure 11 that this would cause turbidity at the K-T boundary (which is not observed). In contrast, a 10^{28} to 10^{29} energy event would give rise to erosion only close to the impact region (10^2 to 10^4 km). Since the K-T boundary layer is not disturbed in any region so far detected, we conclude the energies in the range of 10^{28} to 10^{29} erg would be compatible with the oceanic impact of the K-T bolide. The 10^{29} erg impactor corresponding to 1.6 x 10^{17} grams at 11 km/sec is slightly smaller than the lower bound of impactor mass (3.4 x 10^{17} grams) inferred by Alvarez et al. [1980] from the Ir abundance at Gubbio. Thus the upper bound inferred here from the present analysis based on no turbidity at the K-T boundary corresponds to the lower bound obtained by Alvarez et al., on a completely different basis.

Tsunami Run-up and Terrestrial Extinction

According to the the sea level curve of Vail et al. [1977], sea level was 300 meters above the present level at the end of the Cretaceous, implying that much of what now corresponds to continental platforms, some 13% of the earth's surface, was covered by shallow marine seas. The distribution of terrestrial dinosaur fossils [Ostrom, 1980] in part, bears out the expected range of these largest of land animals whose habitat was at the edge of the shallow marine seas

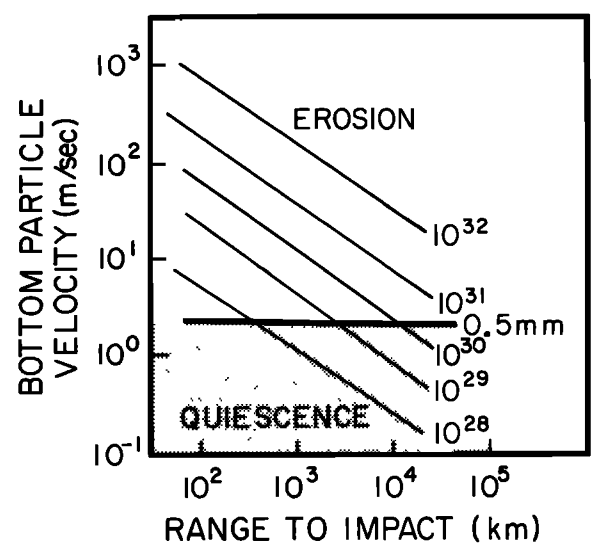

Fig. 11. Horizontal peak particle velocity at sea-floor, water-sediment interface versus range from impact for various energy impactors, is given in ergs. Also shown is critical particle velocity required to induce erosion for 0.5 mm diameter carbonate particles.

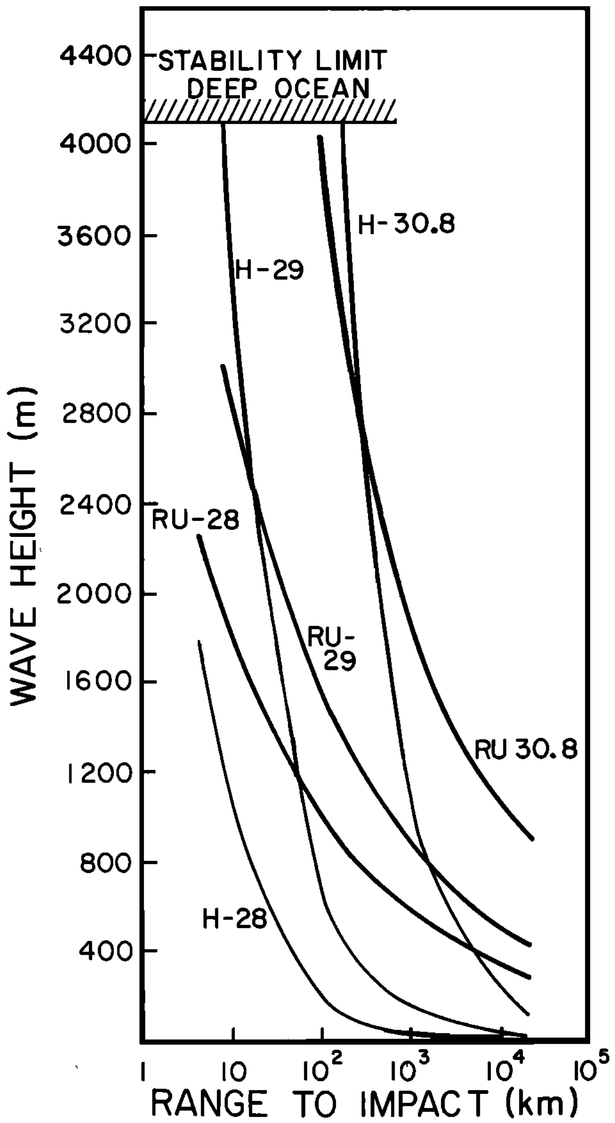

Fig. 12. Wave height (H) and run-up height (RU) versus radial range from impact site. Log_{10} energy of different impactors is indicated after H and RU.

[Schopf, 1982]. Whether tsunami run-up from an oceanic impact of an object with an energy in the 10^{28} to 10^{29} erg range and the accompanying stripping of vegetation could give rise to a sudden extinction is not easily evaluated. Tsunamic interaction of the shorelines even on a continental scale is not easily described. Existing experimental data for run-up from impulsive waves from chemical and nuclear explosions have been summarized by Jordaan [1972]. It is observed that run-up (RU), the elevation above sea level that the water reaches, depends only weakly on slope and may be described

$$RU = k\ (H/L_{eff})^{-1/3}, \qquad (12)$$

where the constant, k, can vary from 0.34 to 0.50. For (3) and (12), we calculate the free-field impulsive wave height and a minimum run-up height (RU) (Figure 12). Equation (12) is based on data corresponding to meter-sized run-ups, how valid it is for the 10^2 m run-ups discussed here is unclear. Run-ups of ~300 to 400 m are calculated for the lowest of energy impactors considered in the previous section. As pointed out by Alvarez et al., [1980], it is difficult to hypothesize an asteroidal object, smaller than 2 to 3 km in diameter and still obtain the observed global Pt-group metal abundances.

The stress on the terrestrial environment and hence possible extinctions arising from large tsunami run-ups on all the continents is difficult to scale from the present data on earthquake-induced tsunamis and resultant bores which are 10^{-2} to 10^{-3} times lower in amplitude. The present calculations, however, strongly suggest that a depositional unconformity should exist at what was the littoral zone of the continents at the K-T boundary, if the K-T bolide did in fact impact in the deep ocean.

Acknowledgments. We appreciate the helpful suggestions and discussions proffered by H. Kanamori, F. Raichlen, and D. Stevenson, and the suggestions for improving the paper made by R. Schmidt and R. McKinnon. We appreciate the assistance of M. Lainhart. This paper was supported under NASA Grant NSG 7129. It is contribution 3792 from the Division of Geological and Planetary Sciences, California Institute of Technology, Pasadena, California, 91125.

References

Alvarez, L. E., W. Alvarez, F. Asaro, and H. V. Michel, Extraterrestrial cause for the Cretaceous-Tertiary extinction, Science, 208, 1095-1108, 1980.

Alvarez, W., F. Asaro, H. V. Michel, and L. W. Alvarez, Iridium anomaly approximately synchronous with terminal Eocene extinction, Science, 216, 886-888, 1982.

Bagnold, R. A., Sand movement by waves: Some small-scale experiments with sand at very low density, J. Inst. Civ. Eng., 27, 447-469, 1947.

Clemens, W. A., J. D. Archibald, and L. J. Hickey, Out with a whimper not a bang, Paleobiology, 7, 293-298, 1981.

Dienes, J. K., and J. M. Walsh, Theory of impact: Some general principles of the method of eulerian codes, in High Velocity Impact Phenomena, pp. 45-104 edited by R. Kinslow, Academic, New York, 1970.

Emiliani, C., E. B. Kraus, and E. M. Shoemaker, Sudden death at the end of the Mesozoic, Earth Planet. Sci. Lett., 55, 317-324, 1982.

Ganapathy, R., A major meteorite impact on the earth 65 million years ago: Evidence from the Cretaceous-Tertiary boundary clay, Science, 209, 921-923, 1980.

Ganapathy, R., Evidence for a major meteorite impact on the earth 34 milion years ago: Implication for Eocene extinctions, Science, 216, 885-886, 1982.

Glass, B. P., R. N. Baker, D. Störzer, and G. A. Wagner, North American microtektites from the Caribbean Sea and their fission track age, Earth Planet. Sci. Lett., 19, 184-189, 1973.

Hageman, L. J., and J. M. Walsh, Help, a multimaterial eulerian program for compressible fluid an elastic-plastic flows in two space dimensions and time, Systems, Science, and Software Report, 3SR-350 1, 1970.

Heezen, B. C., and M. Ewing, Turbidity current and submarine slumps, and the 1929 Grand Banks earthquake, Am. J. Sci., 250, 849-873, 1952.

Holsapple, K. A., and R. M. Schmidt, On scaling of crater dimensions 2. Impact processes, J. Geophys. Res., 87, 1849-1870, 1982.

Hsü, K. J., Terrestrial catastrophe caused by cometary impact at the end of the Cretaceous, Nature, 285, 201-203, 1980.

Jones, E. M., and J. W. Kodis, Gradient acceleration as a mechanism for rapid worldwide dispersal of particulates following a large-body impact (abstract), in Lunar and Planetary Science XIII, pp. 367-368, Lunar and Planetary Institute, Houston, 1982.

Jordaan, J. M., Jr., Impulsive waves: model and prototype correlations, in Advances in Hydroscience, 8, edited by V. T. Chow, pp. 261-304, Academic, New York, 1972.

Kanamori, H., Quantification of great earthquakes, Tectonophysics, 49, 207-217, 1978.

Komar, P. D., Beach Processes and Sedimentation, 429 pp., Prentice Hall, New Jersey, 1976.

Kyte, F. T., Z. Zhou, and J. T. Wasson, Siderophile-enriched sediments from the Cretaceous-Tertiary boundary, Nature, 288, 651-656, 1980.

Kyte, F. T., Z. Zhou, and J. T. Wasson, High noble metal concentrations in a late Pliocene sediment, Nature, 92, 417-420, 1981.

Le Méhauté, B., Theory of explosion generated water waves, in Advances in Hydroscience, 7, edited by V. T. Chow, pp. 1-80, Academic, New York, 1971.

Munk, W. H., The solitary wave theory and its application to surf problems, N. Y. Acad. Sci. Ann., 51, 376-424, 1949.

Nazarov, C. M., L. D. Barsukova, G. M. Kolesov, D. P Naidin, and A. S. Alekseev, Extra-terrestrial event at the CT boundary: New geochemical and mineralogical data (abstract), in Lunar and Planetary Science XIII, pp. 580-581, Lunar and Planetary Institute, Houston, 1982.

Oberbeck, V. R., Application of high explosion cratering to planetary problems, in Impact and Explosion Cratering, edited by D. J. Roddy, R. O. Pepin, and R. B. Merrill, pp. 456-466, Pergamon, New York, 1977.

O'Keefe, J. D., and T. J. Ahrens, Impact induced energy partitioning melting and vaporization on terrestrial planets, Proc. Lunar Sci. Conf. 8th, 3357-3374, 1977.

O'Keefe, J. D., and T. J. Ahrens, Impact mechanics of the Cretaceous-Tertiary extinction bolide, Nature, in press, 1982a.

O'Keefe, J. D., and T. J. Ahrens, The interaction of the Cretaceous-Tertiary extinction bolide with the atmosphere, ocean and solid earth, in Geological Implications of Impacts of Large Asteroids and Comets on the Earth, Geol. Soc. Amer. Spec. Pap., 190, Boulder, Colorado, in press, 1982b.

O'Keefe, J. D., and T. J. Ahrens, Cometary and meteorite swarm impact on planetary surfaces, J. Geophys. Res., 87, 6668-6680, 1982c.

Orth, C. J., J. S. Gilmore, J. D. Knight, C. L. Pillmore, R. H. Tschudy, and J. E. Fassett, An iridium abundance anomaly at the palynological Cretaceous-Tertiary boundary in Northern New Mexico, Science, 214, 1341-1343, 1981.

Ostrom, J. H., The evidence for endothermy in dinosaurs, in A Cold Look at the Warm-Blooded Dinosaurs, edited by R. D. K. Thomas and E. C. Olsen, pp. 15-54, Westview, Boulder, Colorado, 1980.

Parsons, B., Causes and consequences of the relation between area and age of the ocean floor, J. Geophys. Res., 82, 289-302, 1982.

Schmidt, R. M. and K. A. Holsapple, Crater size for large-body impact: Gravity-scaling results, in Geological Implications of Impacts of Large Asteroids and Comets on the Earth, Geol. Soc. Amer. Spec. Pap., 190, Boulder, Colorado, in press, 1982.

Schopf, T. J. M., Extinction of the dinosaurs: A 1982 understanding, in Geological Implications of Impacts of Large Asteroids and Comets on the Earth, Geol. Soc. of Amer. Spec. Pap., 190, Boulder, Colorado, in press, 1982.

Schultz, P. H., D. L. Orphal, B. Miller, W. F. Borden, and S. A. Larson, Impact crater growth and ejecta characteristics: Results from computer simulations (abstract), in Lunar and Planetary Science XII, pp. 949-951, Lunar and Planetary Institute, Houston, 1981.

Smit, J., A catastrophic event at the Cretaceous-Tertiary boundary, Ph.D. thesis, Univ. of Amsterdam, Holland, 138 pp., 1981.

Smit, J., and J. Hertogen, An extraterrestrial event at the Cretaceous-Tertiary boundary, Nature, 285, 188-200, 1980.

Strelitz, R., Meteorite impact in the ocean, Proc. Lunar Planet. Sci. Conf. 10th, pp. 2799-2813, 1979.

Toon, O. B., J. B. Pollack, R. P. Turco, C. P. McKay, and M. Liu, Large body impacts: Evolution of the dust cloud and its effects on the atmosphere, in Geological Implications of Impacts of Large Asteroids and Comets on the Earth, Geol. Soc. Amer. Spec. Pap., 190, Boulder, Colorado, in press, 1982.

Vail, P. R., R. M. Mitchum, Jr., and S. Thomsen III, Seismic stratigraphy and global changes in sea level, Part 4: Global cycles of relative changes of sea level, in Seismic Stratigraphy-Applications to Hydrocarbon Exploration, edited by C. E. Payton, pp. 83-97, Amer. Assoc. of Petrol. Geol. Mem. 26, 1977.

Wiegel, R. L., Tsunamis, in Earthquake Engineering, pp. 253-306, edited by R. L. Wiegel, Prentice Hall, New Jersey, 1970.

(Received June 2, 1982;
revised October 4, 1982;
accepted October 20, 1982).