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

by

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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 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 projectile 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 projectile ejecta 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 impulsive-like giant tsunamis initially having amplitudes of ~4 km, representing the solitary waterwave stability limit in the deep ocean, and contain 10^{-2} to 10^{-1} of the energy of the impact. A maximum bolide energy of 10^{28} to 10^{29} erg, corresponding to a maximum water-sediment interface particle velocity (10^0 to 10^1 m/sec) satisfies the constraint of a lack of observed turbidites in marine sediments in the Cretaceous-Tertiary and Eocene-Oligocene boundary materials. 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 could in turn have caused extinction of large terrestrial animals including the archeosaurs.

Introduction

One of the largest extraterrestrial objects (asteroid or comet) which appears to have interacted with the earth in the last 100 Ma has been the 10^{16} to 10^{18} gram object which produced the worldwide platinum-group element-rich Cretaceous-Tertiary (K-T) (67 Ma) boundary material. The meteoritic association of elements at the K-T boundary has now been recognized in both marine and non-marine 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, private communication, 1982, Smit and Hartogen, 1980, Kyte et al. 1980, Orth et al. 1981, Ganapathy 1981, Hsü 1982, Nazarov et al. 1982). Since the discovery of the K-T boundary layer, extensive searches for other platinum-group element rich layers have concentrated on deep sea drill cores sediment sections 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 fragments (Kyte et al. 1981). A second, considerably larger event at 34.4 Ma associated with the North American tektite strewn field (Glass et al. 1979, Ganapathy 1982, W. Alvarez et al. 1982) appears to nearly coincide with the Eocene-Oligocene boundary and the extinction of a number of species both in the marine and continental realm. A number of mechanisms have been proposed to account for the now widely accepted 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 distribution in the stratosphere [Alvarez et al. 1980, Toon et al. 1982], as well as, global heating due to the enhancement of the terrestrial greenhouse [Emiliani et al. 1982]. The temporal sequence of these and the ejecta interaction heating mechanism are described by O'Keefe and Ahrens [1982b]. The possible effects of a large bolide on land plants and animals especially the archeosaurs is still controversial, e.g. Clemens et al. 1981, Schopf 1982.

No continental impact crater with precisely the expected age (67 Ma) and diameter $\sim 10^2$ to 10^3 km (and $\sim 10^1$ to 10^2 km for the 34 Ma event) have been identified. We assume that such craters may be undetected on land or have existed on the seafloor and have been subducted. Some 51% of the seafloor existing 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 a silicate (asteroidal) and water (cometary) projectiles onto an ocean overlying a silicate planet. We examine the energy partitioned into the water of the ocean versus partitioning that occurs upon terrestrial impact. We also compare the fractions of meteoritical component in the initial high speed 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 at the K-T boundary this phenomena is notably absent in the geologic record we use a calculated minimum bottom horizontal particle

velocity to place a bound on the total energy of the K-T bolide. Finally we examine the open ocean and run-up wave-height, versus, energy and distance. The results of this calculation suggests that the K-T event induced a severe tidal run-up wave which may have stripped the vegetative basis of the terrestrial, especially archeosaurian, food chain at low elevations.

Mechanics of Oceanic Impact

Previously O'Keefe and Ahrens [1982b] have calculated the flow field induced from a silicate bolide impacting an infinitely deep water ocean (and also an atmosphere). We found using the eulerian finite difference calculational methods 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 slowly 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 oceanic water layer [Ganapathy, 1982]. Since the minimum diameter silicate objects is on the order of 3 km and 10 km [Alvarez et al., 1980] for the Eocene-Oligocene and K-T bolides, respectively, 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 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 [1968]. We used the equation of state

descriptions of silicate (anorthite, An), and water [O'Keefe and Ahrens, 1982c]. As can be seen in these cases the ocean is easily punctured by these bolides (which have diameters of 10, 14 and 31 km, respectively) and will impact the earth at 30 km/sec. Although the penetration distance of bolides of ~3 to ~1 projectile diameter into a water covered silicate half-space for the silicate and porous water impactors (depicted in Figs. 1-3) is well described by the present calculations, the final crater diameter and volume is not. Transient craters grow principally laterally for a much longer period after the maximum excavation depth has been achieved [Schultz et al. 1981]. For example, using the empirical similarity scaling parameter for impact of a 10 km diameter silicate 30 km/sec projectile into rock proposed by Schmidt [1981] a final crater volume, V, of 4.5×10^{21} cm^3 (ignoring the ocean layer) is calculated from

$$V = [900 \ (cm^3) \ m/\rho] \ U \ [d]^{1/2}$$

(1)

where m(g), U(km/sec), and d(km) are projectile mass, velocity and diameter and ρ(g/cm^3) is the (silicate) target density. For a spherical bowl shaped crater with a diameter to depth ratio of 5, a 375 km crater diameter is calculated. Assuming a water target and Eq (39b) of Holsapple and Schmidt [1982] a similar sized crater in water is also predicted.

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 Fig. 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. As can be seen in Figs. 5 and 6, some 12 and 14% of the impact energy resides in the water ejecta, for impacts of an equal mass $(1.5 \times 10^{18}$ g) 2.9 g/cm^3, silicate, and 0.1 g/cm^3 water impactors onto a 5 km thick ocean overlying a silicate half-space. 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 $\sim 5^{\circ}$ C temperature increase. We doubt that this distribution of water could be achieved. We suggest in the actual case the shock heated water would largely be distributed 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 (Fig. 7). As can be seen some 10 to 30 times the mass of the bolide of water e.g. 1-5 x 10^{19} g ejecta is launched onto the stratosphere. As Jones and Kodis [1982] pointed 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} g water budget of the earth it is nevertheless 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, whether the time constant of return to equilibrium is sufficiently long that the terrestrial greenhouse is strongly enhanced giving rise to a change

of global climate as speculated by Emiliani et al. [1982] needs careful 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% component of extraterrestrial component (ETC) could be explained if its origin was 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 layer. 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 presumably deposited locally.

It was earlier suggested by Smit [1981] that impact of an asteroidal object onto an ocean might, because of the water ejecta, surpress the lofting of indigenous terrestrial solid ejecta, and explain the extraordinarily high values of ETC found in the K-T boundary layer material. In Fig. 8 we plot our calculations of the minimum total ejecta launched to various altitudes for impact of a series of bolides onto an ocean-covered silicate earth. As demonstrated in Fig. 8 ejecta representing some 20 to 10^2 times the bolide mass is launched onto trajectories which could carry it to stratospheric heights. 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. Now the question which needs to be addressed is, is the value of ETC higher for oceanic versus

terrestrial impact?

In Fig. 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. Notably 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 Fig. 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 impactor. 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. The more intensely shocked and vaporized projectile material is launched to higher altitudes.

Impact-Induced Tsunamis

As is evident in Figs. 1-3, a giant tsunami is expected to result from an impact of a large bolide in the deep ocean which according to Figs. 5 and 6 will contain kinetic and gravitational energy which will amount to some 7 to 9% of the impact energy. 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]

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

(2)

that for the energy impact (6.9×10^{30} erg) assumed in Figs. 1-3, the equivalent value of M_s is 12.7. By comparison, the largest earthquakes have surface wave magnitudes of 9.5. This comparison 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.

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.

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. Using the lack of evidence for a turbidite layer at the K-T boundary we will attempt to place a constraint on the maximum energy and hence presumably the dimension of the K-T bolide. Using the Le Méhauté [1971] fit to empirical data from impulsive sources, the water wave attenuation can be inferred using the large explosion data set (up to 10^{22} ergs) from shallow water explosions given by

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

(3)

where H is the initial wave height (cm), R is radius from the source (cm), and E is explosive energy (ergs). The wave observed propagating from explosions, and we assume to also represent impact sources, begins with the fastest propagating, longest period wave whose effective wavelength is given below (Eq. 11). The initial largest amplitude peak propagates with only a slowly varying wave form, approximately as a solitary wave. How efficiently explosives couple into shallow water waves relative to impactors is not clear. It is however likely from other comparisons of explosive and impact cratering [Oberbeck, 1977] that the explosive data can provide an approximation to the impact case. To examine this issue further we use Eq. 3 to calculate the tsunami height at a radius of 20 km and 90 km corresponding to the configurations presented in Figs. 2 and 3. In the case of the silicate impactor (Fig. 2) the value of H from Eq. 3 is a 17 km compared to the 5 km calculated by finite difference methods. In the case of the more efficient porous water impact (depicted in Fig. 3) Eq. 3 yields a 6 km wave amplitude whereas we calculated a wave amplitude of 25 km via finite difference methods. These cases are both somewhat unrealistic since wave dissipative mechanism are probably poorly represented in finite difference methods and the maximum stable height of impulsive solitary type waves is (Munk, 1949)

$$H = 0.8 \ h$$

(4)

where h is the undisturbed water depth. Nevertheless the impact induced water waves appear to be roughly compatible with Le Méhauté's empirical correlation.

In order to 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 which is given approximately as (Komar, 1976)

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

(5)

For a 5 km deep ocean on the earth this dependence of C on H is shown in Fig. 10. The maximum horizontal particle velocity beneath an impulsive solitary wave at the base of the ocean is given by

$$u \cong NC$$

(6)

where N (and M) is approximately given as [Munk, 1949].

$$N = 0.64 \sin \ (0.4 \ \Pi \ H/h)$$

(7a)

$$M = 0.97 \sin \ (0.4\Pi \ H/h)$$

(7b)

Combining Eqs. 3, 5, 6 and 7a yields values for the maximum horizontal particle velocity at the sea floor during passage of initial, solitary wave, versus, impact energy and radius from impact site (Fig. 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 less than and greater than 0.5 mm and 1 cm as [Komar, 1976]

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

(8)

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

(9)

where D is grain diameter, ρ_s and ρ are grain and fluid density and d_o is the bottom orbital diameter. The near bottom particle motion orbital diameter is given by

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

(10)

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

$$L_{eff} \cong 2\Pi C/M\sqrt{h/g}$$

(11)

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

Although we may have slightly overestimated the coupling of a 7×10^{30} erg impactor (corresponding to 10 km silicate asteroid, impacting at 30 km/sec), it appears that this large an energy impactor striking the deep ocean would cause erosion and we infer from Fig. 11 that this would cause turbidity at the K-T boundary (which is not observed). In contrast a 10^{28} to 10^{29} energy bolide 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.

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 worldwide 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 [Schopf, 1982]. Whether tsunami run-up from an oceanic impact of an object 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

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

(12)

where the constant, k, can vary from 0.34 to 0.50. For Eqs. 3 and 12 we calculate the free-field impulsive wave height and a minimum run-up height (RU) (Fig. 12). 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 a much smaller asteroidal object, 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. These are locally only 10^{-2} to 10^{-3} times lower amplitude. The present calculations, however, strongly suggest that a depositional inconformity 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.

Acknowledgment

Figure Captions

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

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

Fig. 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 thick ocean overlying silicate earth.

Fig. 4. Energy partitioning, versus, dimensionless time for impact of 10 km silicate (An) impactor upon a silicate half-space.

Fig. 5. Energy partitioning, versus, dimensionless time for impact of a 14 km diameter sphere of water at 30 km/sec onto 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 31 km sphere of 0.1 g/cm^3 water at 30 km/sec onto a 5 km water ocean overlying a silicate half-space. Shaded region depicts energy delivered to water layer.

Fig. 7. $\log_{10}$ (minimum water ejected/meteorite mass), versus, $\log_{10}$ (minimum ejecta height, km).

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

Fig. 9. Log_{10} (mass fraction, extraterrestrial material, ejecta), versus, log_{10} (minimum ejecta height, km). Data for fraction ETC measured at 5 sites are comparable to composition of ejecta lofted to minimum altitudes of 10^1 km.

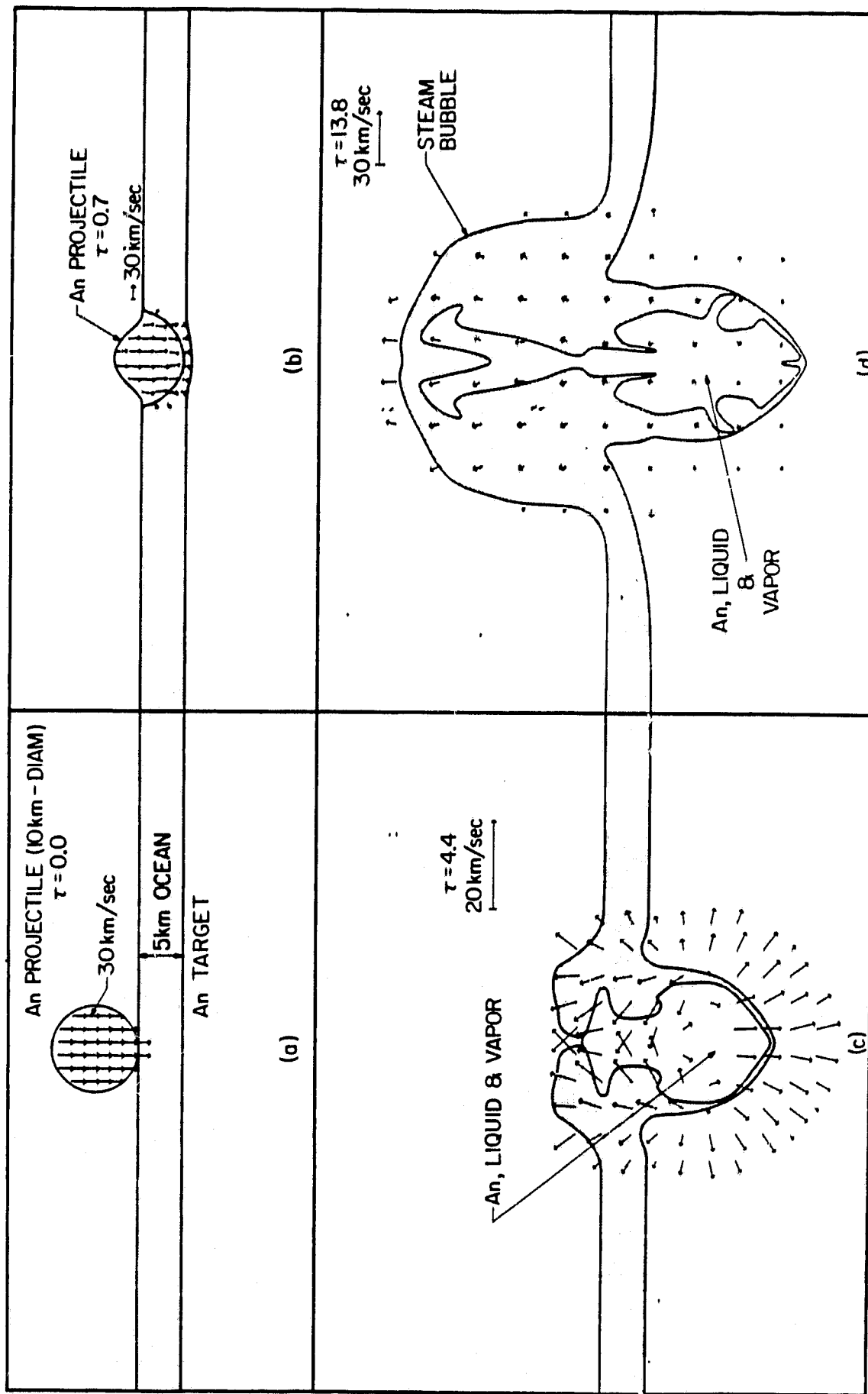Fig. 10. Group velocity, versus, solitary wave height.

Fig. 11. Horizontal peak particle velocity at seafloor, water-sediment interface, versus, range from impact for various energy impactors. Also shown is critical particle velocity required to induce erosion for 0.5 mm and 1 cm diameter carbonate particles.
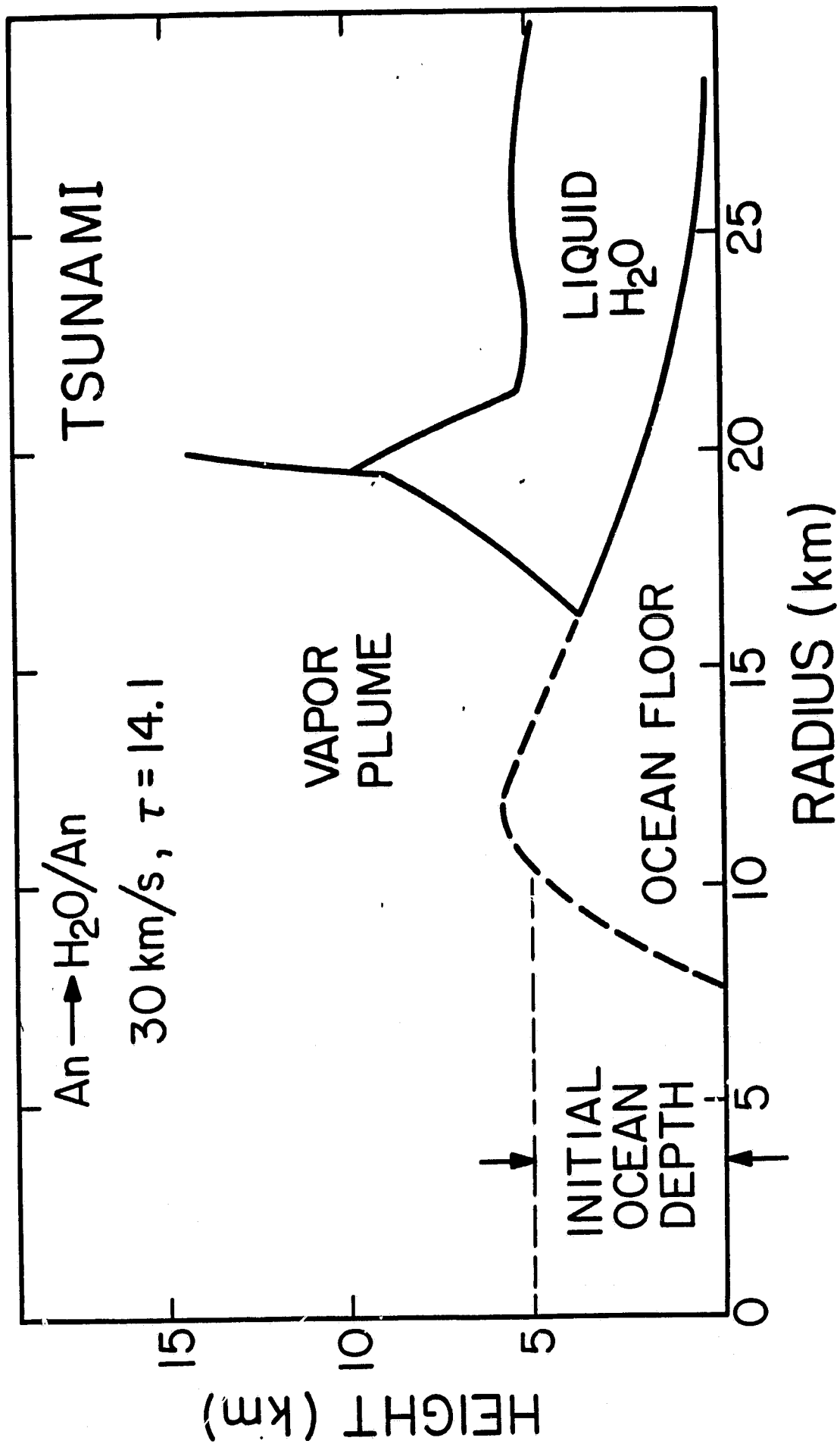
Fig. 12. Wave height (H) and run-up height (RU), versus, impact site. Log_{10} of different energy impactors is indicated.

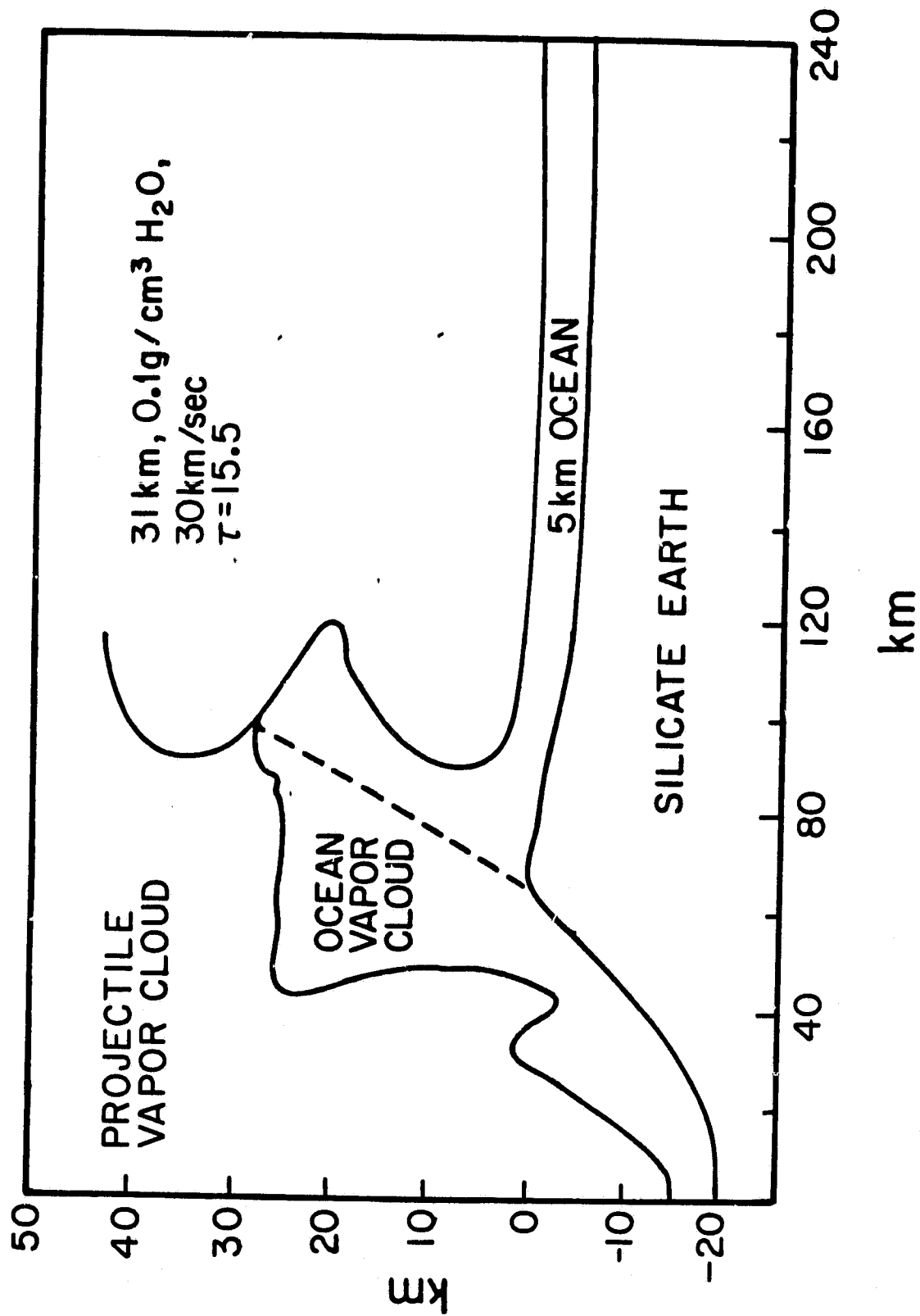TJA82340MFD

An PROJECTILE (10km – DIAM)
$\tau = 0.0$

30 km/sec

5km OCEAN

An TARGET

(a)

An PROJECTILE
$\tau = 0.7$

30 km/sec

(b)

$\tau = 4.4$
20 km/sec

An, LIQUID & VAPOR

(c)

$\tau = 13.8$
30 km/sec

STEAM BUBBLE

An, LIQUID & VAPOR

(d)

TSUNAMI

An → H_2O/An

30 km/s, $\tau = 14.1$

VAPOR PLUME

LIQUID H_2O

OCEAN FLOOR

INITIAL OCEAN DEPTH

HEIGHT (km)

RADIUS (km)

Fraction of Energy

$\tau = tv/d$

$An \xrightarrow{30km/sec} H_2O/An$
$(10km)$ $(5km)$

KE, Target

KE, H$_2$O

KE, Proj.

IE, Target

IE, H$_2$O

IE, Proj.

1.0

.75

.5

.25

0   2   4   6   8   10   12   14

Fraction of Energy

KE, Target (An)

KE, H$_2$O

KE, Proj.

IE, Target (An)

IE, H$_2$O

IE, Proj.

30 km/s

(0.1 g/cm^3) H$_2$O $\longrightarrow$ H$_2$O/An

(30.8 km)   (5 km)

$\tau = tv/d$

1.0   .75   .50   .25   0

2   3   4   5   6

Figure axes (rotated): horizontal axis — LOG_{10} (minimum ejection height, km); vertical axis — LOG_{10} (minimum H_2O ejected/meteorite mass)

Curve labels: 0.1, $H_2O \rightarrow H_2O/An$; $An \rightarrow H_2O/An$; 1.0, $H_2O \rightarrow H_2O/An$; STRATOSPHERE

Y-axis: LOG_{10} (mass ejected/meteorite mass)

X-axis: LOG_{10} (minimum ejection height, km)

0.1, H_2O

An

1.0, H_2O

STRATOSPHERE

OCEAN IMPACT
AT 30 KM/SEC

EJECTA VELOCITY, cm/sec

10^4 10^5 10^6

LOG₁₀ (mass fraction, extra-terrestrial component, ejecta

0.1, 15

2.9, 15

1.0, 45

2.9, 45

2.9, 30

2.9, 30 (10 km, Ocean)

Measured
- Denmark
- Spain
- Central Pacific
- New Zealand
- Italy

MESOSPHERE

TROPOSPHERE

STRATOSPHERE

LOG₁₀ (minimum ejection height, km)

9

SOLITARY WAVE VELOCITY (m/sec) vs SOLITARY WAVE HEIGHT (m)

5 km–OCEAN

BOTTOM PARTICLE VELOCITY (m/sec) vs RANGE TO IMPACT (km)

EROSION

10^{32}

1cm

10^{30}

0.5mm

10^{29}

QUIESCENCE

10^{28}

STABILITY LIMIT
DEEP OCEAN

H-30.8

H-29

RU-28

RU-29

RU 30.8

H-28

WAVE HEIGHT (m)

RANGE TO IMPACT (km)

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