Underwater Shock Waves and Seismic Waves Generated by a Catastrophic Asteroid Impact

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Abstract. The paper describes preliminary analysis for understanding mass extinctions of marine life resulted from strong underwater shock waves and seismic waves which were caused by asteroid impacts, most notable of which occurred 65 million and 250 million years ago. In the past the contributions of underwater shock waves and seismic waves to the mass extinctions have not been intensively discussed. The propagation of impact-induced underwater shock waves and seismic waves and deformation of earth crust are numerically simulated. Although the waves are attenuated, they, other than Tsunami, would be one of the sources which triggered mass extinctions, probably not in a global scale but at least in a regional one.

1 Introduction

It is well understood among astrophysicists that our solar system is circulating along the relatively outer edge of the Milky Way galaxy, which has a vortex structure consisting of many stretching spirally-shaped nebulae. In the course of its circulation, it encounters the spiral nebulae periodically. Figure 1 shows the rate of extinction of species against geological age, million years in unit. We can readily see that a mass extinction occurred every 26.6 million years and in particular two devastating mass extinctions took place 65 and 250 million years ago. The latter corresponds to the so-called P/T boundary dividing paleozoic and mesozoic eras while the former – to the K/T boundary separating mesozoic era from cenozoic one (Kaiho et al. 1999, Rampino 1999).

An asteroid of over 10 km dia. impacted obliquely on Yucatan Peninsula 65 million years ago creating a 170 km dia. crater and led to the extinction of 70% of marine life. A 130 km dia. impact crater was discovered in May 2000 at Woodleigh in Australia, which would be the evidence of an asteroid impact 250 million years ago being the most probable source of the massive Permian/Triassic extinction of almost all life on the Earth (Near Earth Orbit 2000). Kaiho (2001) proposed a hypothesis that a huge crater recently discovered in Siberia might be remnants of a spalling hole created at this impact. Although impacts of small meteorites will not create any devastating damages, such gigantic asteroid impacts on the Earth changes even the course of its history (Glen 1994; Heide and Wlotzka 1995; Miura 1995; Jewitt 2000).

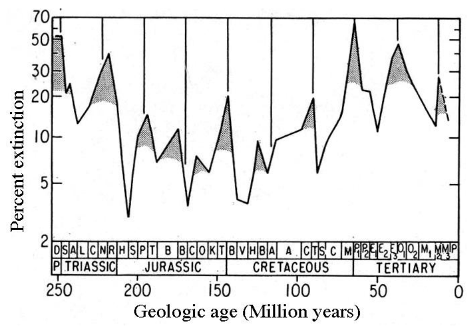


Fig. 1. Rate of extinction of species against geological age in units of million years

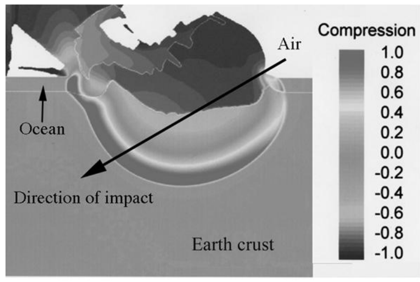


Fig. 2. Very early stage of an oblique impact

An international research team has been formed in SWRC in order to investigate a role of propagation of underwater shock waves and seismic waves in mass extinctions of marine creatures. An analogue experiment is about to start, in which an oblique two stage light gas gun is used (Shinohara et al. 2001). In order to visualize waves in water and solid, an acrylic block is used as a solid base.

Oblique collisions of asteroids with earth, cratering and ejection of shocked surface materials were well studied. Figure 2 shows a result of AUTODYNE 3D simulation. A 13 km dia. asteroid impacted at 30 degree inclination onto earth surface. The impact speed was about 70 km/s. The equation of state of earth crust was assumed to be a polynomial formula. Although slight differences are observable depending upon the type of equation of state for the crust, all main features of early cratering, formation ejecta, initiation of Tsunami look similar.

Theoretical analyses into the problem with qualitative estimates are found in Zeldovich and Raizer (1967). In the case of high-speed impacts, the kinetic energy can be considered to be released instantaneously so that the problem reduces to a point source explosion at the surface of half-space (see Sakurai 1970). Roddy et al. (1987) and Ahrens and O'Keefe (1987) numerically simulated both continental and oceanic impacts.

Large scale forest fires which could be expected to break in the vicinity of the ballistic re-enter of the ejecta, acid rains and, finally, catastrophic changes in climate resulting in break down of food chains and global extinction of numerous species, as the sunshine was interrupted for long time by dust particles floating in stratosphere, have been discussed in detail, e.g. by Glen (1994).

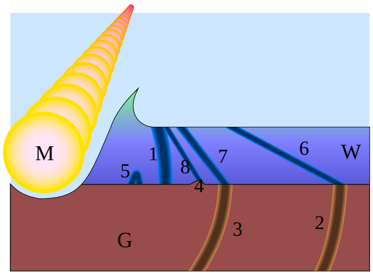


Fig. 3. Major elastic waves in deep water (W) and underlying ground (G) caused by a large meteoroid (M) impact: directly excited shock wave in water (1), longitudinal (2) and transversal (3) body waves in the bottom, surface Rayleigh (4) and Stoneley (5) waves, underwater waves (6),(7),(8) radiated by waves (2),(3),(4)

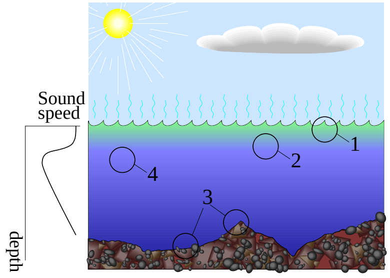


Fig. 4. Factors affecting long-distance propagation of a shock wave in water: unloading at the free surface (1), refraction and dispersion at inhomogeneities, viscous and chemical dissipation in the volume (2), reflection, diffraction and scattering at bottom topographies and inhomogeneities (3) contribute to shock attenuation; the deep water sound channel (4) allows a very long-distance propagation

2 Major Waves Caused by an Impact

Even the extremely strong shock wave caused by an asteroid impact, which results in melting of solid, decays rapidly with its propagation. For typical impact speeds and impactor materials, the pressure in the vicinity of the impact point readily exceeds the Hugoniot elastic limit, but only for ten impactor diameter distance (Ahrens and O'Keefe 1987). After propagating over that distance, waves in the ground essentially reduce to elastic waves, and the respective theory can be applied (Landau and Lifshits 1970; Brekhovskih 1960; Brekhovskih and Goncharov 1985). Major stress waves caused by an asteroid impact exist in sea water and are schematically presented in Fig. 3. First of all, the primary shock wave in water (1) is generated by the impact. The initial energy deposition into the wave is proportional to the impactor's diameter d. Hence, the relative part of the wave energy comprises a small fraction of the total kinetic energy released, which is proportional to d^3. Two types of body waves will be generated in the solid bottom: the longitudinal (2) and transversal (3) waves. The energy deposited into these waves is proportional to d^2. Unloading from the solid surface is the main source of the shear stress causing the transversal wave. Interaction of the longitudinal wave with the layered structure of the crust would also generate transversal waves. Two types of surface waves can be expected at the water/solid interface: the Rayleigh wave (4) at the bottom surface and the Stoneley wave (5) in water close to the bottom. The longitudinal (2) and transversal (3) waves in the bottom, and the Rayleigh (4) wave at the bottom surface will release compression waves into sea water. These waves are indicated in Fig. 3 as waves (6), (7) and (8), respectively.

Theoretical considerations (Sakurai 1970; Melosh 1984), experiments and numerical simulations on the local energy deposition near the surface of an elastic body or liquid indicate that intensity of the compression waves varies essentially from nearly zero values close to the surface due to unloading to its maximum in the direction perpendicular to the surface. This effect is clearly seen in Fig. 5 corresponding to the experiment in which a micro-explosive was detonated on the water-air interface. Though these data may not have a direct application to our case, because close to the impact site the initial energy deposition cannot be that of a point explosion, while the layered elastic structure of the crust should be taken into account at a large distance, however, the angular variation in wave intensities can significantly reduce any effect of the waves close to the surface.

3 Underwater Shock Wave and Stress Waves in the Bottom

If underwater shocks propagate without boundary effects at the surface and bottom as well as without dissipation effects in the volume, the problem would be reduced to cylindrically symmetric, and the pressure jump Δp in the wave in the elastic propagation mode would decay with the distance r proportionally to $r^{-1/2}$, as the wave energy $E \propto p^2$, and the wave front area $S \propto r$ (Brekhovskih and Goncharov 1985). Assuming the initial overpressure of the order of 1 GPa at a distance of 10 km from the impact center, such a wave would have an overpressure of $\Delta p \approx 30$ MPa at a distance of 10,000 km leaving no chance for survival to any fauna object behind. The real case, however, is very different from this idealistic scheme. Figure 4 illustrates effects influencing the long-range propagation of a shock wave in ocean water.

The role of the free surface is shown in Fig. 6, which presents results of a numerical simulation using an adaptive grid and based on the Euler model with the Tait equation of state. The bottom here is considered planar and perfectly reflecting, and the shock wave enters the computational domain from the left at an initial intensity slightly below the Hugoniot limit. The unloading at the free surface leads to its rapid attenuation: the wave has lost more than 99% of its initial overpressure having passed only 18 water depths. Detailed analysis of the numerical data shows that maximum overpressure in the wave close to the bottom decays at an increasing rate in the range from $r^{-2.5}$ to $r^{-3.5}$ by the end of computations. At this final moment, the wave is still well resolved and captured by the local grid refinement, so that the observed effect is not of a numerical origin. Scattering at the irregular bottom and in the water volume, as well as viscous and chemical dissipation would further reduce the wave intensity.

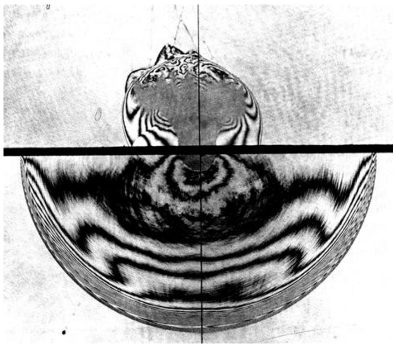


Fig. 5. Angular variation of shock intensity in water by explosion at the water-air interface. Visualization method: double-exposure holographic interferometry

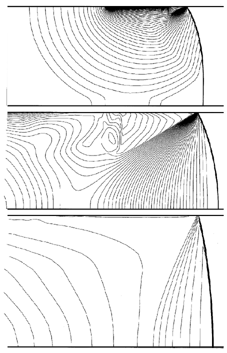


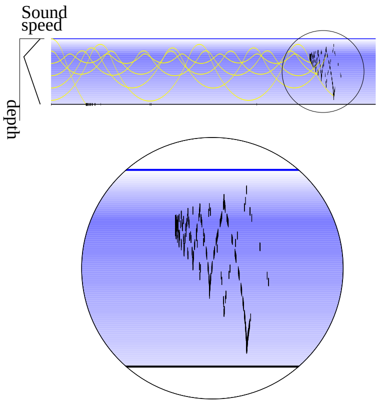
Fig. 6. Underwater shock attenuation by unloading at free surface

The non-monotonic variation of the sound speed with depth, as shown in Fig. 4, creates a wave guide effect, isolating the wave from attenuation at the surface and bottom (Brekhovskih 1960). A simple ray tracing simulation for a model sound speed profile is presented in Fig. 7. While propagating through the wave guide, the initial planar wave front undergoes dispersion forming a series of successive waves, which effectively enlarges the total wave front area thus reducing intensity of each wave in the series.

Major stress waves generated in the ground by asteroid impacts are the longitudinal ones, or P-waves. In the elastic propagation mode, maximum compression caused by this wave decreases as r^{-1} with distance. Its propagation over long distance would also be affected by the dispersion at non-uniform structure of the crust and mantle and by effects of viscosity. Propagating along the ocean bottom, this wave radiates a compression wave into sea water. This process is illustrated in Fig. 8. The elastic model presented in Voinovich et al. (2001) has been employed in this simulation. A water layer W overlays the elastic solid G with the parameters corresponding to the basaltic crust. A sharp compression wave L enters the lower part of the computational domain from the left. The radiated into water compression wave L_W has an overpressure of 3.7% of that in the longitudinal wave. Also seen in the figure is the surface Rayleigh wave R radiating into water R_W. As the sound speed in water is much less than the propagation speed of longitudinal wave in the bottom, the radiated compression wave L_W propagates essentially toward the water surface and traverses the whole water volume unaffected by the stress-free upper boundary.

4 Conclusions

The intensity of the impact-induced shock wave is high enough to be mortal to the life of marine creatures. However, the so-called wave guide zone in the deep



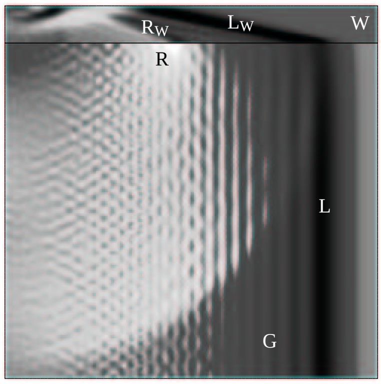


Fig. 7. Dispersion of an initially planar acoustic wave entering the domain from the left by a model variation in the sound speed, as simulated by a ray tracing method

Fig. 8. Simulation of a longitudinal, or P-wave (L) in basaltic ground (G) with a water layer (W) on top of it. R is the Rayleigh surface wave. L_W and R_W are compression waves radiated into water by L and R respectively

water may confine and transmit pressure waves for a long distance. It is an open question whether or not such situations are mortal to marine life. Transversal and longitudinal waves in the elastic ocean bottom propagate for a very long distance without significant attenuation. Effects of dispersion of waves propagating in inhomogenious media with the presence of viscous dissipation have to be analyzed in more detail. Subsequent radiation of compressive transversal and longitudinal waves into water would be more influential to a regional extinction of marine creatures. The impact-caused excitation of transversal and Rayleigh waves and their radiation into water need further analysis, as well as the excitation mechanism and energy deposited into the Stoneley wave. There would be shadow zones caused by the diffraction and refraction of transversal and longitudinal waves. Energy deposited in the Rayleigh wave is concentrated close to the elastic solid surface, so that its radiation into deep ocean water would result in its rapid attenuation. The role of the Stoneley wave needs to be analyzed more, it seems that the shadow zones behind continents and irregularly shaped coastal lines would exist which could be safe zones for survival from mass extinction. The survival of coelacanths, existing fossil fish caught at the east coast of southern Africa, may be one of the evidences.

In addition, simple estimates given in Section 2, as well as analysis of energy partitioning at a large asteroid impact (Ahrens and O'Keefe 1987) explained that the energy deposition into the compression/stress waves is not significant as compared with the kinetic energy and internal energy of ejecta which were ejected toward the opposite direction of impingement of an asteroid.

A regional extinction would evacuate previous species and temporarily promote the migration from other regions. The role of impact-induced seismic waves seems specifically important in this relation by the following reasons. First, the part of impact energy depositon into these waves would be higher in the case of smaller impact events, so that due to frequent impacts these waves could be major sources of life-threatening agency for marine creatures.

Secondly, underwater shock waves or seismic waves exhibit an ecologically clean extinction mechanism, which does not destroy physical conditions and causes no long-term environmental change. Hence, the affected area can be extensively re-populated. The biomass of the extinct organisms might have offered temporal food cycles stimulating selective migration. Substantial amount of the extinct biomass could have contributed to the fossil fuel accumulation.

The impact-generated stress waves propagating in earth crust could shake magma chambers simultaneously in worldwide scale, which would have most probably triggered simultaneous eruptions on the Earth.

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