IMPACT EROSION OF WATER OCEAN ON THE EARLY EARTH WITH A THIN ATMOSPHERE.

V. V. Svetsov, Institute for Dynamics of Geospheres, Russian Academy of Sciences,
Leninskiy Prospekt 38-1, Moscow, 119334, Russia, svetsov@idg.chph.ras.ru.

Introduction: There are several possible sources of terrestrial water [1]. Recent numerical dynamical simulations of planet formation [2], [3] show that a significant amount of water could be delivered to the early Earth during its bombardment by hydrated carbonaceous planetary embryos (100–1000 km in size) and planetesimals (1–10 km) from the outer asteroid belt. However it turns out, that the amount of delivered water depends on an assumed eccentricity of Jupiter. High eccentricities (this case is better in several aspects [2]) lead to formation of "dry" terrestrial planets with the amount of delivered water at best on the order of the mass of the modern ocean (1.5×10^{24} g). If the Jupiter orbit is circular, the water masses delivered by large carbonaceous embryos and by the bombardment of smaller planetesimals are both on the order of ten ocean masses [3]. Comets could deliver from some tenths of the ocean mass [1] to one ocean mass [4].

The typical velocities of planetesimals nearing the terrestrial planets are in the range from 0 to 35 km/s (at infinity), while the velocities of embryos are mainly below 5–7 km/s [2]. Retention of delivered water depends significantly on impactor masses and velocities and the presence of an atmosphere. Moreover, if a water ocean exists, the high-velocity impacts of planetesimals and comets can deplete an ocean, rather than replenish it, because some water mass can escape the planet. The purpose of this work was to calculate the masses of lost and retained water after the impacts of comets and asteroids on the terrestrial ocean of various depths. It was assumed, as a first approximation, that the planet has a tiny atmosphere which does not affect water ejection.

Numerical model and method: It is supposed that a flat surface of a terrestrial crust is covered by water. The late stage of planetary accretion is considered with the gravitational acceleration of 9.8 m/s^2 and escape velocity 11.2 km/s. Numerical simulations have been made for 1-km-diameter asteroids and comets, but because the gravity influences the mass of lost water only slightly for impactor sizes smaller than 10 km, the computational results depend mainly on the ratio of an ocean depth to an impactor diameter. The simulations of the impacts were made via numerical solutions of the 2D hydrodynamic equations by the method SOVA [5]. Granite ANEOS equation of state was used for the crust and asteroids. Equation of state of water has been calculated by I.B.Kosarev. Cometary material was treated as a mixture of equal masses of granite and water with a bulk density of 0.6 g/cm^3.

The losses of water at the typical impact velocities are rather low and arise from a relatively thin near-surface layer. Therefore a high mesh resolution is necessary. I carried out 2D simulations of the vertical impacts of spherical bodies and the impacts at various angles of cylindrical bodies with infinite length and velocities perpendicular to the axis of symmetry. A nonuniform grid had a resolution of 120 cells across the impactor diameter in the vicinity of impacts, the mesh size growing to the periphery. The whole grid size was 800x600. Limited computer capabilities did not enable me to make 3D simulations with necessary accuracy; however a comparison of several 3D variants of simulations with lower resolution with similar 2D ones suggests that the results for the impacts of infinite cylinders correlate with the real oblique impacts of spherical bodies within 50%.

Results of calculations: An example of simulations for the ocean depth equal to 0.5 of the asteroid diameter is shown in Fig. 1. Some mass of oceanic water (about 0.25 of the asteroid mass) and a negligible part of the projectile material are accelerated to velocities above 11.2 km/s.

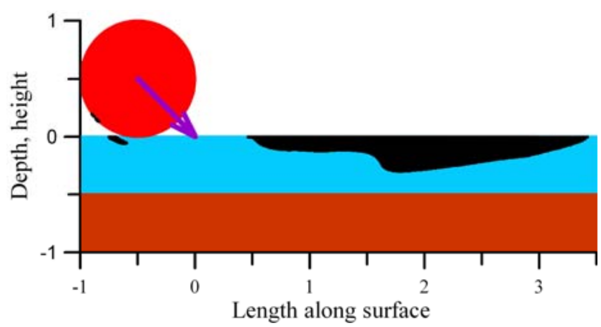

Fig. 1. Crust (brown), water (blue), and asteroid (red) just before the impact at a speed of 25 km/s. The arrow shows the impact direction (45º to the surface). The black areas show material lost after the impact.

The calculated ratios of the mass of escaped water to the asteroid mass as a function of the relative ocean depth *H* and impact velocity *V* (in the range 15–35 km/s) are shown in Fig. 2. At all velocities almost the entire mass of asteroids remains at the planet. At velocities below 15 km/s and for small *H*, asteroids cause insignificant erosion of the ocean. So slow hydrated planetary embryos from the outer asteroid belt leave all their water on the proto-Earth without depletion of the ocean. In contrast, faster and smaller planetesimals (similar to carbonaceous chondrites with water content up to 10%) can eject more oceanic water than they deliver.

Unlike the asteroidal impacts, a significant mass of comets can be lost after their impacts on the ocean. The models of comet formation [6] suggest that the typical sizes of comets are about 10 km and therefore they are larger than the probable ocean depth. As shown in Fig. 3, the losses of water exceed water supply if comets (50% of water) strike the planet with velocities above 30 km/s and the ocean depth is larger than 0.1 of the comet diameter. The efficiency of water delivery (retention minus erosion) is from 35% at 20 km/s to 0 at 30–32 km/s for *H* from 0.1 to 1.

The impact angle dependences of water losses and retention are shown in Fig. 4 for comet impacts at 50 km/s. The difference between the water loss and retention is higher for the impact angle 45º. However it is the most probable impact angle and the results obtained for 45º reflect the integral dependences.

Discussion: The scenarios of "dry" planet formation suggest that no more than 1.5 ocean masses are delivered by hydrated asteroids [2]. In addition, some mass of water could be delivered by planetesimals and embryos from a zone around the Earth orbit if these bodies had water proportion like ordinary chondrites. However, the bombardment of the planet by faster asteroids from the inner asteroid belt can wipe out all this water if their mass is, e. g., 1% [2] of the Earth's mass. A thick atmosphere can retain water; however the existence of such an atmosphere is under question because of the deficit of volatiles in the accreted material. In the case of "wet" planetary formation (circular Jovian orbits) the ocean delivered by the hydrated embryos can survive the bombardment of faster planetesimals due to its high depth (which diminishes erosion, Fig. 2) and a possible occurrence of a dense atmosphere. As the probable comet speeds are fairly moderate, some amount (up to tens of percents) of cometary water must be present in the hydrosphere.

Conclusions: The model of "dry" planetary formation is associated with the problem of possible asteroidal erosion which can destroy the entire ocean. The size and velocity distributions of planetesimals are required for more realistic estimates of ocean survival.

References: [1] Morbidelli A. et al. (2000) *Meteoritics & Planet. Sci., 35,* 1309–1320. [2] O'Brien D. P. et al. (2006) *Icarus, 184,* 39–58. [3] Raymond S. N. et al. (2007) *Astrobiology, 7,* 66–84. [4] Marov M. Ya. and Ipatov S. I. (2004) *LPS XXXV,* Abstract #1410. [5] Shuvalov V. V. (1999) *Shock Waves, 9,* 381–390. [6] Morbidelli A. and Brown M.E. (2005) *Comets II*, Tucson, Univ. Arizona Press, 175–191.

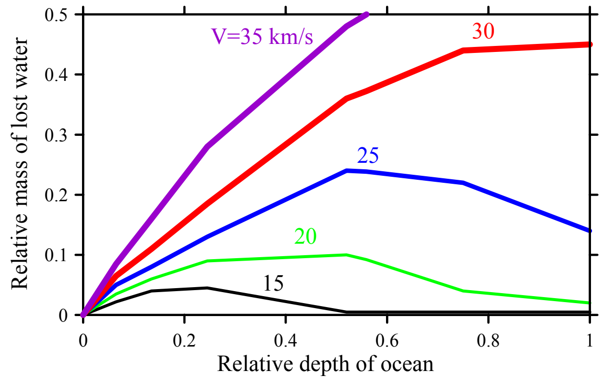

Fig. 2. Losses of water (relative to impactor masses) after the impacts of asteroids at 45º.

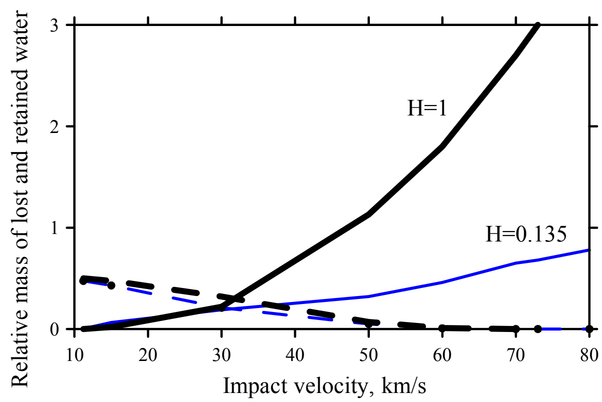

Fig. 3. The solid lines show the losses of oceanic water after comet impacts at 45º on the ocean with relative depth *H*. The dashed lines show cometary water mass retained on the planet after the impacts.

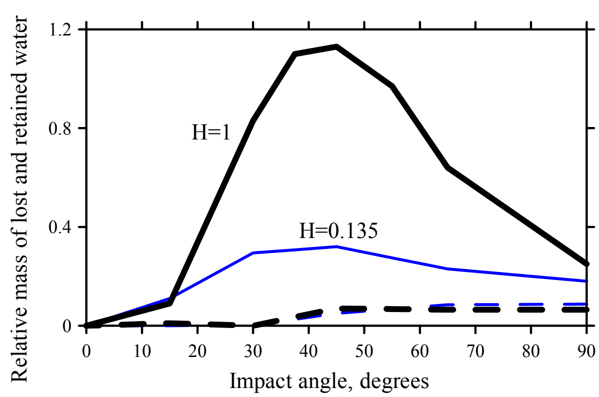

Fig. 4. Relative losses of ocean (solid lines) and retention of water (dashed lines) after the impacts of comets with velocities 50 km/s at various angles.