INVESTIGATING THE EFFECT OF WATER DEPTH ON MARINE IMPACT CRATER MORPHOLOGY.

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Introduction: 70% of the Earth is covered by the oceans, implying that most meteoroid impacts occur into water-covered targets. However, of the ~170 known or suspected impact structures on the Earth only 15-20 are thought to have formed in a marine environment [1], and the majority of these are now on land. The paucity of marine craters is in part due to the effect of the water layer on inhibiting or altering the cratering process and in part due to the young age of the oceanic crust. Here we quantify the relationship between crater diameter and the ratio between water depth and impactor diameter by numerically simulating oceanic impact events. We then use this relationship to examine the effect of the Earth's oceans on the global crater size-frequency distribution and estimate how many craters we should expect to find on the ocean floor today.

Previous Work: Previous experimental and numerical modeling work has shown that the effect of a water layer on crater formation is most sensitively controlled by the ratio between the water depth and the impactor diameter—referred to hereafter as *R* [e.g. 2-8]. However, a definitive relationship between final crater diameter and *R* has not yet been established. By simulating the impact of a 200-m diameter impactor at 15 km s^{-1} into water-covered targets, Shuvalov [3] showed that a shallow water layer ($R < 0.5$-1) has little effect on the cavity forming in the basement; that for $R > 2$ cavity size is reduced as the impactor is completely decelerated, deformed and disrupted during penetration of the water layer; and that for $R > 4$ no crater occurs on the seafloor. Artemieva and Shuvalov [8] also found from their numerical models that for $R > 4$ a submarine crater is almost nonexistent (for a 1-km diameter impactor with an impact velocity of 20km s^{-1}); however, the marine-impact models of [7] did show significant disturbance of the seafloor for $R = 5$ (using the same impactor size and velocity). Laboratory-scale impact experiments [2] provide further quantitative analysis of the effect of water layer thickness on crater size, albeit at a much smaller scale and lower velocity than typical marine craters. Results from these experiments suggest that craters may form in the target beneath water of depths up to 10-20 times the diameter of the impactor (R = 10-20).

Method: To quantify the relationship between final crater diameter and *R* we have simulated over 60 marine-target impact events using the iSALE hydrocode. This is a well-established code [7] that has been used to simulate several terrestrial impact events [e.g. 9-11] and develop a generic, quantitative model for the formation of impact craters in crystalline targets [12]. For all simulations the ANEOS equations of state for granite and water were used to represent the seafloor and ocean. Granite was chosen because, unlike basalt, it is has a well-defined EOS and constitutive model, and because the constitutive model parameters for basalt and granite are similar. We used an impact velocity of 15 kms^{-1}, which is an average velocity for impacts on Earth. Density was kept constant at 2700kgm^{-3}, suitable for a porous stony asteroid and to allow the same material to be used for the impactor and seafloor. The angle of impact in all simulations was perpendicular to the target surface, enforced by the axisymmetric nature of the model.

Three sets of simulations were performed, each with a fixed impactor diameter (L=100m, L=500m and L=1km), to investigate the effect of water layer thickness on crater formation over a range in impactor sizes. The three impactor diameters were chosen to span the range of terrestrial impact events where the effect of a water layer is important, and to keep the maximum water depth investigated within reason. At the lower end, stoney impactors much smaller than 100-m diameter are significantly affected by atmospheric entry (broken up and/or decelerated) and will probably not form a single large impact crater. At the upper end, the maximum depth of the terrestrial oceans (~7 km) implies that a large range in *R* cannot be achieved for impactors much greater than 1-km diameter. Simulations were run varying the *R* value between 0 (no water) and 8 (deep water) for each of the different impactor diameters.

Results: Qualitatively, our model results agree well previous work [e.g. 3, 5, 7, 8 13]; we identify three regimes of behaviour (shallow-water, intermediate-water-depth, and deep-water) depending on the ratio of water depth to impactor diameter, *R*, and whether the impact forms a simple or complex crater.

The deep-water regime occurs for impacts where $R > 8$; in this case, all the impactor's energy goes towards forming a crater in the water layer, and no crater is formed on the ocean floor.

The intermediate-water-depth regime applies only for impacts forming complex craters in the range 3-4 < R < 6-8. In this highly-complex regime the seafloor is affected: by the passage of the shockwave that forms when the impactor strikes the water; by high velocity water resurge flows; and by the temporary removal of the substantial overburden of the water column. Based on our model results, it is unclear what the final manifestation of such seafloor disturbances might be, but it is likely to be broader than the equivalent crater had the impact occurred on land.

The shallow-water regime, which represents all other cases, is characterised by a decrease in crater diameter with increasing R, but little large-scale change in crater morphology.

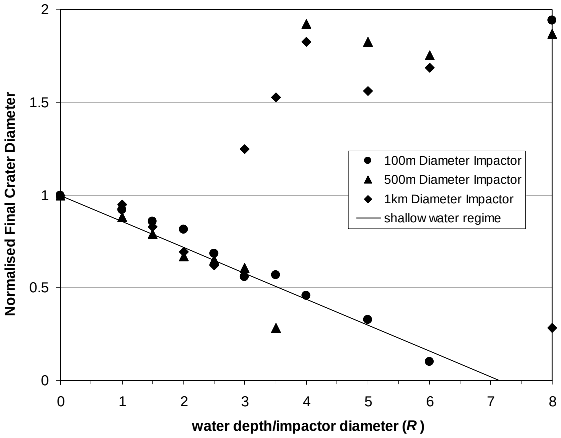

Fig 1: Plot of final crater diameter, normalised by the diameter of the crater formed when no water layer is present, as a function of relative water depth *R* (for impactor diameters of 100-m, 500-m and 1-km). The craters formed within the shallow water regime (see text for further discussion) are well fit by the straight line plotted (Equation 1).

Figure 1 shows our model results of D_N, the ratio of the final crater diameter at a given R to the final crater diameter for R=0 (dry target), as a function of R. Ignoring the data points that correspond to the intermediate water depth regime, a linear regression gives:

$$D_N = 1 - (0.14\pm0.02)R, \quad \text{for } 0 < R < 7. \quad (1)$$

Discussion: Using the quantitative relationship between final crater diameter and the ratio of water depth to impactor diameter (Eq 1), we have calculated expected size-frequency distributions of craters on Earth that for the first time account for the presence of the oceans (Figure 2). The model used makes several necessary simplifications; however, given the uncertainty in estimates of the current terrestrial impactor population, we believe that several important conclusions can be drawn from our model results.

1. The presence of the oceans reduces the number of craters smaller than 1-km in diameter by about two thirds, the number of craters about 30-km in diameter by about one third. For craters larger than ~100-km in diameter the oceans have little effect.
2. More craters of a given size occur in the oceans than on land for craters larger than ~12 km in diameter; at diameters below this more craters of a given size form on land than in the oceans.
3. In the last 100 Ma about 150 impact events formed a 5-20-km diameter impact-related resurge feature, or disturbance on the seafloor, instead of a crater.

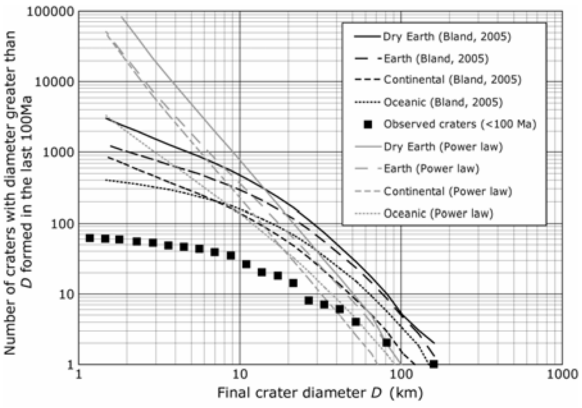

Fig 2: The predicted cumulative size-frequency distribution of craters larger than 1-km in diameter that would form on Earth in a 100 Ma period. Black lines are for results calculated using the impactor population from [14] and grey lines assume a power-law impactor size-frequency distribution derived from observational data. Solid lines represent a 'Dry Earth' case, assuming no oceans are present on the Earth. Wide-dashed lines are for the whole Earth with current ocean coverage. Dashed lines show the craters forming on the continents and dotted lines show those which form in the oceans. For comparison, the observed craters known to have formed in the past 100Ma are also plotted [15].

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