SHOCK WAVE PROPAGATION AND DAMAGE TO THE TARGET IN OCEANIC IMPACT EVENTS.

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Introduction: Most impact events on the Earth will occur in the oceans and seas that cover more than two-thirds of the Earth's surface. However, of the 170 craters documented, only 15-20 are thought to have formed in a marine environment [1]. The youth of the ocean floor, deep sea sediments and the lack of detailed topographical study of the ocean floor explains, in part, the lack of detected underwater craters. In addition, many impacts may not have left any evidence of a crater, because the water depth to projectile diameter ratio was sufficient to prevent cratering occurring. The only deep sea impact structure detected so far is Eltanin (located in the Bellingshausen Sea) [2], which is characterised by a zone of chaotically mixed sediments, most likely originating from impact-induced turbulent water currents [3]. Present observations do not allow identification of an impact structure on the ocean bottom.

We investigate oceanic impacts in the lab through use of the University of Kent's two-stage light gas gun, to examine the influence of a water layer on the cratering process in the target rock. The lab impacts are modelled using AUTODYN-2D (based at UCL), and we attempt to model the deep ocean impact Eltanin, in terms of the propagation of the shock wave through the water column and the target, the peak pressures endured and the damage inflicted on the basement rock.

Laboratory impacts: Impacts of 1 mm diameter stainless steel projectiles into water layers over 17% porosity saturated and unsaturated sandstone (density = 2.35 g cm^{-3} and 2.18 g cm^{-3} respectively) were conducted at 5 km/s. The depth of the water layers was varied from 0 to 12 mm while all other impact parameters remained constant. A saturated target allowed a greater volume of material to be excavated than an unsaturated target, perhaps an intuitive outcome given that the yield strength of the wet target (43 MPa) was found to be approximately half that of the dry target (90 MPa). See [4] for a full discussion.

For our unsaturated sandstone we find that a projectile diameter to water depth ratio of 1:10 is required to prevent a crater forming on the basement rock, comparable with similar experiments performed by [5] into water layers overlying granite and basalt targets. For our saturated sandstone this ratio is 1:12. Both of our data sets lie within the data range presented by [6], for impacts into sand.

Hydrocode modelling of lab impacts: The impacts into unsaturated sandstone were replicated using the numerical modelling package AUTODYN-2D to provide further insight into the cratering process at this scale (see [7] for a general description of the code]. The Smooth Particle Hydrodynamics (SPH) solver was used for the simulations, with a resolution of 20 SPH particles per projectile diameter. AUTODYN-standard material models were used for stainless steel and water. The sandstone target was defined using the shock equation of state, based on input values derived from [8]. Mechanical properties were drawn from our own experiments, the AUTODYN material library and [9].

Comparison of the crater dimensions and morphology produced in AUTODYN and the lab. AUTODYN allows analysis of material status and assigns tags according to whether the material is hydro, elastic, plastic or has failed. The areas which are indicated as 'bulk fail' are of particular interest as these are likely to delineate the spall region observed in the lab, particularly as the lab targets are held vertically, facilitating the ease at which weakened material can fall from the target. In fact, when we plot the profiles of our craters produced in the lab against the craters produced in AUTODYN as delineated by the failed 'spall' zone, we see a very close match (Fig. 1).

Propagation of the shock wave and peak pressures in the underlying basement rock. The peak pressures experienced in an impact event are directly related to the geological/mineralogical signatures recorded in the target rock. The effects of shock metamorphism begin to occur at ~2 GPa [10]. We record peak pressures down to 0.5 GPa in the underlying sandstone for a water depth to projectile diameter ratio of 1:10 (Table 1). For a water depth of 12 mm, merely a scar is visible on the surface of the lab specimen. The resolution of the numerical model was not sufficient to record any damage to the surface at this water depth, and no pressures were recorded in the target, implying that the basement rock remains essentially unchanged. For water depths of 7.5 - 10 mm, our models reveal that although measurable craters are observed in the basement rock, the projectile itself doesn't reach the target. The crater must therefore be due to the shock wave from the impact that blasts the surface at the water-target interface. This effect is illustrated further in the following section.

Modelling the Eltanin impact: The Eltanin impact was modelled in order to compare with other modelling attempts [1,3] and with direct observations, to further our understanding of the influence of a water layer on the signatures found on the ocean floor. We model the Eltanin impact event in terms of investigating the projectile diameter to water depth ratio, the peak pressures recorded in the basement, and the damage to the basement rock. We build similar models to that of [3], but use SPH to model the impact of a 1 km diameter basalt projectile impacting into a water column of 7 km (this accounts for the fact the impact is likely to have been at 45 degrees through a 5 km deep ocean) at 20km/s. We find that the projectile does not reach the ocean floor, but that the shock wave propagates through the water column and is reflected at the water-rock boundary interface (Fig. 2). The pressures recorded in the basement rock (basalt) peak at almost 3 GPa, sufficient to produce some shock metamorphism effects [10]. We also note that the basement rock is 'dented' by the impact event, to a lateral extent of 24 km and to a depth of 250 m. We are unable to model sedimentation using AUTODYN, but it is possible that this impact scar will subsequently be infilled with sediments due to strong resurges of water at the ocean-target interface. Indeed, zones of chaotically deposited sediments with layers of thickness ranging from 20 to 40 m were recovered from sediment cores, although there is no evidence for a crater [2]. Furthermore, fragments of the projectile were also retrieved, and we also observe that some projectile fragments are dispersed into our simulated ocean, which would presumably be distributed around the impact site if the model was allowed to run for longer.

Conclusions: While the effects of impact cratering into water layers on the target can be investigated efficiently in the lab, an advantage of numerical modelling is that the peak pressures across the target can be mapped in order to compare with observations at natural impact structures. We have demonstrated AUTODYN as a suitable tool to replicate our laboratory impacts, and have applied our models to large planetary impacts. In the lab-scale (5km/s) impacts when the water depth is 7.5 to 10 times the projectile diameter, a measurable depression is formed in the basement rock; modelling reveals this to be due to the impact of the shock wave, and not a direct hit by the projectile. Similarly, for the Eltanin model, the 1 km diameter projectile does not strike the ocean floor if it traverses a 7 km deep column of water at 20 km/s. This observation will vary depending on the impact velocity, projectile mass/diameter and water depth.

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References: [1] Shuvalov V. V. & Trubestkaya I. A. (2001) *Solar System Research* 36, 417-430. [2] Gersonde, R. et al. *Nature 390* 357-363. [3] Wünnemann K. & Lange M. A. (2002) *Deep-Sea Research II 49* 969-981. [4] Baldwin E. C. et al. (2007) accepted for publication *Meteoritics & Planet. Sci*. Feb 2007. [5] Milner D. J. (2007) *Thesis, University of Kent* 236p. [6] Gault D. E & Sonett C. P. (1982) *Geol. Soc. America Spec. Papers 190* 69-92. [7] Hayhurst C. J. & Clegg R. A. (1997) *Int. J. Impact Eng. 20* 337-348. [8] Ahrens T. J. (ed) (1995) *AGU Ref. Shelf 3*. [9] Llama R. D & Vutukuri V. S (1978) *Handbook on Mechanical Properties of Rocks VII* 481p. [10] French B. (1998) *Traces of Catastrophe* 120p.

Water depth, mm	Peak Pressure, GPa
0	85
2.5	17
5	4.5
7.5	1.5
10	0.5
12	/

Table 1. Peak pressures in the target as a function of water column depth for laboratory impacts.

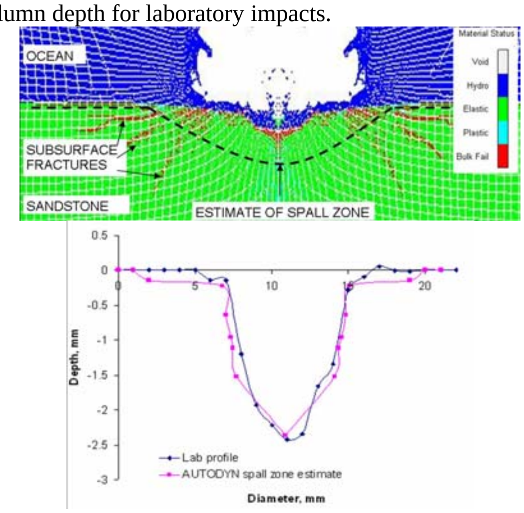

Fig. 1. Output for the impact of a 1 mm stainless steel projectile into 5 mm of water overlying sandstone. Top: AUTODYN material status plot used to delineate spall zone. Bottom: crater profile as determined in the lab compared with profile estimated from the spall zone mapped out above.

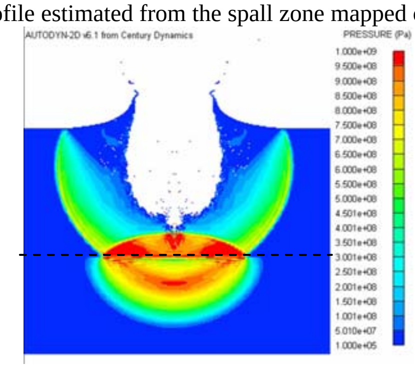

Fig. 2. Pressure contours at 1.77 seconds after impact at the ocean surface. The reflection of the pressure wave occurs at the ocean-target interface (indicated by dotted line).