



Cratering and modification of wet-target craters: Projectile impact experiments and field observations of the Lockne marine-target crater (Sweden)

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Abstract—Marine impacts are one category of crater formation in volatile targets. At target water depths exceeding the diameter of the impactor, the zones of vaporization, melting, and excavation of the standard land-target cratering model develop partially or entirely in the water column. The part of the crater that has a potential of being preserved (seafloor crater) may to a great extent be formed by material emplacement and excavation processes that are very different from land-target craters. These processes include a high-energy, water-jet-driven excavation flow. At greater water depths, the difference in strength of the target layers causes a concentric crater to evolve. The crater consists of a wide water cavity with a shallow excavation flow along the seabed surrounding a nested, deeper crater in the basement. The modification of the crater is likewise influenced by the water through its forceful resurge to fill the cavity in the water mass and the seafloor. The resurge flow is strongly erosive and incorporates both ejecta and rip-up material from the seabed surrounding the excavated crater. A combination of field observations and impact experiments has helped us analyze the processes affecting the zone between the basement crater and the maximum extent of the water cavity. The resurge erosion is facilitated by fragmentation of the upper parts of the solid target caused by a) spallation and b) vibrations from the shallow excavation flow and, subsequently, c) the vertical collapse of the water cavity rim wall. In addition, poorly consolidated and saturated sediments may collapse extensively, possibly aided by a violent expansion of the pore water volume when it turns into a spray during passage of the rarefaction wave. This process may also occur at impacts into water-saturated targets without an upper layer of seawater present. Our results have implications for impacts on both Earth and Mars, and possibly anywhere in the solar system where volatiles exist/have existed in the upper part of the target.

INTRODUCTION

The most common target for impacts on Earth is the approximately 70% of Earth's surface that is covered by seawater and land where water occurs on or near the surface (e.g., land ice, ground water)—all of which are volatile-rich. This paper focuses on the situation where the upper part of the target consists of a layer of water and/or water-saturated sediments. In deep water (i.e., water depth H exceeding the impactor's diameter D), the crater may form only in the water column without being preserved, or reach into the seafloor and form what we prefer to call a marine-target crater (Ormö and Lindström 2000). In these cases, the water strongly influences crater morphology and geology (Ormö et al.

2002). The thick layer of water reduces the extent of the excavation zone into the seafloor. Water constitutes most of the ejecta, and a relatively large part of the preserved seafloor crater is developed in the displacement zone. However, depending on the strength of the substrate, even very shallow water (i.e., $H < D$) can greatly influence the crater morphology if it acts as an agent to destabilize the substrate (Ormö and Lindström 2000; Horton et al. 2006; King et al. 2006).

At water depths much less than the impactor's diameter, the growth of the transient cavity generally follows what is known from the "standard" land-target scenario, and the water is just another layer in the formation of the overturned flap and ejecta curtain (Ormö et al. 2002). It is possible that



Fig. 1. The hemispherical test bed used in the experiments. It has been lined with a plastic sheet so that it can hold both sand and water. The sand surface is 2 m wide, and the depth below the sand surface is 1 m.

the close interaction between the water and the solid ejecta in the ejecta curtain causes fluidized ejecta flow. However, these deposits are likely reworked by the water resurge. Of the known marine-target craters, only Chicxulub (Mexico) has thus far been suggested to have ejecta deposits that may have formed as fluidized ejecta (Kenkmann and Schönian 2005).

The complex processes involved in the formation of marine-target craters require that the analysis be based on a combination of methods, all of which have their own limitations (e.g., geological and geophysical studies, numerical modeling, laboratory experiments). In this paper, we discuss some of the special features noticed at marine-target craters and how small-scale impact experiments may be used to explain the processes behind these features. Special attention is given to the Lockne crater, Sweden, which shows strong influences from the target water on both cratering and modification.

METHOD

The process of crater formation can be compared to an explosion, with some important differences concerning the explosion such as scaling problems, lack of projectile momentum, and gas expansion instead of shock-driven excavation (Melosh 1989). There are also differences between cratering from hypervelocity impacts and the mechanical push from the projectile in low-velocity impacts. This leads to different relations between the impactor properties and the resulting craters. In this study, we are interested in certain aspects of the cratering that are not significantly affected by scaling differences.

The impact experiments were performed in November 2003 in a hemispherical outdoor test pit, 2.2 m wide and 1 m deep (Fig. 1). The pit was lined with a plastic sheet and then filled with a predominantly medium-grained beach sand. The humidity of the “dry” sand was not determined, but it appeared “dry” and noncohesive. Tests were performed with dry sand, water-saturated sand, and water-saturated sand covered by a layer of water. The water depth was selected so that it equaled approximately 5–10% of the expected diameter of the resulting water crater, which is similar to the relation calculated for the Lockne crater (Ormö et al. 2002). The tests were recorded with a digital high-speed camera (1000 frames/s), a digital video camera (about 25 frames/s), and a digital still-frame camera. We used an ordnance disposal device (standard CHUTA IB-060 gun) loaded with a 0.50 cal cartridge with 8 g single base powder that accelerates 4×7 cm cylindrical projectiles of, in this case, either aluminum or steel to a maximum velocity of a few hundred m/s (Fig. 2). The purpose was to generate a crater large enough to allow studies of both cratering and modification (e.g., resurge) with the available equipment for documentation. By analyzing the frames taken by the high-speed camera and relating them to the distance between the camera and the target, we can see that the average velocity was more than about 400 m/s (i.e., the projectile is not recorded by the high-speed camera between ignition and contact with the target). The velocity of the aluminum projectile can be calculated to be 1.7 times higher than that of steel due to its lighter weight. The exact velocity of the projectile is not known, but it is of no importance for this study.

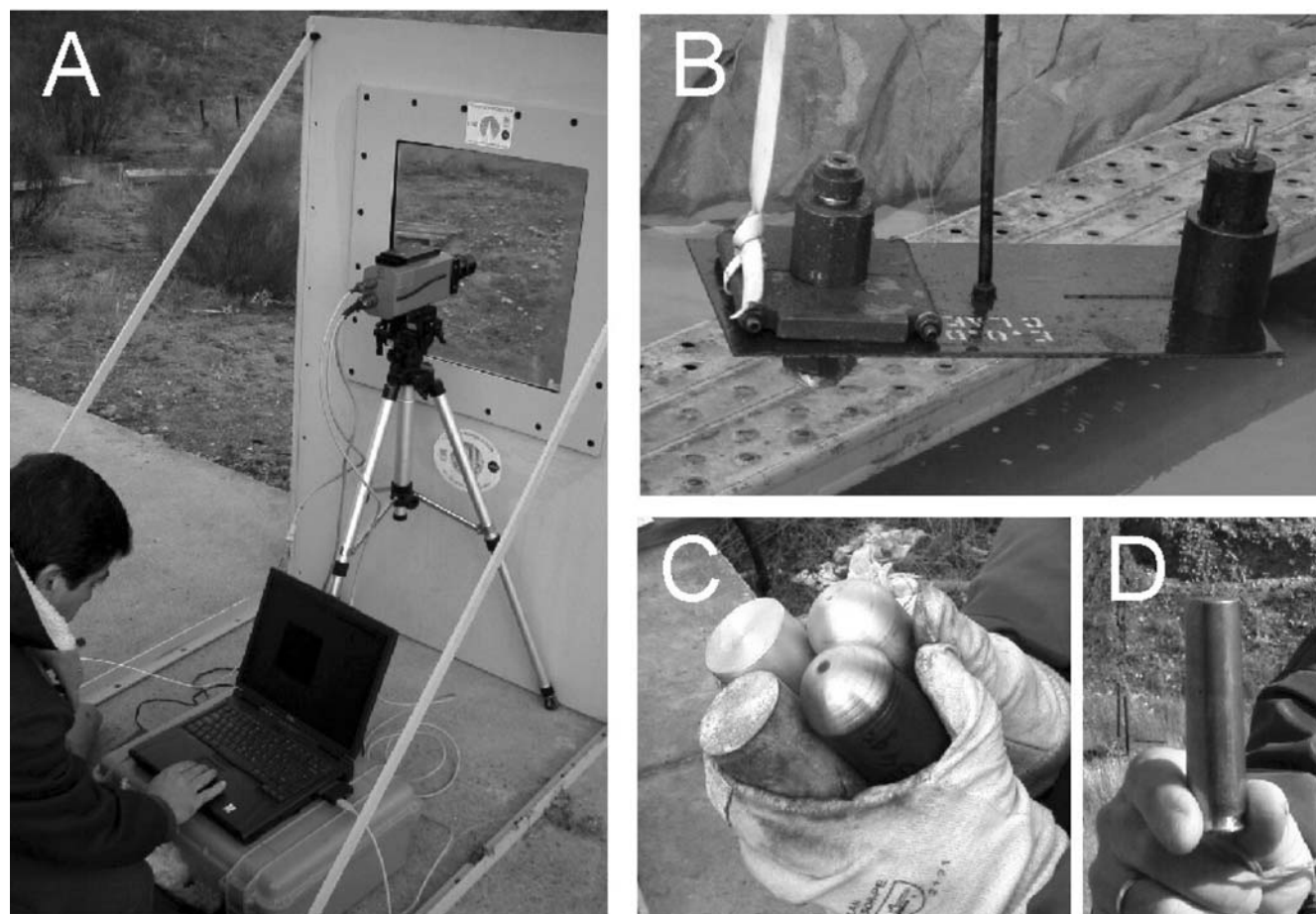


Fig. 2. The equipment used in the experiments. a) A high-speed PHANTOM color CMOS camera recording at 1000 frames/s. b) The cylinder to the left is the gun. The cylinder to the right is a counter weight. c) Round-tip and flat-tip projectiles of either steel or aluminum. d) An electrically ignited cartridge.

GEOLOGICAL SETTING OF THE LOCKNE CRATER

At the time of the Lockne impact in central Sweden about 455 million years ago, the target area was situated on the western fringe of Baltica, a minor continent that much later became the northwestern part of Europe. In the course of its plate tectonic movement across the southern hemisphere sea, Baltica was heading for an ultimate collision with Greenland and North America. The sea in the future collision zone consisted of an eastern platform, probably not deeper than about 200 m, covered by extremely slowly deposited limestone, and descending toward the west through a slope that was likewise covered by limestone of the same general kind. It was on this slope, at a depth of at least 500 m, that the impact struck. A water depth of about 700 m has been found to give a best fit in numerical simulations of the geology and geomorphology of the Lockne crater (Ormö et al. 2002; Shuvalov et al. 2005). To the west of the slope there was an intracontinental basin plain with dark mud deposition (Andersön Mudstone) at a depth of about 1000 m. The western margin of this basin consisted of an east-facing slope

with turbidite deposition (Föllinge Greywacke) and still farther to the west, but still on the continent, a rising belt of overthrust nappes out of which evolved the Caledonian mountain chain. According to Mattern (2005), sand-rich fans form in the immediate vicinity of active tectonism and normally extend 15–85 km. This places Caledonian tectonism, not younger than early Middle Ordovician, at a maximum distance of about 85 km from Föllinge Greywacke localities.

The evolution of the Caledonian mountain chain was continued by further, east-directed thrusting with nappes that ultimately slid over the Lockne crater, providing a thick pile of tectonized rock beneath which the crater survived in an excellent state of preservation.

In addition to the seawater, the target consisted of about 50 m of cemented, sometimes marly, Ordovician limestone overlying a ~30 m thick sequence of mainly poorly consolidated dark argillaceous sediments of Cambrian and Lower Ordovician age. The sediments rested on the nearly flat sub-Cambrian peneplain forming the top of Proterozoic crystalline rocks.

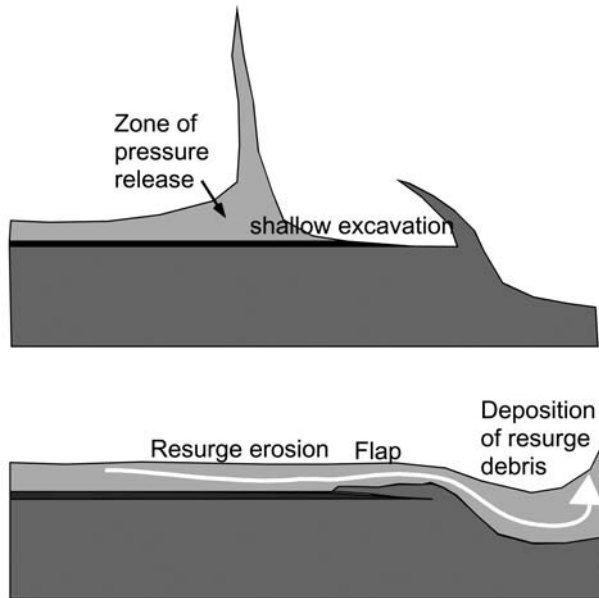


Fig. 3. Highly schematic diagram of a relatively deep water impact showing separate development of the water crater and basement crater, as well as the water resurge during crater modification (white arrow). Light gray = water; the black layer = sedimentary target sequence; Dark gray = crystalline basement. The diagram is based on the Lockne marine-target crater, Sweden.

SPECIAL FEATURES OBSERVED AT THE LOCKNE CRATER

The Lockne crater illustrates an impact into relatively deep water ($H \geq D$). The Lockne impact generated a basement crater 7.5 km wide, surrounded by a 2.5 km wide brim where water and sediments were removed before the deposition of wide ejecta flaps from the nested basement crater (Fig. 3). In a striking difference from “standard” land-target crater excavation, 3-D modeling of the Lockne event shows that the basement crater was generated by a high-velocity water stream initiated by the shock wave propagating through the water (Shuvalov et al. 2005). In addition, modeling shows that the crater center lies between the point of initial projectile/water contact and a point near the rim of the transient basement crater where the projectile hit the seafloor, and that the flaps were formed by overturning of near-surface layers. The results are supported by detailed morphology and geology of Lockne obtained by extensive mapping and drilling (Lindström et al. 2005), and geophysical modeling (Sturkell and Ormö 1998). Tangential stresses acting on the semicoherent flaps as they were overturned outwards from the crater generated wedge-shaped, rip-a-part openings that later channeled the water rushing back towards the crater (Lindström et al. 2005). Strong erosion from the debris-loaded resurge overdeepened the openings to form resurge gullies (von Dalwigk and Ormö 2001; Ormö and Miyamoto 2002). A detailed study of the elevation of the top of the

crystalline basement (i.e., the peneplain) around the crater showed that there is no structural rim uplift of the basement below the flaps (Sturkell and Lindström 2004). This observation is remarkable since at land-target craters structural uplift is responsible for about half of the rim height (Melosh 1989).

The crystalline flaps and large bodies of coherent crystalline ejecta rest on increasingly higher stratigraphic levels in the sedimentary target succession outwards from the basement crater. The removal of sedimentary target rocks prior to the deposition of the basement crater ejecta is a consequence of the circumstance that the crater developed in the water column independently of the crater that formed in the basement (Ormö et al. 2002). The ejecta around Lockne likely were distributed to great distances by the outgoing water surge and again redistributed by the subsequent resurge into the crater (Shuvalov et al. 2005). Interestingly, the coherent ejecta deposits represented by the ejecta from the basement crater are nearly devoid of any material from the sedimentary part of the target. Only the lowermost part of the sedimentary sequence (i.e., poorly consolidated black mud) may be represented in dark matrix in some parts of the otherwise crystalline ejecta deposits (Lindström et al. 2005). In contrast, the resurge deposits are dominated by material from the target sediments. A significantly higher amount of crystalline fragments within some of the sedimentary breccias has made it possible to quickly distinguish between sedimentary breccias formed by the resurge of water loaded with ejecta and rip-up seafloor material (Lockne Breccia), and a mainly autochthonous sedimentary breccia of different genesis (Ynntjärnen Breccia) (Lindström et al. 2005). The formation of the Ynntjärnen Breccia seems to be strongly linked to the cratering process and, therefore, is of great importance to the understanding of the formation of the concentric cavity.

The term “Ynntjärnen Breccia” refers to the type locality near Lake Ynntjärnen, about 3.5 km outside the western rim of the basement crater. Previously, this unit was included in the Lockne Breccia resurge deposit, but it became evident that a division of the Lockne Breccia in two parts was needed. Whereas the Lockne Breccia provides abundant evidence of forceful blending of material from all parts of the target succession—even crystalline rocks—the Ynntjärnen Breccia is composed of strongly shaken sediments, mainly marly limestones, but with the original bedding still visible. Ynntjärnen Breccia often forms the uppermost few meters of autochthonous occurrences of the Ordovician limestone in the vicinity of the crater. The blocks of bedded limestone in the breccia can reach hundreds of cubic meters and have previously been described as autochthonous limestone with breccia injections (Sturkell and Ormö 1997). This generic model can be kept, although the rock in general should be included in the Ynntjärnen Breccia. The Ynntjärnen Breccia sometimes occurs in positions below or near large bodies of

crystalline ejecta. It may also be overlain by Lockne Breccia, sometimes with a gradual transition that can make them hard to distinguish from each other. The reason for this is that the Lockne Breccia to some extent is made up of material ripped up from a shattered limestone substrate (von Dalwigk and Ormö 2001).

RESULTS FROM IMPACT EXPERIMENTS

Experiment 1: Dry Target

An aluminium projectile (235.5 g, flat point) was shot from 40 cm above the sand surface. It generated a crater 64 cm wide and 13 cm deep. The rim height was 2 cm (Fig. 4a). The projectile was buried 15 cm below the apparent crater floor. A second experiment with a steel projectile (686 g, flat point) shot from the same height above the sand surface generated a crater with exactly the same dimensions. However, in this case the projectile was buried 56 cm below the apparent crater floor. The steel and aluminum projectiles have the same dimensions. As no size difference could be detected between the resulting craters, the tests continued with alternating aluminum or steel projectiles with flat or rounded tips.

Experiment 2: Saturated Sand, Less than 0.5 cm Water Depth

A steel projectile (686 g, flat point) was shot from 40 cm above the sand surface. It generated a surface blast in the early part of the excavation stage, removing the surface water to an extent of about 60–70 cm from the center. During this phase, several vents (like miniature geysers) forming in the sand surface to a distance of about 50–60 cm from the point of impact were noticed (Fig. 5a). A distinct crater 25–30 cm wide formed in the wet sand. It lacked a raised rim and did not collapse until it was reached by a resurge of surface water. It appeared that the surface water flow reached the crater rim before the sand was again saturated by water moving through the pore space. Once again saturated, the initial crater collapsed and left a shallow, flat-floored 44 cm wide crater with a 3 mm high rim. The rim was crossed by numerous small furrows from the water resurge (Fig. 4b).

Experiment 3: Saturated Sand Covered by 10 cm Water

An aluminum projectile (212 g, rounded tip) was shot from 40 cm above the sand surface (i.e., 30 cm above the water surface). At an early stage of the excavation, a water spray was formed in a zone around the growing water cavity. Later it was visible that water was ejected at a steep angle (Fig. 5b). Although some water was ejected to 1–2 m above the impact point, the main part of the ejected water formed a cupola ~1 m wide and 50 cm high. This water fell back almost

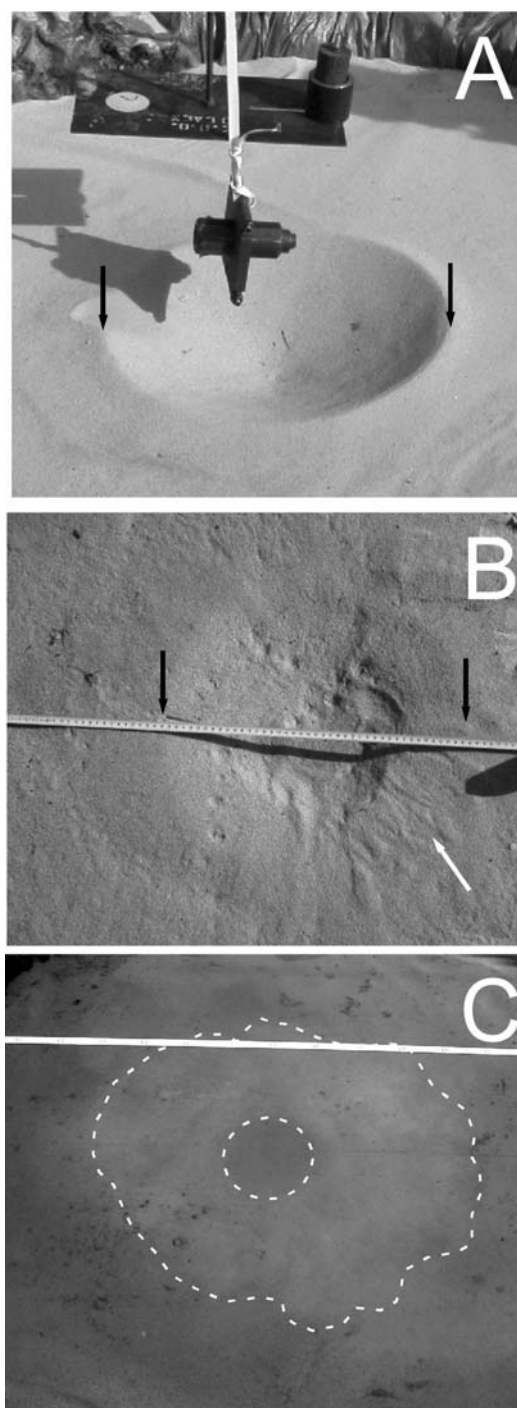
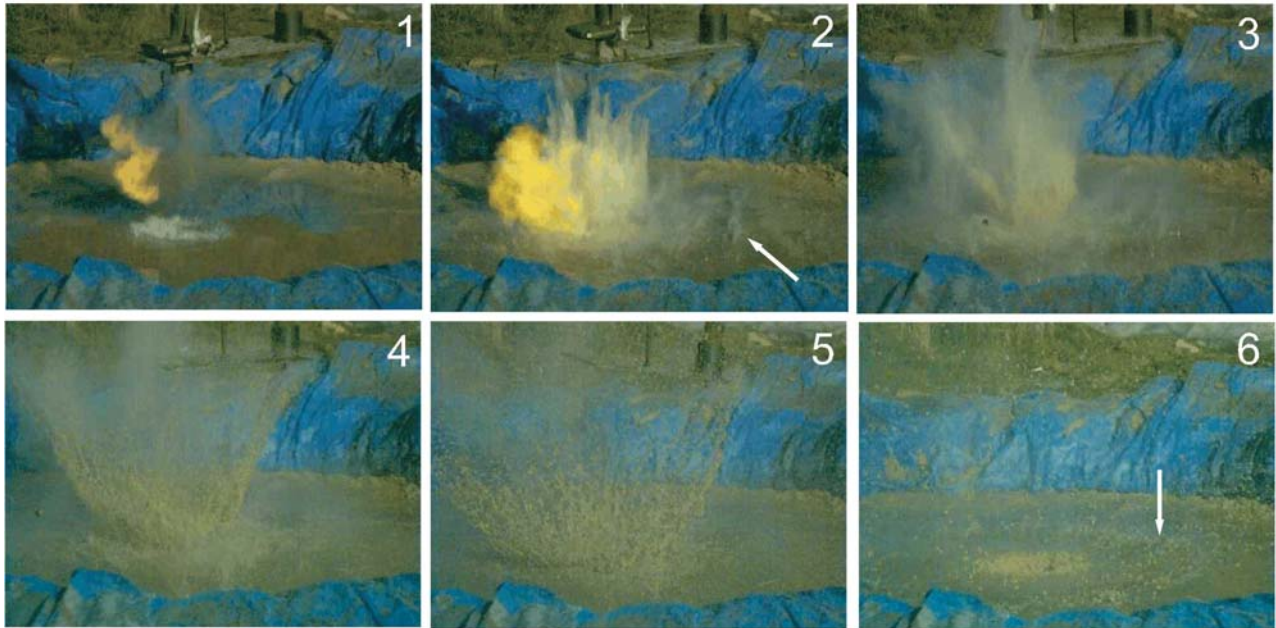


Fig. 4. The resulting craters from the experiments. a) Experiment 1 (dry sand). The rim-to-rim diameter is 64 cm (black arrows). b) Experiment 2 (<0.5 cm of water over saturated sand). The crater is strongly collapsed with furrows from the water resurge visible in the lower right sector of the rim (white arrow). The rim-to-rim diameter of the central depression is approximately 25 cm, and of the weak topographic rim about 45 cm (black arrows). c) Experiment 3 (10 cm of water over saturated sand). The structure consists of a crater 25 cm wide (the circular dark area within the inner stippled line), surrounded by a flat-topped elevated zone 30–40 cm wide and 1 cm thick (the outer stippled line).

A. Experiment 2. Impact into <math><0.5\text{ cm}</math> of water over saturated sand



B. Experiment 3. Impact into 10 cm of water over saturated sand

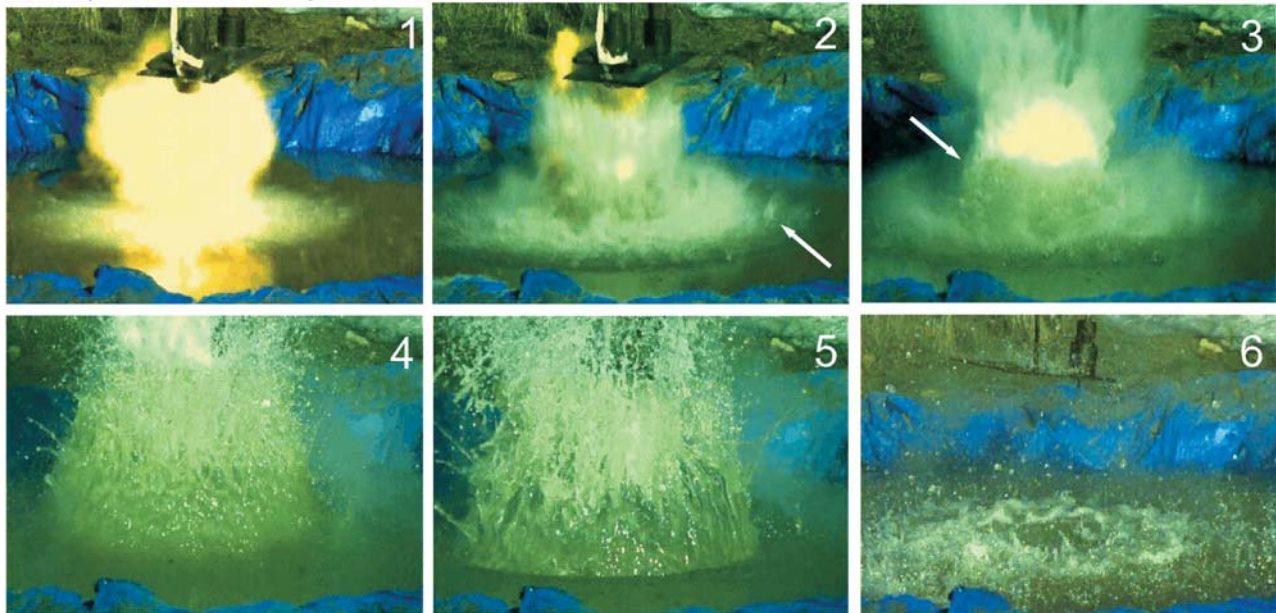


Fig. 5. Impact experiments with a gun for ordnance disposal (4×7 cm cylindrical projectiles of aluminum or steel). a) Experiment 2. Frame 1: The projectile has just penetrated the target and a ring of water spray is forming. The flame is from the gun. Frame 2: The zone of the water spray formation is expanding as the stress wave propagates outwards. The white arrow indicates a “minigeysers” with localized venting of spray. Frame 3: An ejecta curtain of sand begins to form. Frames 4, 5, and 6: The ejecta curtain moves outwards as the crater expands. Venting continues until frame 5. Note the ring (arrow) that forms when the ejecta meets the resurging surface water (Frame 6). b) Experiment 3. Frame 1: The projectile penetrates the target. A white zone with bubbles forms in the water after the passage of the stress wave. The flame is from the gun. Frame 2: The white zone with bubbles is transformed into a spray. The white arrow indicates a location with an irregularity in the spray formation, possibly due to venting from the substrate (“mini-geyser”). Frame 3: An air blast blows the spray outwards. An ejecta curtain of water is forming (arrow). Frame 4: The water crater ejecta curtain expands with steep angle. Frame 5: The collapse of the water ejecta curtain occurs nearly vertically. Frame 6: The vertical collapse of the water ejecta curtain continues during the resurge and generates a ring of foaming water. No central peak of water can be observed, although it is possible that it forms before the complete collapse of the water ejecta curtain.

vertically. The water ejecta did not cause any noticeable wave outward from the crater. Any obvious wave generation was due to oscillations from the crater collapse. There was no significant central peak of water. The cupola of water obstructed the view of the cratering of the substrate, which must have occurred at the center of the growing cavity. The resulting apparent crater in the substrate consisted of a shallow, flat-floored, 25 cm wide crater, surrounded by a flat-topped elevated zone 30–40 cm wide and 1 cm thick, presumably of ejecta from the central crater (Fig. 4c). Most likely, the crater formed in the sand substrate suffered severe modification during the resurgence of the water.

DISCUSSION

Notwithstanding the limitations of our impact experiments, we can see that they help us understand some of the processes responsible for certain features of marine-target craters. Of special interest is the formation of a water spray during the contact and compression stages in both wet-target experiments, as well as the steep rise of the water cavity wall in Experiment 3. Numerical simulations of marine impacts show a zone of pressure release developing as the rarefaction wave passes outwards through the target. This zone is located in front of the expanding water cavity wall (Ormö et al. 2002). It can be assumed that such pressure release will be responsible for water vapor formation and volume expansion. In our experiments, the pressure is not high enough to be considered a true shock wave. We prefer to call it a stress wave. In any case, the propagation of this stress wave through the water and saturated sediment causes a disintegration of the water into tiny droplets (“spray”), possibly due to the release of pressure. Once this spray is formed, it continues to spurt out from the water mass and saturated sediment long after the stress wave has passed. In Experiment 2 it seems to be localized to certain vents (“mini-geysers”); in Experiment 3 there seems to be a more general generation of the spray from the water mass outside the expanding water ejecta curtain. However, a few persistent “mini-geysers” are visible on the water surface (Fig. 5b). It is not known if these are evolving from the water column or if they originate from the saturated substrate. In both wet-target experiments, the zone of ongoing venting of water spray is partly consumed by the growing crater cavity, although much of the zone extends far outside the reach of the transient crater. The spray formation represents a volume expansion of the water. The cause for the localized venting of the spray remains to be further studied. It is known from large-scale explosion experiments in saturated alluvium that violent dewatering of the sediments may cause dewatering pipes and small “pseudo-volcanic sand cones” surrounding the crater (Jones 1977). In these cases, the water escape structures were often aligned along radial and circumferential fissures caused by the explosion. Therefore, it can be assumed that irregularities in the compaction of the

sand, either already existing in the target or caused by the projectile impact, may cause a localized expulsion of the spray.

Possibly, such a violent pore water spray causes fluidization and instability of the sedimentary sequence outside the crater. Similarly, poorly consolidated sediments can become fluidized and injected through other beds (Alvarez et al. 1998). At locality “Berget” at the Lockne crater, Lower Cambrian unconsolidated sand and gravel was injected as a sill into Middle Cambrian shale (Simon 1987; Sturkell and Ormö 1997). If the crater is surrounded by relatively unconsolidated, saturated sediments, these sediments, once fluidized, may continue to slump into the crater over the collapsed rim (cf. Chesapeake Bay, USA, Horton et al. 2006; Powars et al. 2001; Wetumpka, USA, King et al. 2006) and generate a much larger structure than is expected from the amount of kinetic energy released from the impact. The Lockne crater, on the contrary, does not show this type of extensive slumping, possibly due to the relatively thin sedimentary sequence covering the crystalline basement. It is uncertain if the pore water in the limestones and marls in the target at Lockne would be free to move, or rather be bound to the clay minerals preventing a rapid spray formation. Hence, whereas violent dewatering may be responsible for some fluidization and injection of clastic sediments at Lockne, its effect on the formation of Ynntjärnen Breccia can, as of yet, only be assumed. Lindström et al. (2005) suggest that the Ynntjärnen Breccia formed by several processes including vibration during the excavation of the water crater, shock from the deposition of the thick crystalline ejecta deposits, and finally, the overriding resurgence flow. In Experiment 3, which is the experiment most similar to the Lockne impact, a nearly vertical collapse of a very high water-crater ejecta curtain is evident. A similar steep-angle rise of water ejecta to a height of almost 2 km and subsequent vertical collapse is observed in 3-D numerical simulations of the Lockne impact (Shuvalov et al. 2005). It is likely that a vertical collapse of a water crater rim 2 km high would cause strong seismic vibrations of the substrate, and thus contribute to the formation of Ynntjärnen Breccia. Such oscillations of the seabed would further aid the rip-up of sediments during the initiation of the resurgence flow.

It is possible that the lack of structural uplift around the Lockne basement crater is an effect of the basement crater formation mainly in the displacement zone and/or of the cratering driven by the high-velocity water stream causing relatively little fracturing and breccia injection below and outside the basement crater rim. Magnetic modeling by Sturkell and Ormö (1998) shows an “inverted sombrero” shape of the fractured zone of the crater. At the time of the magnetic study, the erosional level of the crater was assumed to be below that of a coherent ejecta layer. An observed asymmetry between extensive near-surface fracturing on the western side reaching about a crater radius outside the

basement crater rim versus the near absence of a similar zone on the eastern side, was explained by a postimpact tectonic tilt of the structure toward the west. New field observations (Lindström et al. 2005) show that the magnetic model corresponds well with the known crater geology, but that the model instead expresses the variable extent of the brecciated crystalline flaps around the basement crater and the relatively intact basement below the rim and the flaps.

The projectile impact experiments will continue in an indoor facility that allows a better control of the target environment and documentation of experiments. We will try to create a gun that allows oblique impacts, not least because this may allow us to film the cratering and resurge from vertical view.

CONCLUSIONS

This paper only touches on a few of the dominant geological and morphological effects of seawater in the formation of marine-target craters. Nevertheless, it is mainly these features that are important for detecting marine-target craters, or craters formed with any kind of volatiles in the upper part of the target, in remote sensing of other planetary bodies in our solar system. Although no strong candidates could be presented, Ormö et al. (2004) assessed that as many as 1400 detectable (i.e., large enough to have been preserved) marine-target craters may have formed on Mars in the most favorable case (i.e., long-lasting oceanic phases). Continued studies of terrestrial marine-target craters may help understand past climatic conditions on Mars.

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