Impacts into Marine and Icy Environments – A Short Review

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Abstract. In this review we discuss the current knowledge of impact events into marine and icy targets. This includes the major consequences of impact in marine depositional basins and on icy targets. We also discuss some of the future fields of research that could be of interest, in particular questions regarding triggering of volcanic activity, tsunami generation, and impact-associated petroleum reservoirs. In the discussion of the icy impact craters a summary of the exploration history is presented, both discussing comets and icy targets. An updated schedule for related missions is given, expressing the importance of knowing these processes also for understanding the development of the solar system.

1 Marine Impacts

1.1 Introduction

Because only few examples are known, impacts into marine environments and icy targets are amongst the least understood and studied parts of impact crater geology. This is, however, in contradiction to their global importance. More than 70 % of the earth is covered by water and 14% (of the earth) by ice (10.5% sea-ice included). These proportions have varied significantly over geological time, when numbers of asteroids and comets have struck both rock, water, or icy targets. Impacts on icy targets are also of great importance in understanding the developments of the various planets and the satellites of the outer planets, e.g., Mars or Europa. In addition, impact mechanisms, crater formation and collapse, melt production and ejecta distribution are poorly known for impact on targets other than solid silicates; the response of water and ice to impact events clearly deserves more thorough studies. So far the general focus of most research has been limited to the more easily accessible sub-aerial (on-land) craters and impacts into solid basement terrain. Moreover, collisions with icy bolides have also received too little attention. It should be added, however, that the last few years this trend has changed somewhat.

Consequently, it is of great interest to summarize information on this topic and point out some of the main, recent developments to better understand the formation of marine craters and ejecta production. Such an approach will result in improved ejecta - crater correlations. A specific aspect of marine cratering, which is not present in subaerial impacts, is the significant water effect. The generated waves and/or tsunamis can severely modify the morphology of the crater and influence post-impact sedimentation. The consequences of marine impacts on the biological evolution, their potential effects on oceanic circulation and the development of short or long-term hydrothermal systems at the bottom of the ocean also deserve attention. Documenting impact on water and ice targets not only contributes to our understanding of the geological record of impact events and enables us to foresee the environmental and hazardous consequences of these events, but it also helps in reconstructing the evolution of other important planetary bodies.

1.2
The Status of Marine Impacts Events

Currently about 170 terrestrial impact craters are known on Earth (Figure 1) Grieve et al. 1995; Gersonde et al. 2002). Twenty five have been recognized as original marine impacts (Dypvik and Jansa 2003, Table 1), the majority of them into continental crust. So far the Eltanin event (Kyte et al.1981; Gersonde et al. 2002) is the only known impact that has occurred in the deep ocean (5000 m water depth in the south Pacific). In the case of Eltanin, the about 1-km-diameter bolide did not reach the sea-floor; only ejecta and no crater have been found. Today, six of the 25 known marine impacts sites are still located in the oceanic environment, whereas, as result of subsequent tectonic processes, the remaining nineteen sites are, presently found on land (Dypvik and Jansa 2003, Table 1). The submarine craters represent consequently about 15% of the crater record: much too little for a planet which is two thirds ocean. The limited marine-crater representation is due to several reasons, e.g., the fact that because of plate tectonics no “old” ocean floor (> 200 million years old) is preserved, the limited knowledge of fine scale topography and structural characteristics of many deep ocean basins, and the lack of constrains on the morphology expected for impact structure formed on the thin oceanic crust. It is difficult, at this point, to estimate if the geophysical characteristics established for craters on land fully apply to marine craters, especially for larger events where the excavation cavity extends beyond the oceanic crust. Ivanov and Melosh (2003) claim that such a huge event is possible, but is highly improbable to have occurred in the past 3.3 Gyr.

Marine impact craters are expected to be buried soon after formation. The immediate infill of the crater should limit erosion, but also quickly hide the structure beneath a veneer of marine sediments. Consequently marine craters are expected to be well preserved in comparison to sub-aerial structures. Subtracting

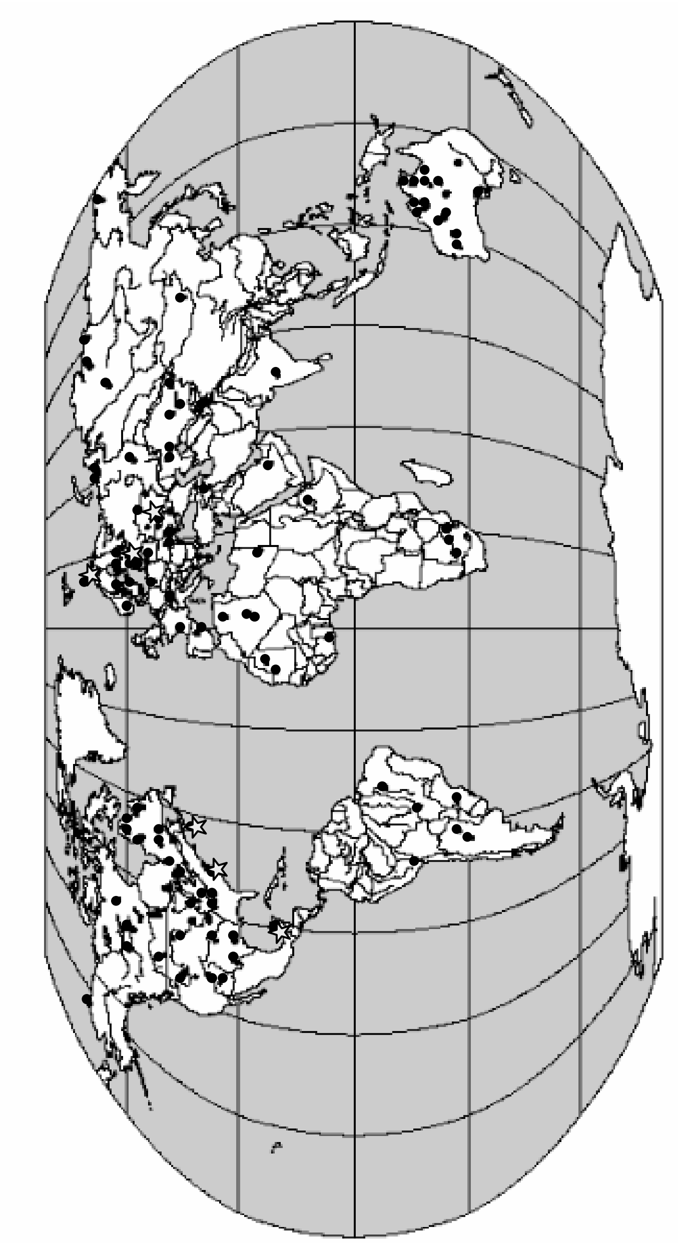

Fig.1 The distribution of impact craters on the Earth. Modified from French (2000). The Chicxulub, Chesapeake Bay, Montagnais, Mjølnir, Kärdla and Neugrund, and Kaluga are marked with star symbols.

the known marine impacts (25) from the number of identified terrestrial craters (170) gives 145 craters, which should have formed on land in the last 3.5 Ga. This is of course a severe underestimation, as new craters are being identified every year (Claeys 1995). Considering the 2 to 1 proportion of ocean on this planet, it would then indicate, after a very rude estimation, that around 300 craters should be expected in the oceanic environment. It is much higher than the 25 found, but far below the very high estimate (8104) of Glikson (1999). In the last 40 years, craters have been extensively studied on planetary surfaces by remote sensing or directly in the field on the Earth (Rondot 1994). Melosh (1989) gave a thorough treatment of the physics of impact cratering in rock. The understanding of impact events in the sea / ocean, and the consequences of cratering processes excavating the oceanic crust, is still in their infancy. The current knowledge of these processes is essentially derived from modeling experiments (Nordyke 1977; Strelitz 1979; Gault and Sonett 1982; O'Keefe and Ahrens 1982; Roddy et al. 1987; Melosh 1989; van der Bergh 1989; Sonett et al. 1991; Crawford and Mader 1998; Shuvalov and von Dalwigk in press; Shuvalov et al. 2002) extrapolated from submarine craters now mainly located in a subaerial setting. These structures may consequently have been exposed to weathering and erosion, which have altered their original morphological features. The submarine crater cores are few, field studies are rare, and geophysical data often much less detailed than for land craters. Detailed sedimentological observations of post-impact sedimentary successions within the crater structure, and process-oriented discussions of ejecta-production, remain inconclusive. However, through the studies of the medium sized Lockne and Mjølnir impacts (Lindstrøm et al. 1996; Dypvik et al.1996; Smelror et al. 2001), a new understanding of shallow marine impact is emerging. Ongoing studies of the larger Chicxulub and the Chesapeake Bay structures will in the close future contribute to document submarine impacting. Unfortunately all these impacts took place on continental crust.

Cometary submarine impacts have been explored by Ormø and Lindstrøm (2000) and by Jansa (1993) after discovering the Montagnais impact crater on the Canadian shelf (Jansa and Pe-Piper 1987). Ormø and Lindstrøm (2000) concentrated mainly on the mechanical processes associated with formation of small submarine craters (<14 km in diameter) in Baltoscandia. Their work and that of Dalwigk and Ormø (2001) document the presence of resurge gullies, about 1 km wide, 3 km long and tens of meters deep, strongly modifying sediment distribution and erosion within the structure.

Submarine impacts can be inferred from the presence of sedimentary features resulting from processes not occurring at subaerial impacts; e.g., formation of tsunamis, high waves, strong currents and features resulting from collapse of central high and crater rim and rush of return water into excavating crater ("resurge" activity). Recently Melosh (2003), referring to a newly released report (van Dorn et al. 1968), claimed that asteroids of the 100 to 1000 m diameter range will produce waves with periods between storm–waves and earthquake-produced tsunamis. According to Melosh, their hazard has been over-rated and they do not pose as great a threat as previously believed.

Impact of a large bolide into marine environments will also generate tremor-like earthquakes, which could result in fluidization of sediments, slope instability, slides, slumping, generation of turbidites, mass flows and debris flows and avalanches. During the past 10 years an increasing number of studies have focused on biological and sedimentological consequence at the periphery of marine impacts (e.g., Alvarez et al. 1992; Smit et al. 1992; Smit et al. 1996; Bohor 1996; Sharpton et al. 1996; Norris et al. 1999; Monteiro et al. 2000; Smelror et al. 2002; Stewart and Allen 2002). In particular, the deposition of massive sand, and debris flows associated with the Chicxulub crater at the K/T boundary studies should be mentioned. The formation of these coarse units, often in a deep sea setting were attributed to the erosion, transport and deposition of sediment generated by tsunamis caused by the collapse of the platform margin or, at more distal sites, to failure of the slope and generation of massive debris flows. These major magnitude sedimentological processes recognized in the field or on seismic lines, were all attributed to the nearby impact and the propagation of shock waves. Discussions of impact structures, such as the Montagnais (Jansa 1993; Jansa and PePiper 1987), Mjølnir (Dypvik et al. 1996; Smelror et al. 2001; Tsikalas et al. 1998), Lockne (Lindstrøm et al. 1996; Sturkell 1998; Sturkell and Ormø 1997), and the Chesapeake Bay craters (Poag 1997) have revealed similar associated sedimentary processes. In addition, ejecta layers identified in the Precambrian Hamersley Group of Australia (Simonson and Hassler 1997; Simonson et al. 1998) are associated with resurge, suspension currents and debris flow deposition. It should also be mentioned that only limited attention has been given to related effects of waves and tsunamis generated by impacts (Bourgeois et al. 1988; Oberbeck et al. 1993; Smit et al.1996; Warme and Sandberg 1996; Warme and Kuehner 1998; Poag et al. 1999; Ward and Asphaug 2000; Shuvalov et al. 2002), and even less to the study of margin collapse, which can be associated with meteorite impacts on continental margins and shelves (Norris et al. 1999). It is likely that the sedimentary record still contains undiscovered traces of impact-induced sedimentary disturbances masquerading as breccias or coarse clastic sequences or diamictites. The Devonian Alamo breccia, which for years was mapped as a regular breccia unit, is a clear illustration of this fact (Warme and Sandberg 1996; Warme and Kuehner 1998).

A wide range of geological and geophysical data have recently been presented from three small to medium sized craters from the East European platform: the 380 Ma old Kaluga (Russia), which is 15 km in diameter (Masaitis 2002), the 20 km in diameter Neugrund (Estonia) of early Cambrian age (535 Ma) (Suuroja and Suuroja 2002) and the 4 km in diameter, 455 Ma old Kärdla crater (Estonia) (Suuroja et al. 2001). These craters are all well preserved, marine, complex craters formed on continental crust, rapidly filled and hidden beneath younger sediments. They show severe resurge effects and probable tsunami / wave effects resulting in locally high rates of sedimentation. This often occurred after the major post-impact modification stage, as was also the case in e.g. the Mjølnir Crater, indicating that local sediment disturbance extended for long after the impact itself. The slumps and avalanches following the resurge and tsunamis were important mechanisms in the post-impact filling of the crater structures. These processes considerably modified the shape and morphology of the structure. It is likely that they also affected the distribution/succession of the impactites, in particular the suevite. They may have hampered the formation or led to a rapid cooling of the melt. The Kaluga, Kärdla and Neugrund craters were formed in shallow (50 – 500 m) waters in epicontinental sea settings, with target areas characterized by rather thin (0-200 m) sedimentary covers on Precambrian basement. The amounts of melt material is minor and only in the Kaluga case has a lense of melt-rock (20 m tagamite) been detected. The consequences of such processes on the development of hydrothermal cells in the crater still remain to be examined. In the three cases mentioned above widespread ejecta have been found, in the Kaluga event the so-called Nava Breccia has been recognized as an ejecta unit up to 500 km away from the crater. In the Nava Breccia the redistribution can be explained by tsunami / wave reworking of ejecta.

The presence of water in the target area also has an influence on the ejecta formation. According to (Melosh 1989) water vapor formed will both accelerate and increase the ejecta formation and distribution, and result in wider distribution of material from the marine impacts than from comparable subaerial impacts.

Simonson and Harnik (2000) suggested that there could be significant and systematic differences in the composition of ejecta from a continental crust target versus pure oceanic crust impacts. Because the vast majority of the mass ejecta comes from the upper part of the target, major differences are expected between a mafic basaltic and a felsic granitic source. It is unlikely for example that vast amounts of the characteristic shocked quartz will be produced by an impact on a pure oceanic target. The produced shock minerals, e.g., olivine, will be much less stable than quartz and much more difficult to characterize as ejecta. As these criteria might be applicable on Archean impacts, such differentiation is not fully applicable in the Phanerozoic cases. In the Phanerozoic, all known marine impact craters so far discovered were formed in shallow seas on continental crust, and the ejecta composition is comparable for terrestrial and shallow marine impacts. The fact that we are missing the pure oceanic impacts and/or fail to identify them in sedimentary sequences, may be due to our tools being aimed at characterizing ejecta from continental crust.

As mentioned earlier, it must be clearly emphasized that so far no impact crater has been identified in oceanic crust. A good example of an impact into the deep ocean is the Eltanin event, 2.5 Myr ago in the Southern Ocean (Eltanin Impact, Kyte et al. 1981; Kyte 2002a; 2002b; Gersonde et al. 1997; 2002). No crater was, however, formed on the ocean floor, but evidences of sediment disturbance in the area where the impact took place, are wide-spread and visible in piston cores and on seismic profiles (Gersonde et al. 1997; 2002). Impact ejecta is encountered in 23 cores drilled over the whole area (80,000 km^2). It is essentially composed of material, such as various solid chuncks of the stony–iron or iron meteorites (howardites or mesosiderites), vesicular impact melt, and glass spherules with Ni-rich spinels most likely condensed from the cloud of vaporized projectile (Kyte 2002a; 2000b). There is no evidence that the Eltanin impact melt contains a significant terrestrial silicate component that might have been incorporated by mixing of the projectile with oceanic crust (Kyte 2000a). Sea water contamination is attested by the presence of high Na content and detectable Cl in the glass (Margolis et al. 1991).

1.3
Marine Impacts - Future Research

Can an oceanic impact, and the formation of a crater in the deep sea, affect the oceanic circulation or can it modify the thermal distribution in the oceans? So far no study has addressed this type of problem. Another fundamental aspect of oceanic crater research is how to identify a crater in the deep ocean; what will it look like? There has been some discussion and speculation (Jones 2000), on the production of huge volcanism as the thin oceanic crust is ruptured during an impact. Jones (2000) advocates that decompression melting would generate massive mafic volcanism. The crater would then lie undetected because hidden by a huge volcanic province. However the debate is active and there is little agreement as to the effects of impact on oceanic crust. According to impact models (Ivanov and Melosh 2003) the production of huge melt volume would be effective only for large (50 km in diameter bolide) sized impact; an very unlikely event in the Phanerozoic. Bolides around 5 km in diameter are well expected to have impacted the ocean in the Phanerozoic. Based on sub-aerial cratering models, it would seem likely that the thin oceanic crust could be perforated by such an event. Even without the production of massive volcanism, the shape, structure and internal morphology of the expected crater is unclear at present time.

Marine impacts and their related effects (submarine slides, avalanches etc.) may result in the formation of tsunamis, e.g., in the case of the Mjølnir impact into the paleo-Barents Sea (Shuvalov et al. 2002). The formation of tsunamis and possible generation of tsunami-related currents occur both along the sea floor in open waters and in the coastal regions (Ward and Asphaug 2000; Ward and Asphaug 2002). Tsunami deposits in deep water as well as run-up situations, have been discussed and recognized around the world in relation with studies of tsunamis (Chague-Goff et al. 2002; Cita et al. 1996; Cita and Aloisi 2000; Bondevik et al. 1997; Goff et al. 1998). Smit et al. (1996) claimed that tsunami deposits would be more easily found in deeper water, below storm wave base. They can be recognized by special sequences of sedimentary structures and textures indicative of high energy deposition and alternating current directions. So far the tsunami deposits described in the literature have very different appearances dependant on a whole range of parameters and characteristics of the different locations and basins (see, e.g., Cita et al. 1996; Cita and Aloisi 2000; Takyama et al. 2000). No doubt this is an extremely complex and poorly known subject.

The search for new craters on the sea bed is an important, but expensive and time-consuming task, which in the future will be a part of the marine science programs. It is clear that the influence of marine impacts for man and biota has had an important influence and naturally its influence for the development of life. At the present only the Chicxulub impact has been shown to have global influence on the biological distribution, but several of the smaller marine impact craters are shown to locally have had serious, but only short time, influence on the local biota (Smelror et al. 2002).

The search for the economic potential of impact craters should also be mentioned. In the marine environment petroleum reservoir rocks are often associated with organic, rich claystone or shales. Donofrio (1998) described several American petroleum carrying impact craters, his example craters, however, are mainly of subaerial origin. The craters are highly fractured, and possess increased porosities in the target area. They may even to some extent carry increased maturation of the possible source rocks. It is possible that the marine impact craters posses a greater potential as traps for petroleum than the subaerial ones, the high exploration expenses and demand for large submarine reservoirs to be economical, may be, however, serious obstacles. Grajales et al. (2000) have elegantly demonstrated that one of the major oil field in Mexico is most likely linked to the Chicxulub impact. The breccia formed by the impact-induced collapse of the Yucatan platform led to the deeper water formation of a porosity-rich reservoir, sealed by the ejecta layer. It is likely that this reservoir extends to the whole Yucatan margin and that similar high porosity brecciated lithologies occur associated with other marine craters.

2 Impact Craters on Ice

Ice is widespread in the Solar System. It can be found on planetary surfaces (Earth, Mars), on the surfaces of planetary satellites (various moons of Jupiter and Saturn for example), and if we take an extreme example the whole surface of Pluto may be ice (Brown 2002). In the case of Pluto the mean mass of the body implies a substantial rocky component to the body, but the surface may be entirely covered by ice.

Ice in this context does not necessarily mean water ice. In the case of Pluto, N_2 and methane ices are more plausible based on observations of reflectance spectra. Minor Solar System bodies such as comets are also commonly described as icy. For comets however, the ice may again not just be pure water ice but will include substantial amounts of silicate materials, other volatiles etc mixed into it. Whether this mixing is uniform, layered or in clumps (i.e., many rocky boulders, each covered in ice all bound together) is one of the great mysteries of Solar System science. Questions such as these will be investigated in detail during the next decade by various space missions (principally, Stardust, Rosetta and Deep Impact, see below).

Like any exposed Solar System surfaces, icy bodies undergo impacts and thus exhibit impact craters. Some of the earliest work concerning impact cratering in ices was that of Croft et al. (1979), who fired rifle bullets into sand-ice mixtures to see what craters would be like in an analogue of an icy Martian regolith. Although the impact speeds were less than 1 km s^{-1}, this represented a new dimension to impact cratering studies with planetological implications. Subsequently Croft (1981a) made studies of impacts at 2 to 6 km s^{-1} into ice and ice-saturated sands, thus moving ice impacts into the hypervelocity regime[1]. The motivation was not just to study Martian impact cratering processes, but also to consider impact records on the icy satellites of Jupiter and Saturn. Since 1981, there have been several laboratory studies of hypervelocity impacts on ices.

Fig. 2. Small icy craters on Europa. Image size is 8.4 km wide and the largest crater visible is approximately 300 m across (Source NASA/JPL).

The Voyager missions to the outer Solar System sent back many pictures of icy bodies, some heavily cratered, some less so. Immediately upon receipt of these images, relative dating of surfaces could be attempted. For example, after allowing for any local perturbation/enhancement of the impact flux at each planet and indeed at different orbital radii from the parent planet, the degree of resurfacing on the icy satellites could be estimated. Craters were thus playing a role in helping understand the nature of these icy bodies. Classification of craters by their morphology was an early activity by researchers. For example, Croft (1981b) reported on size distributions of craters on Ganymede and Callisto. Questions then arose as to whether thermal and/or viscous relaxation were altering crater shape. This was an area where it was thought that impact experiments in the laboratory could provide insights and accordingly Greeley et al. (1982) reported on a series of shots in the laboratory into layered targets with a surface of ice and a clay subsurface. However, the influence of relaxation of ice on crater morphology is still not fully understood. For a recent review see Durham and Stern (2001).

More recently, the Galileo mission to Jupiter has provided a wealth of data concerning the Jovian satellites (and the Cassini mission to Saturn will similarly

[1] The hypervelocity regime is crudely where the impact speed is similar to or exceeds the speed of the resultant compression waves in both target and projectile. For most materials such wave speeds are typically between 1 and 3 km s^{-1}, so impacts at speeds of more than 1 km s^{-1} are usually, and somewhat loosely, referred to as hypervelocity.

revolutionize our knowledge of the Saturnian system). Understanding the craters on these satellites (Figures 2 and 3) will help reveal details of their structure that could otherwise remain obscure. For example, several of these satellites (e.g., Europa) are not considered to be icy rocks, but rather to have a rocky core, a liquid ocean and finally a solid icy surface. Impact craters on such bodies present a fascinating means to probe this structure. Modeling can help understand how deep an ice shell must be to support the observed craters (e.g., see Turtle and Pierazzo 2001). This can present constraints not only on the thickness of the ice, but by implication on the methods and degree of internal heating which are required to sustain the liquid sub-surface ocean and hence the thickness of the covering ice layer. Equally, impacts generate ejecta, and it should be possible for impact produced ejecta to escape from one Jovian satellite and travel to another. So just as we find Martian meteorites on Earth, there may be Europan "meteorites" on other satellites

of Jupiter. And, in return, other bodies may contribute materials to Europa. Understanding these possibilities requires a detailed knowledge of impact mechanics involving ice targets. This has added interest given that Europa is held to be a candidate for searches for life (i.e., it is held to possess sub-surface water oceans and water is a key ingredient of life), see, e.g., Chyba and Phillips (2002) for a recent review. If there is life on Europa one can ask if it has become frozen in the

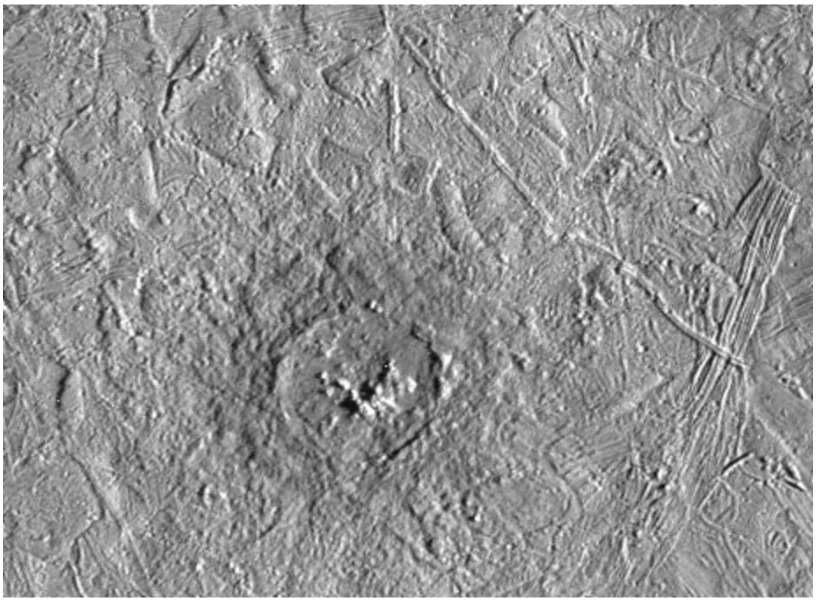

Fig. 3. Crater Pwyll on Europa. (Source NASA/JPL) Crater is approximately 26 km across.

ice, and then if it can be knocked off trapped in icy ejecta as a result of an impact of another body onto the surface of Europa. This intriguing speculation is discussed in a recent paper by Burchell et al. (2003). To consider it in detail one must know if bacteria can survive hypervelocity impacts (see Burchell et al. 2001) and then generalize this to impacts on ice.

When the Cassini mission arrives at Saturn, new questions will arise concerning impact cratering on icy satellites. Titan is a particular satellite of interest for the Cassini mission. Cassini will map it from space and the Huygens probe will be dropped through its atmosphere onto its surface. It has already been hypothesized as to what craters on Titan might look like (e.g., see Lorenz, this volume and references therein).

Comets also present an interesting subject for impact studies. The best images of comet nuclei are shown in Figure 4 (Halley's comet) and Figure 5 (comet Borelly). High resolution images of asteroids (e.g., Eros, see Figure 6) reveal that they are subject to bombardment just like any other Solar System body. Comets are no different in this respect. They have been bombarded after formation. Comets are however different to other icy bodies in at least one important respect, their low density. Estimates of comet density vary, but typically range from 200 to 1500 kg m^{-3}, with a value of 500 kg m^{-3} being typical. Such a value implies porosity. Therefore an impact on a comet is not just an impact on an icy body,

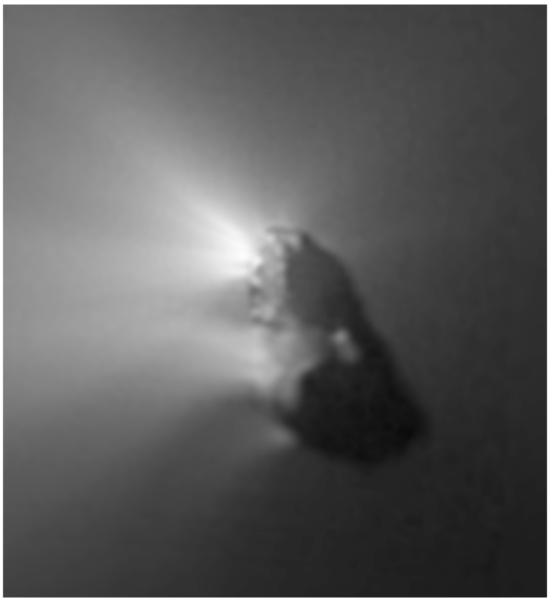

Fig. 4. Halley's comet observed from the Giotto spacecraft. Nucleus size is 8 x 7 x 1.5 km (Source ESA/Giotto).

Fig. 5. Comet Borelly observed from the DS-1 spacecraft. Nucleus is approximately 8 x 4 km (source NASA/JPL).

but also on one that is not well consolidated. This considerably complicates the impact mechanics. The picture is made even more obscure by the lack of detailed knowledge of cometary composition and structure. Worse, these may change quite significantly with time. Here one thinks of comets which pass through the inner Solar System. The material that is ejected to form the beautiful cometary tails that we observe from Earth, is not just depleting the comet nucleus, but in all probability is doing so in a biased fashion, building up volatile depleted crusts over less processed interiors. The dark surfaces of comets in the inner Solar system (given by their low albedo) (Figures 4 and 5) immediately cautions against considering comets with surfaces of pure water ice. Further, the presence of other volatile materials suggests that during their long stay in the outer Solar System, significant amounts of astrochemistry may have occurred on cometary surfaces driven by Solar and interstellar radiation (e.g., galactic cosmic rays etc.). The widely accepted Whipple model of comets as dirty snowballs (based on observation and speculation about comet Encke in the 1950s, see Whipple 1950,1951) probably no longer serves today to adequately describe comets in that our questions have become much more detailed and sophisticated. But what replaces it?

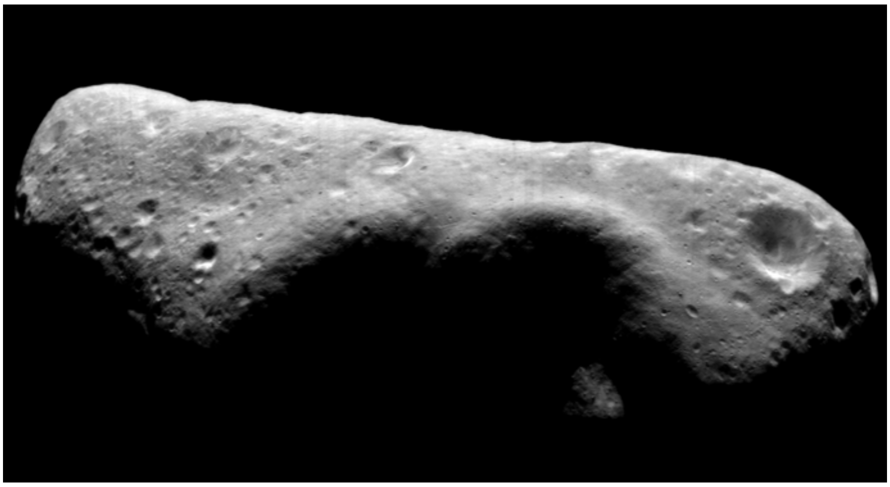

Fig. 6. Asteroid Eros observed from the NEAR spacecraft. Largest dimension is approximately 33 km (Source NASA/JPL).

Several space missions to comets are now underway or soon to be launched. The Stardust mission was launched in February 1999. It will fly past comet P-Wild 2 in January 2004, collect some grains of freshly emitted cometary dust and return them to Earth in January 2006. In addition, it is hoped that the spacecraft's cameras will collect pictures of the comet nucleus with ten times the resolution of those made in previous missions (i.e., the nucleus of Halley's comet, Figure 4, by the Giotto spacecraft in 1986, and the nucleus of comet Borelly, Figure 5, by the Deep Space 1 spacecraft). At that resolution it should be possible to see craters. Indeed even the absence of any traces of cratering will in itself be a statement about the evolution of the surface of the comet.

The next mission to be launched was due to be Rosetta, in January 2003. Due to problems with the launch vehicle the launch has been delayed to February 2004. This mission will rendezvous with comet Churyumov-Gerasimenko in November 2014, orbit it and accompany it on its journey into the inner Solar System. In addition, a small lander will be deployed onto the surface. Comet science will be revolutionized by the Rosetta mission.

But before the Rosetta results will come those from Deep Impact. This mission (see A'Hearn 1999) will also launch in 2004 and in 2005 will drop a 370 kg mass (composed of 46% copper) at 10.1 km s^{-1} into the nucleus of comet Temple 1. The resulting crater (assumed diameter ≈ 100 m, see Belton and A'Hearn 1999) will be imaged by the main spacecraft as it approaches the comet and flies past. Spectroscopy of the expanding vapour plume from the impact site will yield information on comet composition. The growth, final size and shape of the resultant impact crater will yield details of the structure of the comet. Although the mechanisms for crater growth on planetary scales differ from that in the laboratory for impacts (due to the influence of gravity), the Deep Impact event will be at an intermediate scale. The relative roles in crater growth of target material properties and gravity will be interesting (Burchell et al. this volume).

One intriguing possibility of how impacts may affect icy bodies is raised by a consideration of catastrophic disruption of a target body in an impact. Traditionally, this is held to occur when the impact energy density per unit target mass exceeds a threshold related to the strength of the body. A basic rule of thumb for rocky bodies is that if the diameter of the impact crater that would form on a semi-infinite body exceeds 50% of the target body diameter, catastrophic disruption of the target occurs. Is this rule the same for icy bodies? And what if the body is porous, or of low internal strength? For example, see Benz and Asphaug (1999) for a discussion. There is much here that requires investigation. In particular, it has recently been suggested that as comets approach the sun, the release of volatiles from their heated interior may be impeded by the presence of a volatile depleted mantle. An internal pressure may build up (this is advanced for the appearance of sudden jets of activity in discrete locations on a comet nucleus). In which case, if an impact occurs (even at less than the critical energy density for normal catastrophic disruption) will the whole comet explode? This idea has been advanced from recent laboratory impact experiments involving foam targets with an internal pressure and low strength. It would be fascinating to see similar experiments with heated ice targets.

It is reasonably clear that impact cratering on icy bodies will figure substantially in the analysis of data from a variety of space missions in the near future. This analysis will be guided by what is learnt from impact studies at laboratory scales and by detailed hydrocode simulations at Solar System scales. Indeed, further such studies will be triggered by new questions arising from the data from space missions. Some aspects of current such studies are presented in the papers in these proceedings. In the future more experiments and modelling will be required over a wide range of conditions.

3
Conclusions

It may seem odd that the study of marine impacts has been neglected in terrestrial cratering investigations for so long. However, impact craters on land are so much more accessible and obvious and, thus, studied in most detail. This situation is no doubt reinforced by the observation of craters on other solar system bodies, e.g., the Moon, Mars, Venus, asteroids etc., where the exposed surface is rocky. Thus, most studies implicitly assume that impacts occur on rock, not into water, ice or soft sediment successions. Also, some aspects of the impact process are particular to marine impacts (e.g., re-surge currents, tsunamis, etc.), and others directly affect the crater development (i.e., fast refill by water cooling craters in shallow oceans much more rapidly than craters formed on land). In addition, an impact in a marine environment has been shown to a have a direct effect on, e.g., ejecta formation and distribution. Their influence on the geology of the target areas for example formation of porosity rich reservoirs, which can potentially be oil bearing.

Given that, as pointed out in this paper, only 15% of the 170 craters found on the Earth today are believed to have occurred in marine environments, and that water covers such a large part of the Earth, oceanic impacts should not be ignored. In a wider Solar System context ocean impacts may appear to be limited to the Earth. However, it should be remembered that there is evidence for possible oceans or large expanses of water on Mars in earlier times. Thus, some of the discussions about terrestrial oceanic impact may be applicable to Mars as well.

Impacts into ice represent a special field from a terrestrial viewpoint. However, at times in its history the Earth had more extensive coverage of ice than today. Looking further afield in the Solar System, all the outer planets have ice-covered satellites of various sizes. A more complete picture of solar system impact processes requires an understanding of impacts into ice (and water), as well as into rock. A variety of ongoing and planned space missions will yield many observations of craters in icy bodies. These will await detailed interpretation until impacts in ice are better understood. Indeed, there is speculation that one body to be studied (Titan, the largest moon of Saturn) may have some liquid on its surface, permitting the possibility (albeit a small one) of impact craters in a marine environment with an icy sub-surface (rather than rocky subsurface as on Earth).

In conclusion, the old view that impact processes are solely a geologic process involving rock targets, can be seen to be too restrictive. There are many significant effects of the impact process due to the presence of a marine environment. They alter the picture of impacts and result in somewhat different ejecta distributions and compositions than from purely rocky targets. This field is not a new one, but has increasingly matured such that it has now moved into the limelight as regards research into impacts and can no longer remain neglected. Possible areas for future research (e.g., tsunami generation etc.) have been outlined. What is clear is that many new and interesting discoveries in the fields of oceanic and ice impacts await us.

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