THE IMPACT OF CRATERING IN THE OUTER SOLAR SYSTEM

P.M. Schenk, Lunar and Planetary Institute, 3600 Bay Area Blvd., Houston, TX 77058 (schenk@lpi.usra.edu), [2]

Introduction: Working on impact cratering related problems may seem tedious beyond description, but the importance of craters cannot be overstated. The peculiar thermal and mechanical properties of water (and other) ice allow impact craters to record processes and materials that would not otherwise not occur or be so obvious on silicate-rich targets. Craters act as natural drill probes into icy lithospheres. They act as recorders of global stratigraphy and global dynamics (including rotational history). They record the flux of incoming projectiles into planetary systems. They record the thermal history of icy satellites. There is little that impact craters cannot do!

Drill Probes: The dynamics of impact cratering disrupt and dislocate vast amounts of material vertically that would otherwise remain hidden from view [1]. On Ganymede and Callisto, central dome craters expose deeper ice-rich ductile material in the central uplift [2]. Dark halo craters have been interpreted to be ejecta contaminated by dark terrain material buried at shallow depths of 1-1.5 km [3].

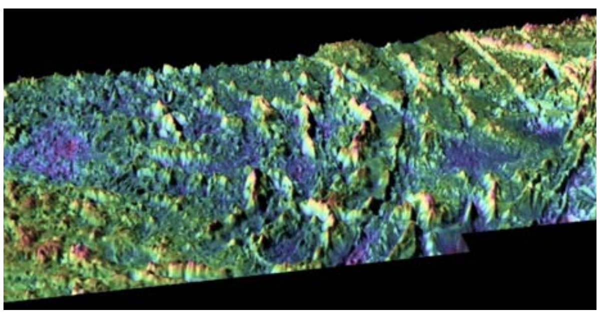

Figure 1. Perspective view of part of the rugged topography (color-coded) of Callanish. This 30-km wide multiring crater is thought to have penetrated near the base of Europa's floating ice shell, fracturing it. Crater center is near left-hand edge of the scene.

Europa is an extreme case. The comparison with Ganymede is especially telling since craters should be very similar on both satellites. Instead of central peaks, we see deformed craters in the 20-25 km diameter range, and multi-ring structures where we should be seeing central pit craters (Fig. 1) [4,5]. Further, the d/D curve for Europa rolls over at 8-10 km (rather than continuing to increase as on Ganymede; Fig. 2) [6]. These anomalies are clearly linked with Europa's "thin" ice shell and subsurface ocean. Recent numerical modeling [e.g., 7, 8] and even the most simplistic conceptual model of impact crater collapse at these transitions [6] all point to ice shells in the 10-20 km range. The Europan crater story refuses to support a thin (<5 km thick) ice shell model for Europa, no matter how deperately one might want it to.

The cratering record on Titan is sparse [9] but those few craters are most similar in appearance to Ganymede craters: Titan has no *near-surface* internal ocean.

An extreme example of planetary drilling is satellite disruption. Clearly, any projectile large enough to form 600-km-wide basins on Iapetus and Rhea would effectively shatter any of the small ring moons orbiting Saturn [e.g., 10]. That so many of them still exist is a continuing puzzle.

Recording Impactors: The more important manifestation is the size-frequency distribution of impactor populations. In the absence of an icy satellite sample return program, this has obvious implications for surface ages. 25 years of effort have not yet converged on a definitive answer to how old these surface are. Despite this, we do know that comets dominate the current flux in the outer solar system [10]. Extrapolating the current observed flux allows us to estimate surface ages to within a few factors (tho with less confident as age increases). Europa's surface is young (<100 my), but Ganymede's bright terrain may be 2 Gyr or more old, depending on the breaks). The various ridged terrains on Enceladus probably have ages of 0 to 1-2 Gyr, depending on flux model [11]. Mapping also shows that resurfacing moved from the (current) equator to the south pole. Triton's surface age may be younger than Europa [12].

The simple story above is marred by the likelihood of intersatellite debris [13], euphamistically referred to as sesquinary cratering. Zahnle and collegues have shown that significant amounts of ejecta can be launched into orbit about the primary planet. Some debris will migrate to other satellites, adding a projectile population not accounted for by comet models (a.k.a. Population II [14]). Indeed, fragmental ejecta from Io may be contaminating Europa [15].

Recording Dynamics: Icy satellites live in peculiar dynamical regimes. They are typically synchronous (although they can be jostled out of this state in the right circumstances [16]), and are subject to various tidal and rotational forces due to proximity to other satellites. Predicted global asymmetries in crater distribution of 30x or more have not materiallized, except on Ganymede where the difference is only a factor of 4 [17]. One interpretation is that Ganymede spent considerable time out of snychronicity, blurring the impact distribution globally. Another outrageous exception is the case of Triton, where all the observed craters are on the leading hemisphere [12]. This is explained by impact of prograde nonheliocentric debris on a retrograde orbiting satellite. The debris could have been blasted off one of Neptune's inner or outer satellites.

Icy satellites have even recorded the impact of tidally disrupted comets [18]. Prominent split comet crater chains are known on Ganymede and Callisto, but none have been found on the other satellites systems.

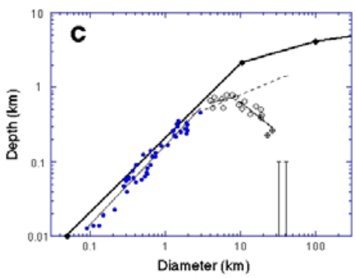

Figure 2. Depth diameter curve for craters on Europa (bottom). The rollover at 8-10 km correlates with impact crater detection of the base of the icy shell. Data from []. Open symbols represent complex craters. Dashed line is the Ganymede curve, which Europa deviated from.

Thermal Probes: The rheology of water ice is strongly sensative to temperature [19]. Larger icy satellites are inherently warmer and more sensative to thermal history than smaller satellites, although some, such as Enceladus and Dione, have not escaped the torch. Ganymede craters record a history of widespread viscous relaxation, mostly on ancient dark terrain. Recent mapping of relaxed crater distribution shows that the period of high heat flows associated with relaxed craters is directly linked to bright terrain formation and that Ganymede cooled considerably afterwards, arresting relaxation. Relaxation has been very important locally on Enceladus and Dione, suggesting that heat flow has been high there but not uniformly so [20].

Another manifestation of thermal history has been the changing morphology of large (D>60 km) impact basins on Ganymede (and Callisto) [5]. Detailed mapping reveals that basin morphology changed from multiring through palimpsest, penepalimpsest (coincident with bright terrain formation), penedome crater, to modern day central dome crater (Fig. 3).

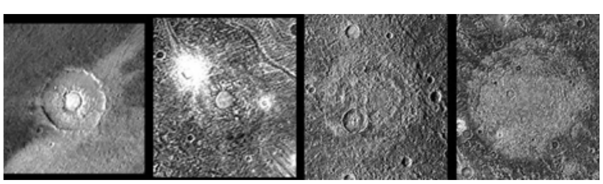

Figure 3. Changing morphology of Ganymede craters over time. From left to right (with increasing age): central dome crater, penedome crater, peneplaimpsest, palimpsest. Craters scaled to appear similar in size.

The most ancient large impacts on the Jovian satellites are characterized by numerous concentric ridges and graben and an absence of large-scale topography [21]. These multiring structures occur nowhere else and are probably a manifestation of very high heat flow and thin lithospheres. Graben spacing can be used to estimate thermal gradients.

Conclusions: Impact craters are key to understanding interior stratigraphy and properties, thermal histories, and a host of other issues in the outer solar system. Much work remains, however. We eagerly await the first results from Pluto encounter in 2015. Continued mapping of impact crater sizes, shapes and statistics is required, especially in the Saturn system. Advances in numerical modeling hold hope of translating observed morphologies and transitions into real properties, such as lithospheric thicknesses, ocean depths, or thermal profiles, glimpsed only darkly at present. Continued research focus on the mechanics and dynamic of impact cratering process (especially as it differs in icy regoliths) will be critical for understandign what craters are telling us. Finally, a return to Jupiter to complete Galileo's failed global mapping objectives is critical for understanding how these unusual impact craters form, are modified, and are distributed. These craters offer some of our best opportunities to map out the stratigraphy and thermal histories of these satellites .

References: [1] Melosh, H.J., Impact cratering,Oxford, 1989. [2] Schenk, P., JGR, 98, 7475, 1993. [3] Schenk, P., and W. McKinnon, JGR, 90, C775, 1985. [4] Moore, J., and others, Icarus, 151, 93, 2001. [5] Schenk, P., et al., in *Jupiter*, Cambridge Press, 2004. [6] Schenk, P., Nature, 417, 419, 2002. [7] Turtle, E., and E. Pierazzo, Science, 294, 1326, 2002. [8] Bray, V., et al., Lunar Planet. Sci. 37, abstr. 1175, 2006. [9] Elachi, C et al., Nature, 441, 709, 2006. [10] Zahnle, K., et al., Icarus 163, 263, 2003. [11] Kirchoff, M., et al., Lunar Planet Sci. 38, 2007. [12] Schenk,P., and K. Zahnle, Icarus, in press, 2007. [13] Alvarellos, J., et al., Icarus, 178, 104, 2005. [14] Smith et al., Science, 215, 504, 1982. [15] Zahnle, K, et al., Lunar Planet Sci. 38, 2007. [16] Showman, A. et al., Icarus 129, 367, 1997. [17] Zahnle, K., et al., Icarus 153, 111, 2001. [18] Melosh, H.J. and P. Schenk, Nature, 365, 731, 1993. [19] Durham, W., and L. Stern, *Annu. Rev. Earth Planet. Sci.* 29, 295, 2001. [20] Schenk, P., Lunar Planet. Sci 38, 2007. [21] McKinnon, W., and H.J., Melosh, Icarus, 44, 454, 1980; Schenk, P. et al., *Lunar Planet. Sci. 28*, 1249, 1997.