IMPACT FRAGMENTATION OF ICE-SILICATE BODIES
by M. A. Lange and T. J. Ahrens, Seismological Laboratory, 252-21,
California Institute of Technology, Pasadena, California 91125

Introduction: Impact processes appear to have dominated the geological evolution of the icy
satellites of Jupiter and Saturn (1, 2). Fundamental questions, which need addressing in order to
understand the cratering histories of icy objects are: what is the largest crater which objects can
sustain without planetary disruption and what the effects of the ultimate strength of the impacted
body on the size and shape distribution of resulting fragments are? The existence of small,
cohering, irregularly shaped bodies around Saturn and Saturn's rings has been attributed to impact
induced fragmentation of larger objects, earlier in Saturn's history (2). Knowledge of basic physical
parameters governing impact fragmentation is relevant for theoretical accretion models of icy planets
and can be used to predict mass- and size distributions of particles in icy regoliths as well as in
icy planetary rings. Laboratory experiments provide a first step towards an understanding of
fragmentation processes and can be used in theoretical models of these phenomena.

Earlier studies on the impact fragmentation of silica glass, basaltic, and water ice revealed
critical specific energies (ke = projectile energy / target mass) of 10^7, 6x10^7, and 3x10^8 ergs/g,
respectively (3, 4, 5). We previously (6, 7) addressed the effect of temperature on fragmentation energies
as well as the size- and shape distribution of resulting fragments of pure ice targets and found
that critical energies depend significantly on target temperatures. The mean densities of the Jovian
and Saturnian satellites indicate that they contain an average of 50 and 30
wt.% silicates, resp.; mean surface temperatures lie at 110 and 70 K, resp. (1, 2). In this study we sought to
(1) determine threshold energies for the transition between different degrees of target fragmentation as a
function of temperature in silicates, (ii) determine the mass and size distribution of resulting
fragments as a function of ke and temperature, and (iii) compare these results with previous studies
on pure ice and silicate rocks.

Experimental Techniques: Cylindrical targets (20 cm diameter, 18 cm height) were prepared by
homogeneously mixing finely crushed ice and 35 wt.% silica sand of comparable grain size (0.1 mm).
Two target temperatures of 257 and 81 K were achieved by either leaving the target in a freezer at 257
K or by use of boiling liquid nitrogen. The thermally equilibrated, uncompressed targets were placed in front of a 20 mm propellant gun which was used to accelerate LEXAN projectiles to
velocities between 0.4 and 0.8 km/s (associated values for ke varied between 1x10^6 and 4x10^6
ergs/g). Immediately after each impact, the resulting fragments were collected and their mass and size
were determined.

Results: Log_b cumulative number n versus Log_b fragment mass m for resulting fragments can be
fitted by straight lines and the constants C and b in n = C m^b have been determined for each
experiment. This equation has been fit to fragment data from a variety of naturally fragmented rocks
(8) as well as for our ice targets (7). The slope b in these distributions is a measure for the
relative abundance of large versus small fragment masses; increasing b values reflect an increasing
number of small fragments relative to the number of larger ones. Our data indicate that b has a tendency
to increase with decreasing degree of target fragmentation, here expressed as B/A to
between mass of largest fragment versus target mass m_f (Fig. 1). Adopting our previous definitions
of fragmentation classes (7) in terms of m_f, (see Fig.1), b decreases with increasing fragmentation class,
in good agreement with our results for ice targets (Fig. 1).

The shape of a fragment can be characterized by the ratios of intermediate to large axis (B/A)
versus the ratio of short to long axis (C/A) (Fig. 2). For ice- and ice-silicate targets at 81 K, no
significant change of B/A with increasing fragmentation class has been observed for targets at 257 K; a systematic decrease in both B/A and C/A with increasing fragmentation class is seen (Fig. 2).

Critical specific energies ke for the transition between each fragmentation class in ice-silicate
targets are obtained from a plot of m_f versus ke (Fig. 3). (Two of our 81 K targets displayed
visible fractures prior to the experiments; they are indicated by ❧ and are excluded from the
previously presented analysis.) The present results define two curves which are similar in shape to
those observed for pure ice targets. However, more energy is needed in ice-silicates as in
impact targets to achieve a certain degree of target fragmentation. Increasing impact energies require
increasing critical energies of ice-silicate targets for a given fragmentation type, contrary to what
has been found in ice targets (Fig 3; 7). Critical specific energies lie at 4.5x10^7 and 7x10^7
ergs/g for transition between fragmentation class I to II, at 1.4x10^8 and 2x10^8 ergs/g for transition from II
to III, and at 0.5 and 0.7 ergs/g for transition from III to IV (=cratering) in ice-silicate targets
at 257 and 81 K, resp.

Discussion and Conclusion: Critical specific energies for the transition between previously defined
fragmentation classes (7) in ice-silicate targets are about 3 to 5 times those found in pure ice
targets and about ten times less than those determined for basaltic targets (Fig. 3; 4). Our data
indicate that the addition of silicates to ice leads to an increase in the dynamic tensile- and
compressive strength of decimeter sized icy targets, which results in larger impact energies required
for a certain degree of fragmentation. This is in good agreement with results of cratering in
impact targets, which suggested the same conclusion (9), as well as with quasi-static
compression tests on ice and ice-silicate mixtures which indicate an increase in ultimate strength
with increasing silicate content (10). We suggest two possible explanations for this observation.
Sand grains in an icy matrix may act as obstructions to microcracks originating in ice and thus
effectively stop the growth of cracks. On the other hand, sand grains in ice have been observed to be
preferential nucleation sites for dislocations (11). This may lead to an increased stress dissipation
in an ice-silicate mixture due to the formation of many small, randomly oriented microcracks, which

© Lunar and Planetary Institute • Provided by the NASA Astrophysics Data System
do not coalesce to form large fractures. Both mechanisms are used to achieve higher ultimate strength values in ceramics by inducing controlled amounts of impurities to a given substance (12).

The mass distribution of ice-silicate fragments show similar characteristics as those seen for pure ice; increasing degree of fragmentation leads to an increase in smaller particles relative to larger fragments. Fragment shapes of ice- and ice-silicate targets are similar with respect to fragmentation class and target temperature. Fragments of 81 K targets have values of B/A and C/A, similar to those found for basaltic targets (13) (Fig. 2).

Based on the definition of ke, one can obtain the ratio r/R of impactor size r to target size R for a given value of ke (r/R = (2k/v^2)^.5; v = impact velocity). Typical impact velocities in the Jupiter and Saturn system lie at 20 km/s. Arguments presented in (7) suggest that our results can be extrapolated to natural impact events on planetary bodies of up to 100 km size. The lower abscissa in Fig. 3 gives r/R for v=20 km/s and can be used to obtain the size of an impacting body which leads to a certain type of fragmentation of an icy planetary object of radius R. Disruption of an 100 km icy object (class II) would thus require an impactor 1.2 km in size.

Acknowledgement: The technical assistance of T. Peng is gratefully acknowledged. M. Lange is supported by a grant from the Deutsche Forschungsgemeinschaft. This work was supported by NASA grant NCL-05-002-105.

Figure 1: Slopes b of linear relations between log_{10} cumulative number and log_{10} fragment mass versus relative mass of largest fragment in previous (7) and present experiments and indicated by cartoons. Fragmentation classes I–III are defined by the vertical dashed lines (see text).

Figure 2: Mean values for B/A versus C/A (A, B, C = long, intermediate, and short axis of each fragment) for present and previous (7) experiments. A mean value of B/A = 0.73 and C/A = 0.5 for 719 basaltic targets is indicated by a + (13).

Figure 3: Specific projectile energy ke versus relative mass of largest fragment for previous (7) and present experiments. Also given is the result for basaltic targets as given by (4). Horizontal, dashed lines mark the transitions between fragmentation classes as indicated by the cartoons. r/R gives the ratio between impactor size r and radius R of a planetary body (maximum R=100 km) for each value of ke and for an impact velocity of 20 km/s.