CENTRAL PIT FORMATION IN CRATERS ON ICY SATELLITES; Paul M. Schenk, Jet Propulsion Laboratory, 4800 Oak Grove Dr., Pasadena, CA 91109

Central pit craters, those where central peaks have been replaced by circular depressions (Fig. 1), are ubiquitous only among larger craters on the Galilean satellites Ganymede and Callisto [1]. The formation mechanism of pits is apparently related to properties of water ice [2,3,4,5] but has remained elusive.

Any model for central pit origin, however, must explain the following new morphological observations for pit craters on Ganymede and the other icy satellites. Depths of central pit craters on Ganymede appear to be constant over the observed size range (40-90 km) [6], rather than slowly increasing with diameter as is typical of normal complex craters. Rim heights for pit craters appear to be proportional to crater diameter, rather than increasing slowly with diameter as is typical of normal complex craters [6]. Maximum rimwall widths (the horizontal distance from rim crest to the beginning of the flat floor) in pit craters are nearly constant at 11-12 km, rather than increasing with diameter as is typical of normal complex craters on the Moon and Mercury [Fig. 2]. As a consequence, the broad flat floors characteristic of pit craters occupy a much larger proportion of the total crater area (Fig. 1) than they do on the Moon. For Ganymede pit craters between 15 and 70 km diameter, pit-width to crater-diameter (w/D) ratios are similar to those of central peaks (~0.2) but increase to 0.4 or more in craters larger than 70-80 km [Fig. 3]. Bright, smooth, circular domes [5] occur within most pits in craters >50 km on Ganymede *and* Callisto [Fig. 1].

The central pit 50% occurrence transition diameter is 40±5 km on Ganymede and 35±5 km on Callisto, and central pit craters on Titania, Tethys and Rhea have diameters consistent with gravity scaling for central pit occurrence [Fig. 4]. The central pit transition diameter may have been lower and central pit w/D ratios may have been larger in the early history of Ganymede [3], suggesting that thermal gradients and heat flow may be important. The breaks in slope of the crater depth, rim height and rimwall width relationships on Ganymede all occur near 40–km crater diameter, the central pit transition diameter. This strongly suggests that the mechanism(s) responsible for pit development also have a strong influence on final crater depth and rimwall collapse processes.

Perhaps the most important constraint is that bright impact melt sheets in fresh pit craters on Ganymede uniformly cover all morphological features of pit craters on icy satellites (Fig. 1), including pits, domes, rimwalls and broad flat floors. *Thus all these features were emplaced during the primary cratering event and not subsequently.*

ORIGIN OF CENTRAL PITS

Explosive Decompression. Observation of pit craters on Mars led to the suggestion that pits form as a result of the explosive decompression of ices buried in the martin regolith [e.g., 2].

Peak Collapse. The similarity of w/D ratios for both peaks and pits in the 15-70 km crater diameter range, and the transitional morphology of the larger central peaks on Ganymede supports suggestions that pits are the result of the prompt collapse of central peaks [e.g., 3,4]. Collapse of a proto-central-peak could be due to overheightening and hence overloading of peak material beyond its strength [3]. The stress and hence effective cohesion at the base of a conical central peak, given by $\rho hg/3$, is ~ 4 bars for the largest peaks on Ganymede, based on a maximum peak height (h) of ~1 km [3,6]. A few bars may seem low for water ice but is very similar to estimates of the yield strength of Ganymede crustal material during the cratering event, based on morphological transition diameters [7] and the plastic rheology crater collapse model of [8], and on measurements of terrace widths [9]. Maximum peak heights on other icy satellites give similar estimates of cohesion.

Peak Melting. Collapse or loss of central peaks could be due to an excessive amount of melt being produced in the region of the central uplift by strong shock pressures and decompression [4]. As uplifted, much of this essentially fluid peak would drain away and collapse, leaving a residual melt 'lake' or refrozen dome within the central depression left behind. None of these models explain very well why a very circular bright dome should form while the pit wall is generally irregular, or why this same bright material is restricted only to the depression. Also, the refreezing process of [4] would take considerably more than the hour or so necessary to excavate the crater and form the bright floor deposit. Some disturbance of the bright floor deposits of Osiris, etc., should occur but none is seen (Fig. 1). These models do little to explain the unusual rim characteristics of pit craters, either.

Impact in a Viscous Target. Laboratory experiments of impact into a thin brittle layer over a weak layer [2] have produced pit-like morphologies, although the essentially liquid material required is unlikely to exist today [10].

Slow Diapirism. Indeed, the circular dome and irregular character of the pit walls suggests a viscous plug intruding a brittle crust [5]. Such domes could form in a few BY, given the probably rheology of the interior [5]. This type of slow diapirism is completely inconsistent with the time constraints imposed by the bright floor deposits in Osiris and other craters (Fig. 1). It too offers little explanation for the narrow rimwalls of pit craters.

Fast Diapirism. The rapid formation times now required of pit crater structures suggests an alternative version of the slow diapir hypothesis, in which a sort of fast diapirism occurs during the primary cratering event. A low-viscosity material at depth could be mobilized during the cratering event, undergoing uplift in excess of that expected from 'normal' crustal materials. This 'plug' would displace floor material radially, creating a depression, and in large craters (>50 km) being exposed as a circular plug. Such a material would have to exist in both Ganymede and Callisto essentially today since the youngest craters on these satellites display the full range of pit crater structures.

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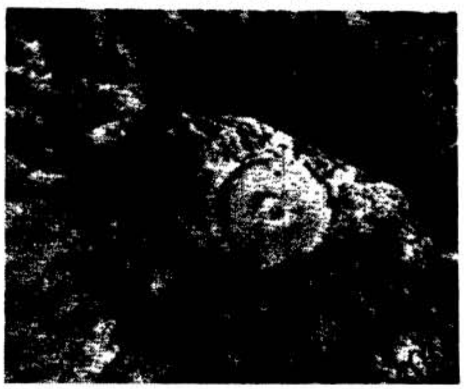
Rapid floor uplift during impact events [11] generates unusually high strain rates of ~10^{-3}/s. Since the depth of the brittle-to-ductile transition within a lithosphere is partly defined by the geologic strain rate and thermal gradient [e.g., 12], an impact could produce a locally defined brittle lithosphere, beneath which the interior responds ductilly to floor rebound. Assuming a thermal gradient of 2 K/km [10] and a strain rate of 2×10^{-3}/s (appropriate for a 40–km–wide Ganymede crater ~2 BY ago), the local impact-induced ductile zone on Ganymede is ~60 km deep, shallow enough to be sensed by a 40-km crater. (For a thermal gradient of 5 K/km, this depth is only 30 km, consistent with enhanced pit formation in Ganymede's early history [3]). For a similar sized crater on the Moon (assuming a thermal gradient of 4 K/km and strain rate of 5×10^{-4}/s), this depth is 400 km. These values are not intended to be precise or to convey exquisite physical meaning. They do suggest that craters in icy bodies form in a mechanically different type of target than do those in rocky bodies. A 40–km crater on the Moon forms in an essentially brittle halfspace, whereas on Ganymede, this brittle lithosphere is underlain at relatively shallow depth by a ductile zone, which may become mobilized as a viscous plug during cratering. Rapid reduction to a uniform crater depth could arrest terrace development as well. Conceptually, this model is most related to the viscous target experiments of [2]. These calculations ignore the weakening effects of acoustic fluidization [8] but this effect is likely to be most important within 1.5 crater radii of the crater center [8]. Similar calculations for Titania indicate that the depth of this ductile zone is ~150 km on this satellite, which roughly scales inversely with Ganymede's surface gravity, consistent with gravity-scaling of central pit onset diameters [Fig. 3].

[1] Smith, B. et al. (1979) Science, 204, 951-972. [2] Greeley, R. et al. (1982) in Satellites of Jupiter, (Univ. Ariz.), 340-378. [3] Passey, Q., and E. Shoemaker (1982) in Satellites of Jupiter, (Univ. Ariz.), 379–434. [4] Croft, S. (1982) Lunar Sci. XIII, 196-198. [5] Moore, J., and M. Malin (1988) Geophys. Res. Lett., 15, 225-228. [6] Schenk, P. (1990), this volume. [7] Schenk, P. (1989) J. Geophys. Res., 94, 3813-3832. [8] Melosh, H. (1982) J. Geophys. Res., 87, 371-380. [9] Pearce, S., and H. Melosh (1986) Geophys. Res. Lett., 13, 1419-1422; Schenk, P., manuscript in preparation. [10] Kirk, R., and D. Stevenson (1987) Icarus, 69, 91-134. [11] Melosh, H. (1989) Impact Cratering, (Oxford). [12] Golombek, M., and B. Banerdt (1986) Icarus, 68, 252-265.



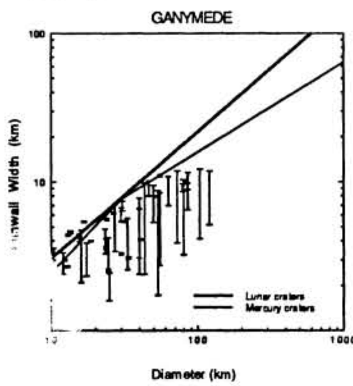
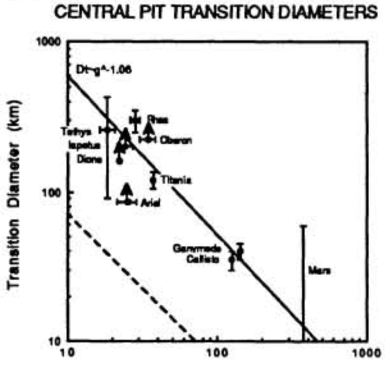


Fig. 1 (left). Bright-rayed central-pit crater Osiris (125 km) on Ganymede. Note the large pit with smooth dome in center, the narrow rimwall, and the uniform bright melt sheet covering the floor.
Fig. 2 (right). Rimwall widths of craters on Ganymede. Each vertical line represents the range of rimwall widths within individual craters.



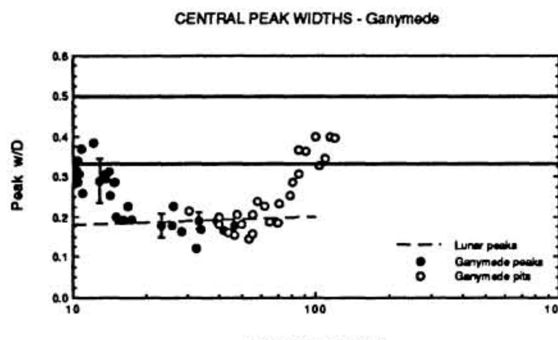


Fig. 3 (left). Known transition diameters of central pit occurrence on icy satellites and planets. Observed range of central pit craters on Mars is also given.
Fig. 4 (right). Central peak and pit width/diameter (*w/D*) ratios on Ganymede. Heavy line (*w/D*=0.33) is characteristic of many icy satellite craters. Lunar curve is representative of central peaks on terrestrial planets.