Cratering on Mathilde

Clark R. Chapman, William J. Merline
Southwest Research Inst., Suite 426, 1050 Walnut St., Boulder CO 80302

and

Peter Thomas
CRSR, Cornell Univ., Ithaca NY 14853

Submitted to Icarus
21 July 1998

No. pages: 18
No. figures: 3
No. tables: 2

Corresponding Author:

Dr. Clark R. Chapman
Southwest Research Institute
1050 Walnut St., Suite 426
Boulder CO 80302

Telephone:	303-546-9670
Fax:	303-546-9687
E-mail:	cchapman@boulder.swri.edu

Running head: Cratering on Mathilde

Abstract

Crater populations on Mathilde are assessed from NEAR fly-by images. Small-to-intermediate sized craters (½ to 5 km diameter) approach saturation equilibrium spatial densities and exhibit a range of degradation states, similar to the crater populations on Ida. They probably represent a population in quasi-equilibrium between the creation and destruction of craters caused by saturated impacts on Mathilde. Very large craters, with diameters approaching or exceeding the average radius of Mathilde itself, dominate the shape of Mathilde and represent a uniquely high spatial density of craters on a planetary surface. Formation of these large craters were remarkably ineffective in modifying, let alone destroying, pre-existing topography. We speculate on why Mathilde may be capable of retaining so many large, relatively well-preserved craters. The overall crater populations on Mathilde are consistent with (although do not uniquely require) the same production function (i.e. same projectile power-law size distribution) observed in the cratering records of the Moon, Gaspra, and (apparently) Ida.

Keywords: asteroids, cratering

INTRODUCTION

The C-type asteroid Mathilde is the third asteroid for which sufficiently high resolution images have been obtained to assess the impact crater population. The other two are Gaspra and Ida, studied earlier this decade by the Galileo spacecraft. (Radar delay-doppler maps of Toutatis and HST images of Vesta also show a few craters, but with inadequate resolution to address most cratering issues.) NEAR's images of Mathilde, obtained during the June 1997 fly-by, are roughly of the quality obtained by Galileo for Gaspra, and permit study of craters larger than 0.65 km diameter (roughly the completeness limit on the highest resolution images) up to the largest crater, which exceeds 30 km diameter.

One's first impression of Mathilde's appearance is dominated by the most important aspect of cratering on Mathilde: the asteroid's shape is largely formed by the rims and concavities of a population of very large craters, some overlapping (Fig. 1). Thus, while Mathilde is not as "irregular", angular, or elongated in shape as Gaspra and Ida, it has an unusual and markedly non-spherical shape due to the large craters that have gouged its surface. As we will describe, the preservation of so many giant craters is unexpected and probably reflects an inherent attribute of Mathilde that makes it different from other cratered surfaces and which may modify our understanding of the fundamental nature of Mathilde and any other asteroids that may be like it (perhaps C-type asteroids, in general).

The higher resolution images of Mathilde reveal, in addition to the large craters, an accompanying population of smaller impact craters that are the dominant small-scale topographic features on the body. Very few, if any, other kinds of topography exist on Mathilde at the resolutions achieved by NEAR (among the rare or absent feature types are positive-relief features, grooves, or indications of endogenic processes). Several ~1 km diameter craters appear to form a chain, but it cannot be proved that it is more than a chance alignment. The population of craters smaller than 5 km diameter resembles that studied in detail on Ida, which was interpreted by Chapman *et al.* (1996a) as being a population dominated by saturation equilibrium. Mathilde's smaller craters do *not* resemble the population of craters observed on Gaspra (Chapman *et al.*, 1996b), which were interpreted as reflecting a production population on a relatively young, or very strong, surface.

In this paper, we present counts and analyses of Mathilde's craters. We attempt to place Mathilde into the context of other asteroids and small bodies that have been studied. We also speculate briefly on the implications of the surprising nature of the largest craters. Finally, we address questions concerning Mathilde's collisional evolution and its cratering "age". We argue that the uncertainties raised by the large crater population render the always-uncertain determination of asteroid cratering ages even more uncertain in Mathilde's case. However, it is likely that Mathilde is relatively "old".

CRATER OBSERVATIONS

Craters larger than 12 km in diameter, recognized as part of work on Mathilde's shape (Thomas *et al.*, 1998), are tabulated in Table 1. The most prominent attribute of Mathilde, besides its anomalously slow spin and its unexpectedly low density (Yeomans *et al.*, 1997; Veverka *et al.*, 1997), is the dominance of its shape by huge craters, of the order of the radius of the object itself. Although major portions of the side away from NEAR could not be seen, due to the brevity of the fly-by in comparison with Mathilde's very slow spin, at least five craters about 20 km diameter or larger can be discerned, on one-half of Mathilde's total area. (Because large craters of these sizes on the back side have rims that might peek around the edge, the "sampled" area may actually be more than 50% of Mathilde's area. The total number of >20 km craters may be 8 or 9, if the back side is equally covered with large craters.) Fully 4 of the observed craters exceed in diameter our current best estimate for Mathilde's radius of 26 km (Thomas *et al.*, 1998).

Until now, an object's radius had been thought to be roughly the empirical limit for the size of crater that could be produced on it without substantially disrupting the body, at least to the point of "resetting" the surface topography. A substantial fraction of bodies, ranging from small planetary satellites like Phobos to objects comparable in size to the Moon, have craters approaching an object radius in diameter. Hubble Space Telescope images of Vesta have been interpreted (Thomas *et al.*, 1997) as showing an enormous polar impact crater with a central peak. Although Thomas (1993) suggested that Deimos may have a very large crater on it, and a few other small bodies have large depression-like structures, Mathilde is clearly a rare case of having a *well-developed* crater significantly larger than the body's radius.

More remarkable than the existence of one large crater (30% larger than the body's radius) is that there are several that have diameters exceeding a radius. It is notable that the rim crests and basic shapes of the craters (as best we can discern them from this single lighting geometry) seem relatively pristine, showing steep walls, and sharp circular rims relatively un-cut and undistorted by later cratering or other geological forces; in particular, they appear unaffected by what must be subsequent impacts of later giant craters. (Obviously, only one of these craters can have been the last one.) Given the relatively low gravity on an object the size of Mathilde, we would not expect the deep continuous ejecta blankets that degrade or erase most topography in an annulus surrounding a crater, which are seen on larger bodies like the Moon. Yet one might have expected that "seismic shaking" and related effects would have damaged other topography, nearby features especially. Evidently this is not the case.

Veverka *et al.* (1997) reported a preliminary assessment of Mathilde's smaller craters from a 400 km^2 portion of our highest resolution imaging sequence, in a region of good lighting and viewing geometry. 91 craters were identified, 70 larger than our apparent completeness limit of 0.6 km diameter. We have now made a more thorough study of 281 craters <12 km diameter on the portions of Mathilde's surface that were imaged at relatively high resolution, with good lighting and viewing geometry, totalling 1155±115 km^2 (Fig. 2). The relevant images (see Table 2) were oversampled by a factor of 3, then smoothed (2 x 2 boxcar) to minimize distraction of the pixelization in recognition and measurement of craters. The images studied and measured for craters were not rectified; that is, the arrays of the NEAR camera's unusual rectangular pixels were displayed in square format so that the image appeared somewhat "squashed" in one direction. Such a presentation has the advantage that the perceived resolution is the same in all directions, which is more natural for the eye and so minimizes potential biases in crater recognizability. (The resulting squashed appearance is analogous to geometrical foreshortening, a phenomenon familiar in crater-counting.) Crater diameters were measured approximately perpendicularly to the direction of foreshortening (i.e. unforeshortened, as determined in rectified images).

The highest resolution crater counts were made from image numbers 42826360 and 42826362 (Fig. 2a); small portions of the counted region are available on only one, not both, images. A total of 145 craters exceeding the completeness limit of 0.65 km diameter were measured from these images. (The earlier counts reported by Veverka *et al.*, 1997, are from a subarea within the studied region on frame 42826362.) A wider, complementary area toward and beyond the limb from these images was evaluated from images 6488 and 6622 (Fig. 2b), on which 51 craters exceeding the completeness limit of 1 km diameter were measured. The latter region included a small sunlit portion of the interior wall of one of the giant craters. Otherwise, all of the counts are on an evidently rather rare portion of Mathilde that is outside of the major craters.

The shape model of Thomas *et al.* (1998) has been used to measure the areas of the counted regions. Differential frequencies were calculated by dividing the counts by the areas and by the bin-widths. They, in turn, have been divided by D^{-3} to yield a standard log-log R-plot (the Relative Plot defined by Crater Analysis Techniques Working Group, 1977), showing crater spatial densities as a function of diameter (Fig. 3). Error bars are based on counting statistics and do not include systematic errors (e.g. completeness in crater recognition at the smallest sizes). The three points plotted at the largest diameters represent all craters over 12 km in diameter, normalized to a sampling area taken to be 58% of Mathilde's total surface area, or 5300±640 km^2. Shown for comparison is geometric saturation (R = 1), which can be thought of as the idealized limit to which craters of a given size can be packed onto a surface. In the real solar system, crater fields interpreted to be in saturation equilibrium typically plot horizontally on an R-plot near R = 0.2 (also shown in Fig. 3).

Another comparison plotted is a best fit for craters found on Ida (Chapman *et al*., 1996a), which are interpreted as being in saturation equilibrium (except at the largest diameters on one portion of Ida). It is evident that Mathilde's crater population <5 km diameter is similar in slope and density to Ida's, confirming a general visual impression that Mathilde's surface (as distinct from global shape) resembles Ida's. (The crater density on Mathilde is slightly greater than reported in the preliminary counts of Veverka *et al.* (1997), and is no longer slightly deficient compared with Ida.)

We should note, however, that the regions where we have counted Mathilde's smaller craters are located preferentially (although not entirely) outside of the giant craters, whose interiors were largely shadowed or hidden. So, if the largest craters are part of the production function (and were not, for example, all formed at one early epoch), then the average global density of smaller craters on Mathilde would be lower than what we show. The large- and mid-sized craters are reasonably peppered with smaller craters, suggesting that they either predate or accompanied the formation of the smaller craters. Small craters have somewhat reduced densities on sunlit inner slopes of the giant craters, which could imply that the giant craters were formed comparatively recently. More likely, the lower counts reflect loss of small craters by mass-wasting of the crater rims; in fact, it is somewhat surprising how many small craters *are* present on the comparatively steep walls.

Mathilde is definitely more heavily cratered than Gaspra and it shows a shallower slope (smaller index of the power-law approximation to the size distribution) than that observed for most craters on Gaspra (which, in Gaspra's case, were interpreted to represent the production function). A qualitative assessment of crater morphologies on Mathilde indicates a range from relatively deep, fresh craters to shallow, rather degraded craters. Such a range of morphologies is also consistent with our inference that Mathilde's surface is in (quasi-)equilibrium with the cratering process.

The five largest craters, with diameters in the range 20 - 33½ km are included in Fig. 3. It is evident that craters larger than 12 km diameter exceed the empirical equilibrium densities seen elsewhere and that the largest craters are near the geometric saturation limit. Obviously, the formation of large craters in the production function must cause the densities of smaller craters to oscillate in time -- small craters gradually increase following a big impact, then suddenly are "reset" when the next big impact erases such craters within its perimeter and perhaps beyond (see Chapman & McKinnon, 1986). In the case of Mathilde, there is no evidence for such erasure of small craters beyond the rims or lips of the giant craters, which is quite a remarkable observation.

INTERPRETATION

The observed size distribution of craters on Mathilde presents no fundamental surprises, except for the asteroid's unexpected capability to *record and retain* so many giant craters. It is widely believed that, to first order, the production function of objects that crater asteroids is the same as that responsible for cratering the Moon. In the case of the Moon, the production population rises at a positive slope on an R-plot for crater diameters larger than about 7 km (Neukum & Ivanov, 1994). In such cases, the observed crater population should mimic the production function, even under cases of saturation (Chapman & McKinnon, 1986). Within our large error bars, the Mathilde data are consistent with the lunar cratering production population, the small-size branch of which was also observed on Gaspra (and probably on one part of Ida). However, because of the evident saturation, a unique production population for Mathilde cannot be inferred.

The surprise is *not* that so many large craters could have formed on Mathilde. Rather it is that all of them can still remain there, with relatively fresh topography, and that the later cratering events (especially the last one) did not destroy pre-existing topography and reset the surface. One can surmise that Mathilde's composition or internal structure may play some role in localizing the damage from an impact crater, perhaps by damping the shock waves generated by the impacts. This is in sharp distinction, especially, to Gaspra (Veverka *et al.* 1994), where a faceted shape and relative lack of craters has been attributed to previous bombardment, despite the lack of any large crater visible on Gaspra's surface, which would be the record of the last, destructive impact.

Not only do several of the giant craters appear to be relatively fresh and well preserved (apart from a few overlapping, much-smaller craters), but they appear to have had no observable effect in blanketing or otherwise degrading the surrounding crater populations. Mathilde is large enough, and its escape velocity high enough, so that most ejecta would be expected to be retained on Mathilde (compare calculations by Geissler *et al.*, 1996, for the smaller Ida). Perhaps very little ejecta escaped beyond the rims of the giant craters. Cratering in sand, for example, yields much lower ejecta velocities than does cratering in rock (Stöffler *et al.*, 1975). Perhaps Mathilde is a such a weak, underdense body -- we know that its bulk density is remarkably low, about 1.3 g/cm^3 -- in which crater growth is enhanced but ejecta velocities diminished even more than for sand. (One can imagine, as an extreme gedanken experiment, cratering in styrofoam, packaging materials, or mashed potatoes.) On the other hand, Asphaug *et al.* (1998) find that ejecta velocities are actually enhanced from the confined region of damage in a porous (but not strengthless) target, so possibly most of the ejecta from the giant craters was mobilized enough to escape Mathilde entirely, which is an alternative possibility for lack of visible blanketing.

It is interesting to speculate that Mathilde's presumed inherently weak, low-density material (characteristic of carbonaceous chondrites) and a rubble-pile structure (expected to be common for objects its size, based on collisional modelling) might be responsible for the asteroid's ability to retain multiple giant impact craters, in which case similar attributes may be found for other C-type asteroids. But our observations, so far, involve statistics of one. And, so long as such an unusual attribute of Mathilde as its very slow spin remains unexplained, the properties of C-type asteroids in general must await future exploration by spacecraft, or at least high-resolution groundbased radar.

The question has been posed about whether Mathilde's giant craters are indeed of explosive impact origin. We presume that they are, but we must admit that some of the identifying traits of impact origin are difficult to verify, in this case. For example, one does not expect clusters of proximate secondary craters to be formed on a small body. The size of the giant craters relative to the body, and the limited viewing afforded during the fly-by, make it difficult to assess crater rim heights, crater depth/diameter ratios, and other attributes to see how well they conform to norms for impact craters. While one could speculate about other processes that might yield giant hollowed-out features on this body, we see no compelling reason to seek an alternative to our impact presumption.

It is not possible to estimate an age for Mathilde based on cratering densities alone. Mathilde orbits in generally the same portion of the asteroid belt as Gaspra and Ida and, therefore, should encounter roughly the same projectile population. But cratering ages that have been modelled for Gaspra and Ida depend on estimates/assumptions of their collisional strength (see Davis *et al.*, 1996). In the case of Mathilde, the presence of the giant craters (which one might reasonably have expected to have broken up Mathilde and/or reset its surface) argues for greater caution in attempts to calculate collisional ages. It is plausible that Mathilde (like Ida) has existed for more than a billion years in roughly its current configuration, but our images have little to add to that inference.

ACKNOWLEDGEMENTS

This research was supported by the Near Earth Asteroid Rendezvous project at the Applied Physics Laboratory of Johns Hopkins University, funded by NASA. We thank the NEAR engineers for accomplishing this remarkable fly-by and to other members of the NEAR Science Team for discussions. We are especially grateful to Lucy McFadden and Joe Veverka for reviewing an earlier version of this manuscript.

REFERENCES

Asphaug, E., S. J. Ostro, R. S. Hudson, D. J. Scheeres, and W. Benz 1998. Disruption of kilometre-sized asteroids by energetic collisions. *Nature* **393**, 437-440.

Chapman, C. R., E. V. Ryan, W. J. Merline, G. Neukum, R. Wagner, P. C. Thomas, J. Veverka, and R. J. Sullivan 1996a. Cratering on Ida. *Icarus* **120**, 77-86.

Chapman, C. R., J. Veverka, M. J. S. Belton, G. Neukum, and D. Morrison 1996b. Cratering on Gaspra. *Icarus* **120**, 231-245.

Chapman, C. R. and W. B. McKinnon 1986. Cratering of planetary satellites. In *Satellites* (J. A. Burns and M. S. Matthews, Eds.), pp. 492-580. Univ. of Arizona Press, Tucson.

Crater Analysis Techniques Working Group 1977. Standard techniques for presentation and analysis of crater size-frequency data. *Icarus* **37**, 467-474.

Davis, D. R., C. R. Chapman, D. D. Durda, P. Farinella, and F. Marzari 1996. The formation and collisional/dynamical evolution of the Ida/Dactyl system as part of the Koronis family. *Icarus* **120**, 220-230.

Geissler, P., J.-M. Petit, D. D. Durda, R. Greenberg, W. Bottke, M. Nolan, and J. Moore 1996. Erosion and ejecta reaccretion on 243 Ida and its moon. *Icarus* **120**, 140-157.

Stöffler, D., D. E. Gault, J. A. Wedekind, and G. Polkowski 1975. Experimental hypervelocity impact into quartz sand: Distribution and shock metamorphism of ejecta. *J. Geophys. Res.* **80**, 4062-4077.

Thomas, P. C. 1993. Gravity, tides, and topography on small satellites and asteroids. *Icarus* **105**, 326-344.

Thomas, P. C., R. P. Binzel, M. J. Gaffey, A. D. Storrs, E. N. Wells, and B. H. Zellner 1997. Impact excavation on asteroid 4 Vesta: Hubble Space Telescope results. *Science* **277**, 1492-1495.

Thomas, P. C., J. Veverka, J. F. Bell, B. E. Clark, M. Robinson, L. A. McFadden, M. C. Malin, C. R. Chapman, W. Merline, and S. Murchie 1998. Mathilde: Size, shape, and geology. Submitted to *Icarus*.

Veverka, J., P. Thomas, A. Harch, B. Clark, J. F. Bell III, B. Carcich, J. Joseph, C. Chapman, W. Merline, M. Robinson, M. Malin, L. A. McFadden, S. Murchie, S. E. Hawkins III, R. Farquhar, N. Izenberg, and A. Cheng 1997. NEAR's flyby of 253 Mathilde: Images of a C asteroid. *Science* **278**, 2109-2114.

Yeomans, D. K., J.-P. Barriot, D. W. Dunham, R. W. Farquhar, J. D. Giorgini, C. E. Helfrich, A. S. Konopliv, J. V. McAdams, J. K. Miller, W. M. Owen Jr., D. J. Scheeres, S. P. Synnott, B. G. Williams 1997. Estimating the mass of asteroid 253 Mathilde from tracking data during the NEAR flyby. *Science* **278**, 2106-2109.

TABLES

Table 1. CRATERS >12 KM DIAMETER

#	Long., Lat. (deg)*	Diam. (km)
1	27.7, 98.4	33.4
2	186.9, -66.2	29.3
3	263.8, 73.0	28.7
4	88.9 , -46.0	28.5
5	256.5, -12.3	19.9
6	191.6, 14.6	16.4
7	30.9 , -39.5	12.3

* The tabulated position is in a longitude/latitude reference defined by Thomas *et al.* (1998).

Table 2. IMAGES EVALUATED FOR CRATERS <12 KM DIAMETER

MET	Range (km)	Phase (deg)	Scale (m/pixel)
42826360	1210	93.3	0.115 x 0.195
42826362	1210	92.5	0.115 x 0.195
42826488	1757	59.0	0.167 x 0.283
42826622	2872	48.0	0.273 x 0.462

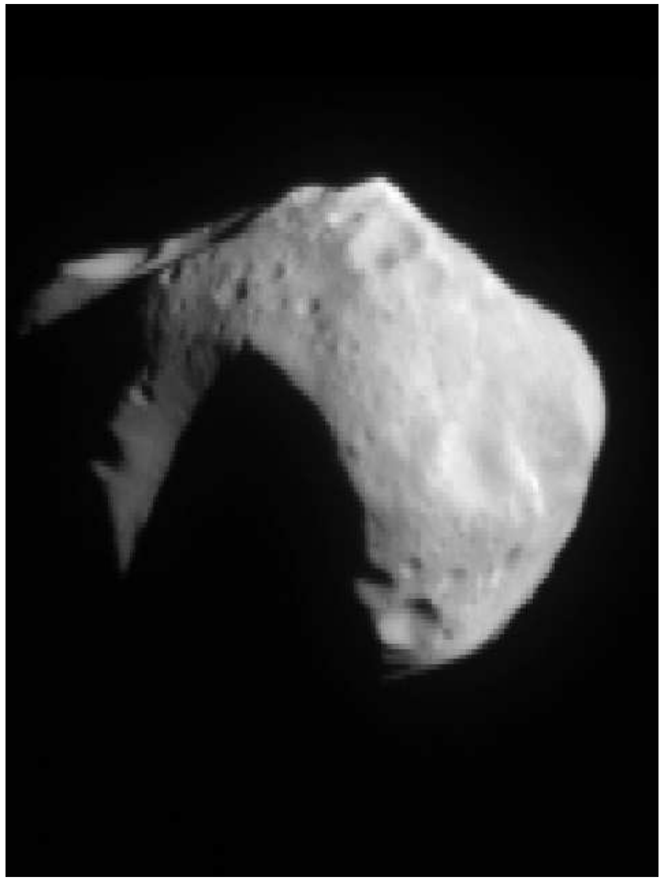

Fig. 1. View of Mathilde showing shape dominated by large craters (42826638).

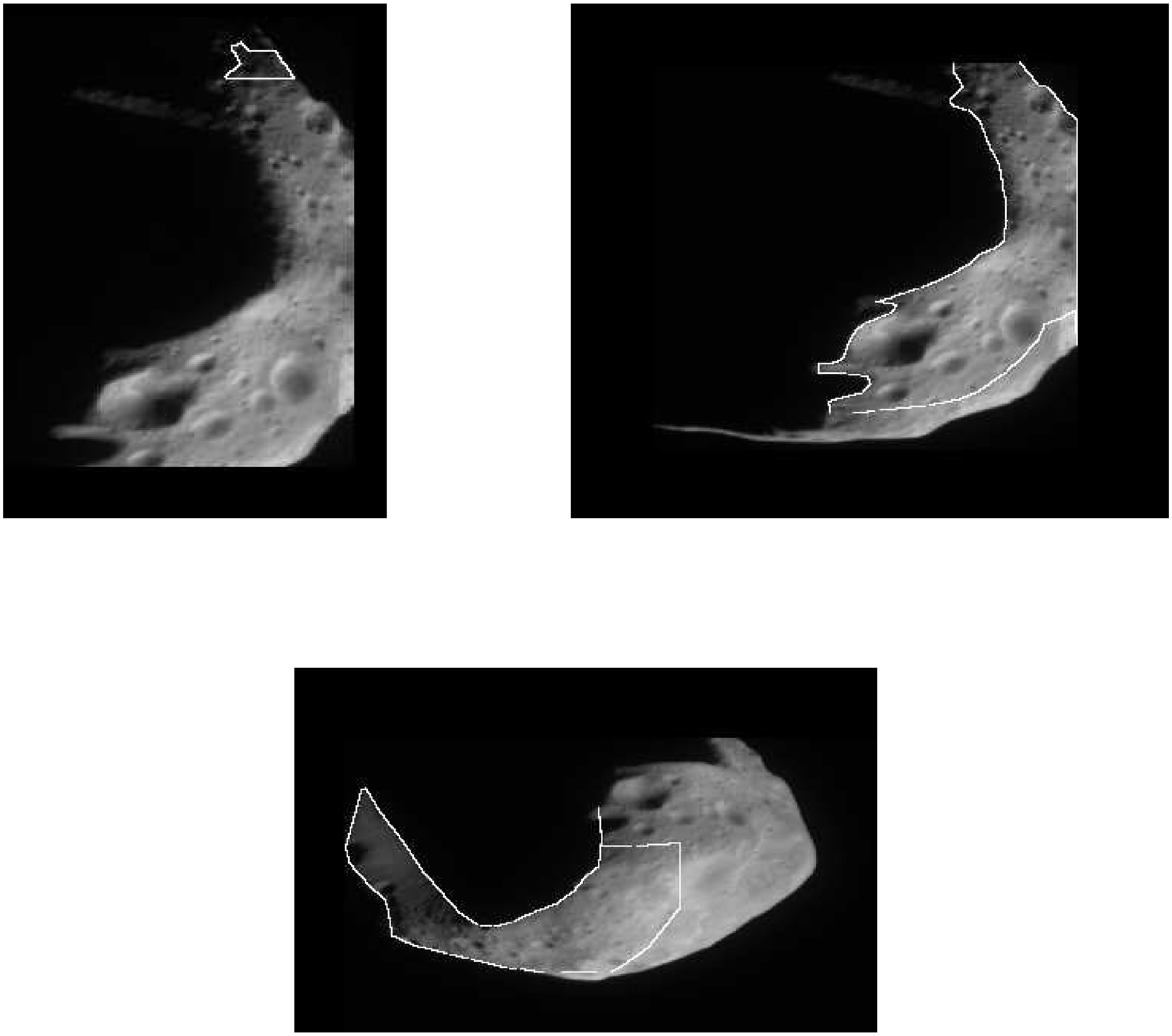

Fig. 2. Regions counted on (a) frames 42826360 and 42826362 (totalling 514 km^2), and (b) frame 42826488 (totalling 640 km^2). Areas are uncertain by 10%. Frames are unrectified and inverted.

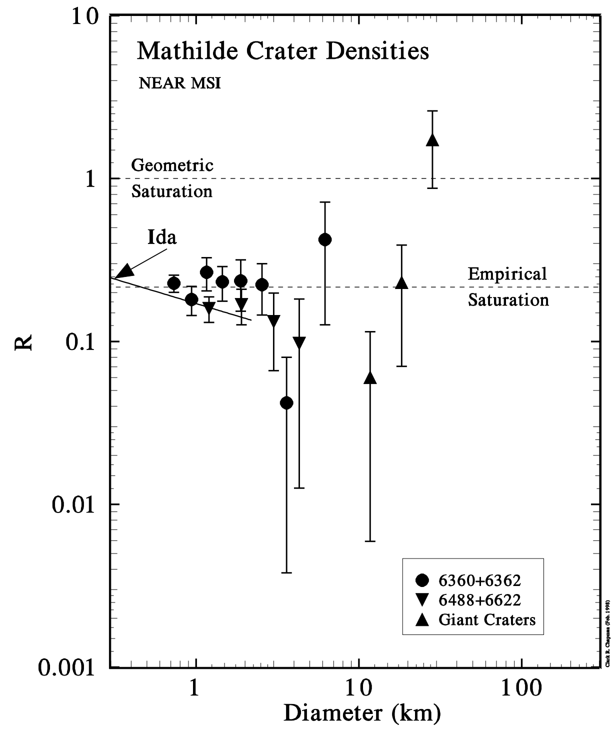

Fig. 3. R-plot of crater spatial densities for Mathilde. A reference least-squares fit for Ida is indicated. Also plotted are geometric saturation (R = 1) and a density typical of saturation equilibrium on other planets, satellites, and asteroids (near R = 0.2). The error bars are based on counting statistics and do not take into account either potential systematic loss of craters near the resolution limit or the ~10% errors in estimates of areas counted.