Cratering on Gaspra

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Abstract.

Galileo flyby images of 951 Gaspra show a crater population dominated by fresh craters several hundred meters in diameter and smaller. They must represent a production population because their spatial density is low (few overlaps) and because degraded craters are underabundant; equilibrium may be attained at diameters near to or below the resolution limit of the best image. We have counted, measured, and classified craters from the highest resolution, "high phase" image, which shows >600 craters in 90 km^2. The differential population index (0.2 - 0.6 km) for the fresh, obvious craters is very "steep" (-4.3 ±0.3). It probably reflects the index of asteroidal projectiles; it is much steeper than the theoretical value of -3.5 for collisional equilibrium. Gaspra's crater population differs from that observed on Phobos but resembles those observed on the Moon and Mars at these sizes (consistent also with the near-Earth asteroid population). Gaspra's fresh craters are superposed on a landscape that appears "smoothed" at a vertical scale of hundreds of meters. Some "soft", subdued crater-like features, commonly ~>500 m across, are visible. Some of these are associated with the linear grooves on Gaspra and may be endogenic features. Many others are probably pre-existing impact craters deeply blanketed or otherwise much degraded.

Gaspra's largest-scale shape is highly irregular, perhaps faceted. The biggest facet exceeds the largest crater (relative to body radius) ever observed on a satellite or expected from collisional fragmentation models. Facets cannot be successive crater-forming impacts; later scars would have destroyed earlier ones. Far-encounter images show a more lumpy than faceted visage of Gaspra; the two craters are ~3 km in diameter, not even half the radius of Gaspra. We expect that Gaspra was created by collisional fragmentation of a larger parent body. Its gross configuration may reflect collisional spallation of the parent. Certainly, megaregolithic processes of reaccumulation and blanketing and/or shaking are evident, due to subsequent sub-catastrophic collisions. Gaspra's subdued craters peek through the effects of the last such collision. That smoothed surface has been cratered ever since by the steep production function, which, however must become shallower again below 10 m. Since the overall density of fresh craters is low, Gaspra must be relatively youthful. Scaled to a calculated 0.5 Gyr age for bodies of its size, based on asteroid collision models and assuming that Gaspra does not have metallic strength, its cratering lifetime is ~0.2 Gyr, with large modelling uncertainties.

The cumulative volume of all visible craters could create a regolith only <10 m deep, even if all ejecta were retained by Gaspra's weak gravity. Gaspra's modern soil-like regolith, produced by the steep production function, is probably very thin. Indeed, Gaspra's surface must be under net erosion and provides an inadequate environment for any mature weathering and reworking of its surface layer during the last 0.2 Gyr.

Introduction

In October 1991, the Galileo spacecraft made the historic first-ever encounter with an asteroid, 951 Gaspra. This paper analyzes Gaspra images in terms of cratering, collisional evolution, and regolith development. The first images studied after encounter were the second highest resolution views (the "four color" sequence), which showed several dozen craters (preliminary analysis by Belton, *et al*., 1992). In May 1992, the highest resolution (54 m/pixel) "high phase" image was returned from the spacecraft's tape recorder. Finally, lower resolution pictures of Gaspra from other perspectives were received in November 1992.

The present article was prepared in late 1992 and early 1993. After a delay, it was submitted for publication in October 1993, but without regard for the first data returned from Ida the previous month. Since this work represents the first stages of an analysis of asteroid cratering data from a unique, never-to-be-repeated reconnaisance mission to an asteroid, we decided to revise it in response to the referees and in the context of other concurrent analyses of Gaspra (including papers in the special Gaspra issue of *Icarus*, Vol. 107, No. 1, 1994, for which this paper was originally intended). We decided *not* to consider Ida in this work. A paper analyzing the Ida cratering data is in press (Chapman *et al.*, 1995); that analysis builds on the foundation established in the present paper, and updates and revises some Gaspra interpretations in the light of both data sets. Those updates for Gaspra are speculative, however, for we have sampled only two asteroids, which have a variety of different characteristics -- size, semi-major axis, family membership, and inferred composition (perhaps including strength). They have very different crater populations on their surfaces, but it is not clear which combination of variables is responsible for the differences. It may very well be that the present analysis of Gaspra has validity independent of anything subsequently learned about Ida.

The Flora region of the inner asteroid belt is populated by small, S-type asteroids, generally thought to be fragments of one or more larger precursor asteroids that were catastrophically disrupted by collisions. Gaspra is presumably such a fragment. It is debated whether Gaspra belongs to an identifiable Hirayama family (Williams, 1979; Zappalà *et al.*, 1990). Nevertheless, Flora-region asteroids like Gaspra probably reflect comparatively recent catastrophic collisions.

The collisional evolution of asteroids is a theoretical, model-dependent subject for which there are no good analogs in nature; impact energies involved are far beyond the range of experiments. There are uncertainties about the modes of break-up and the morphology of collisional remnants and fragments. Some researchers have regarded rock fragmentation, spallation, and erosion as applicable to asteroid collisional outcomes (e.g. Ip, 1979). Others, emphasizing the importance of self-gravity of targets tens of kilometers and larger, expect some large asteroids to have megaregolith-like properties of a "rubble pile" (Chapman, 1978). It is unknown whether nth-generation fragments of such rubble piles should also possess rubble-pile-like traits. One idea, strengthened by radar images of Castalia (Ostro *et al.*, 1990) and Toutatis (Ostro *et al.*, 1993), is that some small asteroids may be lumpy, compound objects, composed of two or more large objects. Two factors are particularly crucial to Gaspra's collisional evolution: (a) the size distribution of the projectiles striking it and (b) its physical strength.

<u>Size Distribution</u>

While there are long-standing theoretical reasons (cf. Dohnanyi, 1971) for believing that the differential numbers of smaller members of a collisionally evolved population should follow a power law with an exponent ("population index") of -3.5, there have been no direct observational constraints on the size distribution of main belt asteroids smaller than Gaspra (mean radius = 6.1 km; Veverka *et al.*, 1994) or at the sizes of the much smaller projectiles that crater it. A prime objective of the Galileo Gaspra encounter was to determine the population index of craters on its surface. Assuming energy scaling, that population index would directly reflect the index of the projectile population.

Chapman *et al.* (1992) and Belton *et al.* (1992) reported preliminary interpretations of the several dozen craters visible on the first image returned following the Gaspra encounter. Because of resolution-limited incompleteness at diameters <~0.5 km and due to poor statistics (2 craters or less) at diameters >~1 km, the population index could be determined over a range of only a factor of 2 (based on about 30 craters), allowing values of -3.0 to -4.5. Compared with the wide range of possible size distributions discussed before the encounter (cf. Namiki and Binzel, 1991), even this rough indication of the steepness of the size distribution was significant. It was pointed out that an extrapolation to smaller diameters would approach equilibrium and a range of degraded crater morphologies might appear near the resolution limit of the high-phase picture (54 m/pixel).

<u>Gaspra's Impact Strength</u>

The idea that Gaspra might be a fragment from catastrophic disruption of a precursor body is based on collisional models, which give lifetimes for rocky objects tens of km in size that are much shorter than the age of the solar system (Farinella *et al.*, 1992; Namiki and Binzel, 1991). The conclusion depends on how small a projectile is required (striking at typical velocities of ~5½ km/sec) to disrupt a "proto-Gaspra" (i.e. it depends on the precursor body's "strength"). How long Gaspra will survive in its present form depends on its own strength.

The relevant strength is a body's "impact strength," which is related -- but not identical -- to the more familiar crushing or tensile strengths measured in the laboratory. Obviously, a more energetic impact would be needed to disrupt a cohesive body made of metal than one made of rock. There is a literature on how the effective impact strength of a cohesive body varies with scale. Larger target bodies are believed to be increasingly weaker than laboratory-scale objects made of the same material until compression due to self-gravity begins to strengthen bodies tens of km in size and larger (Fujiwara *et al.*, 1989; Housen and Holsapple, 1990). On the other hand, physically weaker bodies may be more difficult to disrupt and have a paradoxically higher impact strength (Ryan, 1992; Greenberg *et al.*, 1994).

The modeled lifetimes for Gaspra mentioned above are based on the assumption that it has the expected impact strength for a cohesive body made of rock. It is plausible that it is a rocky body because its surface reflection spectrum is dominated by the signature of olivine, a common rocky mineral, and its class (S-type) has been argued (cf. Wetherill and Chapman, 1988) as possibly containing parent bodies for certain stony meteorites. But Gaspra may, instead, have the strength of iron alloy because its reflectance spectrum is *most* compatible with the mineralogy of stony-iron meteorites (Gaffey, *et al.*, 1993), which have laboratory strengths more nearly like metal than like rock. (The magnetic anomalies observed during the Gaspra fly-by [Kivelson, *et al.* 1993] do not distinguish between these two possibilities because meteorites of most types have substantial remanent magnetization.)

Apart from inherent material strength, there is the question of whether the physical configuration of the body is that of (a) a cohesive, "monolithic" body or (b) a rubble pile or some other cohesionless assemblage bound only by its weak gravity. In this paper, we calculate collisional ages on the assumption that Gaspra is a single body of rocky strength. However, there is a double-lobed aspect in some far-encounter images of Gaspra that suggest it may be a rubble pile (which may not affect its collisional lifetime very much [Ryan *et al.*, 1991]). Also, as mentioned above, it *could* be a solid object with the strength of nickel-iron alloy (which would greatly lengthen its collisional and cratering ages). For these two reasons, any determination of Gaspra's *absolute* age is very uncertain.

High-Phase Image Counts

The highest resolution, high-phase image of Gaspra is the chief source of data on Gaspra's craters. Photographic prints with a scale of 1 mm per pixel were used by one of us (CRC) for crater identification, classification, and measurement in the area of good feature visibility shown in Fig. 1, for which the area is 90 km^2. Secondary sources of data were used to verify these results, study applicable systematic errors, evaluate personal equations, and identify different crater classification criteria. These include: (a) detailed counts/measurements from a 41 km^2 portion of Gaspra by CRC and two others using IRAF-based image processing software; (b) measurements by several associates of GN using a stereo photocomparator (cf. Neukum and Ivanov, 1994); and (c) earlier studies of craters from the 4-color images by CRC, MJSB, GN, and others.

In the primary analysis, 607 craters were identified and measured larger than ~100 m diameter (the picture scale is 54 m per pixel, with measurements recorded to the nearest pixel). Craters were placed into diameter bins; diameters were measured perpendicular to the terminator.

We also classified craters by morphology. The resolution is not adequate to apply actual geomorphic measurements, such as crater depth, to any but the largest craters. However, craters subjected to erosion and degradation by a steep population index of subsequent cratering form a continuous spectrum of shapes that is readily and consistently subdivided into classes. In previous studies of lunar craters by Chapman (1968), Chapman *et al.* (1970), Trask (1967), and others, between 3 and 5 classes, ranging from fresh to highly degraded, have proved useful in studying cratering processes. Here we use three classes: "Class 1" means un-degraded, sharp, bowl-shaped crater; "Class 2" means well-defined crater, but noticeably shallower or softer than the freshest craters; "Class 3" means an indistinct, shallow crater, occasionally misshapen or encroached on by another crater (a few Class 3 craters are so indistinct as to be very difficult to recognize). Care has been taken to minimize systematic biases due to differences in resolution, lighting geometry, and photographic image density.

Crater counts necessarily become incomplete as the resolution limit is approached. We estimate that our counts are drastically incomplete for craters with diameters of 2 pixels (110 m) and somewhat incomplete for diameters of 3 pixels (or larger for highly degraded craters). The most reliable information on the size distribution is for the size range of 0.2 to 0.85 km. Bins for sizes larger than 0.85 km often have only 1 crater per bin, or none, for the individual classes. This sampling of the high phase frame more than doubles the dynamic range of diameters for reliable and statistically significant counts over that first analyzed by Belton *et al.* (1992) and increases the number of craters counted by more than a factor of ten.

Size Distributions

Fig. 2 (see also Table 1) presents differential frequencies (counts per km^2 per km diameter increment) for each class separately and for all craters. Symbols with down-arrows at 10^{-2} represent approximate upper limits. Turn-downs at the smallest diameters are evident due to incompleteness. Enhancements of Class 2 and 3 craters at the expense of Class 1 near 0.2 km reflect (a) the onset of crater-saturation equilibrium processes and/or (b) the classifiers' inability to distinguish Class-1-sharpness for craters only a few pixels across.

Fig. 3 shows unweighted least squares fits for the high-quality total crater data, shown with solid symbols, and for statistically reliable counts for the summation of Classes 1 and 2 (termed "fresh" craters in this article). (Following Chapman and Haefner [1967], we note the danger of using weighted least squares fits in cases like this: as the y-axis counts rapidly increase -- which would carry much weight -- there is increasing potential for incompleteness and systematic error in diameter measurement as the resolution limit is approached. Therefore, we prefer unweighted fits to carefully selected data points. Plotted error bars for the total crater counts are based on $\sqrt{N}$ statistics; we stress that systematic errors cannot be estimated accurately and are most important where $\sqrt{N}$ error bars are small.)

Fig. 4 shows the R-plot equivalent of Fig. 3. Here, differential frequencies are divided by D^{-3}, thus representing the spatial density of craters of different sizes. A horizontal line corresponds to a differential power-law index of -3; an approximate empirical representation of crater "saturation equilibrium" is plotted at a density of 0.3, along with reference curves for Phobos, Mimas, and the lunar maria (from Chapman and McKinnon, 1986). ("Saturation equilibrium" refers to the theoretical relationship expected for craters under the condition that newly formed craters with a steep power-law production function erase pre-existing craters and form an unchanging, observable population with an index of -3; the R-value of this line varies for different situations but is typically a few tenths.)

Although plots of cumulative size distributions are misleading for reasons given by Chapman and Haefner (1967), we show some here because of their widespread use. Fig. 5 displays cumulative counts for each class separately and for total craters; larger symbols indicate more reliable data. Least squares fits, through reliable data points only, are shown for fresh craters (Classes 1 and 2), for degraded (Class 3) craters, and for total craters. (Although slopes of cumulative distributions tend to be about one unit shallower than for differential distributions, they vary by a couple tenths here; the differential fits are more reliable.)

It is evident that, while the slope of the total crater population is about -3.8 (differential), it actually reflects the combination of two different populations with different morphological characteristics. Consistent with visual impression, the large majority of craters, following a steeper slope, are fresh. But at diameters of 0.5 km and larger, the shallow craters with softened morphology actually predominate. Some show an affinity for Gaspra's grooves, and thus may not be impact craters, but the majority of soft craters are probably degraded impact craters. Most geological processes of degradation erase small features more rapidly than large features. Thus the fact that the processes that degraded these larger craters did *not* affect the abundant smaller, fresh craters demonstrates that the subdued craters are the (larger) remnants from an earlier population of craters that was present before the most recent violent episode in Gaspra's history substantially reset the surface. At that time, general large-scale erosion, blanketing, or shaking of Gaspra's surface created the smoothed surface on which the fresh craters subsequently formed. The fresh craters can be taken to represent directly (if energy scaling applies) the cratering production function because their spatial density, at observable sizes, is too low for their numbers to be affected by mutual overlap or erosion.

Different analysts have slightly disparate criteria for identifying and classifying craters. Some (e.g. GN) are more conservative in recognizing craters on Gaspra than CRC, whose counts are reported above (see comparisons of counts in Figs. 6 and 7); their total crater counts more nearly resemble those for only the fresh craters of CRC. Such differences are responsible for a range of reported slopes for the Gaspra total crater population. However, all analyses of the Gaspra craters (including Carr *et al.*, 1994) agree that the production function is close to -4.3, as represented by the predominant fresh crater component. The only possible remaining reservation may concern our interpretation that many of the larger, subdued depressions are degraded impact craters.

The fresh craters exhibit a very steep differential slope of -4.3 ±0.3. We take this to be the production function for craters in the size range of 0.2 to 0.6 km. The crater production function represents a mapping of the projectile population (with constant ratio of crater-to-projectile diameters = 10 for Gaspra, for its mean impact speed with the asteroidal population of 5.5 km/s, Farinella *et al*., 1992), provided that energy scaling in the strength regime applies. Given Gaspra's low gravity and the very thin regolith that we infer to be present (see below), strength scaling probably does apply for the smaller craters on Gaspra, although there is probably a transition toward gravity scaling for the largest craters. Independent of uncertainties in applicable scaling, the slope for small main-belt asteroids 20 to 60 m in diameter must be dramatically different from the value of -3.5 predicted for collisional equilibrium in the asteroid belt from both analytical theory (e.g. Dohnanyi, 1971, Wetherill, 1968) and numerical simulations (Davis *et al.*, 1985). While there may be doubt about the degree to which asteroids tens of km in diameter (to which the referenced studies were applied) are collisionally evolved, there can be no possibility that asteroidal projectiles tens of meters in size are somehow "unevolved" original objects; they cannot be original objects pre-dating the current collisional regime, but must instead be a product of currently operating processes. Thus the theory and modelling are called into question.

Such a steep population index in this size range has been observed elsewhere in the solar system. Small craters hundreds of meters in diameter show a steep slope similar to Gaspra's for both the Moon (cf. Neukum *et al.*, 1975a,b, Chapman *et al.*, 1970) and Mars (Soderblom *et al.*, 1974; Strom *et al.*, 1992). Some investigators (since Shoemaker, 1965) have regarded these slopes as due to "background secondary" craters landing far from their primaries while others (Neukum, 1975a,b; Neukum and Ivanov, 1994) have maintained that they are chiefly primaries due to asteroids and comets. In view of the low escape velocities from asteroids as small as Gaspra, craters on its surface clearly cannot be due to immediate, high-velocity secondary impacts. Analogous ejecta that would form secondaries on the Moon, instead go into heliocentric orbit and join the complex of other debris from catastrophic fragmentation and cratering events on other asteroids. While Hartmann (1995) has termed such objects as "asteroidal secondaries," they have been traditionally, and more usefully, treated as one component of the complex of interplanetary debris. The re-impact of such projectiles, whether collisionally evolved or not and whether derived from Gaspra or from other asteroids, we regard as *primary* cratering in this paper.

Rabinowitz (1993) reported that small Earth-approaching objects in the 10 - 100 m size range discovered by the Spacewatch telescope also exhibit a ~-4.4 slope, although it remains uncertain if this is a near-Earth selection effect or should be considered representative of the asteroid population as a whole. To the degree that the near-Earth asteroids and small lunar and Martian craters might be ascribed to comets, which have a poorly known size distribution, we note that small comets are surely overwhelmed by asteroidal projectiles in the asteroid belt itself where inter-asteroid collision frequencies are estimated to be 1 to 2 orders of magnitude higher compared with the Earth-Moon system. Now that the Galileo Gaspra data demonstrate that the steep slope may be characteristic of the inner asteroid belt itself, asteroid collisional models must be reassessed.

Indeed, initial attempts to understand "wavy" variations from the theoretical -3.5 slope, partly inspired by the Gaspra data, are already underway (cf. Campo Bagatin *et al.*, 1994).

As shown in Fig. 4, Gaspra's crater population is apparently distinct from that found on Phobos (and also Deimos), which is visibly dominated by large craters, even disregarding Stickney (see Fig. 6 of Veverka *et al.*, 1994). Phobos's craters show a differential slope near -3, down to 100 m diameter (Thomas and Veverka, 1980), clearly different in shape from the populations seen on the lunar maria and on Gaspra. This may reflect saturation equilibrium (as defined above) from much longer relative exposure to the same steep population of projectiles (Thomas *et al.*, 1979). An alternative explanation for the different crater distributions on Phobos and Gaspra is that debris from past cratering (or even break-up and reassembly) of the Martian satellites, trapped by the planet's gravity near Phobos's orbit, may be characterized by a different population index than are asteroidal projectiles, and that cratering by that population predominates over the asteroidal component on Phobos's surface. Either interpretation of Phobos is thus compatible with the idea that a single production function (with a shallow slope at large diameters and a steep slope at small diameters) is currently manifest throughout the inner solar system and the asteroid belt.

Collisional Age and Cratering Age

Gaspra (as distinct from a precursor proto-Gaspra) evidently has not been heavily cratered (or, indeed, cratered at all) by projectiles that would form craters a substantial fraction of its radius. (Here, we ignore such possible large features as the "facets," but will return to them below.) Its surface has been exposed to subsequent cratering for only a portion of its expected lifetime, defined as the mean interval between catastrophic collisions energetic enough to disrupt it and disperse >50% of its mass, destroying it as an identifiable body. A basic review of asteroid collisional modelling is by Davis *et al.* (1989).

<u>Cratering Age</u>

Gaspra's "cratering age" is only slightly better constrained by Galileo data than it was beforehand from purely theoretical arguments. For secure chronologies, there is no substitute for absolute radiometric ages, which we have only for the Moon and for meteorite parent bodies (whose association with particular asteroids is generally unknown). For all other bodies, including Mercury, Venus, Mars, and Gaspra, we must rely on our very poor knowledge of the absolute impact rates on those bodies.

The essence of the following analysis is application of telescopic knowledge of the population of large asteroids and their resulting collisional frequencies ("intrinsic collision rate"). Through extension to smaller bodies, based on uncertain knowledge of the size distribution, we calculate the projectile flux on Gaspra. (The steep size distribution observed by Galileo helps our extrapolation from telescopically observable asteroids to smaller sizes; this, plus the observed crater density, are the chief inputs that Galileo data make to the age calculations.) Then crater scaling laws are employed to translate projectile sizes into crater sizes and thus calculate the cratering rate. By comparing rates with crater densities observed by Galileo, we derive a cratering "age" for Gaspra. We express the age not only in years but also as a fraction of Gaspra's mean collisional lifetime, which is a model age calculated using the same asteroid collisional frequencies and scaling laws.

These models employ uncertain physics and, in any case, depend on Gaspra's (unknown) composition. In what follows, we assume that Gaspra behaves like strong rock; it probably makes little difference if it is compositionally or structurally weaker. But it would make a *big* difference if Gaspra were strong.

We discuss Gaspra's cratering age in comparison with a lunar benchmark, the post-mare crater population. We calculate production rates for 1 km craters on the Moon and on Gaspra using the known production rate of 10 km craters on the Moon, the telescopically observed asteroid size distribution (extrapolated conservatively and then augmented slightly at small sizes by a steeper -3.5 slope, more conservative than the observed crater distribution on Gaspra and the lunar crater production function), the intrinsic collision rate for Gaspra, and strength- or gravity-scaling for rock where appropriate to find ratios of projectile-to-crater size.

The production rate of >10 km diameter lunar maria craters is 0.3 x 10^{-14} km^{-2} yr^{-1} (Neukum *et al.*, 1975a,b). Sizes of projectiles to produce 1 and 10 km craters are obtained from Holsapple Schmidt scaling (Melosh, 1989) for competent rock in the gravity regime. There are about 375 times as many lunar maria craters >1 km as there are >10 km (Neukum *et al.*, 1975a,b), yielding a crater production rate (for >1 km craters) of 1.1 x 10^{-12} km^{-2} yr^{-1}. For Gaspra, the projectile size needed to form a 1 km crater at the mean impact speed of 5.5 km/s into basalt in the strength regime is 100 m. The asteroid size distribution we use is based on a conservative extrapolation of the Palomar Leiden Survey (slope -2.95, due to Farinella *et al.*, 1992) down to the projectile size (175 m) that produces a 2.5 km lunar crater, where the lunar curve begins to turn up, and -3.5 for somewhat smaller sizes. This yields a Gaspra crater production rate (for >1 km craters) of 5.7 x 10^{-11} km^{-2} yr^{-1}, which is about 50 times the lunar crater production rate. The result is conservative; the ratio would be higher, and Gaspra's age correspondingly younger, if there are even more smaller asteroids (as in the Namiki and Binzel [1991] "Population I" case), which is more likely than that there are fewer.

Taking the lunar maria to be 3.5 b.y. old and observing that Gaspra has about 3 times as many 1 km fresh craters as the lunar maria (Fig. 4), we find Gaspra's cratering age to be 210 m.y. (As a check, alternative calculations were made using a different scaling law [Shoemaker and Wolfe, 1982] and adopting the Neukum *et al.* [1975a,b] lunar standard size distribution as applicable to the asteroidal size distribution for extension to small sizes; they yield ages of ~200 to ~400 m.y., depending on particular parameters. Carr *et al.* [1994] derived Gaspra's cratering age to be between 20 and 300 m.y.)

Collisional Age and Youthfulness

A self-consistent calculation of the modeled lifetime for an object of Gaspra's size between catastrophic disruptions is 550 million years. We use the same asteroid size distribution and intrinsic collision rates (hence velocities) as for the cratering age calculation. For strain rate scaling, an object of Gaspra's size is shattered and disrupted by a 350 m projectile. Thus Gaspra's apparent age is 210 m.y./550 m.y. ≈40% of its mean lifetime -- comparatively, but not exceptionally, young. (Namiki and Binzel [1991] and Carr *et al.* [1994] got younger ages for the steeply sloping case because they attached the steeply sloping power-law to the observed asteroid distribution at a larger size.)

Gaspra's model lifetime could be as old as many billions of years (dating it back to the epoch of the Late Heavy Bombardment) if it is much stronger than rock, as could be true if it has the inherent strength of ductile metal. (If the surface were as strong as solid metal, as well, the deduced cratering age would also be correspondingly older.) Ironically, Gaspra could behave as a "strong" body even if it were mechanically weak, for some extreme scaling assumptions discussed below, because of possibly less effective coupling of kinetic energy into dispersion of fragments.

The best answer for Gaspra's cratering age is that it is probably a couple hundred million years old (it could be several times younger or a couple times older than that age), unless it is made of iron alloy, in which case it could date back to the Late Heavy Bombardment. Further improvement in absolute chronology must await return of documented samples for age-dating or considerable advances in asteroid fragmentation modelling.

Large Craters, Impact Scars, and "Facets"

The highest resolution images of Gaspra reveal a dearth of obvious impact craters larger than 1.5 km diameter. However, there are several large-scale features on Gaspra that conceivably reflect the effects of very large impacts. Gaspra appears to be an exceptionally irregular body. One attribute of its gross morphology are several planar elements, loosely termed "facets" (Thomas *et al.*, 1993). One such facet shows in profile in both the four-color and high-phase pictures and looks intriguingly like a giant crater with a diameter considerably exceeding the mean radius of Gaspra itself, although detailed morphometry (Thomas *et al.*, 1993) shows that it is almost planar and is not concave. Another facet, presented face on, dominates the Gaspra's landscape in the high-phase image. The high phase picture reveals hints of still another large feature, approaching 80% of Gaspra's radius, just emerging from the terminator; conceivably it is a giant crater. Up to eight facets on the visible side of Gaspra have been tentatively interpreted as craters by Greenberg *et al.* (1992, 1994).

Playback in November 1992 of a full sequence of lower-resolution images of Gaspra, covering much of its surface during a full rotation period, clarified the question of large or very large craters on Gaspra. Two intermediate size craters about 3 km in diameter are seen, but there is no crater even half the radius of Gaspra. Furthermore, some of the new likenesses of Gaspra look more nearly like a peanut, suggestive (although less obviously) of the contact binary shapes of some other imaged asteroids, Castalia and Toutatis. (It is intriguing that the most prominent grooves observed on the high-phase image are near the "neck" between Gaspra's two apparent "lumps".) Despite lower resolution, the full set of images suggests that Gaspra is more nearly lumpy than the angular, faceted visage presented to Galileo near closest approach. The actual shape has been well determined by Thomas *et al.* (1993); its qualitative description in words depends on the eye of the beholder. Neither the "lumpy" nor "faceted" characterizations are clearly ruled out by the data.

Let us consider the possibility that Gaspra's shape has, in fact, been whittled away by large impacts, leaving facet-like craters. Gaspra would be the first object observed in the solar system to have craters approaching or exceeding its radius (see McKinnon *et al.*, 1991; Holsapple, 1994), despite the widespread belief (e.g. Hartmann, 1984) that most solid surfaces are "saturated" with craters, including basin remnants. Fragmentation theory has long suggested that small target bodies struck by impacts sufficient to make such a large crater would not only fragment and pulverize the target body throughout, but would also partition enough energy into ejecta fragments so as to disrupt and disperse the fragments, thus ending the target's existence as an identifiable body. Therefore, how could Gaspra retain a crater so large? Even if a way were found to retain one such large crater, how could half a dozen or more giant impacts on the body fail to have destroyed all remnants of the previous large impact scars? Let us amplify on these questions.

Fig. 6 shows, in addition to the cumulative crater curves, frequencies for ~7 facet-craters. (Here we take the applicable area of Gaspra to be 215 km^2 since some facets are recognizable on Gaspra's profile. Greenberg *et al*. [1994] evaluate a facet frequency about half as big.) Plotted on an R-plot (as in Fig. 4), the facets diverge to about 1.5 orders of magnitude above the extrapolation of the -3.8 slope at 10 km. The density of purported facets even exceeds the crater density observed on Mimas, which is the body most heavily covered by craters of this size, and also exceeds the usual equilibrium crater density cap for the solar system generally.

Most planetary crater populations become quite shallow in the range of several km to several tens of km diameter (cf. Neukum *et al.*, 1975a,b; Chapman and McKinnon, 1986). However, even allowing for the observed turn to shallower slope near 1 km diameter (faintly evident in Gaspra's Class 3 and total crater counts), the facets exceed any plausible extension of the observed crater population on Gaspra by at least an order of magnitude. Therefore, if they are real impact scars, they cannot be part of the production function expressed by Gaspra's fresh craters, or even by its soft, degraded craters. Instead, they must reflect cratering of Gaspra from a much earlier epoch, the late heavy bombardment (~7 times the cratering age of the degraded craters on Gaspra or ~20 times the cratering-age of the fresh crater population); see Fig. 8.

Gaspra could have survived for so long (10 times its modeled age, calculated above) only if the giant impacts somehow failed to disrupt it. An even more difficult question is how a succession of giant impacts could have failed to destroy the surface topography of pre-existing impact scars; we should expect to see only the latest impact scar, rather than 7 or 8 of them. Is it conceivable that Gaspra is a "pillow" in which a long history of large impacts not only leaves the body intact, but also most of its surface topography intact as well, except right at the site of each giant impact? Although such a model is incompatible with traditional views about catastrophic collisions of small bodies, there has been recent thinking in this field that moves part-way toward the view that Gaspra (if not its topography) might stay intact after large impacts.

According to these recent models (cf. Ryan, 1992), Gaspra may be of the optimum size to be physically weakened in such a fashion that it ironically behaves relatively "strongly" against collisional disruption. Housen and Holsapple (1992) and their collaborators have shown that strain-rate strength-scaling, like we used above, causes asteroids to be physically weaker with increasing size (until self-gravity strengthens them at still larger sizes) than in the case of traditional energy scaling. Results of numerical modelling of collisional break-up using hydrocodes (cf. Ryan, 1992) show exaggerated effects beyond simple strain-rate scaling. Even if a target once began as hard rock, an impact shock wave would thoroughly fracture its interior into cohesionless, fractured "rubble" long before the flow-field begins to eject target material from the developing crater. Accordingly, the kinetic energy coupling to the ejecta would be poor and much of it would not leave the target's weak gravitational field. Therefore, the body would be rubblized, badly shaken, and rearranged, but not dispersed (the physical weakening actually increases the impact strength). Whether this scenario actually would result in a crater-like scar or facet is doubtful. More likely, the viscously-fluidized body would retain little structure from the event, not to mention from its previous history. These ideas are very tentative: the hydrocodes have been too newly applied to asteroidal problems to develop faith that their rather arbitrary fracture criteria are valid.

Pre-existing topography should be erased by such large impacts so that, at most, only a single facet-crater (the latest one) remains visible. Greenberg *et al.* (1994) have introduced a regolith "jolting" mechanism as a way to destroy small pre-existing topography. This particular mechanism destroys craters smaller than 150 m in diameter. However, no argument has been offered by Greenberg *et al.* or others about how even much larger topography could withstand the whole suite of topography-destroying effects, beyond the single jolting effect, of such energetic impacts (the hydrocode calculations do not model surface topography).

A more plausible scenario for interpreting a faceted Gaspra is as the inherent shape of a remnant core left over after previous giant collisions *did* succeed in dispersing much of proto-Gaspra. Perhaps the facets are giant spall zones, created all at once in a catastrophic, disruptive collision. A possibly relevant result of applying hydrocodes to asteroidal collisions (Benz and Asphaug, 1994) is the development of deep spall zones, which are peeled away, leaving a more coherent core. Gaspra could be such a core -- thoroughly brecciated, no doubt -- with facets representing the locus of spallations. (Such facets would then be remnants of one or more impacts, but they could not be thought of as individual crater-like impact scars.) Gaspra's interior would then be thoroughly fractured, although possibly not wholly disaggregated and reassembled as in the traditional model of a "rubble pile." To reveal the core's shape, most disaggregated material would be required to have escaped and not reaccumulated.

Regolith and Megaregolith

Gaspra's crater production function spans the transition between shallow-sloping distributions at sizes larger than a few km and steeply-sloping distributions at diameters smaller than about 1 km. Gaspra's size, compared with this transition diameter, profoundly affects Gaspra's nature, including both its deep interior (as discussed in the previous subsection) and its optical surface. Extensive Apollo-driven studies of small crater populations and regolith on the Moon in the 1960's can guide our thinking about Gaspra cratering. We show in this section that Gaspra's large-scale properties probably reflect its responses to large, rare impacts in the shallow-sloping regime, while its optical and small-scale surface characteristics are shaped by the steeply-sloping population of impactors that is expressed by the craters observed on its surface.

First, let us consider one major *difference* between the cases of the Moon and Gaspra: gravity. As a body well below 70 km in diameter, Gaspra has been expected (Veverka *et al.*, 1986)[1] to be in the regime

[1]Veverka *et al.* (1986). Due to a typographical error in that reference (Housen, pers. comm., 1991), the correct value for the transition between ejecta retention and total ejecta escape is about 70 km diameter for a rocky body, not 20 km which actually

where virtually all of its ejecta escapes to space, if its surface is made of strong rock or metal. Formally, models predict regoliths of <1 mm for such cases (Housen *et al.*, 1979). The scouring of any temporary debris that does remain would be enhanced by the steep slope of the production function observed on Gaspra (see below). However, it is difficult to predict how much ejecta remains on a strong-surfaced Gaspra after each cratering event because of (a) inadequate experimental data on very low velocity ejecta (few meters/sec) and (b) uncertainties in whether strong materials actually respond "strongly" to larger impacts (Housen, 1992).

If Gaspra is made of weak, cohesionless material so that its larger craters are in the gravity regime (as Veverka *et al.*, 1986, applied to the Martian satellites), half or more of its ejecta would be retained from those cratering impacts (most ejecta from small impacts are not retained, even for cohesionless material: see below). By analogy with Phobos and Deimos (slightly larger and smaller than Gaspra, respectively), perhaps 10 or 20 m of regolith could eventually develop on a weak Gaspra. However, due to its comparatively young cratering age (40% of collisional lifetime, as calculated above), the regolith depths developed to date would be less than half such eventual depths. Even with 100% ejecta retention, the total volumes of the observed production population of craters on Gaspra (discounting facets and any fortuitously placed giant crater on the small remaining unseen part of Gaspra) can account for only several meters of globally distributed ejecta (Carr *et al.*, 1994, generously estimate 10 m). Such a regolith is too thin to be visible at the resolution of our image or to explain the prominent overall softening of Gaspra's shape.

Since its size is near the theoretical transition between essentially bare rock and moderately deep regoliths (depending on target strength), Gaspra provides a unique opportunity to study regolith on a small body, without the complication (for Phobos) of reaccumulation of debris in the gravity well of a parent planet. Asteroids only somewhat smaller than Gaspra apparently lack even thin regoliths as judged from the failure of thermal infrared data to adhere consistently to the "standard thermal model" (Lebofsky *et al.*, 1979). What ejecta are retained should be very widespread around Gaspra due to its low escape velocity; the concept of "ejecta blankets" around craters, familiar on the Moon, has little pertinence to small asteroids. Very little debris can remain close to a parent crater, except for late-stage, low-velocity blocks, which cannot effectively cover surfaces. The roles of spalls (Hörz and Schaal, 1981), seismic jolting by impacts (Greenberg *et al*., 1994), and sub-crater brecciation in forming the texture of Gaspra's surface all deserve further scrutiny.

Shallow Production Function (Large Diameters)

Let us briefly review some fundamentals about lunar regoliths, which provides an analog for Gaspra. When the differential power-law slope of a production function is much shallower than -3, as it is expressed on the terrestrial planets for craters larger than a few km in diameter, particularly between 10 and 50 km, the largest craters dominate in *area* and wholly overwhelm the cratering process volumetrically (cf. Chapman and McKinnon, 1986). Such cratering is inherently episodic and catastrophic, with rare, giant events being responsible for most of the energy deposition, most ejecta volume, and most damage generally. It is this kind of process that is responsible for the megaregoliths on planetary surfaces. These layers are giant in scale (tens of km in depth due to non-basin craters alone) but immature in reworking because much of the volume is processed in only a single giant event, or at most in a few somewhat smaller events. In the asteroid belt, such events probably generate rubble pile structures. After a few generations of rubblization, a still larger impact disrupts the body. There is no time for the bodies to be thoroughly pulverized and reworked, or eroded away by smaller impacts before they are destroyed. Thus there is a conceptual equivalence between an asteroidal rubble pile and a lunar megaregolith.

Steep Production Function (Small Diameters)

Now consider a differential power-law significantly steeper than -4, as expressed on Gaspra, the Moon, and Mars at diameters smaller than a kilometer. In this case, not only do the *small* craters totally overwhelm the

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applies to icy bodies.

area covered by craters, but they also dominate volumetrically (the break-even point is -4.0 where equal logarithmic intervals in size contribute equal volumes). In this case, big events (i.e. km-scale cratering) are exceedingly rare, and yet at a hundred meters, the craters approach saturation equilibrium densities. Craters ten times smaller have saturated the surface countless times and have actually processed much more regolith volume than the larger craters. On the Moon, this processing in the course of the last 3.5 b.y. has resulted in the generation of many meters of a thoroughly churned and reworked soil layer termed the regolith. (Steeply sloping crater populations, and their relationship to regolith processes, were studied by Chapman, 1968; Chapman *et al.*, 1970; and Soderblom, 1970.)

The regolith is not merely a thinner, more recent analog to the megaregolith. If the size distribution extended to basin sizes at a -4.3 slope, there would be practically no Copernicus-size craters on the Moon (even despite the greatly enhanced cratering rate during the Late Heavy Bombardment) and certainly no basins would have been expected to be formed since the universe began! Extension to ever smaller sizes, however, has the opposite effect: on a lunar-sized body or bigger, gravity retains the ejecta, so the same materials are constantly reworked by innumerable tiny impacts, and they are progressively weathered and comminuted. Over-turn and burial by comparatively large, deep events almost never happens -- except that, on the Moon, there are occasional effects due to sparse impacts in the tens of km size range, since the -4.3 slope is not maintained to such large sizes (and because the Moon is not destroyed by such large impacts, which would end the life of a smaller body like Gaspra).

In the case of an asteroid with low gravity, the effects are very different from those on the Moon. Instead of the countless generations of tiny impacts churning the same layer, much of the ejecta are lost from each tiny impact. Even if the asteroid is made of weak, regolith-like material, available data suggest that 80% or more of the ejecta will escape immediately (except for rare km-scale and larger impacts: the variation of retention with crater scale has been demonstrated by Housen, 1992). Therefore, the volumetrically dominant zapping by small impacts will efficiently erode Gaspra's surface into space. There will be no steady-state soil layer: what small fraction remains after one surface-saturating exposure to impacts will be efficiently scoured away by the next. The surface will be nearly bare. Moreover, such scouring will progress into the object's surface to a far greater depth than the depth of any putative regolith that might blanket the surface (generated from occasional large craters, for example). In short, the surface of such an object would be sand-blasted and softened by the hypothesized steeply sloping impactor population.

Applications to Gaspra

How do these regolith models apply to Gaspra? If the observed steep size distribution extends to much smaller sizes than the ~100 m diameter resolution limit, scouring could have eroded Gaspra to depths of tens to hundreds of meters and contributed to the softened attribute of its surface. Mathematically, of course, the steep power-law could not continue to zero (it would imply infinite volume in small particles); furthermore, there are observational constraints to the population of meteoroids smaller than a meter in size (Ceplecha, 1992) explained perhaps by processes that deplete objects <1 m diameter (e.g. Poynting-Robertson drag). We can establish rough limits on how far the steep size distribution extends from the morphology of the visible craters. The fact that Gaspra's fresh crater population itself is *not* eroded and softened on a vertical scale exceeding many tens of meters (i.e. the craters do not exhibit a spectrum of morphologies characteristic of an equilibrium erosive process, except possibly at smaller scales near our resolution limit) demonstrates that the -4.3 slope of the cratering production function must turn over to a shallower slope at 10 m (or larger), corresponding to projectiles ≥ 1 m across.

This constraint requires that much of the observed softening of Gaspra's surface, and the degraded morphologies of the larger soft craters, have some other explanation. Gaspra's softened surface, on which the fresh craters were formed, probably is related to megaregolith processes associated with one or more older, large impacts (see also Carr *et al.*, 1994). Perhaps Gaspra was blanketed or shaken by the last of these rare, large impacts. This raises a question: where is the fresh scar of the last impact? Although the crater's own ejecta, encircling Gaspra, could partly blanket the crater, it would be far too thin to obscure it altogether. Is the scar one of the smaller "facets"? Maybe the responsible crater is fortuitously hidden on the remaining unimaged portion of Gaspra. A final possibility is that the two 3 km diameter craters seen on the approach images might have produced a sufficient volume of retained ejecta to account for the global blanketing of Gaspra, although they seem too small.

Gaspra's steep production function affects interpretations of remote-sensing observations of Gaspra's surface. Belton *et al.*, (1992) discussed Gaspra's photometric and colorimetric properties in terms of regolith and alteration processes. The exposure of Gaspra's surface to space weathering has been short (compared with the Moon, for example), since its surface is being eroded down at the rate of perhaps a couple centimeters per 100,000 years. Furthermore, there must be very little reworking of material on Gaspra -- it is mostly being lost to space after a single generation. Occasionally there will be residual surface material retained from larger impacts in the gravity regime, and the substrate (originally megaregolith?) may itself not be particularly coherent. So there may be some materials available for down-slope movement in response to seismic shaking by impacts. But, in general, the opportunities for large-scale effects of regolith processing on Gaspra are poor, which raises questions about how megaregolith exceeding 50 m in depth can become optically altered throughout its volume, as proposed by Carr *et al.* (1994).

Discussion and Conclusions

The steep size distribution of Gaspra's cratering projectiles is not yet understood. Possibly it reflects a recent, transient break-up event rather than the time-averaged conditions in the asteroid belt. One of the few natural ways known to produce a very steep size distribution of particles is in a single, very energetic event. Indeed, secondary crater distributions on the Moon (e.g. near Copernicus) were first shown by Shoemaker (1965) to follow a -4.5 size distribution. A supercatastrophic collision in the Flora region of the asteroid belt (i.e. an impact far exceeding in energy per unit volume what is necessary for mere break-up and dispersal) might have produced a particularly steep size distribution of fragments. If it was recent enough, there might not have been time for the population to relax to collisional equilibrium. Conceivably, such a break-up in the inner asteroid belt, where dynamical escape hatches to planet-crossing orbits exist, might also be manifest in the Earth-approaching asteroid population observed by Spacewatch and in the small-crater populations on Mars, where absolute chronologies are uncertain. An objection to such an explanation is the existence of the same steeply sloped population of craters on the Moon, on surfaces known to be several billions of years old. Perhaps the lunar craters *are* background secondaries, after all. More likely, we still have some fundamental things to learn about asteroid collisional evolution.

Gaspra's early history will never be known with certainty, for the more recent impacts have modified it much since then. Nothing in Galileo's images is inconsistent with the expectation that it is a collisional remnant from the catastrophic fragmentation of a precursor body. Its lumpy aspect is consistent with a rubble-pile structure, while its faceted aspect from Galileo's final vantage point suggests, instead, that it may be a more nearly monolithic (although presumably still internally fractured) core from a disrupted precursor. In either case, Gaspra probably reaccumulated or at least retained sufficient ejecta to build up a megaregolithic structure. After hundreds of millions of years, there were one or more subsequent large impacts, the latest of which covered up all but the larger pre-existing craters, and degraded them to the shallow, indistinct state we see today (the soft craters) and formed the surface on which the still later fresh crater population was superposed.

Our conclusions qualitatively agree with those of Greenberg *et al.* (1994). Both interpretations recognize a population of pre-existing, large, older craters on Gaspra as well as a youthful population of small, fresh craters. We both agree (along with Carr *et al.*, 1994) that a large collisional event, comparatively recently in Gaspra's history, erased much of the older small-scale topography, providing a clean slate for the more recent cratering. The interpretations differ in that our population of older, degraded craters are all under 1 km in diameter, rather than the much larger facets. (We can acknowledge that only one very large crater can exist on Gaspra. The large crater responsible for resetting the surface is either on an unimaged part of Gaspra or it is one of the debatable facets.) Quantitatively, we calculate the cratering age of Gaspra to be about 40% of its expected collisional age, whereas Greenberg *et al.* believe it is just 5% of a somewhat older lifetime.

Gaspra's early history may lie somewhere in between the case of its being repeatedly bombarded but preserved, like a pillow, and the case of its being successively spalled and whittled away. Certainly there has been appreciable reaccumulation of some ejecta during its history of generally disruptive and dispersive collisions. Gaspra's grooves, ridges, and other lineated features may reflect the subsequent "tectonic" shifting of the resulting megaregolith. Gaspra *as we know it* was created by collisional disruption and subsequently modified, perhaps more than once. Some hints about its next-to-last form may still be visible.

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Figure Captions

Figure 1. The regions for the crater counts reported here are shown on the high-phase image of Gaspra. The primary counting region is essentially the entire visible surface, except for portions near the limb. The smaller area is the 41 km^2 "central area."

Figure 2. Differential crater counts for Gaspra, including counts for three morphological classes. Frequencies are per km^2 per km diameter increment. Symbols plotted at 10^{-2} are rough upper limits corresponding to zero counts in the plotted increment.

Figure 3. Unweighted least square fits (power laws) for total craters and for fresh craters alone (Classes 1 and 2); $\sqrt{N}$ error bars are shown. Open circles are counts for total craters not included in the fits (incomplete at small diameter, poor statistics at large diameters); counts for fresh craters not included in fits are not shown. The slopes of the population indices are given.

Figure 4. R-plot of surface densities of Gaspra craters, with comparisons for other bodies. Unweighted least squares fits are shown (with derived population index) for the solid symbols (filled circles for total craters, x's with central filled diamonds for fresh craters).

Figure 5. Cumulative counts (*not* normalized to area) are shown for total, fresh (Classes 1 and 2), and soft (Class 3) craters. Unweighted least squares fits are plotted through more reliable data (larger symbols), with population indices shown.

Figure 6. Cumulative crater counts, and least squares fits, as in Fig. 5 for total and fresh craters. Also, for comparison, counts for total craters by GN, and counts by CRC from the 4-color frame (note roll-over to incompleteness for the two leftmost open circles). The -2.6 slope fit to the total data is extended for reference. Counts of possible facet-craters are also shown (see text).

Figure 7. Cumulative counts for total craters by three analysts for a small, central area shown in Fig. 1.

Figure 8. This schematic plot shows cumulative curves for the same production function measured by Gaspra's fresh crater population, multiplied by factors of 3 and 20, respectively. Thus, if the cratering age for Gaspra's fresh-crater population is ~200 m.y., as we have calculated, the other curves are for 600 m.y. (a little older than Gaspra's modeled collisional lifetime), and 4 billion years (assuming Gaspra had survived that long), for assumed constant cratering rate. The smaller ends of the older distributions would be truncated, perhaps as shown, by loss of old, small craters. Compare with observed densities of fresh craters, soft craters, and facets on Fig. 6.

Table 1
Gaspra Crater Counts and Frequencies*

		Class 1		Class 2		Class 3		Total	
Diameter (km)	**Increment width (km)**	**Number**	**Frequency**	**Number**	**Frequency**	**Number**	**Frequency**	**Number**	**Frequency**
0.11	0.04	6	(1.66)	87	(24.16)	62	(17.22)	155	(43.06)
0.16	0.055	21	(4.24)	115	(23.23)	93	18.79	229	46.26
0.21	0.055	24	4.85	61	12.32	18	3.64	103	20.81
0.265	0.055	17	3.43	14	2.82	13	2.63	44	8.89
0.32	0.055	13	2.63	11	2.22	4	0.8	28	5.66
0.375	0.055	1	0.2	3	0.6	2	0.4	6	1.21
0.43	0.055	4	0.8	1	0.2	4	0.8	9	1.82
0.485	0.055	1	0.2	1	0.2	1	0.2	3	0.61
0.54	0.055	2	0.4	3	0.6	1	0.2	6	1.21
0.65	0.275	2	0.08	0	(0.01)	6	0.25	8	0.32
0.95	0.275	0	(0.01)	0	(0.01)	1	0.04	1	0.04
1.20	0.275	1	0.04	0	(0.01)	0	(0.01)	1	0.04
1.50	0.275	0	(0.01)	1	0.04	0	(0.01)	1	0.04
1.90	0.55	0	(0.01)	0	(0.01)	1	0.02	1	0.02

*Frequencies are per km^2 per km diameter increment. Values of 0.01 are assigned arbitrarily for zero counts. Other values in parentheses suffer from incompleteness and/or classification bias (see text).