CRATERING ON IDA

Clark R. Chapman, Eileen V. Ryan, William J. Merline
Planetary Science Institute/SJI, Tucson, Arizona 85705

Gerhard Neukum, Roland Wagner
Institut für Planetenerkundung, 12484 Berlin, Germany

Peter C. Thomas, Joseph Veverka
Center for Radiophysics and Space Research, Cornell Univ., Ithaca, NY 14853

Robert A. Sullivan
Dept. of Geology, Arizona State Univ., Tempe, AZ 85287

Submitted to *Icarus*
Special Issue on Ida

31 March 1995
revised: 8 August 1995

Corresponding Author:

Clark R. Chapman
Planetary Science Inst.
620 N. 6th Ave.
Tucson, AZ 85705

Phone: 520-622-6300
Fax: 520-622-8060
E-mail: cchapman@psi.edu

No. of Words (all text): 6,800
No. of Figures: 5 (one in color)
No. of tables: 2
No. of Pages (excluding figures): 30

Proposed running head: Cratering on Ida

Abstract. Craters on Ida have a size distribution consistent with equilibrium under conditions of crater saturation over the range 100 m to 1 km diameter. The density of craters is high and they follow a -3 differential slope. The craters show a full spectrum of degradational morphologies at both large and small sizes. Craters >2 km diameter (and especially those >5 km) are more prevalent on one part of Ida; a sub-equilibrium, production population is seen on the other part, which rises steeply and reaches equilibrium for diameters <1 km, consistent with the production population found on Gaspra. We calculate that the visible craters should have contributed appreciable regolith, ~150 m average depth. If Gaspra and Ida have similar strengths and are subject to impact by the same projectile population, then Ida is ~10 times older than Gaspra, roughly 2 b.y. old. Ida could be younger, however, if it underwent early heavy bombardment in the aftermath of the break-up of the Koronis precursor body.

Introduction and Overview

Ida is the second asteroid for which good images of its crater population have been obtained. The first, Gaspra, was found to have a population of generally fresh craters at less-than-saturated densities. Small craters on Gaspra are especially abundant compared with its very rare large craters; that is, the index of the differential power law approximating the size distribution is very "steep", ~-4.3 (cf. Belton *et al.*, 1992, Chapman *et al.*, 1995a). In several respects, these findings were a little surprising. Until Galileo's Gaspra fly-by, the lunar surface had been the standard for assessing the projectile flux and production function for cratering in the inner solar system. Like Gaspra, the Moon shows a steep power-law size distribution in the size range of Gaspra's craters, but there has been ambiguity in interpretations of lunar regolith processes (for instance, Shoemaker [1965] and many later researchers attributed the steep size distribution to "background" secondary craters, which would not be expected to be manifest on a small asteroid like Gaspra). Moreover, until Galileo examined Gaspra, there were no direct observations of the population of small projectiles in the asteroid belt; they are much too small to be seen with Earth-based telescopes. Instead, our knowledge about objects responsible for cratering larger asteroids was based on (a) theoretical extrapolations to small sizes of the population of known larger asteroids, (b) numerical modeling of collisional processes, and (c) impact experiments carried out only at much smaller, laboratory scales, generally in the presence of terrestrial gravity. Until the Galileo Gaspra images showed otherwise, the prevailing view (cf. Dohnanyi, 1971) had been that the size distribution of projectiles in the asteroid belt, especially at the smaller sizes responsible for Gaspra's craters, should be in collisional equilibrium, with a power-law index of -3.5, not as steep as -4.3.

In advance of Galileo's fly-by of Ida, one might -- in the absence of other information -- have expected its crater population to be similar to Gaspra's. Some researchers thought that, because of Ida's larger size, regolith development might be more advanced on Ida. However, inferences from astronomical data concerning the lightcurve amplitudes and spin periods of members of the Koronis family, of which Ida is a member, hinted that Ida might actually be younger than Gaspra (e.g. Binzel, 1988), which might be evident from the observed crater population. Most simply, Ida might be found to have even fewer craters on it than Gaspra. Instead, Ida was found to be covered with craters.

In this paper, we present representative crater statistics for Ida from the Galileo images. We concentrate on the size-frequency relationship for craters and also briefly consider the variety of crater morphologies. More detailed discussion of crater morphology, including depth/diameter ratios, are in Sullivan *et al.* (1995) and regolith processes are evaluated by Asphaug *et al.* (1995). We compare Ida's crater population with that on Gaspra and briefly consider broader implications of our result for the impact history of Ida and the Koronis family. We present crater counts on Dactyl (see also Veverka *et al.*, 1995), which also indicate saturation on that small body; Dactyl's smooth shape, as well as the smooth character of Ida at similar spatial scales, probably reflects the steep power-law production function for craters smaller than 100 m diameter.

We will show that Ida exhibits a population of craters that is in equilibrium, or nearly in equilibrium, with the cratering process. Much of Ida's surface is essentially saturated with craters, displaying nearly the maximum spatial density of craters that is geometrically and geologically possible. Moreover, the craters span the full spectrum of morphologies, from fresh to highly degraded, a situation also diagnostic of equilibrium conditions. This contrasts with Gaspra's sparse production population of predominantly fresh craters. Despite a nearly saturated population of craters on Ida, there is evidence -- at least on one part of Ida -- for a production population at diameters >1 km that is consistent with the production population on the Moon. As we will discuss, regional variations in large-crater densities may reflect underlying structural heterogeneities within Ida.

The straightforward interpretation of Ida's craters in comparison with Gaspra's, which we will develop in this paper, is that Ida is an older body, perhaps ten times older. On the other hand, Ida's presence in the Koronis family plus considerations of its small moon Dactyl raise the possibility, thus far incompletely evaluated, that early intense cratering of Ida following the break-up of the Koronis parent body may be responsible for many of the craters, and that Ida is correspondingly younger than the straightforward interpretation.

Crater Data

Several of us (CRC, EVR, WJM: henceforth, the PSI group) have obtained a representative sample of crater data from various Solid State Imaging (SSI) images of Ida (images studied most closely are summarized in Table 1). The goal was to sample the crater population at smaller crater sizes, and to effectively do a census of all craters larger than about 1 km over much of the surface of Ida (excluding the minority of regions that were imaged at only very poor resolution and low phase angle). We also investigate whether there is significant regional variation in the crater populations. An independent assessment of the crater populations on Ida and Dactyl by others of us (GN, RW: henceforth, the Berlin group) was carried out using the same stereocomparator procedures previously employed by the Berlin group (cf. Neukum 1983).

The PSI group developed a semi-automated method to display an image and mark crater edges with a cursor. The diameters and size-frequency distribution are then determined automatically. The method does *not* automate crater identification or classification. The method was originally applied to analyze crater data from images of Gaspra (Chapman *et al.*, 1995a) and to evaluate data compression techniques that are being implemented for Galileo's Jupiter orbital tour. Briefly, the image can be examined by the analyst at a variety of magnifications, contrast settings, and software spatial filters. The longest projected dimensions of a crater are marked by two x,y positions from which the diameter is calculated.

In addition to marking the edges of the crater, the analyst estimates the feature's overall morphological class on a scale ranging from 1=pristine and fresh to 3=highly degraded. Generally, craters with clear, distinct rims, and dark, well-defined interior shadows or shadings fall into Class 1. When the shadings are less distinct (i.e., the interior bowl is more shallow and worn down) and the rims more rounded or overlapped, the crater is assigned to Class 2. Craters that are indistinct, very worn, with almost no relief are placed in Class 3.

An example of craters identified on one of the images is shown in Fig. 1. Circles are plotted (*not* showing the actual foreshortening) to indicate the identified craters. Colors indicate the three morphological classes. In addition to such data obtained from our semi-automated method, we also report, compare, and discuss crater diameters measured in a more traditional way (by CRC) from large format photographic prints of portions of the Ida high-resolution mosaic; the latter counts were previously reported by Belton *et al.* (1994), but are included here for more detailed analysis and comparison with other crater data.

The Ida data are not homogeneous. Although the modest number of pictures cover almost all of the surface of the asteroid, they are necessarily taken at a variety of lighting and viewing geometries, and the resolution varies greatly among the images. Thus the visibility of craters of various sizes and morphologies varies across any particular image as well as from image to image. We have attempted to correct our measurements and classifications for such effects, and have included data only from regions with relatively favorable lighting and viewing geometries. We have also determined the diameter at which small craters -- particularly of degraded morphologies -- are lost due to resolution limitations, and we do not report counts for craters of such sizes.

To determine size frequency relations, the PSI group counted craters within diameter bins and applied *unweighted* least squares fits over the selected diameter range. The fits are unweighted so that they are not dominated by craters near the small-size cut-off, which overwhelmingly dominate counting statistics but are more likely to be subject to systematic errors (e.g. imprecise diameter estimates for craters just a few pixels across, incomplete detection of shallow craters, etc.); in any case, since the small craters alone do not reflect the size distribution over its full range, they should not receive undue weight (cf. Chapman and Haefner, 1967). Counts based on very few craters at relatively large sizes are also excluded when more statistically meaningful counts are available at the same diameters (e.g. from larger counting areas). The crater counts are normalized to estimates of the areas of the regions in which the craters were counted, based on latitude/longitude grids from the shape model of Thomas *et al.* (1995). We display the ensemble of PSI data in Fig. 2 as differential frequencies (counts per km^2 divided by diameter interval); some of these data, separated regionally, are shown as cumulative frequencies in Fig. 3. The Berlin data are shown only in the cumulative format in Fig. 4.

Crater Statistics

The general differential size distribution of craters on Ida shown in Fig. 2 is from several different areas and was obtained with several different techniques. For the *smallest* craters on Ida, two different analysts analyzed the same representative region from the center of the high-resolution mosaic using two different procedures. One of us (EVR) used the semi-automated crater measurement technique while another (CRC) measured a photographic print. The former method, with variable scale display, permitted measurement and classification of craters down to 0.1 km (about 3 pixels per crater diameter). For middle-size craters, the same analysts used the same methods for analyzing different parts of the middle and near-terminator regions of the high-resolution mosaic. Because of the larger area measured by one of us (CRC), those counts extend to slightly larger crater sizes. Finally, for the largest craters, we show data (semi-automated technique, EVR) from 4 different images covering most of the well imaged portions of Ida. These extend the crater statistics to diameters as large as 10 km.

The PSI results have been fit to a power-law. The resulting index, or "slope" on a log-log plot of differential frequency vs. diameter, is -3.1. The curve does not clearly deviate much from

-3 anywhere along its full length (we will discuss regionally variable departures at the largest sizes below). Furthermore, the height of the curve (i.e. its relative density, as illustrated in Fig. 5c of Belton *et al.*, 1994) is near the maximum level expressed on other lunar, satellitic, and planetary cratered terrains (cf. Hartmann 1984). Clearly, Ida has, at least approximately, a "saturated" population of craters, exhibiting the classic -3 slope characteristic of equilibrium for production populations with slopes steeper than -3.

Further confirmation that Ida's crater population is in equilibrium, or nearly so, is given by the crater classifications. To within broad uncertainties due to the subjective nature of the morphological classifications on images with widely differing lighting, viewing geometry, and resolutions, it appears that there is a full spectrum of morphological degradation -- from fresh to highly degraded -- exhibited for craters both large and small (see Fig. 5b in Belton *et al.*, 1994). This complete spectrum of morphologies, which is in sharp contrast to Gaspra's domination by fresh craters, is a further characteristic of saturation equilibrium (cf. Chapman *et al.*, 1970).

The PSI group has also addressed the question of whether or not there are significant differences in crater populations on different parts of Ida. In Fig. 3, we plot cumulative size-frequency relations from four different images of Ida, each covering substantially different territory on the asteroid. When the counts are aggregated and averaged, without regard for regional variations, they yield the open squares shown in Fig. 2.

Overall, the crater densities are rather similar in different regions and do not deviate dramatically from the -3 slope, especially at smaller diameters. In detail, however, there are apparently significant differences, especially at large diameters (>2 km diameter). The region covered in dataset B lacks very large craters, resulting in a slope steeper than -3 which falls below the equilibrium line at larger diameters. This region appears to contrast with the heavily cratered region of Mammoth, Lascaux, and Undara on the high resolution mosaic (dataset A). The dichotomy may be artificially enhanced by the somewhat less favorable lighting for dataset B. In Table 2 we list our diameter measurements for craters larger than 2 km diameter. Note that the saddle-shaped feature Vienna Regio, regarded by Asphaug *et al.* (1995) as a probable impact site possibly responsible for antipodal fracturing on Ida, has *not* been included as a crater in this analysis; its inclusion would reduce the apparent dichotomy.

Our work is in accord with the suggestion of Thomas *et al.* (1995) that Ida is divided into two roughly hemispheric regions, a less heavily cratered hemisphere called Region 1, and a more heavily cratered Region 2. All 6 of our largest craters lie in Thomas *et al.*'s Region 2 (however, our 7th largest crater, which is in Region 1, is effectively the same size as our 6th largest). Although there *really are* more large craters in Region 2 than in Region 1, an important question is whether the dichotomy reflects systematic differences in the creation or obliteration of large craters in the two regions, or instead if it can be explained away as just chance variations due to statistics of small numbers. We consider alternative explanations for the dichotomy in the next section.

Refined analysis of high resolution views of Ida's surface has revealed minor differences in cratering at smaller spatial scales (cf. Sullivan *et al.*, 1995, who discuss the dark floor craters and adjoining regions). But the overall populations of small and intermediate sized craters on different parts of Ida appear to be generally similar in Fig. 3, to the degree the variable resolution of the images permits us to examine the question. This is consistent with global saturation of craters by a steeply sloping production function and an absence of widespread crater obliteration processes, other than small-scale cratering itself, during recent epochs on Ida.

The Berlin data (Fig. 4) may be directly compared with the PSI counts plotted cumulatively in Fig. 3. In general, the Berlin analysts have tabulated somewhat fewer craters per square km than have the PSI analysts. This reflects systematic differences in the recognizability of craters that have characterized early studies of other heavily cratered terrains by the Neukum and Chapman groups over the years. This is an entirely natural systematic difference, given the gradual obliteration and disappearance of craters as recognizable topographic features; the Neukum group adopts a slightly more conservative threshold for crater recognizability.

The Berlin data, like the PSI data, show greater variability at large diameters in the regions selected for study. Particularly evident in the Berlin data is the progressive departure of large craters below the equilibrium curve as diameter increases. As indicated by the curving line in Fig. 4, these data -- as well as the PSI data for Region 1 -- follow the production function curve derived by Neukum *et al.* for the Moon and Gaspra (Neukum *et al*., 1975; Neukum and Ivanov, 1994) until it intersects the empirical equilibrium line. At smaller diameters, the counts follow the slope of the equilibrium line.

Cratering and Obliteration Processes on Ida

Transition from Steep to Shallow Production Function

There is a straightforward interpretation of the Ida crater data in the context of cratering and obliteration theory (cf. Chapman and McKinnon, 1986). There is a common misperception that under circumstances of saturation cratering, the resulting crater population follows an equilibrium distribution (differential slope = -3) that carries no information about the production function. This is true, however, only for sizes where the production population has a very steep slope, steeper than about -3.5. (Even in that case, crater morphologies can indicate just how steep the production function is.)

In cases where the size distribution is shallower, around -3 or less steep, a true equilibrium crater population is never established. Instead, the stochastic effects of the relatively common largest impacts impose what has been termed quasi-equilibrium, in which the spatial density of intermediate size craters oscillates up and down, but trends gradually upwards, until the next giant impact occurs, causing widespread obliteration and a sudden loss in the density of smaller craters. As pointed out by Chapman and McKinnon (1986), in this case of quasi-equilibrium under cratering by a shallow-sloped production function, the shape of the visible crater frequency curve at any one time *is the production population*.

The actual physical obliterative processes that dominate on an asteroid are different from those that are most effective on the larger bodies (e.g. Moon, outer planet satellites) studied in the past. For 10 to 100 km craters (far into the shallow-sloped regime) on the surface of a body with appreciable gravity, the obliteration of smaller craters is primarily due to crater overlap and ejecta blanketing. On a small asteroid like Ida, and especially like Gaspra, these obliterative processes are less efficacious. There is a smaller dynamic range of craters for which the shallow slope is applicable (e.g. the maximum crater size on such an asteroid is *much* smaller than 100 km). Also, due to lower gravity, ejecta blankets are spread much more thinly (some fraction of ejecta is even lost at greater than escape velocity) and are thus less effective at obliterating craters. Counterbalancing the lesser effects (on small bodies) of obliteration by giant crater ejecta blankets are the more important effects (on small bodies) of seismic "jolting" (cf. Greenberg *et al.*, 1994).

Despite the high density of craters on Ida, which is nowhere more than a factor of a few less than equilibrium density, we see effects of both the steep and more shallow sloped regimes on Ida. These are most evident in the Berlin counts (Fig. 4) and in the Fig. 3 counts for Region 1. Both show the steeply sloped production function at small sizes and the shallow sloped production function at diameters >1 km -- and the transition region in between. There is other evidence that the size distribution of interplanetary projectiles in the inner solar system shows just such a transition near 1 km. It is not only seen on the Moon but it has more recently been confirmed by direct sampling of the population of near-Earth objects (Rabinowitz 1993). On Ida, the population of craters smaller than 1 km is evidently everywhere in true equilibrium. At larger diameters, however, it is in quasi-equilibrium with the sporadic production of very large craters.

We wish to emphasize an important conclusion about the production population responsible for cratering Ida: not only are Ida's craters *consistent* with being cratered by a production population like that evident on Gaspra and on the Moon, but going from 10 down to 1 km diameter, we seem to see the actual transition from shallow to steep slope of the production population. Although the visible craters are at equilibrium at still smaller sizes, it may well be that the production population on Ida of craters of these sizes continues at the same steep slope seen on Gaspra (about -4.3).

Regional Variability

There are two alternative interpretations of the regional variability in the large crater population of Ida. First, consider Ida's cratering history since its surface was formed or last reset (e.g. since Ida itself formed, or since the last time it was struck by an object big enough to jolt it and disrupt its surface). Perhaps Region 2 has just chanced to reach an equilibrium crater density while Region 1 has not quite yet reached equilibrium. It is not very likely, but hardly impossible, for the 6 largest craters to all strike one hemisphere of Ida. In this case, where we interpret Ida's dichotomy to be due to chance, Ida is just approaching saturation and the apparent cratering age of its surface is its actual cratering age, not just a lower limit.

Alternatively, the regional dichotomy reflects more fundamental geological processes operating on a thoroughly crater-saturated surface. Somehow, despite repeated bombardment on all sides, crater obliteration has been more effective on one hemisphere than the other. In this case, Ida has been cratered for an indeterminant length of time, so its apparent cratering age is only a lower limit to its actual age. Region 1 would then be interpreted as a part of Ida where large craters were subsequently obliterated by a process that left large craters in Region 2 substantially unaffected. How could crater obliterative processes operate *regionally* rather than globally on an asteroid? One could hypothesize that a recent impact (e.g. Azzurra or Vienna Regio) distributed ejecta chiefly over Region 1, obliterating pre-existing large craters. However, the area of Region 1 (1900 km^2) is too large for ejecta from a single impact to eradicate large craters analogous to the large craters seen in Region 2.

More plausibly, shock waves from such a big impact were locally much more destructive in Region 1 than in Region 2. This might happen, for example, if Ida structurally resembled a rubble pile, composed of a couple of large chunks, with poor seismic continuity throughout the body; then the major impact might chiefly jolt the portion it struck, destroying craters on that part (while leaving one large new one!), but leaving craters on the other parts unscathed. Vienna Regio, for example, could be the impact scar that denuded most of Region 1. The preliminary modeling of Asphaug *et al.* (1995) actually led them to propose that a Vienna Regio impact affected the *opposite* hemisphere, rather than the hemisphere in which the Vienna Regio scar is located. But there is much more work to do to assess possible regional effects of various large craters on Ida.

We cannot unambiguously choose between these two alternatives. Given the small number of large craters (half dozen, or so) that most dramatically define the dichotomy on Ida, the reader will have to form an independent judgement about the relative roles of chance clustering of large craters and regionally varying obliterative processes in shaping Ida's surface.

Cratering Age of Ida

Cratering and collisional ages of asteroids are very poorly known because samples are not yet available for applying laboratory age-dating techniques. Published estimates (such as the 200 m.y. quoted by Belton *et al.*, 1992, for Gaspra) from theoretical modeling of collisional processes are highly model dependent. While absolute ages are very poorly known, there is some merit in considering the *relative* cratering ages of Gaspra and Ida. The cratering age of Ida is more ambiguous than for Gaspra due to the possibility that its apparent age is only a lower limit to its true age. This is not true for Gaspra, where the predominant crater population is clearly in production. Let us compare Ida and Gaspra, assuming that they have the same collisional strengths and that they are cratered by the same projectile production function. We further assume that the impact rate has been identical on each, which is true today to within a factor of 2 (Bottke *et al.*, 1994). (Assumptions about strength, projectile population, and cratering rate are discussed at the end of the present paper.) In this case, Ida is older than Gaspra by at least the factor necessary to build up the observed Gaspra production function until it at least meets the average distribution on Ida throughout the diameter range observed on Ida.

The production function is not observed on Gaspra for crater diameters larger than about 1 km, where counting statistics run out. However, following the discussion of Chapman *et al.* (1995a), at >1 km it probably begins to become more shallow than the observed -4.3 slope that obtains between 0.2 and 0.6 km, likely resembling the shape of the lunar production function (cf. Neukum *et al.*, 1975). It is near 3 km diameter that such a Gaspra production function would differ from the observed distribution on Ida by the largest amount, about a factor of 10 (but regionally variable on Ida between about 5 and 15). Thus Ida could be simply interpreted to be about 10 times older than Gaspra, possibly older if Ida's age estimate is a lower limit.

Ida is unlikely to be many times older than this lower limit, however. Otherwise the probability becomes increasingly high that it would have been collisionally disrupted before now. Since the slope of the production function is so shallow at diameters larger than several km, when crater saturation occurs at such diameters, it implies a high probability that Ida would also be hit by an object larger than the threshold for catastrophic disruption. We argued (Belton *et al.*, 1992; Chapman *et al.*, 1995a) that Gaspra's cratering age was 40% of its expected collisional lifetime, based on standard collisional models. Since lifetimes against collisional disruption in the general case (cf. Williams & Wetherill, 1994) scale as the square-root of the diameter, Ida's expected lifetime would be about 1½ times Gaspra's collisional lifetime; a more detailed calculation reported by Belton *et al.* (1994) gives it as 3 times Gaspra's. Thus Ida's collisional lifetime should be roughly 7 times the *cratering age* of Gaspra, so its minimum cratering age we inferred above (~10 times Gaspra, or roughly 2 b.y.) is already somewhat older than its expected lifetime.

The modest discrepancy is not a serious one, however, given the large uncertainties in the modeling. Moreover, the lifetimes against disruption of both Gaspra and Ida may be prolonged, compared with standard collisional models, due to the predictions of scaling relationships for bodies of these sizes (Ryan, 1992; Housen and Holsapple, 1990; Chapman *et al.*, 1995a). Scaling suggests that large impacts fracture and rubblize the target body, but does not succeed in actually disrupting it and dispersing the fragments. An added consideration is the presence of an older population of craters on Gaspra (Carr *et al.*, 1994; Chapman *et al.*, 1995a), indicating that re-initialization of its surface was likely due to a subcatastrophic impact, causing seismic jolting and destruction of topography, rather than due to actual collisional break-up. Such processes are expected to be more efficacious on Gaspra than on the larger Ida, so that crater populations could survive on Ida for much longer than on Gaspra. This would be even more true if seismic ringing were enhanced on Gaspra due to possibly greater internal coherence (e.g. if it were a monolithic, even metallic, fragment rather than highly fractured within).

Regolith, Megaregolith, and Rubble Piles

What are the implications of the observed crater population for Ida's regolith? Chapman *et al.* (1995a) argued that the regolith produced on Gaspra by on-going cratering processes (as distinct from a pre-existing megaregolith or rubble pile structure), must be very thin, perhaps only a few meters thick. The situation is quite different for Ida. First, because of its larger gravity, Ida tends to retain a larger fraction of cratering ejecta. More important, its ten-times older age and larger cross-section means that it has had a chance to be struck by numerous large impactors, manifested by the observed population of large craters. According to Housen (1992), an increasingly large fraction of ejecta is retained from such larger craters, which are formed fully within the gravity regime. A lower limit to the regolith depth comes from assuming that most of the volumes of the largest visible craters are spread around the 3900 km^2 surface area (Thomas *et al.*, 1995) of Ida; taking a nominal depth/diameter ratio ~6 we calculate that the craters in Table 2 contribute ~150 m of regolith, if ~80% of ejecta is retained, which is roughly what Housen (1992) suggests. (This estimate, of course, does not include any possible contributions from previous craters, now obliterated.) These theoretical expectations for a deep regolith are borne out by many photogeologic interpretations of images of Ida (Belton *et al.*, 1994; Sullivan *et al.*, 1995).

Ida's earlier history, or that of its presumed precursor (the object that broke up to form the Koronis family), may have led to an "original" internal structure for Ida resembling a "megaregolith." Ida's formation, and the largest collisions that shaped it subsequently, were due to projectiles in the shallow-sloped portion of the production function, where the largest, rarest impacts dominate over the cumulative effects of the frequent, smaller impacts. So if Ida were formed as a rubble pile with the size distribution of constituent pieces like that observed for members of asteroid families, or if a few subsequent large impacts struck Ida, its interior would consist of several chunks or coarse "rubble". Repeated reworkings of such a megaregolith at depth would not be expected.

The relevant processes are different for Ida's smallest observable features. There the steeply sloping production function results in appreciable erosion, widespread redistribution, and significant ejection of materials from the surface of Ida. (Actual ejection to space by cratering impacts near our resolution limit may be less on Ida than on Gaspra; Ida's regolith may buffer impacts and reduce ejecta velocities which otherwise would far exceed escape velocity due to cratering in the strength regime. Similar sized impacts penetrate Gaspra's thinner regolith, resulting in more efficient ejection. Erosion must be even more important on Dactyl than on Gaspra, even if Dactyl had the structure of regolith, because of its exceedingly low gravity.) Thus on Ida there should be an interplay between the episodic regional redistribution of ejecta by the largest craters (presumably accompanied by massive seismic shaking) and the continual small scale erosion of materials. On Gaspra, because of its smaller size, comparative youth, and thinner regolith, erosion has probably dominated over deposition and regolith redistribution, but the opposite is true for Ida.

Caveats to Comparisons Between Gaspra and Ida

So far, our discussion has been based on two assumptions: (a) Gaspra and Ida are made of the same materials (have the same strength) and (b) the cratering rate has been the same on both of them. Let us consider alternative assumptions.

We have very little robust evidence concerning the internal structure and composition of either Gaspra or Ida. However, Ida must have a rocky composition, based on bulk density constraints (ρ_{Ida}=2.6±0.5 g cm^{-3}) set by Dactyl's orbit (Belton *et al.*, 1995). The preferred composition is ordinary chondritic (Chapman *et al.*, 1995b), but other, differentiated rocky compositions are also possible. Although earlier analyses of Gaspra by the Galileo Imaging Team have been based on the assumption that Gaspra had a rocky composition, it very well could be largely metallic, instead. Gaspra's non-chondritic, olivine-rich spectrum is compatible with a stony-iron composition, derived from the core-mantle interface regions of a precursor body. In this case, comparisons between Gaspra and Ida become very muddy, although they would primarily modify the tentative conclusions about Gaspra, not about Ida. A strong, metallic object could readily have collisional lifetimes at least an order of magnitude longer than a stony object. Also, craters made in solid metal would be much smaller than those made by the same projectiles in rock or regolith.

Ida's membership in the Koronis family, one of the three most populous and well-defined families in the asteroid belt, and the presence and nature of its satellite Dactyl raise questions about the assumption that Gaspra and Ida have been subjected to roughly the same impacting flux from the same population of projectiles. It is possible that there was an early burst of cratering of Koronis family members by other fragments from the break-up of proto-Koronis, before the present orbital distributions had evolved. Preliminary calculations of the immediate aftermath of family disruption (Binzel, 1995, priv. comm.; Davis *et al.*, 1995) do not imply any huge early bombardment, but the potential remains that many or most of Ida's craters may have been created in its early history, in which case the saturated population would not necessarily reflect long (billion year or longer) exposure to the current projectile flux.

The crater population on Dactyl (see Fig. 5; also, Veverka *et al.*, 1995; discussed by Chapman *et al.*, 1995b) is similar to Ida's and is apparently saturated. Individual features also raise questions about the projectile population near Ida. A chain of craters on Dactyl, plus a central positive relief feature in one crater (which may be a block from a low-velocity impact), imply the potential existence of another, localized, low-velocity population of impactors in the vicinity of Ida. Possibly, in the immediate aftermath of the proto-Koronis break-up, while Dactyl was being captured into its current, presumably stable orbit around Ida, other similar objects may have impacted Ida. (Such impacts need not be restricted to the epoch of Koronis family formation. Other satellites less stable than Dactyl, or fragments from collisional break-up of an earlier, larger proto-Dactyl, may have impacted Ida DACTYL!!! during intermediate epochs.)

These possibilities are difficult to evaluate. There are few if any clear cases on Ida of crater morphologies indicative of low velocity impacts (Sullivan *et al.*, 1995). In any case, whatever contribution early, intense and/or locally-derived cratering may have made to Ida's current appearance, the details would have been at least partially masked by later ongoing cratering by heliocentric projectiles. We conclude that we must keep an open mind about the relative contributions of initial versus subsequent-and-continuing cratering on Ida. Thus our model age calculations for Ida, about 2 b.y., need not be viewed as ruling out younger ages inferred from astronomical observations of the Koronis family members. Perhaps further studies of the Koronis family, both observational and theoretical, will resolve the age of Ida.

Despite the uncertainties, Ida is clearly a heavily cratered object that has nearly reached (or somewhat exceeded) the exposure to asteroidal projectiles necessary to saturate its surface with craters and produce a deep surficial regolith. There are indications that the cratering production function observed on the Moon and Gaspra may be responsible for Ida's cratering, as well; certainly Ida's crater data are consistent with that interpretation.

Acknowledgements

We thank numerous colleagues for discussions. This is Contribution #332 of the Planetary Science Institute, a division of San Juan Capistrano Research Institute. This paper reports one phase of Galileo Project research, supported by NASA and managed by the Jet Propulsion Laboratory.

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Figure Captions

Figure 1. Picno EJU0105 (SSI image S0202561935), showing superimposed circles representing identified craters within the counting region indicated. Red = class 1 (freshest morphology), blue = class 2, green = class 3 (most degraded).

Figure 2. Differential size distribution for Ida with unweighted least squares fit (power-law index = 3.1). The legend refers to the datasets as defined in Table 1.

Figure 3. Cumulative size frequency distributions from four different images of Ida, showing substantially different regions. The legend refers to the datasets defined in Table 1. The dashed line has a -2.0 slope characteristic of equilibrium distributions (-3.0 differential).

Figure 4. Cumulative size frequency data for craters on Ida, measured by the Berlin group. An approximate lunar crater equilibrium curve (dashed line) is shown, for reference. The standard lunar production function (solid line; Neukum *et al.*, 1995), scaled for Ida, is placed through the data points for Ida's larger craters.

Figure 5. Cumulative size frequency data for craters on Dactyl, measured by the Berlin and PSI groups. The solid line shows the Ida crater distribution (from the PSI group), for reference.

Table 1. Ida Crater Base					
Dataset	**Image #**	**PICNO**	**Diff. Slope**	**Area (km^2)**	**Crater Diam. Range (km)**
A	s0202556000	EJU0048	-2.8	422	1.2 - 7.
B	s0202559400	EJU0066	-3.3	541	0.8 - 5.
C	s0202561300	EJU0078	-3.0	623	0.6 - 14.
D	s0202561935	EJU0105	-3.0	567	0.5 - 8.
E	mosaic*	Hi-Res CRC	-3.2[#]	322	0.4 - 2.8
F	mosaic**	Hi-Res 2 CRC	-3.2[#]	25	0.16 - 0.8
G	mosaic**	Hi-Res 2 EVR	-3.1	25	0.09 - 0.8

* A 322 km^2 region of the Hi-Res mosaic was measured. The mosaic comprises images s0202562300, s0202562313, s0202562326, s0202562339, and s0202562439.

** A 95 x 200 pixel region (25 km^2) of the Hi-Res mosaic.

[#] Slope for E and F combined.

Table 2. IDA CRATERS >2 KM DIAMETER

Crater	Diam. (km)
Undara	14
Mammoth	10
Lascaux	10
Orgnac	9
Unnamed (south of Undara)	8
Azzurra	7
Castellana	7
Unnamed (west of Postumia)	6
Postumia	5
Sterkfontein	5
Unnamed (west of Postumia)	5
Unnamed (west of Postumia)	4
Unnamed (east of Postumia)	4
Unnamed (south of Kazumura)	3
Viento	2
Kazumura	2
Bilemot	2