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Collisional History of Gaspra

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Interpretation of the impact record on Asteroid 951 Gaspra requires understanding of the effects of collisions on a target body of Gaspra's size and shape. Recent hydrocode models show that major impacts on Gaspra may leave craters larger than previously thought possible and that they can create substantial regolith and produce global jolting capable of erasing many smaller craters. A Gaspra-size body has a mean lifetime of about 10^9 years and is likely to have several impact craters of 4 km diameter or larger, which is consistent with the number of observed concavities on Gaspra. The steep size distribution of small craters on Gaspra implies an even steeper distribution for small asteroids, and the relative paucity of kilometer-size craters seems to require a twice-in-a-Gaspra-lifetime impact to have occurred about 50 myr ago. All of these considerations consistently point to a scenario in which several of the very large concavities (>4 km diameter) on Gaspra are probably impact craters. © 1994 Academic Press, Inc.

I. INTRODUCTION

The geology and geophysics of a small asteroid like 951 Gaspra are dominated by impact processes, which have determined both global structure and surface morphology. The environment in the Main Belt ensures that impacts are quite frequent over the life of a small asteroid and even sets limits on the likely survival time for the body itself. On the other hand, the thermal and tectonic processes that are so important on larger planets are probably unimportant on Gaspra-size bodies.

Because other processes have not modified the surface of Gaspra, the surface retains craters that provide a record of its impact history. However, interpretation of the impact record requires recognition that, while impact records on larger planets and satellites provide a helpful comparison, the results and evidence of any given impact on a small body may be very different. Interpretation must take into account models of the effects of collisions on a target body of Gaspra's size and shape, recognizing that impact features may have morphologies different from craters on larger planets and that impact processes erase and modify surface features even as they produce new craters.

Crater counts on the 140 km^2 of Gaspra imaged at high resolution by the Galileo spacecraft (Fig. 1) show a steep size-frequency distribution (cumulative power-law index near -2.5, or even somewhat steeper) from the smallest resolvable size (150 m diameter) up through the largest feature (1.5 km diameter) of familiar crater-like morphology (Belton *et al.* 1992, Neukum *et al.* 1992, Chapman *et al.* 1993). Two craters with diameters of about 3 km are seen on another part of Gaspra's surface on lower-resolution frames, which (on a number per area basis) are consistent with the steep power law. Strictly speaking, the power-law published by Belton *et al.* predicted only one crater of 3 km diameter or larger over the whole surface, but the discrepancy is not statistically significant.

In addition, in the high-resolution frames there appear to be as many as eight roughly circular concavities with diameters >3 km visible on the asteroid. If one restricts crater counts to features with traditionally recognized crater morphologies, these large concavities might not be included (e.g., Belton *et al.* 1992, Neukum *et al.* 1992, Chapman *et al.* 1993). However, in this paper we use a broader definition of craters, to include any concave (relative to the global curvature) structures that represent local or regional damage centered at an impact site, whether or not they resemble the products of impacts on larger, more familiar planets and satellites. We are not suggesting that there is something wrong with limiting the definition of "crater" to familiar-seeming structures; that definition may be appropriate in some contexts. However, in the context of deciphering an asteroid's collisional history in terms of the population of smaller objects that

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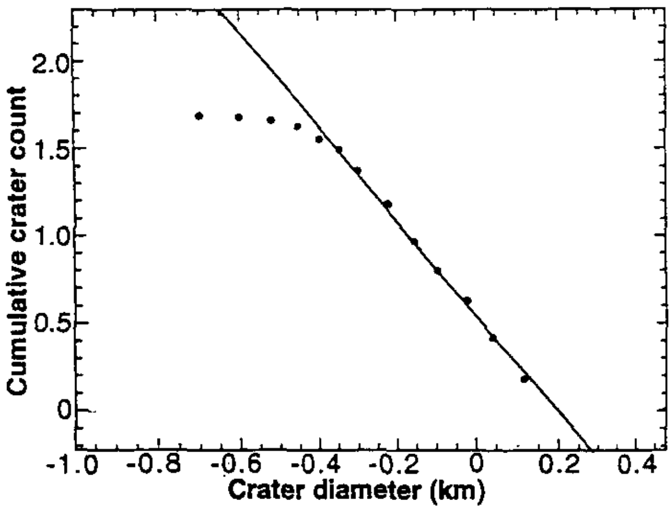

FIG. 1. Size distribution for craters counted on Gaspra by Belton *et al.* (1992), based on medium-resolution images returned by the Galileo spacecraft in late 1991. Ordinate is the log of the counts. More recent counts on higher resolution images (Chapman *et al.* 1993) follow nearly the same power law (log–log straight line) as shown here, down to crater diameters of 100 m, near the limit of resolution. These counts do not include multikilometer impact craters, which we argue do exist on Gaspra.

bombarded it, we need to emphasize the continuity from the effects of minor impacts up through the most energetic hits that the target can survive. With our more inclusive definition, the larger concave features on Gaspra are candidates for consideration as craters.

Aside from lack of familiarity with the range of possible morphologies of craters on small bodies, acceptance of the multikilometer features as craters has been approached cautiously by other authors for two additional reasons. First, scaling laws (the physically plausible algorithms for extrapolating from experimental data) indicated that Gaspra could not have sustained such large-crater-forming impacts without being disrupted; and second, extrapolation of the power-law size distribution found for smaller craters on Gaspra would predict less than one crater larger than 1.5 km diameter per 140 km^2, and none larger than 4 km over the entire surface.

This paper discusses the observational evidence for large concave features, some of which may be craters in our generalized sense of the word. We describe theoretical and numerical modeling that modify earlier ideas about applying impact scaling laws to small bodies, show the major role of global resurfacing due to jolting associated with large crater formation, and discuss ways to reconcile the probable power-law size distribution of impactors with the non-power-law distribution of possible larger craters on Gaspra.

II. CANDIDATE LARGE CRATERS

In Fig. 2, we identify nine candidate concave regions that appear on the highest-resolution Galileo images. Evidence regarding these candidates comes not only from the concave appearance in this image, but also from the suite of lower-resolution images and from the shape-fitting work by Thomas *et al.* (1993a). All of these regions are concave (relative to the general figure of the body) to some degree.

Consideration of the lower-resolution images suggests that Gaspra has a double lobed ("peanut-like," or "contact binary") appearance, which was evident in the first image returned by Galileo in November 1991 and is more strongly apparent in the set of earlier shuttered images at even lower resolution (e.g., Figs. 3–5). The seemingly double-lobed shape may be an expression of underlying structure; perhaps Gaspra comprises two gravitationally bound, relatively strong blocks covered by weak rubble and regolith. The regions labeled 3, 4, and 5 in Fig. 2 all lie along the "neck" between the two dominant lobes and thus may be associated with that structure rather than being impact craters. On the other hand, Thomas *et al.* (1993a) do not recognize a double-lobed figure. If they are correct, then one or more of these regions remain possible craters.

Region 9, with diameter 1.5 km, is generally agreed to be a crater and has been included in published crater counts, e.g., it is the largest crater in the distribution reported by Belton *et al.* (1992). For regions 6 and 8, in Fig. 2 the locations on the limb and the lighting give an appearance that is very crater-like, especially if one takes into account the superposition on the highly irregular figure of the planet. Regions 2 and 7 are each slightly concave, but the lighting and viewing geometry make characterization of these features difficult.

Region 1 (diameter 5 km), like 6 and 8, appears to be a good candidate for craterhood. Moreover, as one looks back through the imaging sequence at the lower-resolution frames, this feature is viewed from an increasingly vertical perspective (e.g., Figs. 3 and 4), where it appears, in fact, nearly circular. Still further back in the sequence (Fig. 5), 1 is again seen edge-on on the limb, but from a direction nearly opposite that of Fig. 1. It retains its crater-like appearance from all these perspectives. An interesting feature of 1 is the bulge across its center, which may be a central peak, or perhaps the product of downslope sliding of material across the floor of this feature. Unlike most planetary craters, in which downslope usually means toward the center of a crater, in region 1 the downslope would run across this region, which as a whole is tilted relative to the gravitational horizontal (Thomas *et al.* 1993a).

Of the five candidate concavities, only 1 is viewed from a variety of orientations and all those views are consistent with its being a crater. Thus it seems plausible that some of the others, as well, are craters within our inclusive definition. Setting aside preconceptions about

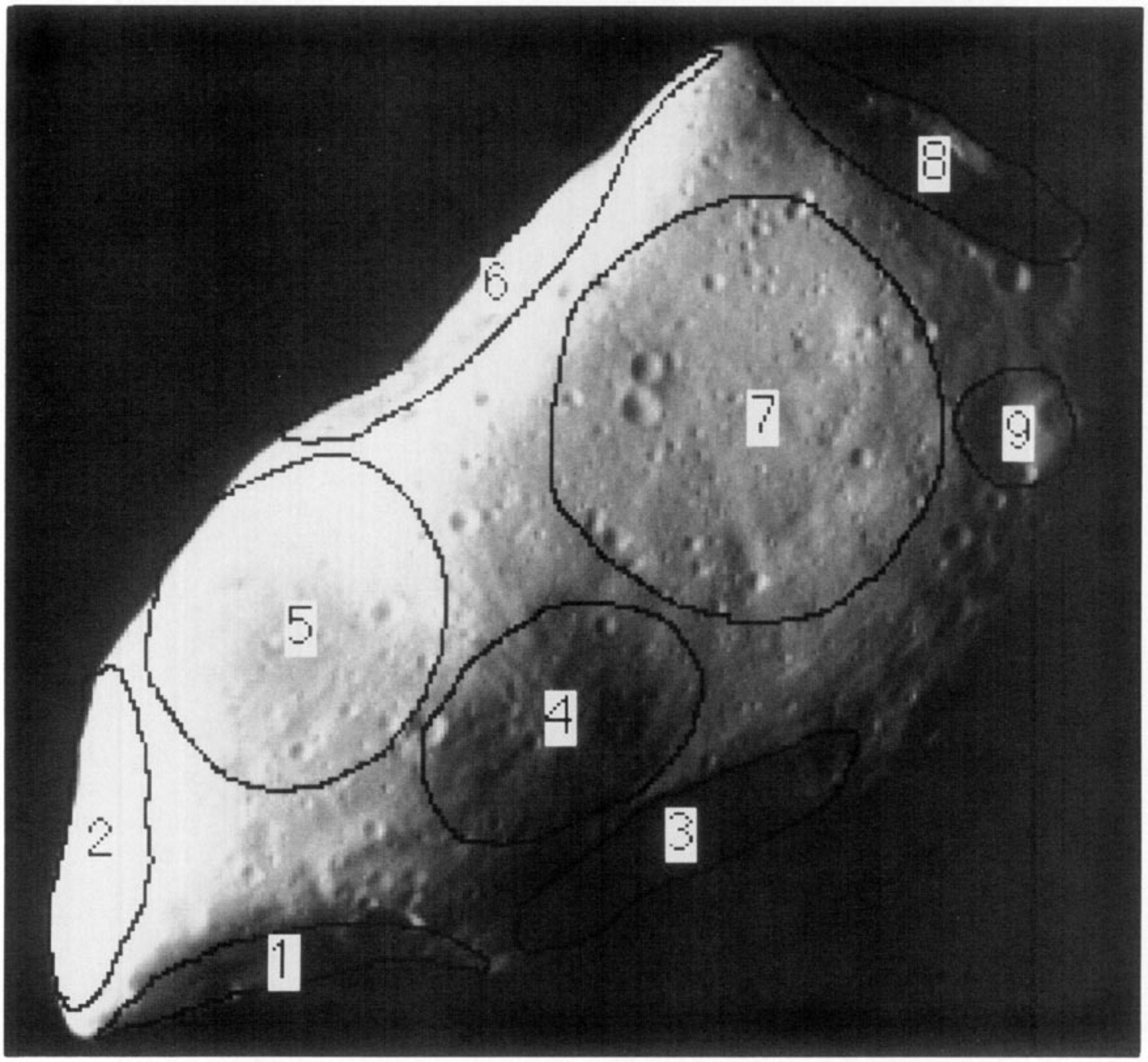

FIG. 2. A high-resolution frame showing candidate regions of concavity, some of which we believe may be impact craters. The regions are numbered for reference in the text.

the physical possibility or morphology of large craters on a small asteroid, Galileo images suggest that there may be as many as eight craters larger than 4 km in diameter on Gaspra, or equivalently two per 140 km^2, the reference area for the counts reported by Belton *et al.* (1992).

This number is inconsistent with the predictions of none larger than 4 km from both (a) conventional scaling laws for impact effects and (b) extrapolation of the Belton *et al.* (1992) power-law distribution. In the next section (III) we address point (a), showing that very large craters are consistent with improved scaling. In Section IV we address point (b), showing that inclusion of larger concavities in crater counts gives a size distribution that is consistent with a reasonable collisional history.

III. MODELS OF EFFECTS OF IMPACTS

III.A. Previous Models

An extensive literature has developed on scaling results of impact experiments at small scales on Earth to the conditions relevant to various planetary problems (Housen *et al.* 1983, Melosh 1986, Vickery 1986, Housen and Holsapple 1990). These scaling laws are based on a sophisticated understanding of many of the physical processes involved.

In these schemes, a body of Gaspra's size is taken to be in a "strength scaling" regime, where the outcome of an impact event is controlled by the strength of the material involved, rather than by gravitational binding. Figure 6 shows the size of crater predicted (Vickery 1986) for a given size impactor at the average speed for asteroid

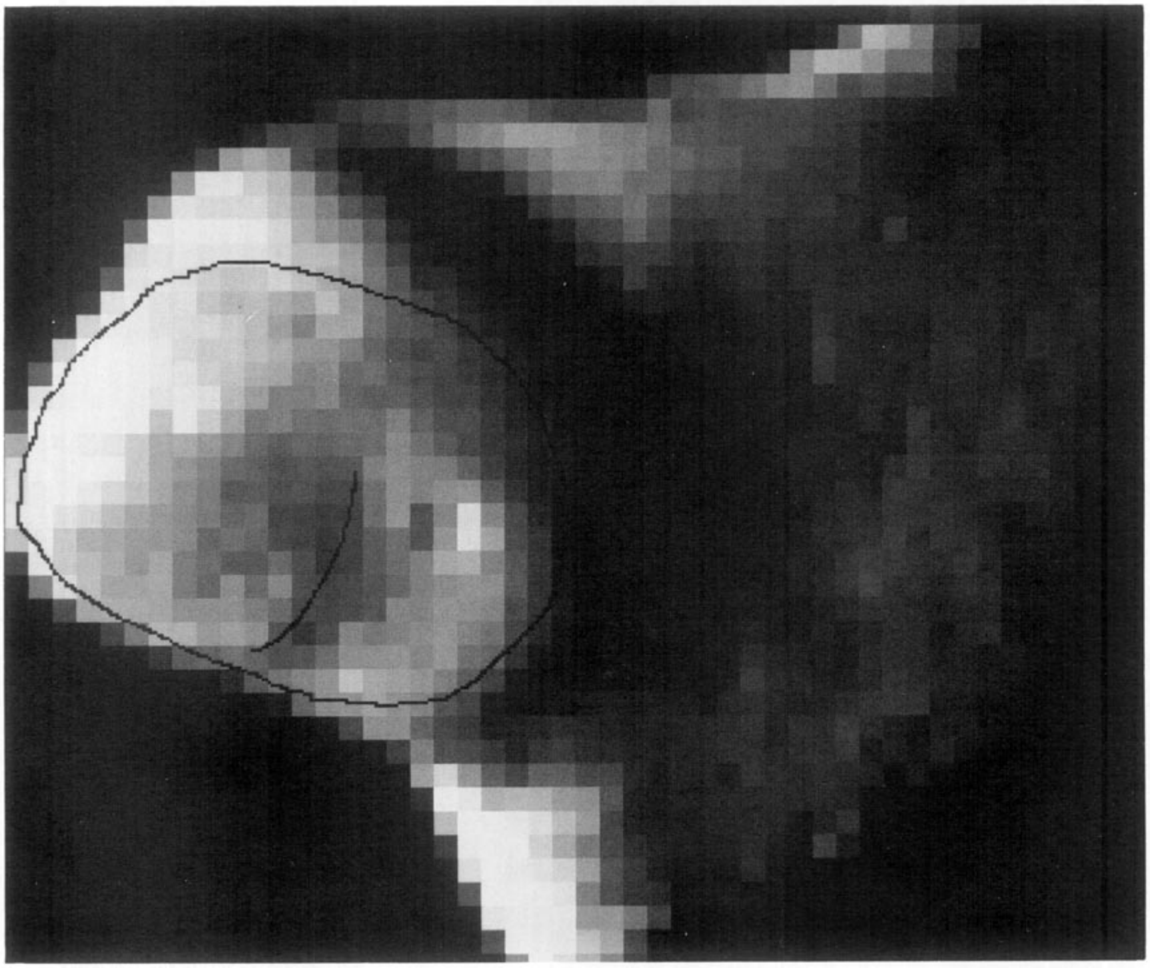

FIG. 3. An earlier, lower-resolution image is seen from a direction more nearly normal to Region 1 (outlined) than in Fig. 2. The smile shown inside Region 1 is edge of the central bulge visible in most images showing this region as mentioned in the text. The viewing geometry and lighting show the narrow neck that separates the double lobes of Gaspra's figure.

collisions, 5.3 km/sec. The slope for the strength scaling law in Fig. 6 is 1. Thus, according to this law, the power-law index for the size-distribution of an impacting population will equal the index for the craters it produces.

This strength-scaling law was used by Belton *et al.* (1992) to infer a size distribution for the very small asteroids that bombard Gaspra. The distribution adopted by Belton *et al.* for small asteroids is an extrapolation of the Palomar–Leiden Survey (PLS; Van Houten *et al.* 1970) results down to diameter 175 m, connected to a steeper power-law for asteroids smaller than 175 m to match the size-distribution of Gaspra crater counts, assuming the strength scaling shown in Fig. 6 and collisional frequency computed by Farinella *et al.* (1991). Although Belton *et al.* did not explicitly define the population they adopted, it can be inferred to be

$$dn = 2.7 \times 10^{12} D^{-2.95} dD \quad \text{for } D > 175 \text{ m} \qquad (1)$$

$$dn = 4.7 \times 10^{13} D^{-3.5}\, dD \quad \text{for } D < 175 \text{ m}, \qquad (2)$$

where dn is the number of main-belt asteroids between diameter (in meters) D and $D + dD$. We refer to this population as the "Galileo Reference Population" or GRP, because it provides a standard of comparison as we consider various effects.

The strength scaling laws also predict that an impact by an asteroid larger than 350 m in diameter will catastrophically disrupt Gaspra. This limit is shown by the dot at the end of the strength scaling line in Fig. 6. The frequency of such impacts determines the mean expected lifetime of a body of Gaspra's size, which for the Galileo Reference Population is about 500 myr (Belton *et al.* 1992). Throughout this paper, "lifetime" refers to the mean expected lifetime of a body of Gaspra's size, which is not necessarily the same as either the actual age of

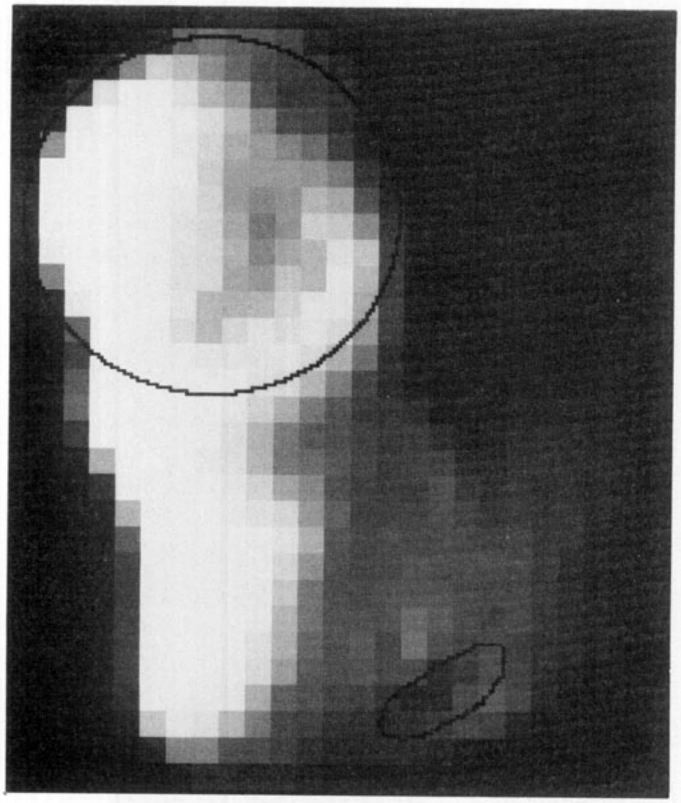

FIG. 4. An even earlier and lower-resolution image shows a face-on view of Region 1 (outlined). The smaller crater is one of the two 3-km craters, which are in a region only visible in Galileo's low-resolution images.

Gaspra or the period over which currently existing craters have accumulated.

For larger or extremely weak target bodies, crater size is usually assumed to be controlled by gravity rather than by strength. Although it has been generally assumed that Gaspra is outside the regime where gravity scaling applies, we can extrapolate the gravity-scaling law (Melosh 1989) to a Gaspra-sized body, as shown in Fig. 6. Gravity scaling, if it were relevant, would result in much larger craters and a different power-law index from strength scaling.

III.B. Hydrocode Simulations

Recent hydrocode modeling of impacts by Nolan *et al.* (1992) shows that for a given impact, crater size is much larger than previously assumed on the basis of scaling laws. Nolan *et al.* used the two-dimensional (i.e., axisymmetric) hydrodynamic model for impacts that was described by Melosh *et al.* (1992) and by Asphaug and Melosh (1993). The model is unique in that it explicitly includes brittle fracture (Grady and Kipp 1987) as a thermodynamic process in solving the fluid equations for flow in an impact. Brittle fracture is assumed to occur by the propagation of flaws, which grow within a material at a rate proportional to the strain rate. The constant of proportionality is determined from experiments. A fundamental property of the Grady–Kipp fracture theory is that once sufficient fractures have grown in a computational cell (which may be one long fracture or many short ones, depending on the strain rate), the cell no longer has any tensile strength. In the code by Melosh *et al.*, the fracture is represented by a statistical description of the flaws within each computational cell of the material.

Melosh *et al.* (1992) have subjected the code to extensive tests and verification. As an additional test we have compared results of some of our simulations with those of a three-dimensional smoothed-particle hydrodynamic code by Benz and Asphaug (1993), an independently developed model also used for impact simulations. Their code is based on the same fracture theory, but individual flaws are treated explicitly, rather than by the statistical description used in the code of Melosh *et al.* Although the Benz and Asphaug code contains more physical detail, we find that the results from these comparison tests are essentially identical.

III.C. Crater Size

The crater size for a given impactor size from Nolan *et al.* (1992) is plotted in Fig. 6. There are some uncertainties in interpretation of the numerical results, because some subsurface, potential ejecta was still in motion at the end of the computer runs. Uncertainties are shown by the upper and lower limits; a straight line that represents our adopted fit to the results is also shown. The size of the largest crater that can be sustained by a target of this size is significantly greater than indicated by the conventionally adopted strength scaling. Also, for any size impactor, the resulting crater is greater than given by strength scaling; for the largest impactors, craters approach the sizes predicted by extrapolated gravity scaling.

The fact that the hydrocode results make this transition from near strength-scaling to near gravity-scaling can be interpreted in terms of the mechanics of the impact process shown by the hydrocode models. They show that for the larger impactors, crater excavation is preceded by an advancing shock front. As the shock unloads behind the front, a tensile regime shatters the material. Excavation of the crater then occurs in effectively strengthless material. Thus, even though Gaspra is very small, gravity may be a more important governing factor than strength, which may explain why the results approach those of gravity scaling. For the smaller impactors studied in the Nolan *et al.* hydrocode experiments, crater sizes are closer to the predictions of strength scaling.

The increased size of the largest craters relative to the predictions of strength scaling is also due in part to the global curvature of the target surface, which is significant

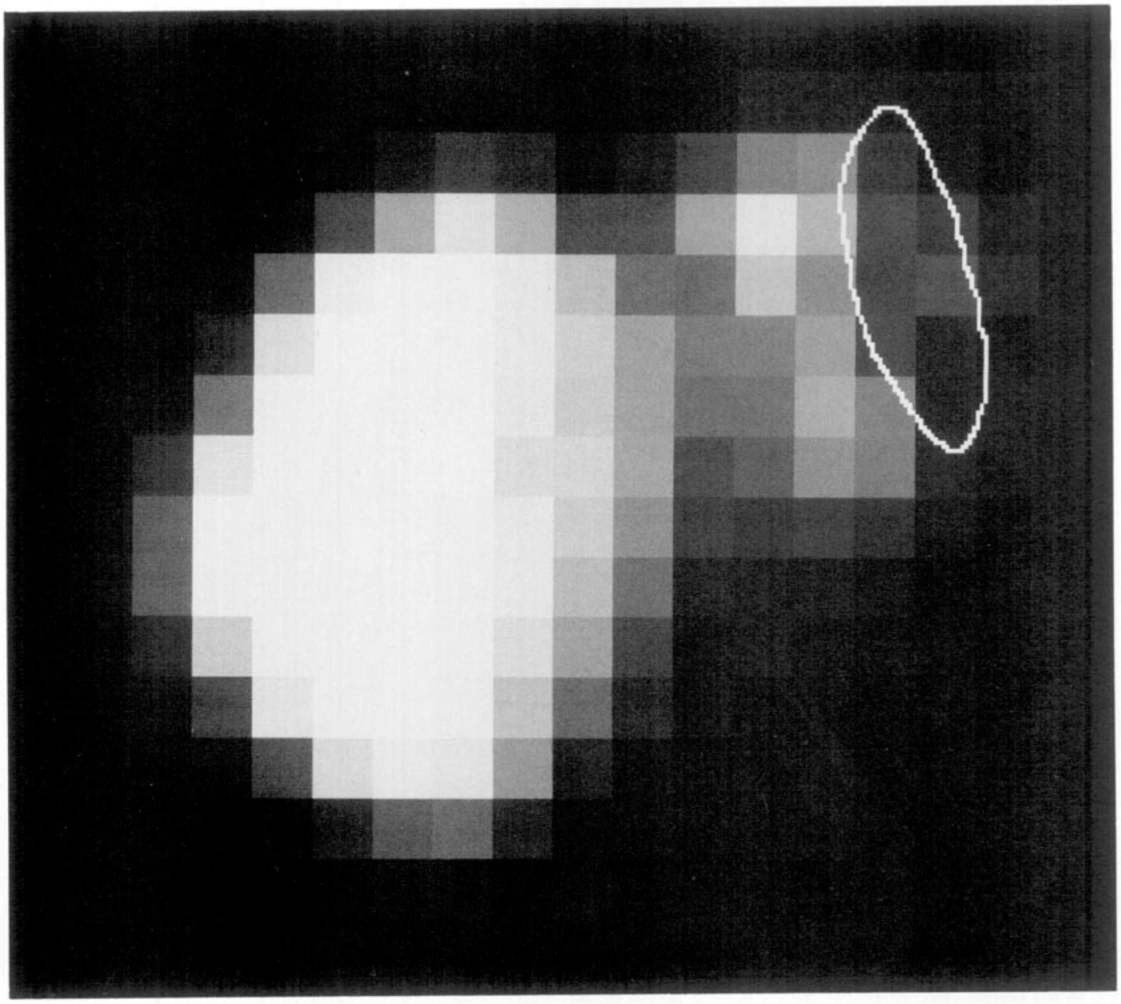

FIG. 5. In this extremely low-resolution image, taken early in the Galileo sequence, Region 1 (outlined) is again seen nearly edge-on, but from the opposite direction of Fig. 2. The far rim of the concavity is catching sunlight which lights up one pixel. This view corroborates the evidence from the other images that Region 1 is a large concavity. As in Fig. 3, the double-lobed figure is apparent.

at these sizes. The hydrocode assumes a spherical figure, while most scaling laws to not take surface curvature into account (E. Ryan, personal communication). The spherical assumption is clearly not ideal for Gaspra, but is a great improvement over previous modeling.

III.D. Catastrophic Disruption

The hydrocode results show that Gaspra-size bodies can withstand, without being catastrophically disrupted, impacts by bodies up to 500 m in diameter, which is considerably larger (and thus less frequent) than previously thought. For the GRP, this change would increase the average expected lifetime of a Gaspra-size body up to about 1 byr, twice that estimated from the strength-scaling limit. (Although the rationale of Belton *et al.* (1992) for originally adopting the GRP would be moot if strength-scaling indeed breaks down, we still use this population as a standard of comparison.) These results also invalidate the assumption that impact craters must be smaller than 3 km in diameter. A Gaspra-size body could easily withstand, without disruption, a hit that would produce an 8-km crater, which is the size of the largest crater candidate (6) discussed in the previous section.

Do these results mean that a Gaspra-sized target is stronger or weaker than previously estimated? In the sense that larger craters are formed for a given impact, the target might be considered weaker. However, since the target can survive a more energetic impact, it is in another sense stronger. Such simple categorizations are oversimplifications and counterproductive to understanding the impact mechanics. Just as in design "less is more," in this field "weak" can be "strong," for example when weak materials are ineffective at transporting energy through a body and thus prevent catastrophic disruption. Currently we do not have results from hydrocode experi-

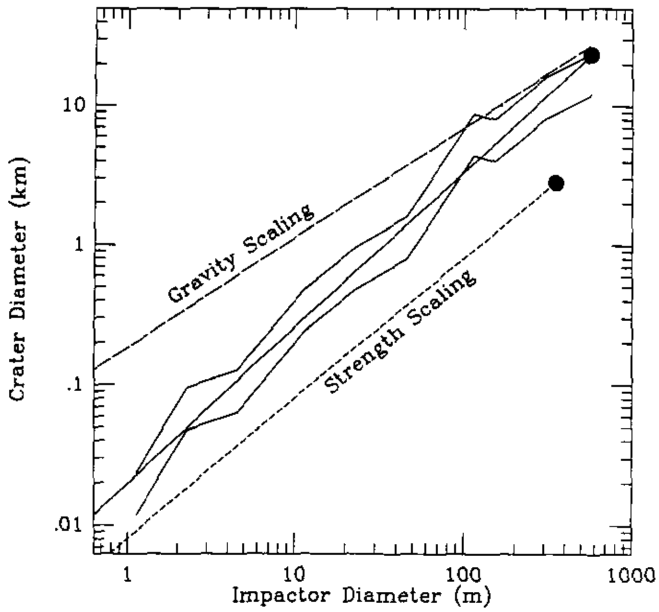

FIG. 6. Crater size as a function of impactor size, for impact velocity 5.3 km/sec. Large dots indicate the largest impactor size that does not disrupt the target. The jagged curves give upper and lower bounds based on hydrocode modeling of impact effects. The straight line between them is the fit to the data adopted in this paper. Crater sizes are larger than predicted by the strength scaling usually assumed to apply for targets as small as Gaspra. At the large size end crater sizes are close to those extrapolated by gravity scaling.

ments over a wide enough range of parameters to propose a new formulation or corrections to scaling theory; that would be beyond our intent in this paper. We do know that hydrocode results do not fit scaling laws where we have tested them. The most meaningful interpretation in terms of existing theory is the transition from strength to gravity scaling as described above.

These processes for creating large craters may also help explain the existence of Stickney on Phobos (Asphaug and Melosh 1993). Similarly, in explaining the Pharos feature on Proteus, Croft (1992) has argued that impacts into small bodies should leave craters much larger than predicted by the scaling laws of Housen *et al.* (1983) and Housen and Holsapple (1990), and that such targets can survive impacts that leave craters almost as large as the target body.

III.E. Global Jolting

Another important effect demonstrated by the hydrocode studies is the global jolting of surface material. In the numerical experiments done by Nolan *et al.* (1992), for an impact that produces a given size crater, there is a characteristic speed imparted to material near the surface over the entire target body. This effect is similar to the jolt produced by hitting the bottom of a pan full of sand. Taking into account the gravity of the target, we convert the speed at which the surface material moves into a jump distance. Topography will be destroyed, or at least substantially smoothed, if its horizontal or vertical scale is smaller than the jump distance and the regolith thickness.

We can roughly quantify the effect of a given impact on global topography. More precise determination would be difficult and probably not necessary at the level of detail of current work. We assume that surface material is launched at the characteristic speed at an angle 30° from the vertical. A ballistic trajectory then gives the horizontal jump distance. For example, when a crater of 5 km diameter is formed, regolith over the entire surface jumps about 30 m. Assuming that the regolith is thicker than 30 m, the jolt erases topography on that scale.

We assume the height and width of a typical crater rim to be about 1/5 of the diameter of a crater. In the above example, the impact that created a 5-km crater also erases all craters up to 150 m. Topography and compositional inhomogeneities on a scale greater than 30 m would be preserved. This model of erasure, combined with the surface velocity from the hydrocode models, yields the relationship (shown in Fig. 7) between the size of a crater produced on a Gaspra-sized target and the crater size below which all craters on the body are substantially obliterated by the accompanying jolt. The large impact events are analogous to erosional and tectonic processes on terrestrial planets in terms of their ability to modify crater size distributions.

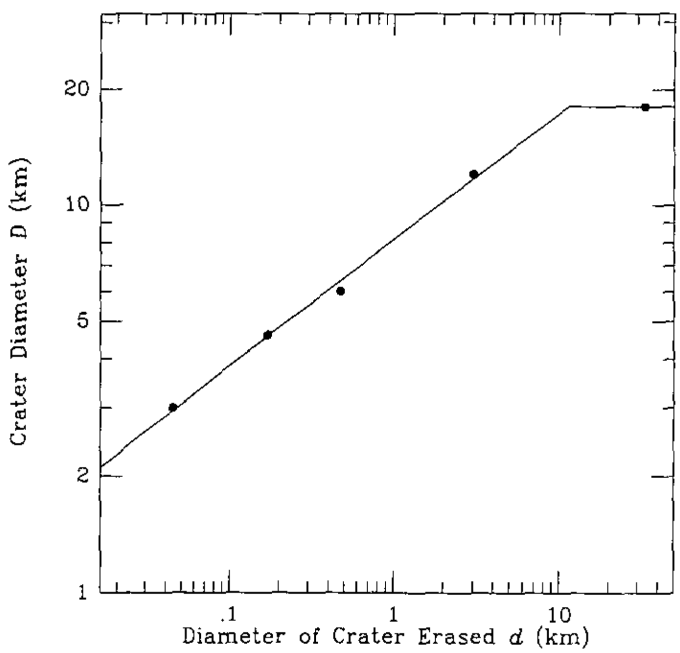

FIG. 7. The relationship between the diameter D of a crater produced on a Gaspra-size target and the diameter d below which all craters on the body are substantially obliterated by the accompanying jolt.

Is the regolith thick enough for this process to work? Belton *et al.* (1992) argue on theoretical grounds that any regolith on Gaspra would have to be very thin (less than a few meters), although they recognized that some was needed to help explain the distribution of color and albedo variations (see Section VII). Their case was based on a model in which regolith formation is a result of retention, elsewhere on the planet, of material ejected from craters (Housen *et al.* 1979). For weak, cohesionless surface material, substantial fractions of ejecta can be retained as regolith even on a Gaspra-size body. However, if the surface material is initially very strong, with correspondingly fast ejecta velocities, nearly all ejecta can escape the surface so regolith would not form by this mechanism. With less than a few meters of regolith, even the global surface velocities revealed by the hydrocode would not erase topography on any significant scale.

However, the process of global impact shock by large cratering events, as revealed by the hydrocode, not only imparts velocity to surface material everywhere, but also fragments material to a much greater depth over the whole surface than had previously been assumed. Even where there was no regolith originally, it would be created. This process is not only the fall-back of crater ejecta considered by Housen *et al.* (1979), but also it is *in situ* pulverization, accompanied by the modest velocities that give the erasure of craters on the scales shown in Fig. 7.

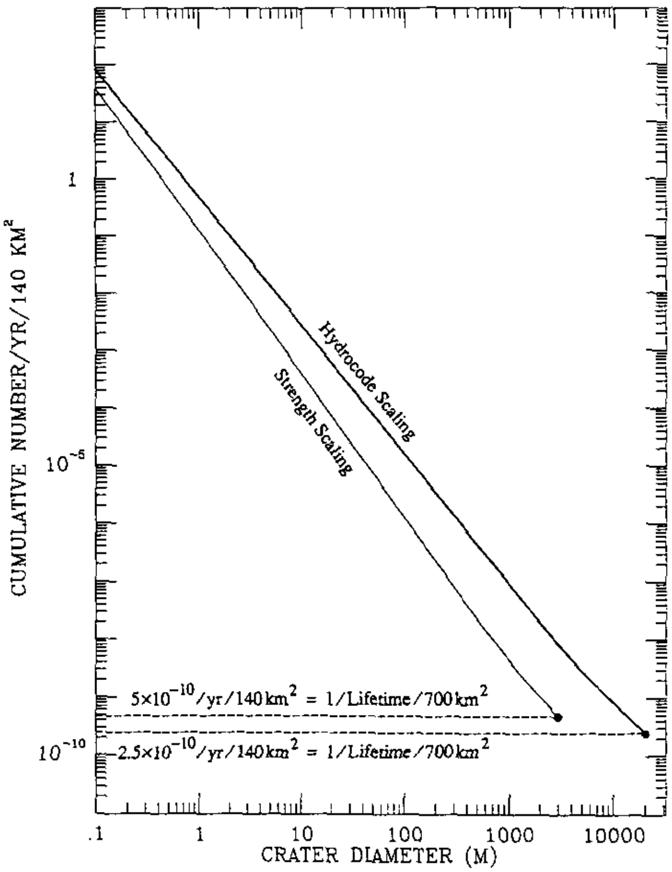

FIG. 8. Cumulative number (i.e., number greater than a given size) of craters produced per year per 140 km^2 on Gaspra by the "Galileo Standard Population" of asteroids. One line is based on strength scaling, as adopted by Belton *et al.* (1992), and the other is based on the hydrocode results. Each line is terminated at the largest impact that does not disrupt Gaspra according to the corresponding impact model. The maximum size crater in each case corresponds, by definition, to one impact per lifetime of the target body per total surface area.

IV. EFFECT OF IMPROVED IMPACT MODELS ON CRATER SIZE DISTRIBUTIONS

In Fig. 8, we show the cumulative size distributions (the number larger than any given size) that would result from the GSP, using the intrinsic collision frequency based on the actual orbital distributions for main-belt asteroids (Bottke *et al.* 1993). Results are shown for both the assumption of strength scaling and the crater production law based on the hydrocode results (Fig. 6). Each curve is terminated at the greatest impact allowed according the corresponding law. The hydrocode model permits larger craters, and a correspondingly lower frequency of catastrophic disruption (longer lifetime). For each curve the termination at the right corresponds, be definition, to a frequency of 1/lifetime/(total surface area). The total surface area is about 700 km^2.

Thus for the crater size distribution based on conventional strength-scaling, we have

$$1/\text{lifetime}/700\ \text{km}^2 = 5 \times 10^{-10}/\text{year}/140\ \text{km}^2,$$

which yields

$$\text{lifetime} = 4 \times 10^8\ \text{years},$$

confirming to a reasonable approximation the result of Belton *et al.* (1992).

For the distribution based on the hydrocode results,

$$1/\text{lifetime}/700\ \text{km}^2 = 2.5 \times 10^{-10}/\text{year}/140\ \text{km}^2,$$

which yields

$$\text{lifetime} = 8 \times 10^8\ \text{years} \approx 1\ \text{byr},$$

twice that of Belton *et al.* as noted in the previous section.

Figure 9 shows the results from Fig. 8, multiplied by the lifetime of Gaspra, and plotted over the range of the cumulative distribution for which we have actual crater-count data. The power-law from Belton *et al.* (1992) which represents a fit to their crater counts, is also shown (heavy straight line). We also show our own modification of the

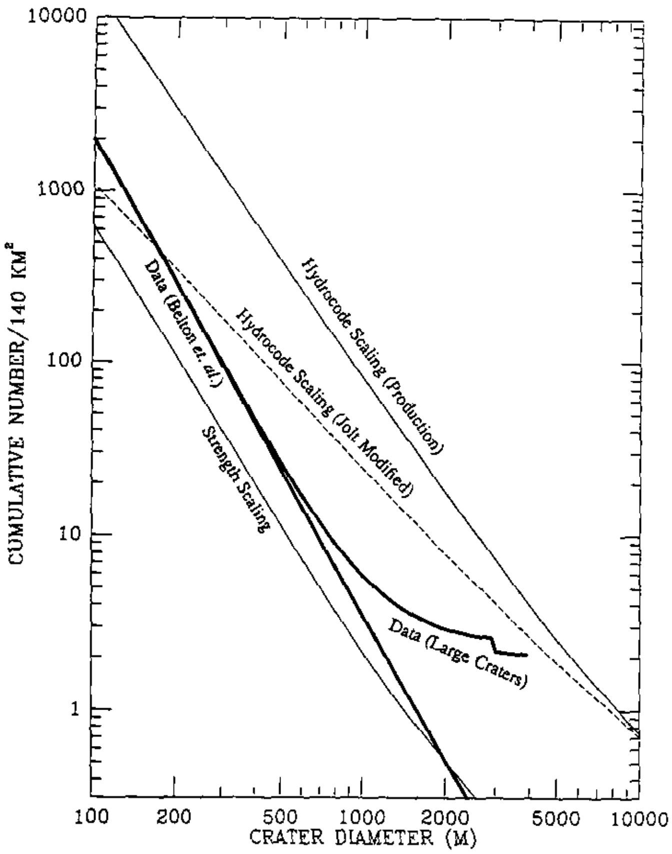

FIG. 9. Curves based on the models shown in Fig. 8 are converted to number of craters produced over the full mean lifetime of the body (10^9 years for hydrocode and half that for the strength scaling) and plotted on a scale appropriate for comparison with observed crater counts. The latter are indicated by heavy lines (labeled "data"), the straight one being the power law determined by Belton *et al.* (1992) and the curved one including multikilometer craters as discussed in this paper. The dashed line shows modification to the hydrocode scaling curve when jolt erasure is taken into account.

data (heavy curved line), which includes the two 3-km craters seen on images not yet available to Belton *et al.* (1992), and which includes in addition about two craters per 140/km^2, in accord with our discussion in the previous section.

Naturally, the strength-scaling model is close to the Belton *et al.* (1992) crater-count power-law (within the uncertainties in the data quoted by them), because the GSP was selected so as to ensure reasonable agreement, while being "conservative" in the sense of minimizing numbers of small asteroids. (If the GSP were adjusted by steepening the small body segment to match the steepness of the crater counts, the agreement could be even better.) Note, however, that the strength-scaling model agrees with the data only if the actual age of the surface (time that craters have been accumulating) is near the assumed lifetime of 5×10^8 years. If, for example, the craters have only been accumulating for 10^8 years, the asteroid population would have to be five times the GSP in order for the strength-scaling model to fit the Belton *et al.* data. In any case, the strength-scaling model does not admit the presence of the large craters in our modified data curve, which has been a reason that the existence of large craters has been discounted by other workers.

In Fig. 9 the hydrocode-law curve is less steep than the strength-scaling one. It is also much higher, because a given impact makes a larger crater according to this law. In order for this curve to match the Belton *et al.* (1992) data, the asteroid population would need to be considerably steeper than the GSP; also, the number of asteroids in the contributing size range must be about an order of magnitude smaller than the GSP, or the period of time that craters have been accumulating must be an order of magnitude shorter than the Gaspra lifetime (corresponding to the hydrocode results) of nearly 10^9 years.

The theoretical curves in Figs. 8 and 9 discussed so far, do not account for processes that can erode or remove craters. They are "production curves"; i.e., they represent the total numbers created over the assumed period, but not necessarily the numbers remaining for observation. For a meaningful comparison with the observed counts, we need to take obliteration processes into account. The model of Belton *et al.* (1992) did not include such processes. However, the hydrocode results require that we consider the jolt effect, which can remove many small craters for each relatively large crater formed.

For example, the hydrocode curve in Fig. 9 shows that about 2 craters larger than 5 km are produced on 140 km^2 during Gaspra's lifetime. That is about 10 craters over the total (700 km^2) surface. Each such event destroys all craters smaller than 150 m, so craters of 150 m in diameter are cleared from the surface about 10 times during this period. Therefore we expect only about 1/10 of the 150-m craters that have been created to remain. Similar calculations done at all sizes give the modification to the "jolt-modified" curve shown in Fig. 9. The unmodified (production) hydrocode curve represents all craters created during a lifetime, while the jolt-modified curve represents the number expected to be observable late in the asteroid's lifetime.

This modification does not improve the agreement with observed crater counts. Agreement with the observed power-law would require an even more extremely steep asteroid size distribution than if jolt had been ignored. Moreover, the jolt modification does not provide a way to explain the observed excess of large craters relative to the power-law.

To summarize the results of this section, we confirm that the strength-scaling law adopted implicitly by Belton *et al.* (1992), combined with the Galileo Standard Population (GSP) of small asteroids, agrees with the crater counts reported in the same reference. However, that scaling law is probably not appropriate. Moreover the theory does not agree with the crater counts that include large craters. On the other hand, the more realistic hydrocode-based scaling gives results that agree neither with the Belton *et al.* counts nor with the counts that include additional large craters. In the next section we consider solutions to this dilemma.

V. FITTING A MODEL TO THE DATA

Three aspects of the model can be modified to fit the data. First, although we assumed the GSP in the discussion above, there is considerable latitude in the possible size distribution of asteroids in the relevant size range of impactors (below about 200 m diameter). Second, local obliteration of previous craters by impact events can be modeled. At a minimum, the removal of previous craters within a new crater resembles the effect of a "cookie cutter" and must affect the size distribution. Third, inevitable stochastic variations in the timing of larger impact events can modify crater counts significantly, whereas we and most researchers usually assume that impacts in any size range are uniformly distributed in time.

Figure 10 shows some possible effects of changing the asteroid size distribution. These and all results in this section are based on the hydrocode scaling law. In both of the size distributions used for Fig. 10, the asteroids larger than 175 m follow the GSP (Eq. (1), based on the PLS), but the exponent q for the smaller bodies is -3.5 (same as GSP) in one case and -4 in the other case. The production curve almost matches the steep slope of the observed power-law for the case $q = -4$. Once the jolt modification is made, however, even the case $q = -4$ does not yield a crater distribution as steep as that observed.

We also show in Fig. 10 further modifications to the theoretical distributions due to the cookie-cutter effect (local obliteration). In the algorithm used to generate these curves, we assume that any impact obliterates (from recognizability as a crater) any crater whose center was within C times the radius of the new crater (where C is the obliteration factor) and whose radius is less than the radius of this obliteration region. We assume that the obliteration is due to the direct blast within the new crater's rim and ejecta and regional jolting beyond the rim. The hydrocode results are not precise enough to determine whether such a model is realistic or not, but we try this model to begin to explore the kind of effects that such a process can have on crater counts.

Figure 10 shows that the cookie-cutter effect can introduce a curvature at the upper size end of the distribution, which is qualitatively similar to the large-crater data. Here we have taken $C = 2$. The curvature is due to the fact

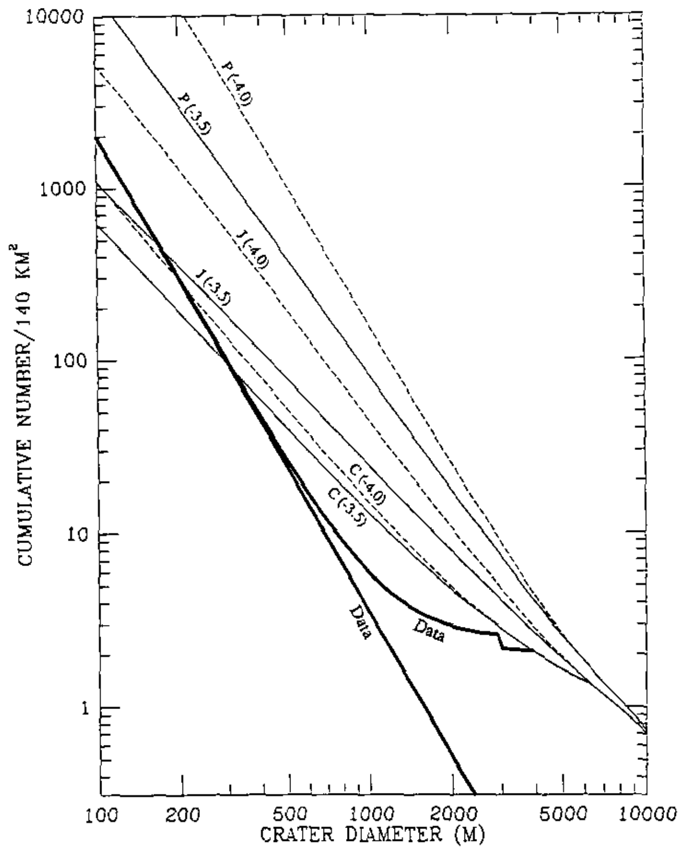

FIG. 10. Production curves ("P") based on the hydrocode scaling law for two different asteroid populations. Jolt modifications of each production curve are also shown, labeled "J". Further modifications due to the cookie cutter effect are labeled "C". None matches either data curve very well.

that the largest craters are never removed by cookie cutters. Also, at the smaller size end, it can in some cases steepen the distribution relative to the jolt-modified curve. Both of these effects could potentially contribute to making theory match the observations. The qualitative effects are in the direction of improving the fit to observations, but quantitatively still have a long way to go.

Next we consider an impacting asteroidal population with the PLS power law (Eq. (1)) extending down to diameters of 50 m, at which point the size distribution steepens to $q = -3.5$ and -4, respectively. Placing the bend in the size distribution at 50 m is consistent with (a) Strom's (private communication) estimate of the bend in the population responsible for cratering Mars and (b) Rabinowitz' (1993) observations of small asteroids near the Earth; it is not consistent with the results for the Moon cited by Belton *et al.* (1992) as the rationale for the selection of the bend at diameter 175 m. Mars might have been impacted by a more representative sample of asteroids than the Moon, but the discrepancy probably demonstrates the range of uncertainty in interpretation of lunar

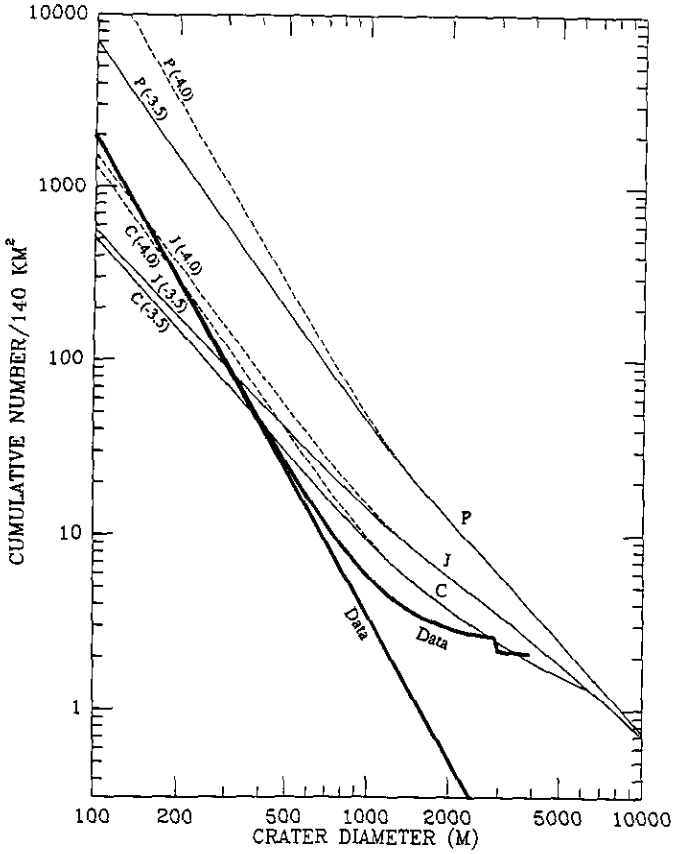

FIG. 11. Production, jolt-modified, and cookie-cutter modified crater populations for two different assumed asteroid populations. Cookie-cutter algorithm (see Fig. 12) is optimized to produce a dip near 1 km, but it is not enough to match the data.

and martian planetary cratering data regarding the impacting populations.

Figure 11 shows the production curves for Gaspra craters based on such populations, and the corresponding jolt-modified curves. The bend due to the assumed asteroid population transition at 50 m is at the right place to contribute to the curvature in the observed crater distribution on Gaspra. The jolt-modified curve for the $q = -4$ case matches the observed counts at 100 m and 4 km, but does not curve down as deeply as the data between those sizes, with the greatest disagreement near 1 km.

We further modify the theoretical curves in Fig. 11 by accounting for the cookie-cutter effect. For Fig. 11, we have adopted a cookie-cutter model optimized to enhance the dip in the population needed around 1 km: Here the obliteration factor C depends on the size of the new crater, as shown in Fig. 12: All craters smaller than 500 m act as cookie-cutters just as big as the crater (no effect due to ejecta or regional jolting), while craters larger than 8 km can destroy all craters up to 2.5 radii away.

The effect of this cookie-cutter model is in fact to deepen the dip in the size distribution of the theoretical curves down toward the data, but even with this optimal model, the agreement is not compelling. The discrepancy remains a factor of nearly 2 between 500 m and 2 km. Since there are so few large craters, statistical fluctuations may be important.

VI. EFFECT OF TIMING OF LARGE IMPACTS

All of the theoretical curves discussed above assume (as most researchers do) that impact events at any size occur uniformly over time and that the last impact occurred at time 1/frequency ago. For example, for all of the asteroid populations considered in this paper, the production curve for craters on Gaspra shows that about two events probably occurred during the asteroid's billion-year lifetime that were able to destroy all craters smaller than 4 km by global jolting. Thus, in all the curves constructed above, we assumed that Gaspra is actually about 1 byr old and that the last such impact was 1/2 billion years ago.

If, in fact, such an event occurred more recently (for example 50 myr ago), (a) the numbers of craters in 1991 larger than 4 km would be unaffected because the event would have only jolted away craters <4 km, (b) the numbers of craters in 1991 smaller than about 100 m would be unaffected because they have only accumulated since the last global jolt-erasure event, which was less than 50 myr ago, but (c) between 100 m and 4 km, numbers would be substantially reduced.

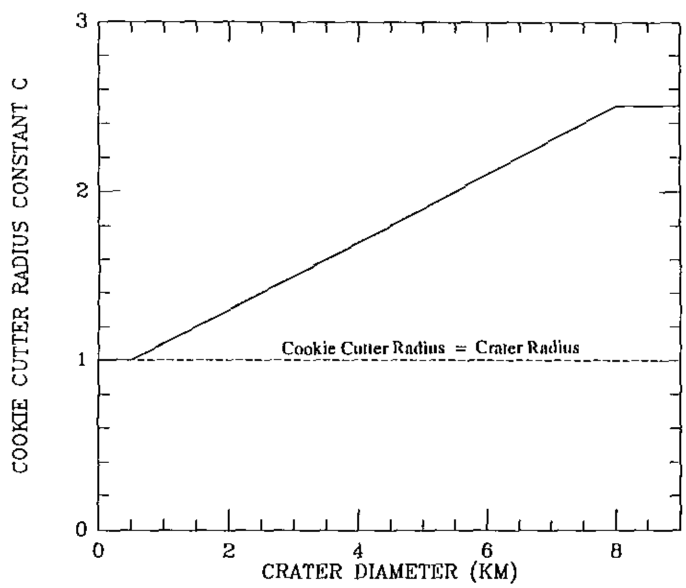

FIG. 12. Size-dependent crater obliteration factor (size of the cookie cutter) assumed in the models shown in Fig. 11. Large craters are assumed to destroy all topography out to 2.5 times their own radii due to regional jolting and ejecta emplacement; small craters only destroy terrain within their own rims.

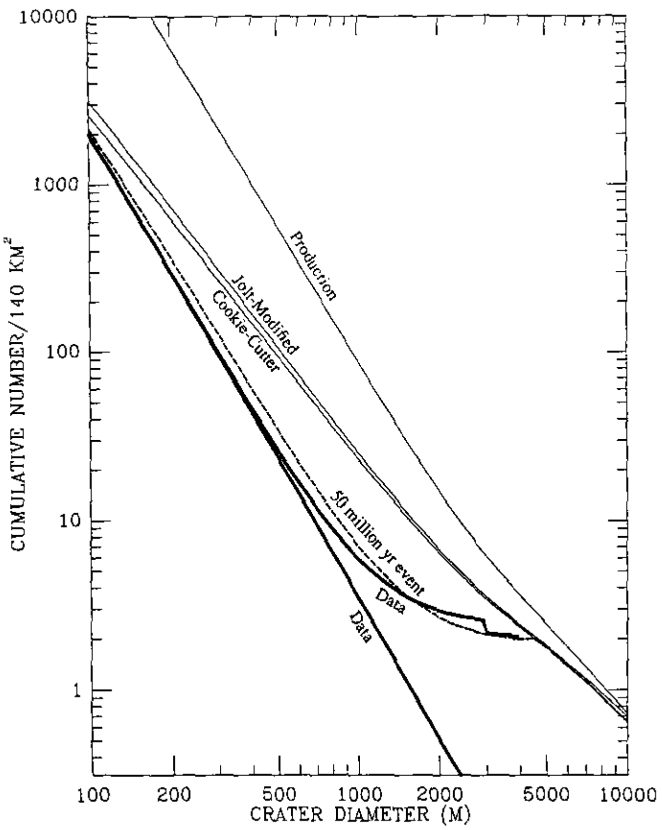

FIG. 13. Production function based on the hydrocode scaling, with an asteroid population that turns up to $q = -4$ at diameter 100 m. Jolt modification creates a more shallow slope. The conservative cookie-cutter invoked here has little effect. The dashed line shows the effect of advancing the time from 500 to 50 myr ago for the most recent event capable of destroying all craters <4 km.

Such a scenario would in fact explain the current size distribution of craters on Gaspra. In Fig. 13 we show the production curve assuming an asteroid population that follows the PLS (Eq. (1)) down to diameter 100 m and then bends up to an index $q = 4$ for smaller asteroids. As usual, the jolt-modified curve reduces the slope significantly. It is close to the observed crater size distribution at 100 m and at 4 km. Here we adopt a conservative cookie-cutter model that has little effect on the size distribution ($C = 1$, rather than the optimized C from Fig. 12, which was used in Fig. 11).

The dashed line in Fig. 13 shows the effect of having the most recent destroyer of 4-km craters occur 50 myr ago. As discussed above, it reduces the numbers between 100 and 4 km, and we see that the agreement is quite good with the observed crater counts, where of course we are including a couple of craters larger than 4 km in our estimate of observed craters.

Is it unreasonable for a 500-million-year event to have happened only 50 myr ago? The probability of an occurrence at least that recent is about 10%. The probability that it occurred near 500 myr ago would have been comparable. In fact, for an observation of any single asteroid, we should anticipate that one or more major impact events are likely to have occurred at a time in the past very different from 1/frequency. As illustrated by Fig. 13, the actual timing of such events can have a dominant effect on the size distribution of observed craters.

If we observe numerous Gaspra-sized asteroids we would expect to see results of a distribution of timing of major impacts. As images are obtained of other small asteroids by spacecraft, such as Galileo images of Ida, and by improved Earth-based radar (Ostro 1993), we anticipate crater size distributions that will reflect such a range. It will be surprising if Ida is modified by big-event timing in the same way as Gaspra appears to have been.

VII. DISCUSSION AND CONCLUSIONS

In this paper we have considered several aspects of the collisional processes that affect small asteroids and that are important now that images are available. We find that these effects were strong and perhaps dominant in controlling the impact record observed on Gaspra. By taking these processes into account, we have found that we can obtain reasonable agreement with the observed crater counts on the asteroid, but only if those counts include the large impact features that have been ignored in previous surveys. In this section we summarize our important conclusions and relate them to a few other observations and ideas about Gaspra.

Hydrocode models of impacts into Gaspra-size targets show that events that create multikilometer craters shock much of the target body. As a result, crater sizes are near those predicted by gravity-scaling, rather than the smaller sizes predicted by the strength-scaling rules adopted for small targets in previous studies. For a given impact a larger crater forms than had previously been expected, so Gaspra can survive hits that leave craters comparable in size to itself. Consequently its expected mean lifetime against collisional disruption is about 1 billion years, twice previous estimates.

The same impact models show that events that create those large craters must jolt the entire surface, so somewhat smaller craters and other surface features may be modified severely if not completely erased. In this view the currently observed smaller craters have accumulated only since the last erasure event, which is a fraction of the likely age of Gaspra.

The implications of these impact-model results for Gaspra's crater counts are profound. Contrary to strength-scaling, the distribution of craters produced on the surface does not directly echo the distribution of asteroids. The asteroid population would need to have an even steeper power-law to match a given crater production distribution. The problem of matching the steep observed crater size distribution is exacerbated further by the jolt effect, which tends to flatten the distribution. The cookie-cutter effect can steepen the distribution over the size range of most observed craters, while preserving the largest ones, but the effect is may not be great enough to match observations unless the asteroid population is incredibly steep.

We have shown that plausible stochastic variations in the timing of large impacts can have major effects. Specifically, we can match the actual crater counts by invoking a relatively recent impact capable of erasing by jolt all craters smaller than 4 km, about 50 myr ago, or about 1/10 the mean interval between such events. In other words, from the point of view of the production of currently existing craters smaller than 4 km, the surface of Gaspra is effectively only 50 myr old, although the asteroid itself is probably much older.

This agreement between the model and the actual crater counts works if and only if some of the multikilometer concavities are impact craters. While we have not offered conclusive observational evidence that they are craters, we have shown that the reasons that Belton *et al.* (1992) and others have discounted them are not valid. For example, the idea that a Gaspra-size body could not sustain an impact that left such large craters is disproved by the hydrocode; also the argument that the large craters do not fit on the same power law as smaller craters is rendered moot by physical processes that produce non-power-law distributions. It is completely plausible that several multikilometer concavities on Gaspra are impact craters.

The elongated figure of Gaspra, with a somewhat pinched waist confirmed by the recently received low-resolution images, may require the support of two or more internal solid blocks, overlain by a substantial regolith. Such a structure may have been the result of the original formation event, in which a precursor body was disrupted and some pieces of various sizes remained gravitationally bonded to form Gaspra. Other observational evidence for this physical model are the surface grooves (Thomas *et al.* 1993b), which may be related to downslope movement and sinkage of regolith into the interstices between blocks after the formation event, perhaps abetted by impact jolting.

An implication of the hydrocode results is that Gaspra must be a rubble pile due to the global shock and fracturing of large impacts. Whether the required internal blocks could survive the repeated shock is problematical. The hydrocode models run so far indicate fracturing throughout the body, but internal fragments can remain several kilometers in size. Moreover, it is possible that for nonspherical, inhomogeneous targets internal reflections will concentrate impact energy in some regions and minimize it elsewhere. Thus survival of large, intact, internal blocks that support the elongated figure may be consistent with the impact model we have adopted in this study.

Global impact shock and surface jolting, which we have shown to have important effects on the crater size distribution, also helps explain other observed properties of Gaspra. The presence of a thick, repeatedly jolted regolith provides a natural explanation for the softened morphology of Gaspra's surface as noted by Belton *et al.* (1992) without needing to invoke sand-blasting by small impactors. It also explains why the crater population includes both relatively fresh craters and modified ones with smoother morphology. In the crater-population model adopted in this paper, a given jolt erases all craters smaller than a certain size and preserves all larger craters. This model is probably appropriate for the current level of detail. In fact, of course, there would be a more gradual transition between total erasure and perfect preservation, with intermediate-size craters only partially modified. A higher-order model would include such effects, and the cumulative degradation of repeated jolt events, for comparison with the observed craters' size- and modification-distributions.

The surface distribution of material of various spectral classes seems to require the presence of a regolith (Belton *et al.* (1992). Optically fresh, mafic materials are found preferentially high on ridges, while altered material is found downslope. The downslope movement of regolith thus inferred by Belton *et al.* is consistent with the expected effects of continual global jolting.

The long-awaited first imaging of an asteroid has revealed a remarkable body, with a figure and cratering record requiring careful interpretation. The asteroid's current condition is explained by complex impact processes, including stochastic events that may have had dominant effects. Thus, while underlying processes shaping other asteroids must be similar, we can anticipate a variety of expressions of these processes as we image other asteroids in the near future.

Note added in proof. Since the modeling described in this paper was performed, two lines of recent research have corraborated our results: (1) The curve labeled "cookie-cutter" in Fig. 13, which also includes crater production modified by jolt, would be the expected crater size distribution for a typical surface without the relatively recent giant impact that we have invoked to explain the depletion of kilometer-scale craters on Gaspra. Preliminary crater counts on recent Galileo images of 243 Ida are remarkably close to that prediction. (2) Since our hydrocode modeling revealed that Gaspra-size bodies have greater resistance to catastrophic disruption than suggested by earlier scaling laws, various revisions of the scaling laws have been moving closer to our results (as discussed at the Catastrophic Disruption Workshop, Gubbio, Umbria, 1993). The most recent publication on this subject (Barge and Pellat 1993) contains scaling laws that agree well with the disruption criterion that we report here.

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