



Interplanetary sand traps

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Images from the asteroid Itokawa reveal unexpected seas of sand. New research suggests that the origin of those seas may be known to every golfer: It is easy to get trapped in sand, but hard to get out.

Asteroids have been lyrically described by planetary scientist Erik Asphaug as scraps on the floor of the planetary bakery, and indeed many tons of those scraps fall to Earth every day. Unlike bakery crumbs, asteroids and their icy cousins, comets, are unexpectedly varied. Many asteroids are oddly shaped as you can see in the images that appear with the online version of this Quick Study. Kleopatra, for example, looks like a dog bone and Eros resembles a tooth. Others are round or, like Saturn's moon Pan, flattened like a cosmic pierogi. And the comet 67P/Churyumov-Gerasimenko actually has sand ripples.

You might expect that banging stones together on Earth or in space would produce similar outcomes, but few terrestrial rocks are as peculiar as Kleopatra and company, and much of the diversity seen on our planet is produced by geological forces or erosion by wind or water that asteroids and comets lack. The variety of interplanetary bodies is surprising, and planetary scientists hope that by understanding the root causes of that diversity, we can gain insight into the history of the solar system.

A case in point is Itokawa (see figure 1), an asteroid that was visited by the Japanese craft *Hayabusa* in 2005, after a 28-month, 2-billion-km voyage and precision landing. The visit returned spectacular photographs that revealed strong separation between lowlands filled with pebbles and highlands occupied by large boulders but completely lacking fine grains.

On Earth, grain separation occurs through known mechanisms. An immense landslide populated Canada's Nicolum Valley with its large boulders; ocean currents produced pure

white beaches in the Caribbean and pure black beaches in Hawaii; and wind blew sand into the Calanshio Sand Sea in Libya. None of those mechanisms, however, exist on Itokawa.

Explanations for Itokawa's size segregation have focused on the Brazil nut effect, by which vertical vibration in the presence of gravity allows small grains to slip beneath larger ones and ratchet the largest bodies upward. That mechanism brings the largest in a bowl of mixed nuts—the Brazils—to the top. It also produces an Iowa farmer's largest crop: springtime boulders that must be cleared before planting. Those boulders were not dropped from above by space aliens; they rose from below after repeated cycles of frost heave and collapse.

On Itokawa, there is no frost heave, nor is there vertical vibration—indeed it is often unclear what vertical means on such a small and irregular gravitational body. Impacts from smaller asteroids could cause vibrations, but those would come from all directions and cause horizontal vibrations that, interestingly, make larger objects sink rather than rise. (See the article by Troy Shinbrot and Fernando J. Muzzio, *PHYSICS TODAY*, March 2000, page 25.)

Ballistic segregation

New research by my colleagues and me (see the additional resources) suggests an alternative explanation for Itokawa's size segregation. Itokawa is a rubble pile, which means that rubble—interplanetary crumbs—accumulates under its own gravity. Most of the crumbs are small: The total volume of pebbles on Itokawa is comparable to that of the boulders, but pebbles have on the order of 1/1000th the diameter of the boulders. So, conservatively, there must be well over a million pebbles

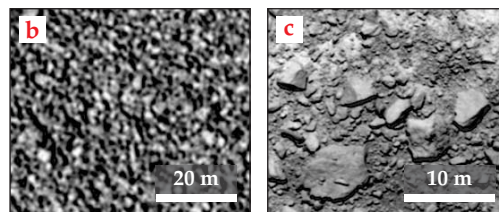
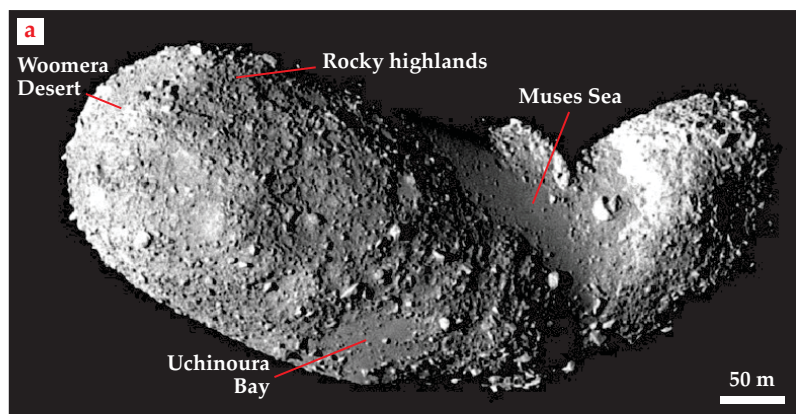
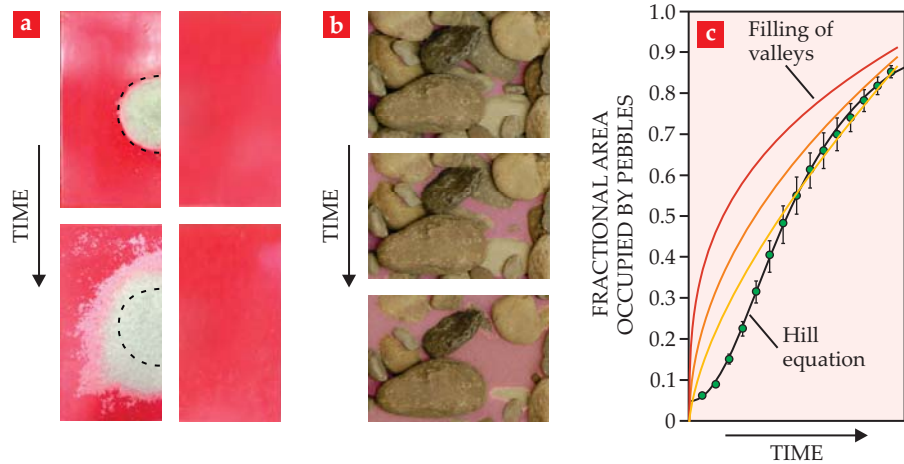


FIGURE 1. SIZE SEPARATION on the asteroid Itokawa. (a) The sandy Muses Sea lies adjacent to rocky highlands. The other landmarks honor important sites from the *Hayabusa* mission that photographed the asteroid's (b) Muses Sea pebbles and (c) rocky regions. (Courtesy of the Japan Aerospace Exploration Agency.)

FIGURE 2. BALLISTIC SEGREGATION

in simple experiments. **(a)** A red ceramic tile representing a large boulder has been uniformly sprinkled from above with small pebbles. When the tile has an initial accumulation of pebbles (left), the accumulation grows; when there is no initial accumulation (right), the pebbles bounce away and the tile remains clean. (The images show half of each tile.) **(b)** Uniformly sprinkling pebbles (pink) onto river rocks produces growing pebble seas in lowlands and leaves rocks in highlands. **(c)** The green data points showing the measured growth of the pebble seas are well fitted by the Hill equation (black curve) but not by models (colored curves) in which valleys of various shapes fill as pebbles flow downhill under the influence of gravity.



for every boulder, which means that the vast majority of collisions between the particles that made up Itokawa must have involved pebbles.

When a pebble hits a boulder, it bounces away. On the other hand, when a pebble hits other pebbles, it sinks in, because its impact energy is lost in numerous collisions. That is why sandbags are used to stop rifle bullets and why sand traps on golf courses are, well, traps.

A consequence of that basic observation may be a surprise: If you sprinkle pebbles onto a landscape containing both boulders and beds of other pebbles, the pebbles will bounce away from the boulders and will be absorbed into the beds. So beds of pebbles must grow while boulders remain bare, a result we call ballistic segregation. Figure 2a illustrates the process for the simplest possible landscapes, ceramic plates representing a boulder, with and without a small bed of pebbles. As we uniformly sprinkle pebbles onto both landscapes, the bed grows but the bare plate ejects almost all incoming pebbles and remains nearly pebble-free.

Ballistic segregation should obey a mathematical law called the Hill equation. Known to all physiologists but to few physicists, the equation earned Archibald Hill a share of the 1922 Nobel Prize in Physiology or Medicine for its accurate description of the “cooperative” way in which hemoglobin absorbs oxygen. Hemoglobin can change shape so that once some oxygen has been absorbed, more is readily bound; extant pebble seas absorb more pebbles through multiple collisions.

The Hill equation can be expressed as

$$F(T) = \frac{1 - F_0}{1 + (k/T)^n} + F_0,$$

where $F(T)$ is the fractional area of coverage by pebbles at time T , F_0 is the initial coverage, and k depends on material properties. The exponent n defines how cooperative a process is. For $n > 1$, modest accumulations of pebbles promote greater accumulations in the sense that $F(T)$ grows faster than linearly with time; for $n < 1$, the presence of pebbles inhibits further accumulation.

When we sprinkle pebbles onto random arrangements of stones such as shown in figure 2b, we find that small seas of pebbles grow according to the Hill equation, with $n = 2.15 \pm 0.06$, significantly cooperative. Figure 2c shows data from multiple experiments along with a fit to the Hill equation.

It may seem that pebbles simply flow downhill to fill valleys. However, we established quantitatively that this is not the case by calculating the surface areas exposed by a fluid flowing at constant rate into valleys of various shapes and comparing those with the area actually measured; figure 2c shows several examples.

The simple experiments illustrated in figure 2 show that the tendency of pebbles to bounce away from boulders and to be absorbed by beds of other pebbles causes a growth of sand seas that can be predicted both qualitatively and quantitatively. As with any reputable model, the ballistic separation idea raises at least as many questions as it answers. Sand seas have been seen on both the small asteroid Itokawa and the small comet Churyumov–Gerasimenko. Was that chance, or is the growth of sand seas generic? Is ballistic segregation involved in the formation of the small-particle ponds seen on the much larger asteroid Eros? Why aren’t sand seas observed on still larger bodies such as the Moon? As with all viable granular segregation models, ballistic segregation works well with two grain sizes, but real particles are broadly distributed in size, and no existing model accounts for how a realistic distribution of particles sorts so that particles of a particular size dominate.

We have some clues. For instance, the ballistic segregation hypothesis breaks down when the escape velocity of particles exceeds about 20 m/s (about 100 times Itokawa’s escape velocity, twice Eros’s, and 1/100th the Moon’s), because particles returning to the surface faster than that will shatter on impact. So we expect sand seas to predominate in smaller asteroids. For now, we will await reports from future missions to provide new answers, new surprises, and, ultimately, new questions.

Additional resources

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- H. M. Jaeger, R. R. Nagel, R. P. Behringer, “Granular solids, liquids, and gases,” *Rev. Mod. Phys.* **68**, 1259 (1996).
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