



Where was the biggest impact in the Solar System? **Rick Lovett** finds one candidate not too far from home.

# A lopsided planet

**M**ORE THAN FOUR billion years ago, Mars was hit by an asteroid. Nothing surprising in that: one look at the Red Planet's crater-pocked surface is enough to reveal the violence of its early history. But this wasn't your ordinary space rock – it was a dwarf planet, about the size of Pluto.

An asteroid that large can leave a serious dent in a planet. In this case, that dent is the Borealis basin, a giant lowland sprawling across most of Mars's northern hemisphere.

The basin is, quite simply, the dominant feature of the northern half of Mars. If Mars once had a large ocean, these were its abyssal depths. Not only is it huge – it is wider than Russia at over 10,000 km across at some points – but even the rocks are unique, with different magnetic signatures than are found elsewhere on the planet. Beneath the surface, the crust is different, too, only half as thick as the crust beneath the southern hemisphere's highlands. The result is so marked that the difference is often referred to as the 'crustal dichotomy', with the up to 6,000 m high rise between the lowlands and the highlands sometimes referred to as the dichotomy boundary. The Red Planet, it seems, is also the lopsided planet.

**THE IDEA THAT** the northern lowlands might be a humongous impact crater isn't new. American geologist Steve Squyres of Cornell University in New York (now the principal investigator on the Mars rover team) first proposed it in 1984. But the idea languished for one simple reason: the basin didn't look right.

Craters are usually circular. The basin isn't. Partly that's because a group of gigantic volcanoes – including Olympus Mons, the largest volcano known in the Solar System – sprawl across a large portion of the dichotomy boundary. The lava clearly erupted at a later date, and there's an enormous amount of it. The entire volcanic region, known as the Tharsis rise, is several times the size of Australia, with the highest peaks soaring more than 30,000 m above the basin floor. Looking at a topographic map, it's nearly impossible to figure out where the original dichotomy boundary might have lain.

East of the Tharsis rise is another complication: a broad swathe of hills, craters, and canyons that also overlays the original dichotomy boundary. Called Arabia Terra because it's shaped roughly like the >>

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>> Arabian Peninsula, it confuses yet another segment of the boundary with a 1,000-km-wide terrace of much gentler slope.

For years, therefore, most scientists discounted the giant-impact hypothesis. Instead they offered theories ranging from a series of overlapping impacts (large but not gigantic) to tectonic processes. Of these, the multiple-impact theory was the simplest ... but least satisfying. "Not only does [it] complicate an otherwise elegant solution, but there is an uncomfortable lack of evidence for individual, overlapping impact basins," says Mark Hammergren, an astronomer at Chicago's Adler Planetarium.

Uncertainty about the precise boundary wasn't the only problem with the impact theory. How could an impact that big

not melt the entire surface of the planet, producing an ocean of magma that would obscure all traces of what had occurred?

Also, scientists thought an impact that large would produce a crater with an elevated rim. But the dichotomy boundary rises no higher than the highlands beyond.

**THEN, IN 2008**, a trio of papers in a June issue of *Nature* changed the game.

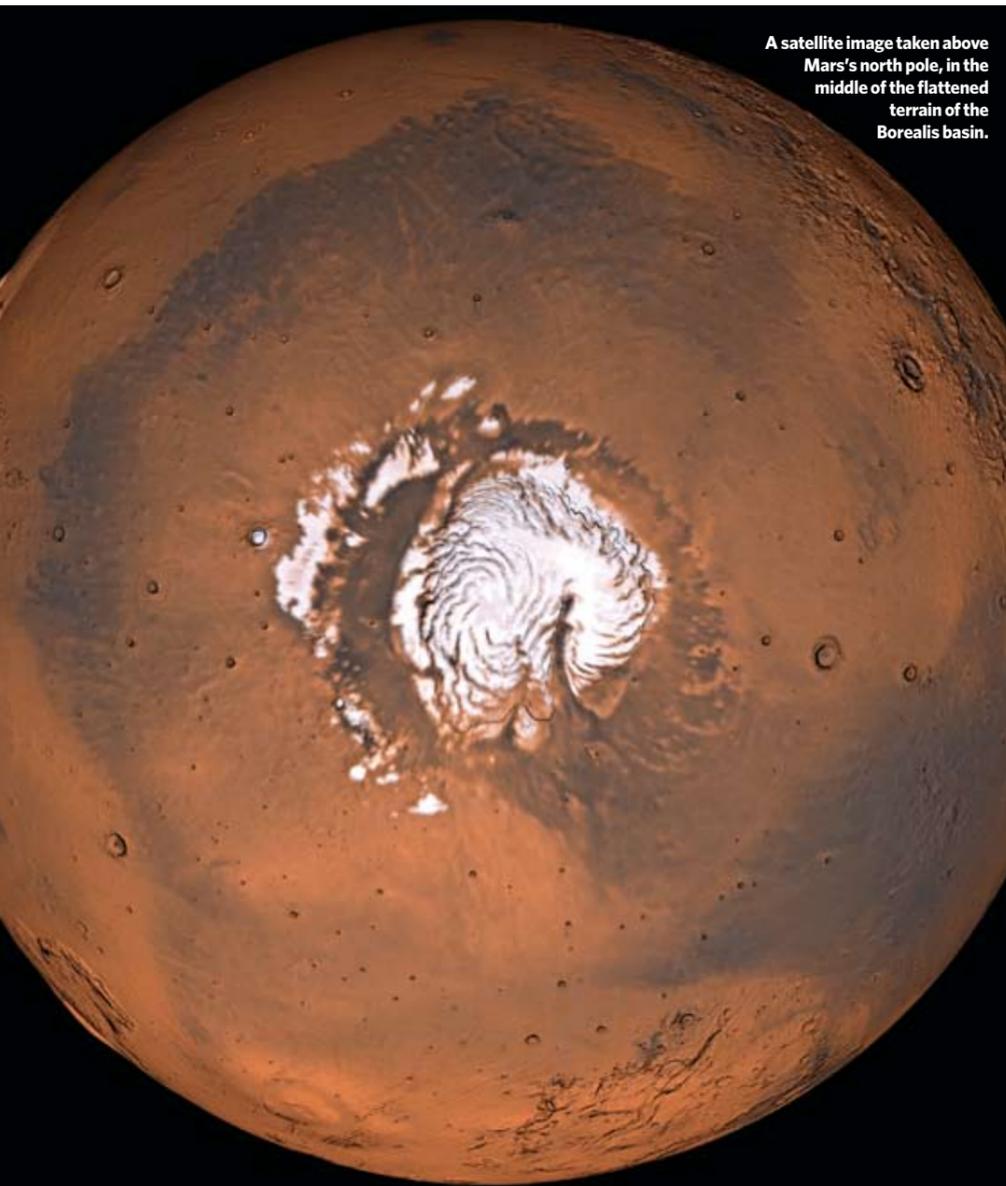
In one, a team led by planetary scientist Jeffrey Andrews-Hanna, then at Massachusetts Institute of Technology in Boston, used satellite measurements of the Martian gravity field to study the thickness of the crust beneath the Tharsis volcanoes.

"If you just look at the topography, all you can see is the surface," he says. "But if

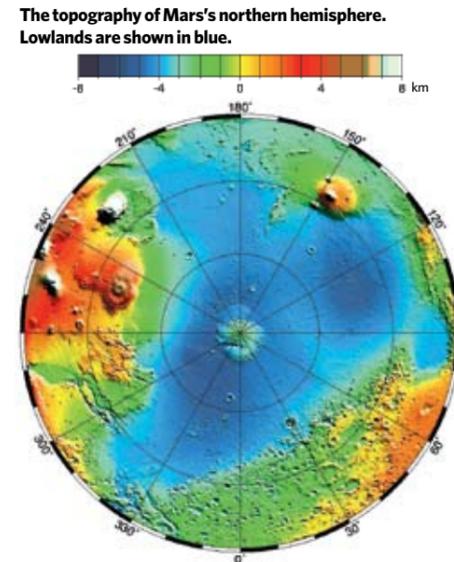
you look at the gravity field you can probe the subsurface. By analysing the gravity and topography simultaneously we are able to distinguish between the Tharsis rise and the topography buried beneath it."

This let Andrews-Hanna's team find the crustal thinning that marks the dichotomy boundary, tracing the Tharsis segment of it for the first time. "It was actually very smooth and gently curving," he says.

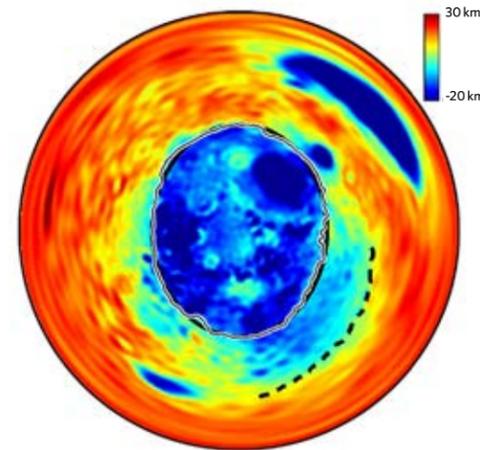
Arabia Terra was now also less of an obstacle. On one side, it had always been clear where the original boundary's exit point from Arabia Terra lay – on that part of Mars, the boundary is a dominant feature of the terrain. But now, its entry point was also known on the Tharsis side. All that was needed was to connect the dots.



A satellite image taken above Mars's north pole, in the middle of the flattened terrain of the Borealis basin.



Mars's crustal thickness viewed from above the centre of the Borealis impact. The crater's boundary is traced and the dotted line shows Arabia Terra's southern edge.



NASA/MOLA / NASA-JEFFREY ANDREWS-HANNA, M. MARINOVA, O. AHARONSON, E. ASPHAUG / CALTECH, UCSC

create a crater and [watch] waves 100 km in size ripple through the planet."

The final score? Impact theory: 3 and competing theories: 0.

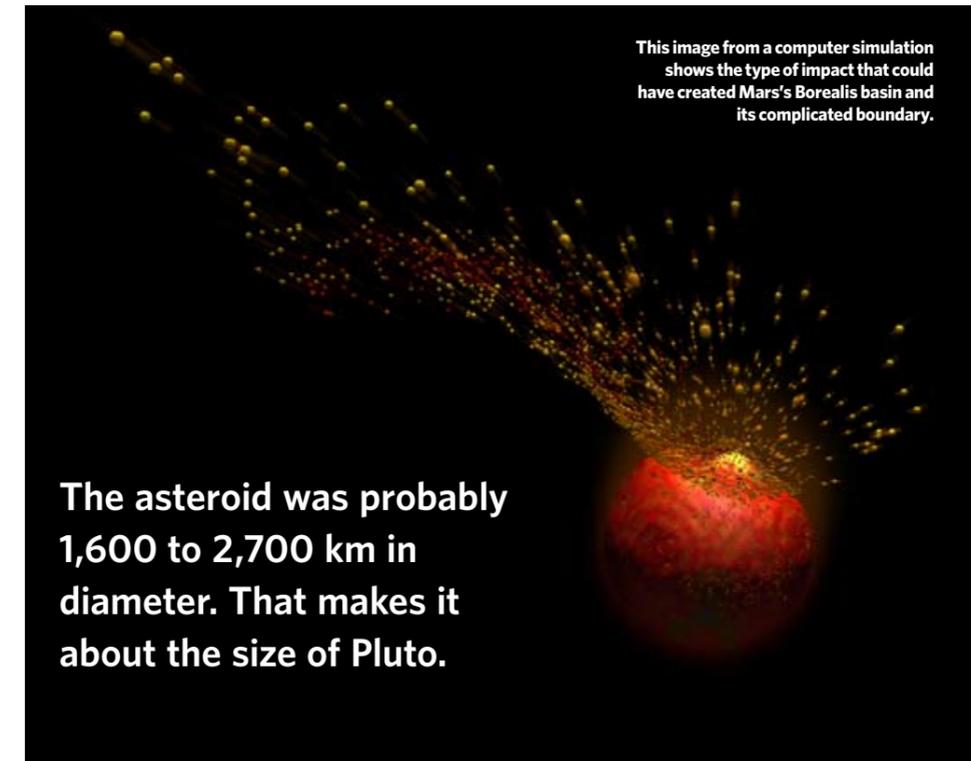
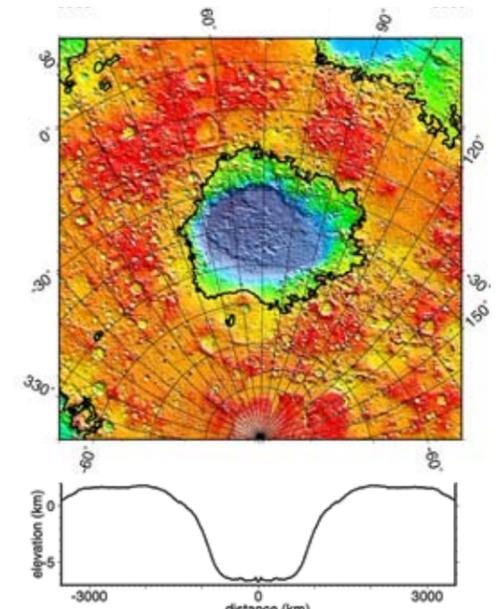
**OTHER SCIENTISTS WERE** impressed.

Such an impact wouldn't have been bizarre, Hammergren notes. "Early in the formation of the Solar System there was a substantial population of large impactors, and many would have shared Mars's orbit."



Prior to the finding that the Borealis basin was caused by a single impact, our Moon's South Pole-Aitkin basin (above) and Mars's Hellas basin (right) were tied as the largest impact crater in the Solar System at around 2,500 km wide - just over a quarter of Borealis's width.

But that wasn't all. Aharonson's team also found that the 'sweet spot' impact wouldn't have created the elevated rim expected by prior theorists. And Nimmo's team predicted that shock waves from the impact would travel around the planet and converge on the opposite side, disrupting that part of the crust's pre-existing magnetism. (Something similar has been seen on the sides of the Moon and Mercury opposite from big impact craters.) That's >>



This image from a computer simulation shows the type of impact that could have created Mars's Borealis basin and its complicated boundary.

The asteroid was probably 1,600 to 2,700 km in diameter. That makes it about the size of Pluto.

At first the boundary still seemed odd-shaped – something like a giant S-curve or sine wave. Then the scientists thought to look at it from a different angle: straight down from above the Martian pole, which lies near the basin's centre. They saw a much simpler shape: a giant ellipse, 10,600 km long by 8,500 km wide.

"There is only one process we know of that will produce giant ellipses like this, and that's a giant impact," Andrews-Hanna says. "The [other] largest impact basins in the Solar System, Hellas impact basin on Mars and the South Pole-Aitkin basin on the Moon, are elliptical."

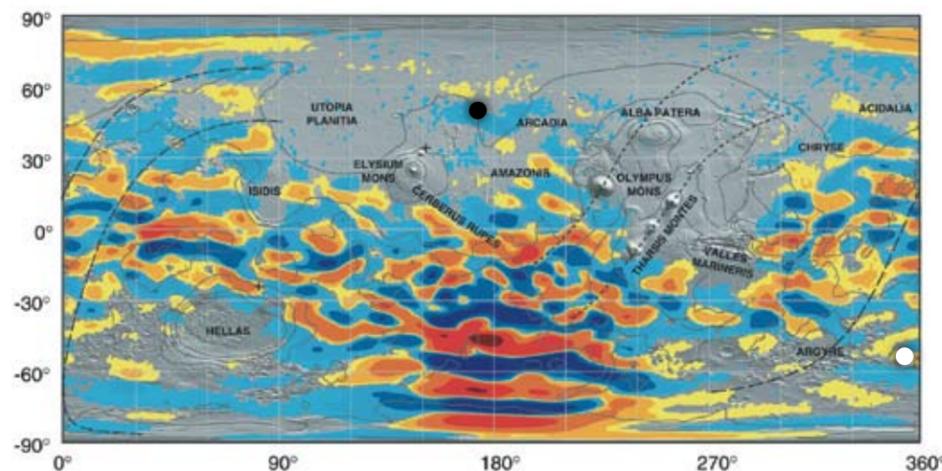
The reason lies in a combination of spherical trigonometry and impact angles. Small craters are indeed round. Large ones, if the impactor hits at an angle, can be elliptical. It's a natural consequence of a large rock angling in toward a spherical planet. "We would not expect the circular pattern smaller craters have," says Walter Kiefer, a planetary scientist at the Lunar and Planetary Institute in Houston, Texas.

**IN A SECOND** paper in the same issue of *Nature*, a team led by Oded Aharonson – a planetary scientist at California Institute of Technology in Los Angeles – modelled the impact that could have created the basin without destroying the Southern Highlands.

"The impact would have to be big enough to blast the crust off half the planet, but not so big that it melts everything," says Francis Nimmo, a planetary scientist at the University of California, Santa Cruz.

It wasn't a calculation that could have been done when Squyres first proposed the impact hypothesis. The computers of that era simply weren't up to it. But now, after cranking 500 simulations of impactor size, velocity and impact angle through a supercomputer, Aharonson's team found that the asteroid was probably 1,600 to 2,700 km in diameter, striking at an angle of 30 to 60 degrees. That makes it half to two thirds the size of the Earth's Moon. It was also relatively slow moving, striking at a speed between six and 10 km per second.

The calculations are highly technical. "You treat the planet as a fluid and give it the properties of rock and iron," explains Craig Agnor, a planetary scientist at Queen Mary University of London, Britain. Along with Nimmo, he coauthored the third study, which used a different model to confirm Aharonson's findings. "You can watch the materials of the planet flow to



A map of Mars's magnetic field. The dark blues and red represent a strong magnetic field, while the grey regions have a weak magnetic field. The black dot is the Borealis basin's centre of impact and the white dot shows the opposite point on the planet. Both regions have unusually weak magnetic fields.

>> interesting, because the Martian magnetic field is anomalously weak in that area.

He explains by comparing the crust's magnetic field to a bunch of arrows painted on the rocks – each marking the direction of the magnetic field at the time that bit of rock solidified. Initially, these arrows all point the same way. Then, the shock wave hits, scrambling them. “They reassemble with the arrows pointing in random directions,” Agnor says. Rather than reinforcing each other, arrows now offset each other, reducing overall magnetism.

“We haven't proved the giant-impact hypothesis,” Andrews-Hanna told *The New York Times* “but I think we've shifted the tide.”

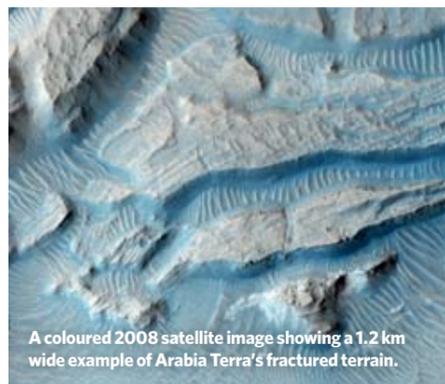
Kiefer agrees. Yes, the case isn't proven. But “[they] have answered many of the objections around the impact model.”

**THE TIDE CONTINUES** to shift. In a paper at the 2010 Lunar and Planetary Science Conference, in a suburb of Houston, Texas,

## Shock waves from the impact would travel around the planet and converge on the opposite side, disrupting that part of the crust's pre-existing magnetism.

Andrews-Hanna (now at the Colorado School of Mines in Golden, Colorado) turned his attention to Arabia Terra.

What, he wondered, created it? Could the impact have been involved here, too? Clues came from the fact that Arabia Terra's broad, relatively gentle slopes separate two steeper escarpments. One, on the basin side, falls rapidly to the bottom of the lowlands. The other, on the south



A coloured 2008 satellite image showing a 1.2 km wide example of Arabia Terra's fractured terrain.

side, makes the final 3,000 m rise to the highlands. The two slopes are parallel to each other, about a 1,000 km apart, like a pair of giant steps separated by a wide, slightly tilted platform.

Thinking about this, Andrews-Hanna came to a startling conclusion: Arabia Terra

represents an enormous landslide in which millions of square kilometres of land slid partway into the basin.

Suddenly, he realised something that had been troubling him. “One characteristic of the largest impact basins on all of the planets is that they are surrounded by a bull's-eye pattern of rings, with a regular and predictable spacing,” he says. “The southern edge of Arabia Terra lies where

Olympus Mons is part of the Tharsis rise region that masked the crater boundary of the Borealis basin.



one would predict one of these rings to be.” Furthermore, the terrace-like middle section is consistent with what is seen in other large multi-ring structures.

But the multiple rings don't extend all the way around the Borealis basin. On topographic maps, they're visible only in Arabia Terra – extending only one quarter of the way around the basin.

Other multi-ring structures, however, are also incomplete, particularly the one around the Moon's 2,500 km South Pole-Aitkin basin. Perhaps that's a clue to the angle at which the asteroid came in. Or some form of seismological focussing of the impact's shock waves.

What's interesting is what the topography tells us about how Arabia Terra – and perhaps other such terraces – was formed.

One critical clue lies in the way the inner scarp lines up with the rest of the dichotomy boundary. Or rather, the way it doesn't line up. It appears to be offset about 300 km into the basin, suggesting

PHOTOLIBRARY: NASA; FRANCIS NIMMO



Mars is home to the Solar System's largest canyon, Valles Marineris (pictured). It seems it may also house the largest impact crater.

that the entire terrace is the remnant of a gigantic landslide. If so, it would have been the Solar System's largest known landslide – the equivalent of shifting most of Australia 300 km northward.

Most landslides occur on the surface, where rocks tumble, drop or slide downslope. But gravity measurements indicate that in Arabia Terra, the deeper rocks seem to have shifted farther into the crater than the surface ones. What this means, Andrews-Hanna says, is that the landslide appears to have occurred deeper, where the rocks are weaker and more able to slide. The surface rocks were merely dragged along with them.

How quickly did this occur? Possibly very rapidly. On the Moon, Andrews-Hanna says, one similar landslide may have occurred so rapidly it was complete before material blasted out of the crater even had time to hit the ground. “On the other hand,” he says, “things might happen more slowly with a giant basin like Borealis.”

A landslide, however, isn't the only way the impact might have created Arabia Terra's terrace. James Head III, a geophysicist at Brown University in Providence, Rhode Island, thinks it might instead have been a ‘rotational slump’ – where a large block of crust broke from the Southern Highlands as a result of the impact. The southern side dropped, forming the southern escarpment, while the northern side rose, like the opposite end of a giant see-saw, thereby forming the northern escarpment.

But either way, Head and Andrews-Hanna agree that it is likely that the northern lowlands, the dichotomy boundary, Arabia Terra and the Southern Highlands were all formed virtually instantaneously, as the result of a single event. “It certainly wasn't a good time to be a Martian,” Andrews-Hanna jokes.

## It would have been the Solar System's largest known landslide, the equivalent of shifting most of Australia 300 km northward.

**WHEN THE FIRST** Viking photos were returned from Mars in the 1970s, the Red Planet was revealed as a world of superlatives. It had the Solar System's tallest known volcano (Olympus Mons) and the largest canyon (Valles Marineris). Now, it appears that we can add to that the largest known impact basin – a full four times larger than the two prior candidates: Mars's Hellas basin (which punches a deep hole in the Southern Highlands) and the Moon's South Pole-Aitkin basin, roughly tied at 2,300 to 2,500 km in diameter.

“Imagine an impact stripping half the crust from the northern hemisphere of Mars,” Hammergren notes. “That's big.”

But even that may not truly have been the Solar System's largest-ever impact. There is mounting evidence that all four inner planets were at some point clobbered just as hard, if not harder.

Mercury, for example, seems to have too much iron core (or too little rocky mantle) for its size. One theory is that it got hit by something huge: big enough to blast most of the mantle into space.

Likewise, Venus has an unusual rotation. Not only is it very slow, at once every 243 Earth days, but it spins in the opposite

direction to every other major body in the Solar System. This, some scientists think, may be the result of another massive impact that killed its youthful spin.

Finally, current theories of the Moon's origin suggest it was formed from debris created when Earth collided with an asteroid the size of Mars.

“This is how planets finish their business of formation,” says Erik Asphaug, a professor of Earth and planetary sciences at the University of California, Santa Cruz, who was part of Aharonson's team. “They collide with other bodies of comparable size in gargantuan collisions. The last of those big collisions defines the planet.”

“These impacts were incredibly devastating,” Andrews-Hanna adds. “But without them we wouldn't have the terrestrial planets we see today.”

Rick Lovett is a science writer in Portland, Oregon.