GRAIL

BENEATH THE SURFACE

Two probes have mapped the Moon's gravity in unprecedented detail. **Paul Sutherland** investigates their findings

A little over a year after the GRAIL probes were deliberately crashed into the surface of the Moon, scientists have used the data they collected to produce the most detailed picture of its interior ever.

Ebb and Flow, the twin probes that made up the GRAIL (Gravity Recovery and Interior Laboratory) mission, spent nine months in lunar orbit. During this time they measured variations in the Moon's gravitational 'pull', in a bid to learn more about how our natural satellite formed and what its composition is.

The spacecraft, each the size of a small washing machine, were able to detect changes in the distance between themselves with extraordinary precision – just a few thousandths of a millimetre – leading to the discovery that the Moon's gravity field is highly uneven. Lunar basins, craters and mountain peaks were all studied in greater detail than ever before. But Ebb and Flow also mapped the large invisible regions that have so much gravitational pull they can influence spacecraft in lunar orbit. The presence of these regions explains why probes circling the Moon have been seen, seemingly for no reason, to veer off their prescribed course.

On the double

Launched in September 2011, the GRAIL probes took more than three months to travel to the Moon and spent another two getting into orbits where they could map lunar gravity in tandem. From March until May 2012, Ebb and Flow carried out their primary mapping mission, flying in near-circular orbits from pole to pole at an altitude of around 55km. The mission entered a second phase in August 2012, when the probes were dropped to an altitude of 23km – so low that the mission team had to keep making adjustments to stop them from being knocked off course and crashing.

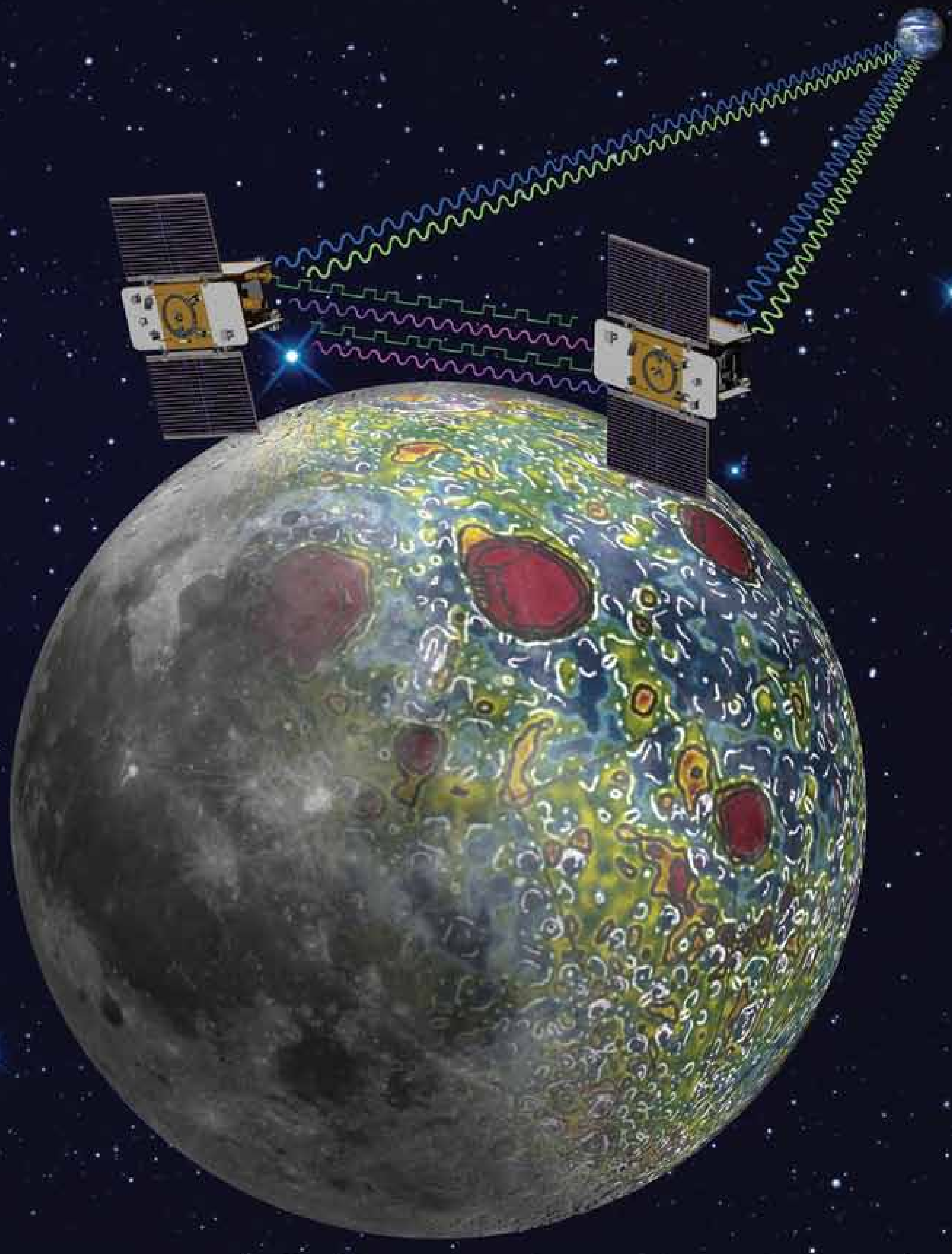
GRAIL's readings would vary as the probes flew, sometimes due to obvious surface features, such as flying over a crater in the ground, where the pull weakened, or over a mountain range, where it would increase. But as they circled the Moon, they also acted as a cosmic X-ray machine, scanning beneath the surface. ▸

NASA/JPL-CALTECH, NASA/JPL-CALTECH/MIT

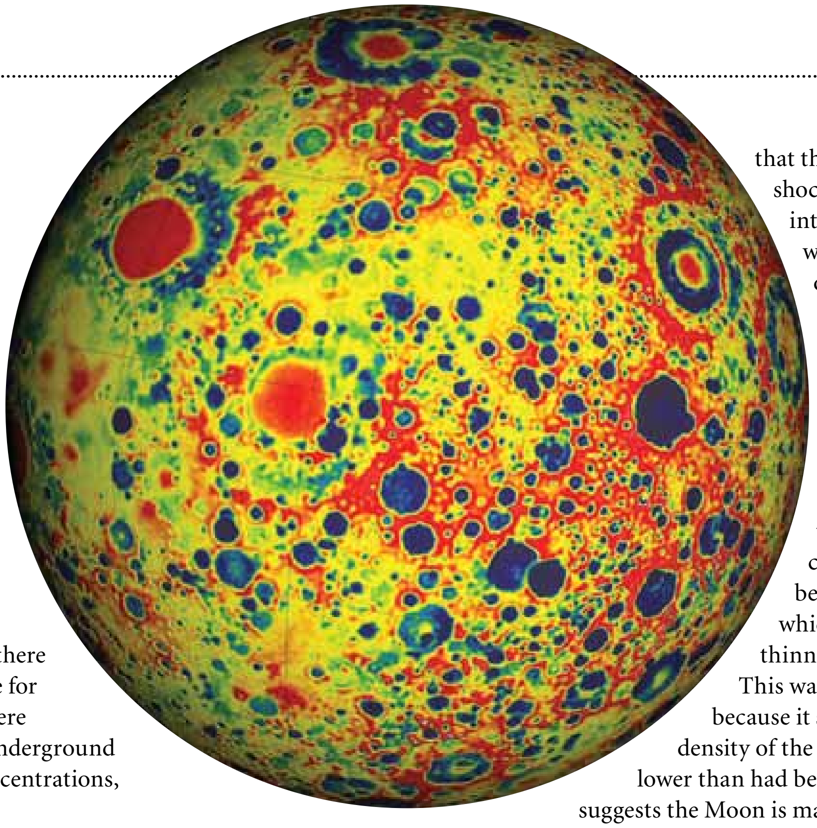
HOW DID **GRAIL WORK?**

The GRAIL mission involved placing twin probes a short distance apart in the same orbit around the Moon. Flying together over mountains, craters and hidden underground features, they moved slightly towards and away from each other due to the varying gravitational pull. An instrument on board each probe, called the Lunar Gravity Ranging System, was able to make highly precise measurements of the reactive changes in their velocities. From this data, mission scientists were able to produce a detailed map of the Moon's gravitational field in extremely high resolution.

GRAIL's lunar studies essentially mirrored the work of another pair of satellites called GRACE (the Gravity Recovery And Climate Experiment) which have been orbiting the Earth since 2002 to map our own planet's gravitational field.



GRAIL's synchronised flying formation was the key to its ability to collect data



▸ Most of the gravitational anomalies detected by GRAIL were due to the patterns of features on the lunar surface. But a small number of these fluctuations – around two per cent – came from the effect of features beneath it. The results gave scientists an unprecedented insight into the internal structure of the Moon and what it was made of. For example, strong gravitational pulls were found in areas where there was no topographical cause for them. Instead, the forces were produced by large, dense underground regions known as mass concentrations, or mascons for short.

Planetary scientists believe that the mascons are the result of impacts from giant asteroids smashing through the Moon's thin crust. These features give us glimpse about four billion years into the Solar System's past, when the Late Heavy Bombardment rendered our cosmic backyard something akin to a shooting gallery.

The previously hidden mascons clearly stand out on GRAIL's lunar gravity map as they resemble the bullseye on a dartboard. Scientists think that the asteroid impacts sent shockwaves through the lunar interior that reverberated within the crust and drew dense material from within the lunar mantle that lies beneath the crust – creating the telltale ringed pattern.

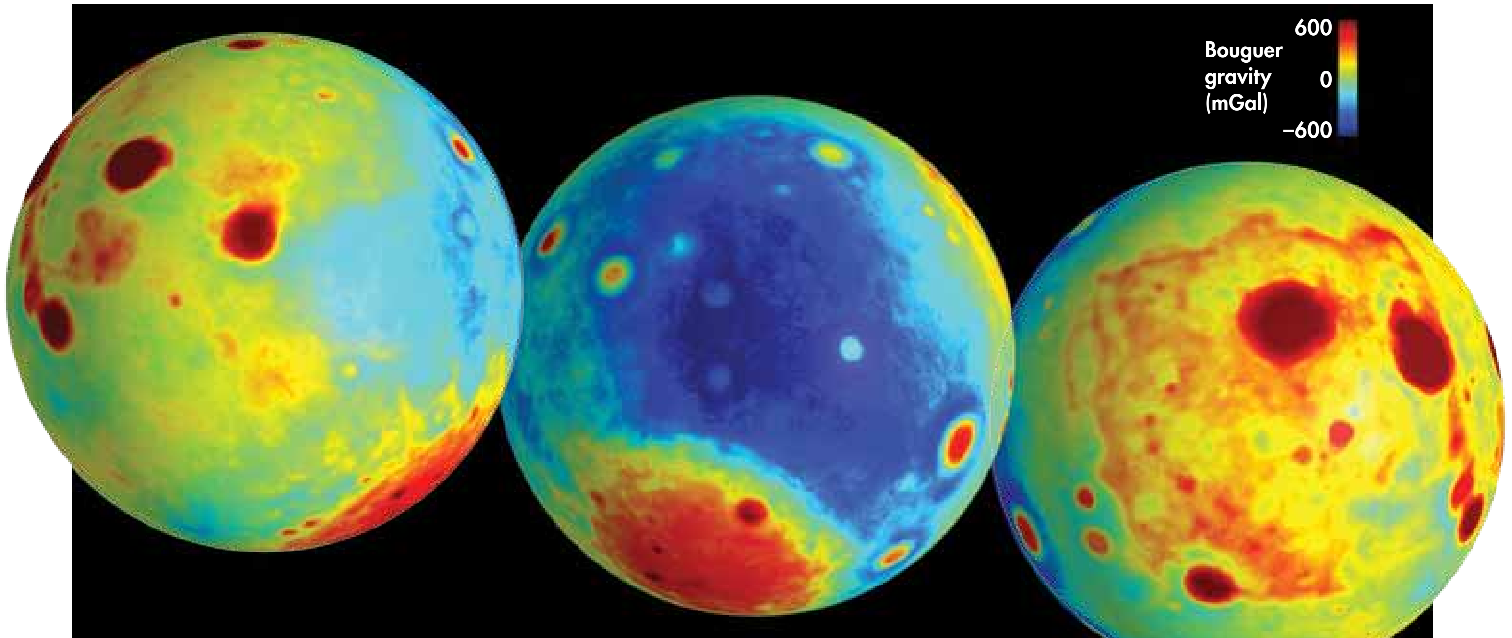
▲ **The mascons appear as concentric 'bullseyes' in GRAIL's gravity map of the Moon**

Crust patterns

GRAIL data also revealed that the average global crustal thickness is between 34 and 43km, which is about 10-20km thinner than had been thought. This was an important result because it showed that the general density of the highland crust is much lower than had been generally believed and suggests the Moon is made up of much the same material as the Earth, which in turn supports the idea that the Moon formed from material ejected when Earth was struck by a giant body the size of Mars early in the Solar System's history. Mission scientists also learned that the crust was porous and had been smashed up to a depth of several kilometres, a feature they now believe to be common to all terrestrial planets.

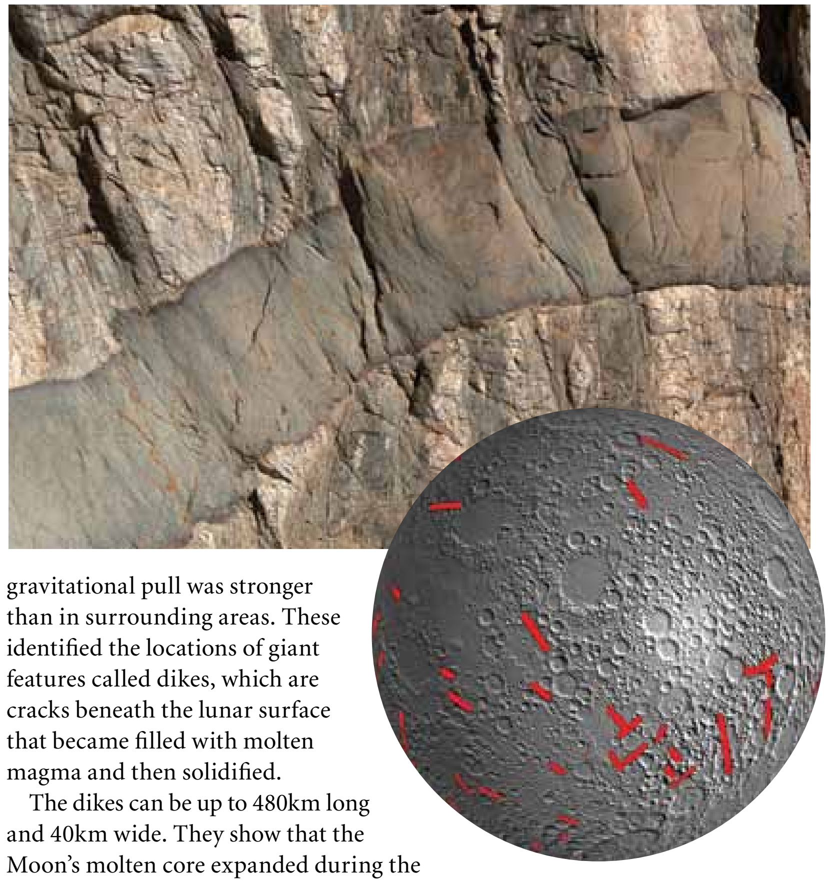
As well as mascons, GRAIL discovered several linear patterns in its gravity map where the gravitational pull was stronger than in surrounding areas. These identified the locations of giant features called dikes, which are cracks beneath the lunar surface that became filled with molten magma and then solidified.

NASA/JPL-CALTECH/MIT/GSFC, NASA/JPL-CALTECH/CSM X 3, MARLI MILLER/VISUALS UNLIMITED/ SCIENCE PHOTO LIBRARY, NASA/GSFC/ASU, NASA/GSFC/ARIZONA STATE UNIVERSITY



UNDERLYING GRAVITY

The colourful images of the Moon produced using GRAIL data are examples of Bouguer maps, which show regions of different gravitational pull once the effects of surface features such as mountains and craters have been removed. In the absence of topographical influences, only Bouguer gravity remains, revealing mass anomalies within the Moon. These patterns, highlighted in false colours for clarity, show the locations of such features as mascons and dikes. They also reveal differences in the thickness of the lunar crust across the Moon and variations in the density of the crust and mantle. Regions of stronger gravity are red, weaker areas blue. The prominent red circular blobs indicate the presence of the mascons produced by giant impacts.



▲ **Dikes exist on Earth – the top image is from the US; GRAIL found their lunar cousins, in red above**

The dikes can be up to 480km long and 40km wide. They show that the Moon's molten core expanded during the first billion years of its history, just as planetary modellers had predicted, and the Moon became as much as 10km greater in diameter.

Grasping gravity

The lack of tectonic activity on the Moon means that it has changed little over billions of years, making it a relic from the early Solar System. GRAIL's treasure trove of data, therefore, can help scientists learn about the formation of planets outside our own Earth-Moon system. Space probes have detected mascons beneath impact basins on Mars and Mercury too, and so information about the lunar examples will give researchers some understanding about how they have altered the crusts of other rocky worlds. When astronauts eventually return to the Moon, the GRAIL data will help them calculate how much energy will be needed to scale mountains or crater walls.

"The GRAIL mission to measure the gravity field of the Moon was a resounding success and exceeded our expectations," says Dr David E Smith, GRAIL's deputy principal investigator. "The two prime reasons that led to this success were the very high accuracy of the GRAIL measurements and the very low altitude above the lunar surface from which the measurements were made. Together, they enabled us to derive the gravity field of the Moon with unprecedented accuracy and with very high surface resolution."

Smith says the mission has improved scientists' understanding of lunar gravity by several orders of magnitude. They have now measured the gravity field's resolution at the surface to 5-10km, compared with 80-100km previously.

"GRAIL has enabled us to see into the crust and derive the change in crustal density and porosity with depth," he adds. "We are seeing features below the crust that have no manifestation on the surface and are believed to have originated very early in lunar history.

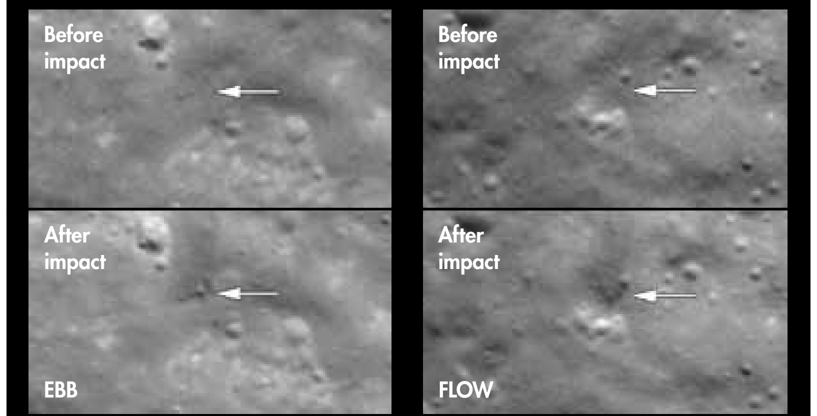
"While we continue to study the crust of the Moon we are beginning to look carefully at the GRAIL data for gravity signals from the lunar interior that can provide information about the lunar core, tides and the mantle."

The science team believe the way to build on GRAIL's success is to send a spacecraft to land on the Moon to study its interior and return lunar samples to Earth. "The next steps in understanding the surface of the Moon should probably come from a lander that returns a sample to Earth," Smith says. "For the interior, we really need seismic measurements from several points on the lunar surface. Tentative plans are being developed for both ideas while not ignoring the desire to understand the presence of water ice at the lunar poles. There is much to be done!"

ABOUT THE WRITER

Paul Sutherland is a space journalist, and the author of *Where Did Pluto Go?*. Each month he reports on the latest space research in *What I Really Want to Know* on page 106.

THE DEMISE OF GRAIL



▲ **New craters can be seen at the crash sites of both GRAIL probes after impact**

On 17 December, 2012, after firing their thrusters a final time to use up fuel, Ebb and Flow were both crashed deliberately into a 2.4km-high peak near the lunar north pole. This dramatic finale to the mission was designed partly to avoid them coming down randomly on a NASA heritage site, such as where the Apollo missions landed, but also to extract further useful gravitational data from the descent. The collisions occurred at 6,050km/h, close to crater Goldschmidt. They took place in darkness, but streaks of ejecta plus small new craters formed by the impacts were later imaged by the Lunar Reconnaissance Orbiter. The crash zone was named the Sally K Ride Impact Site after the first US woman in space, who died earlier that year.