How the Moon arose has long stumped scientists, and rocks brought back in the 1970s deepened the mystery. Now Dutch geophysicists argue that it was created not by a massive collision 4.5 billion years ago, but by a runaway nuclear reaction deep inside the young Earth, as **Marcel Crok** reports.

BIRTH OF THE MOON

2MASS/UMASS/IPAC-CALTECH/NASA/NSF

IT HAPPENED 4.5 BILLION YEARS AGO, when the Earth was barely 50 million years old. Life didn't exist; the planet was a violent, boiling fireball. Then, without warning, the unimaginable happened. Deep within the core, a tremor started. The young Earth shuddered and erupted. From its bowels spewed a trillion-tonne column of molten and vaporised rock. On this day the Moon was born.

In his renovated Saxon farmhouse in Peize in the north of the Netherlands, retired nuclear geophysicist Rob de Meijer vividly paints a picture of the cataclysm: "The material in the Earth's mantle heated up some 8,000ºC and was completely vaporised. This huge bubble of gas forced itself up through the still liquid mantle," he says. "As a result, part of the Earth's mantle and crust were blown away, as well as the early atmosphere. From the debris, the Moon could have formed rather quickly."

The Earth ejecting the Moon: isn't that a rather fanciful scenario? Not according to de Meijer and his colleague, petrologist Wim van Westrenen from the Free University in Amsterdam. They argue that this hypothesis is the logical consequence of new data, and also that an erupting Earth solves a number of unsolved and profound astronomical mysteries.

Weighing in heavily against the theory, though, is the fact that over the last few decades, scientists have reached consensus on a very different hypothesis for the origin of our Moon. According to that scenario, the young Earth was hit some 4.5 billion years ago by a primordial celestial body the size of Mars.

That impact would have been 100 million times as powerful as the meteorite impact that ended the age of dinosaurs 65 million years ago. The heat of such an impact would have vaporised a large part of the Earth's crust and mantle. Under this scenario, the impacting behemoth burrowed deep into the Earth, only to bounce back again. ››

›› Yet escape was out of the question. The core of the celestial body, rich in iron, was swallowed by the much heavier Earth and sank to its centre. The remainder was flung out to space, together with vast quantities of terrestrial debris, where it ended up in orbit around the Earth. In less than 100 years, this debris then accreted into our Moon.

Today, most scientists agree this 'impact hypothesis' is the most likely chain of events. The case was considered more or less closed in 2003 after geophysicists presented computer simulations which showed that a Mars-sized impactor could indeed deliver a Moon with the correct size and orbit.

But with their outlandish new hypothesis, de Meijer and van Westrenen are rocking the boat all over again.

ALREADY THE BASIC ASSUMPTION of de Meijer's theory is controversial – the concept that powerful, spontaneous nuclear chain reactions occured deep inside the Earth.

It all started 50 years ago in a study in the journal *Chemical Physics*, when Japanese geochemist Paul Kuroda conjectured that natural nuclear reactions happen in the Earth, in so-called 'georeactors'. He argued that early in Earth's history, many radioactive elements were still naturally 'enriched', because their spontaneous decay had only just started.

Kuroda's idea was controversial until 1972, when French researchers found the defunct remnants of a natural reactor in Gabon in Western Africa. This reactor, near the surface, was probably extinguished two billion years ago by lack of water, which is necessary to moderate the speed of the neutrons that cause uranium fission.

American geophysicist J. Marvin Herndon was one of those who concluded that, even now, the Earth's core still holds a giant georeactor. De Meijer has serious doubts about this, like many geochemists. After all, uranium and thorium – the natural ingredients required for a georeactor – scarcely mix with iron, the main ingredient of the Earth's core. But that doesn't mean that a georeactor deep within the Earth is ruled out, he says. Recent publications hint that the convoluted boundary between core and mantle, the D′′-layer (D-double-prime layer), would be an ideal location for a georeactor.

"This boundary layer must have been in place 4.5 billion years ago," says de Meijer. "Such georeactors might still be in existence now, without us noticing."

He took his idea further by collaborating with van Westrenen, with whom he is co-authoring a book on the interior of the Moon and Earth.

The origin of our Moon has been a mystery for centuries – compared to other moons in the neighbourhood, ours is anomalously large relative to its planet, but its density is low.

"When he told me about it for the first time...I was extremely sceptical," van Westrenen told me as we sat in his university office. "This would take me only two minutes to refute," I thought. "[But], I still can't debunk his story. That makes it interesting enough to work on and see how far we can take it."

THE ORIGIN OF THE MOON has been a mystery for centuries, mainly because our long-time celestial companion is the odd one out in our Solar System. Compared to other moons in the neighbourhood, our Moon is anomalously large relative to its planet (see p72 graphic). On the other hand, its density is rather low, suggesting it contains much less iron than Earth. The core of the Moon contains just four per cent of its total mass, whereas the Earth's core contains 30 per cent.

Before man set foot on the Moon almost 40 years ago, there were still three theories to explain its origin. The first stated that the Moon, like the Earth, was the result of the accretion of cosmic dust into ever more massive chunks. The second argued that the Moon formed elsewhere in space and was later captured by Earth, without impact. Under the third hypothesis, the primordial Earth was spinning so fast that the matter that formed the Moon flew from Earth, by the apparent centrifugal force.

This last one, the 'fission hypothesis', was proposed as early as 1880 by George Darwin, son of the famous father of evolution, Charles Darwin. As evidence, he put forward the Pacific Ocean. This gaping hole, he suggested , was visible evidence that a large mass was missing from the Earth.

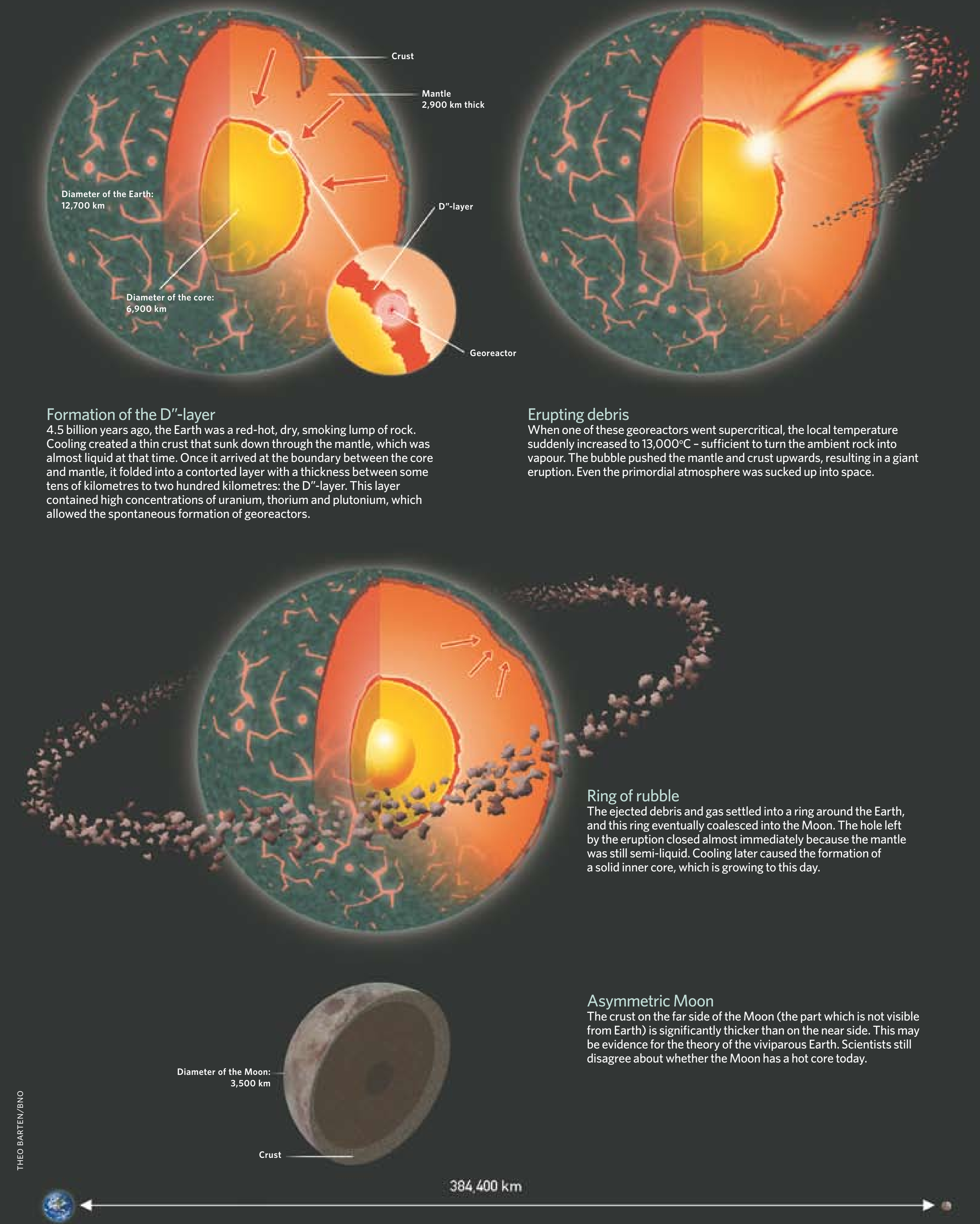
It didn't take Apollo missions to refute Darwin's idea. The discovery of plate tectonics provided a more plausible explanation for the Pacific Ocean. Also, around 1930 other scientists calculated that although a day would have lasted just 2.5 hours, the early Earth was spinning too slowly to eject so much matter. "The centrifugal force was insufficient for a Moon to escape," says de Meijer.

One of the purposes of the Apollo missions was to gain more insight into the origin of the Moon and to help arbitrate between the two remaining hypotheses. But an analysis of the Moon samples brought back to Earth led to the conclusion that neither hypothesis could be correct.

"The density of the Moon turned out to be much lower than the Earth's density," says van Westrenen. "That excludes the accretion model, which says that the Earth and the Moon were formed from the same primordial material. [They] are simply too different."

Paradoxically, the second hypothesis – that the Moon was formed elsewhere in the Solar System and later captured – was excluded for exactly the opposite reason.

"In that respect, the Earth and the Moon are too similar," adds van Westrenen. "The ratio of isotopes oxygen-17 and oxygen-18 are identical in terrestrial and lunar rock, and deviates strongly from the isotope ratio in meteorites from Mars." These isotopes carry information about the distance from the Sun the rock formed, and indicate that the Moon and Earth must have formed at roughly the same distance. ››



Formation of the D′′-layer
4.5 billion years ago, the Earth was a red-hot, dry, smoking lump of rock. Cooling created a thin crust that sunk down through the mantle, which was almost liquid at that time. Once it arrived at the boundary between the core and mantle, it folded into a contorted layer with a thickness between some tens of kilometres to two hundred kilometres: the D′′-layer. This layer contained high concentrations of uranium, thorium and plutonium, which allowed the spontaneous formation of georeactors.

Erupting debris
When one of these georeactors went supercritical, the local temperature suddenly increased to 13,000°C – sufficient to turn the ambient rock into vapour. The bubble pushed the mantle and crust upwards, resulting in a giant eruption. Even the primordial atmosphere was sucked up into space.

Ring of rubble
The ejected debris and gas settled into a ring around the Earth, and this ring eventually coalesced into the Moon. The hole left by the eruption closed almost immediately because the mantle was still semi-liquid. Cooling later caused the formation of a solid inner core, which is growing to this day.

Asymmetric Moon
The crust on the far side of the Moon (the part which is not visible from Earth) is significantly thicker than on the near side. This may be evidence for the theory of the viviparous Earth. Scientists still disagree about whether the Moon has a hot core today.

Impact theory

The formation of the Moon according to the giant impact theory. This is the most widely accepted theory of the Moon's formation. It says that an object about the size of Mars collided with the Earth around 4.6 billion years ago.

Material from the outer layers of both bodies was thrown into orbit around the Earth, forming a disc, and this material coalesced to form the Moon. This theory explains many features of the Moon, such as the absence of volatile substances from its rocks (due to the intense heat generated by the impact) and its lack of an iron core (since it formed from rocky surface material).

PHOTOLIBRARY

SHORT OF PROVIDING ANSWERS, the Moon missions generated many more questions. Some researchers then moved on to study other things, convinced that there wasn't enough data to solve the mystery. It was in this theoretical vacuum, in the mid-1970s, that two groups independently formulated a new idea: the impact hypothesis.

According to Bill Hartmann and Donald Davis of the Planetary Science Institute in Tucson, Arizona, and Alastair Cameron and William Ward of Harvard University in Boston, a cosmic object dubbed Theia (the mother of the Moon in Greek mythology), collided with the primordial Earth and created the Moon.

Van Westrenen himself signed up wholeheartedly to this hypothesis. "At first, the impact hypothesis seemed to solve all our problems," he says. "It gives you an Earth and Moon with the correct size, in the correct orbit."

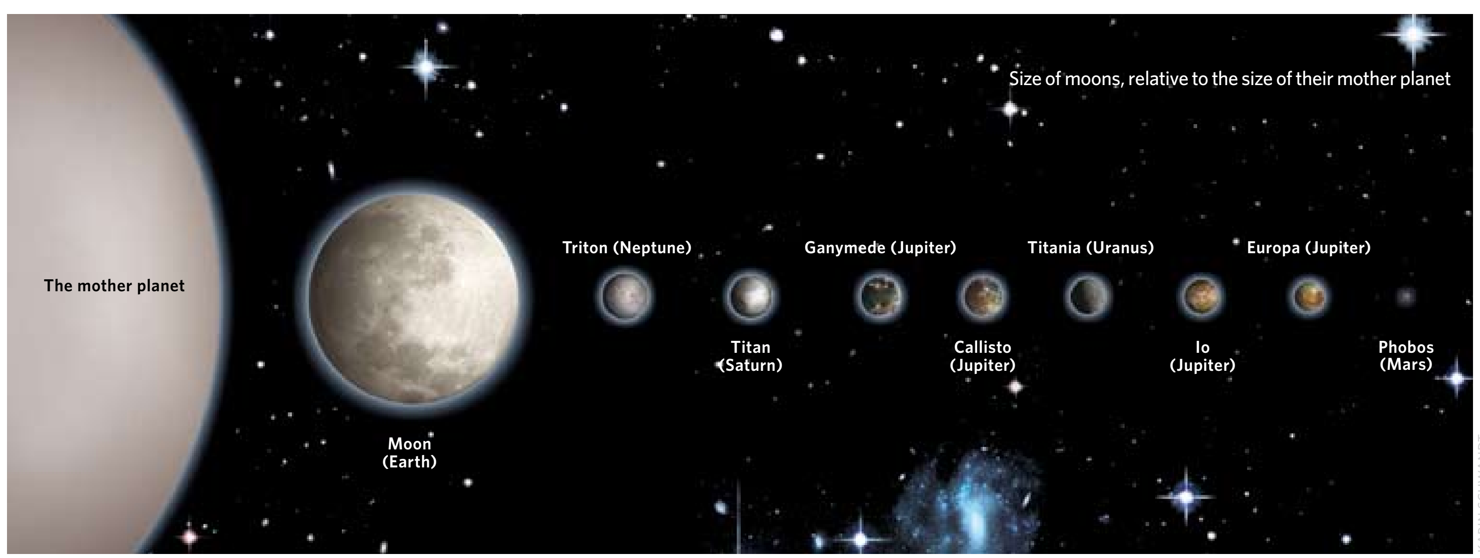
A quarter of a century later, though, things have changed. In particular, computer simulations of the impact have become more advanced and detailed. And in turn, they have generated new mysteries.

It appears, for instance, that the impact needs fine-tuning to fit the data. "It can't have been a head-on collision," says van Westrenen. "It must have been a glancing collision with a moderate relative velocity. Any deviation in these parameters, and things go wrong; you knock the Earth apart or you don't end up with a Moon, because the debris will take off in all directions."

But the main puzzle that came from the simulations – detailed in the British journal *Nature* in 2003 – was that 'successful' impacts produce a Moon of about 80 per cent mantle material from the impactor.

"If the Moon is mainly made of impactor material, than it is much less likely that the ratio of oxygen isotopes for Moon and Earth would be the same," says van Westrenen. "That is only possible if the Earth and Theia were formed at the same distance from the Sun, which means that they have been chasing each other in more or less the same orbit until they collided."

The problem is that we don't see anything like that elsewhere in the entire Solar System.



KARIN SCHWANDT

At the University of Arizona in Tucson, planetary scientist Jay Melosh is one of the proponents of the impact theory. "The similarities do suggest that the proto-Earth and its impactor were formed at almost the same distance from the Sun. But that is not such a crazy idea," he argues. "The object must have been close to Earth, simply because it did impact, while other embryonic planets did not."

Robin Canup, from the Southwest Research Institute in Boulder, Colorado, and author of the 2003 *Nature* paper, agrees with Melosh: "We calculated the conditions for the impact velocity. This indicates that the impactor originated somewhere between the present orbits of Mars and Venus." That is, somewhere near the orbit of the Earth.

It was a case of overheating rather than exploding: the mantle was already about 5,000°C, and the georeactor that went supercritical generated so much heat that it increased by an additional 8,000°C.

Melosh maintains that the impact theory is still rock-solid. "This problem with the isotope ratio is to be regarded as a small puzzle within the solid framework of the impact hypothesis," he says. "There is no need at all to ditch the impact hypothesis and put ill-conceived ideas about exploding georeactors in its place."

VAN WESTRENEN AND DE MEIJER, however, have other data to nurture their theory. This evidence comes from thousands of kilometres beneath our feet.

In a major breakthrough reported in the U.S. journal *Science* in 2005, Earth scientists Maud Boyet and Richard Carlson of the Carnegie Institution in Washington DC, concluded that both a partition between the Earth's mantle and core, and another within the mantle, formed within 30 million years of the planet being born.

This internal partition isolated the lower mantle, the D″-layer, from the rest of the mantle (see graphic on p71).

Boyet and Carlson arrived at their conclusion by investigating the rare earth elements samarium (Sm) and neodymium (Nd). Samarium-146 is a radioactive element that decays relatively speedily, with a half-life of 103 million years, to neodymium-142.

At present hardly any samarium-146 is left on Earth. Theoretically, terrestrial rock should contain just as much neodymium as the primordial material from which the Earth was formed – samples of which sometimes still reach the Earth in meteorites.

But the researchers discovered something odd. Rock from the Earth's mantle contains more neodymium than these meteorites. The only conceivable explanation is that samarium was distributed unevenly throughout the planet, because the overall concentration should be equal to that in meteorites.

But where can this neodymium-poor rock be? Not in the Earth's core, because neither samarium nor neodymium can bond chemically to iron. That only leaves the D″-layer. This chunky boundary layer between core and mantle must be low in neodymium.

Boyet and Carlson discovered that the Moon has a peculiarity too: rocks that are just as rich in neodymium as the Earth's mantle.

This makes the impact hypothesis very improbable indeed, according to van Westrenen. "Considering that at this giant impact 4.5 billion years ago the Earth's core and Theia's core fused, it is most improbable that isolated layers deep within the planet survived the impact. Yet this is what the data from Carlson and Boyet suggest."

Carlson was candid about this over the telephone: "Our data show a strong similarity between terrestrial and lunar rock, but there is no good explanation for that at all."

How the impact with Theia took place, and how the D″-layer survived this impact while the Earth's core fused with the core of the impactor, is beyond Carlson's comprehension as well.

PHOTOLIBRARY

Even the primordial atmosphere was not safe: it must have been sucked away from the Earth by the erupting matter.

›› Research into the mysterious D″-layer, some 2,900 km down, is now very popular. "It's the most dynamic region within the Earth," says van Westrenen. "It is a very hot layer that is one of the causes for the outer core, which generates the Earth's magnetic field, staying molten."

The D″-layer is puzzling because it exchanges heat with the surroundings, but hardly any material. It also varies in thickness from a few tens to hundreds of kilometres. Carlson compares the layer to a landscape of icebergs, floating on the outer core.

But why would georeactors be located in this layer, of all places? The answer to this question is also found in the recent literature. "The origin of this isolated reservoir in the D″-layer is to be found in the primordial crust," says de Meijer. "It must have sunk like a brick into the then largely liquid mantle, all the way to the core–mantle boundary."

There the primordial crust stayed, afloat on the outer core. "This layer could very well be poor in samarium, which provides a nice explanation of Boyet's and Carlson's results."

The sunken primordial crust has another asset: fissile material. In 2005, another team calculated that almost half of all uranium and thorium in the mantle must have ended up in the D″-layer in this way.

For de Meijer, everything began to fall into place after this discovery. "If there is any place where a natural georeactor can start up, it must be in the D″-layer," he recalls thinking. Wasn't it then possible that a runaway nuclear reaction in the D″-layer had ejected the Moon from the Earth?

"Actually, [the other team] could have come to the same conclusion," he says, pointing to the place in his garden where he was working when the idea struck him.

De Meijer went back to the drawing board to calculate. Not only did he require sufficient uranium and thorium for the spontaneous generation of georeactors, he also needed enough energy from these georeactors to launch the Moon. He started with the latter, imagining a simple model, with an Earth circled by a much less massive Moon.

"These calculations showed that it is possible to launch a Moon if the georeactor generated about 0.5 x 10^{30} joules. That is gigantic," he says. By way of example, a one gigawatt nuclear reactor generates just 10^{17} joules a year, so you'd need the annual energy production of 10^{13} of these reactors to get the same amount.

This would put the Moon at a distance of about a 100,000 km, much closer than today's 380,000 km. In the 4.5 billion years since then, the Moon has slowly drifted away from us — a process that is still going on today, at about four centimetres a year.

THE NEXT CRUCIAL QUESTION was whether the D″-layer contained enough uranium and thorium at that time for georeactors to exist, and whether these could generate enough energy. At first, the prospects were unfavourable. The estimated concentration of uranium and thorium in the D″-layer 4.5 billion years ago was 0.6 parts per million (ppm), while no less than 250 ppm was necessary for a georeactor. So de Meijer was short by a factor of 400 and his idea seemed to be somewhat doomed.

But again, geochemistry came to his rescue. The D″-layer is rich in the mineral calcium perovskite. By lucky coincidence, uranium and thorium like to occupy the location of calcium in the crystal lattice, pushing out the calcium. "All the uranium and thorium will end up almost exclusively in the calcium perovskite," says de Meijer. "We know approximately how much calcium perovskite there is, and this produces a concentration of 12 ppm uranium and thorium. And that is only the average over the entire layer, a gigantic concentration."

According to the latest scientific insights, we get to a factor of 20 below the 250 ppm that is needed. "We're hardly worried about the remaining factor of 20, considering all the uncertainties when dealing with the inside of the Earth," says van Westrenen. "The D″-layer is not homogeneous...there will be hotspots where the concentration of uranium and thorium is much higher."

De Meijer adds: "We're also reassured by the fact that you need only five per cent of all uranium and thorium in the D″-layer to launch the Moon. That is not outrageously much."

NATUURWETENSCHAP & TECHNIEK, DEC 2007

The idea is also supported by geologist Alex Corgne at Macquarie University in Sydney, an expert on the subject of the mineralogy of the D″-layer who says, "The conclusions by de Meijer and van Westrenen are completely credible."

SO IT'S LIKELY that all ingredients for a georeactor were present within the young Earth. What remains, though, is how to get it started.

Like J. Marvin Herndon's georeactor in the core, georeactors in the D″-layer must be fast breeders: nuclear reactors designed to 'breed' fuel by producing more fissile material than they consume. In this type of reactor, the neutrons generated by the spontaneous fission of uranium-235 are used to transform uranium-238 and thorium-232 into new fissile material - uranium becomes plutonium-239, thorium becomes uranium-233.

There was certainly no shortage of suitable isotopes. In the early days of the Earth, no less than 25 per cent of all uranium was fissile uranium-235; today, after 4.5 billion years of decay, only 0.7 per cent remains. Man-made nuclear reactors generally use enriched uranium, in which the uranium-235 content has been increased to four per cent. But the young Earth contained a potent mix.

Considering this, according to de Meijer, it was simply a case of getting overheated rather than exploding. The mantle was already hot — about 5,000ºC — and the georeactor that went supercritical generated so much heat that it increased by an *additional* 8,000ºC.

"All rock vaporised. It literally created a large bubble of gas in a fluid soup. When you put a pan of soup on the fire, you also get bubbles of vapour that shoot up," he says.

It was Archimedes's law at work. The difference in density propelled the bubble of vapour upwards, taking everything in its path with it, including parts of the mantle and crust. Even the primordial atmosphere must have been sucked away from the Earth by the erupting matter.

What happened after that is speculation. "Presumably, a ring of debris formed around the Earth, out of which the Moon then gradually coagulated," guesses van Westrenen.

This raises the question: could something similar happen today? Researchers don't think so; the Moon drew so much energy from the Earth in that blast that too little is left for an encore. However, de Meijer believes that the georeactors in the D″-layer remain active.

"There could still be places where fissile isotopes reach the critical concentration for forming a georeactor. Remember that georeactors are fast breeders that produce more fuel than they use," he says.

He also knows how to find out. Both natural decay of uranium and thorium produce antineutrinos, tiny particles that can fly straight through the Earth and you and me. Considering the inaccessibility of the D″-layer, an antineutrino detector is the only way known to prove the existence of a georeactor. But such a detector must be able to detect the energy and direction of the antineutrinos, because artificial nuclear reactors produce them, too.

De Meijer has been working on precisely this type of direction - sensitive detector. "We made a design that looks feasible. The next step is building a prototype. We hope to start soon."

MARCEL CROK *is a science journalist for* Natuurwetenschap & Techniek *magazine in The Netherlands.*