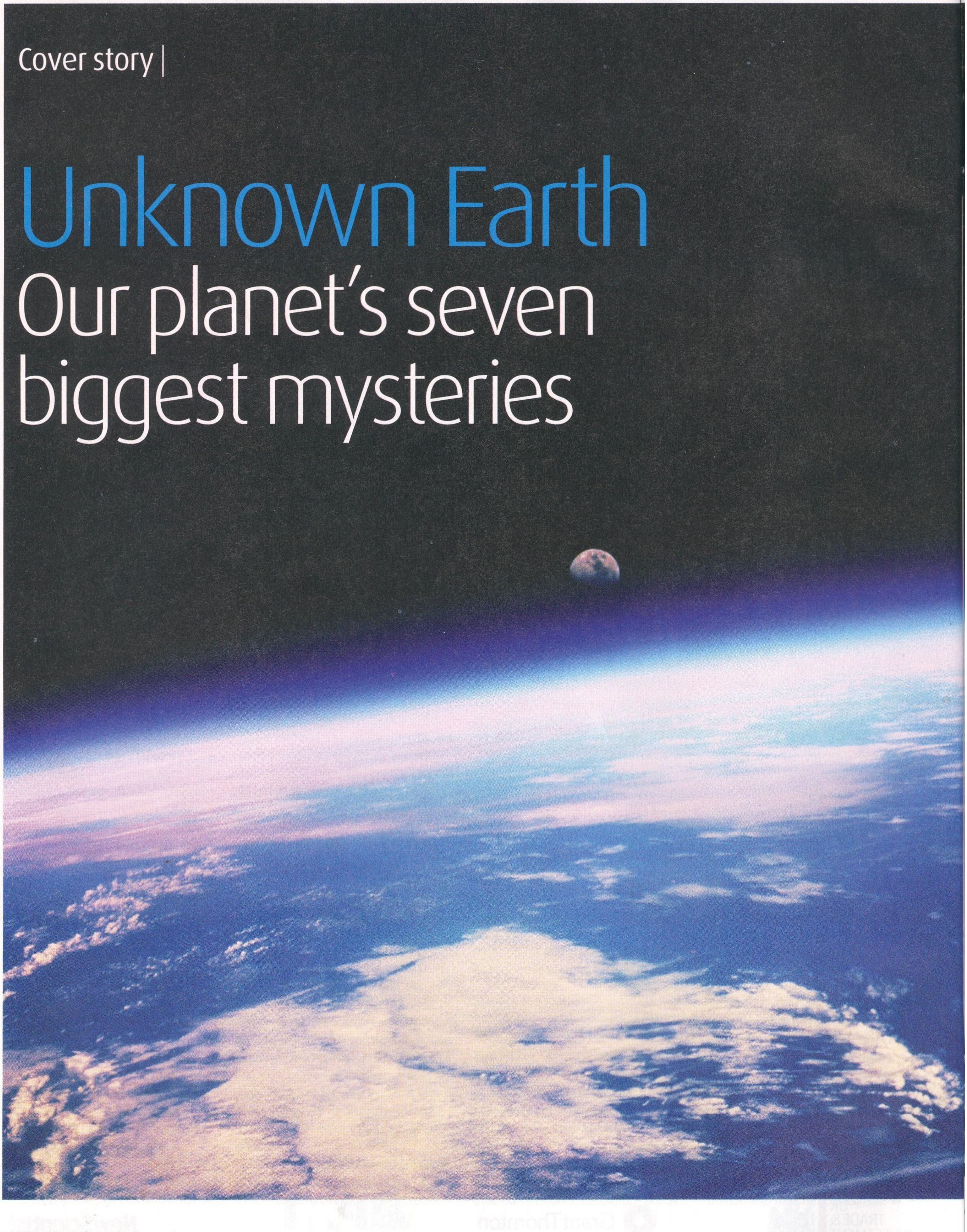
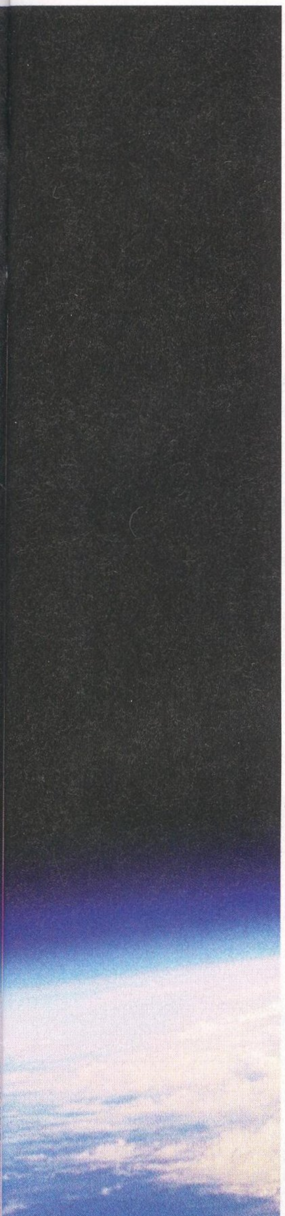
Unknown Earth

Our planet's seven biggest mysteries




NASA/ROGER RESSMEYER/CORBIS

It's the place we call home, but there is much about planet Earth that remains frustratingly unknown. How did it form from a cloud of dust? How did it manage to nurture life? And just what is going on deep within its core? *New Scientist* investigates these and other fundamental questions about our beautiful, enigmatic world

1

How come Earth got all the good stuff?

Look around our solar system and you could be forgiven for thinking its eight planets drifted in from completely different parts of the cosmos. Yet they all formed from the same cloud of gas and dust that surrounded the sun more than 4.5 billion years ago. As gravity pulled this cloud together with the sun at its centre, dust grains collided and stuck to each other, growing in size and generating ever larger gravitational fields. These clumps collided and merged, building the planets we know today.

That's the big picture, but the details of what happened in the early stages of Earth's life remain a mystery. Solving it is fundamental to understanding why Earth is so suitable for life. We know that its distance from the sun provides the right amount of heat and light to make the planet habitable, but that alone is not enough. Without the unique mix of carbon, hydrogen, nitrogen, oxygen, phosphorus and sulphur that makes up living things, and without liquid water on the planet's surface, life as we know it could not have evolved. Chemically speaking, Earth is simply better set up for life than its neighbours. So how come we got all the good stuff?

What we do know is that different elements would have condensed from the cloud at different temperatures, which would depend on their distance from the sun. We cannot know exactly what happened next, though, because Earth rocks have been compressed, melted and weathered too many times to retain any clues about how they formed. And, since most of the planets in the solar system are out of reach, meteorites are our best hope. They formed at the same time as the planets, and since then have remained largely undisturbed. But to study them, we have to wait for one to fall from space.

A class of meteorite called chondrites match many aspects of Earth's composition, which suggests they may have formed from the same raw materials. However, there are subtle differences that are proving tough to explain. For example, the mix of oxygen isotopes in chondritic meteorites does not match those found on Earth. So far no one knows why, but since oxygen is the most abundant element in the Earth's crust, making up nearly half of its mass, it is a mystery that cannot be ignored.

Another big unknown is how Earth acquired its life-giving water supply. Being so close to the sun, it was probably too hot ▶

for water to simply condense out of the gas cloud as the planet formed, and any that did collect would have evaporated away during the titanic collision that formed the moon (see "What happened during Earth's dark ages", right). The most popular explanation is that the water arrived later, in the form of icy comets from the outer solar system that rained down in the period known as the "Late Heavy Bombardment". As yet, though, there is no firm evidence to confirm this as the source of Earth's water.

Clearly we need new insights into how planets form. The European Space Agency's Herschel Space Telescope, which takes to the heavens later this year, could provide some of the answers. With a mirror that is almost one-and-a-half times the size of the Hubble Space Telescope's, it will peer deep into space and use its infrared detectors to give us an unprecedented look at the dusty clouds where new stars and planets are forming, and where brand new planets may be striking it as lucky as Earth did. **Stuart Clark**

2

What happened during Earth's dark ages?

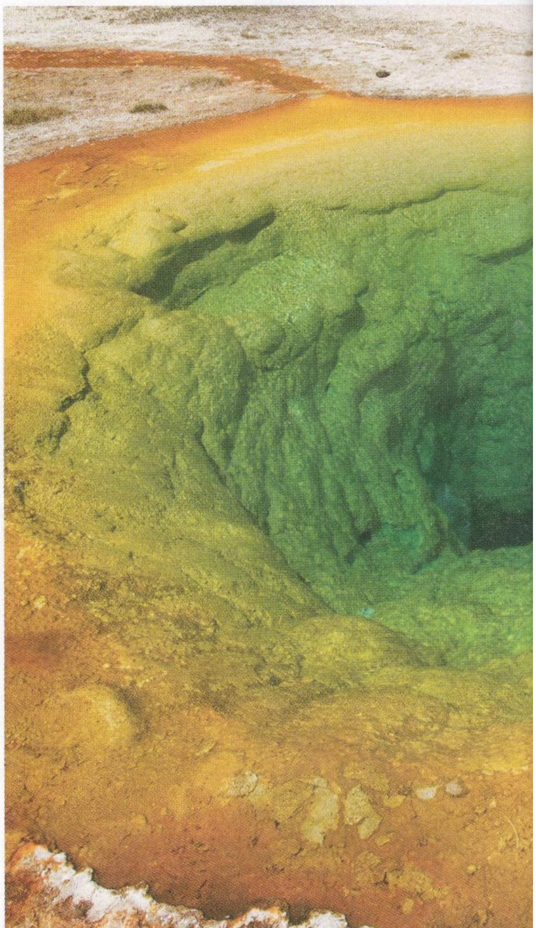
Some 4.53 billion years ago, as the infant Earth was settling down in its orbit around the sun, disaster struck. Our young planet was dealt a glancing blow by an object the size of Mars. Debris from the impact was thrown into Earth's orbit to form the moon, and the energy of the collision supplied enough heat to melt the Earth's upper layers, erasing our planet's previous geological record. This has left a yawning chasm in our knowledge of the planet's first 500 million years, a period that has become known as the Hadean era, Earth's darkest age. We know almost nothing about it.

"Time zero" for the solar system is generally agreed to be 4.567 billion years ago, and by 4.55 billion years ago, about 65 per cent of the Earth had assembled. Then, 20 million or so years later, the wayward object struck, sending vaporised silicon into the atmosphere. This condensed and fell as lava rain, depositing a sea of molten rock at a rate of perhaps a metre per day. The Earth melted to its core, and the process of forming a solid surface began all over again.

The Earth's crust today is composed almost

3

Where did life come from?



Leaving aside the remote possibility that life arrived on Earth on a meteorite from somewhere else, we have to assume that it emerged from whatever physical and chemical conditions existed in the planet's youth. Working out what these conditions were is problematical, mainly because the Earth we live on today retains almost no trace from that time.

To date, the earliest evidence for life comes from sedimentary rocks that are 3.8 billion years old. Discovered in the 1990s in west Greenland, these rocks have an unusually low proportion of the heavy isotope of carbon. This is thought to be a sign of micro-organisms at work, because the lighter isotope passes more easily through cell walls and so accumulates wherever microbes have been.

These rocks were laid down at a time when the planet was recovering from the impact that formed the moon (see "What happened during Earth's dark ages", above). Primordial oceans and continents were forming, but the process was interrupted every now and again by a large asteroid striking the planet and boiling the oceans. Darwin envisaged life emerging in a "warm little pond"; in fact, it was almost certainly a hot, briny cauldron.

This is a radically different environment from the one we live in, but perhaps that is to be expected. There are no recorded instances of an "origin-of-life" event on modern Earth, so perhaps the right conditions no longer exist. Or perhaps it is happening on such tiny scales that we have not noticed.

Analogous conditions to early Earth do still exist. They can be found surrounding hydrothermal vents on the sea floor, where geothermal activity pumps geysers of scalding water into the ocean. These areas support vast collections of micro-organisms, many with startlingly primitive metabolisms and none of which rely on sunlight for energy. Whether hydrothermal vents were

> **"Life almost certainly emerged in a hot briny cauldron"**

exclusively of rocks no older than 3.6 billion years, so traces of the hellish Hadean environment that followed the impact are thin on the ground. Of the ancient rocks that remain – amounting to about one part per million of the crust – most have since been modified by heat or pressure. But thanks to tiny resilient crystals, called zircons, there are some clues.

Zircons, found in the rocks of the Jack Hills in Western Australia, are Earth's oldest minerals. They are composed of exceptionally durable zirconium silicate crystals and contain a high concentration of uranium, which allows their age to be determined from the amount of radioactivity that remains. And even though they are found within much younger rocks, many zircons date to more than 4 billion years old.

They cannot tell us exactly what happened as the molten Earth cooled, but their oxygen content shows that they formed in water, suggesting that Earth's oceans were in place more than 4 billion years ago. This raises new questions: oceans need to sit on a solid surface, so what was this crust like? So far there are no clear answers. Perhaps the most obvious observation about the Hadean crust is that it no longer exists. While this is frustrating, it is itself a clue: perhaps plate-tectonic action was much more vigorous back then.

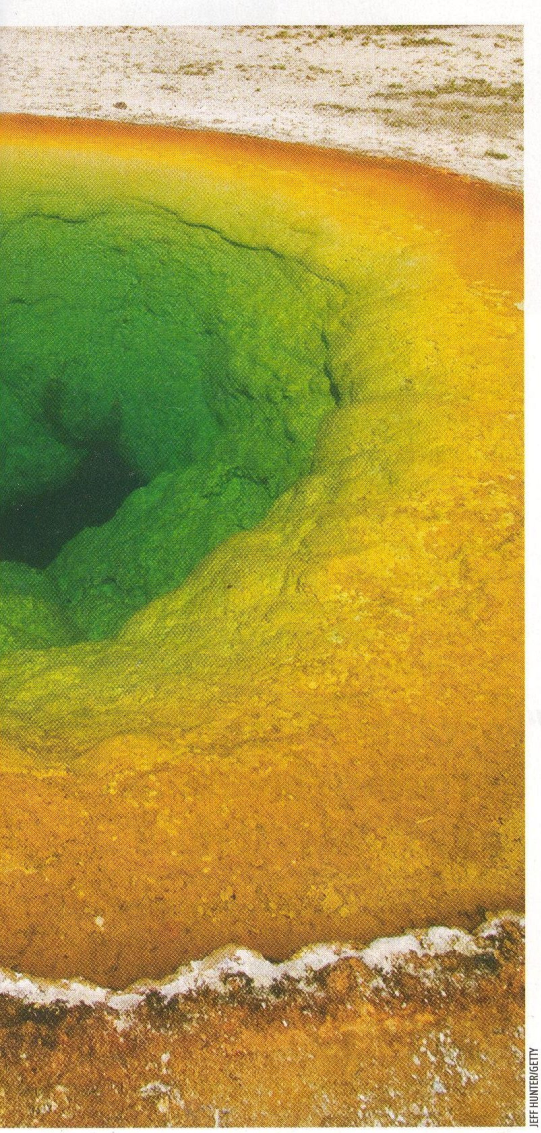
There are two other ways we can learn more about the Hadean. On Earth, concerted searches for more ancient rocks or minerals, combined with ever-improving methods of microanalysis, should yield further clues about what the Earth was like as it formed for the second time.

Secondly, mineral prospecting on the moon and Mars could reveal what Earth was like before the catastrophic impact – as rocky debris from the impact is what formed the moon. Unlike Earth, neither of those worlds have remelted, so there is a much greater chance of finding truly ancient rocks on their surface. We may even hit the geological jackpot and find a piece of the Hadean Earth that was blasted into space by an asteroid impact, and which subsequently landed on the Moon or Mars. Researchers into the Hadean are nothing if not optimistic. Stuart Clark

life's point of origin or simply an early haven is unknown, however.

Another difficulty is working out exactly what happened to bring lifeless chemicals together to form living organisms. Here we are faced with a chicken-and-egg situation: for DNA to do its thing it needs proteins, yet the blueprints for those proteins are provided by the DNA. So which came first? The most likely answer is now thought to be that they evolved at the same time through a network of reactions between simpler chemicals. This makes it doubly difficult to work out when early organisms crossed from chemicals into life.

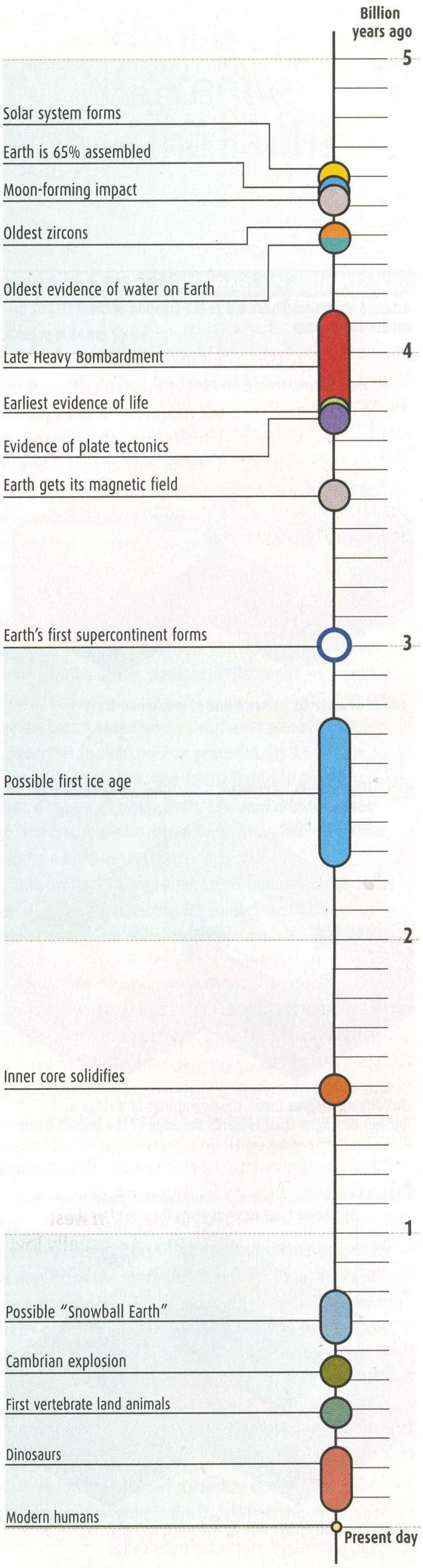
Geologists are turning to Mars for answers. There are no plate tectonics there to destroy the evidence, and sedimentary rocks can be found that date back to the time of life's origin on Earth. The hope is that, unlike their counterparts on Earth, these rocks preserve some record of chemistry before life emerged. It's a long shot, but they might even record an origin-of-life event that gave rise to life forms that may yet be clinging on somewhere on the Red Planet. **Stuart Clark**



It may look uninviting, but hot salty water was the height of luxury for early life forms

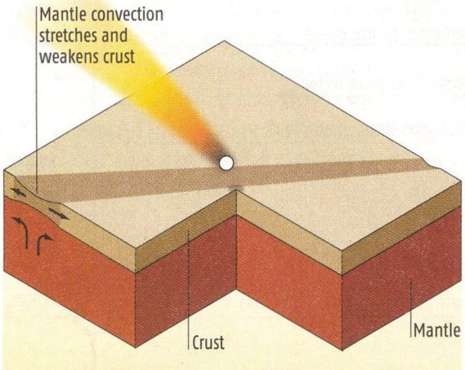
JEFF HUNTER/GETTY

EARTH'S STORY SO FAR

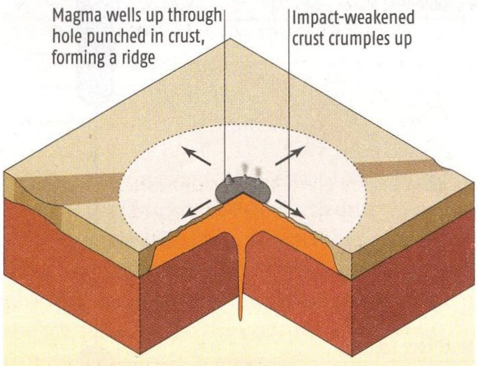


KICK-STARTING PLATE TECTONICS

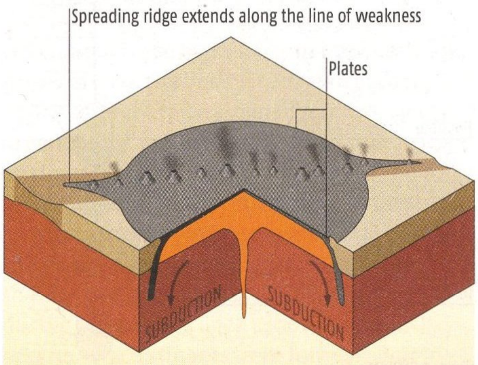
Asteroid strikes may have led to the creation of the subduction process



Comet or asteroid strikes a line of weakened crust



Solidifying magma forms the beginnings of a ridge and pushes damaged crust towards the edge of the impact crater



Plates form on either side of the ridge and dive under more buoyant, undamaged crust at the crater's edge

4

Why does Earth have plate tectonics?

Without plate tectonics our planet would be a very different place. The constant recycling of the Earth's crust provides us with a stable climate, mineral and oil deposits and oceans with a life-sustaining balance of chemicals. It even gives evolution a kick every few hundred million years.

Earth is the only planet we know of that has plate tectonics. So what went right? Models have shown that for plate tectonics to get going a planet has to be just the right size: too small and its lithosphere – the solid part of the crust and upper mantle – will be too thick. Too big and its powerful gravitational field squeezes any plates together, holding them tightly in place. The conditions also have to be just right: the rocks making up the planet should be not too hot, not too cold, not too wet and not too dry.

Yet even if these conditions are met there is one more crucial factor that needs to be introduced. Somehow the lithosphere has to be cracked in such a way that one piece will dive down beneath the other. Today we see this process, known as "subduction", at the rim of many ocean basins, as cold, dense ocean floor slides under the more buoyant continental crust and dives into the mantle.

However, early Earth was much warmer than it is today, and instead of having a brittle outer crust it had a sticky kind of goo, in which the first cracks must have appeared. Numerous computer models have tried to simulate conditions in which a break in the crust would spontaneously occur, but so far all have failed.

A hot mantle plume could have made the first hole, bursting up from below. Or perhaps an asteroid or comet was the trigger, piercing the gooey surface layer on impact and setting up a chain of events that created the first moving plates (see diagram, left).

Another big unknown is when this might have happened. There is very little record in oceanic crust because most of it is not old enough – oceanic crust is usually destroyed in subduction zones just 200 million years after being created in an ocean ridge. Yet evidence from oceanic crust that has avoided subduction is providing clues. "Ophiolites" are slivers of ancient oceanic crust, which were pushed on top of continental crust at a subduction zone rather than being pushed down beneath it. A recent study dated a sample of what is thought to be an ophiolite in Greenland to 3.8 billion years ago – the oldest suggestion of plate tectonics yet.

Whatever the exact date plate tectonics began, it has shaped and reshaped the surface of our planet ever since. The process recycles water, carbon and nitrogen, creating an environment that is perfect for life. It also created many of the oil, gas and mineral deposits that we find on Earth – pressurising and baking rock deposits to just the right degree. Volcanoes spewing carbon dioxide into the atmosphere and the grinding of tectonic plates work together to keep the

> **"For plate tectonics to get going conditions have to be just right"**

DOUGLAS PEEBLES/CORBIS

climate liveable (see "Why is Earth's climate so stable?", page 34).

Plate movement also makes oceans open and close, mountains rise and fall and continents gather and split. Every 500 to 700 million years, plate tectonics brings the continents together to form a supercontinent. The last, Pangaea, existed 250 million years ago, and in roughly 250 million years the continents will crash together again.

When these supercontinents slowly break up, separating landmasses and forming shallow seas, evolution goes into overdrive, forming countless new species which colonise the new habitats.

Eventually, the lithosphere will seize up, as Earth cools and convection currents in the mantle become too weak to push the plates around. No one is quite sure how much longer plate tectonics has got to run, or whether it will stop before our planet is consumed by the sun. But let's not worry too much about that: by the time it happens humans are likely to be a distant memory in the life of the planet. **Kate Ravilious**

The firey oozing of the Earth's mantle slides the tectonic plates around the planet. But what got it going in the first place?

5

What is at the centre of the Earth?

In a word: iron. But that isn't the end of the story. There is still much to learn about what the Earth's core is like and how it came to be.

What we do know is that the core starts 2890 kilometres down, and that its diameter is 6800 km. It is comprised of two layers, the molten iron outer core and the solid inner core, which is made of nickel and iron and is roughly the size of the moon.

It hasn't always been this way. Initially the planet was just one big jumble with no obvious structure. Then the heaviest elements, mostly iron and a little nickel, settled towards the centre and formed a core.

Exactly when and how this happened is still up for debate. One idea is that the core formed suddenly, in an avalanche towards the centre. Others believe the iron slowly trickled down. Radioactive isotopes measured in volcanic rocks that originated deep in the Earth indicate that the core formed when the planet was somewhere between 30 and 100 million years old. By 3.5 billion years ago, swirling motion in the liquid iron core had set up a magnetic field. Then, around 1.5 billion years ago, the centre of the core cooled enough to crystallise, creating a solid inner core.

One mystery surrounding the core has recently been solved. It has been known for some time that seismic waves travel faster through the eastern side of the core than the west, but nobody could work out why. Now simulations have shown that this is most likely due to swirling eddies of liquid iron in the outer core that pull down cool material from near the boundary with the mantle and plaster it onto the solid inner core. For the past 300 million years most of the iron eddies have been under Asia, causing the inner core to grow to around 100 kilometres larger on its eastern side than on the west.

This could have implications for the Earth's magnetic field, which is generated by convection in the outer core. Some researchers think that turbulence caused by the growth of the inner core may, over time, make the magnetic field less stable and more likely to flip, causing Earth's north and south magnetic poles to swap places. When this happens – as it has done in the past – the planet is left temporarily unprotected from the energetic particles streaming out from the sun, known as the solar wind. This would leave us with no shield against magnetic particles from the solar wind. This would certainly bring down our computer systems and may prove to be damaging to life too. When this will happen next, however, nobody knows. Kate Ravilious

6

Why is Earth's climate so stable?

Earth wasn't always the only water-world in the solar system. Mars and Venus also appear to have started out wet but, as conditions changed, they lost their oceans. So how has Earth managed to avoid a similar fate?

Our planet's climate is remarkably stable, and has remained in a narrow, liveable, range for almost 4 billion years. The key appears to lie in the interplay between plate tectonics, carbon dioxide and the oceans (see "The Earth's thermostat", below).

The cycle begins with volcanoes spewing CO_2 into the atmosphere, which helps keep the planet warm, thanks to the greenhouse effect. This warmth allows seawater to evaporate, forming clouds and rain. As the rain contains dissolved CO_2 it is slightly acidic and so it reacts with surface rocks to dissolve carbon-containing minerals into the water.

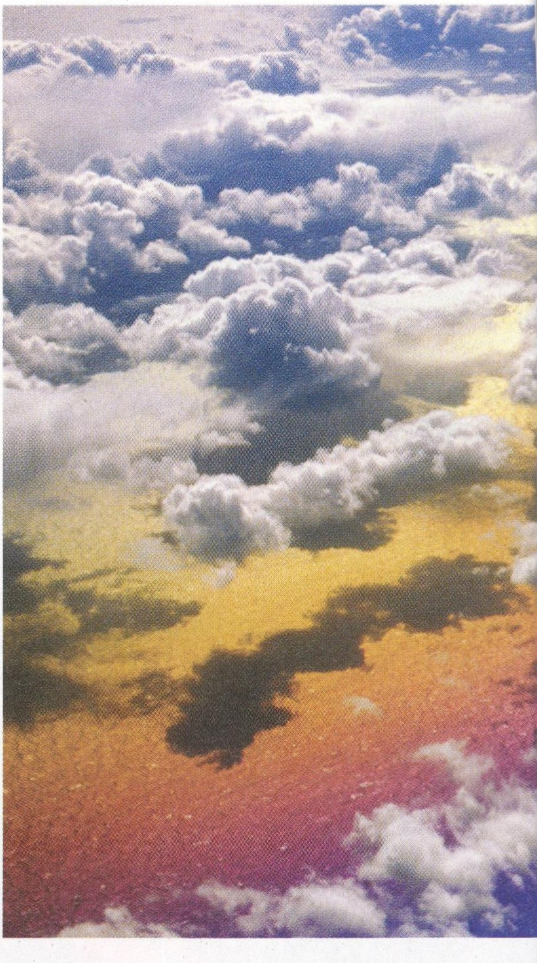
This mixture is then washed out to sea, where the minerals build up and eventually precipitate out to form new carbon-containing rocks on the seabed. Sooner or later, plate tectonics carries these rocks into a subduction zone, where CO_2 is baked out of them by heat of the Earth's interior and later returns to the atmosphere via volcanoes.

This cycle turns out to be an extremely effective thermostat. When the planet is warm, rainfall increases, speeding the rate of atmospheric CO_2 removal and cooling the planet. When it is cold, rainfall decreases, allowing volcanic gases to build up in the atmosphere, warming the planet.

Venus and Mars probably had similar thermostats early on. Venus, though, was too close to the sun and the extreme heat overloaded its thermostat. A warmer atmosphere can hold more water than a cooler one before it must rain, and since water vapour acts like a greenhouse gas, it contributes to further warming. Eventually these factors stacked up until the planet warmed enough for its oceans to evaporate. At the same time, solar radiation high in the Venusian atmosphere split water into hydrogen and oxygen, allowing the lightweight hydrogen atoms to escape into space. So Venus lost its water for good, and with it any control over its thermostat.

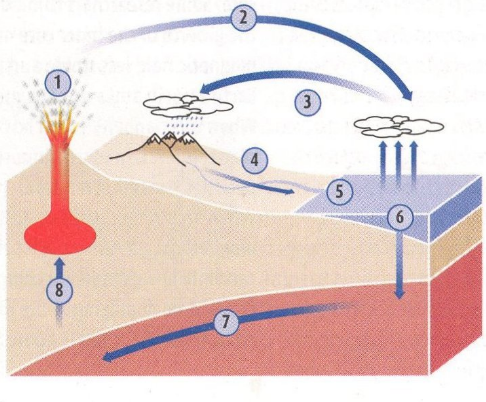
Mars, on the other hand, was too small to maintain its thermostat. Its relatively weak gravity made holding on to heat-retaining gases in its atmosphere difficult. Meanwhile, with a higher surface-to-volume ratio than Earth, the core cooled quickly, shutting down plate tectonics and eliminating the source of planet-warming CO_2.

The cooling of the core also turned off the Red Planet's magnetic field – a by-product of an active core. Without a magnetic field, Mars is exposed to the full force of solar radiation. This breaks down water molecules into hydrogen and oxygen, leading to the loss of water from Mars's atmosphere in a similar process to that which occurred on Venus.


FRANS LANTING/CORBIS

THE EARTH'S THERMOSTAT

Unlike Venus and Mars, which lost their water to runaway climate change, Earth has a handy thermostatic cycle built in



1 Volcanoes spew CO_2 into the atmosphere

2 CO_2 keeps Earth warm via the greenhouse effect

3 Warmth helps seawater evaporate, forming rain

4 Rain contains CO_2 so is slightly acidic and dissolves minerals from the rocks into the water

5 Dissolved carbon-containing minerals wash into rivers and into the sea

6 Minerals precipitate out to form new carbon-containing rocks

7 Rocks are eventually subducted into the mantle, where the CO_2 is released

8 CO_2 returns to the atmosphere through volcanoes

On Earth, the moon has played an additional role in keeping the climate habitable. It damps wobbles that would otherwise cause Earth's axis to tilt wildly. Even small wobbles are enough to launch ice ages, but the ones we have experienced are nothing compared to those on Mars, which flops over on its side under the influence of Jupiter's gravitational pull.

Life on Earth also plays its part. Many marine organisms use dissolved CO_2 in the ocean to build external skeletons and calcium carbonate shells. After death, these sink to the seabed and over time form new carbon-rich rock. The rate of this process increases if atmospheric CO_2 rises, causing an increased drawdown of CO_2 into the ocean. This in turn causes a reduction in atmospheric CO_2 and the temperature drops.

Now, of course, humans are playing their part. The changes we make to the climate by burning fossil fuels could last millions of years but, after we've gone, Earth's underlying thermostat should be able to regain control. That is not guaranteed, however. Both Venus and Mars were habitable once. Perhaps we should heed their warning and take better care of the thermostat our planet has so generously provided. **Richard Lovett**

Unlike its neighbours, Earth has kept a lid on its climate – and its water – for 4 billion years

7

Can we predict earthquakes and volcanic eruptions?

Volcanic eruptions and earthquakes are tangible proof that we live on a planet made up of fidgeting tectonic plates. Since most faults and volcanoes occur along plate boundaries, it is fairly easy to predict where in the world they will happen. Unfortunately for the people who live near to them, working out when is more complicated.

Long-term probabilistic predictions of earthquakes based on what has happened in the recent past are not too much of a problem. People living in the San Francisco Bay area, for example, know that there is a 62 per cent chance of a major earthquake there in the next 30 years. Short-term warnings – on the scale of seconds – are also now becoming possible. Japan recently launched just such a system, which aims to give people enough time to run for cover or dive under a table.

While these kinds of measures can undoubtedly save lives, it would be more useful to have warnings on timescales of weeks or days, to evacuate the areas most at risk. If the Earth gives out warning signs on these timescales, however, no one has yet worked out how to read them.

Mainstream attempts to forecast quakes usually involve models of the stresses and strains on a given fault, estimates based on when the fault last moved, and satellite measurements of ground motion. More controversially, some researchers believe that electrical disturbances on the edge of the Earth's atmosphere – which some say have preceded a number of major earthquakes – could also be used as a predictor. The idea is that changes in stress leading up to an earthquake could increase pressure on rocks in such a way as to induce electric currents. These could trigger a release of radon gas or alter surface temperatures and ultimately affect the Earth's electromagnetic field in such a way as to be detectable by satellites. Strange cloud formations above faults immediately before earthquakes have also been suggested as a possible warning sign.

> **"It is becoming possible to predict when volcanoes will erupt"**

While accurate earthquake forecasts are still a way off, it is becoming possible to predict when volcanoes will erupt. Recent advances in our ability to decipher the warning signs has led to a number of successful evacuations. Three months before the dramatic eruption of Mount Pinatubo in the Philippines in June 1991, for example, scientists detected tremors on its flanks. Soon after, the volcano started steaming and puffing out clouds of ash. As activity increased the government ordered an evacuation of 60,000 people, saving thousands of lives.

While not all volcanoes give such clear signals, even the smallest of signs can be now be used to predict eruptions. Subtle changes in the sound of the ocean were successfully used to forecast the eruption of Piton de la Fournaise, on the island of Réunion in the Indian Ocean in July 2006 and April 2007. Scientists monitoring the low-frequency seismic waves generated by the ocean hitting the sea floor had noticed that when an eruption was imminent, sound waves passing through magma chambers slowed down. Based on this observation, local people were evacuated with several days' warning.

Keeping an eye on the weather could also aid predictions. Pavlof, an active volcano on the Alaskan peninsula, is most active during the autumn and winter. One explanation is that the storms at this time cause water levels to rise around the volcano, squeezing the magma up like toothpaste out of a tube. It is possible that climate change could have a similar effect. Melting ice sheets and rising sea levels will change the loads on earthquake faults and the flanks of coastal volcanoes, and could make quakes and eruptions more likely.

Worse still is the prospect of another supervolcano eruption. The last, 75,000 years ago, plunged Earth into a volcanic winter for hundreds of years – and wiped out 60 per cent of the global human population.

Eruptions occur every few hundred thousand years so we know another is on the way. The two main candidates are being monitored – Yellowstone in Wyoming, and Campi Flegrei in southern Italy – but no one knows when they will blow. Perhaps that's a good thing, as there is nothing we can do to stop them. **Kate Ravilious** ●