VOL TWO / *ISSUE* FOUR

NewScientist THE COLLECTION

OUR PLANET

FROM THE CENTRE OF EARTH… TO THE EDGE OF SPACE,

THE DEEP PAST… TO THE DISTANT FUTURE

OUR WORLD AS YOU'VE NEVER SEEN IT BEFORE

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NewScientist
THE COLLECTION

VOL TWO / ISSUE FOUR
OUR PLANET

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The wonders of the place we call home

WHAT does home mean to you? Probably somewhere familiar, comfortable and safe. Certainly, Earth provides all these things, and more besides. Yet the true nature of our home planet is far more awe-inspiring and mysterious, and sometimes hazardous in the extreme.

Formed about 4.6 billion years ago from the debris of the big bang and long-dead stars, Earth started as just another ball of molten rock orbiting an unremarkable star. Yet somehow it became one of the most amazing planets in the universe: the only one we know of that harbours life.

For this we must thank Earth's unique character. Neither too hot nor too cold, it is rich in water and other life-friendly chemicals that are constantly recycled by a complex atmosphere and remarkably dynamic surface. It even has a giant protective shield – a geomagnetic field that keeps deadly solar radiation at bay.

Yet despite centuries of research, only now are we starting to understand Earth's complexity. Geologists exploring deep within its crust are unravelling the violent upheavals that gave birth to the land we stand on. We are also beginning to map the world in intimate detail from above, thanks to instruments on orbiting satellites that spot tiny ground movements, measure ocean currents and size up hurricanes as they form.

But the more we learn, the more tenuous our hold on this planet appears, and there is still much we don't know. This issue of *New Scientist: The Collection* will help you see Earth in a new light and appreciate what makes it so special.

Chapter 1 reveals our planet's origins. Here lie some of the biggest questions: where did water come from? How did life form? And what lies at the planet's core?

Chapter 2 explores the forces that shape our planet. Some work slowly, forming and reforming continents over millennia, whereas others strike like lightning. It turns out that even our own activities are capable of influencing the shattering power of quakes and volcanoes.

Chapter 3 takes a grand tour of the most spectacular features of our planet's past. See the world transformed by ice, watch deluges of biblical proportions, and witness the birth of the moon, thanks to a nuclear bomb at Earth's centre.

Chapter 4 investigates our impact on the climate, documenting the dramatic transformations – some expected, but others far more surprising – that a warmer world will bring. It also examines how we might counter these changes using technology, if we dare.

Chapter 5 is all about Earth's atmosphere and water. Here you'll discover extreme weather, vanishing clouds, vast rivers in the sky and cities set to sink below the waves.

Finally, Chapter 6 looks forward to a familiar, yet rather different world. How might we reshape Earth's surface through engineering? What form would the planet take had we never been here? And how will it bounce back when we disappear?

From the centre of Earth to the edge of space, let *New Scientist* guide you through the wonders of our remarkable planet. Home will never seem the same again.

Ben Crystall, Editor

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Unknown Earth

Our planet's seven biggest mysteries

NASA/ROGER RESSMEYER/CORBIS

CHAPTER ONE

HOME SWEET HOME

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). One of the most popular explanations 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. NASA's James Webb Space Telescope, which takes to the heavens in October 2018, could provide some of the answers. With a mirror that is almost three 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 orbit to form the moon, and the energy of the collision melted Earth's upper layers, erasing our planet's previous geological record. This has left a yawning chasm in our knowledge of its first 500 million years, an era known as the Hadean.

"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. Earth melted to its core, and the process of forming a solid surface began all over again.

Earth's crust today is composed almost exclusively of rocks no older than 3.6 billion years,

3 Where did life come from?

Leaving aside the remote possibility that life arrived on Earth on a meteorite, 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 problematic, however, mainly because the Earth we live on today retains almost no trace of that time.

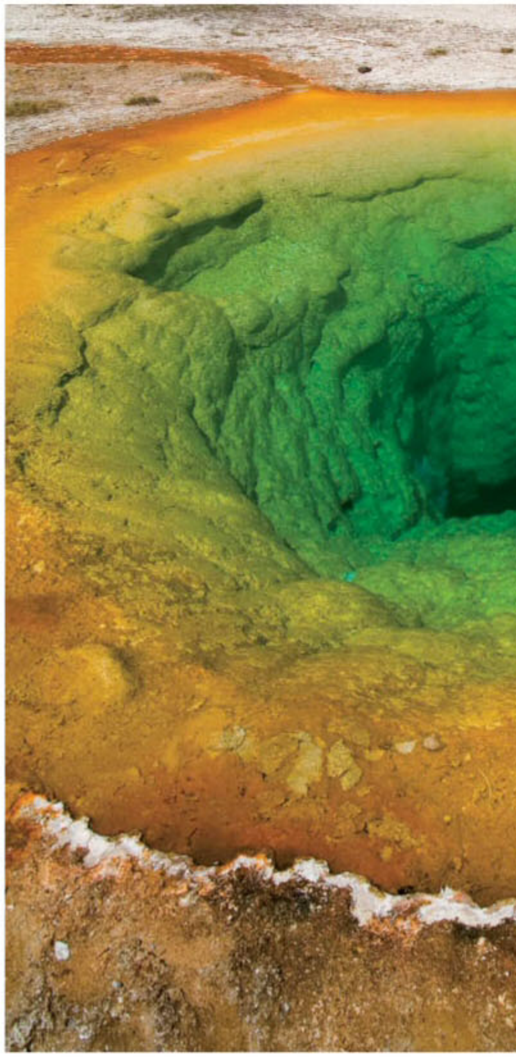
To date, the earliest evidence for life comes from sedimentary rocks that are 3.8 billion years old. Discovered in the 1990s in western Greenland, they have an unusually low proportion of carbon-14, the heavy isotope of carbon. This imbalance is thought to be a sign of microorganisms at work because the lighter isotope, carbon-13, passes more easily through cell walls and so accumulates wherever microbes are – or were – active.

These rocks were laid down at a time when the planet was recovering from the impact that probably 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 microorganisms, many with startlingly primitive metabolisms and none of which rely on sunlight for energy.

"Clues about when life began may be found on Mars"



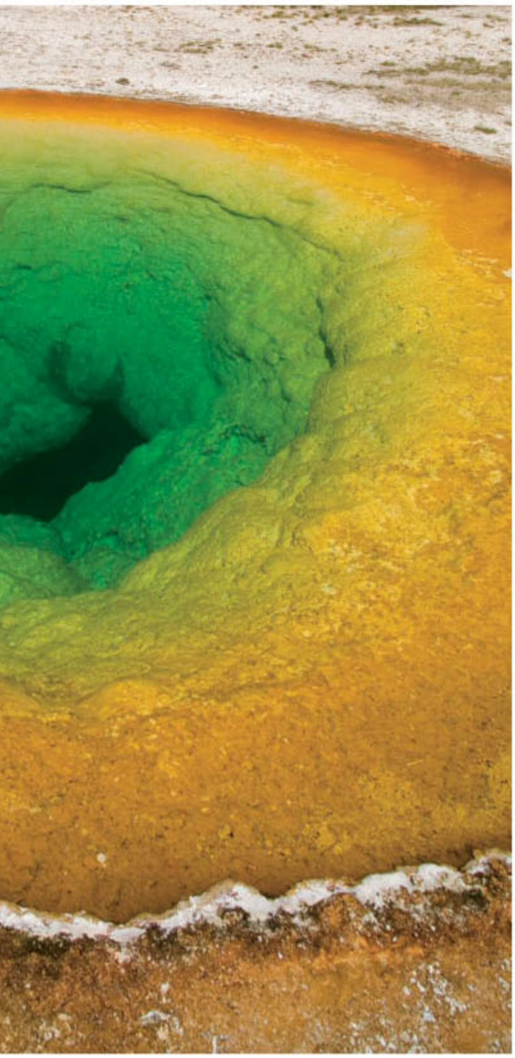
so traces of the hellish Hadean environment that followed the impact are thin on the ground. Of the ancient rocks that remain – amounting to about one part per million of the crust – most have been modified by heat or pressure. But tiny resilient crystals called zircons give some clues.

Zircons found in 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 embedded within much younger rocks, many of the zircons themselves are 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 solidified for the second time.

Mineral prospecting on the moon and Mars could also reveal what Earth was like before the impact. 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.
Stuart Clark
(For an alternative scenario for the formation of the moon, see page 62)



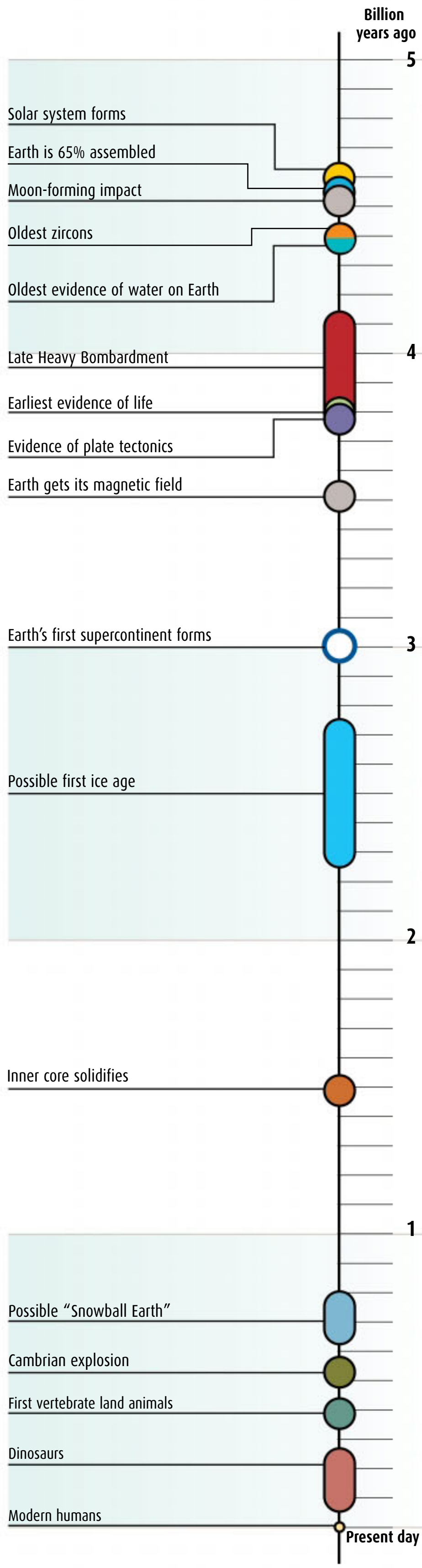
It may look uninviting, but hot salty water was the height of luxury for early life forms

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

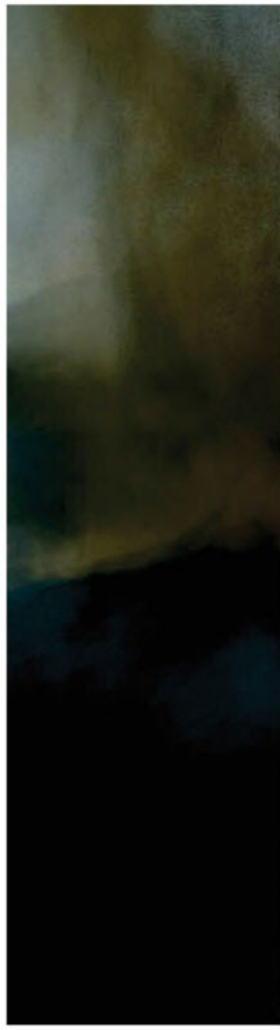
Another difficulty is working out what happened to bring lifeless chemicals together to form living organisms. Here we are faced with a chicken-and-egg situation: for DNA to do its thing it needs proteins, yet blueprints for those proteins are provided by the DNA. So which came first? The most likely 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 life began.

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**

EARTH'S STORY SO FAR



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.

With the possible exception of Mars, Earth is the only planet we know of that has plate tectonics. So what went right? Models have shown that for 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. Other conditions have to be right too: 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. So far, computer models have struggled to simulate conditions in which a break in the crust would spontaneously occur.

A hot mantle plume could have made the first hole, bursting up from below. Or perhaps an asteroid or comet was the trigger (see "Deeper impact", page 45), piercing the gooey surface layer on impact and setting up a chain of events that created the first moving plates (see diagram, left).

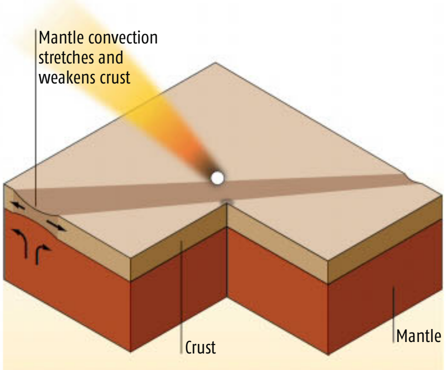
Another big unknown is when this might have happened. There is very little record in oceanic crust because most of it is not old enough – it is usually destroyed in subduction zones just 200 million years after being created at an ocean ridge. Yet evidence from oceanic crust that has avoided subduction 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 2007 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

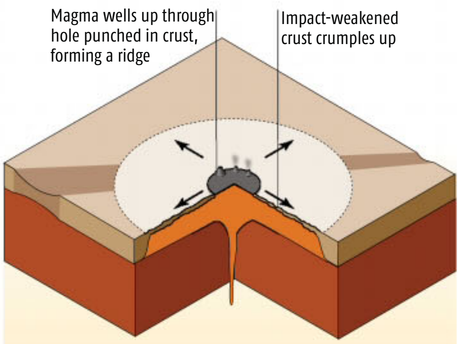
"For tectonics to get going, conditions have to be just right"

KICK-STARTING PLATE TECTONICS

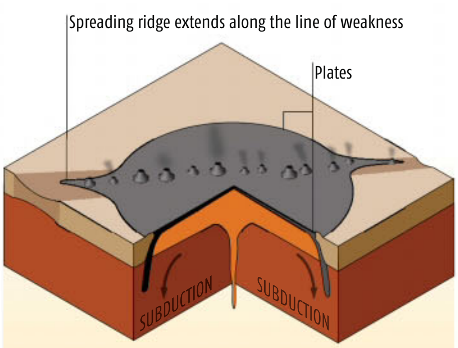
Asteroid strikes may have led to the creation of the subduction process



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

climate liveable (see "Why is Earth's climate so stable?", page 12).

Plate movement also makes oceans open and close, mountains rise and fall and continents gather and split. Every 500 to 700 million years, the continents come together to form a supercontinent. The last, Pangaea, existed 250 million years ago, and in roughly 250 million years another will come together (see "Pangaea, the comeback", page 40).

When these supercontinents slowly break up, separating landmasses and forming shallow seas, evolution goes into overdrive, forming countless new species that 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 fiery 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.

We do know that the core starts 2890 kilometres down and 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. 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 cooled enough to crystallise.

One mystery 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. 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 CO2 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 CO2 it is slightly acidic, and so 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 CO2 is baked out of them by the 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 CO2 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 CO2.

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.

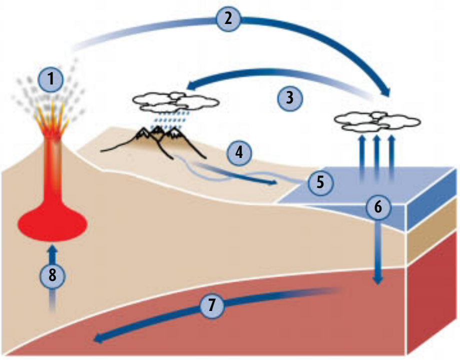
On Earth, the moon has played an additional role in keeping the climate habitable. It damps wobbles that would otherwise cause Earth's axis to tilt wildly. Even small wobbles are enough to launch ice ages, but the ones we have experienced are nothing compared to those on Mars, which flops over on its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

Life on Earth also plays its part. Many marine organisms use dissolved CO2 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 CO2 rises, causing an increased drawdown of CO2 into the ocean. This in turn causes a reduction in atmospheric CO2 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**

THE EARTH'S THERMOSTAT

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



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

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

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 plate boundaries, predicting when is much more difficult.

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. In 2007 Japan 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 earthquakes 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 a way that induces 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. Unusual cloud formations above faults immediately preceding an earthquake have also been suggested as a possible warning sign.

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 have 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.

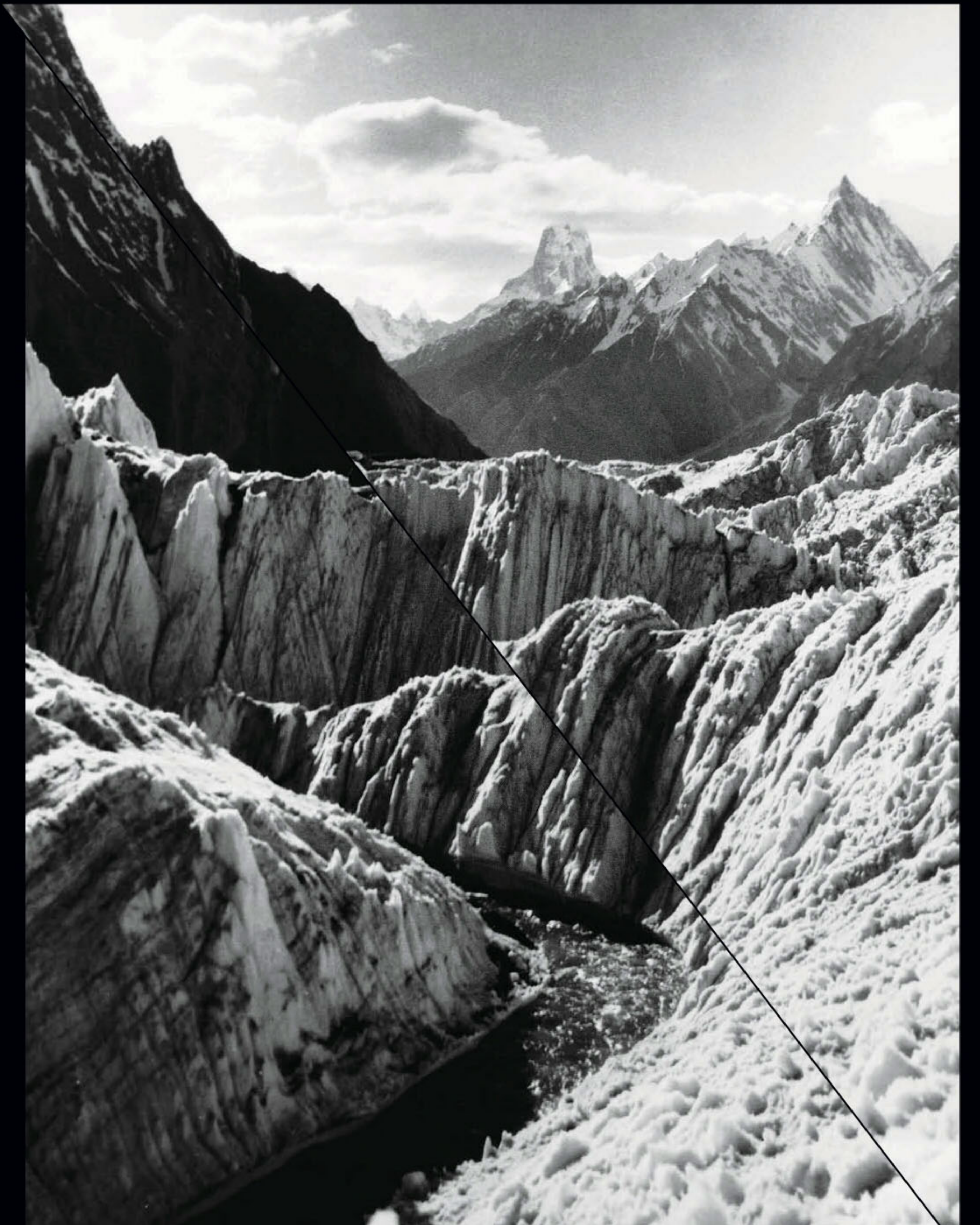
Although not all volcanoes give such clear signals, even the smallest of signs can now be used to predict eruptions. Subtle changes in the sound of the ocean were successfully used to forecast the eruption of Piton de la Fournaise on the island of Réunion in the Indian Ocean in July 2006 and April 2007. 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 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 (see "Earth shattering", page 48).

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 – Yellowstone in Wyoming and Campi Flegrei in southern Italy – are being monitored, 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**

(For more on earthquake prediction, see page 34)



RISE OF THE UPPER CRUST

Dry land was essential for life like us to evolve – but how did Earth evolve dry land? A unique landscape in Pakistan holds the clues, says **Jeff Hecht**

OLIVER JAGOUTZ doesn't have much room for rocks in his narrow tenth-floor office at the Massachusetts Institute of Technology. But the geologist keeps a couple of samples on hand to show visitors how Earth produces something unique in the solar system: continents.

The rocks come from a landscape half a world away, in the remote, hostile mountains of northern Pakistan. But they are a rare record of goings-on deep below Earth's surface. Along with three to four tonnes of other rocks from the region that Jagoutz and his colleagues have gathered over the years, they could hold the key to the enduring mystery of our planet's dry land – and much else besides.

Earth's surface is like no other in our solar system. Sitting atop the partially molten mass of the planet's mantle, like the frothy film on the surface of a simmering pot, are a series of vast slabs of solid rock: the tectonic plates of Earth's crust. That's strange enough, but the crustal plates also contain two rather different ingredients, as Jagoutz's samples show. The first – a heavy, dark rock called gabbro – is typical of the basalts that line the ocean basins. The second, a granite characteristic of Earth's continents, feels light by comparison.

DEAGOSTINI/GETTY

It's a small but crucial difference. Oceanic crust floats lower on top of the mantle and sinks back into it at subduction zones, where two tectonic plates collide. The oldest oceanic crust is just 200 million years old. The less dense continental crust, meanwhile, bobs higher like an iceberg on water. Plate collisions tend to push it upwards to form mountain ranges, so it can hang around much longer: the oldest known continental rocks are 4 billion years old.

For most of its history, Earth has had just enough water to lay a thin blue skin over the lower, but not the higher, parts of this surface. The relatively stable proportions of sea and land provided an environment unusually suited for complex life as we know it to develop over billions of years. Small wonder the interest in how this situation came about. "The holy grail of geology is to understand the first continental crust," says Jagoutz.

In numbers, the difference between oceanic and continental crust is small. Oceanic crust has a composition similar to that of the mantle, consisting of about 50 per cent silicates. The continental crust is the anomaly, with up to 60 per cent of these lighter minerals.

The continental material makes up a tiny part of Earth's bulk – by mass, it is about 0.5 per cent the size of the mantle – but something somewhere must have given it this fundamentally different composition. We think we know where this transformation occurs: above oceanic crust that is sinking into the mantle at a subduction zone. Heat and pressure squeeze fluid from the sinking crust, which rises and liquefies mantle rocks above. As this material continues to rise, it begins to separate out into lighter and heavier components. The lighter stuff eventually returns violently to the surface as volcanic magma, where it forms the basis of new continents. As for the heavier stuff, the thought was that it must sink, although where or how, no one could quite tell.

A process like this must have been going on since Earth was very young, and is thought to continue today near largely submarine fault lines where two tectonic plates converge and one subducts. A prominent example is the Izu-Bonin-Mariana ridge, an arc of volcanoes running 2800 kilometres south from Tokyo to the Mariana Islands and Guam, part of the "ring of fire" encircling the Pacific.

Drilling down into such areas could ›

"Drilling down into the crust, you are happy if you observe just the top 5 kilometres"

MYSTERY OF THE MISSING LEAD

The geological formations of Kohistan have already revealed chunks of heavy rock dropping off Earth's crust and into the mantle (see main story). But the region's unique geography could also answer a perennially thorny question: why Earth's composition doesn't seem to match that of any meteorites. Meteorites are made of the raw material left over from the solar system's construction phase that should also have gone into making our planet.

Taking an average of all known terrestrial rocks gives an unusual ratio of two kinds of lead isotope formed by the decay of radioactive uranium, compared with "primitive" lead that has been around since Earth formed. For decades, geologists have searched for a missing reservoir of rocks with high levels of primitive lead. "It has to be stored somewhere. It hasn't left the Earth," says Oliver Jagoutz of the Massachusetts Institute of Technology.

The falling chunks might be just that missing reservoir. Together with Max Schmidt of the Swiss Federal Institute of Technology in Zurich, Jagoutz examined the rocks from Kohistan and found that the material dropping back into the mantle contains between 6 and 40 times as much primitive lead as previously known upper mantle material brought to the surface through volcanic eruptions.

With such high levels of primitive lead, these sinking rocks need only make up a small percentage of the mantle to potentially explain the discrepancy. Totting up the balance sheet, terrestrial rocks would then be close to matching the elemental composition of a particular sort of meteorite known as a chondrite.

This could be a decisive piece of evidence in a long-running dispute about Earth's origins. Without having seen such rocks in the mantle directly, it's still far from an open-and-shut case, but Jagoutz is confident. "These are the rocks that were hidden in the mantle," he says - so heavy that they almost never reach the surface for geologists to find.

provide evidence to test the theory, but that is expensive and difficult, especially in marine environments. What's more, penetration depths are limited. "You can be happy if you observe just the top 5 kilometres," says Jagoutz.

As an Austrian who grew up in Germany and started researching volcanic arcs in Switzerland, Jagoutz was never particularly keen on life on the high seas anyway. "I don't like ships, so I don't go on them," he says. "I got seasick, and it was just not worth it."

Fortunately, Earth's past tectonic convulsions do provide some openings for a landlubber. On occasions, volcanic arcs have collided with continents, and the geometry of the collision has skewed their internal layers, forcing them upwards and spreading them horizontally, to be exposed on the surface following subsequent erosion.

Examples of these prostrated sections are found all along the Pacific coast of North America: in parts of Baja California in Mexico, the core of the Californian Sierra Nevada mountain range and much of Vancouver Island in Canada.

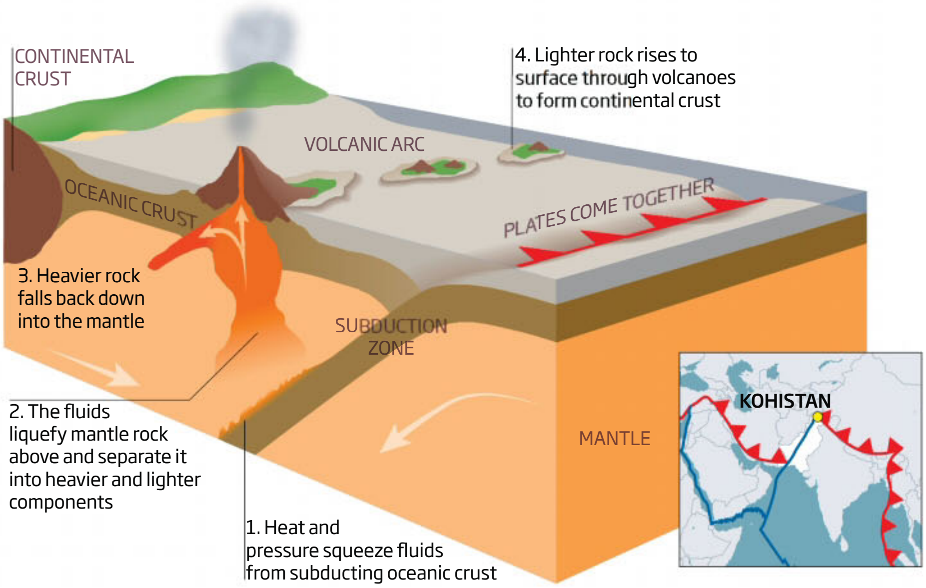
But none of these areas presents a continuous record – rocks from some eras are missing – nor do they extend down to the critical layer for the creation of the continental crust. This lies either side of a line known as the Mohorovičić Discontinuity, or "Moho" for short, which marks the point where the crust meets the mantle (see "Driller thriller", page 18). Typically 35 to 40 kilometres under continents and 7 to 10 kilometres beneath the sea floor, the Moho is marked by the change in density – shown in a change of speed in seismic waves – between the solid crust and the more mobile, slow-flowing rock below.

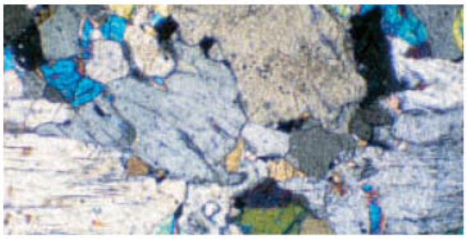
A first tantalising window on the deep opened up in 1989, when geologist Susan DeBari of Western Washington University in Bellingham was studying the Talkeetna volcanic arc, parts of which now lie exposed in south-central Alaska. The properties of some rocks there showed they must have formed at pressures and temperatures corresponding to depths of 30 to 35 kilometres, just at the line of the Moho. There was also evidence of a very dense sort of gabbro, containing as little as 45 per cent silica, that was heavier than the mantle rocks just beneath.

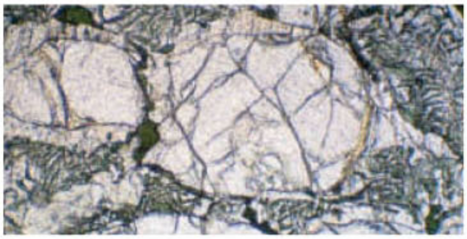
This looked very much like the heavier rock that would be the by-product of making the material of the continental crust. Its position in the exposed arc seemed to imply it would have gone on to sink down into the mantle, under the influence of gravity, had tectonic events not lifted it up and smeared it across the landscape instead. "That dropping-off at the bottom is really the key to creating continental crust," says DeBari. But it wasn't a clincher: only a few hundred metres of rock below the Moho were exposed, not enough to

Making a crust

In Kohistan, northern Pakistan, rocks that once underlay the boundary between tectonic plates are exposed at the surface. What they show could help to explain how light continental crust comes to exist







LEFT: JAGOUTZ ET AL RIGHT: PIERRE BOUILHOL

The rocks of Kohistan could hold the key to how Earth made its continents

show what was actually happening at the bottom of the arc.

A decade or so earlier, geologists had identified that formations in Kohistan, in the north-east of Pakistan, and the neighbouring Ladakh province in India were also remnants of an ancient volcanic arc. This had formed some 150 million years ago near the equator, close to a subduction zone in the now-vanished Tethys Ocean between Eurasia and what is now India. Subduction of the edge of the plate carrying India pulled the continent northward until it collided with the volcanic arc about 50 million years ago and began to bulldoze it in the same direction. Then, about 40 million years ago, India collided with Eurasia – with the volcanic arc squashed between.

This great continental train wreck, which also threw up the Himalayas, scooped a huge vertical section of the arc onto the top of the Eurasian continental crust, leaving chunks exposed horizontally in an eye-shaped region some 400 by 200 kilometres. In the millions of years since, continuing pressure crumpled it into mountains, resulting in Kohistan: a geological landscape unique on Earth.

When Jagoutz, then at the Swiss Federal Institute of Technology in Zurich, started investigating the Kohistan deposits in 2000, they "were described in a few different places, but nobody really studied them in great detail", he says. In the following years, he and a few colleagues went back to the region repeatedly, spending up to three months at a time mapping and studying rock formations, hiring jeeps or donkeys to reach sites and camping in the mountains. At the end of each season, they would haul a tonne or more of rock samples to the airport at Islamabad to ship them back to Europe.

In his office at MIT, Jagoutz opens an old paper map and traces the arc deposits with his finger, showing how the geometry of the continental collision bent the formation and spread it across the surface, and pointing to the thin line marking the suture between the arc and Eurasia. The ability to do fieldwork over such a large area was essential to get the big picture of the processes going on under the surface. "With square kilometres of outcrops, we can wander around and see what is representative and what is not," he says.

Sketching out that big picture has taken years of painstaking microscope work, analysing thin slices of the samples to identify their crystalline structure and chemical composition, revealing the depth at which they formed. Each sample was then carefully mapped back to the location where it was found. In this way, Jagoutz determined that the Kohistan rocks formed at a range of depths up to 50 kilometres down. Those further to the north came from shallower depths, while those further to the south originated deeper. "We have the whole sequence of the arc exposed," he says. "We can walk through the entire crust, essentially just by walking from north to south." The sequence in Kohistan goes all the way down to rocks that crystallised at the Moho – and even a little deeper.

"A great continental train wreck scooped a chunk of Earth out onto the surface"

The details proved complex, but it was clear that the Moho, at the time it got scooped to the surface, was shedding rock like nobody's business. About 70 per cent of molten rock in the zone of transformation was in the process of dropping off back into the mantle, forming a tail of heavy material. Dangling about a dozen kilometres down into the mantle, this stuff consisted of just 45 per cent silica and was enriched in heavy metals such as lead. Further up, lighter, high-silica rock was left to rise – and, had the continents not collided, some of it would eventually have erupted through volcanic openings on to the surface.

A mathematical model showed that chunks must have dropped off the base of the Kohistan arc as regularly as every few hundred thousand years. "In geological terms, something that happens in a hundred thousand years is momentary," says Jagoutz.

What makes Jagoutz's results revolutionary, says Peter Kelemen of the Lamont-Doherty Earth Observatory in Palisades, New York, is that they show how continental crust can be formed in a single step, not the several stages of chemical refinement previously assumed. Rock rising from the mantle mixes with fluid from subducted ocean crust and is distilled as it ascends, forming light continental crust, as well as a heavy slag that sinks back down (see diagram, page 16). "Oli's result is definitive, really cool," says Kelemen.

That's not all. The high lead content of the heavy rock exposed in Kohistan could shed fresh light on Earth's origin (see "Mystery of the missing lead", left). Analysis of the rocks of Kohistan is allowing the plate-tectonic forces that spread the volcanic arc across Kohistan to be reconstructed. The results could also explain the tremendous, puzzling force with which India slammed into Eurasia to throw up what is now the world's highest mountain range. A single subduction zone could only have tugged the two land masses together at a rate of 8 to 10 centimetres a year. India was travelling much faster than this – perhaps because the volcanic arc squashed in between the landmasses meant not one, but two subduction zones were doing the pulling. In a more controversial idea, the force could have come from an upwelling plume of hot material in the mantle (see "Earthly powers", page 26).

It is already an impressive haul from a few tonnes of rock. The sting in the tail is that there might be a limit to how much we can continue to refine these ideas at present. Jagoutz's last trip to Kohistan was in 2007, since when unrest has made the region less safe to travel to. The hope is that the samples he has already collected hold enough detail to continue to unpick the mystery of beneath. At least the landlubber Jagoutz can be sure he won't have to get on a boat. ■

Driller thriller

A bold plan is under way to dig into the Earth's mantle for the first time, and as Jheni Osman discovers, there may be surprises lurking down there

AN UNLIKELY explorer is floating off the east coast of Japan. At first glance, the colossal ship resembles a cross between a cruise liner and the Eiffel Tower. Perched on deck are a helipad, several large cranes and a huge scaffold tower around 30 storeys high (see picture, overleaf).

In the control room, a supervisor monitors the screens before setting the scaffold in motion. "Confirm the hole position," he says. Inside the tower, machinery whirs as the world's longest drill is lowered towards the ocean floor. Its ultimate destination, when it gets there, will be uncharted territory.

So goes a typical day on board Chikyu, a Japanese drilling vessel designed for deep-sea geology. If it isn't drilling into faultlines it is probing hydrothermal vents or underwater methane deposits. But ultimately the ship has a much more ambitious goal. Geologists are planning to use Chikyu to drill all the way through the crust and into the mantle to fetch a cache of rock samples. This feat has never been done before – in fact, no one has even come close.

If the project succeeds, it will be one of earth science's most spectacular ventures. Comparable to a moon shot, it could transform our understanding of our planet's evolution, and challenge the fundamental paradigms of earth science. There is even a chance that we will find something unusual lurking down there, something few would have thought possible until recently.

SAM WILLIAMS

This is not the first time geologists have yearned to explore the deep Earth. In 1909, Croatian meteorologist Andrija Mohorovičić discovered that seismic waves, triggered by earthquakes, travelled significantly faster below a depth of 30 kilometres than they did higher up, hinting that these deep rocks had different compositions and physical properties. With this discovery, Mohorovičić secured his place in the annals of science. This step change in seismic velocity was named the Mohorovičić discontinuity – aka the Moho – and marks the upper boundary of the mantle.

Geologists now know that the top of the mantle lies 30 to 60 kilometres beneath the surface of thick continental crust, and as little as around 5 km below the seabed at points where the crust is at its thinnest. What happens at those depths shifts tectonic plates, moulds the land we stand on, and unleashes the fury of earthquakes and volcanoes. It has therefore shaped all life on the planet – including us.

Yet it wasn't until the late 1950s that scientists felt the urge to investigate the mantle. At the time, the idea of plate tectonics was still hotly debated. Harry Hess of Princeton University and other early advocates of the theory claimed that hot convective currents from deep within the mantle were driving floating tectonic plates around the planet's surface. Hess and colleague Walter Munk felt hampered by the lack of physical evidence for the theory, and turned to some of their drinking buddies from the US National Academy of Sciences. At a wine-fuelled breakfast in California in April 1957, the so-called American Miscellaneous Society hatched a plan to fetch mantle samples. Project Mohole was born.

Numerous challenges had to be met – everything from finding funding to inventing the technology to keep a drilling ship stationary on the high seas. They couldn't borrow ideas from offshore oil companies – they weren't drilling in deep water at the time – so the Mohole team developed a technology called dynamic positioning, in which cleverly placed propellers and thrusters keep a ship stable and in place. The first core was drilled to 183 metres off the coast of Guadalupe Island in the Pacific in April 1961. It was also the last.

Soon after the expedition returned, the leading scientists were sidelined, management changed hands, costs spiralled, and a certain young politician called Donald Rumsfeld stuck his nose in. In 1966, Project Mohole folded after the US Congress voted to drop its funding.

Despite this, drilling into oceanic crust did continue. Still, we have never got further than about a third of the way to the mantle. The closest a drill has got is a 1507-metre borehole off the coast of Costa Rica, known prosaically as Site 1256. It's not the deepest hole ever but the crust there is estimated to be less than 5.5 kilometres thick. Some boreholes on land extend much deeper from the surface, but since continental crust is far thicker, their deepest points are tens of kilometres from the mantle.

In 2011, some of the geologists behind Site 1256 decided it was time to revive Hess and ›

Munk's ambitions. A new Project Mohole – called Mohole to Mantle – was launched.

As far as the geologists behind the project are concerned, there is a clear scientific rationale to firing up the drill once more. After all, while the mantle makes up 68 per cent of the Earth's mass, we actually know very little about it. "There are currently no pristine mantle samples, so we just have hints of what's going on," says Damon Teagle at the UK's National Oceanography Centre in Southampton, who is part of the international team working on the Japanese-led project.

Some samples have reached the surface, but they are all contaminated. For example, rare rocks called mantle nodules have erupted in volcanoes, showing the mantle is made of magnesium-rich, silicon-poor minerals like olivine and pyroxene.

And in some parts of the ocean floor, rocks that were once part of the mantle lie exposed, but contact with seawater has changed their composition dramatically. Think of these samples as the difference between Martian meteorites and actual rocks picked up from the Red Planet. Without fresh samples, geologists struggle to confirm even simple facts about our planet, including what exactly the mantle is made of, how it formed and how it works.

Precious stones

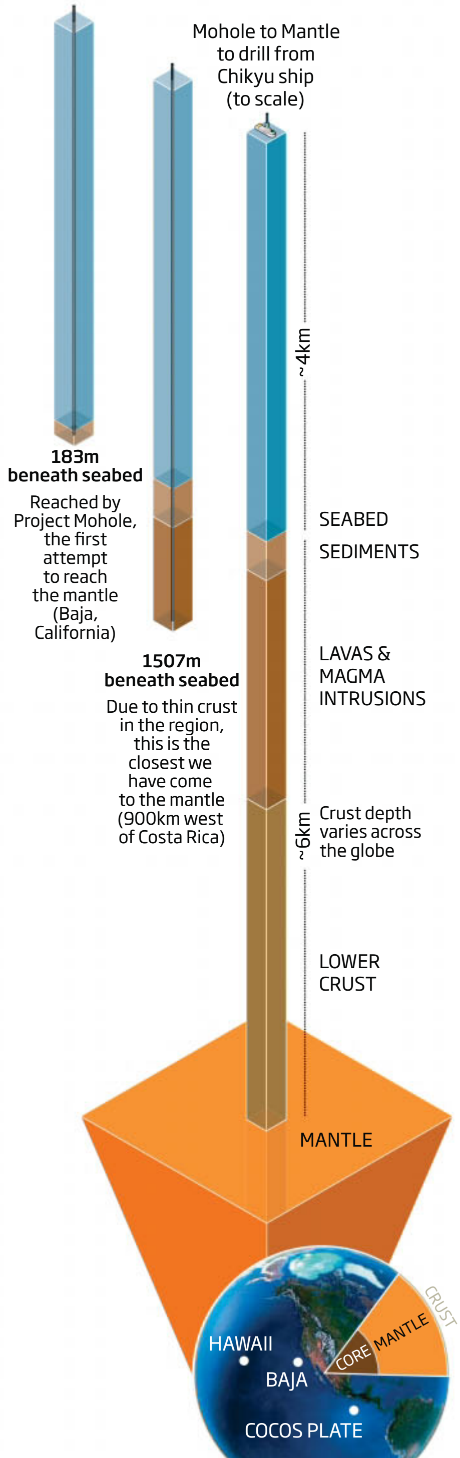
Instead, they have had to piece together their theories about the mantle using indirect evidence. Its broad layering structure is inferred by tracking the speed of seismic waves, as Mohorovičić did. Further clues to its composition have come from meteorites, which were forged from the same cosmic debris as our rocky planet, or more recently via exotic methods such as looking at the neutrinos produced during the radioactive decay of certain elements (see "Messengers from the underworld", page 22).

Many questions remain unanswered, however. Getting our hands on tracers of mantle convection, such as noble gases and isotopes, would reveal how and when our planet differentiated into the core, mantle and crust, and when plate tectonics started. Identifying the chemicals and isotopes that make up the upper mantle would show how water, carbon dioxide and energy are transferred to the crust, and how they influence global geochemical cycles. And finding out how heterogeneous the mantle is would reveal how magma wells up and then erupts onto the sea floor at mid-ocean ridges.

Perhaps the most extraordinary thing we

Digging deep

Geologists have never drilled more than one third of the way to the mantle, but that may change with the Mohole to Mantle project, which aims to sample this molten rock



The proposed Mohole to Mantle drilling sites have shallow water, cool rocks and a thin crust

Chikyu will join a select group of vessels taking explorers to new realms

might find in the mantle is life. While any creatures won't quite live up to the prehistoric monsters envisioned by Jules Verne in *Journey to the Centre of the Earth*, they would still be significant. Recent discoveries suggest such extremophiles might be possible.

In 2011, Tullis Onstott at Princeton University uncovered microscopic roundworms, known as nematodes, living an incredible 4 km below the surface in a gold mine in South Africa. Considering their size, Onstott likened the discovery to finding Moby Dick in Lake Ontario. He has also found single-celled microbes at even greater depths – up to 5 km down.

Life also thrives deep under the sea floor. Microbes have been recovered from a mud core drilled to over 1.6 km down off the east coast of Canada. The researchers who found them speculate they might be hundreds of millions of years old. "We showed that the bacteria might be dividing as slowly as, say, once in 100,000 years," says John Parkes of Cardiff University, UK.

Pressure does not seem to be a problem for many extremophiles. In the lab, microbes can tolerate up to 1000 atmospheres, and there are bacteria living happily under 11 km of water in the Mariana Trench in the western Pacific. In fact, pressure is crucial for survival in searing hot conditions, because it stops water boiling – steam can be a killer.

So temperature could be the deciding factor. Just below the Moho, geologists believe it could be as low as 120 °C. "This is tantalisingly close to the known upper limit for life: 122 °C," says Parkes. An organism living on hot ocean vents was shown to be capable of growing at

this temperature in 2008.

Still, Matt Schrenk at Michigan State University in East Lansing, who studies microbiology in extreme environments, thinks the chances of finding mantle life are slim. Apart from the heat, he says, fluid circulation will be minimal, so the flow of nutrients would be too.

Despite his doubts, Schrenk supports the Mohole to Mantle project because he thinks it could define the physiological limits of life – and even help the study of climate change since the biosphere down there may influence the circulation of the "deep" carbon cycle. Deep life could also prove useful in medicine. "If the organisms are evolutionarily distinct, they could carry out unique activities or possess unique enzymes that could be of use in biotechnology," he says.

Mantle samples could also help us unravel the role of microbial life in the evolution of our planet. Geophysicist Norman Sleep at Stanford University in California has found that life can be dragged into the crust by the process of subduction – and its products, such as ammonium, can be sucked even further down. Essentially, all the nitrogen in the mantle comes from subducted ammonium in organic matter. This raises the possibility that life on the very early Earth changed the composition of the mantle – and useful samples for studying life in this period might still be down there.

At the National Oceanography Centre, Teagle and colleagues have been helping to assemble all of these scientific reasons for the Mohole to Mantle project. Teagle says it's not surprising that it has taken decades to pick up where Project Mohole left off. "Technology, time and money were previously the limiting factors to drilling to the mantle," he says.

First, consider the accuracy required to drill 6 km into the crust beneath the ocean floor. "It will be like lowering a piece of steel string the width of a human hair to the bottom of a 2-metre-deep swimming pool," says Teagle, "and then drilling 3 metres into the foundations." That means a new extra-long drill will have to be built for Chikyu, which cannot reach such depths at the moment.

"It's like lowering a thin hair into a swimming pool and drilling it 3 metres into the foundations"

BOTH PHOTOGRAPHS JAMSTEC

Many pipes sheath the drill between the ship and the ocean floor

New materials will also be required. When drilling a 30 centimetre-wide hole in hard igneous rock at a speed of 1 metre an hour, drill bits only last about 50 hours. They can also fail catastrophically and be ground into smooth stumps. The uber-tough materials being developed for the project will need to cope with pressures of 2 kilobars and temperatures of up to 250 °C.

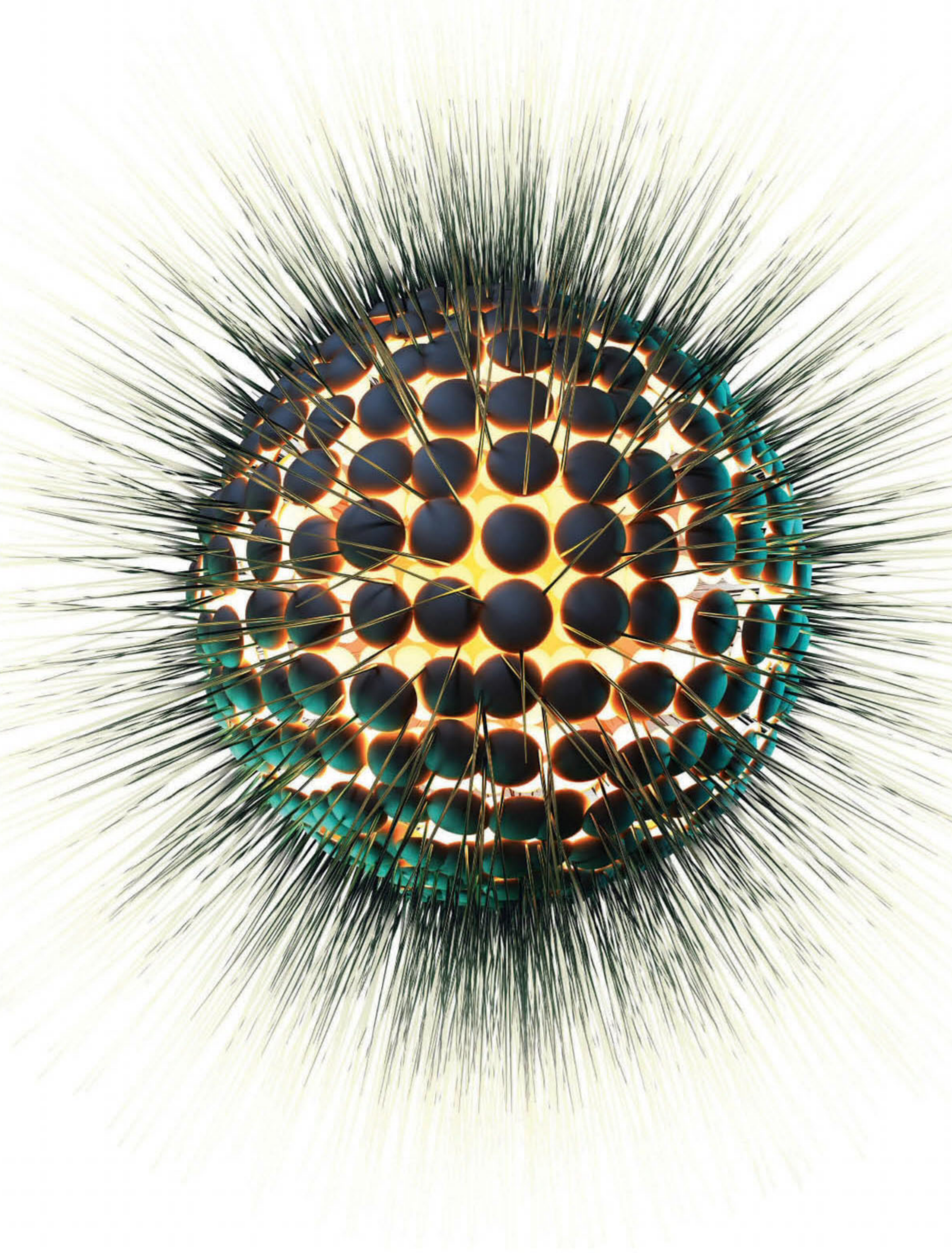
The good news is that an independent review carried out in 2011 by Blade Energy, a deep-water drilling firm, concluded that the project is technically feasible. "It always used to be that an engineer would invent some gadget and then ask scientists whether they could use it in some way. More and more now, the needs of science are driving technology," says Teagle.

In fact, whether the plan succeeds relies less on technology and more on political and scientific will. Teagle reckons the operation of the research vessel alone will cost at least $1 billion. Fortunately, the Japanese government is committed to covering a significant portion of these costs. While this is a big investment, it is understandable considering that Chikyu might eventually help with earthquake forecasting. And it's not only the Japanese who are getting behind the project – others have expressed interest too.

Progress has been slow, but the project team hopes to strike mantle gold within a decade. First, a decision needs to be made on which of the three potential drilling sites to choose. They are all in the Pacific – one candidate includes the original Project Mohole site – and each one is relatively close to mid-ocean ridges, where new crust forms. Rising magma pushes up the seabed here, making the water shallow enough to reach down with a drill.

The rocks at the three sites have also cooled down enough to penetrate safely and, crucially, the crust formed quickly, so it should be reasonably uniform – which will make drilling easier.

Getting to the mantle is going to be extraordinarily tough, but Teagle sees the project as vital to answering some of the biggest questions challenging geologists today. It will give us a significantly better understanding of how our planet evolved, he says, as well as defining the limits of life. "The project will require a space-mission level of planning, but will cost a fraction of going back to the moon or returning rocks from Mars. Yet a pristine mantle sample would be a geochemical treasure trove, like bringing back the Apollo rocks." ■



Messengers from the underworld

Neutrinos escaping Earth's bowels have fascinating tales to tell about our planet – if only we can catch them. **Anil Ananthaswamy** goes hunting

WILLIAM MCDONOUGH doesn't mince his words about our attempts to get to grips with the lump of rock we call home. "Think of it as many blind people grabbing an elephant," he says. While we learn ever more of other worlds in our solar system and beyond, our picture of the Earth beneath our feet remains surprisingly sketchy. What exactly is it made of? How did it form? We are left groping for answers.

McDonough, a geochemist at the University of Maryland, aims to change that. His goal is to shed light on the planet's most mysterious region – the vast netherworld of mantle that lies between the hot central core and thin outer crust. Light, though, is not McDonough's thing: he and his colleagues are planning to get their answers using neutrinos. Implausible as it might sound, these reclusive particles could be just the thing to spill the beans about our planet's past and present. There is just one proviso: we have to catch enough of them first.

It is not that we know absolutely nothing about the elephant below. We know that about 4.6 billion years ago, in an outer spiral arm of the Milky Way, a dense cloud of hydrogen gas and dust began to collapse in on itself. Its centre ignited to make the sun, while farther out grains of dust slowly coalesced to form larger and larger solid bodies. A few million years later, some of them had grown big enough to form rocky planets.

We also know roughly what went into making these planets. The sun is mostly hydrogen and helium, volatile elements that would not contribute much to a rocky planet. But spectroscopic studies of the sun's surface also reveal heavier, less volatile elements, among them oxygen, carbon, iron, silicon, aluminium and magnesium. Meteorites – rubble left over from the planetary construction works – periodically rain down on us and contain a broadly similar inventory. These materials, then, are the substance of our planet.

What lies beneath

But how much of each element is there, and where are they? Studies of the planet's magnetic field, and of seismic waves passing through Earth's core, indicate that it is a partially molten mix of iron and nickel. Various scratchings and scrapings of Earth's outermost crust show it consists mostly of various oxide and silicate minerals (see diagram, page 25).

So far, so good. But what lies between core and crust, in the huge bulk of Earth's mantle? The mantle makes up about two-thirds of the planet's total mass. Knowing its composition would improve immeasurably our idea of Earth's chemical inventory and give us clues about conditions when it formed. Depending on the surrounding temperature, subtly varying amounts of different elements would have condensed out of the solar nebula into solid matter. Knowing how those elements are spread in the mantle now – homogeneously, in patches of different compositions or in layers – will also tell us whether the whole mantle is a churning mass constantly redistributing matter and heat. This would give us a better handle on what drives processes such as plate tectonics and volcanism.

Clues about the mantle's composition are currently limited to rock samples ejected by volcanoes or left exposed when portions of tectonic plates fail to slip neatly below one another at plate boundaries. Such rocks are seen in some mountain ranges towards the edges of continents such as the Pyrenees in Europe and the Japanese Alps. But are they representative of the whole mantle or just its uppermost layers? To find out, we need a way of analysing material far beyond the magma chambers of volcanoes or the reach of conventional drills.

Enter – or rather exit – neutrinos.

Neutrinos are the neutral, near-massless particles that hit the headlines in 2011 for their do-they-don't-they flirtation with breaking the speed of light (it turned out they don't). But they – or more precisely an antimatter variant called electron antineutrinos – are also spewed out in vast numbers by chains of radioactive decays originating with uranium and thorium nuclei, in rocks far down in Earth's interior.

How does this help? Because like silicon and all those other elements, uranium and thorium were present, albeit in smaller amounts, in the solar nebula, and would have condensed out in different amounts at ›

"By tracing uranium and thorium in the mantle, we can begin to understand Earth's inner machinations"

different temperatures. If we knew how much uranium and thorium went into making Earth, we would know what these conditions were and could extrapolate how much of everything else we would expect to find inside. By tracing where in the mantle uranium and thorium are distributed, we can also begin to understand our planet's inner machinations. "The key to understanding Earth models is to find out where and how much uranium and thorium are in the mantle," says geophysicist Steve Dye of the Hawaii Pacific University in Kaneohe.

And there is no better way of doing that than by counting the "geoneutrinos" that their decays produce. Because they hardly interact with normal matter, these particles race unimpeded through Earth's interior, allowing detectors near the surface to snag them as they leave.

In principle, at least. In practice, that same flightiness makes neutrinos far more likely to pass through our detectors too. Geoneutrino hunting takes skill and a lot of patience.

Fortunately, we have spent more than a decade developing that. The Kamioka Liquid-Scintillator Antineutrino Detector (KamLAND), which came into service near the central Japanese city of Hida in 2002, consists of 1000 tonnes of a transparent liquid solution that, when hit by a neutrino, emits a flash of light. It is situated 1 kilometre down, the better to shield it from cosmic-ray muons, whose signals mimic those of neutrinos.

In 2005, KamLAND saw the first, faint signal of electron antineutrinos from Earth's bowels, but it was drowned in a din of antineutrinos produced by nearby nuclear power plants. In 2007, a detector upgrade and the temporary shutdown of one of the largest nuclear plants allowed the signal to shine through. By the end of 2009, KamLAND had recorded 106 electron antineutrinos with the right energy to come from decays of uranium and thorium within Earth.

Meanwhile, the Borexino experiment was also getting glimpses. Situated at the Gran Sasso National Laboratory in central Italy, this smaller detector was built to pick up neutrinos from nuclear processes in the sun. Combining data from the two experiments was enough to produce the first concrete geophysical predictions from geoneutrinos alone: that the decay of uranium and thorium in the mantle and crust contributes about 20 terawatts (TW) to the heat escaping from Earth's interior.

These are the sorts of numbers we need if we are to start outlining what lies beneath. Earth radiates about 46 TW of heat through its surface, from two sources: "radiogenic" heat produced in radioactive decays, and "primordial" heat stored up during Earth's formation as particles collided and iron sank to the core. Establishing how much surface heat comes from each source has wide ramifications for our picture of Earth. For example, if material in the mantle is convecting slowly, or in layers with limited heat transfer between them, little primordial heat will be transported from Earth's innards to its surface. If so, the lion's share of Earth's heat flux – 30 TW or more – must be of radiogenic origin. The neutrino experiments suggest the true figure is lower, implying that the mantle is mixing relatively thoroughly.

Hidden puzzles

The radiogenic heat flux also indicates that the planet has an overall uranium content of some 20 parts per billion. Exposed mantle rocks contain similar amounts of uranium, suggesting that they are indeed representative of the mantle, and backing up the idea that the entire mantle is mixing efficiently. But it also hides a puzzle. The exposed mantle rocks are dominated by a magnesium iron silicate mineral, olivine, and their uranium content is appreciably higher than that of a class of meteorite called enstatite chondrites. These meteorites have long been thought to be representative of the material that made Earth, and are dominated by another silicate material, pyroxene. That raises the question of where this pyroxene-dominated material is – hidden in pockets deep in the mantle, perhaps? Or is Earth's composition different from that of enstatite chondrites?

The ratio of olivine to pyroxene in Earth's mantle is crucial to pinning down where and when the planet formed in the solar nebula. Olivine would have precipitated out at a slightly higher temperature than pyroxene, so there would have been more of it closer to the sun, or earlier in the planetary construction process when temperatures were higher.

We are still a way away from the answers. With the numbers of geoneutrinos as yet spotted, there is a lot of wiggle room in the estimate of radiogenic heat flux: the 20 TW figure comes with a quoted error of about ±9 TW, making it hard to discount any scenario of mantle composition or mixing. KamLAND and Borexino alone are unlikely to put the debate to rest. A third detector, due to switch on in 2015, could make a decisive difference.

This is SNO+, situated deep underground at the Sudbury Neutrino Observatory in Ontario, Canada. It is about the same size as KamLAND, but because it is under 2 kilometres of rock, it

INSIDE SOURCES

Hunters of "geoneutrinos" from inside the Earth (see main story) are wearily familiar with confounding sources of neutrinos, from cosmic rays to nuclear reactions in the sun and our own nuclear plants. But to map goings-on inside Earth's mantle, we also need to rule out neutrinos from Earth's crust and core.

The crust is thin relative to the mantle, but its proximity to underground detectors means its geoneutrino signal can overwhelm the one from the mantle. While a student at the University of Maryland, College Park, Yu Huang used geological and seismic data to characterise the crust's rock formations right down to the mantle boundary in a region centred on Canada's next-generation SNO+ neutrino experiment. The aim was to estimate how much uranium and thorium is there, and so how many neutrinos their decays are likely to produce.

"If we can pound down the uncertainty of the composition of the continental crust in the area around SNO+, we can improve on what would be the signal coming from the Earth's mantle," says William McDonough, who was Huang's supervisor.

Meanwhile, the core seems to have gone quiet. Not too long ago, geophysicists thought it likely that there was enough uranium in the core to make it a giant nuclear fission reactor. But simulations done by McDonough and his colleagues show that at the high temperatures and pressures found in the magma oceans that filled early Earth, uranium almost exclusively prefers the company of elements found in mantle-like rocks to the iron and nickel of the core.

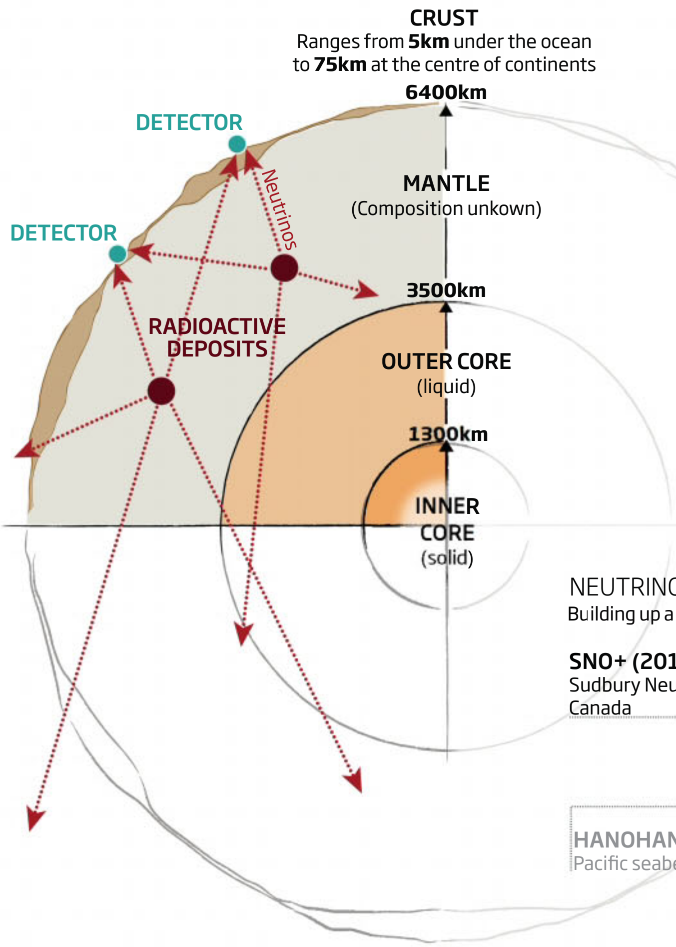
Nuclear fission also produces neutrinos that are higher in energy than those produced by the radioactive decay of uranium and thorium. The Borexino experiment at the Gran Sasso National Laboratory in Italy has put an upper limit on such neutrinos from a natural reactor in the Earth's core, attributing at most a comparatively measly 3 terawatts of surface heat to such processes.

Mantle mysteries

The composition of Earth's mantle, which comprises most of the planet, is unknown. Neutrinos emitted by radioactive deposits within it will tell us how much of each element the mantle is likely to contain and also whether it moves and mixes, or stays solid and stationary

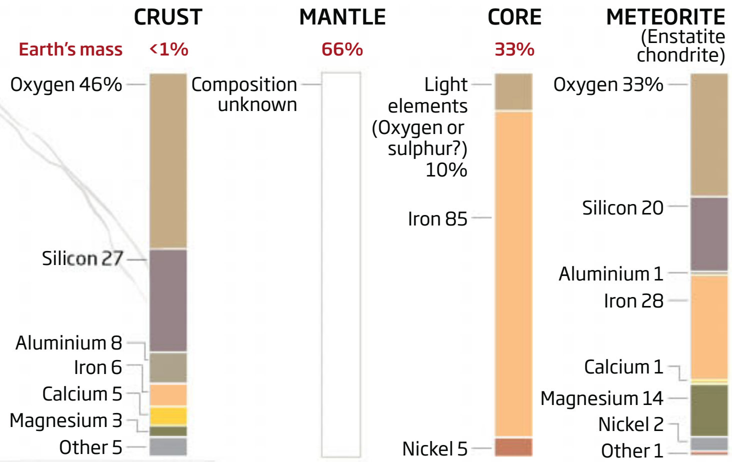
DETECTING NEUTRINOS

Neutrinos pass unimpeded through Earth's interior, and can be picked up by detectors near the surface



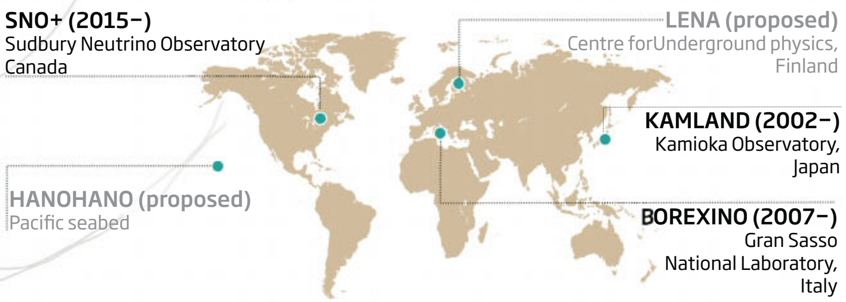
METEORITE MATCH

If the overall composition of the crust, mantle and core add up to the same as that of meteorites formed at the same time, it will tell us much about the conditions in which our planet formed. To match the meteorites, the mantle will have to be dominated by oxygen and silicon, with a generous dash of magnesium and iron



NEUTRINO NETWORK

Building up a 3D picture of neutrino emissions will require many detectors dotted across the globe



will be better protected from cosmic ray muons. And, says McDonough, "it is not surrounded by a thousand neutrino flashlights": there are far fewer nuclear reactors in Ontario than Japan. With lower background counts, SNO+ should observe geoneutrinos by the bucketful – by neutrino standards, anyway. "It'll probably get 25 geoneutrinos per year," says Dye. Over a few years, that might be enough to shrink the error on the radiogenic heat measurement and start building some certainties.

That is just the beginning. Ideally, we want to map where geoneutrinos come from, and so get a finer-grained picture of the distribution of uranium and thorium and the homogeneity and mixing of the mantle. That means cutting out geoneutrinos from other sources, such as the crust and core (see "Inside sources", left), and will require a network of detectors looking for neutrinos coming up from different places and at different angles. This would allow us to find out more about

> **"All it takes is one unlikely thing, and our vision of how the planet functions and evolved could change"**

peculiar regions of the mantle, such as the "super-plumes" below Africa and the Pacific Ocean that have been invoked to explain anomalous areas of volcanism. The velocity of seismic waves drops dramatically through these regions, which seem to extend from the mantle-core boundary half the way to the surface, suggesting that they are less viscous and perhaps therefore hotter. That might be because they contain larger amounts of decaying uranium and thorium. If so, they should be geoneutrino hotspots.

An ambitious project proposed by John Learned of the University of Hawaii at Manoa, supported by Dye and McDonough, would help settle such questions. The Hawaiian Anti-neutrino Observatory, or Hanohano, is a detector designed to be taken out on a barge and dropped down to the ocean floor. The water overhead would protect the detector from confounding cosmic-ray muons. What's more, the ocean floor has the thinnest crust, with a uranium content 10 times less than that of the continental crust. A detector there will essentially see a pure mantle signal. Others have proposed constructing a detector called LENA, most likely to be sited in Finland.

That is for the future, but geoneutrinos offer some answers for the taking. "All it would take is for us to find one seemingly unlikely thing, and it could change our vision of how the planet functions and has evolved," says Learned. And what is true for one planet in an undistinguished spiral arm of the Milky Way could also inform our ideas of how similar planets formed elsewhere, and under what conditions. Reason enough to let neutrinos loosen our blindfolds, and give us a better view of this planetary elephant of ours. ■

KRISTOF EMORY/NATIONAL GEOGRAPHIC

Earthly powers

Plate tectonics can't explain everything, so what else is shaping our planet's surface? **Anil Ananthaswamy** investigates

"A LOT of people thinks that the devil has come here. Some thinks that this is the beginning of the world coming to a end."

To George Heinrich Crist, who wrote this on 23 January 1812, the series of earthquakes that had just ripped through the Mississippi river valley were as inexplicable as they were deadly. Two centuries on and we are no closer to an understanding. According to our established theory of Earth's tectonic activity, the US Midwest is just not the sort of place such tremors should occur.

That's not the only thing we are struggling to explain. Submerged fossil landscapes off the west coast of Scotland, undersea volcanoes in the south Pacific, the bulging dome of land that is the interior of southern Africa: all over the world we see features that plate tectonics alone is hard pressed to describe.

So what can? If a new body of research is to be believed, the full answer lies far deeper in our planet. If so, it could shake up geology as fundamentally as the acceptance of plate tectonics did half a century ago.

The central idea of plate tectonics is that Earth's uppermost layers – a band of rock between 60 and 250 kilometres thick known as the lithosphere – is divided into a mosaic of rigid pieces that float and move atop the viscous mantle immediately beneath. The theory surfaced in 1912, when German geophysicist Alfred Wegener argued on the basis of fossil distributions that today's continents formed from a single supercontinent, which came to be called Pangaea, that broke up and began drifting apart 200 million years ago.

Wegener lacked a mechanism to make his plates move, and the idea was at first ridiculed.

Iceland's volcanoes may be the product of rising plumes in the mantle

But evidence slowly mounted that Earth's surface was indeed in flux. In the 1960s, people finally came to accept that plate tectonics could not only explain many features of Earth's topography, but also why most of the planet's seismic and volcanic activity is concentrated along particular strips of its surface: the boundaries between plates. At some of these margins plates move apart, creating rift valleys on land or ridges on ocean floors, where hotter material wells up from the mantle, cools and forms new crust. Elsewhere, they press up against each other, forcing up mountain chains such as the Himalayas, or dive down beneath each other at seismically vicious subduction zones such as the Sunda trench, the site of the Sumatra-Andaman earthquake in December 2004.

And so plate tectonics became the new orthodoxy. But is it the whole truth? "Because it was so hugely successful as a theory, everybody became a bit obsessed with horizontal motions and took their eye off an interesting ball," says geologist Nicky White at the University of Cambridge.

That ball is what is happening deep within Earth, in regions far beyond the reach of standard plate-tectonic theory. The US geophysicist Jason Morgan was a pioneer of plate tectonics, but in the 1970s he was also one of the first to find fault with the theory's explanation for one particular surface feature, the volcanism of the Hawaiian islands.

These islands lie thousands of kilometres away from the boundaries of the Pacific plate on which they sit. The plate-tectonic line is that their volcanism is caused by a weakness in the plate that allows hotter material to well up passively from the mantle. Reviving an earlier idea of the Canadian geophysicist John Tuzo Wilson, Morgan suggested instead that a plume of hot mantle material is actively pushing its way up from many thousands of kilometres below and breaking through to the surface.

Mapping the underworld

That went against the flow, and it wasn't until the mid-1980s that others began to think Morgan might have a point. The turnaround came when seismic waves unleashed by earthquakes began to reveal some of our underworld's structure as they travelled through Earth's interior.

Seismic waves travel at different velocities through materials of different densities and temperatures. By timing their arrival at sensors positioned on the surface we could begin to construct a 3D view of what sort of material is where.

The resulting images are rough and fuzzy, but seem to reveal a complex, dynamic mantle. Most dramatically, successive measurements have exposed two massive piles of very hot, dense thermochemical material sitting at the bottom of the mantle near its boundary with Earth's molten core. One is under the southern Pacific Ocean, and one beneath Africa. Each is thousands of kilometres across, and above each a superplume of hotter material seems to be rising towards the surface.

That could explain why the ocean floor in the middle of the southern Pacific lies some 1000 metres above the surrounding undersea topography, another thing plate tectonics has difficulty explaining. Something similar goes for the African plume. "If you go south of the Congo all the way down to southern South Africa, including Madagascar, that whole region is propped up by this superplume," says White.

Seismic imaging reveals smaller plume-like features extending upwards in the upper ›

"It's very difficult to decipher the history of the Earth in deep time, over hundreds of millions of years"

reaches of the mantle beneath Iceland and Hawaii – perhaps explaining both these islands' existence and their volcanism.

Off the coast of Argentina, meanwhile, the sea floor plunges down almost a kilometre, directly above a mantle region that seismic imaging identifies to be cold and downwelling. And although southern Africa is being propped up by its superplume, smaller hot upwellings and cold downwellings at the top of that plume seem to correspond with local surface topography. The Congo basin, for instance, lies on a cold area and is hundreds of metres lower than its surroundings. "Africa has quite an egg-box shape," says White.

Almost everywhere we look, there is evidence of vertical movements within Earth reshaping its surface. "At the time plate tectonics was formed, the deep interior was unknown, so people drew cartoons," says Shun-ichiro Karato, a geophysicist at Yale University. "This is beyond cartoons."

What is less clear is how the mechanisms work. Standard plate-tectonic theory has it that material plunging into the mantle at subduction zones is recycled in the shallow mantle, reappearing through volcanic activity near the subduction zone itself or further afield at boundaries where two plates are being pushed apart. Blurry yet tantalising images, however, show sections of subducted plates at various stages of descent through Earth's interior towards the lower mantle (see diagram, right).

That material clearly can't all stay down. "You need to preserve the mass balance of the mantle," says Dietmar Müller of the University of Sydney, Australia. "As you are stuffing plates down into the mantle, that initiates a return flow of material going up."

But how exactly? Simulations performed in 2011 by Bernhard Steinberger at the GFZ German Research Centre for Geosciences in Potsdam and his colleagues show how a subducted slab, once it arrives at the boundary between the mantle and the core, can bulldoze material along that layer. When this material meets a thermochemical pile, plumes begin to form above.

"We can see plumes developing at more or less the right places," says Steinberger. For example, their model shows that slabs being subducted beneath the Aleutian Islands near Alaska could trigger a plume beneath Hawaii, creating a hotspot that fuels the Hawaiian volcanoes.

Fossil landscape

Meanwhile, Clint Conrad at the University of Hawaii at Manoa and his colleagues have modelled the effect of a tectonic plate moving one way while the mantle beneath is moving in the other direction. They found that if this "shearing" effect occurs in a region where the mantle varies in density or the overlying plate changes in thickness, it can cause mantle material to melt and rise. This model accurately predicts that volcanic seamounts are present on the west but not the east of the East Pacific Rise, a mid-ocean ridge that runs roughly parallel to the western coast of South America. Seismic measurements indicate that the mantle and the plate to the west are moving in opposite directions; to the east they are not. The model also predicts that the shearing effect is largest under the western US, southern Europe, eastern Australia and Antarctica – all areas of volcanic activity away from plate boundaries.

If the dynamics of the deep Earth can change surface topography today, the same must have been true in the past. But while fossil and geological records tell us how drifting plates remapped the planet's surface over eons, seismic imaging only works for the here and now.

"It's more difficult to decipher the history of the Earth in deep time, over hundreds of millions of years," says Müller.

White and his colleagues found some clues to a small part of the story off the west coast of Scotland in 2011. They set off explosions from a ship and recorded the reflected waves, to get a sense of what lies beneath the sea floor. What they saw buried under more recent layers of rock and sediment were fossil landscapes some 55 million years old, replete with hills, valleys and networks of rivers. "They look just like somewhere you could go for an afternoon walk," says White – only they are 2 kilometres beneath the seabed.

By analysing the way these rivers had changed course over time, the team showed that the region was once pushed almost a kilometre above sea level before being buried again, all in the space of a million years. That is far too quick for plate tectonics to throw up a mountain range and have erosion wear it down again.

Instead, White points his finger at a blob of hot mantle material that he says travelled radially outwards from the mantle plume that is possibly fuelling the volcanoes in nearby Iceland. "If the plate is like a carpet, rats running underneath the carpet would make it go up and down," he says.

Müller's team has identified similarly precipitous vertical movements of the land that is now in eastern Australia, during the Cretaceous period between 145 and 65 million years ago. Again, the timescales involved more or less discount simple plate tectonics. "We are pretty sure this has something to do with a convecting mantle," says Müller.

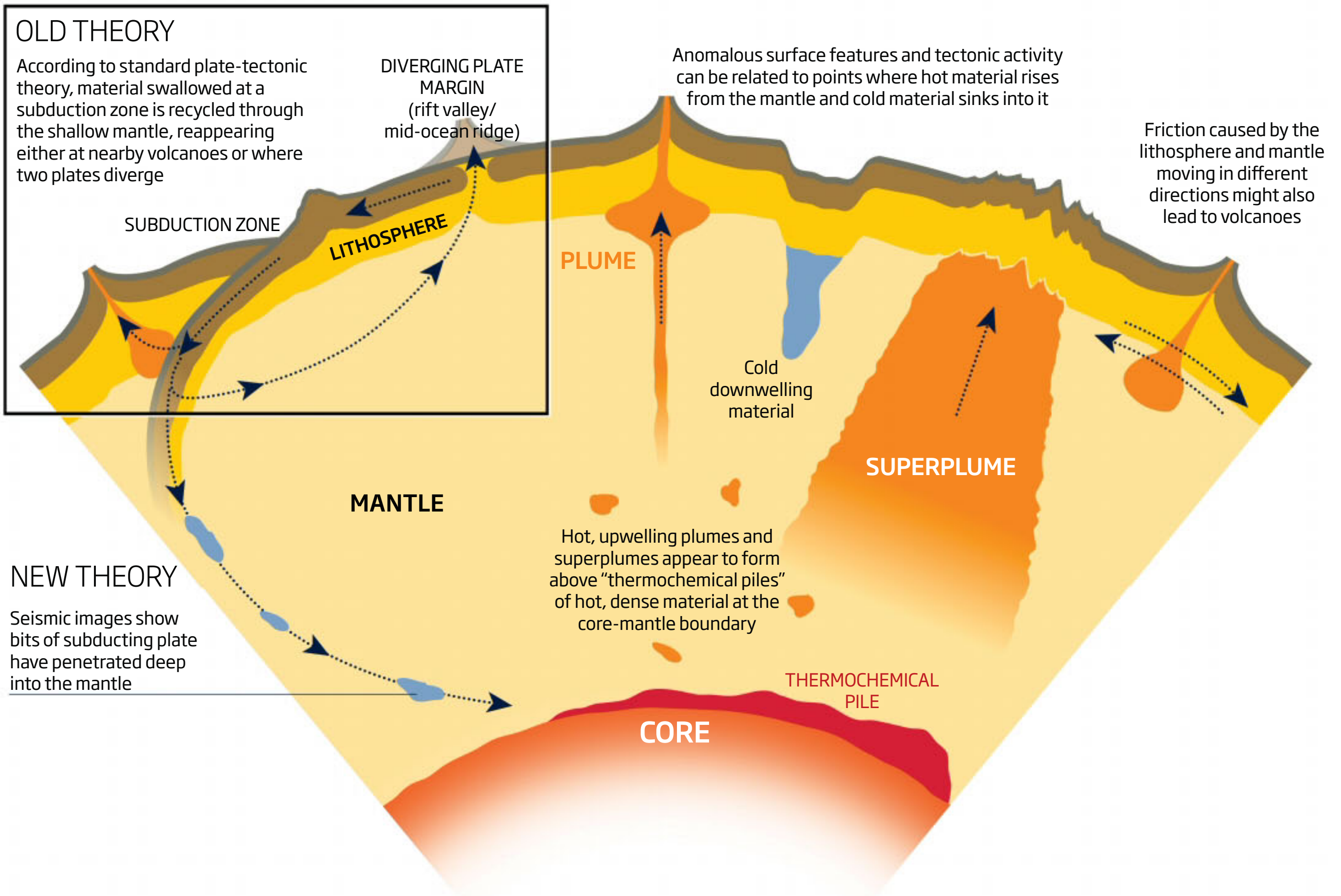
Even iconic events of Earth's tectonic past might not be all they seem. The Himalayas had formed by 35 million years ago, after the Indian plate separated from the supercontinent Gondwana, sped north and slammed into the Eurasian plate. That is still the broad picture, but plate tectonics struggles to explain why India zoomed towards its

RICHARD A COOKE III/STONE/GETTY

Hawaii's volcanoes pose a problem for traditional theories of plate tectonics

Digging deep

Seismographic images suggest that the workings of the deep Earth have an important effect on surface features



target at speeds of up to 18 centimetres per year. Today, plates only reach speeds of about 8 centimetres per year, a limit set by how fast subducting slabs can sink into the mantle.

Steven Cande and Dave Stegman of the Scripps Institution of Oceanography in La Jolla, California, think they have the answer. In 2011, they used computer models to argue controversially that the horizontal force exerted by the mushrooming head of the Reunion plume, thought to be the source of the massive outpouring of lava that formed the Deccan Traps in western India about 67 million years ago, sent India on its headlong path.

The anomalous and periodically devastating seismicity of the US Midwest, meanwhile, might be explained by plate tectonics and the propagation of surface stresses – or the root causes might go deeper. In 2007, Alessandro Forte of the University of Quebec at Montreal, Canada, and his colleagues implicated the ancient Farallon plate, which started slipping into the mantle along the west coast of North America during the Cretaceous. Their model suggests that the plate has now burrowed deep enough to cause a downwelling below the mid-Mississippi river valley, deforming the overlying lithosphere sufficiently to trigger the disastrous events of two centuries ago (see "Quake escape", page 36).

It all adds up to a picture in which more than plate tectonics is at work in shaping our planet's past, present and future. "It's just amazing to think that Earth's surface is rather less stable than plate tectonics in its simplest form would have it," says White.

Iceland's anomalies

Not everyone is convinced. Gillian Foulger of the University of Durham, UK, argues that the region around Iceland, for example, is no hotter than the rest of the mid-Atlantic ridge, a diverging plate margin on which the island also sits. Iceland's topography and volcanic activity can be adequately explained by the tectonic activity at such a plate boundary without invoking a plume-driven hotspot. She and fellow "aplumatics" also point out that, while seismic waves do travel slower in the shallow mantle beneath Iceland, Hawaii and other supposed hotspots, these velocity anomalies don't extend all the way down to the bottom of the mantle where, according to the theories that have been advanced, the plumes supposedly begin their journey. "That's never been seen, not one single time, in a reliable way," she says.

Enthusiasts for a deeper explanation of Earth's surface activity think it is only a matter of time and better seismic imaging before these objections are also countered.

Efforts to improve imaging are already under way in the form of Earthscope, an ongoing project to blanket the US with seismographs, giving geologists a fine-grained look at the mantle underneath. What is needed, however, are similar projects to understand crucial regions of the mantle, such as those below Africa and the Pacific Ocean. "If you can design a grand whole-Earth experiment, where you have seismometers scattered evenly all over Earth's surface, at sea and on land, you can do a brilliant job in making better sharp tomographic images," says White.

If we can do that, will history repeat itself, the doubters be won over, and another hotly disputed model become the new orthodoxy? Müller certainly thinks so: "Geology is on the cusp of another revolution like plate tectonics." ■

CHAPTER TWO

PLATES, QUAKES AND CATASTROPHES

Quakin' all over

What is an earthquake? What causes them? And will we ever be able to predict one with certainty? Seismologist **Susan Hough** explains

QUAKE BASICS

Our awareness of earthquakes dates back to our earliest days as a sentient species, but for most of human history we have not understood their causes. It's only in the past century that scientists have been able to answer the question: what exactly is an earthquake?

Earthquakes in the ancient world, including in the Mediterranean region and Middle East, occurred frequently enough to have been part of the cultural fabric of early civilisations. Legends ascribing geophysical unrest to the whims and fancies of spiritual beings are a recurring theme in ancient cultures. A little later, the scholars of classical antiquity began to seek physical explanations. Both the Greek philosopher Aristotle and the Roman historian Pliny the Elder proposed that earthquakes were the result of underground winds.

"The Greek philosopher Aristotle proposed that quakes were the result of underground winds"

The earliest scientific studies of earthquakes date back to the 18th century, sparked by an unusual series of five strong earthquakes in England in 1750, followed by the great Lisbon earthquake of 1755 in Portugal. Early investigations included cataloguing past earthquakes and trying to understand the seismic waves of energy generated during the events. These waves, which radiate from the earthquake's source and cause the ground to heave, remained the focus of scientific efforts until the end of the 19th century. Indeed, the word "earthquake" is derived from the ancient Greek word for "shaking", although when modern scientists say "earthquake" they are generally referring to the source, not the ground motion.

Following the 1891 Mino-Owari earthquake – the strongest inland quake ever to have hit Japan – and the devastating 1906 San Francisco earthquake, attention shifted to the mechanisms that give rise to these events. Using data from triangulation surveys – an early forerunner to GPS – conducted before and after the San Fransisco earthquake, American geophysicist Harry Fielding Reid of Johns Hopkins University in Baltimore developed one of the basic tenets of earthquake science, the theory of "elastic rebound". This describes how earthquakes occur due to the abrupt release of stored stress along a fault line (see diagram, right).

Another half-century elapsed before the plate tectonics revolution of the mid-20th century provided an explanation for the more fundamental question: what drives earthquakes? We now know that most earthquakes are caused by the build-up of stress along the planet's active plate boundaries, where tectonic plates converge or slide past each other.

Other earthquake causes have also been identified, such as post-glacial rebound, when the crust returns to its non-depressed state over timescales of tens of thousands of years following the retreat of large ice sheets. However, such processes only account for a tiny percentage of the overall energy released by earthquakes due to plate tectonics.

Thus modern science has established the basic framework to understand where, how and why earthquakes happen. But the devil continues to lurk in the details.

JIM MCHUGH/SYGMA/CORBIS; BEAR IMAGES/UNIVERSITY OF CALIFORNIA

Charles Richter (left) borrowed the term "magnitude" from astronomy.

HOW DO WE MEASURE EARTHQUAKES?

By the early 20th century, geologists knew that some earthquakes create visible rips across Earth's surface, which gives indications of their force. But since most fault ruptures are entirely underground, we need other methods to size up and compare earthquakes.

The earliest scales were called intensity scales, which typically assign Roman numerals to the severity of shaking at a given location. Intensity scales remain in use today: well-calibrated intensity values derived from accounts of earthquake effects help us study historical earthquakes, for example.

To size up an earthquake directly, one needs to record and dissect the waves it generates. Today, this is done with digital seismometers, but it wasn't always so. The first compact instrument capable of faithfully recording small earthquakes was called a Wood-Anderson seismometer. When the ground shook, a mass suspended on a tense wire would rotate, directing a light onto photosensitive film. The image "drawn" by the light reflected the severity of the seismic waves passing through.

In the early 1930s, American seismologist Charles Francis Richter used these seismometers to develop the first magnitude scale. Richter's scale is logarithmic, with each unit increase in magnitude corresponding to a 30-fold increase in energy release. A magnitude 7 earthquake thus releases 900 times more energy than a magnitude 5.

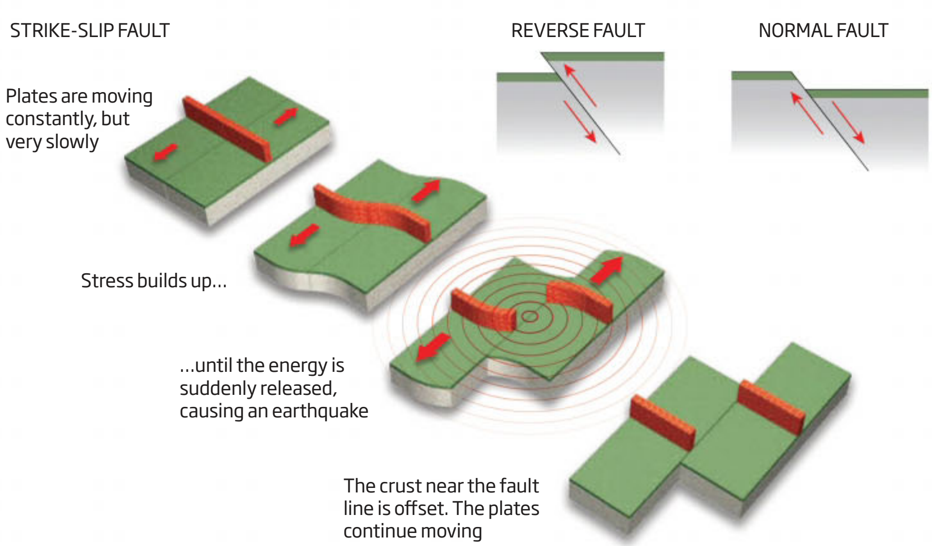
Magnitude values are relative: no physical units are attached. Richter tuned the scale so that magnitude 0 (M0) was the smallest earthquake that he estimated could be recorded by a surface seismometer under ordinary conditions. Earthquakes with negative magnitudes are possible but thus unlikely to be recorded.

The scale is also open-ended, but Richter might have had an upper limit of M10 in mind: he also tuned the scale so that the largest recorded earthquakes in California and Nevada were around M7, and surmised that the 1906 San Francisco quake was probably around M8. (The largest recorded since then was the Valdiva earthquake, which hit Chile in 1960 with an estimated magnitude of 9.5.)

Relationships have been developed since to relate the energy released by earthquakes to magnitude. In the 1960s, Keiitti Aki introduced a fundamentally different quantity: the "seismic moment". This provides a full characterisation of the overall size of an earthquake and is the measure generally used in scientific analyses.

The so-called moment-magnitude scale was introduced to convert the seismic moment to an equivalent Richter magnitude. This is the number usually reported in the media, though strictly speaking it is not "on the Richter scale", because it is calculated differently to Richter's formulation. Nonethelsss, moment-magnitude values are useful for comparing the size of earthquakes.

The "elastic rebound" theory describes how earthquakes occur at faults due to the movement of plates



Understanding the shaking caused by earthquakes is crucial if we are to prepare for these events – but the impact of an earthquake on people and cities depends on more than magnitude alone. Earth's crust can amplify or dampen the severity of shaking

SHAKE, RATTLE AND ROLL

Seismic waves cause perceptible ground motion if they are strong enough. For seismic hazard assessment, the study of ground motion is where the rubber meets the road. If we understand the shaking, we can design structures and infrastructures to withstand it.

The severity of earthquake shaking is fundamentally controlled by three factors: earthquake magnitude, the attenuation of energy as waves move through the crust, and the modification of shaking due to the local geological structure.

Bigger earthquakes generally create stronger shaking, but not all earthquakes of a given magnitude are created equal. Shaking can depend significantly on factors such as the depth of the earthquake, the orientation of a fault, whether or not the fault break reaches the surface, and whether the earthquake rupture is relatively faster or slower than average.

Attenuation of seismic waves varies considerably in different regions. In a place like California or Turkey, where the crust is highly fractured and relatively hot, waves dissipate – or attenuate – quickly. Following the 1906 San Francisco earthquake, pioneering geologist G. K. Gilbert observed: "At a distance of twenty miles [from the fault] only an occasional chimney was overturned… and not all sleepers were wakened." In regions that are far from active plate boundaries, such as peninsular India or the central and eastern US, waves travel far more efficiently. The three principal mainshocks of the 1811-1812 New Madrid earthquake sequence in the central US damaged chimneys and woke most sleepers in Louisville, Kentucky, some 400 kilometres away. In 2011, the magnitude 5.8 Virginia earthquake was felt in Wisconsin and Minnesota, over 1500 km away (see "Quake escape", page 36).

Local geological structures such as soft sediment layers can amplify wave amplitudes. For example, the M8 earthquake along the west coast of Mexico in 1985 generated a ringing resonance in the lake-bed sediments that underlie Mexico City.
And in Port-au-Prince, some of the most dramatic damage in the 2010 Haiti earthquake was associated with amplification by small-scale topographic features such as hills and ridges.

Characterisation of the full range and nature of site response remains a prime target for ground motion studies, in part because of the potential to map out the variability of hazard throughout an urban region, called "microzonation". This offers the opportunity to identify those parts of urban areas that are relatively more and less hazardous, which can guide land-use planning and appropriate building codes. Rubber, meet road.

"Earthquakes far from major plate boundaries can often be felt over 1000 kilometres away"

MUSTAFA OZER/AFP/GETTY BACKGROUND IMAGE: SIPA PRESS/REX FEATURES

TKYODO/REUTERS

The tsunami that hit Japan in 2011 caused more damage and deaths than the shaking

TSUNAMI!

Undersea earthquakes can generate a potentially lethal cascade: a fault break can cause movement of the seafloor, which displaces the water above to form a tsunami wave.

Tsunamis can also be generated when earthquakes trigger undersea slumping of sediments, although these waves are generally more modest in size.

Tsunami waves spread out through the ocean in all directions, travelling in the open ocean about as fast as a jet plane. They have a very long wavelength and low amplitude at sea, but grow to enormous heights as the wave energy piles up against the shore.

STRONGEST LINKS

Earthquakes are often related to one another - one can lead to another - but there are common misconceptions about what drives them and the ways that they are linked.

It is an enduring misperception that a large earthquake is associated with a sudden lurching of an entire tectonic plate. If one corner of the Pacific plate moves, shouldn't it be the case that other parts of the plate will follow suit? The idea might be intuitive, but it is wrong. The Earth's tectonic plates are always moving, typically about as fast as human fingernails grow. What actually happens is that adjacent plates lock up, causing warping of the crust and storing energy, but only over a narrow zone along the boundary. So when an earthquake happens, this kink is catching up with the rest of the plate.

Earthquake statistics do tell us, however, that the risk of aftershocks can be substantial: on average, the largest aftershock will be about one magnitude unit smaller than the mainshock. Aftershocks cluster around the fault break, but can also occur on close neighbouring faults. As the citizens of Christchurch, New Zealand, learned in 2011, a typical largest aftershock (M6.1) had far worse consequences than the significantly bigger mainshock (M7), because the aftershock occurred closer to a population centre.

In addition to aftershock hazard, there is always a chance that a big earthquake can beget another big earthquake nearby, typically within tens of kilometres, on a timescale of minutes to decades. For example, the 23 April 1992 M6.1 Joshua Tree earthquake in southern California was followed by the 28 June 1992 M7.3 Landers earthquake, approximately 35 kilometres to the north. Such triggering is understood as a consequence of the stress changes caused by the movements of the rocks. Basically, motion on one fault will mechanically nudge adjacent faults, which can push them over the edge, so to speak, following delays ranging from seconds to years.

An additional mechanism is now recognised as giving rise to triggering: the stress changes associated with seismic waves. Remote triggering occurs commonly - but not exclusively - in active volcanic and geothermal areas, where underground magmatic fluid systems can be disrupted by passing seismic waves.

Overwhelmingly, remotely triggered earthquakes are expected to be small. Here again, recent advances in earthquake science, as well as centuries of experience, tell us that earthquakes do not occur in great apocalyptic cascades. However, in recent decades scientists have learned that faults and earthquakes communicate with one another in far more diverse and interesting ways than the classic foreshock-mainshock-aftershock taxonomy suggests.

Many avenues for earthquake forecasting have been explored, from changes in animal behaviour to electromagnetic signals. Yet predicting exactly when an earthquake will happen remains impossible. Still, there is a great deal we do know about the Earth's shaking in the future

FORECASTING: WHAT WE KNOW

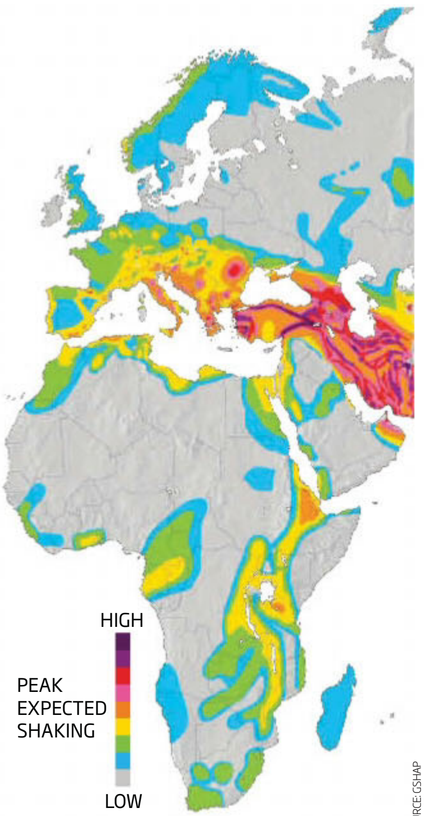
When seismologists are asked whether earthquakes can be predicted, they tend to be quick to answer no. Sometimes even we geologists can forget that, in the ways that matter, earthquakes are too predictable. We know where in the world they are likely to happen. For most of these zones, we have quite good estimates of the expected long-term rates of earthquakes (see map, below right). And while we often cannot say that the next Big One will strike in a human lifetime, we can say it is very likely to occur within the lifetime of a building.

We know the largest earthquakes occur along subduction zones, where a tectonic plate dives beneath another into the Earth's mantle, with rupture lengths of more than 1000 kilometres and an average slip along a fault of tens of metres. But any active plate boundary is fair game for a big earthquake, at any time. For example, two years before the 2010 earthquake in Haiti, geophysicist Eric Calais and his colleagues published results of GPS data from the region, noting that "the Enriquillo fault is capable of an M7.2 earthquake if the entire elastic strain accumulated since the last major earthquake was released in a single event". While this exact scenario did not play out in 2010, it wasn't far off. We can say for sure that people living on plate boundaries will always face risk.

Future large earthquakes are expected in California. Research by James Lienkaemper and his colleagues estimates that sufficient strain is stored on the Hayward fault in the east San Francisco Bay area to produce an M7 earthquake. An earthquake this size is expected, on average, every 150 years. The last one was in 1868. Local anxieties inevitably mount knowing such information, but earthquakes occur by irregular clockwork: if the average repeat time is 150 years, it could vary between 80 to 220 years. So we are left with the same vexing uncertainty: an "overdue" earthquake might not occur for another 50 years, or it could happen tomorrow. On a geological timescale there is not much difference between sooner versus later. On a human timescale, sooner versus later seems like all the difference in the world.

Earth scientists have made great strides in forecasting the expected average rates of damaging earthquakes. The far more challenging problem remains finding the political will and resources to prepare for the inevitable.

Geologists use hazard maps to illustrate earthquake risk in a region. This one essentially shows the peak shaking that policymakers should prepare for in the next 50 years



SOURCE: GSHAP

California schoolchildren perform earthquake practice drills; below: "Shake tables" test how buildings will act in an earthquake

COLORADO STATE UNIVERSITY/NATIONAL SCIENCE FOUNDATION

JUSTIN SULLIVAN/GETTY

MEGAQUAKE MYTHS

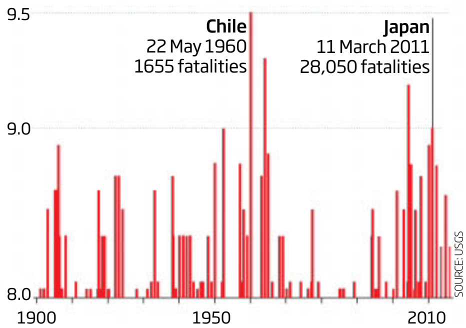
Since the M9.1 Sumatra-Andaman earthquake struck on Boxing Day in 2004, another five earthquakes with magnitudes of 8.5 or greater have occurred on the planet, including the Tohoku, Japan, earthquake in 2011 (see diagram, below). This apparent spate has led some to wonder if earthquake frequency is increasing. Careful statistical analysis reveals that it is not.

The recent rate of very large earthquakes is unusual, but not a statistically significant increase relative to expected variability. And the overall energy release by earthquakes in the past eight years is still below the combined energy release of the two largest recorded earthquakes: the 1960 Chilean quake and Alaska's quake on Good Friday 1964.

Anthropogenic climate change could conceivably influence earthquake rates in some areas: the post-glacial rebound associated with the retreat of glaciers provides a source of stress that can drive earthquakes (see "Earth shattering," page 48). Such quakes could have a significant local impact, but their overall energy release will continue to be dwarfed by that of earthquakes caused by plate tectonics.

While there is no reason to believe that megaquakes are on the rise, there is little doubt that more and worse megadisasters due to earthquakes lie ahead in our future – they are the inevitable consequence of explosive population growth and concomitant construction of vulnerable dwellings in the developing world.

Earthquakes measuring magnitude 8 and above since 1900



WHY SO DIFFICULT?

In the 1970s and 1980s, leading scientists were quoted in the media expressing optimism that reliable short-term prediction of earthquakes was around the corner. This was fuelled by promising results from the Soviet Union, and the apparently successful prediction of the 1975 earthquake in Haicheng, China. Since then, this optimism has given way to varying degrees of pessimism. Why are earthquakes so hard to predict?

Any number of possible precursors to earthquakes have been explored: small earthquake patterns, electromagnetic signals and radon or hydrogeochemical changes. Many seemed promising, but none have stood up to rigorous examination.

For example, in March 2009, Italian technician Giampaolo Giuliani made a public prediction that a large earthquake would occur in the Abruzzo region of Italy. His evidence? An observed radon anomaly. The prediction was denounced by local seismologists. The M6.3 L'Aquila earthquake struck the area on 6 April, killing 308 people.

This gets to the issue of reliable precursors. It is possible that radon was released due to the series of small earthquakes, or foreshocks, that preceded the main earthquake. It is also possible it was coincidence. Scientists explored radon as a precursor in the 1970s and quickly discovered how unreliable it is. Once in a while radon fluctuations might be associated with an impending earthquake, but usually they are not. Meanwhile, big earthquakes hit regions where anomalies were absent. The same story has played out with many other proposed precursors.

That's not to say that seismologists have neglected to investigate precursors – on the contrary, they are examining them with increasingly sophisticated methods and data. However, a common bugaboo of prediction research is the difficulty of truly prospective testing. To develop a prediction method based on a particular precursor, researchers compare past earthquakes with available recorded data. One might, for example, identify an apparent pattern of small earthquakes that preceded the last 10 large earthquakes in a given region. Such retrospective analyses are plagued by subtle data selection biases. That is, given the known time of a big earthquake, one can often look back and pick out apparently significant signals or patterns.

This effect is illustrated by the enduring myth that animals can sense impending earthquakes. They may respond to weak initial shaking that humans miss, but any pet owner knows that animals often behave unusually. People only ascribe significance with hindsight.

Most seismologists are pessimistic that prediction is possible. But the jury is out. One unanswered question is what happens to set a quake in motion. Some sort of slow nucleation process may be involved, and perhaps earthquake precursors do exist. The challenge is to move this into the realm of statistically rigorous science.

QUAKE ESCAPE

Roaming clusters of seismic energy could explain how large earthquakes occur where we least expect them, says **Ferris Jabr**

BEATRICE MAGNANI spends her days navigating the Mississippi river in a US Army Corps of Engineers vessel that tows an airgun and a hydrophone. "It's kind of a Mark Twain thing," she says. Every 7 seconds, the airgun pops, expelling a bubble of pressurised air into the sediments beneath the river bed.

Magnani uses the pressure and timing of the reflected waves to create a picture of what lies beneath the Mississippi's murky waters. In a geologically quiet continental interior such as the US Midwest, sediments of different ages should be stacked in layers as neat as those of a Black Forest gateau. Under the Mississippi, however, they are not – in places, they are broken or folded in on themselves. "Something must have deformed them after they were deposited," says Magnani, a seismologist at the University of Memphis, Tennessee.

Something like a huge earthquake. Just over 200 years ago, between 16 December 1811 and 7 February 1812, a series of four massive quakes ripped through the Mississippi embayment, a low-lying, sediment-filled basin stretching from the Gulf of Mexico northwards to Cairo, Illinois. Centred on the town of New Madrid in present-day Missouri, the quakes measured around magnitude 7 on modern scales, and possibly as much as magnitude 8. In the last of them, the Mississippi river flowed backwards, the riverbanks spewed sand, and Reelfoot Lake – today a popular hunting and fishing preserve in north-west Tennessee – formed as the ground opened to swallow displaced water.

That, on the face of it, is rather unexpected. New Madrid lies far from typical arenas of

The serenity of Reelfoot Lake in Tennessee belies a violent birth

major seismic upheaval, where one of Earth's tectonic plates meets another. But the earthquakes there were no unique occurrence. In 1556, the most deadly earthquake on record occurred in Shaanxi province in China's northern interior, again nowhere near a plate boundary. Some 800,000 people were killed as, according to a contemporary report, "mountains and rivers changed places". On 23 August 2011, a magnitude 5.8 quake struck with an epicentre near Mineral, Virginia. There were no deaths, but the incident caused chaos and confusion up and down the US east coast. Earthquakes have struck the interiors of India and Australia in the recent past as well.

These "intraplate" earthquakes have long been a mystery. "They are the last frontier for plate tectonics," says Magnani. What we are finding out now, though, is giving us pause for thought. It might be that it's not just San Francisco and Los Angeles that are susceptible to significant earthquakes, but New York, Sydney and perhaps even London too. Should we be worried?

Earth's tectonic plates are the jigsaw-like pieces of its rocky outermost layers, and drift about on more viscous material below. Where plates meet, they move against one another and push each other up and down. Along the San Andreas fault in California, the North American and Pacific plates grind against each other at a rate of 33 to 37 millimetres a year, building up the stress released in earthquakes. Records indicate that California experiences a magnitude 7 or greater quake every 100 to 150 years; the last was the magnitude 7.8 San ›

WATER WORKS

Could "intraplate" earthquakes far from tectonic plate boundaries be the work of wind and weather? This is highly likely, according to some researchers.

Championed by John Costain of Virginia Tech University in Blacksburg, who died in 2015, they support a controversial idea called hydroseismicity. Beneath your feet, water from the atmosphere and from rivers, lakes and streams seeps into whatever spaces it can find in the porous earth, including geological fractures and faults. Rapid changes in the water table, caused for instance by a hurricane, can suddenly change the fluid pressure in these faults – and that might trigger earthquakes.

In particular, Costain believed that Hurricane Camille, which hit the Gulf coast of the US in August 1969, caused two earthquakes that hit Virginia later that year, affecting the same area in which 2011's magnitude 5.8 quake struck.

Like much about intraplate earthquakes, hydroseismicity is still far from textbook science, but evidence that the weather influences tectonic movement is increasing. Separate research teams suggest that hydroseismicity is responsible for intraplate earthquakes in India and Spain. And over millions of years, monsoons have eroded so much earth that they have sped up the anticlockwise rotation of the Indian plate. Changes in sea level also seem to influence the incidence of earthquakes on the Easter microplate in the southern Pacific.

Seth Stein of Northwestern University in Evanston, Illinois, and colleagues think that the movement of frozen water might account for seismicity in the US Midwest, too. In 2010, they proposed that the retreat of the ice cap at the end of the last ice age released pent-up energy that caused faults in the area around New Madrid to fail. If that all stands up, climate change is likely to make such effects more pronounced: as melting ice caps release pressure on faults below, more quakes could be on the horizon (see "Earth shattering", page 48).

"The earthquakes appear to be jumping from one fault to another across long distances"

Francisco earthquake in 1906.

Things might not be much different for intraplate earthquakes. Earth's crust is engaged in a slow but constant process of ripping itself apart and crashing back together. At places such as the Mid-Atlantic ridge, the nearest plate boundary to the east of New Madrid, this ripping has succeeded, creating a region of volcanism where new material is constantly spewing up from Earth's interior. In other places, however, the rip never quite happens. The result is an unstable region that, though often unremarkable at the surface, is more easily stressed than the rock around it.

These weak spots in Earth's crust are strained by the same geological restlessness that strains faults at plate boundaries; it just takes longer. That, it had been assumed, could explain why intraplate earthquakes occur far less frequently than those at plate boundaries.

In the 1980s, it became clear that New Madrid sits atop such a failed rift. Dubbed the Reelfoot rift, it lies buried beneath the southern and Midwestern US and seems to have shuddered regularly in recent millennia. Magnani's colleague Martitia Tuttle digs around New Madrid in search of geological features called sand blows, produced when a powerful earthquake shakes the soil so much that it loses strength and behaves like a liquid, spewing from the ground in a tiny mud volcano. The plains around New Madrid are dotted with sand blows that formed 200 years ago. Underground, Tuttle has found more, suggesting that large tremors racked the area in AD 300, 900 and 1450.

The United States Geological Survey (USGS) suggests that there is a 25 to 40 per cent chance of a magnitude 6 or larger quake hitting the New Madrid area in the next 50 years, with a 7 to 10 per cent chance of an event as big as the one two centuries ago. Back then, there were hardly any settlers in the region. Today, a quake that size would displace 7.2 million people in Arkansas, Missouri and Tennessee, and cost at least $300 billion, according to a 2009 report funded by the US Federal Emergency Management Agency.

New Madrid might not be the only area at risk. Magnani's studies of the deformation of Mississippi sediments have uncovered a 45-kilometre-long fault north of Memphis that seems to be part of the Reelfoot system. The 10-kilometre-long Marianna fault in Arkansas, discovered in 2009, could see a magnitude 7 quake, says Haydar Al-Shukri of the University of Arkansas at Little Rock. "The seismogenic potential involves a much larger area than just the active faults we see today," Magnani says. "New Madrid is just the latest incarnation."

Clustered and migrating

Seth Stein of Northwestern University in Evanston, Illinois, and his colleagues have come to a further startling conclusion after 20 years of using GPS to map the seismic zone around New Madrid. If the faults in the area are still under strain, they should be moving, just as they are at the San Andreas fault, for instance. But they are not. In 2009, Stein and his colleague Eric Calais suggested that New Madrid is now in a deep seismic slumber from which it should not be expected to awake for hundreds, if not thousands, of years.

That leads Stein to make a controversial claim. He doesn't buy the idea that intraplate earthquakes are akin to interplate earthquakes, hitting home less frequently but in similarly predictable places. Instead, he characterises them as episodic, clustered and migrating. Seismic energy can jump within a network of small faults that snake their way through the middle of a tectonic plate, he says – and that is just what is going on beneath the US Midwest. "If I had to guess, I would say that over time the motion in New Madrid will be transferred into seismic zones in Indiana and further south into Arkansas," he says. Whether that will happen on a timescale of decades or centuries, he cannot say.

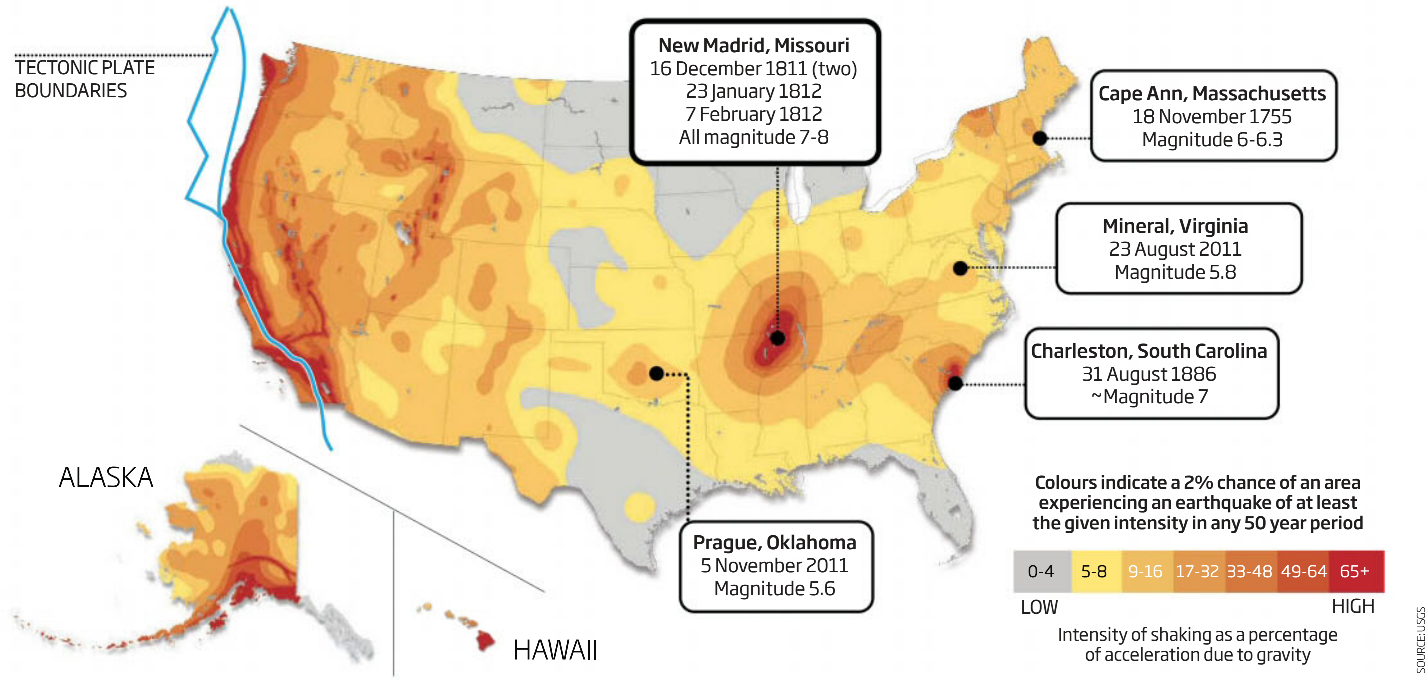
Work by Stein's collaborator Mian Liu of the University of Missouri in Columbia suggests that there could be truth in this picture. Last year Liu analysed the occurrence of intraplate earthquakes over 2000 years in the north of China, scene of some of the most devastating historical examples, including the 1556 Shaanxi quake. Liu showed that the epicentres of intraplate earthquakes in China hop around haphazardly. Areas of violent shocks become quiescent; previously docile areas suddenly become active. "The earthquakes appear to be spatially migrating, jumping from one fault to another across long distances," he says. He

STEVE HELBER/AP/PA PHOTO

The 2011 Virginia earthquake caused upheaval but no deaths

Great shakes

Even areas well away from plate boundaries may experience significant earthquakes, as this map of US seismic risk based on historical data shows. The region around New Madrid stands out - but it is by no means the only place affected



thinks that faults in the middle of a plate are mechanically coupled, so that an earthquake along one changes another's susceptibility to future movement.

If so, that could have huge ramifications for our understanding of intraplate quakes. Take the Virginia quake of 2011. Its epicentre was in the Central Virginia seismic zone, which has experienced many quakes of around magnitude 3 over the past 120 years, but was not considered particularly at risk of anything bigger. If Stein and Liu's ideas are right, the culprit might be seismic energy that roamed into the area from elsewhere. The nearby Western Quebec seismic zone, for example, extends over the northern border of New York State, and was visited by a magnitude 5.6 earthquake in 1944. The Eastern Tennessee seismic zone, stretching from north-east Alabama to south-west Virginia, is also highly active, although most quakes in the region are small. Two magnitude 4.6 earthquakes have occurred there in recent decades: one near Knoxville, Tennessee, in 1973, and another near Fort Payne, Alabama, in 2003.

That amounts to a wake-up call, says Stein's colleague Suzan van der Lee. "Earthquakes like the ones in Virginia and New Madrid could happen anywhere, including in Boston or Chicago," she says.

In 2008, Lynn Sykes of Columbia University in New York City catalogued all 383 quakes in a 39,000-square-kilometre area around New York City from 1677 to 2007 and estimated the future risk. He concluded that New York can expect a magnitude 5 quake once every century, a magnitude 6 quake every 670 years and a magnitude 7 quake every 3400 years. That highlights a gulf between perceived and actual risk, says consultant geologist Roger Musson, who until last year worked at the British Geological Survey in Edinburgh, UK. "An earthquake of magnitude 5.5 to 6 in New York would not come as a surprise to seismologists who have ever studied the area," he says. "But it would come as a surprise to most people who live there."

The same goes for other major cities. An earthquake of estimated magnitude 5.7 hit the Dover straits off south-east England in 1580, causing a pinnacle to fall off Westminster Abbey in London some 150 kilometres away. A magnitude 4.3 quake struck the same region in 2007. We should not overstate the risks, Musson says: most modern buildings in these areas could easily withstand a magnitude 5 or 6 quake. Skyscrapers in particular have enough "sway" in them to counteract the effects, but historical monuments and older buildings such as police stations, schools and fire stations made from unreinforced brick could be vulnerable.

"Quakes like the ones in Virginia and New Madrid could also happen in Boston or Chicago"

Any larger earthquakes could be more problematic. A magnitude 6.5 quake below Manhattan could cause $1 trillion in damage, according to Mary Lou Zoback, a former USGS seismologist who now works at Stanford University in California. She suggests that not just building codes, but also critical infrastructure – such as electrical and telecommunications networks, and water and fuel pipelines – need to be upgraded to reflect the small but real danger.

In the US at least, more information on the vulnerable areas might come soon. USArray, a mobile system of hundreds of seismometers that began crawling eastwards from California in 2004, has studied the area around New Madrid. As part of that project, another experiment called Flexible Array has used its network of seismometers to study the area for several years. Each seismometer records sound waves generated by vertical and horizontal movements in Earth's crust, building up a complete picture of the rocks and the faults that riddle them.

"The array will help us answer questions about intraplate earthquakes," says van der Lee. Almost every third US state is thought to have a piece of failed rift in it, she says. Why some, like the Reelfoot, are seismically active but others are not remains a big unanswered question. "Until we find a clear pattern that explains intraplate quakes, we have to expect they could happen anywhere." ■


ANDREW JUDD

Pangaea, the comeback

It's hot, cramped and there's an extreme hurricane on the horizon. Welcome to the future Earth.
By **Caroline Williams** and **Ted Nield**

IT'S the year 250,000,000 and Earth is alive and well. Humans have long since perished, but the planet is still home to a bewildering array of life forms. Yet apart from a few mysterious fossils there is no trace that we ever existed.

If we could visit this future Earth, we would barely recognise it. The continents have crashed together to form a single gigantic supercontinent, surrounded by a global ocean. Much of the land is inhospitable desert, while the coast is battered by ferocious storms. The oceans are turbulent on the surface, stagnant at depth and starved of oxygen and nutrients. Disease, war, or asteroid collisions have pushed humans and many of the species we know today to extinction, and competition has seen off all but the hardiest of the rest.

This supercontinent isn't the first on Earth, and it won't be the last. Geologists now suspect that the movements of Earth's continents are cyclical, and that every 500 to 700 million years they clump together. Unfolding over a period three times as long as it takes our solar system to orbit the centre of the galaxy, this is one of nature's grandest patterns. So what drives this cycle, and what will life be like next time the continents meet?

The continents move because of circulation in Earth's mantle beneath the seven major tectonic plates. Where the plates meet, one is forced below the other in a process called subduction. This pulls apart the crust at the other side of the plate, allowing new molten rock to well up to the surface to fill the gap. The process means that oceanic crust is constantly being created and destroyed, but because the continents are made from less dense rock than the heavier and thinner oceanic crust that forms the ocean floor, they ride higher in the mantle and escape subduction (see "Rise of the upper crust", page 14).

As a result, the continents hold their shape for hundreds of millions of years as they glide slowly around the planet. Inevitably, though, continents collide, and sometimes clump together to form a supercontinent.

The most recent, Pangaea, formed 300 million years ago and was already breaking up 100 million years later as the dinosaurs evolved. Some 1.1 billion years ago, another supercontinent, called Rodinia, formed, breaking up 250 million years later. Before that, another, and there were almost ›

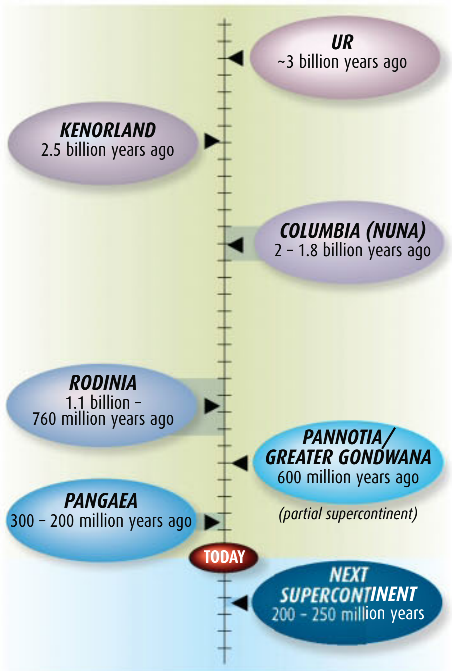
"The vast reduction in available habitat will lead to a mass extinction"

certainly many more still earlier, but since the formation of one supercontinent tends to destroy evidence of its predecessor, no one can be certain about exactly how many there have been. What is generally agreed is that there have been two true supercontinents containing all or nearly all the land on Earth – Pangaea and Rodinia – and there may have been many more true or partial supercontinents, including Pannotia, Columbia, Kenorland and Ur (see diagram, below).

Right now, we are halfway through a cycle. The Pacific is gradually closing, as oceanic crust sinks into subduction zones in the north Pacific, while the Mid-Atlantic ridge is feeding out new ocean floor as the Americas move apart from Europe and Africa. Africa is moving northward, heading for the southern coast of Europe, while Australia is also on its way north towards south-east Asia. The continents are

SUPERCONTINENTS PAST AND FUTURE

At least two previous supercontinents existed, Pangaea and Rodinia. Further back evidence is hard to come by so their existence is more controversial



moving at about 15 millimetres per year – similar to the speed your fingernails grow.

Roll the clock forward 50 to 100 million years and it's easy to get a rough idea where things are going. But seeing further into Earth's future takes more than just projection of the continents' current movements. Christopher Scotese, geologist and director of the Paleomap project, likens the problem to predicting your drive along a highway. "You can make a guess at where you're going to be in 5 or 10 minutes, but there are always accidents, people change lanes, or the road may diverge and you have to make a choice."

There are two main ways today's continents could fit together. If the Atlantic continues to widen, the Americas will eventually crash into Asia. Alternatively, a subduction zone might somehow open up in the Atlantic and reel the sea floor back in, forcing Europe and America back together. This would essentially recreate Pangaea.

In 1992, geologist Chris Hartnady, then at the University of Cape Town in South Africa, took up the challenge of "pre-constructing" the next supercontinent. As the Atlantic continues to widen, "the Americas, swinging clockwise about a pivot in north-eastern Siberia, seem destined to fuse with the eastern margin of the future supercontinent", which Harvard University geologist Paul Hoffman called "Amasia".

In this vision of the future, Australia will continue northward while Africa stays more or less in its present position. Antarctica won't join the supercontinent, remaining at the South Pole. "It's not attached to any subduction zone so there is no reason for it to move," Hoffman says.

Roy Livermore, now at the Open University, UK, came to a similar conclusion. In the late 1990s he created his own version of Amasia – a future supercontinent he called Novopangaea. "I have taken the liberty of opening up a new rift between the Indian Ocean and the North Atlantic," he says. "We know the East African Rift is active, so we project that into the future by opening a small ocean. East Africa and Madagascar move across the Indian Ocean to collide with Asia; Australia has already collided with south-east Asia." South of what is now India, a mountain chain has risen from the sea along a new subduction zone. Just south of it is Antarctica.

In Livermore's future, all the present continents take part. "I don't believe Antarctica is going to stay at the pole," he says. "I want it to come north." For this to happen, he postulates a new subduction zone will open up to drag it that way. "The beauty of all this is that no one will ever be able to prove me wrong," he says.

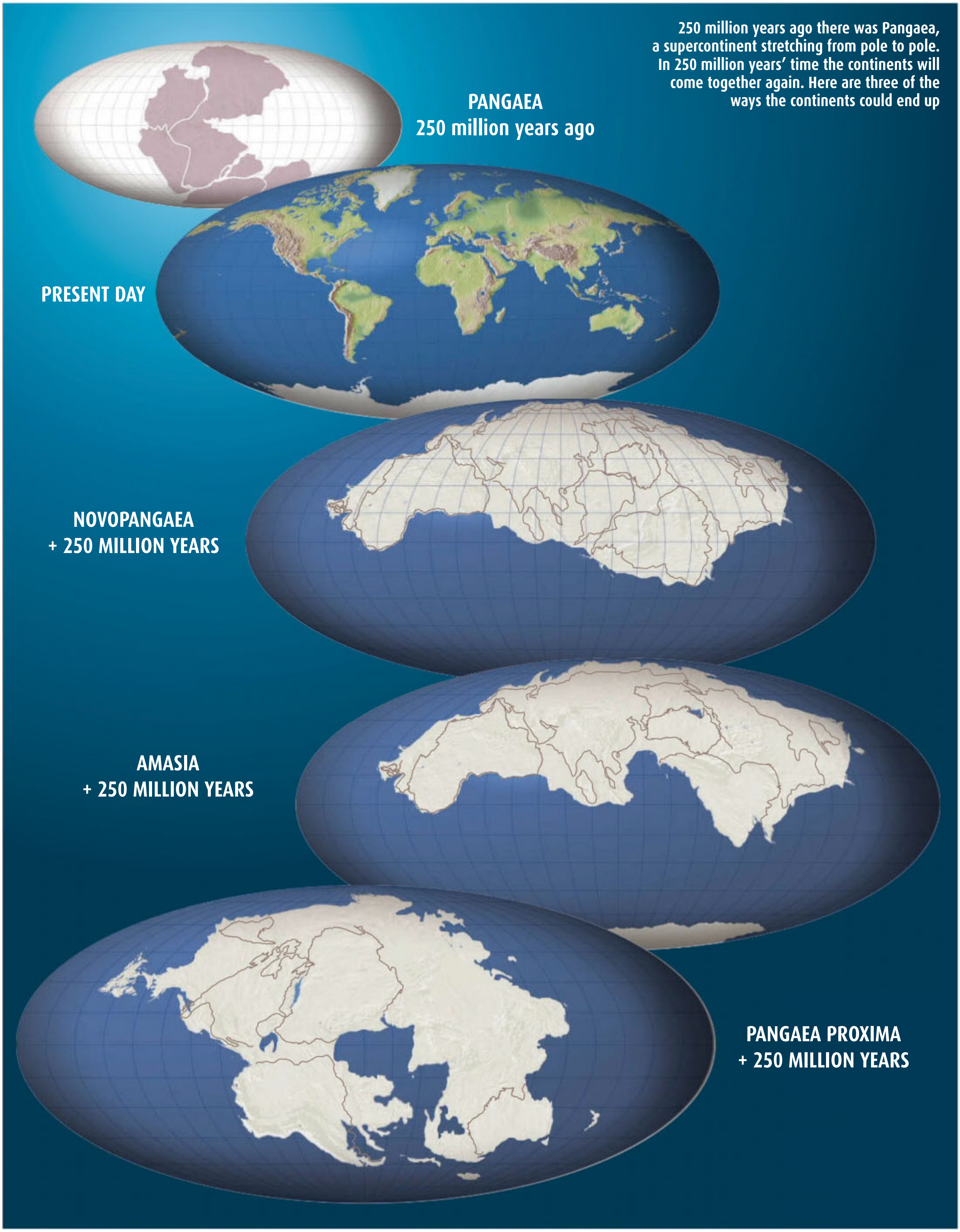
That may be true, but other researchers disagree on how the future planet will look. Scotese has spent much of his career reconstructing where today's continents used to lie, and now applies this knowledge to project the continents into the future. He sees the planet's distant future very differently to Hoffman and Livermore.

Making mountains

Like them, he predicts that over the next 50 million years Africa will continue north, closing the Mediterranean and driving up a Himalayan-scale mountain range in southern Europe. Australia will rotate and collide with Borneo and south China. But 200 million years later, everything will change, he says. Subduction starts up on the west side of the Atlantic. The widening stops and the Atlantic begins to shrink, bringing most of the world's land masses back together as North America comes crashing into the merged Euro-African continent.

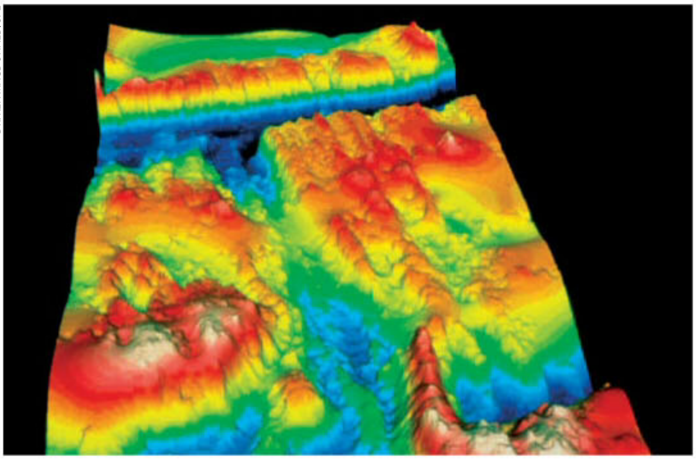
Scotese originally called the resulting supercontinent Pangaea Ultima, but has recently renamed it Pangaea Proxima, meaning the next Pangaea. "The name Ultima bothered me because it implies that it's the last supercontinent," Scotese says. "This process will continue for another couple of billion years."

He says a new Atlantic subduction zone could start if a small existing subduction ›


250 million years ago there was Pangaea, a supercontinent stretching from pole to pole. In 250 million years' time the continents will come together again. Here are three of the ways the continents could end up
PANGAEA
250 million years ago
PRESENT DAY
NOVOPANGAEA
+ 250 MILLION YEARS
AMASIA
+ 250 MILLION YEARS
PANGAEA PROXIMA
+ 250 MILLION YEARS

NASA/CORBIS

DR. KEN MACDONALD/SPL



Hurricanes like this are mild compared with future hypercanes

Without the Mid-Atlantic ridge, the sea would close quickly

zone, such as part of the Puerto Rico trench in the Caribbean, spread up and down the American coast as a result of changing stresses on the planet. Under the right circumstances, he says, the crust could start to tear along this line, signalling the beginning of the end for the Mid-Atlantic ridge. Today it lies halfway between Europe and the Americas, but "if we were to start subduction in either the western Atlantic or the eastern Atlantic, then the ridge would be forced to move toward the subduction zone", he says. "Eventually it would be subducted and we'd have an ocean with a subduction zone but no ridge. That means we close the ocean, and we close it pretty fast."

For now there is nothing to show whose model is right, but what everyone agrees on is that life on the next supercontinent – however it forms – will be tough. "Supercontinents create extremes," says Paul Valdes, a climatologist at the University of Bristol, UK. We can tell what Pangaea's climate was like from geological evidence: the positions of climate-sensitive deposits such as coal, which originates in warm, wet conditions, for example, or the mineral deposits called evaporites that form when lake sediments dry out in a hot climate. This evidence can then be used to build computer models to forecast what the climate might be like in the future. The models that result suggest that supercontinents are prone to violently changing seasons.

"In Pangaea, tropical latitudes could be quite hot, up to perhaps 44 °C. Mid-latitudes had very hot summers with very cold winters when it could get down to -20 or -30 °C with very heavy snowfall," Valdes says. "In summer it would all melt, producing major flooding." Despite this, vast areas of the interior would have been dry, because rain clouds would not have been able to penetrate far inland. In such extreme climates, only a small proportion of the land could support life. In Pangaea, Valdes says, the best real estate was probably in a narrow zone just outside the tropics on the north coast of the Tethys Sea.

The vastness of the supercontinent's land mass will also provoke extreme weather. "Monsoons form because of temperature differences between the land and ocean. If you have a huge land mass, it warms up a lot and stimulates a mega-monsoon," Valdes says.

The next supercontinent's weather could be even worse. If the supercontinent happens to form at the end of an active volcanic phase, leaving behind an atmosphere rich in carbon dioxide and a warmer planet, warm surface waters could drive extreme hurricanes, or "hypercanes". These huge weather systems, thousands of kilometres across and some 50 per cent stronger than today's strongest hurricanes, would batter the landscape with wind speeds of more than 400 kilometres per hour.

Life will also be difficult in the oceans. The global conveyor system of currents that keeps today's oceans oxygenated and stocked with essential nutrients depends on the size and shape of the ocean basins, and therefore the positions of the continents. Move the continents and these conveyors could cease to exist. As a result, below a few hundred metres the waters will become stratified and anoxic, and little will be able to survive.

The reef-fringed coasts close to the equator will be full of life, but even here life won't be easy. As the continents crowd together, there will be a vast reduction in the area of shallow seas, which will probably lead to a mass extinction as species from all over the world are thrown together and forced to compete. Something similar will happen on land. The formation of Pangaea has been implicated in the greatest species loss of all time, the Permian mass extinction, due in part to the huge reduction in available habitats.

Life has a knack of making the best of new situations, however. As Pangaea formed and the southern ice caps melted 290 million years ago, there emerged perhaps the Earth's eeriest ever ecosystem. Dense forests of now-extinct *Glossopteris* trees stood up to 25 metres tall on the southern coast of the Tethys Sea and stretched inland to within 20 degrees of the South Pole.

Despite having only a summer of feeble light to sustain them, they were able to survive months of unremitting winter darkness. Trees close to the coast were lashed by mega-monsoon winds and rains roaring in from the Tethys, with thick cloud obscuring the already weak sunshine. As winter approached, *Glossopteris*'s tongue-like leaves would fall to the oxygen-starved peat before six months of total darkness. Not surprisingly, analysis of fossilised growth rings shows that *Glossopteris* grew frenetically when it could.

Whatever life has to cope with on the next supercontinent, humans won't be around to see it. The next supercontinent is no more than a glint in the planet's eye, but already it has valuable lessons to teach us: clever we may be, but the Earth marches on, with or without us. ■

The idea that geology is what happens beneath our feet has suffered a blow – from space, says **Matt Kaplan**

Deeper impact

ON THE west coast of India, near the city of Mumbai, lies a tortured landscape. Faults score the ground, earthquakes are rife, and boiling water oozes up from below forming countless hot springs.

These are testaments to a traumatic history. Further inland, stark mountains of volcanic basalt provide compelling evidence that this entire region – an area of some 500,000 square kilometres known as the Deccan traps – underwent bouts of volcanic activity between 68 and 64 million years ago.

We don't know why. The Deccan traps lie far away from any tectonic plate boundaries, those fractures in Earth's crust through which lava usually forces its way up from the planet's interior. No volcanism on the scale implied by the Deccan traps occurs on Earth now. However, smaller, equally mysterious "hotspots" dot the globe away from plate boundaries – the smoking volcanoes of the Hawaiian islands, for example, or the bubbling geysers of Yellowstone National Park in Wyoming.

Geologists have generally thought that the history of such features can be traced through the slow churnings and contortions of rock under pressure in Earth's mantle. But it seems there is more to it than that. Sometimes volcanic activity needs – and gets – a helping hand from above.

It was in the late 1960s that oil companies prospecting off India's western coast found something odd in the rocks beneath the ocean floor. Sediments laid down on an ocean bed over millions of years generally form rocks resembling a layer cake, with the layers getting older the deeper you delve. That was true in the boreholes drilled off the coast near Mumbai, to a point. But some 7 kilometres down, in a layer of rock deposited 65 million years ago, the neat progression abruptly stopped. Beneath it was a layer of shattered rock, followed by a layer of solidified volcanic lava up to 1 kilometre thick.

Something equally dramatic lurked onshore in the layered lava flows of the Deccan traps. These flows are interrupted by intermediate layers of sedimentary rocks, indicating that the volcanic activity that shook and remodelled the area from about 68 million years ago was not continuous. It was also not catastrophic; fossils found in the sedimentary layers suggest that dinosaurs had coexisted with this activity reasonably well.

But rooted in layers of lava dating from 65 million years ago – around the time dinosaurs disappeared from Earth's fossil record – are colossal spires of lava of a fundamentally different composition. These spires are up to 12 kilometres high and 25 kilometres across at their bases, so that their tips appear as surface hills. The lava they are made of is highly alkaline and rich in iridium, an element rare in the Earth's crust but which commonly occurs in meteorites.

"The lava in the Deccan traps is rich in iridium, an element rare in Earth's crust but which commonly occurs in meteorites"

To palaeontologist Sankar Chatterjee of Texas Tech University in Lubbock, all of this was telling a story. In 1992, he recounted it to the world: the entire basin area off the coast of Mumbai, he claimed, was a huge undersea impact crater, some 500 kilometres across, formed when a meteorite 40 kilometres in diameter slammed into Earth 65 million years ago and convulsed its surface. He named the crater Shiva, after the Hindu god of destruction and renewal, and touted it as the big brother of Chicxulub, a crater 180 kilometres across under the Yucatán peninsula in Mexico, which dates to the same time.

This claim was bound to stir controversy. The aftermath of the Chicxulub impact supposedly did for the dinosaurs and many other species that disappeared in a wave of extinctions around that time. If Chatterjee was right, Chicxulub was unlikely to be the whole story.

Most geologists were unconvinced. For a start, the Shiva crater was simply too large. Whereas massive impacts were common in the rambunctious early days of the inner solar system, the absence of recent large craters on Mercury, Venus and Mars strongly suggests that those days are long gone. "These surfaces demonstrate that objects larger than 30 kilometres have not produced impacts in the last 3 billion years," says planetary geologist Peter Schultz of Brown University in Providence, Rhode Island.

Chatterjee responds that there are still objects of the right size out there, for example the near-Earth object 1036 Ganymed that NASA is monitoring closely, although it is happily not on a collision course with Earth. Moreover, he says that studies off the Indian coast by oil companies in the 1990s revealed gravitational anomalies that add weight to his arguments.

The exact strength of the gravitational pull an object feels at Earth's surface differs from place to place. It is weaker in areas dominated by low-density granite rocks, for example, and stronger where high-density basalt rocks dominate. If you cross from one side of the posited Shiva crater to the other, the gravity signal weakens towards the centre before reversing and becoming much stronger again towards the proposed rim.

That, says Chatterjee, squares with the idea that a meteorite hit what is now the Mumbai coast from the south-east at an oblique angle of 15 degrees to the horizontal, obliterating the crust entirely and scraping away a portion of the upper mantle, too. The impact would have thrown up a granite peak 50 kilometres high that collapsed back down through a pool of ›

> "A superpowerful pressure wave created by a huge impact from space could rattle volcanic plugs and activate dormant volcanism"

rock below that had been melted in the impact.

That would explain not only the anomalous area of lower gravity under the ocean, but also the odd geology of the Deccan traps. As the granite peak collapsed it too melted, causing the impact crater to overflow and creating enormous melt ponds of alkaline, iridium-rich lava in the charred surroundings. Meanwhile, the shock of the impact caused the moderate Deccan volcanic eruptions, already occurring nearby, to go into overdrive. "A lava trickle became a torrent," says Chatterjee. This torrent of normal lava enclosed the iridium-rich lava overflow from the impact, producing the stunning enclosed spire architecture seen in the Deccan layers today.

That is at best half an answer: it does not explain where the Deccan volcanic activity came from in the first place. Many palaeoscientists, including Chatterjee, think this was linked to a hotspot currently active under the island of Réunion in the Indian Ocean. This hotspot may well have been beneath the area of the Deccan traps 68 million years ago, before continental drift moved them apart.

Even so, it is a contentious claim: to suggest that impacts can amplify volcanic activity is to give them a far greater influence on Earth's recent geological history than has conventionally been allowed. The effects might not just be volcanic, either. According to Chatterjee's calculations, the force of the impact could have been enough to open up a new rift in Earth's crust to the west of the crater, causing a tiny sliver of western India to migrate out into the sea as new oceanic crust forced its way up. The most obvious sign of such a detached sliver today lies almost 2800 kilometres south of the Indian mainland – the island group of the Seychelles.

Comparison with other impact sites shows that if the Shiva crater exists and if it is as big as proposed, the impact would indeed have released enough energy to have such effects. "The physics of the process is undeniable," says geophysicist Adrian Jones of University College London. Even if the Shiva impact never happened, in a startling twist it seems an impact could well have caused the massive Deccan eruptions.

To understand how that might be requires an abrupt change of scene, to the icy permafrost of northern Siberia. This region contains a huge expanse of volcanic rock just as curious as the Deccan traps – and, at some 2 million square kilometres, roughly four times the size. These Siberian traps contain slabs of lava up to 3 kilometres thick that were formed in a single event 251 million years ago.

For geochemist Asish Basu at the University of Rochester in New York, this was fascinating, not least because the lava's date tallies with the largest mass extinction known, the Permian-Triassic extinction, in which over half the existing animal families died out.

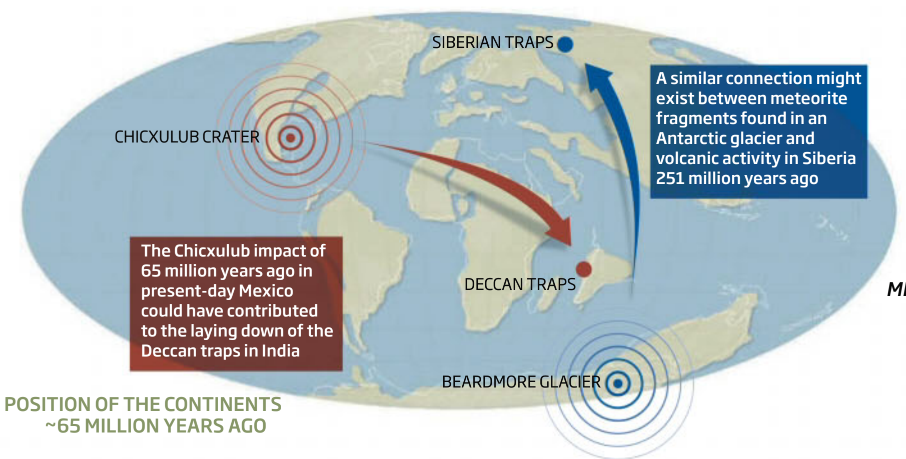
Where did so much lava come from over such a short period? When Basu analysed the chemical composition of the rock to find out, it threw up a surprise. The lava showed abnormally high concentrations of the isotope helium-3, generally a signature of rocks from far down in Earth's interior. "Something was causing the deep mantle to come up, but we did not know what," says Basu.

A hole punched by an impact, perhaps? Basu was aware of Chatterjee's work, and it was tempting to float a connection between two huge unexplained lava flows, each dating from the same time as a mass extinction. So Basu travelled to India to do his helium analysis on the rocks there, too. He came up with the same anomalous result.

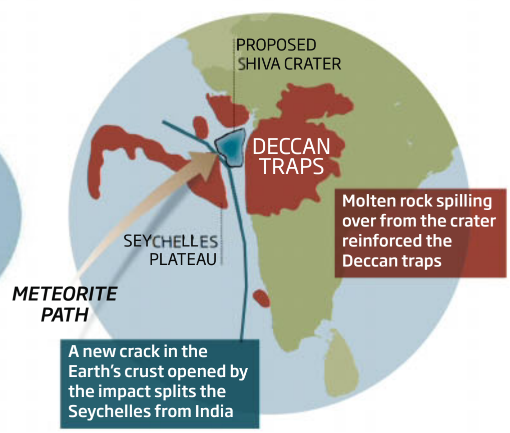
For Basu, that only deepened the mystery. For one thing, there was no noticeable impact site anywhere near the Siberian lava flows. For another, he was not convinced that the Shiva site was actually an impact crater.

Smash hits

A meteor strike on one part of Earth's surface might create seismic shock waves that propagate through the planet's interior and cause volcanic outbreaks in other parts of the world



An alternative theory for the Deccan traps* is that their formation was assisted by an impact close by



*Traps are areas of solidified flood basalt forming "step-like" hills

Were the Deccan traps formed by an ancient meteor strike?

DINODIA PHOTOS/GETTY

His brainwave was that it didn't matter. "A big impact anywhere would have shaken the planet and created pressure that might have amplified deep-mantle volcanic activity already in progress," he says. If that was so, whether Shiva was an impact crater or not was irrelevant. An impact anywhere in the world could have been the trigger for the Deccan volcanism; arguably, it could even have been the well-documented Yucatán impact.

Shaken and stirred

Basic physics says that is plausible. "The idea of volcanic activity being primed and increased by energy waves sent through the mantle by impacts elsewhere on the planet is a reasonable one," says Jones. Pressure waves from earthquakes travel extremely well through the inner layers of the Earth: seismographs in Europe and the US routinely pick up tremors thousands of miles away in China, for instance. A superpowerful pressure wave such as one created by a huge impact could well have done enough to rattle volcanic plugs and stir lava domes, activating otherwise mild or dormant volcanism.

To lend credence to the idea, what Basu needed was evidence of a meteorite impact 251 million years ago – not in Siberia, but anywhere. That had him stumped until 2003, when he and his colleagues were handed a 251-million-year-old rock sample from near the Beardmore glacier in Antarctica. Within the rock, they found inclusions with an odd chemical composition that looked for all the world like meteorite fragments. They published a paper detailing the exciting discovery and its possible implication: that the two largest volcanic events in the past billion years could have been caused by meteor impacts.

The claim caused a considerable stir, and many geologists dismissed the Antarctic finding out of hand. "A lot of criticism came because folks figured it wasn't possible for meteorite fragments to last so long," says Eric Tohver of the University of Western Australia in Perth. Meteorites are mostly metal and would usually be expected to rust away into nothingness over 100 million years, even if buried. The fragments must be modern, said the critics, and somehow have infiltrated the sediments.

Undeterred, Basu and his colleagues pressed on with their exploration. In March 2010, at a conference of planetary scientists in Houston, Texas, they presented what they consider to be a smoking gun: more meteorite fragments, this time enclosed in clay containing fossils that date them to 251 million years ago. Clay readily absorbs water, drawing off moisture and preventing meteorite fragments from rusting away.

Scepticism remains. "Small meteorites fall from the sky all the time," says Schultz. "Just because these meteorite fragments are the same age as the Siberian lava does not mean they and the Siberian lava flows are related."

As debated as Chatterjee's and Basu's ideas are, the concept that extraterrestrial bodies might have direct geological effects is now more widely accepted. "The idea of impacts causing volcanism is absolutely plausible," says Vicki Hansen, a planetary geologist at the University of Minnesota, Duluth: modelling shows that impacts can readily melt a planet's surface layer where it is relatively thin. And a new analysis by a team of US and European geologists calculates that energy from the Chicxulub impact was sufficient to trigger volcanic eruptions anywhere on earth.

The question is what sorts of volcanic activity this might generate. Might impacts help to explain the hotspots of Hawaii and Yellowstone, for example? Hansen is open-minded, but sceptical. "There can be little doubt that an impact could spawn a type of hotspot given the right conditions," she says. The crust beneath Hawaii, though, seems relatively intact, and the hotspot looks to be the result of a bulge of superheated mantle, or "plume", forcing its way up for reasons unknown. We know less of what underlies Yellowstone; there is no evidence yet that an impact played a significant part there.

With other hotspots it is a different story. The Ontong Java plateau lies beneath the western Pacific, north of the Solomon Islands, and it is a hotspot that was active some 125 million years ago. The upper layers of the mantle are uplifted there, but not as much as under Hawaii. A likely explanation is that an impact fractured the crust, allowing melt from below to rise and spill out as an eruption. The escape of so much melt material would reduce the density of what was left behind, causing the mantle bulge seen today.

How long such impact-induced fireworks might have lasted is another area of debate. Tohver thinks not so long – a few hundred thousand years, perhaps a few million. "It is a lot like dropping a spoon into thick pea soup," he says: the initial large disturbance would quickly die down. Schultz agrees, on the basis of studies of other solar system bodies. "Theoretical models concluded that impacts could not trigger sustained eruptions," he says.

Jones begs to differ, arguing that better modelling will show that sustained eruptions can result from impacts. "A major difference between the Earth and our neighbouring planets is that Earth is still very hot and geologically active, so may be much easier to melt with impacts," he says.

The debate will rage on, but one thing seems certain: accumulating evidence means the days of thinking about geology without considering influences from above are numbered. "Geologists don't typically consider impact hypotheses, perhaps for psychological reasons," says Hansen. "We have been trained to consider things that come from within our planet." Being forced to consider the effects of random meteorite strikes adds another complexity to an already involved subject. But in the end, says Hansen, "we are never going to get anywhere if we keep trying to understand our planet with our hands over our eyes and ears". ■

FEW things are more likely to prompt instant ridicule from climate sceptics than the idea that there might be a link between global warming and geological disasters such as earthquakes, volcanic eruptions and tsunamis. "Earthquakes are caused by tectonic plate movements – they are not caused by Bubba driving his SUV down the highway," is typical of the responses found in the denialist blogosphere.

Yes, the Earth moves all by itself, but it is becoming increasingly clear that climate plays a part in when and how often. What happens on the surface can suppress quakes and eruptions – and trigger them. There are already signs of such effects in the world's northern regions, which are warming fastest.

Indeed, a 2012 special report on extreme events and disasters related to climate change, commissioned by the Intergovernmental Panel on Climate Change, included a short section on it. So what exactly is going on and what can we expect during the next century and beyond?

The idea that climate change can affect events such as earthquakes is not as outlandish as it might first seem. While the power of earthquakes comes from the movements of tectonic plates deep beneath the surface, even these stupendously massive structures can be influenced by what is happening at the surface. The rapid erosion of huge quantities of material by the monsoon rains in India, for instance, has affected the motion of the Indian plate over the past few million years.

On a more immediate timescale, there is already plenty of evidence that human activity can trigger earthquakes. The building of vast dams has often been linked to seismic activity, for instance. Some blame the Great Quake of Sichuan in 2008, which killed 80,000 people, on the recently constructed Zipingpu dam just 5 kilometres away from the epicentre.

LEE FROST/ROBERT HARDING WORLD IMAGERY/CORBIS

GNS SCIENCE

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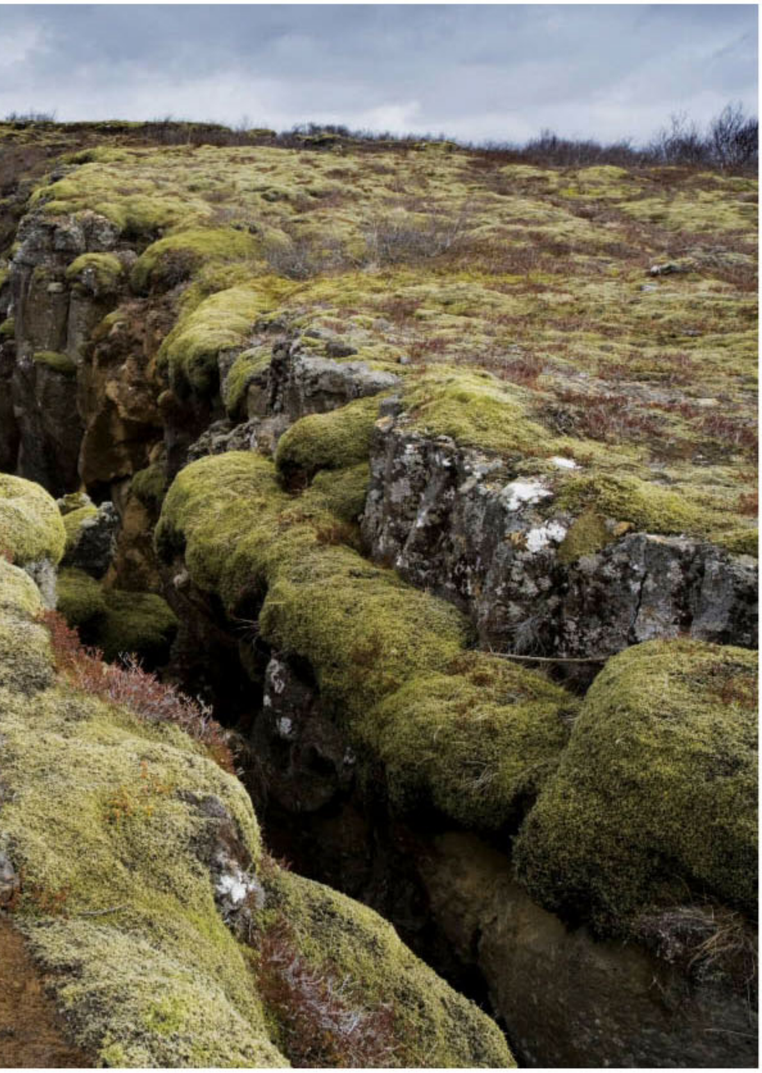
Could global warming really lead to more earthquakes, volcanoes and tsunamis? Caroline Williams investigates

Earth shattering



Quakes in geological hotspots like Iceland may happen sooner than they otherwise would have

JAMES BALOG/AURORA PHOTOS/CORBIS

A warm spell caused a landslide on Mount Cook (far left). Rising seas can trigger seismic activity at coastal faults such as San Andreas (left)

Mining and drilling activities can also trigger small earthquakes – it is well known that fracking, for example, can do this – and at least one project has been cancelled because of fears of further quakes. And if small drilling projects can trigger quakes, it is not so surprising that altering the climate of the entire planet will have an effect too.

The crux of the problem is simple: anything that increases or decreases the load on Earth's crust causes stresses and strains. When this happens slap bang on top of one of the world's many volcanoes or geological faults, where the crust is already under strain, it can make the area more or less likely to erupt or slip. And there is a very heavy substance with movements that depend largely on the weather and the climate: water.

During past ice ages, vast ice sheets several kilometres thick built up over northern Eurasia and North America. The weight of the ice pinned down faults and suppressed the flow of magma. When the ice melted, there was a flurry of earthquakes and volcanic eruptions as faults began to move again.

These ice sheets were so massive that sea level rose by 120 metres after they melted. However, even far smaller changes in the distribution of water are enough to trigger earthquakes and volcanic eruptions. A 2010 study of earthquakes on the Easter microplate in the Pacific, for example, found that a dip in local sea levels of only 20 centimetres due to changes in trade winds before an El Niño event raised the average number of monthly earthquakes from two to eight. When El Niño arrived, raising the local sea level by 50 centimetres, fewer earthquakes occurred.

And Mount Pavlof, an active volcano on the Alaska peninsula, erupts more often in the winter. This may be a result of sea levels rising by 30 centimetres in the winter due to local storms, says Steve McNutt, a volcanologist at the University of Southern Florida in Tampa. This would squeeze magma upwards as the weight of the water on the seabed either side of the peninsula increases.

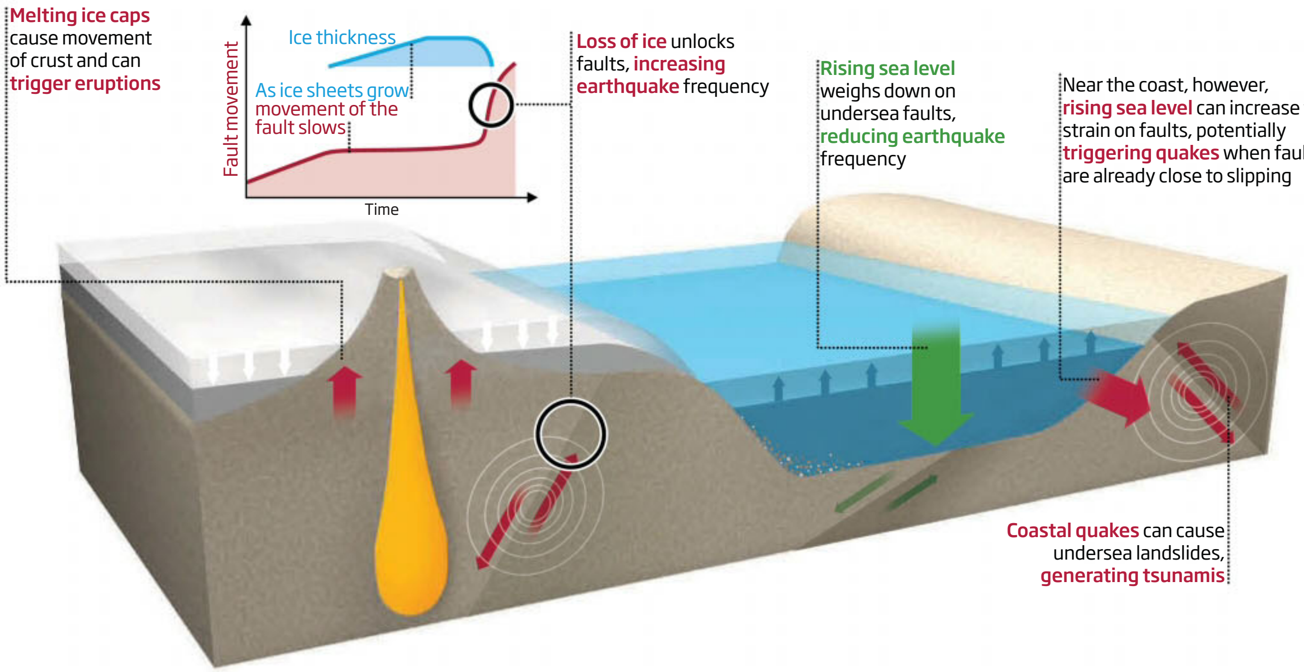
Melting glaciers

While these two examples are seasonal and linked to the weather, in Alaska there are signs of climate-driven changes. "I think of Alaska as the 'canary in the cage' because it is very tectonically active, there are a lot of active faults, a lot of volcanoes and it's very high latitude and that is where the temperatures are rising most rapidly," says Bill McGuire, a volcanologist at the Hazard Centre at University College London.

In the south of Alaska, large glaciers sit over a major fault where the Pacific-Yakutat plate dips under the continent. During the past ›

How warming affects quakes and volcanoes

Melting ice sheets and rising sea levels can alter the existing stresses on faults and magma chambers, triggering earthquakes and eruptions. Global warming may mean such events occur sooner than they might otherwise have done, but there will not necessarily be more overall (see inset)



century, the glaciers that have pinned down and stabilised the fault have thinned by hundreds of metres, and the crust beneath has rebounded by up to 20 millimetres per year.

Ice loss was particularly fast during a warm spell between 2002 and 2006. The frequency of small earthquakes in the area increased during this time, according to Jeanne Sauber of NASA's Goddard Space Center in Maryland and Natalia Ruppert of the University of Alaska, Fairbanks.

"You need a certain amount of strain to accumulate for a quake and climate change may bring that forward"

Sauber and Ruppert also think that the magnitude 7.2 St Elias earthquake in this region in 1979 occurred earlier than it might otherwise have done, due to the loss of ice. The quake was in an unpopulated area and no one died.

Even if climate change is indeed to blame these are relatively minor events. On a global level, there has been no significant increase in either volcanic eruptions or earthquakes as a result of the warming over the past century. Certainly, no researcher is claiming there is any connection between climate change and major disasters such as the Japanese megaquake in 2011.

There is, however, evidence that warming has triggered major landslides (see "Slip-sliding away", page 52). And there has been very little warming so far compared with what is to come: McGuire thinks we will we see a clear effect on volcanoes and earthquakes when climate change really gets going. "Earthquakes and volcanic eruptions over a hundred years would cluster. You need a certain amount of strain to accumulate and climate change may bring forward the time that takes," he suggests. This will mean more earthquakes and eruptions in a given period, rather than more in total, he says.

The main reason is melting ice. There is far less ice now, of course, than at the end of the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As Iceland's biggest ice cap melts, an extra volcano's worth of magma is forming last ice age. But the planet is warming much faster, so sea level may rise as fast as it ever did before. While sea level rose just 0.17 metres over the 20th century, most glaciologists expect sea level to rise around a metre by the end of the 21st century (see "Five metres and counting", page 80). This would add an extra tonne per cubic metre to undersea and coastal faults.

The good news is that it will probably weigh down and stabilise faults beneath the sea floor. The bad news is that it will create extra stress at the coast. Here there will be a kind of see-saw effect as the seabed is pushed down. That could add enough stress to trigger a quake on faults that straddle the coast, or run parallel to them, such as the San Andreas fault in California, the North Anatolian fault in northern Turkey, and the Alpine fault in New Zealand.

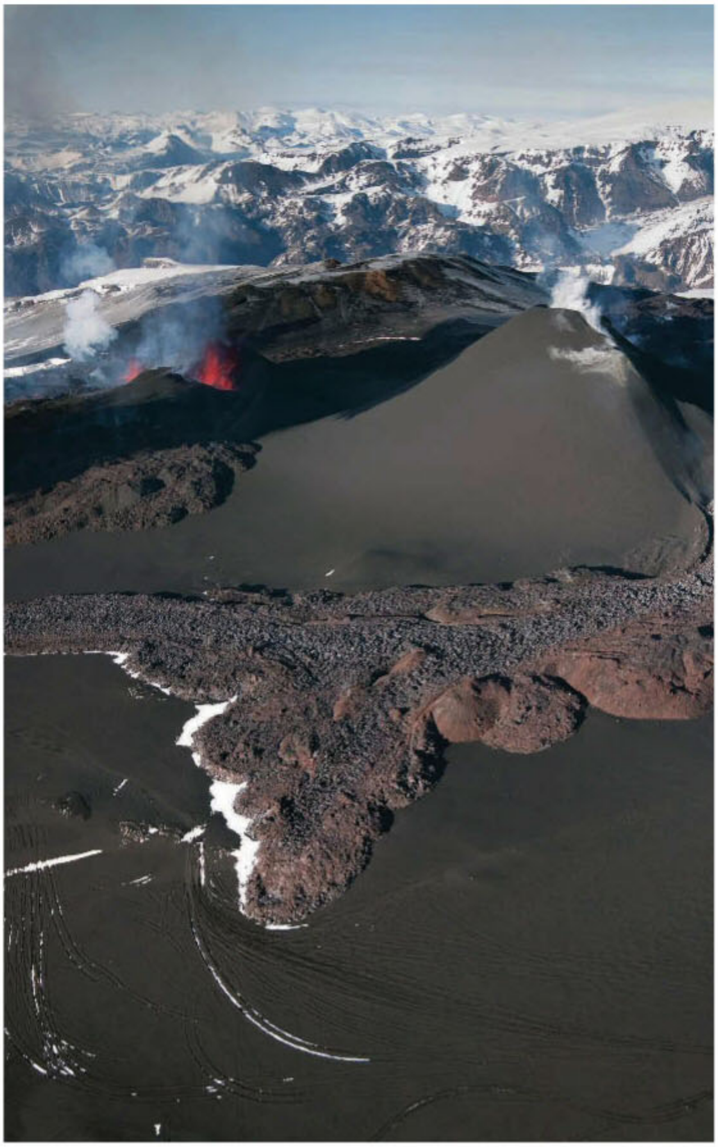
The next hundred years of sea-level rise is only likely to trigger an earthquake on a fault system that is already very close to failure, says Karen Luttrell, a geologist at Louisiana State University at Baton Rouge. Still, that could mean people suffering an earthquake that otherwise would not have happened in their lifetime.

Apart from this coastal effect, the areas most likely to be affected are sparsely populated and are already hotspots for geological activity, such as Iceland. Its largest ice cap, Vatnajökull (pictured left), sits on top of two active volcanoes. The ice cap has lost 10 per cent of its mass since 1890, which is having two effects.

The crust is rebounding, potentially bringing the magma chambers beneath closer to collapsing and triggering earthquakes. It also causes more magma to be produced at depth, as lower pressure can lead to rocks melting. This second effect is peculiar to Iceland, where hot magma is already close to the surface because it lies along the Mid-Atlantic ridge.

Carolina Pagli of the University of Leeds, UK, and Freysteinn Sigmundsson of the University of Iceland in Reykjavik have calculated that the thinning of the ice cap is increasing magma production each year by 10 per cent. To put it in perspective, the extra 1.4 cubic kilometres produced in each century is similar to the 2 cubic km per century already produced under the Bardarbunga volcano. So almost a volcano's worth of extra magma is being produced due entirely to the melting of the ice.

Adding more magma to an existing chamber is likely to mean more frequent eruptions as the chamber fills and empties more quickly. "It is likely to cause an increase but it is not possible to tell when," Pagli is quick to point out. "We don't know how quickly the magma that is being produced moves to the surface," she says.



NORDICPHOTOS/GETTY

Even eruptions as remote as that at Eyjafjallajökull in 2010 cause chaos

"Extensive ice-cap melting could reawaken long-dormant faults in Greenland and Antarctica"

While Iceland is a special case, in that it sits over a major spreading ridge, Pagli points out that wherever ice caps or glaciers above volcanoes melt, they will cause the crust above the magma chambers to flex, which might make them more likely to fail. "Volcanoes in Antarctica may be subject to this," she suggests. There are also chains of volcanoes covered by large glaciers in the Aleutian Islands in Alaska and parts of Patagonia.

In Greenland and Antarctica, extensive melting of the ice caps could even reawaken long-dormant faults. This would result in earthquakes that would not have occurred otherwise, and some of them could be major ones. Both polar regions are seismically

NASA

Melting permafrost has triggered extreme landslides in the Russian Caucasus

quiet at the moment, but according to Andrea Hampel, a geologist at Hannover University in Germany, that is probably because of the vast amount of ice that is weighing them down. While few people live near these areas, coastal earthquakes in remote places could still cause major disasters by triggering tsunamis that speed across oceans and hit densely populated areas.

Around 8000 years ago, after the end of the last ice age, there was a massive underwater landslide, called the Storegga slide, off the coast of Norway. An estimated 3200 cubic km of seabed slid down the edge of the continental shelf, generating a huge tsunami with waves up to 25 metres high, which engulfed parts of Scotland, Norway and Iceland.

SLIP-SLIDING AWAY

High-altitude mountain areas are warming fast, melting the permafrost that holds many slopes together. In areas such as Alaska, New Zealand, the Russian Caucasus and the Alps in Europe, the result has been an increase in rock and ice landslides over the past few decades.

"Gradual warming causes long-term thaw of permafrost that generally reduces rock strength, while high-temperature events act in much less time, days to weeks, and can be considered as landslide triggers," says Christian Huggel, a glaciologist who studies glacial hazards at the University of Zurich in Switzerland. And if temperatures quickly fall again, meltwater freezes and expands, destabilising the slope yet further.

Huggel and his team have linked several rock-ice avalanches across the world's mountains to this kind of rapid warming. The worst yet – and the largest rock avalanche on record – was in the Russian Caucasus in 2002. Part of the Dzhimarai-Khokh mountain (pictured left) collapsed, smashed into the Kolka glacier below, picked up 100 million cubic metres of rock and ice and raced down the mountainside at 80 metres per second, killing 100 people. Temperature recordings from sensors embedded in the rock suggest the permafrost gave way at the bottom of the section that slipped.

A similar story played out on Mount Steller, Alaska, three times – once in 2005 and twice in 2008 – and also on Mount Cook, New Zealand, in 1991, and on Mount Rosa in the Swiss Alps in 2005 and 2007 – all after warm spells lasting up to 10 days and in some cases followed by a refreeze immediately before the landslide. On these occasions, no one was killed, although the Mount Cook avalanche narrowly missed an occupied Alpine hut, and both Mount Rosa avalanches hit what was a glacial lake until it drained in 2003. Had the lake still been full, the community of Macugnaga below would have been hit by a devastating outburst flood.

Huggel predicts that brief warm spells in the highly populated Alps will become 1.5 to 4 times more common in the next few decades compared with the past 50 years.

If that is the case, it is only a matter of time before lives are lost again. "A similar event [to the Russian landslide] in the Alps could cause the death of thousands of people and damage of the order of billions of dollars," says Huggel.

But it might be possible to save lives. "Often, but not always, there are precursory signs of instabilities that should not go unnoticed in densely developed mountain regions," he says. Any advance warning would buy time for people to make their escape.

Tsunami risk

The slide is thought to have been triggered by earthquakes, which in turn were caused by the rebounding of the crust in northern Europe after the ice melted. Studies of the sea floor show that the Storegga slide was one of a series of megaslides in this area over the past 500,000 years, most of which occurred in the aftermath of ice ages.

Underwater slides could occur off many coastlines around the world. A 1998 tsunami that killed 2000 people in Papua New Guinea, for instance, was caused by an undersea slide triggered by an earthquake. So if rising sea level triggers more earthquakes in coastal areas, in theory it will also increase the odds of underwater slides and thus of tsunamis.

Overall, then, the evidence does point to a small but real increase in the likelihood of earthquakes, volcanic eruptions, landslides and tsunamis over the next century or so as a result of climate change. The effect is likely to be greatest in areas where few people live, minimising the threat to lives. Even those who live far from any volcanoes or quake zones, however, could feel the economic and practical consequences.

The eruption of the Eyjafjallajökull volcano in Iceland in April 2010 grounded flights across Europe for nearly a week, while eruptions at Tavurvur in Papua New Guinea in 2014 and at Indonesia's Mount Raung in 2015 had a similar effect across the Pacific. None of these eruptions had anything to do with climate change, but it is the type of problem that we – or our children – are likely to see more of if McGuire's predictions about more frequent eruptions are borne out.

In a world that is going to suffer from ever more catastrophic floods and storms, killer heatwaves and devastating droughts, the risk of a few more earthquakes and volcanic eruptions, mostly in remote areas, might seem to be a relatively minor issue. That may well be true, but it is yet another item to add to the already long list of adverse consequences predicted or beginning to occur as a result of climate change. Events such as earthquakes also strike with little if any warning, so they can kill far more people than, say, hurricanes and floods.

What's more, geological events such as earthquakes, volcanoes and tsunamis have always been seen as completely beyond our control. Now it appears this is no longer entirely true – we have the power to prevent at least a few of them if we choose to. ■

4.5 BILLION

Hadean

MORGAN SCHWEITZER

1 BILLION

Neoproterozoic

CHAPTER THREE

THE DEEP PAST

2.5 BILLION

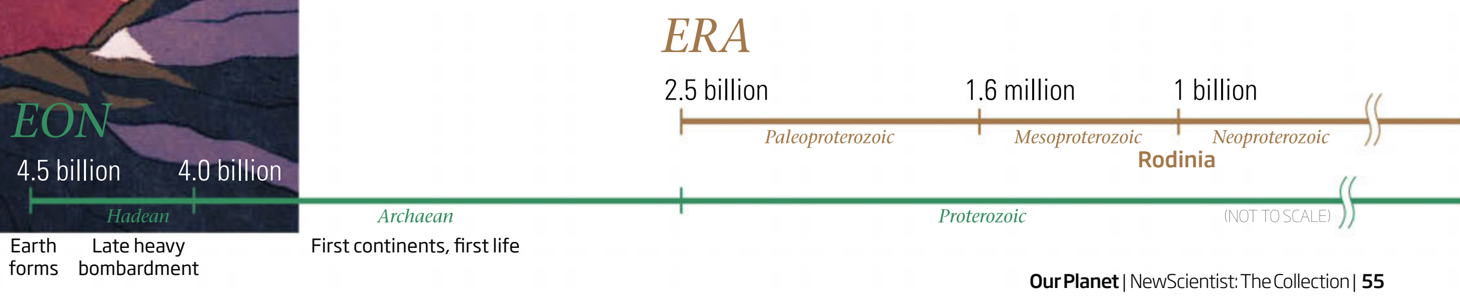
Paleoprterozoic

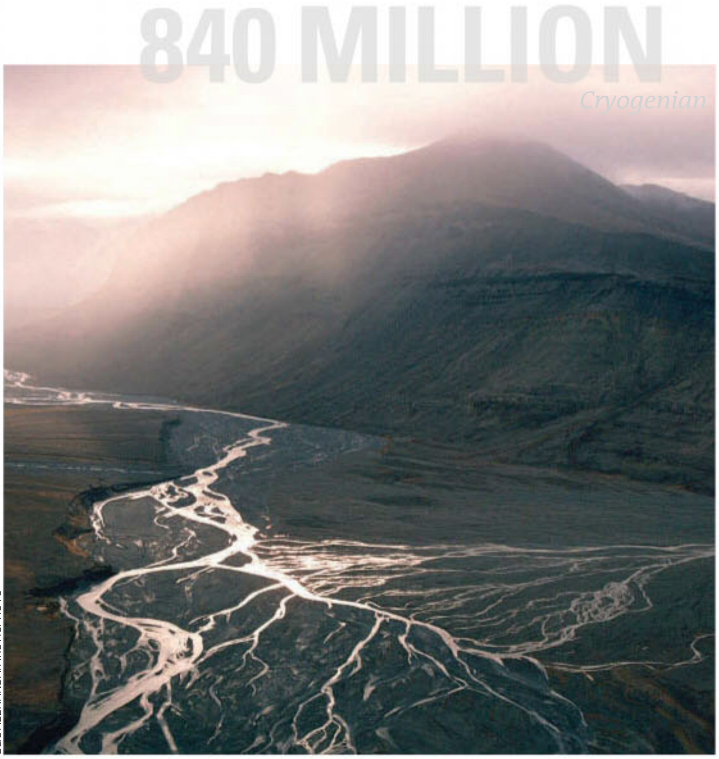
THE TIME TRAVELLER'S GUIDE TO EARTH

OUR PLANET HAS SOME SPECTACULAR SIGHTS – BUT THEY ARE NOTHING COMPARED TO ITS PAST. FOR THE ULTIMATE TOUR, HOP IN OUR TIME MACHINE…

THE Earth is full of awe-inspiring natural wonders that are on many people's see-before-I-die list: the Grand Canyon, the Himalayas, the Amazon, the Antarctic, and many more. But what about the places that disappeared before we had a chance to see them? Earth has a deep history and its past is full of spectacular features that are now lost in the mists of geological time. So, if you had a time machine, where would you go?

Sadly, many awesome geological features are genuinely lost: erased by the forces of plate tectonics, we have no way of knowing where they were or when. Even so, there are plenty of past glories we know about that are worth a trip through time. Here are our seven wonders of the very ancient world.





B&C ALEXANDA/ARCTICPHOTO

Braided river systems like those found in the Arctic once covered the whole Earth

RIVER WIDE, MOUNTAIN HIGH

RODINIA,
1 BILLION YEARS AGO

From its source high in the Peruvian Andes to its mouth on the coast of Brazil 6400 kilometres away, the Amazon river flows across almost the entire breadth of a continent. The mountain range it springs from is even longer, stretching 7000 kilometres from the tropical jungles of Venezuela in the north to the icy wilderness of Tierra del Fuego in the far south.

Impressive on today's Earth. But quite piddling by the standards of the deep past.

The first stop for your time machine is way back, a billion years ago, when Earth's landmasses were fused in a supercontinent called Rodinia. Peer out of the window and you'll see an unfamiliar world. All life then was unicellular and entirely marine, so Rodinia's vast expanse is completely barren. But what it lacks in biological richness it makes up for in vast river systems and mountain ranges.

As the continental building blocks that made Rodinia crashed together about 1.2 billion years ago, large portions of crust were lifted up, much as the ongoing collision between the Indian and Eurasian plates is generating the Himalayas now.

It is tempting to think that such great forces would push up absolutely enormous mountains. Although we have no way of knowing how high they were, it is unlikely that anything much loftier than the Himalayas has ever existed on Earth, says geologist David Rowley of the University of Chicago. Weathering erodes away mountains as they form, and gravity dictates how much load Earth's crust can bear without buckling. Account for that, and Mount Everest is about as high as a mountain can be.

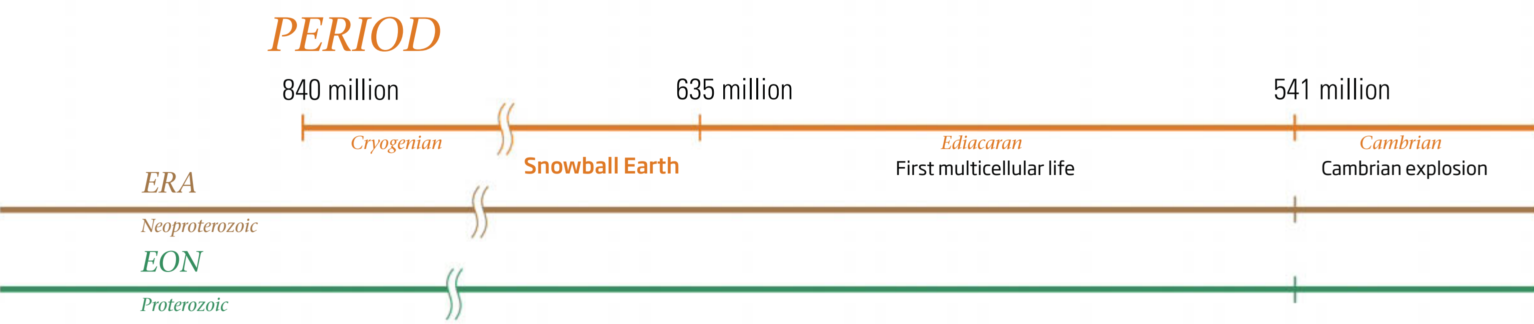
But by another measure, Rodinia's mountains are mind-blowing. Imagine taking the Andes, Rockies, Himalayas, Alps, Atlas and Urals and stringing them together end-to-end, and you're getting close to the length of Rodinia's principal mountain chain.

"The range stretched across the entire supercontinent, maybe 15 to 20,000 kilometres," says Robert Rainbird of the Geological Survey of Canada in Ottawa. Its eroded remains can still be found across North America and Europe, including parts of the Appalachians and the Highlands of Scotland.

And just as mountain ranges like the Andes and Himalayas give rise to great rivers today, so too did those of Rodinia – but with a big difference. "There was no vegetation to constrain the rivers so they would have just flowed unconstrained across the barren landscape," says Rainbird.

Similar river systems, characteristically braided into many smaller channels, exist in the vegetation-free high Arctic today, but on Rodinia they were vastly bigger. Rainbird and his colleagues have found sediments from the Rodinian mountains 3000 kilometres away on the other side of North America, as well as in India, Antarctica, Scandinavia and Siberia, indicating river systems that spread across the whole supercontinent. "They would have been very dominant features, far longer and wider than the Amazon," says Rainbird. The rivers would also have fed huge inland seas far bigger than anything we have on Earth now, he says.

Rodinia began to break apart about 750 million years ago, splitting its vast mountain range into pieces. By the time the landmasses reassembled into the next supercontinent, Pangaea, around 300 million years ago, the land was covered in vegetation. So while Pangaea might also have been home



to huge mountain ranges, the great rivers of Rodinia are possibly unique in Earth's history.

If monster rivers and massive mountain ranges are not your thing, another feature of Rodinia might make it worth a visit: shorter days. The moon will look larger than you've ever seen it, because it was closer to Earth back then. That made the planet rotate faster, like a spinning ice skater with arms and legs tucked in. Sedimentary rocks that contain a record of the height of the tides around 900 million years ago indicate a Rodinian day lasted somewhere between 19 and 21 hours.

Graham Lawton

SNOWBALL EARTH

EVERYWHERE,
700 MILLION
YEARS AGO

These days, if you want to see a glacier near the equator, you must scale the rarefied heights of Mount Kenya or the Ecuadorian Andes. Around 700 million years ago it was a bit less of an effort. In fact, you'd struggle to find somewhere that wasn't frozen over.

You've arrived in the middle of the Cryogenian period, so called because the planet was repeatedly sheathed in ice in a series of "snowball Earth" episodes. The greatest of these Cryogenian snowballs, the Sturtian glaciation, began 716.5 million years ago. In the space of a few years, land and sea across the globe were swallowed up by sheets of ice that eventually became kilometres thick. They did not melt for another 55 million years. Earth was literally a snowball, like today's Antarctica from pole to pole.

That, at least, is the story many geologists have come to accept since Joseph Kirschvink of the California Institute of Technology in Pasadena first advanced the idea of snowball Earths in the early 1990s. Ancient glacial deposits laid down at tropical latitudes – for example in north-western Canada, which 700-odd million years ago straddled the equator – tell a story of sea ice between 1.5 and 3 kilometres thick, says Kirschvink.

The same region also provides clues to the Sturtian glaciation's cause. The Franklin Large Igneous Province, a vast area of volcanic rock covering more than 1 million square kilometres, can be dated to shortly before the glacial layers. It seems the eruption of a supervolcano brought vast volumes of basalt to the surface that quickly weathered under tropical rainstorms – a chemical process that sucked huge amounts of the greenhouse gas carbon dioxide out of the atmosphere. Temperatures plunged and the polar ice caps began to advance.

From then on things proceeded with a speed unusual for Earth processes. As the seas froze, water vapour, itself a potent greenhouse gas, could no longer evaporate into the atmosphere in the usual quantities. "It was like throwing a master off-switch on the

JOHN EASTCOTT AND YVA MOMATIUK/NATIONAL GEOGRAPHIC CREATIVE

This was what the equator looked like 700 million years ago. And the rest of the world too

hydrological cycle," says Kirschvink – and the big freeze gathered pace towards the equator. You won't want to open the door of your time machine, because even at the equator it will be -50 °C, the sort of cold you can only reliably find today deep in the Antarctic.

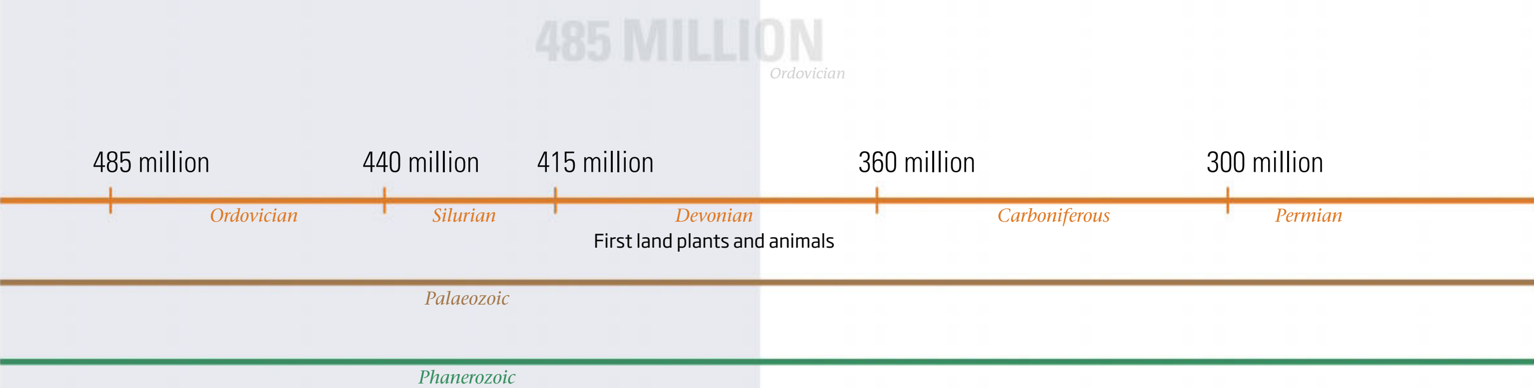
> "In the space of a few years, the land and sea were swallowed by ice sheets"

Perhaps because of its sheer drama, the snowball Earth idea remains controversial. Some geologists opt for a less harsh "slushball Earth" variant. But Kirschvink thinks the sheer geographical spread of glacial deposits now dated to the same time tell their own story. "It's a hard snowball, dammit," he says.

Eventually, CO_2 seeping out from undersea volcanoes began to warm things again, and cracks in the ice stayed open. Then, snowball Earth was over almost as quickly as it began. "You throw water vapour into the atmosphere, and fresh meltwater absorbs sunlight and warms," says Kirschvink. "As you start to open the snowball, it drives it till it's gone."

Yours will be the only eyes around to see these startling transitions: the most advanced witnesses to the beginning of the Sturtian glaciation were single-celled zooplankton. Kirschvink wonders whether these little critters, engaged in an increasingly desperate doggy paddle for survival, might have inadvertently contributed to their own predicament. "My pet hypothesis is that zooplankton evolved that excreted fecal pellets which sank rapidly to the bottom, burying carbon there and getting the CO_2 out of the system," he says.

Certainly life seems to have had a hand in an earlier snowball episode beginning around 2.4 billion years ago. "There we think it had a biological trigger from day one," says Kirschvink – the evolution of photosynthesising cyanobacteria that ›



sucked CO_2 from the atmosphere.

Whatever their triggers, the rapidity with which Earth succumbed to the deep freeze is a reminder that small perturbations can have huge consequences in our planet's complex and sensitive climate system – a lesson we would do well to take to heart, says Kirschvink. "We're twiddling knobs where we don't know what they connect to."

Richard Webb

EXTREME DESERTS AND TORRENTIAL RAINS

PANGAEA,
250 MILLION YEARS AGO

252 MILLION

Triassic

If you're looking for extreme vistas and even more extreme weather, you can't go far wrong with Pangaea. Earth's most recent supercontinent came together about 300 million years ago and started to break apart 125 million years later. To experience it at its most extreme, set your time machine for about 250 million years ago.

The best way to begin your visit would be to hover at the edge of the atmosphere and gaze down at the vast expanse of land. The continent is C-shaped, with the warm Tethys Sea nestled within the curve. From the other side of the planet all you see is an unbroken expanse of ocean, Panthalassa.

For your first stop on the surface, why not head for the equatorial desert? To experience it at its most punishing, aim for the centre of the continent close to the equator. Climb out, and where you're standing will one day be somewhere in the western Sahara. But Earth's greatest desert today has nothing on this one.

This point in time is just after the Permian mass extinction, which wiped out around 90 per cent of species. One proposed cause is a super-greenhouse climate, which persisted for several million years and rendered much of Pangaea's interior uninhabitable. "It was extraordinarily hot – it would have been the norm to have temperatures above 50 °C," says Paul Wignall, who researches palaeoenvironments at the University of Leeds, UK. Expanses of reddish dust stretch as far as the eye can see. In the distance you can just make out the mighty Central Pangaean Mountains, unless it's a windy day, when you'll be face-to-face with a boiling red sandstorm.

Next we recommend a quick zip east to the shores of the Tethys Sea. You're here to marvel at Pangaea's most extreme sight: the mega-monsoon. Monsoon rains happen when moisture-laden sea air is blown onto land and forced upwards, cooling and condensing the water to make rain.

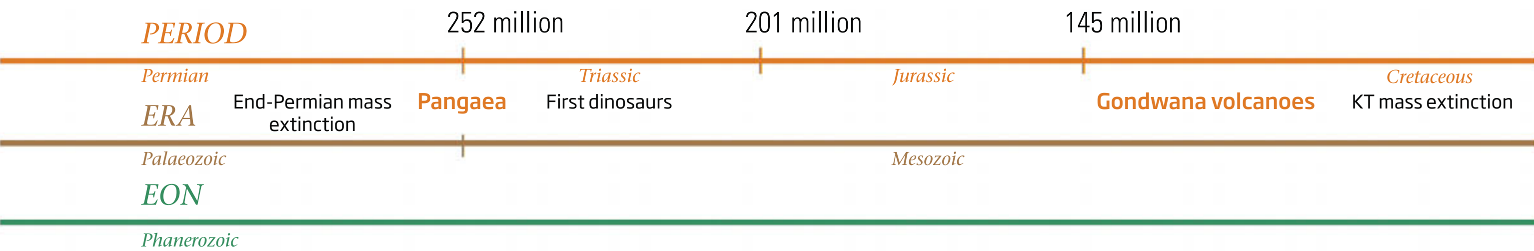
> "The ash and aerosols would darken Gondwana's skies for years to come"

At the edge of the Tethys, you risk getting utterly drenched. The sea was probably as warm as hot soup, about 40 °C, says Wignall. That meant the air above it was wringing wet. On top of that, the mountains bordering the sea's north shore were among "the mightiest ever seen on Earth", according to geology writer Ted Nield in his book *Supercontinent*. That would have forced huge amounts of warm wet air up to great heights, cooling it quickly and unleashing a deluge that makes today's monsoon in India look like a light shower. At least it would have been warm.

We know more about Pangaea than its supercontinental predecessor Rodinia (see page 56). But Earth's tectonic plates are constantly on the move and most geologists

201 MILLION

Jurassic



think the continents repeatedly coalesce and split apart in a 500-million-year cycle, so there may have been many more before Rodinia. And the cycle continues: in about 250 million years the world's land masses will come together again in a future supercontinent called Pangaea Ultima. If only our time machine went forward...

Joshua Howgego

THE LARGEST VOLCANIC ERUPTION IN EARTH'S HISTORY

GONDWANA,
135 MILLION YEARS AGO

Welcome to hell on Earth, aka the Paraná-Etendeka province, circa 135 million years ago. The time-travel tourist slogan? "If the dinosaurs don't get you, the volcanism will!"

By the time you arrive, the southern remnant of Pangaea, Gondwana, has already spent millions of years pulling itself apart, separating what we now know as South America from Africa. This rifting was one of the factors that created the red-hot cataclysm you've come to see. As the rift worked its way north, Earth's crust became thinner. Meanwhile, a superheated portion of the mantle was welling up, heating the crust from below. Eventually, magma broke through and flooded across the landscape. The modern-day remnant of this is called the Paraná-Etendeka traps, expanses of basalt covering more than 1.3 million square kilometres of Brazil, Uruguay, Paraguay, Argentina, Namibia and Angola.

For the most part, this would be like the volcanism that gave us Iceland – passive, gentle and only rarely explosive. You didn't come here for gentle, though. Happily for thrill seekers, a lot of the magma is rich in silica. "That's the key to explosive eruptions," says Sarah Dodd of Imperial College London. "Silicic magma is highly viscous and so it traps volcanic gases. These build up, and ultimately propel magma explosively towards the surface."

The Volcanic Explosivity Index gives you an idea of what's in store: the eruption you're here to see has the maximum ranking of 8, which is described as "apocalyptic" (one ranking above "mega-colossal"). This score is given to any event that ejects more than 1000 cubic kilometres of rock, as the supervolcano Toba did in Indonesia 74,000 years ago, much to fledgling humanity's inconvenience. The PE traps produced at least nine apocalyptic eruptions, probably over several million years. They are the most violent eruptions in Earth's history, as far as we know.

But we're gonna need a bigger scale, because the largest of them spewed at least 8600 cubic kilometres of rock – based on what we can see in South America and Africa today – and perhaps as much as 26,000 cubic kilometres if you factor in far-flung ash and gases. That's enough material to cover the entire UK to a depth of 100 metres. And hopefully you brought provisions, because this eruption will take several months.

An event on this scale will incinerate, smother or choke everything for hundreds of kilometres in every direction. Lava from one eruption travelled 650 kilometres. So in modern terms, if it happened in the Highlands of Scotland you would want to park your time machine no closer than London.

From that distance you would see the black clouds mushrooming, as an almost inconceivable volume of ash is lofted by explosive force and heat into the upper atmosphere, darkening Gondwana's skies for years to come. "This ash, combined with sulphate aerosols also produced by the eruption, will reflect solar radiation, quickly plunging the world into a volcanic winter for years after," says Dodd. For comparison, the much smaller Toba eruption was estimated to cause about 10 degrees of global cooling in the year immediately following, with temperatures not recovering for over a decade.

If you stay to watch the immediate aftermath, you will see the local vegetation coated in ash and ravaged by acid rain. This large-scale destruction of plant life will take with it the entire regional food chain, wiping out numerous dinosaurs. The sulphate aerosols are relatively short-lived though, and the ash would eventually settle. So after a few years of cooling, the colossal amount of carbon dioxide also pumped out by the eruption will bring a much longer period of global warming. That aspect, at least, is one you don't need a time machine to experience.

Sean O'Neill

SUPER-GREENHOUSE

THE ARCTIC,
55 MILLION YEARS AGO

Pack your cozzie, we're going to the Arctic. It's going to be hot and steamy. There will be palm trees and crocodiles.

This is the Paleocene-Eocene thermal maximum, or PETM, of 55 million years ago. For the past few million years, Earth has gradually been getting hotter and hotter, and is now on the verge of a planetary heatwave the likes of which have rarely been seen.

Even before the mercury peaks, it's pretty toasty. The poles are essentially ice-free, the deepest reaches of the oceans are 8 °C warmer than today, sea levels are roughly 70 metres higher, and there are crocodile-like champsosaurs in the Arctic Ocean. The fact that they thrived so close to the North Pole ›

33 MILLION

Oligocene

means water temperatures must have been no less than 5 °C even in the permanent darkness of winter. Today's average winter temperatures at the North Pole hover around -34 °C. You may also catch a glimpse of the hippopotamus-like *Coryphodon* in the warm swampy forests along the ocean shores.

Fast forward a few million years and you will see freshwater turtles, which seems bizarre until you consider that the Arctic basin is almost entirely enclosed by land. River water streaming off the land is floating on top of the heavier saltwater, forming what may have been one of the biggest lakes the planet has ever seen. Great for swimming, too, as the water is a pleasant 23 °C.

The other end of the world would also have been experiencing swimsuit weather. "At the peak of the PETM you get ferns on Antarctica, so that's seriously toasty," says Kate Littler of the University of Exeter in the UK.

All this warmth is the result of a big rise in greenhouse gases in the atmosphere, though no one knows what caused it. One possibility is intense volcanic activity, another that deposits of solid methane sitting at the bottom of the sea melted, releasing their load in one great gassy belch. Or maybe Antarctica's permafrost thawed, releasing a big puff of CO_2.

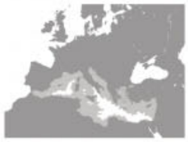
Either way, after millions of years of gradual warming, temperatures suddenly jumped by at least 5 °C in just 20,000 years. It is a tough time for life on the sea floor, where an extinction was going on, but life on land seems to be flourishing. If you drop down in the lush forests of South-East Asia, you might be lucky enough to spot a new class of mammal that has only just evolved: the primates. They look a bit like tarsiers or bush babies, eat insects, and in the very, very distant future will give rise to the only animal to have occupied all four corners of the planet: us.

Our species is also the only one with the power to trigger something even greater than the PETM: a similar amount of warming but 100 times faster. The PETM is firmly in Earth's past – temperatures returned to normal after about 200,000 years – but some say it is a window onto the future.

Catherine Brahic

THE ZANCLEAN FLOOD

STRAIT OF GIBRALTAR,
5.33 MILLION YEARS AGO



Standing at Punta de Tarifa, the southernmost point of mainland Europe, the mountains of Morocco are clearly visible across the Strait of Gibraltar. This busy stretch of water, just 14 kilometres across at its narrowest, is the gateway between the Atlantic Ocean and the Mediterranean Sea, and the closest thing to a border between Europe and Africa.

Visiting it 5.4 million years ago, the picture is very different. The mighty Atlantic is there, but the Med is nowhere to be seen. In its place is a vast basin, glittering with salt crystals and dappled with lakes of hypersaline water. This land, connecting what would become Europe and Africa, is 2.7 kilometres below sea level at its lowest point. It's quite a spectacle: Earth's lowest land today is the Dead Sea basin, a mere 430 metres below sea level.

You have arrived at the height of the Messinian Salinity Crisis, when tectonic movements have closed the Strait of Gibraltar, cutting off the Mediterranean. In the hot and dry climate, it took perhaps 1000 years for the sea to evaporate almost completely. Its remains can still be found today, under the sea floor and along its shores in the form of thick deposits of salt and gypsum.

The basin didn't stay desiccated for long. As time rolled on, the climate grew cooler and wetter, and rivers flowing into the basin turned it into a type of wetland called a lago mare, or "lake sea". But to the west, a

> "In all, 3 million cubic kilometres of Atlantic water floods into the basin"

cataclysm was brewing.

If you want to see it, hop back in your time machine and set the dial for 5.33 million years ago. A combination of tectonic subsidence, erosion and sea-level rise is just about to let the sea back in.

The Zanclean flood – named after the geological age in which it happened – probably started slowly, gradually filling about 10 per cent of the basin over thousands of years. But we arrive in time for the ending – a deluge of biblical proportions, according to Daniel Garcia-Castellanos of the Institute of Earth Sciences Jaume Almera in Barcelona, Spain. For some reason the rate of inflow suddenly soared, filling the basin completely in the space of a few months, raising the Mediterranean by about 10 metres a day. Every

CORBIS

The Strait of Gibraltar was once a rocky barrier between the Atlantic and Mediterranean

second, a billion cubic metres of water roars past, 5000 times more than the Amazon today. The sight is awe-inspiring.

In all, 3 million cubic kilometres of Atlantic water floods in, gouging a channel 250 metres deep and 200 kilometres long that can still be seen on the bed of the Strait of Gibraltar.

And it could happen again. Not enough water comes from rivers flowing into the sea to compensate for evaporation: it needs the Atlantic to keep it topped up. If tectonic forces were to seal off the strait, the Med would eventually dry up once more.

Graham Lawton

Doggerland

DOGGERLAND

THE NORTH SEA,
10,000 YEARS AGO

From the Victorian pier at Cromer on the east coast of England, the North Sea looks bleak and uninviting. But nip back 10,000 years – the blink of an eye in geological time – and it is a very different sight.

At the dawn of the Mesolithic, as the last ice age was coming to an end, sea levels were significantly lower than today and Britain was connected to mainland Europe by a fertile plain stretching as far as Denmark. Welcome to Doggerland, named after the submerged sandbank familiar to anyone who has ever tuned in to the poetic counsel of the UK Shipping Forecast.

Long considered a featureless land bridge, Doggerland has recently been revealed as a prehistoric paradise of marshes, lakes, rivers – and people. In 2008, University of Bradford archaeologist Vincent Gaffney and colleagues used seismic survey data gathered by a Norwegian oil company to reconstruct this lost world beneath the North Sea. The result is a map covering 23,000 square kilometres – an area roughly the size of Wales.

Top of the list for the discerning time-traveller, Gaffney says, is a ride over the Outer Silver Pit Lake, now a depression in the floor of the North Sea. Fed by the river Thames to the east and the Rhine to the west, this is where Doggerland's people congregate to fish, hunt and gather berries. "This was prime real estate for hunter-gatherers," says Gaffney. Today, North Sea trawlers occasionally dredge up traces of these people from the seabed – a spear point fashioned from deer bone, for example. But not much else is known about them.

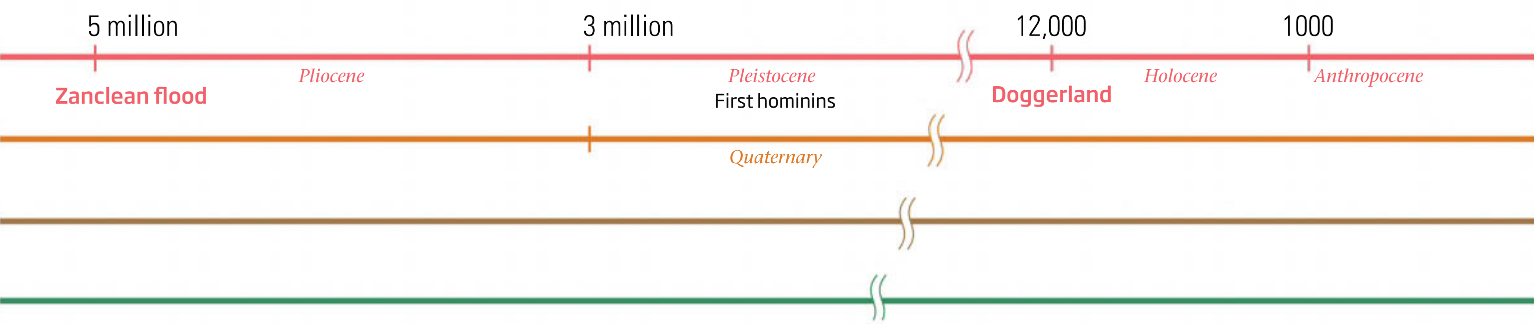
What we do know is that they were victims of climate change. As the world warmed and the glaciers melted, sea levels rose by around 2 metres every century, gradually engulfing low-lying areas. Over a few thousand years, Doggerland transformed into an archipelago.

Then came the wave. Set the time machine to 8150 years ago and you will witness something that few people have ever seen, and fewer still lived to tell the tale: a mega-tsunami. This was triggered by a massive undersea landslide off the coast of modern-day Norway, known as the Storegga Slide.

A 2014 study estimated that roughly 3000 cubic kilometres of sediment collapsed, probably triggered by an earthquake, generating a giant tsunami that surged across what was left of Doggerland. According to John Hill of Imperial College London, who led the research, if you were on Scotland's east coast – or preferably hovering above it – you'd see it battered by 12-metre-high waves. Some estimates have waves exceeding 25 metres crashing into the Shetland Islands.

Any remaining islands of Doggerland would have been devastated and catastrophically flooded, leading Hill and others to suggest that the Storegga Slide sounded the death knell for its people. But others suspect that they had long ago fled to higher, drier ground – some to the Scandinavian hills, some to France and the Netherlands, and others to the higher ground of what is now the British coast. Either way, the result was a cultural separation of Britain and mainland Europe that would last for centuries. ■

Daniel Cossins



THE DAY THE EAR EXPLO

Evidence that a nuclear time bomb tore the world apart could be staring down at us

HUMANITY has witnessed some pretty loud bangs during our short sojourn on Earth. Take Krakatoa. When the Indonesian volcano exploded in 1883, the din was audible 3000 kilometres away, and the ash thrown into the atmosphere cooled the world for decades. Then there are the explosions of our own making. The most powerful nuclear weapon ever detonated, the Soviet Tsar bomb of 1961, created a 10-kilometre wide fireball in the atmosphere.

But if Wim van Westrenen, a planetary scientist at the VU University in Amsterdam, the Netherlands, is right, these cataclysms are nothing compared with an experience Earth went through 4.5 billion years ago. With the paint barely dry on the new planet, a giant nuclear reactor deep in its interior went super-critical. The result was an atomic bomb that dwarfs our puny efforts. Detonating with the force of 11,000 billion Tsars, the explosion was enough to rip our infant world open.

It is a controversial idea, but there is circumstantial evidence if you want to find it, from traces of smaller "fossil reactors" deep underground in equatorial Africa to the conspicuous imbalance between the heat Earth gives out and the amount it receives from the sun. But van Westrenen makes a more audacious claim. The biggest piece of evidence for Earth's violent atomic past, he says, is the serene body that watches over us most nights: the moon.

Accounting for the moon's origin has always been a problem. It is just too big. No other planet in our solar system has a satellite that is proportionally so large: it is over one quarter of Earth's diameter. Such a body could not have been captured in passing, as other planets are thought to have snared their smallest satellites. In 1879, George Darwin, the astronomer son of Charles, proposed a different idea. He suggested that the early Earth spun so quickly it fell apart, spitting a bit of itself into space.

every night, says **Stuart Clark**

CARINIJOE/PERSPECTIVES/GETTY

That idea was popular for a time, but fell foul of planetary dynamicists in the early 20th century, who found that the numbers just did not add up. They looked at Earth and the moon's angular momentum, a measure of the rotational energy stored in a body. The total amount in a given system always stays the same, unless there is an interaction with an outside body. If the moon started off as part of Earth, then the angular momentum of today's Earth and moon is the amount Earth had to play with on its own in the past.

If that was the case then Earth pre-break-up must have been rotating faster in the past. Indeed, the extra angular momentum would have shortened its day to just 4 hours. The problem with Darwin's hypothesis was that for Earth's outwardly directed centrifugal force to overwhelm the inwardly acting gravitational force and break the planet apart, it would have had to be rotating even faster, spinning about once every 2 hours.

As Darwin's idea fell out of favour, another has taken its place. Known as the giant impact hypothesis or "big splat", the idea is that a game of interplanetary billiards sent a Mars-sized object careering towards the infant Earth. Striking our planet a glancing blow, this foreign body shattered on impact, sending up a giant plume of debris that eventually coalesced to become the moon.

At first, there was nothing much to favour the big splat over any other explanation for the moon. "It was proposed because nothing else worked," says Matija Cuk, a planetary scientist at the SETI Institute, California. But that has changed as we have refined our picture of what the early solar system was like. Evidence suggests planets formed when asteroid-like rocks smashed into one another, coalescing to build bigger and bigger bodies. It is perfectly reasonable to expect huge impacts in the latter stages of this process. "We know that impacts are important to planet formation," says Cuk. ›

Be that as it may, we might be forced to think again. The big splat itself could be quashed by new analyses of moon rocks brought back by the Apollo astronauts. According to the giant impact hypothesis, these did not all come from Earth, so you would expect them to show some differences in composition compared with terrestrial rocks and, in particular, contain different amounts of isotopes of the same element.

And that is the problem. When cosmochemist Junjun Zhang, then at the University of Chicago, and colleagues completed an analysis in unprecedented detail of moon rocks in 2012, they found that the oxygen, chromium, potassium and silicon isotopes are indistinguishable from Earth's. Then in February 2013, Hejiu Hui, a geologist from the University of Notre Dame in Indiana, and his colleagues discovered that several samples thought to be fragments of the first crust formed on the moon, including the famous Genesis rock brought back by Apollo 15 astronaut David Scott, contained water. In the hellish aftermath of a giant impact, the heat generated should have melted the rocks and driven off the water.

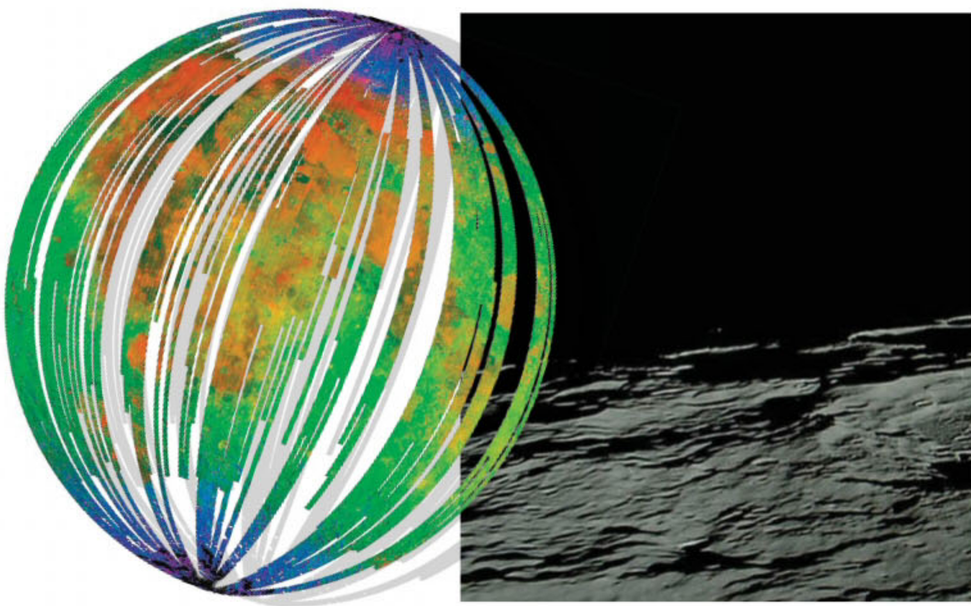
Blast in the past

Hui is in no doubt of the significance of the findings. "This does challenge the giant impact scenario," he says. Van Westrenen is more forthright: "The chemical composition of the moon deals the original giant impact scenario a fatal blow. It cannot be right."

Taken at face value, the findings strongly suggest that the moon was once a part of Earth that was somehow blasted into space without being contaminated by rocks from a colliding planet. To avoid the angular momentum problem that plagued Darwin's solution, however, a massive energy kick has to be delivered quickly and cleanly. Van Westrenen's calculations show it must be the equivalent of 40 million billion atomic bombs of the size dropped on Hiroshima.

It was nuclear geophysicist Rob de Meijer at the University of the Western Cape, South Africa, who first drew van Westrenen's attention to a possible source. The idea that self-sustaining nuclear reactors might be buried in Earth has been around for 60 years. It seems almost certain that small ones were once active. In 1972, the French Alternative Energies and Atomic Energy Commission (CEA) was mining the Oklo region of Gabon in West Africa for uranium when it discovered a significant depletion of the uranium isotope U-235 that suggested it had been processed as if by a nuclear reactor.

"George Darwin, son of Charles, reckoned that Earth spun so quickly it fell apart to make the moon"



Further exploration led to the uncovering of 16 natural fossil reactors between 1.5 and 10 metres across. Each was active around 2 billion years ago and probably continued on and off for a few hundred thousand years, kicking out around 100 kilowatts of power until they exhausted their supply of uranium.

Bigger reactors have also been proposed – indeed, it has been suggested that Earth's core harbours a massive nuclear reactor. Van Westrenen was quickly convinced that something similar could explain the origin of the moon. "A nuclear blast is the only thing we could come up with that could produce the necessary energy quickly enough," he says.

It would need something a lot larger than the Oklo reactors, though, and energy would have to be generated in a subtly different way – more akin to our fast breeder reactors. The basic idea is that heavy elements such as uranium, thorium and plutonium were concentrated in dense rocks that sank deep into Earth shortly after its formation. They accumulated at the boundary of the outer core and the mantle, where the restless geological forces brought them closer together to form large reservoirs.

Decaying radioactive nuclei within these rocks spit out fast-moving neutrons that can set off reactions of their own. But if the neutrons strike the right type of nucleus, such as uranium-238, they can be absorbed. The result is plutonium-239, which is itself a fissile material. If this absorption goes on unchecked, the fissile material builds up until enough fuel is present to go supercritical and explode.

An internal nuclear reactor could explain why Earth, like many of the planets in the solar system, gives out conspicuously more energy than it receives from the sun. This surplus energy powers the Earth's magnetic field, volcanoes and earthquakes, and much of it is thought to come from radioactive processes within the planet. That seems to be confirmed by a steady stream of ghostly neutrinos, caught by the KamLAND and Borexino neutrino detectors, based in Japan and Italy, respectively (see "Messengers from the underworld", page 22). The energy of their quarry shows all the hallmarks of by-products of nuclear reactions, coming up from Earth's interior. What is not clear is whether these neutrinos are coming from the natural radioactive decay of elements within Earth, or whether natural reactors are enhancing their release in certain regions. A definitive answer would require a global network of neutrino detectors capable of building up a map of radioactive deposits within our planet.

Even if evidence for global "georeactors" was found, most people would still need a lot of convincing that they were capable of forming the moon. Some form of the standard scenario still has Cuk's vote. "I don't think you can separate the moon's formation from a giant impact," he says.

FAR LEFT: ISRO/NASA/JPL-CALTECH/BROWN UNIV/USGS/SPL; LEFT: JAXA

The moon's minerals show that the moon and Earth are one and the same

"An internal nuclear reactor could explain why Earth gives out more energy than it receives from the sun"

Having said that, he admits something has to give to save the big splat. Ironically, his idea starts with the conservation of angular momentum – the cast-iron concept that put paid to Darwin's earlier hypothesis of the moon budding off from Earth.

Giant impacts have the problem that they impart a lot of energy to Earth – so much so that the planet starts spinning faster than the 4-hour rotation that conservation of angular momentum says was possible at the point the moon was formed. But that's if Earth and the moon form a closed system. Together with his Harvard colleague Sarah Stewart, Cuk devised a cunning way to siphon off excess angular momentum using a third body: the sun.

The idea is that a peculiar alignment of the sun, Earth and moon created a situation known as an evection resonance. This trapped the moon in orbit, preventing the steady drift away from Earth that it has been on ever since it formed. Such a situation could have persisted for 100,000 years or so, says Cuk. In that time, Earth, sun and moon were locked together in a gravitational threesome during which the early Earth's excess angular momentum could be transferred through the moon to the sun. Eventually the moon broke out and started to recede again from Earth – as it still is, by a few centimetres every year.

The real pay-off came when Cuk and Stewart worked out what this meant for a giant impact. This mechanism allows Earth to spin faster in the past, so it would need less of a smacking to catapult the moon into orbit. Instead of a Mars-sized impactor, one with just half the mass could have hit Earth at a steeper angle, burying itself deep inside our world. Cuk and Stewart's computer simulations show that would provide just enough energy to explode a plume of solely Earth rocks into orbit – providing a moon isotopically indistinguishable from Earth.

A different sort of "giant impact lite" has been proposed by planetary scientist Robin Canup of the Southwest Research Institute in Boulder, Colorado. She envisages two planets, each about half the size of Earth, colliding slowly. In the ensuing coalescence that gave birth to our planet, the moon was formed from the leftovers, ensuring both bodies were made from the same ingredients.

These two models are very different, but they both have the advantage of saving something of the giant impact model without having to propose anything as wacky as a vast, explosive nuclear reactor deep inside Earth. Van Westrenen is unruffled, pointing out that a faster-spinning Earth as envisaged in Cuk's model makes the energy required to form the moon during a nuclear detonation lower, too.

He has a proposal to test his idea. With their ability to change one element into another, deep-Earth reactors would increase the level of the isotope xenon-136 in the ejected material that formed the moon. This isotope is only formed in violent astrophysical processes such as supernovae, or through the radioactive decay of elements such as uranium and plutonium. Any excess in the moon's xenon level compared with that found in meteorites, which represent chemically unchanged material from the solar system's dawn, would indicate that nuclear processes were in play during our satellite's birth. In principle, xenon levels could be measured by future lunar drilling experiments.

Such excavations are most probably decades away, however. In the meantime, the competing explanations for the moon's origin will continue to slug it out. "There is a lot more work to be done," says Cuk.

The good news is that, whatever the outcome, there's no ticking time bomb under our feet: the relatively short-lived isotopes that would have helped to power van Westrenen's explosion have mostly decayed away by now. Whether or not Earth truly did explode one day 4.5 billion years ago, we are unlikely to experience its like again. ■

THE GREAT THAW

Just 20,000 years ago, ice ruled the planet. So why did it relax its grip? Anil Ananthaswamy reports

KEENPRESS/NATIONAL GEOGRAPHIC STOCK

DURING the summer of 2008, workers excavating Ground Zero in Lower Manhattan dug right down to the bedrock. There, they found something unexpected: a huge pothole more than 10 metres deep, the crevices around it crammed with stones of several different kinds of rock. The consulting geologist immediately recognised these features. The stones had been carried there from many miles away by a glacier that had ground across the bedrock. At some point, a swirling torrent of glacial meltwater had carved out the pothole.

From potholes in New York City to forests beneath the sea, evidence of the time ice dominated the world is all around us. The last great ice age began around 120,000 years ago. One massive ice sheet, more than 3 kilometres thick in places, grew in fits and starts until it covered almost all of Canada and stretched down as far as Manhattan. Another spread across most of Siberia, northern Europe and Britain, stopping just short of what is now London. Elsewhere, many smaller ice sheets and glaciers grew, vast areas turned into tundra and deserts expanded as the planet became drier.

With so much ice on land, sea level was 120 metres lower than it is today. Britain and Ireland were part of mainland Europe. Florida was twice the size it is now, with Tampa stranded far from the coast. Australia, Tasmania and New Guinea were all part of a single land mass called Sahul. The planet was barely recognisable.

Then, 20,000 years ago, a great thaw began. Over the following 10,000 years, the average global temperature rose by 3.5 °C and most of the ice melted. Rising seas swallowed up low-lying areas such as the English Channel and North Sea, forcing our ancestors to abandon many settlements. So what drove this dramatic transformation of the planet?

Mysterious changes

We have long known the thaw began with an increase in summer sunlight in the northern hemisphere, melting ice and snow. It is what happened next that has remained mysterious. Soon after the thaw began, for instance, the southern hemisphere began to warm while the northern hemisphere cooled – the opposite of what was expected from the changes in sunshine. Now, after nearly two centuries of wrestling with seemingly contradictory findings, we think we finally understand how the ice age ended.

It all began in the 1830s, when Louis Agassiz noticed that characteristic features created by glaciers, such as scratches in the bedrock and "erratic" rocks dumped far from their place of origin, could be found far from existing glaciers. Similar discoveries were soon being made all over the world, from Canada to Chile. It became clear that there had been a whole series of ice ages.

What had made the ice come and go? In 1864, James Croll proposed that changes in the amount of sunlight reaching different parts of Earth's surface, due to changes in the planet's orbit, were responsible. He also suggested that the orbital effects had been amplified by various feedback mechanisms, such as the melting of heat-reflecting snow and ice, and changes in ocean currents.

"Florida was twice the size it is now, with Tampa stranded far from the nearest coast"

Croll got many of the details wrong, but he was on the right track. Early in the 20th century, the Serbian astronomer Milutin Milankovitch concluded that summer sunlight in the northern hemisphere must be the crucial factor and spent years painstakingly calculating how this had changed over the past 600,000 years. His ideas weren't accepted at the time, but in the 1970s studies of ocean-sediment cores revealed that the advances and retreats of the ice ages did indeed coincide with "Milankovitch cycles".

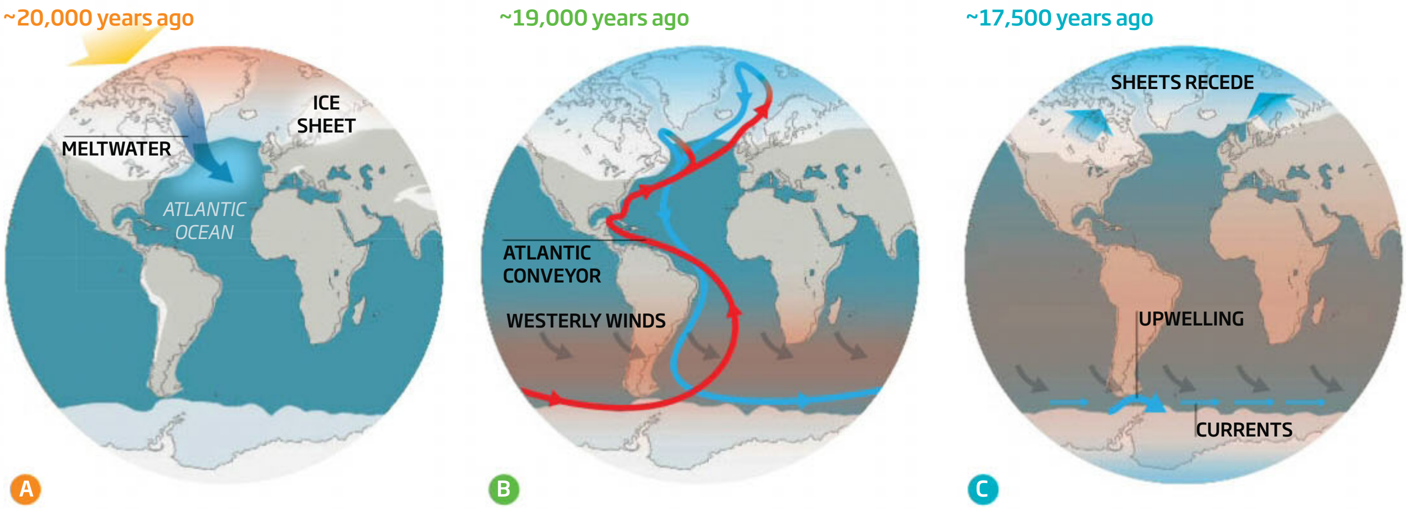
Yet many enigmas remained. For starters, the changes in sunshine were tiny. Even if they were amplified by more of the sun's heat being absorbed by the planet as snow and ice melted, it was hard to account for the scale of the global changes. What's more, when summer sunshine increases in the northern hemisphere, it decreases in the southern hemisphere. This had led Croll to suggest that ice ages alternate between hemispheres: when the north freezes the south thaws and vice versa. But it had long been clear that the whole world had warmed at around the same time.

The answer to these puzzles seemed to emerge in the 1980s, when ice cores drilled in Antarctica revealed an astonishingly close correlation between atmospheric carbon dioxide levels and temperature.

"For the last million years, you see these two going up and down together through each ice age, and it's almost in perfect lockstep," says ›

The end of the ice age

A small change in sunshine triggered a chain of events that led to the whole world warming by about 3.5°C



A Changes in Earth's orbit lead to an increase in northern summer sunshine, melting the edges of the huge ice sheets in the north. Massive quantities of fresh water flood into the Atlantic

B The fresh water slows the Atlantic conveyor current, plunging the far north into a cold spell. The southern hemisphere, however, warms because ocean heat is no longer being carried north

C These changes push the band of westerly winds south, warming Antarctica, melting sea ice and stirring up the Southern Ocean. Deep waters rise to the surface and release long-trapped carbon dioxide

Jeremy Shakun of Boston College, Massachusetts. "It's about as beautiful a correlation as you ever get from nature."

If CO_2 levels had risen soon after the thaw began in the north, it would explain why the southern hemisphere began to warm too. It would also help to explain the magnitude of the changes. But this promising idea ran into a major problem: by around a decade ago, it had become clear that the Antarctic started warming a few hundred years before CO_2 levels began to rise. So while soaring CO_2 levels undoubtedly warmed the planet – they are now thought to be responsible for about half of the warming as the ice age ended – they weren't the initial cause. "Something else was causing Antarctica to warm," says Daniel Sigman of Princeton University.

Pollen puzzle

This wasn't the only mystery. In the 1930s, studies of sediments containing the pollen of the alpine flower *Dryas octopetala* and other plants suggested that almost as soon as Europe began warming, it suddenly got cold again. This cold phase, called the Oldest Dryas or Mystery Interval, lasted from around 17,500 years ago to 14,700 years ago. Ice cores later showed Greenland cooled at the same time.

Yet during this period Antarctica warmed steadily. "On the detailed scale, the south seems to warm before the north," says Sigman. But what would make the southern hemisphere warm even as the northern hemisphere cooled? It could not be due to orbital changes or rising CO_2 levels – but it could be due to changing ocean currents.

As the vast ice sheets began to melt 19,000 years ago, stupendous quantities of fresh water poured into the North Atlantic (see diagram, above). Studies of marine sediments off the Irish Sea coast, for example, show that the sea level there rose about 10 metres in just a few hundred years.

Today in the North Atlantic, salty water arriving from the tropics cools, becomes very dense and sinks to the bottom. These deep, cold waters flow all the way to the southern hemisphere, while on the surface warm water – including the Gulf Stream – flows north. This system of currents is called the Atlantic meridional overturning circulation.

> **"Sunshine increased in the northern hemisphere, yet the southern hemisphere warmed first"**

The huge quantities of fresh water pouring into the ocean 19,000 years ago would have diluted the salty water, making it less dense. Result: a slowdown in the overturning circulation. The proof came in 2004 from a study of ocean sediments. The ratio of two heavy elements, which indicates the speed of the deep current, showed that the overturning circulation had almost ground to a halt 17,500 years ago.

The result was a kind of see-saw effect. With much less heat being carried north by the surface currents, the northern hemisphere cooled. The tropical and subtropical regions of the southern hemisphere, by contrast, began warming as they were losing less heat to the north. This explains many puzzling findings. The slowdown of the Atlantic current can also help explain why CO_2 levels rose during the great thaw (see graph, below right).

By the 1990s, the search for the source of the CO_2 was focusing on the Southern Ocean. Isotopes in ocean sediments suggested that a huge reservoir of CO_2 had built up in deep waters during the ice age. It is thought that a lack of vertical mixing, along with a cover of sea ice, trapped the gas. During the thaw, however, the ocean was "uncorked" and much of the CO_2 escaped into the atmosphere.

Confirmation came in 2012, thanks to a very detailed isotopic analysis of the CO_2 trapped in ice cores from Antarctica. "The CO_2 must have come from the deep ocean," says team member Jochen Schmitt of the University of Bern in Switzerland.

Increased vertical mixing in the Southern Ocean is now widely accepted as being behind the release of CO_2. In 2009, for instance, Bob Anderson of the Lamont-Doherty Earth Observatory in New York reported that the Southern Ocean saw big increases in the growth of plankton with silica shells during the Oldest Dryas, when the southern hemisphere began warming. As the growth of these organisms is limited by how much dissolved silica there is in surface waters, the increases must be due to the upwelling of water rich in silica and other nutrients.

But what caused it? There are two ideas. Sigman points out that Antarctica began warming at almost the same time as the waters just south of the equator. By itself, though, the shutdown of the Atlantic current should only have warmed waters in the tropics, not those as far south as Antarctica.

In 2007, his team proposed that when the Atlantic conveyor shut down, it was replaced by a local overturning circulation in the waters around Antarctica. Dense surface water sank and deep water welled up, releasing both heat and CO_2. "That would explain both the Antarctic warming and the CO_2 rise," says Sigman.

Anderson and his colleagues, however, think that the increased upwelling was driven by changes in winds. Earth has distinct bands of prevailing winds, driven by the temperature differences between the poles and the tropics, coupled with the planet's rotation. Their positions can change when the temperature differences change.

During the ice age, the band of westerlies in the southern hemisphere – which sailors call the Roaring Forties due to their latitude – would have been further north. The see-saw effect shifted it southwards over the Southern Ocean, warming Antarctica and stirring up the sea around the frozen continent. In particular, the wind-driven circular current would have produced more upwelling in the shallower region between South America and Antarctica.

While the details are still being debated, the big picture now seems clear. "There is still some disagreement about the processes occurring in Antarctica as the last ice age

As the ice melted at the end of the ice age, sea levels rose more than 120 metres

ended," says Anderson. "But at least the broader features are pretty well accepted."

In 2012, Shakun and colleagues drew together many of these strands of research with an analysis of 80 different records of temperature and atmospheric composition over the past 22,000 years. Their work pretty much confirms the sequence of events that ended the ice age.

It goes like this: around 20,000 years ago, the northern ice sheets had spread so far south that just a small increase in sunshine led to extensive melting. As fresh water poured into the North Atlantic, the overturning circulation shut down, cooling the northern hemisphere but warming the southern hemisphere. These changes were mostly due to a redistribution of heat – by 17,500 years ago, the average global temperature had risen just 0.3 °C.

Changing winds or currents, or both, then brought more deep water to the surface in the Southern Ocean, releasing CO_2 that had been trapped for thousands of years. As atmospheric levels climbed above 190 parts per million, the whole planet began to warm. The far north was the slowest to respond, but by around 15,000 years ago, as CO_2 levels approached 240 ppm and the Atlantic overturning circulation sped up again, temperatures started to shoot up. The recovery of the overturning circulation had the opposite effect in the southern hemisphere: warming stalled and the release of CO_2 stopped.

Around 12,900 years ago, the see-saw swung again. Temperatures in northern latitudes suddenly plummeted and remained cold for about 1300 years. This cold snap, called the Younger Dryas, is thought to have been caused by a colossal meltwater lake in North America, which held more water than all the Great Lakes put together, suddenly flooding into the Atlantic and shutting down the overturning circulation once again.

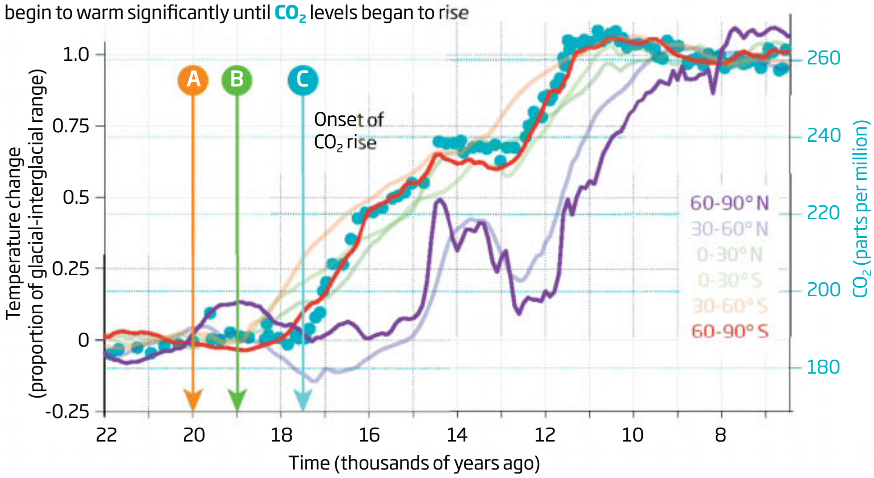
The Southern Ocean, meanwhile, started releasing CO_2 again. Levels in the atmosphere shot up to 260 ppm, causing the whole planet to warm rapidly over the next couple of millennia. By around 10,000 years ago, Earth had been transformed. The ice had retreated, the seas had risen and our ancestors were learning how to farm.

Technically, though, the ice age has not actually ended. The ice has advanced and retreated many times over the past few million years, but some ice has always remained at the poles. Perhaps not for much longer, though. It took just a small increase in sunshine and a gradual, 70-ppm rise in CO_2 to melt the great ice sheets that once covered Eurasia and North America. Since the dawn of the industrial age, levels have risen by 130 ppm and counting. If we haven't already pumped enough CO_2 into the atmosphere to melt the ice sheets on Greenland and Antarctica, we might soon.

Fortunately for us, it might take thousands of years for the last great ice sheets to vanish altogether. If it does happen, though, perhaps one day builders in Antarctica will find massive potholes in the bedrock carved by meltwater, and reflect on another dramatic transformation of the planet. ■

Getting warmer...

Temperature reconstructions show that the world as a whole didn't begin to warm significantly until **CO_2** levels began to rise



SOURCE: SHAKUN, 2012

SESSE LIND/LINK IMAGE/GALLERYSTOCK

The heat is still on

Global warming hasn't stopped, despite what some sceptics claim. **Michael Le Page** gives the lowdown on the slowdown

Warming has not peaked. Instead, it looks as if the sea is taking the strain

"GLOBAL WARMING ON PAUSE" "WHY HAS GLOBAL WARMING STALLED?" "HAS GLOBAL WARMING STOPPED?"

FOR a few months back in 2013, the newspapers were full of headlines like these. You could have been forgiven for forming the impression that global warming wasn't proceeding as expected.

While most mainstream media were careful to point out that the apparent pause in warming was probably just a temporary hiatus, a few outlets suggested there was more to it than that. "The climate may be heating up less in response to greenhouse-gas emissions than was once thought," one magazine claimed.

What was going on? Had global warming really slowed or stopped? If so, why? And does this mean the world won't warm as much as previously expected in the future?

Claims that global warming has stopped are nothing new. The vast majority don't stand up to scrutiny, but the recent talk appears to be different. This time it's climate scientists themselves talking of a slowdown – and they have even been publishing papers about it.

The past decade has been the hottest since records began – that's not in dispute. However, the average surface temperature of the planet seems to have increased far more slowly than it did over previous decades. The rate of warming was just 0.04 °C per decade from 1998 to 2012, significantly lower than the average 0.11 °C warming per decade since 1951 (see "How much has warming slowed?" right).

Yet this doesn't necessarily mean that climate change has stopped, any more than the very rapid warming seen in the 1990s meant that it had accelerated. Instead, a standard explanation is trotted out to explain these changes in pace: natural variability.

Surface temperatures go up and down all the time because of changing winds and currents, and phenomena such as volcanic eruptions. This variability can easily obscure the underlying warming trend. Remove the known contributions of natural variability from the observed surface temperature, and you see a much steadier warming trend (see "Putting the brakes on", page 72).

Yet glibly blaming natural variability for the recent surface slowdown is unlikely to satisfy those who are genuinely sceptical about global warming. How, they might ask, can we be sure that the plateau in surface temperatures is due to natural variability masking the underlying warming trend, and not because warming has actually slowed or stopped?

To answer this, it helps to think about heat energy rather than temperature. The reason the planet has been warming over the past century is because rising levels of greenhouse gases act like extra blankets, reducing heat loss from the top of the atmosphere.

In terms of heat, there are three possible reasons why Earth's surface temperature hasn't increased much recently. The first is that the sun has been getting dimmer. The sun's heat output rises and falls in an 11-year cycle, and measurements by spacecraft show it did dip particularly low recently.

The second reason could be that more heat than usual has been escaping from the top of the atmosphere. One possible cause is increased levels of sulphur aerosols in the ›

HOW MUCH HAS WARMING SLOWED?

The surface of the planet is now more than 0.6 °C warmer than it was in 1951. The pace of warming has varied tremendously over this time: it started accelerating in the 1980s, hit 0.28 °C per decade in the 1990s but fell to 0.09 °C in the 2000s.

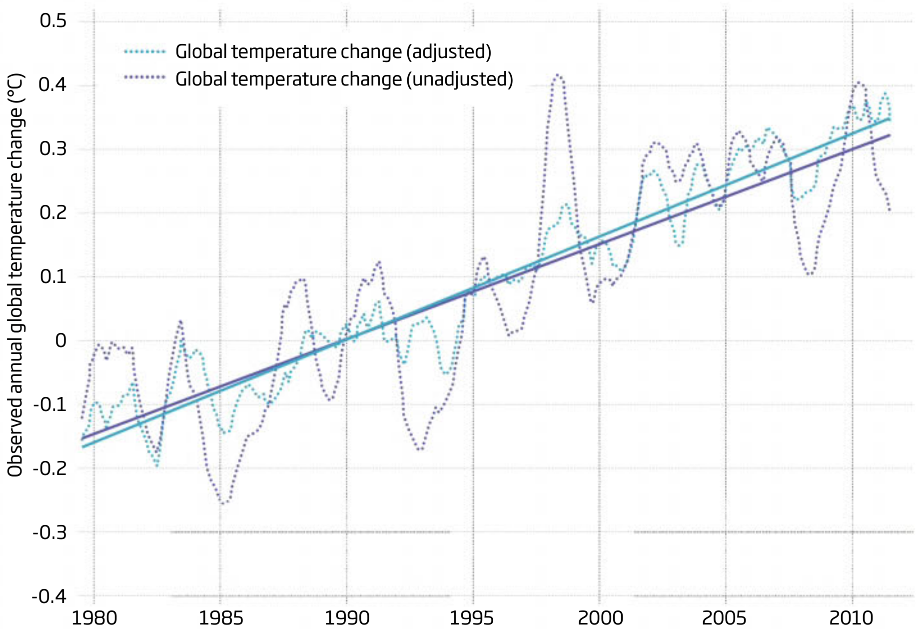
So the planet is not warming as fast as it was. But the details vary greatly according to how you calculate the trend. Pick the very hot year of 1998 as your starting point and the slowdown appears most dramatic: the rate of warming from 1998 to 2012 was just 0.04 °C per decade. If this rate continued, the planet's surface would be just 1 °C hotter in 2100 than in 1950 – which is well under the "dangerous level" of 2 °C.

But these figures are based on the global surface temperature record compiled by the UK's Hadley Centre, and its record does not include the fastest-warming region on Earth, the Arctic, as there are so few observations there. According to NASA's record, which guesstimates Arctic temperatures based on the nearest weather stations, the warming rate was 0.07 °C per decade from 1998 to 2012. And according to a study out in November 2013, by Kevin Cowtan of the University of York, UK, which extrapolated Arctic temperatures from satellite data, the 1998 to 2012 rate was 0.12 °C per decade. If he is right, warming has only slowed very slightly, from 0.18 °C per decade in the 1990s to 0.16 °C in the 2000s – which would still take us over the danger limit of 2 °C by 2100.

Cowtan's study is not likely to be the final word. Satellites measure temperature far above the ground, so extrapolating to the surface is difficult. But whatever the precise figures, there is every reason to think warming will not only continue but accelerate greatly over the coming century (see main story).

Putting the brakes on

If you look only at surface temperature records for the last couple of decades the rise in global temperature seems to be slowing (**purple line**). However, if you add in short-term variations in solar emissions, volcanic eruptions and the El Niño southern oscillation this slowdown almost disappears (**blue line**)



SOURCE: RAHMSTORF ET AL 2011

atmosphere. These aerosols don't prevent the sun's rays entering our atmosphere, but they do reflect more of the sun's heat back into space. Sulphur aerosols are produced by volcanic eruptions – one of the big causes of natural variability – as well as from coal burning and other human activities. Sure enough, levels of sulphur dioxide have risen in the past decade, mainly due to lots of small volcanic eruptions.

Lastly, it is possible that the planet has still been gaining heat, but that more of it has ended up somewhere other than the lower atmosphere, whose temperature we focus on. The most obvious culprit is the ocean. Water covers more than 70 per cent of the planet and the stuff has a huge capacity to absorb heat: around 3000 times as much energy is needed to warm a given volume of water by 1°C as is needed to warm the same volume of air.

Observations show that a whopping 94 per cent of the heat energy gained by the planet since 1971 has ended up in the oceans, with another 4 per cent absorbed by land and ice (see "Where is the heat going?" page 73). So all the surface warming since 1971 is due to just 2 per cent of the heat. If just a little more heat than usual has been going into the oceans, it will have had only a slight effect on ocean temperatures, because of water's huge capacity to absorb heat, but a large effect on atmospheric temperature. And several studies suggest that recently the oceans have indeed been soaking up even more heat than normal.

Why? Well, heat constantly sloshes back and forth between the oceans and atmosphere – this is the main cause of natural variability. What happens in the vast Pacific Ocean matters most. During a phenomenon called an El Niño, when westerly winds spread hot water across the top of much of the tropical Pacific, so much heat flows into the air that the entire surface of the planet warms. There was an especially strong El Niño in 1998, which is why it was such a warm year.

During the opposite event, called a La Niña, when easterly winds spread upwelling cold water across the sea surface, the tropical Pacific soaks up so much heat that it cools the planet's surface. And lately there have been lots of La Niñas. "We have not seen a major El Niño for the past 15 years," says Shang-Ping Xie of the Scripps Institution of Oceanography in San Diego, California (see below). "But there have been several long-lasting La Niñas." A model study by Xie, published in 2013,

WHY DIDN'T MODELS PREDICT THE SLOWDOWN?

Prediction is not just very difficult, it is sometimes impossible. The slower rate of surface warming over the past decade seems to be due to a combination of factors, including a series of cold La Niñas in the Pacific, an extra-low low in solar output and higher volcanic emissions (see main story). None of these kinds of natural events can be reliably predicted.

Perhaps it isn't surprising, then, that out of 114 runs of the latest models, just three produced a trend from 1998 to 2012 as low as that observed. The reason models fail to predict short-term trends is not that the models don't include natural variability - they do. Individual runs of climate models zigzag up and down wildly, and often exhibit periods of a decade or more when surface temperatures barely increase or even cool despite a strong long-term warming trend, just as we are seeing now.

Rather, the problem is that the timing and magnitude of natural events in each model run differ from those in the real world. In one model run, for instance, there might be a La Niña in 1998, and in another conditions might be neutral, whereas in the real world there was an exceptionally strong El Niño that year.

But what if instead of allowing La Niñas and El Niños to occur spontaneously, you tell the model when they really did take place? When Shang-Ping Xie and Yu Kosaka at the Scripps Institution of Oceanography in San Diego, California, did this for the first time by feeding the recorded values for sea surface temperatures in the tropical Pacific into a model, it reproduced the observed global surface temperature from 1950 remarkably closely.

It even reproduced many of the regional and seasonal characteristics of the slowdown. This close match was achieved even though the model didn't include volcanic emissions after 2005 or the recent solar low. "All this suggests to me that for the current hiatus, the Pacific [surface] cooling is the major driver," Xie says.

The unpredictability of natural variation means climate models may never be any good at forecasting the next five or 10 years (though some groups are trying to adapt them for this purpose). The key point is that short-term natural variability does not matter when predicting how much the world will warm over the next century or three. So the fact that models did not predict the slowdown is no reason to doubt their long-term projections . Think of it this way: we can be sure that the next winter will be much colder than the summer, even though we can't say how temperatures will change from day to day.

showed that this alone could explain the slower surface warming.

Whatever the cause, observations suggest that more heat than usual has gone into the ocean, and particularly the deep ocean. "The ocean is warming at depth," says study author Kevin Trenberth of the National Center for Atmospheric Research in Boulder, Colorado. So some researchers such as Trenberth and Xie think the slowdown is mostly due to the oceans.

Unknown oceans

Not everyone is convinced. The Argo network of probes for measuring ocean temperatures was only completed in 2007, so although we have a good idea of how much heat there is now in the oceans, it is hard to be sure how much it has changed in the past. We are also uncertain about the effects of aerosols and so on, which leaves room for debate.

The mainstream view expressed in the latest Intergovernmental Panel on Climate Change report is that about half of the surface slowdown is due to the oceans, and the other half due to the sun and extra volcanic aerosols. "It's three or four things added up," agrees Gavin Schmidt at the NASA Goddard Institute for Space Studies. But he is not convinced that the oceans are one of these things. They have continued to soak up heat, but we can't be sure that they have been soaking it up faster than usual, says Schmidt.

He suspects that soaring aerosol emissions from China may have contributed to the slowdown. Possibilities like this cannot be ruled out, responds Jochem Marotzke of the Max Planck Institute for Meteorology in Hamburg, Germany, who helped write the relevant parts of the latest IPCC report, but there is no evidence for them.

While there may be uncertainty about the precise causes of the slowdown, there is no doubt about the big picture. Measurements show that sea level is rising faster than ever, at around 3 millimetres a year on average. At least 1 millimetre per year of this is due to the expansion of seawater as it warms, showing that the ocean is gaining heat independently of measurements of water temperature. The rest is due to the melting of land-based ice.

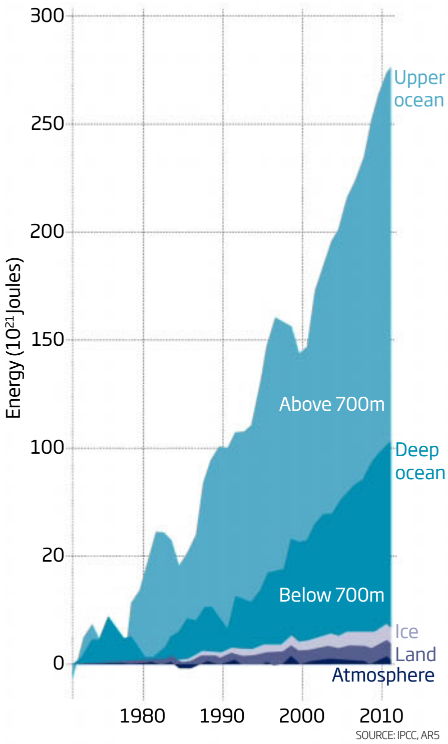
So if you define global warming in terms of the total heat content of the atmosphere, land and oceans – as most scientists would – then there has been no hiatus. "Global warming has not stopped," says Marotzke. "Sea ice is still melting, the ocean is still taking up heat and sea level continues to rise." In fact, Trenberth

QILAI SHEN/PANOS PICTURES

Industrial emissions reflect heat out into space and could help slow the planet's warming

Where is the heat going?

Different parts of the planet are gaining heat energy at different rates, with the ocean absorbing the vast majority



thinks that the process may have accelerated.

So what happens next? Does the slowdown mean global warming isn't going to be as bad as we thought? The fact that surface temperatures have not been rising as fast as they were is good news. To the extent that this is due to less heat coming in from the sun or more being reflected into space by aerosols, we have struck lucky. That heat is gone forever.

Increased ocean heat uptake is more of a mixed bag. Much of the heat going into the oceans will stay there. This heat will not warm the atmosphere (good) but it will contribute to sea level rise via thermal expansion (not good), and it will mean the oceans take up less heat in the future (bad).

Some of the heat now going into the oceans, though, will slosh back into the atmosphere, leading to rapid surface warming (very bad). "Part of the heat is lost," say Trenberth. "Some of the heat comes back in the next El Niño."

The big question is when? Schmidt and others expect warming in the lower atmosphere will soon speed up again, but there is no way to be sure. Most of the factors responsible for natural variability, from solar output to El Niños, can't be reliably predicted. But Trenberth thinks that a longer term change in ocean conditions called the Pacific Decadal Oscillation is playing a big role. This reverses every two or three decades as a result of changing winds and if past behaviour is anything to go by, it will switch phase in the › next five or 10 years, Trenberth says. If he is right, that would end the slowdown.

There is another possibility: the increased ocean heat uptake might result from ways we are altering the planet. Wind speeds have risen over the ocean, for instance. In theory, faster winds could be driving stronger vertical currents and thus pushing more heat down into the depths. If so, the slowdown could continue for years, perhaps even decades.

How much warmer?

Assuming that isn't the case and that surface warming will soon speed up, just how much warmer will it get? One method of estimating how much the surface will warm in response to a given rise in carbon dioxide levels – known as climate sensitivity – is to look at how much it has warmed in response to the rise so far. Since CO_2 levels have shot up over the past 15 years but temperatures have only risen slightly, calculations using the latest figures suggest sensitivity is slightly lower than in calculations from a decade ago.

Climate sceptics have seized upon this, but there are many reasons not to get excited. First, if temperatures in the lower atmosphere do rise very rapidly over the next few decades, these estimates will have to be revised upwards again. Meanwhile, other methods of estimating sensitivity, such as looking at changes in the climate further in the past or using models, still point to higher values.

The bottom line is that talk about global warming stopping or pausing is misleading. It is good news that the world's surface hasn't warmed as fast as previously over the past decade. Yet we have still seen terrifying weather extremes, from unprecedented rainfall in Colorado and record heat in Australia to the power of typhoon Haiyan (see "Running wild", page 88). All the while heat is still pouring into the oceans. All the evidence suggests that atmospheric warming will soon accelerate again, and it could do so with a vengeance. ■

Unpredictable events like volcanic eruptions can alter the rate of climate change in the short-term

GARY BRAASCH/CORBIS

UPDATE

This feature was originally published in December 2013, at the height of the "slowdown" hype. Subsequent research has largely confirmed the main points: the surface of the world did not warm as fast as it might have otherwise done over the past two decades because a combination of natural factors, from higher volcanic activity to higher heat uptake by the oceans, all of which partly counteracted the global-warming trend from greenhouse gas emissions.

The details still vary greatly depending on which record of past temperatures is used and how trends are calculated. In June 2015, for example, a study that made further corrections for biases in records of sea temperatures – because of changes in the way ships measured it, for instance – concluded that the world has in fact warmed slightly faster since 1998 than in the previous decades. If that's right, there never was a slowdown, let alone a hiatus, in surface warming.

Such findings are debatable, but there is no doubt that the total amount of heat energy stored in the oceans, atmosphere and land surface has continued to rise. So if you prefer to define global warming in terms of heat content rather than surface temperature, as many scientists do, there definitely has not been any slowdown.

Most importantly, though, global temperatures are now shooting up fast. According to most of the main records of global temperature, 2014 was the warmest year since the industrial age began. This year, the surface temperature is set to jump by a whopping 0.1 °C, meaning that by the end of 2015 the world will have warmed more than 1 °C since pre-industrial times. In other words, we will be more than halfway to the level of "dangerous" warming that a world climate treaty is supposed to prevent.

The reason for this sudden jump in surface temperature is the current El Niño Southern Oscillation event in the Pacific, which spreads warm water across the surface of much of the ocean, resulting in a significant transfer of heat to the atmosphere.

The El Niño will probably end in 2016, but it appears that Pacific surface temperatures could continue to be warmer than usual because of another periodic phenomenon known as the Pacific Decadal Oscillation. This has been in a cold phase for the past two decades but now appears to be switching to its warm phase, says Kevin Trenberth of the National Center for Atmospheric Research in Boulder, Colorado.

If it does switch, we can expect rapid surface warming to continue. In other words, if there ever was something that could be called a hiatus or slowdown in warming, it's over now.

THAW POINT

Far from shrinking as scientists expected, the sea ice around Antarctica is growing. What's going on, asks Stephen Battersby

PAUL NICKLEN/NGS

The world is set to defrost. All over the planet glaciers are retreating, while tundra thaws. The ice caps of Greenland and Antarctica are looking fragile, and the Arctic's once-vast raft of sea ice is shrinking at an alarming pace. And down south, in the seas around Antarctica, the sea ice... well... er... seems to be growing.

In the few decades we have had satellites keeping watch, the area of the Southern Ocean covered by sea ice in winter has grown bigger, hitting record levels in recent years. The increase is small, but it is surprising – and something of a mystery. "The Arctic is doing exactly what we would expect," says Paul Holland of the British Antarctic Survey. "The Antarctic is not."

A couple of years ago, Holland thought he had cracked the mystery: stronger winds were to blame, his team concluded. But now Holland thinks they got it wrong. So what in all the icy hells is going on down there? The answer matters to more than penguins. If or when the sea ice starts to shrink instead of growing, it could have knock-on effects around the world, from interfering with ocean currents to giving a nudge to the teetering West Antarctic ice sheet, the collapse of which would raise sea level by several metres.

Vast amounts of water are locked away in the great ice sheets in Antarctica. Almost the entire continent is covered by ice sheets that are nearly 2 kilometres thick on average, hiding whole mountain ranges. Where this ice slips off the land into the sea, it forms floating ice shelves hundreds of metres thick. Half the coast is surrounded by ice shelves, some of them immense.

Beyond lies the sea ice. It is distinct from the ice shelves, because it forms when the surface of the sea freezes and is about a couple of metres thick on average. Unlike in the Arctic, in Antarctica almost all the sea ice melts in spring and reforms each autumn and winter (see "Polar opposites", page 78).

Baffling behaviour

Now the frozen continent is warming up – with unexpected consequences. As recently as 2007, the official prediction was that the ice sheets would grow over the 21st century, because higher snowfall would more than compensate for higher ice losses. In reality, satellite gravity measurements show the ice sheets have already started to shrink.

Ice shelves are not following the script either. They have been thinning faster than expected, and several have disintegrated abruptly. The collapse of the enormous Larsen B ice shelf in 2002 shocked most glaciologists.

Most baffling of all is the behaviour of the sea ice. According to the majority of climate models, it should be shrinking as the air and waters around Antarctica warm. And in some places, such as in the Amundsen and Bellingshausen seas west of the rapidly warming Antarctic Peninsula, the sea ice is doing just that. But in others, it is growing (see "Thick and thin", page 78). Overall, the area covered by sea ice in winter is slowly increasing.

This is good news. Although Antarctic sea ice is mostly around in the 24-hour darkness of winter, there are still several million › square kilometres of it left in the spring when the sun is high. By reflecting a little more sunlight, the extra spring sea ice should slightly slow the warming of the seas around Antarctica. (In contrast, the Arctic Ocean is absorbing more heat and warming faster as the area of summer ice shrinks – a positive feedback.)

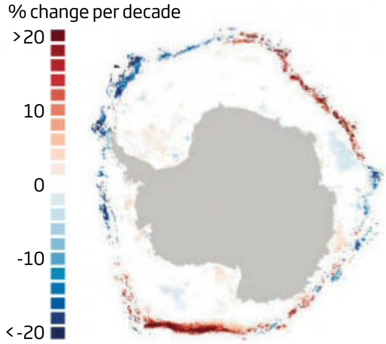
Indeed, satellite measurements show that the oceans around Antarctica are reflecting 0.9 per cent more sunlight in summer, says Norman Loeb of NASA's Langley Research Center in Hampton, Virginia, whereas the Arctic is absorbing 5 per cent more. The big question is what happens next. "If instead it were shrinking like the Arctic, you would imagine a significant effect," says Holland.

The loss of Antarctic sea ice would not only lead to more warming, it would also affect ocean currents. As the sea ice forms in winter, extra-salty water is left behind. This cold, dense water sinks down to the ocean depths and flows around the globe before eventually slowly surfacing again in tropical seas.

The waters around Antarctica, though, are becoming fresher and less dense because the ice shelves are melting faster, and more snow and rain now fall on the Southern Ocean. This is hindering the sinking process. If the sea ice retreats then sinking might stop altogether, changing ocean circulation around the globe.

Thick and thin

Sea ice concentration has declined in places around Antarctica, especially around the West Antarctic Peninsula, but grown in others



SOURCE: NATIONAL SNOW AND ICE DATA CENTER. SEPTEMBER 2014

That would affect sea temperatures and thus the climate in ways that are hard to predict.

So the sea ice is important, but right now we have no idea whether it will continue to slowly increase over the coming decades, or suddenly disappear. "There is a pressing need to understand this," says glaciologist Sharon Stammerjohn of the Institute of Arctic and Alpine Research in Boulder, Colorado.

In 2012, Holland thought his team had the solution. "We made the simple claim that stronger winds from the south were carrying cold air off Antarctica, and dragging ice north," he says. In autumn and winter, this would create gaps where new ice could form as well as cooling exposed water. A study of 20 years of satellite images seemed to support the idea.

It seemed like a satisfying explanation for the sea-ice paradox, given that there is no doubt that the winds around Antarctica have been strengthening. This is partly due to global warming and also partly the result of the hole in the ozone layer created by our pollution. Natural variability may also play a part.

Blowing in the wind

But when Holland looked again at what was happening, he began to doubt the wind explanation. This time, he looked at ice changes in a different way. Instead of focusing on the area of sea ice, he looked at how fast it was melting or forming. This is a more direct way to see the influence of climate changes, Holland says. "For example, warming wouldn't directly decrease the amount of ice in a season, but rather its melting rate."

From this viewpoint, there is no longer an autumn lockstep between wind and ice. The most glaring clash is in the Bellingshausen Sea. There, the autumn winds have become stronger. They blow from the north, which must be shoving more ice in towards the coast, keeping it from spreading, as well as carrying warmer air from temperate regions.

Indeed, the overall area of autumn sea ice here has declined, which would seem to fit with that idea. But if the stronger winds were the key factor affecting ice growth, the ice should be growing more slowly. In fact, during autumn it is growing faster than it did a few decades ago. "That destroys my earlier work," Holland says.

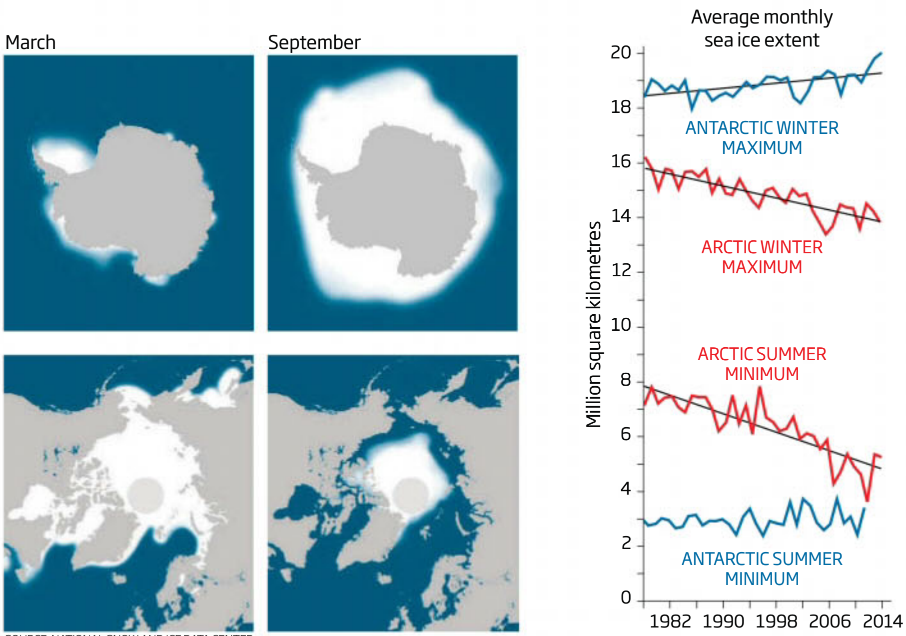
He now thinks that to understand these changes in sea ice, we need to focus on what's happening in the spring. In the Bellingshausen Sea, ice is now retreating earlier in the springtime, letting the ocean absorb more solar heat. That warming should delay the regrowth of ice – accounting for the decline in ice area in autumn. But when the ice does grow back, it happens quickly, because now the ocean is open to the air, it rapidly loses its heat again.

In other words, sea ice has a tendency to bounce back from big spring losses. This was first noted in Antarctica by Stammerjohn, in a 2008 study that looked at how ice is changing region by region and season by season.

These feedback processes also happen in

Polar opposites

In Antarctica the extent of winter sea ice has increased slightly. In the Arctic, the extent of winter and summer ice has dropped dramatically



SOURCE: NATIONAL SNOW AND ICE DATA CENTER

MARIA STENZEL/NGS

"There is a pressing need to understand what's happening to the sea ice"

Ice work: studying sea ice is extra tricky in Antarctica, where thick snow blocks radar

the Arctic, says Dirk Notz at the Max Planck Institute for Meteorology in Hamburg, Germany, which may explain why summer sea ice there seems to recover somewhat every time it hits a new record low. None of this even begins to explain why Antarctic sea ice is growing overall, but if these trends originate in the spring, that's where we should look for what's really causing them, says Holland. "I hope it is a trail that will lead to the truth."

Notz, however, is not convinced that Holland is right to focus on whether sea ice is melting or forming faster or more slowly than it used to. "He is looking at a change in a rate of change," he says. "I do not think it's a measure that is important."

So Notz's team thinks that the wind explanation still holds. The reason most climate models have been projecting sea-ice losses, they argue in a study published in December 2014, is that they are too coarse-grained. They miss details of Antarctic topography that deflect winds northwards and spread out sea ice, allowing more ice to form.

However, there are almost certainly other forces at work. Changes in deep ocean circulation are bringing in more warm water around West Antarctica. This is thought to be the main reason for the thinning of the ice shelves there, says Stammerjohn, and may be speeding up the loss of sea ice too. Elsewhere, she suggests, less ocean heat may be welling up, allowing more sea ice to form.

And could the rush of fresh water from the thinning ice shelves be playing a part, too? Fresher water not only freezes more readily, it is also more buoyant, so a surface layer of fresher water may be stopping warmer water rising to the surface.

Blind satellites

However, the greatest increase in fresh water is around the Amundsen Sea, where the glaciers are retreating fast, yet sea ice there is still shrinking, too. So the fresh water appears to be having little effect, Stammerjohn says, although the case is not entirely closed.

In the end, it is not so surprising that we are struggling to understand Antarctica. This region is a lot more complex than the Arctic, yet observations are much scarcer because the region is so remote and forbidding. Simply building instruments tough enough to survive the conditions is difficult, let alone deploying them. Even satellites see less here. In the Arctic it is possible to use radar altimeters to measure ice thickness, but in the Antarctic there is a lot more snow sitting on the ice, which absorbs the radar signal. Yet monitoring ice thickness is critical for understanding what's happening. Robot subs are now being used to rove under the ice to measure its thickness, but so far they provide only a snapshot of a small area.

Besides better observations, we need better models. Trying to build climate models that match what's happening in Antarctica may be the most productive way to resolve the debate about the causes of the sea-ice increase. "It's a lot of things working against or for each other, which makes it hard to get one's head around what really will happen," says Notz. But if he is right about the role of small-scale topography then we are nearly there – the key will be improving model resolutions from 100 kilometres or so down to a few kilometres to get the wind directions right.

Holland thinks we're still far from the answer, but he too thinks better modelling is the way forward. "When we get a model that matches what happens in the spring, we can look in the model to see what it's doing."

In the meantime, with many of the other effects of global warming kicking in much sooner and harder than we expected, let's keep our fingers crossed that the stubborn seas around Antarctica continue to buck the trend for a few more decades. Sometimes it's good to be wrong. ■

DISTINCTLY DIFFERENT

ANTARCTICA	ARCTIC
Land and ice surrounded by ocean – sea ice can drift into warmer waters and melt	**Ocean surrounded by land – sea ice is mostly locked in**
Sea ice is temporary – almost all of it melts each summer	Sea ice is semi-permanent – about half the ice survives the summer
Winter ice area has increased slightly. Volume change unknown	**Area of summer ice has halved and volume shrunk by three-quarters**
Because it is dark in winter, the extra ice is only reflecting a little more solar heat	Exposed seas are absorbing more solar heat in summer

Five metres and counting

Only drastic action will prevent a 20-metre rise, finds **Michael Le Page**

FRANCESCO ZIZOLA/EYEVINE

WHATEVER we do now, the seas will rise at least 5 metres. Most of Florida and many other low-lying areas and cities around the world are doomed to go under. If that wasn't bad enough, without drastic cuts in global greenhouse gas emissions – more drastic than any being discussed ahead of the critical climate meeting in Paris in December 2015 – a rise of over 20 metres will soon be unavoidable.

After speaking to the researchers behind a series of recent studies, *New Scientist* has made the first calculations of what their findings mean for how much sea level rise is already unavoidable, or soon will be.

Much uncertainty still surrounds the pace of future rises, with estimates for a 5-metre rise ranging from a couple of centuries – possibly even less – to a couple of millennia. But there is hardly any doubt that this rise is inevitable.

We already know that we are heading for a rise of at least 1 metre by 2100. The sea will then continue to climb for many centuries as the planet warms. The question is, just how high will it get?

No return

According to the latest report by the Intergovernmental Panel on Climate Change (IPCC), over the next 2000 years we can expect a rise of about 2.3 metres for each sustained 1 °C increase in the global temperature. This means a 5-metre rise could happen only if the world remains at least 2 °C warmer than in pre-industrial times up to the year 4100. That doesn't sound so bad: it suggests that if we found some way of cooling the planet, we could avoid that calamity.

Unfortunately, this forecast, published in 2013, is not the whole story. In 2014, two teams independently reported that several massive glaciers in West Antarctica have already passed the point of no return.

Ian Joughin of the University of Washington, Seattle, modelled the fate of the Thwaites glacier. "No matter what, the glacier continued to lose mass," he says. The loss of those glaciers alone will raise sea level 1.2 metres. If they go, Joughin says, it's hard to see the rest of the West Antarctic surviving.

Others agree. "I think these are very convincing studies," says Anders Levermann of the Potsdam Institute for Climate Impact Research in Germany, one of the authors of the sea level chapter in the most recent IPCC report. "The West Antarctic ice sheet is gone."

The reason is that the West Antarctic ice sheet sits in a massive basin, its base as much as 2 kilometres below sea level. At the moment, only a little ice on the edges is exposed to the warming waters around Antarctica. As the ice retreats, however, ever-deeper parts of the basin will be exposed to warming waters, leading to ever more of it being lost. The process is irreversible because once it starts, it will continue as long as warm conditions persist. This means a 3.3-metre rise is now unavoidable.

"As the ice retreats, ever-deeper parts of ice basins will be exposed to warming waters and will melt"

And that's not all (see chart, right). Even in the unlikely event that we manage to limit warming to 2 °C, we're in for a 0.8-metre rise as the oceans warm and expand. Mountain glaciers around the world will contribute 0.4 metres. Adding those figures to the 3.3 metres, we get 4.5 metres in total, or 5 metres rounded up. That's conservative, given that it doesn't count any melting from East Antarctica or Greenland.

Most of the ice in East Antarctica is more stable than that in West Antarctica because it rests on land above sea level. There are two large basins, the Aurora and the Wilkes, with floors that are below sea level, but these are shallower than the West Antarctic one. We had thought only massive warming would destabilise the ice in these basins.

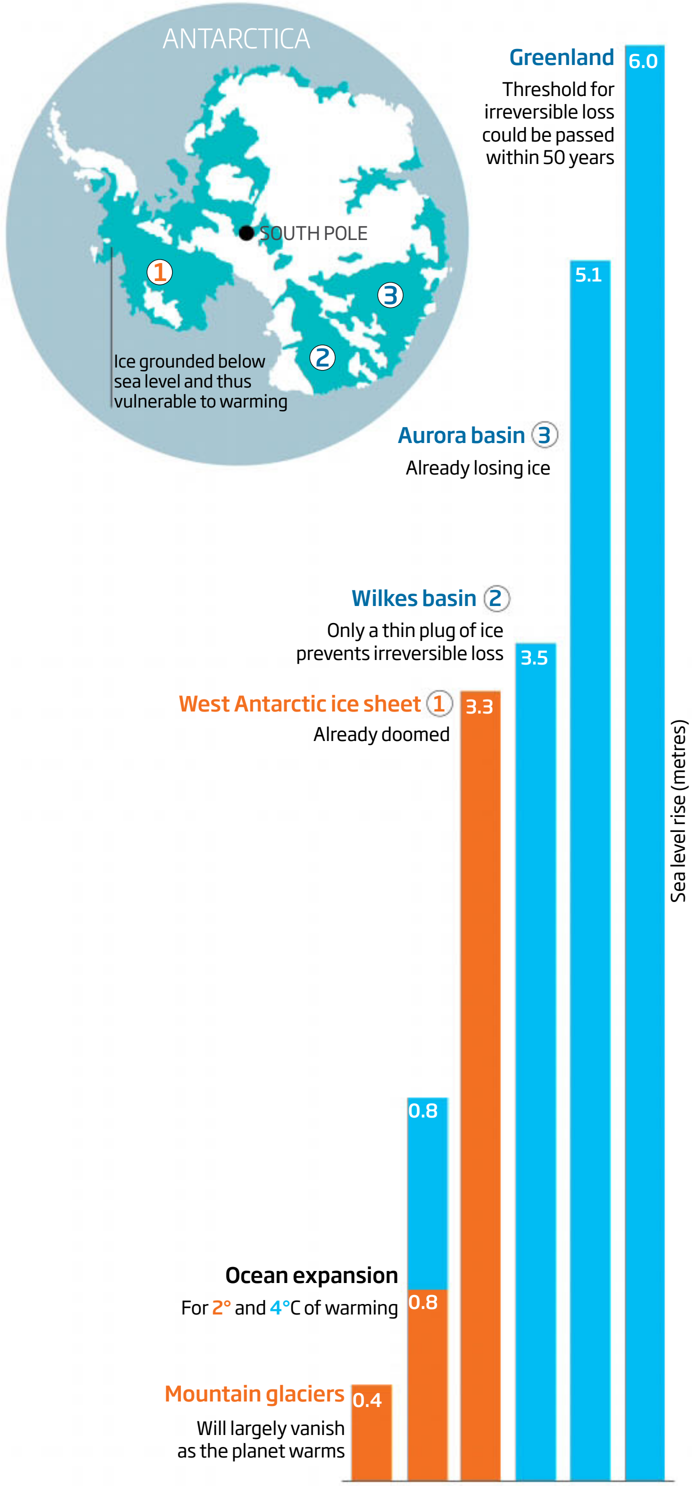
Trough threat

However, Totten, the main glacier that drains the Aurora basin, is thinning, says Jamin Greenbaum of the University of Texas at Austin. His team reported in March 2015 that radar sounding has revealed a trough under the ice that could let warm water enter the basin and trigger enough melting to

Still dreaming of that seaside villa?

Meltdown imminent

Our warming world faces massive sea level rise. At least 5 metres is already locked in (orange), although it could be much worse (blue). What we don't know is how fast it will happen



eventually raise sea level by 5.1 metres. "The mind-blowing thing is that there is as much ice in one glacier in East Antarctica as in all of West Antarctica," says Greenbaum.

The situation is similar in the Wilkes basin. It's not losing ice yet, but once a small amount on the margins is lost, it will continue disintegrating until enough ice has melted to raise sea level 3.5 metres, Levermann's team reported in 2014.

What will it take to kick-start the loss of all this ice? Not much. During the Pliocene period around 4 million years ago, when the planet was 2 or 3 °C warmer at times, sea level was over 20 metres higher than now. Researchers suspect that much of this came from the Aurora and Wilkes basins.

Support for this idea comes from an improved ice sheet model that, for the first time, includes dynamic processes such as cliff collapse resulting from ice sheets being undercut by warming waters. In January

2015, a team including Richard Alley of Pennsylvania State University reported that Pliocene conditions will lead, so the model indicates, to ice loss not only in Aurora and Wilkes but also in several smaller East Antarctic basins. Together, they hold enough ice to add at least 15 metres to global sea level.

We are currently on course for a world even warmer than the Pliocene, which means we could soon trigger the loss of the Wilkes and Aurora ice – if we haven't already.

Then there's Greenland. The ice here mostly rests on land above sea level, so should take thousands of years to melt. You might think, then, that there is plenty of time left to save it. Not so, says Alexander Robinson of the Complutense University of Madrid, Spain.

He says his team's studies show that we are already nearing the point of no return for Greenland. "Within the next 50 years, we could be committing ourselves to continuous sea level rise from Greenland over the next thousands of years," he says. "That's a very profound thing to think about."

The reason is that as warming continues, various positive feedbacks will kick in. As the surface of the ice sheet lowers, for instance, it experiences higher temperatures. In theory, the melting could still be stopped if temperatures fall, but because carbon dioxide persists in the atmosphere for many centuries, says Robinson, it is hard to see how that could happen (see "Can geoengineering save coastal cities?", below).

The loss of Greenland's ice would add at least 6 metres to global sea level. And in this business-as-usual scenario, ocean warming would contribute 1.6 metres or more. Adding all this up leads to the frightening conclusion that we don't have much time left before we're on a one-way street to a world with seas 20 metres higher. "It's kind of scary," says Robinson.

NASA

This break-up will be traumatic

"Within 50 years, we could be locked into sea level rise from Greenland's thaw, lasting thousands of years"

It will take thousands of years for the seas to rise to this extent, but much of the rise could happen early on – within the first few centuries – although no one can say for sure. Joughin thinks the IPCC estimate of up to 1.2 metres by 2100 could still be in the right ballpark. "It's likely to be on the high end [of the IPCC estimate] but not far outside."

Yet in the improved ice model that Alley's team ran, Antarctica alone added 5 metres to sea level in the first two centuries. That model was run with warm Pliocene-like conditions from the start, not where we are at now.

It might not take too long to reach a similar point, though. We're in danger of soaring past Pliocene levels of warmth as early as the middle of the century if we don't slash emissions soon. In the study, the West Antarctic ice sheet collapsed in mere decades in response to this kind of warmth.

What's more, the model might still leave out some melting processes, Alley says. "It is possible that this rather short timescale is not the worst possible case." ■

CAN GEOENGINEERING SAVE COASTAL CITIES?

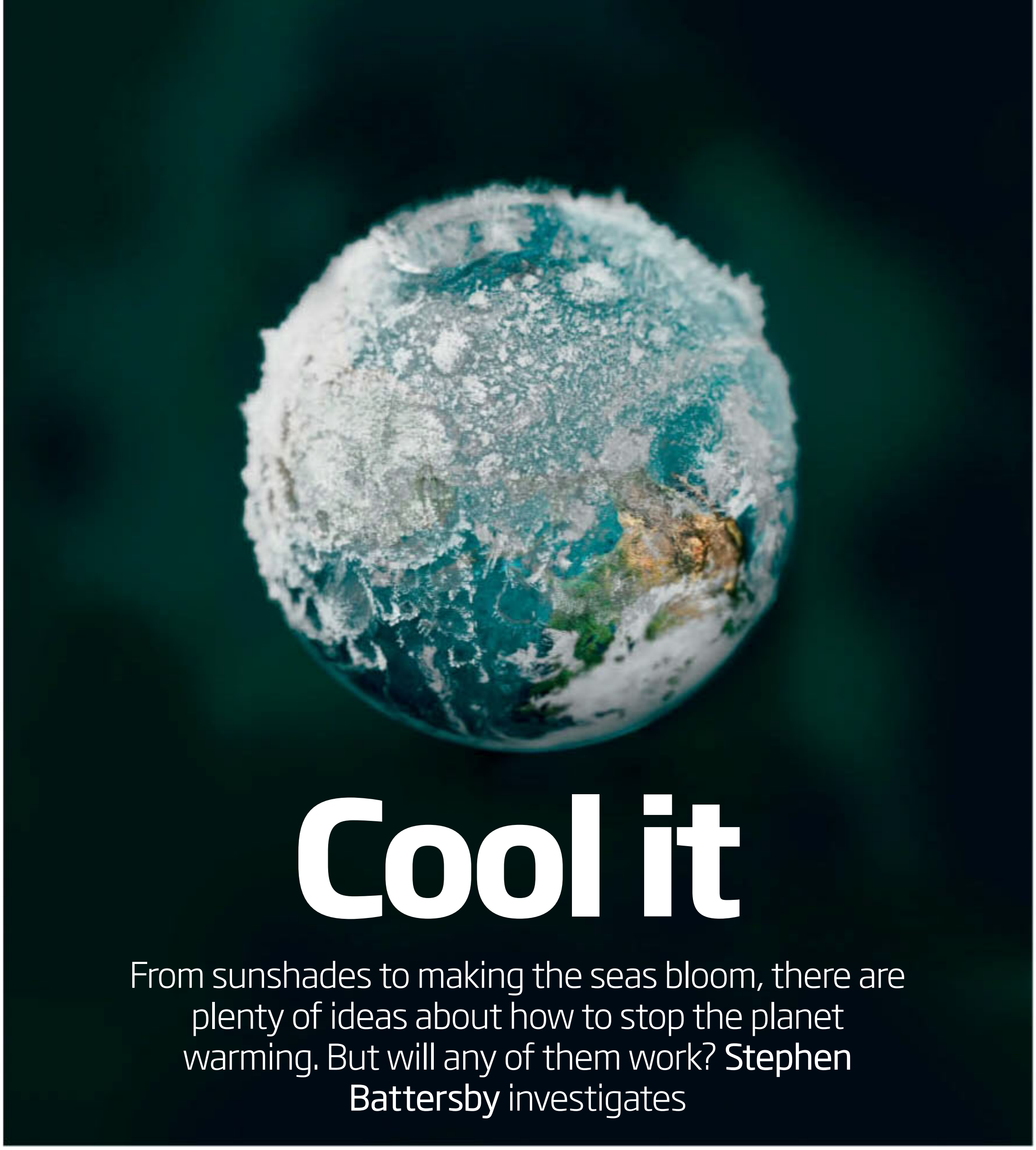
It's already too late to prevent massive sea level rise (see main story). Or is it? Can geoengineering stop low-lying cities sinking beneath the waves?

It certainly won't be easy. "Once you kick in the melting feedbacks, it's very hard to shut them off," says Alexander Robinson of the Complutense University of Madrid. To have any chance, we have to get the planet's temperature back down to pre-industrial levels in the not-too-distant future. "I personally see that as quite unlikely," Robinson says.

One key problem is that most geoengineering methods, such as pumping sulphates into the atmosphere, rely on reflecting sunlight and would cool the tropics more than the poles (See "Cool it", page 83). Cooling the poles enough to halt ice loss would devastate the rest of the world, slashing rainfall, for instance.

The best solution would be to suck all the excess carbon dioxide from the atmosphere, but the immense scale of the task and the speed required make this seem nigh on impossible. Other suggestions, such as building huge barriers between warming waters and glaciers, don't look feasible either.

Another major problem is that until cities start drowning (see Swamped", page 106), it is hard to see politicians spending trillions on megaprojects. And once they begin to drown, it will already be too late to prevent major sea level rise.



WESTMAC

Cool it

From sunshades to making the seas bloom, there are plenty of ideas about how to stop the planet warming. But will any of them work? **Stephen Battersby** investigates

OOPS. We really didn't mean to, but we seem to have broken the planet. Is there anything we can do to make it better?

Climate change is already upon us, melting ice, killing forests and making floods and heatwaves more intense. Meanwhile, global emissions of carbon dioxide and other greenhouse gases continue to increase, promising far worse to come. Even if we stopped all emissions tomorrow, temperatures would keep rising for decades, with potentially catastrophic consequences ranging from famines to rapid sea level rise (see "Five metres and counting", page 80).

So perhaps it is time to get serious about the audacious idea of geoengineering. The hope is that by deliberately tinkering with our planet's climate machine, we might be able to fix our gargantuan blunder, or at least avoid some of the most serious consequences – or just buy ourselves a bit more time to cut emissions.

Dozens of schemes have been devised to cool the planet. We could launch a vast fleet of ships to whiten the clouds by spraying salt mist, or squirt sulphuric acid into the stratosphere to reflect the sun. Send a swarm of mirrors into deep space. Engineer paler crops. Fertilise the oceans. Cover the world's deserts in shiny Mylar. Spread cloud-seeding bacteria. Release a global flock of microballoons.

These schemes are ingenious, but would any of them work? Or would they just make things worse and hasten catastrophe? Short of taking the biggest gamble imaginable and actually trying one out, the best that we can do is try to explore each idea with detailed calculations and computer models. As the results of such studies mount up, we're starting to get an idea of what geoengineering might – or might not – be able to achieve.

Some ideas can be dismissed with relative ease. Covering deserts in reflective plastic, for example, could reflect a lot of sunlight and cool the planet somewhat, but it probably is as crazy as it sounds. It would devastate ecosystems, alter regional climate patterns and require an immense army of cleaners to keep it going.

Others are beyond our powers today. To shade Earth with a swarm of space parasols would require an estimated 20 million

"Two schemes stand out as being both highly potent and feasible. Both involve some form of sunshade"

rocket launches. Without some radical new technology, that would be astronomically expensive and fatally polluting. "This is complete science fiction," says Tim Lenton of the University of Exeter, UK. "We ought to stop talking about it."

Many other schemes, such as painting roofs white, are certainly feasible – but can they actually fix the climate? The basic problem, of course, is that rising levels of greenhouse gases in the atmosphere are acting like a blanket around Earth, trapping heat. Sometime this century we are likely to have doubled the concentration of CO_2 in the atmosphere, reducing heat loss by about 3.7 watts per square metre, averaged across the planet. To stop Earth warming, any geoengineering scheme either has to block as much incoming heat from the sun or increase heat loss from the top of the atmosphere by as much.

We have other prerequisites for our global refrigerator (see diagram, opposite). It needs to work without drastically altering regional climates, while also preventing sea level from rising. Ideally we want to stop the oceans becoming so acidic that coral reefs vanish, too.

But the first test is potency. In 2008, Lenton and Nem Vaughan of the University of East Anglia in Norwich, UK, combined various model results with their own calculations to assess the potential cooling power of a couple of dozen proposals. "It was born of frustration," says Lenton. "I had been at one too many workshops where people were advocating their pet technologies and arm-waving about 'was this more effective than that'."

They found that many schemes would make little difference. Take the idea of making roofs and roads whiter to reflect more sunlight. Even with optimistic assumptions, this could only reflect about 0.15 watts per square metre – at best a minor contribution to restoring Earth's heat balance.

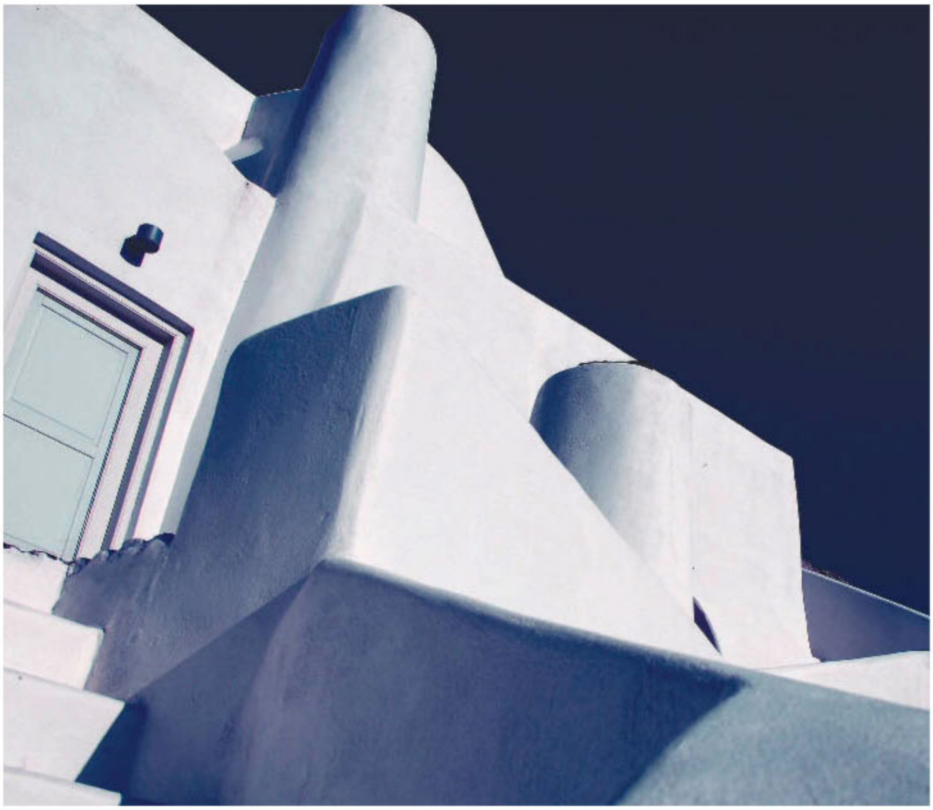
A seemingly more promising plan is to fertilise the seas. Plankton consume CO_2 as they grow, and sometimes their dead bodies sink to the sea floor and get buried, locking this carbon away. Adding nutrients that are in short supply, such as iron, could boost plankton growth. By the end of the century, this could improve the radiation balance by as much as 0.2 watts per square metre, Lenton and Vaughan calculated. Handy, but not a game-changer – and again that's the top-end estimate, which could fall considerably as we learn more about this process.

Many of the other proposals, such as encouraging downwelling in polar regions to speed up the transport of carbon into the ocean depths, are even more limited. But two schemes stand out as being both highly potent and relatively feasible. Both involve some form of sunshade.

One idea is to whiten marine clouds – specifically the low, flat stratus clouds that cover a large swathe of sky. Ships scattered across the world's oceans would send plumes of fine salt spray up into the air. By acting as nucleation sites, the salt particles should encourage droplets of water to form in clouds. With more droplets per cubic metre, these clouds would be whiter than normal, and reflect more sunlight. Potentially, this could offset the entire warming from a doubling in CO_2.

Cloud-whitening has its upsides, such as not involving any hazardous chemicals. But cloud nucleation is not well understood, so it might not work as well as its proponents suggest, and cooling only the oceans could disrupt local climate. A study published in 2012 found that seeding clouds over the Pacific might alter rainfall patterns in a similar way to the highly disruptive La Niña weather phenomenon, for instance.

The other leading contender is an old one:

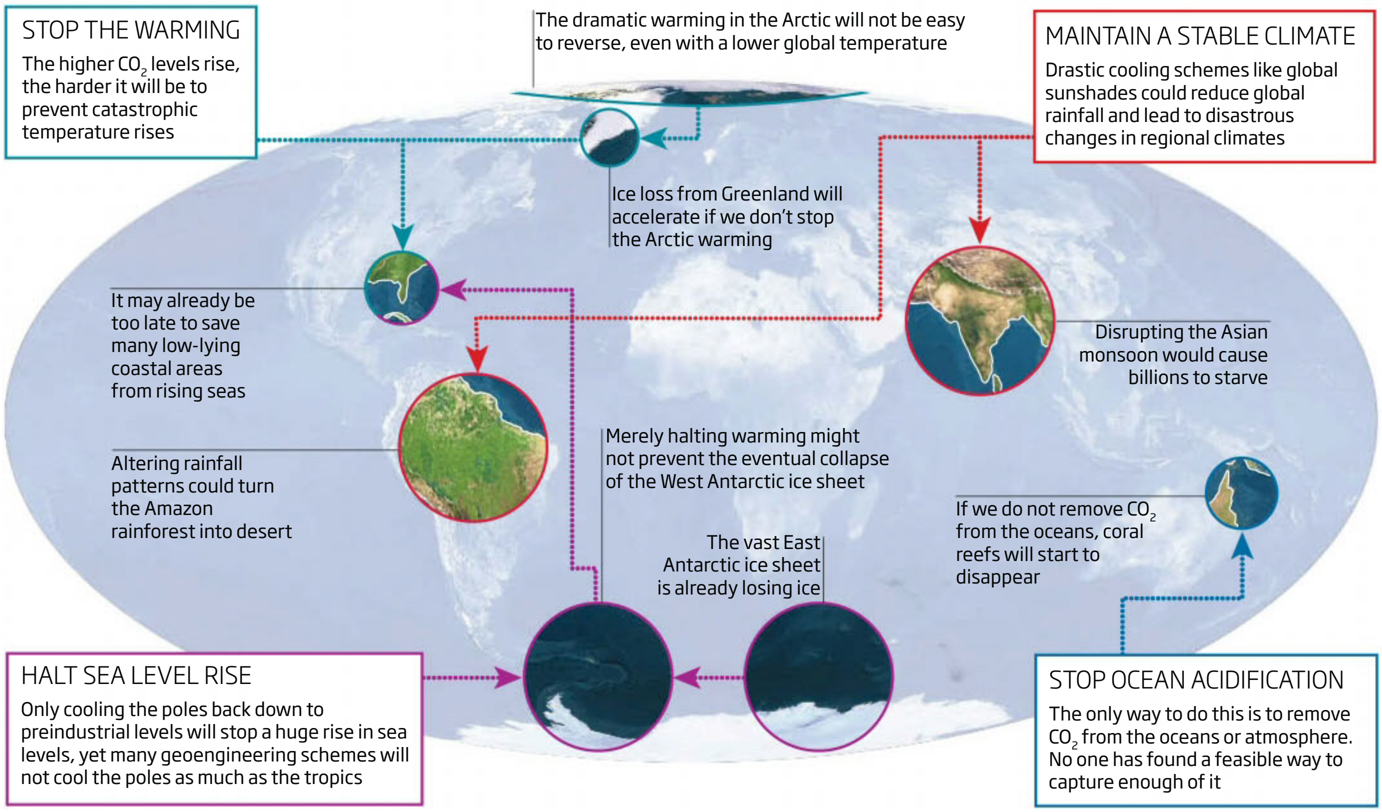


Painting roads and buildings white will do little to stop warming

RENAN ROSA/AURORA PHOTOS/CORBIS

The challenge

Cooling an entire planet is an immense task in its own right. But to avert catastrophe, any geoengineering scheme must also meet several other requirements



fill the atmosphere with a haze of fine particles. In fact, we are doing this already. Sulphur dioxide pollution forms fine droplets of sulphuric acid that already reflect an estimated 0.4 watts per square metre. But SO_2 from fires and factories doesn't remain in the atmosphere for long, so its effects are limited. If sulphate gets as high as the stratosphere, however, it can linger for years, so its cooling effect is much greater. The proof comes from volcanic eruptions large enough to inject SO_2 into the stratosphere. The 1991 eruption of Mount Pinatubo in the Philippines cooled the planet by up to 0.5 °C over the following couple of years.

Bargain price

To balance the warming effect of a doubling in CO_2, we would need to pump up to 5 million tonnes a year of SO_2 into the stratosphere. According to Justin McClellan of Aurora Flight Sciences in Cambridge, Massachusetts, whose team evaluated several ways to deliver the sulphates, this would cost about $10 billion per year. Compared with the stupendous costs and consequences of global warming, this is an absolute bargain. Sea level rise alone will swallow up many trillions of dollars' worth of cities and farmland.

Unfortunately, our sulphur spray may barely slow the seas' advance. Sulphur droplets do not linger in polar regions as long as they do in the tropics, making them less effective polar coolants. So even if aerosol injection brought the average global temperature back down to that of the 1800s, the poles would not be as cold as they were and the ice caps would keep melting. This might not be enough to avert catastrophes such as the collapse of the West Antarctic ice sheet, which would raise sea level more than 3 metres.

It is not clear whether a different kind of reflector, such as solid metallic particles or tiny, shiny balloons, would be any better. Pumping out a gas is so much simpler and cheaper, so most studies have concentrated on sulphates.

While coastal plains and cities drown, the rest of the planet might dry out. With any kind of sunshade, less sunlight will reach the sea surface, reducing evaporation. So far, the effect of sulphur pollution has been outweighed by warming, which increases evaporation. But if we reduced the temperature to the preindustrial level this way, there would be a dramatic decline in rainfall. That might be avoided by not reducing the temperature as much – but then the ice sheets would melt faster.

Sunshades could also have disastrous regional effects, according to climate models. If they disrupted the monsoons, they could bring permanent famine to billions. "Or say you changed the circulation patterns that feed moisture to the Amazon rainforest," says Tim Palmer of the University of Oxford. "You might turn the Amazon to desert."

In 2010, Myles Allen of the University of Oxford and his colleagues looked at the effect of varying amounts of sunscreen in the stratosphere using a detailed climate model. They found that there is no solution that works for everyone. An amount of aerosol that would take China close to comfortable preindustrial temperature and rainfall might cool India far too much.

Or it could be the other way round. Climate models agree fairly well on the global effects of sunshade schemes, but produce different patterns of regional climate change.

This may be because of the different assumptions and values used in different studies. Or it may be due to the limitations of existing climate models. As they improve, their regional projections may start to agree with each other, which would give us some ›

YOU CANNOT BE CIRRUS

The high, wispy cirrus clouds that sometimes grace an otherwise blue summer sky may seem an unlikely enemy, but David Mitchell is making plans to attack them. Destroying cirrus might not only reduce global temperature but also help save the ice caps and curb extreme weather.

Clouds have complex effects on Earth's heat budget, reflecting some incoming sunlight and trapping a lot of outgoing infrared radiation. Lower-altitude clouds such as marine stratus also radiate a lot of heat from their tops out into space, so overall they cool the planet. Icy cirrus clouds radiate much less heat, so their net effect is to warm us up.

In 2009, Mitchell – based at the Desert Research Institute in Reno, Nevada – suggested that we could use aircraft to spread bismuth triiodide, a non-toxic compound that should seed relatively large ice crystals. These would fall from the sky faster than natural cirrus ice, so the clouds would disperse.

Preliminary attempts to model the process, which Mitchell presented at a meeting in 2012, indicated that this could cool the planet by about 2 watts per square metre – enough to prevent half of the warming from a doubling of CO_2.

Better still, the method ought to work best where it is most needed, at high latitudes. Concentrating efforts here could protect our fragile ice caps. It would also help to restore the temperature difference between tropic and pole. That difference has been eroded by the rapid warming in the Arctic, which is thought to be one reason why we are seeing more extremes of weather.

The modelling is at a very early stage, Mitchell cautions. "Lots of research needs to be done on representing cirrus in global climate models – and not just for geoengineering." He would like to see a cloud-seeding experiment in a small area to see what really happens.

What's more, dispersing cirrus shares many of the risks of sunshade schemes (see main story): it may well have disastrous regional effects, and stopping it abruptly would be dangerous.

STOCKTREK/CORBIS

"No solution works for everyone. Cooling Earth enough to save one country could devastate another"

degree of confidence in them.

Some of the factors affecting regional climates are inherently unpredictable, though. How much of the rainforests will be left standing in 100 years' time? How much will emissions fall, if at all? How will ecosystems respond? As a result, we can never be 100-per-cent certain that any particular scheme will have the desired result.

This makes any sunshade highly risky. If it turned out to have some terrible consequence and we suddenly stopped replenishing sulphates or whitening clouds, the planet would warm very rapidly over the next few years. Such a sudden transition would be even more damaging than a gradual warming to the same level, giving no time for people and wildlife to adapt. "You are upping the stakes," says Lenton. And if we reach for the sulphates, we might need another type of geoengineering, such as cirrus seeding (see "You cannot be cirrus", left)

Sulphur aerosols from large volcanic eruptions can cool the planet for a few years

to cool the poles, prescribing not just one but two dangerous drugs for the planet.

So instead of blocking sunlight, maybe we should get at the actual cause of the problem and actively scrub CO_2 from the air. The concentrated gas could then be pumped into underground reservoirs such as depleted gas and oil fields. But no one has devised an efficient method for doing this. "The problem is you're trying to capture a very dilute gas, which is inherently costly compared with capture from a concentrated source like a power station," says Lenton.

With existing technology, there is no realistic prospect of mopping up all the extra CO_2 we are adding to the atmosphere in time to prevent further climate change. Even an industrial effort on a vast scale could take centuries, and the longer CO_2 emissions keep rising, the greater the challenge will be.

Instead of covering the planet in carbon-eating machinery, how about speeding up the reaction of CO_2 with silicate rocks? Over millions of years, this process, called weathering, soaks up vast amounts of CO_2, which is eventually returned to the atmosphere by volcanoes. But to deal with just a single year's worth of emissions, we'd need to grind up at least 7 cubic kilometres of rock and spread it so thinly that it would cover several per cent of Earth's land surface. So this process cannot save us either.

What about modifying land use and agriculture to capture more carbon? Simply planting forests remains a good thing, although geography limits its potential to about 0.5 watts, and all that carbon could end up back in the atmosphere if forests die or burn as the planet warms.

Locking away carbon

One way to lock away the carbon stored by plants is to turn them into charcoal – biochar – and bury it. Another is to burn crops in power plants fitted with carbon-capture technology. These ideas need land, so they will compete with food production. Lenton has calculated that the total benefit could be a useful 0.3 watts by 2050 – but only if we increase farming efficiency and eat less land-hungry, methane-belching meat. At present, meat consumption is rising while crop production is already being hit by extreme weather and water shortages, so this looks optimistic barring some breakthrough, such as genetically altering plants to enable them to capture more of the sun's energy.

Carbon-capture schemes, then, can at best slow the pace of warming over the coming century. If they are implemented as alternatives to cutting emissions – for instance, to earn carbon credits that can be sold to those who want to emit CO_2 – they won't achieve even this.

They will also be of no use if we are nearing a tipping point such as the widespread dying of forests, the massive release of methane from thawing permafrost or the collapse of the West Antarctic ice sheet. So perhaps we should keep the potent but risky schemes such as sulphur sprays in reserve for the direst circumstances? Perhaps. But Lenton, who helped to define the notion of tipping points in a paper in 2008, is sceptical. "People say that is why we need solar reflection in our back pocket, but they haven't proved you could get early warning of a tipping point, or deploy in time, or that these schemes would not cause other tipping points," he says.

"With existing technology, there is no realistic prospect of mopping up all the excess CO_2"

If we wait until the last possible moment, then, it could be too late to avert climate chaos. "You shouldn't think of this as a magic button that you can press if things get out of control – it may turn out to be a bit of a nightmare," Palmer says. And even if we did go for the nuclear option of a sunshade scheme, almost all climate scientists agree we would still need to make aggressive cuts in emissions.

There are a few dissenters. Peter Cox at the University of Exeter points out that higher CO_2 boosts the growth of some kinds of plants and reduces water loss, as plants don't have to keep their pores open as long. So if you could have higher CO_2 without the droughts, floods, storms and growth-impeding heat that global warming will bring, then food production would increase.

Maybe we could achieve that with sunshields. "In terms of the things we care about most, it might be a better option than conventional mitigation," says Cox. Such a cool-but-carbonated future carries frightening risks, though, and Cox is only suggesting we consider the notion.

In the end, the greatest obstacle to any drastic form of geoengineering may turn out to be politics. "You can't have competing geoengineering programmes, there has to be just one," says Allen. "So some supranational body would have to decide on the weather."

Achieving agreement may be almost impossible, because different countries will have different priorities. Some are most threatened by sea level rise, others by sheer heat or shifting rainfall. And if the Kyoto protocol is any guide, if any agreement is eventually reached it might be a far cry from what's actually needed.

However, international agreement will be needed only for big sunshield schemes, with their global dangers. There is nothing to stop individuals, institutions or countries going it alone with a bit of biochar or some other carbon-capture scheme. It may seem mundane compared with shiny space mirrors, but for now perhaps the safest tools for engineering the planet are to be found down on the farm. ■

CHAPTER FIVE
WEATHER AND WATER

Our weather is not only becoming more extreme, it's becoming even more extreme than anyone expected. **Stephen Battersby** investigates why

Running wild


ITS NICKNAME is the icebox of the nation. The village of Pellston in Michigan often sees arctic winters, with a thermometer-shattering record low of -47 °C in 1933. Even by late March, it is usually a very chilly place. But not in 2012. On 22 March that year, the Pellston weather station registered a temperature above 29 °C, vaporising the previous record for that date by more than 17 degrees.

This was just one of thousands of weather records smashed by the "summer in March", a 10-day event that affected much of North America in 2012. Many people enjoyed the unseasonal warmth, but most of the other extraordinary weather events of the past decade or so have been far less welcome. In 2003, the summer in Europe was so hot it killed tens of thousands. Pakistan was hit by severe rainstorms and floods in 2010 and again in 2011, and then a heatwave in June 2015 which killed thousands. Tropical cyclone Pam, which struck the South Pacific earlier the same year, was one of the most powerful ever recorded in the southern hemisphere.

Climate scientists have long warned that global warming will lead to more heatwaves, droughts and floods. Yet some of these recent extremes are way beyond the predictions of our climate models. ›

"Events like the 2003 and 2010 heatwaves were expected to occur only after greater warming, towards the end of the century"

And there have been extremes of cold as well as heat. In Rome, ancient monuments began crumbling after the big freeze that hit Europe in February 2012, and on the northern edge of the Sahara desert, the streets of Libya's capital Tripoli were blanketed with snow. January 2015 brought record snow falls and low temperatures to the US and Europe.

It seems that our weather is getting wilder – more variable as well as steadily hotter. The big question is why? Is this just a blip, or are we in for even more freakish weather as global warming accelerates over the coming decades?

Even in an unchanging climate, our weather varies a lot. Each summer will be different. Take the average summer temperature each year, and you will get a series of numbers scattered about a long-term mean, distributed in a pattern more or less like a bell curve. Wait long enough, and you will sweat though a few very hot summers and grumble through a few very cool summers.

Over the past century, the surface temperature of the planet has increased by 0.8 °C on average, which has shifted the familiar range of weather into warmer territory. Cooler summers have become less likely and warmer summers more likely. Contrary to what you might think, this kind of shift increases the odds of extremely hot summers by more than it raises the odds of slightly warmer summers (see "Shifting weather", right).

The rising temperature is leading to other kinds of extreme weather, too. Warmer air can hold more moisture – in fact, its capacity increases exponentially as the temperatures rises. This means that when rain falls it can become a deluge, increasing the chance of catastrophic floods.

Damper downpours

Floods are not the only result. When water vapour condenses to form clouds, it releases latent heat, and this heat is what powers most kinds of storms, from thunderstorms to hurricanes. With a wetter atmosphere, there may not necessarily be more storms, but those that do occur will tend to be more powerful because there is more heat to power them. The damage done by storms rises rapidly as wind speeds increase.

So simple physics tells us that global warming should make extreme weather more extreme, from stronger storms to hotter heatwaves, drier droughts and damper downpours. This is indeed what has been happening around the world – except that in recent years, the magnitude of some of the record breakers has been jaw-dropping.

In 2003, temperatures in Europe were much higher than in any summer for at least 500 years. Stefan Rahmstorf of the Potsdam Institute in Germany points out that in Switzerland the average summer temperature broke the previous record by 2.4 °C. It is not unusual for the records for particular days to be broken by fairly wide margins, but for the average of an entire season to be so much warmer is extraordinary. Then there was the Russian heatwave of 2010. Even averaged over Europe as a whole, this heatwave was more extreme than the one in 2003.

More recently, there was the summer in March. Because it was so early in the year, it was a disaster only for fruit growers – trees blossomed too early and then got hit by frost, wiping out over 90 per cent of crops in some places – but it could have been much worse. "If such unusual conditions had occurred during July or August, the impact would have been enormous," says Dim Coumou, a colleague of Rahmstorf.

More and more people are being affected by all this extreme weather. In a 2012 poll in the US, 82 per cent of people reported that they had personally experienced extreme weather or a natural disaster in the past year, and 35 per cent said they were personally harmed either a great deal or a moderate amount by one or more of these events.

There is little doubt that things are going to get even worse. What is especially worrying, though, is that the rise in extremes can't be accounted for solely by the 0.8 °C warming so far. Events like the 2003 and 2010 heatwaves were projected to occur only after much greater warming, towards the end of this century. And while one or two freak events might be dismissed as simple bad luck, there have been suspiciously many of them in the past decade.

James Hansen of Columbia University's Earth Institute in New York has analysed

Shifting weather

THE THEORY

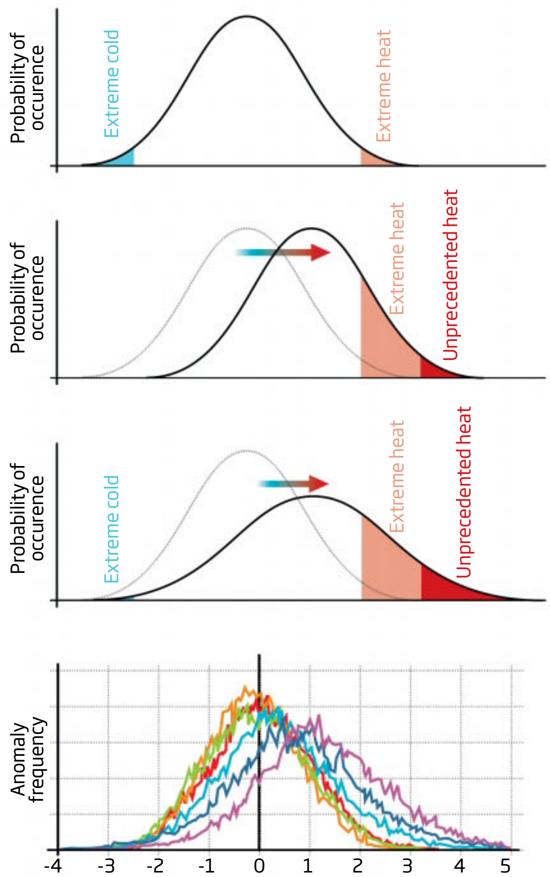
In a constant climate, temperatures should fit a bell curve - average temperatures are most likely and extremes of hot and cold are rare

If the climate warms, this probability distribution will shift. Even in the simplest scenario, if the distribution shifts but the shape remains the same, the probability of moderate heat increases slightly while the probability of extreme heat increases greatly

In theory, the distribution could not only shift but also widen, if weather becomes more variable as it warms. This is worse, as it means there will be an even greater increase in the probability of extreme heat, yet extreme cold will still occur occasionally too

WHAT'S REALLY HAPPENING

Land temperatures over the northern hemisphere show the bell curve is both shifting and widening as the planet warms



Anomaly distribution for June, July and August (standard deviations from normal local temp. 1951-80)

SOURCE: IPCC, HANSEN 2012

records of local temperatures across the globe, in each case totting up June, July and August to get an overall temperature for this period. The results show that an increasing area of the planet's surface is experiencing highly anomalous heat extremes each year, relative to the period 1951 to 1980 (see charts, page 92).

To a large extent, this is just what is expected in a warming world. However, Hansen's analyses show there is more to it than that. The weather is not only getting warmer, but more variable. Between 1951 and 1980, the average range in local summer temperatures across the entire globe was 0.55 °C; from 1981 to 2010, it had gone up to 0.58 °C. Over land the variability is greater, and its increase is faster. Some locations, especially those far from the stabilising influence of the ocean, see much more variability and more increase. Project that into the future, and we already have more cause for concern than we had with the mere rise in mean temperature.

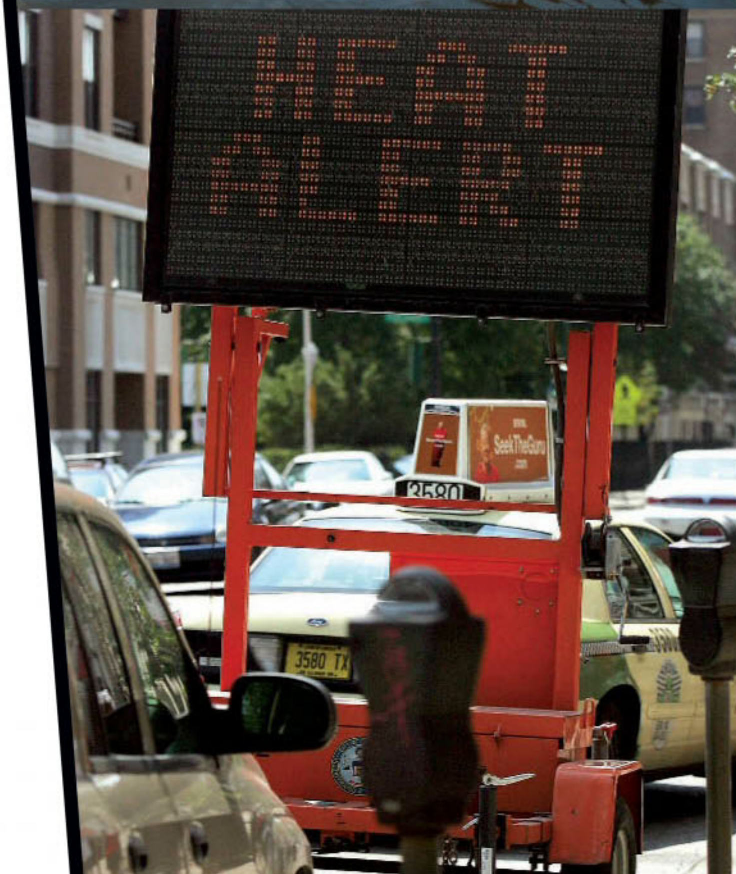
Implausibly hellish

But even in the context of this somewhat more jittery climate, the mega-heatwaves of the last decade or so stand out as implausibly hellish. Is something else happening to make temperatures soar like this?

Quite possibly, says climate modeller Pier Luigi Vidale at the University of Reading, UK. He thinks that plants and soils might explain some of the unprecedented heatwaves. Where land is covered by vegetation, much of the sun's heat is absorbed by plants. They stay cool – and keep the land cool – by sucking up water and letting it evaporate from their leaves. But when the soil dries out, plants close their pores and stop transpiring. "It is the same as if you don't drink any water and stop sweating," says Vidale. When the sun's heat is no longer channelled into evaporating water, it all goes into the land and the air above it. The result is a jump in temperature.

This has been happening for as long as there have been plants on land, but it is becoming more common and affecting greater areas because winter precipitation has become more erratic, sometimes failing to soak the soil thoroughly. At the same time, the growing season has lengthened and become warmer, so plants are sucking up more water.

In 2004, while he was part of a team led by Christoph Schär at the Swiss Federal Institute of Technology in Zurich, Vidale studied this process in a regional climate model. Although previous models had included drying soils, the representation was too simple, Vidale says, as plants shut down transpiration too suddenly. With the improved model, some of the simulations looked like the summer of 2003, and other models have since produced similar results. They all suggest that over land, ›



Warmer air holds more water, leading to heavier rainfall in places

P88-89
L TO R: TYLER HICKS/NYT/EYEVINE;
XINHUA/EYEVINE;
CAMERON SPENCER/GETTY;
G. COUSULICH/GETTY;
GUY EDWARDES/PLAINPICTURE

TIM BOYLE/GETTY;
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CHRIS STEELE-PERKINS/MAGNUM PHOTOS

P92-93
ARTYOM KOROTAYEV/AFP/GETTY;
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where soils can dry out, summer temperatures do not follow an exact bell curve. Instead, there are more mega-heatwaves.

However, a lot of uncertainty remains. Part of the problem is accurately modelling the role of plants and soil. Even details such as the species of plant are important, because plants with deep roots will keep transpiring long after those with shallower roots. "The biophysical models are not yet accurate enough," says Robert Vautard of the Climate and Environmental Sciences Lab at Saclay, France.

Measuring the actual moisture content of soils could improve things, but it is not easy. "You can make a measurement here, but a few metres away it's not valid any more," says Vidale. "In Europe we only have a few monitoring stations for soil moisture. Many of us have been arguing for more." Satellites can give an indication of surface soil moisture over a wide area, but not how much is available to deep roots.

While drying soils could be partly to blame for some recent off-the-chart heat extremes, they are not the whole answer. Vidale's model may have reproduced the scorcher of 2003 – but it also predicted that such hot summers would be unlikely before the end of this century. And of course this phenomenon cannot account for all the weird weather we are experiencing. You don't need to be a climate expert to conclude that a heatwave did not cause snow in Tripoli. But some researchers think they know what might be to blame for that – a lazy jet stream.

Jet streams are high-speed winds that carve a snaking path through the upper atmosphere (see "Jet extreme", page 94). The two polar jet streams, one in each hemisphere, are driven by the difference in temperature between warm tropics and cold poles. In the tropics, the atmosphere is puffed up by higher temperatures: "It's like there is a hill from the tropics tilted down towards the poles," says Jennifer Francis of Rutgers University in New Jersey.

Gravity pulls some of this air down towards the poles. Because of Earth's spin, the air gets deflected off to one side, which is what drives the polar jet streams from west to east.

The positions of the jet streams aren't fixed. They move around, shifting south or north and also developing big meanders, or waves. "You can get such a big wave, it breaks off as an eddy that gets left behind, just sitting and stewing in its own juice," says Francis. "When this happens, the weather near the eddy stays the same for days or even weeks."

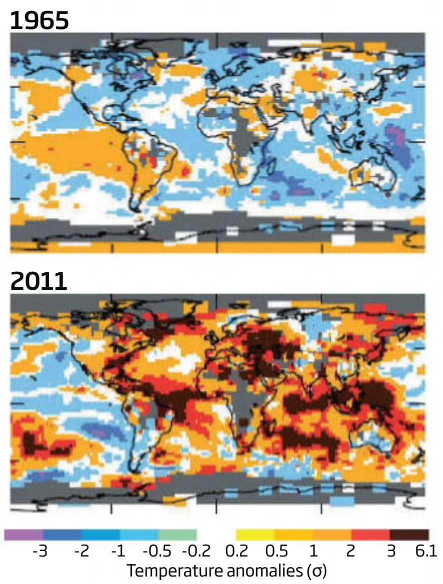
Humanity is now messing with this vital component of the atmosphere. The Arctic is warming far faster than the rest of the planet, in part because its sunlight-reflecting snow and ice is melting to expose dark, sunlight-absorbing land and sea. This is reducing the temperature difference between the tropics and the Arctic. In work published in 2009, Francis showed that in summers with less sea ice in the Arctic – meaning more heat being absorbed by the ocean – the atmospheric hill had a more gentle slope. The upshot is that the engine driving the northern polar jet stream is weakening.

As the jet stream slows down, it takes a more mazy path, with meanders that move around more slowly. That is crucial, because the jet stream pushes weather systems around. So when the stream's position changes more slowly or stays in one place for weeks – what meteorologists call a blocking pattern – the weather is more likely to become extreme. If the jet stream shepherds one low pressure system after another towards you, then you will soak – as happened in south-west England in January 2014, producing record rainfall. If the sluggish stream holds a high-pressure system in place, you will roast.

"It's not news when you have one or two hot or cold days. If it goes on for a week or two,

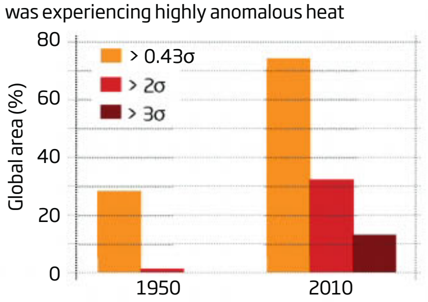
Heat anomalies

Area of the world's surface experiencing statistically anomalous temperatures during June, July and August relative to 1951-1980 mean



σ = standard deviations from the mean local temperature

Extreme heat anomalies (>3σ) covered less than 0.2% of the planet during 1951-1980 but from 2006 to 2011 between 4% and 13% of the world was experiencing highly anomalous heat



SOURCE: HANSEN 2012

As hotter and drier periods become more common, the risk of wildfires will soar

"It's not news when you have one or two hot or cold days. But if it goes on for weeks, people start freaking out"

then people are freaking out because their harbour is freezing over," say Francis. Blocking patterns have played a part in much of the extreme weather around the northern hemisphere in recent years, including some of the freezing winter weather and record snowfalls, and the summer in March.

Other researchers have confirmed that the jet stream has been weakening, and shown that this leads to more blocking events. Now Francis has found another effect of the warming Arctic. "I got thinking – if you are warming the north more than the south, that will stretch the northern peaks of high-pressure ridges farther northward." Working with Stephen Vavrus of the University of Wisconsin-Madison, she used highly detailed weather models to recreate past events and trace the contours of atmospheric pressure. And indeed the high-pressure ridges have tended to stretch further north in recent years. That makes the meanders of the jet stream more extreme, bringing warm air further north, and cold air further south – to places such as Tripoli.

So it appears the northern hemisphere is in for more weather chaos as the planet warms. In some years, the jet-stream mechanism could cancel out the drying-soils mechanism but in others it could amplify it, because a lazy jet stream will occasionally produce exceptionally dry winters and springs, as well as hot spells in the summer. The polar jet stream in the southern hemisphere is unlikely to be affected in the foreseeable future, though, because Antarctica is warming more slowly than other parts of the world.

Provoking the elements

There could well be other, as-yet-unidentified mechanisms contributing to the wildness of our weather now, or which might kick in as the world warms further. For example, having roused the air and the earth against us, we may also be provoking another element. The ocean joins with the atmosphere in a roughly periodic pattern called the El Niño Southern Oscillation, or ENSO, in which warm water sloshes back and forth across the surface of the Pacific Ocean partly in response to changes in the trade winds.

ENSO's changing moods already cause all sorts of mayhem, and as the water sloshing around gets even warmer, the mayhem is likely to increase. The Australia and Pakistan floods of 2010 and 2011 were due to unusually warm surface waters loading the air with moisture, probably caused by a combination of ENSO and climate change.

A big question is whether things could get even worse. What if ENSO and other climatic oscillations don't just continue as before in an ever hotter world, but become even greater in magnitude? Are we pushing these pendulums in a way that makes them swing more wildly? "So far there is no clear evidence either way," says Rahmstorf, "but we are changing the whole energy balance of the climate system, so in a way it would be surprising if these patterns of variation did not change."

Part of the problem with studying these phenomena is that our climate models are relatively coarse, though they are improving. A European collaboration called PRIMAVERA, which includes Vidale's group in Reading, is developing global climate models with a spatial resolution of 5 kilometres, compared with a more typical resolution of tens of kilometres. Vidale hopes this will be able to show how processes are connected across the globe, and allow researchers to tease apart the influence of soils and atmospheric circulation on weather extremes.

Such models might give a better idea of just how extreme future extremes could become, although there is of course no way to predict one-off weather events years in advance. Then again, as earlier models missed the changes in the jet stream, these new ones could still be blind to some unanticipated mechanisms.

In the meantime, there are some things we can do to prepare. European health services now have better contingency plans for a mega-heatwave than they had in 2003. We can design buildings to cope with extreme heat, and planners might consider avoiding putting vital infrastructure in areas at risk of flooding.

But adaptation can be very costly, and the very nature of more variable weather poses problems. Farmers could learn to cope if it was consistently drier or hotter, for instance, but if the weather continues to become more variable and there is no way to know whether to expect frost or floods, hail or heatwaves, then each season will become an ever greater gamble. "It is difficult to adapt to unprecedented extremes, as they always involve some element of surprise," says Rahmstorf.

While no one can say exactly what's going to happen to our weather, all the signs are that we're in for a bumpy ride. "We are seeing these extremes after only 0.8 degrees of global warming," says Rahmstorf. "If we do nothing, and let the climate warm by 5 or 6 degrees, then we will see a very different planet." ■

The jet streams that dictate our weather seem to be changing – but how, and what's to blame, asks Fred Pearce

Jet extreme

AIRTEAMIMAGES

Thanks to the jet stream, transatlantic flights can be an hour quicker

AS DEPUTY director of the Japan Esperanto Society, it was clear what language Wasaburo Ooishi would choose to publish his discovery in. Unfortunately, it meant hardly anyone noticed.

In the mid-1920s Ooishi, a meteorologist in his day job, was releasing research balloons near Mount Fuji when he saw something odd. Once the balloons had climbed high into the atmosphere above the clouds, they suddenly hurtled out eastwards over the Pacific. Persistent high-level winds, often stronger than a hurricane, were blowing from west to east over Japan.

Other people had observed something similar in Europe, but Ooishi was the first to put two and two together and pinpoint the existence of a permanent, narrow tunnel of wind circling Earth at mid-latitudes, travelling at 100 to 400 kilometres per hour.

Gradually, knowledge of the jet stream circulated around the globe, too – albeit by unconventional means (see "Fu-Go no go", page 96). Today, surfing the jet stream is commonplace: slipstreaming on it eastbound can slice up to an hour off a flight across the Atlantic. And as we have learned more about the jet stream, it has become clear that it is no rarefied curiosity. Its speed and path is the invisible hand guiding most weather systems on the continents below. When it falters, extremes of all sorts can result, from freeze-ups to droughts, heatwaves and catastrophic floods.

That makes it all the more worrying that, just lately, the jet stream has seemed to be changing. But is it really? And, if it is, how and why?

Earth's atmosphere actually has several different jet streams at different latitudes. The strongest are the polar jet streams, one each in the northern and southern hemispheres. A few hundred kilometres across, these polar jet streams carve a sinuous path at the top of the troposphere, the lowest layer of Earth's atmosphere. They lie anywhere between 7 and 12 kilometres up, at latitudes generally between 50 and 70 degrees, although with periodic excursions beyond.

Their origin is simple enough. Where cold, dense polar air meets warmer, lighter air from near the equator, winds rush in to equalise the pressure difference. Earth's west-east rotation diverts these winds from what would otherwise be a north-south trajectory to one travelling east. In the southern hemisphere, the polar jet encircles the Antarctic, mostly over the Southern Ocean. In the northern hemisphere, it passes over North America, Europe and Japan – some of the most densely populated places on Earth.

And we feel its drag on the ground. The fronts and low-pressure systems familiar in our weather forecasts are the jet stream's ›

US ARMY PHOTO

FU-GO NO GO

Wasaburo Ooishi's pioneering research into the jet stream in the 1920s was "essentially ignored" in the West because he published his research in Esperanto (see main story). So says John Lewis of the US government's National Severe Storms Laboratory in Reno, Nevada, who has researched the affair.

The turnaround came during the second world war when, now in conflict with the US, Japan hatched a plan to surprise Uncle Sam by using the wind to express-deliver bombs. Hydrogen balloons rode the jet stream from Japan, carrying incendiary devices that were timed to drop on arrival over land. Guided by Ooishi's wind charts, 9000 balloon bombs, called Fu-Go, were unleashed from Japan between November 1944 and April 1945.

Luckily for the US, Japan's meteorologists got the timing wrong. The jet stream was a little weaker than Ooishi had calculated, and the balloons took 96 hours on average to cross the Pacific, rather than the estimated 65 hours, says Lewis. All but about 300 of them dropped their bombs harmlessly into the Pacific Ocean. One that did make it hit a power line, blacking out the Hanford nuclear weapons plant in Washington, which was then preparing the atomic bombs destined for Hiroshima and Nagasaki. Another Fu-Go bomb landed on a Sunday school picnic in Oregon, killing six people - the only combat casualties on the US mainland during the entire war. That made the West finally wake up to the jet stream's power. Balloon bombs spoke louder than Esperanto.

earthbound manifestations, as its high winds pull the air below around the planet (see diagram, right). Most of Europe's weather rides in under the jet stream from the Atlantic and most of the weather in the western US comes from the Pacific in a similar manner. If you are north of the jet stream – and so beneath air from the poles – it will be cold. If you are to the south, it will be warm. If you are under the jet stream's path, as it sucks moist air upwards water will condense, and fronts will bring changeable, rainy weather.

But the jet stream does not follow a straight line. It meanders like a river on a flat floodplain, sometimes moving north, sometimes south. Most often, such meanders are triggered by the stretching and squashing of the air as the jet stream passes over mountains. Known as Rossby waves, they travel slowly east, typically taking a week to cross North America, for instance.

Occasionally, they get stuck, generally when the jet stream slows as a result of random fluctuations in the temperature difference between polar and non-polar air. That brings "blocking highs" within the loops of the malingering meanders. Bits of the globe get stuck under a vast tongue either of hot, dry air stretching north from the tropics in summer, or of ice-cold air reaching south from the Arctic in winter.

A couple of days of hot or cold, wet or dry doesn't matter much to most people. But a couple of weeks can matter a great deal. The long heatwave in Europe in 2003 – a classic piece of sticky weather, in all senses – killed an estimated 70,000 people (see "Running wild", page 88). Meteorologists now blame the dust bowl in the US Midwest in the 1930s on a faltering jet stream that tracked south, diverting the usual rains and triggering drought in the blocking zone.

Arctic heatwave

The jet stream has been particularly weak during several recent northern winters, meandering erratically and bringing polar air plunging as far south as Florida – where chilled iguanas fell out of the trees – and delivering long cold winters in western Europe that, for some, made a mockery of the idea of global warming. The massive summer heatwave of 2010 that sparked forest fires across Russia also arose because an exceptionally long-lasting blocking high brought hot dry air up from Africa for weeks on end. At the same time, further east, another long loop in the jet stream pushed wet air down from the north towards the Himalayas, where it interacted with the Asian monsoon and delivered huge floods down the Indus river. At one stage, a fifth of Pakistan was under water.

A changeable jet stream and intermittent blocking highs have always been part of

"The jet stream brought polar air south to Florida, where chilled iguanas fell out of the trees"

weather in the middle latitudes, but some researchers see a worrying trend. In 2008, Cristina Archer, now at the University of Delaware in Newark, and Ken Caldeira of Stanford University in California analysed jet-stream data from 1979 to 2001 and found a small but significant slowing of the northern polar jet stream during that period. In late 2012, James Overland of the US National Oceanic and Atmospheric Administration reported that the jet stream had been meandering more in the past five years than in the previous three decades. Also in 2012, Jennifer Francis of Rutgers University in New Brunswick, New Jersey, found that since the 1990s its average speed in autumn has fallen by 14 per cent over North America and the North Atlantic, with its path growing more idiosyncratic.

At a US Senate hearing in July 2013, Francis went so far as to suggest that a weakened jet stream had caused tropical storm Sandy to take the unusual path that devastated parts of Manhattan the previous year. She was

UPI/EYEVINE

speaking days after Anchorage, Alaska, and Norilsk in Siberia reported temperatures more akin to the Mediterranean – all blamed on blocking highs funnelling heat north.

Meanwhile, the southern hemisphere's polar jet has also gone walkabout, drifting poleward but strengthening in recent decades. There is strong evidence that both are due to the ozone hole in the stratosphere above. This southern drift may be reducing rainfall in the south of Australia, because this area is now less often under the southern polar jet stream.

In the northern hemisphere, however, Francis thinks something odd is afoot that has nothing to do with ozone holes. In March 2012, together with Stephen Vavrus of the University of Wisconsin-Madison, she published her idea that the culprit is the rapidly warming Arctic. The Arctic is heating up two to three times faster than most of the rest of the planet, as white snow and ice that reflect solar energy back into space are disappearing, to be replaced by dark, energy-absorbing ocean and land. This "Arctic amplification" means that the temperature difference between the Arctic and lower latitudes is diminishing. Since this difference creates the jet stream, it will weaken too. "The dynamics are complicated, of course, but what we are seeing is the effect of Arctic amplification on the jet stream. I am convinced of it," she says.

By no means everyone is persuaded by Francis's argument, however. Michael Lockwood at the University of Reading, UK, for example, doesn't discount Arctic effects, but thinks changes in the stratosphere caused by low solar activity might also be playing a part in slowing the jet stream. "The jury is out," he says. "I wouldn't rule out either factor, or indeed that they are working together." And the apparent role of stratospheric ozone loss in the acceleration and poleward shift of the southern hemisphere jet shows that stratospheric influences can also be strong on the jet streams beneath.

Poles apart

Perhaps the strongest backing for Francis's idea about the northern jet stream comes from the fact that it weakens and wavers most obviously in autumn, right after the September peak of seasonal ice loss in the Arctic Ocean, when the north-south temperature gradient is at its smallest.

Many researchers remain cautious about drawing definitive conclusions, however. Modelling studies do show that if all the Arctic sea ice disappears at the end of summer, the probability of blocking episodes increases, making colder spells more likely the following winter, says Julien Cattiaux of the French National Centre for Meteorological Research in Toulouse. "But recent blocking episodes are single exceptional events, and their rarity prevents us from drawing any conclusions on long-term changes."

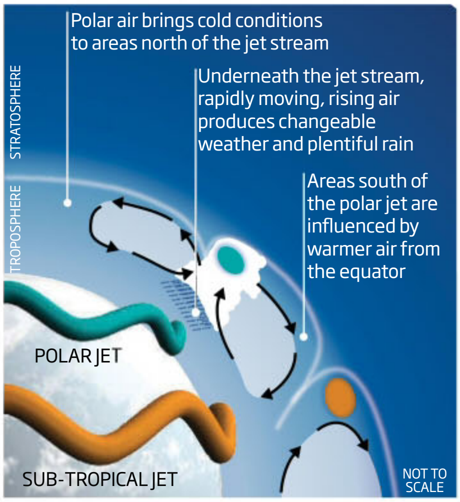
Elizabeth Barnes of Colorado State University in Fort Collins is more critical. She argues that the slower and wavier jet stream described by Francis was in fact "an artefact of the methodology" used to measure the Rossby waves. She has reanalysed Francis's numbers, and argues that poleward movement of the northern polar jet stream corrupted the data and that the weather was not sticking any more than it used to. "We find no significant increase in blocking highs in any season," she says.

The dispute got personal, with Francis publicly accusing Barnes of not taking a "balanced approach" in her work. One leading figure in the field refused to comment on the work when contacted by *New Scientist* for fear of being seen to take sides. Atmospheric physicist Joanna Haigh of Imperial College London strikes a more emollient note. "I don't think Barnes is saying this [greater wave activity] doesn't happen, just that Francis hasn't properly established it," she says.

What this brouhaha does establish is how difficult it is to say with great confidence what the future holds for the jet stream. Most of the big computer models developed to predict

Moving on up

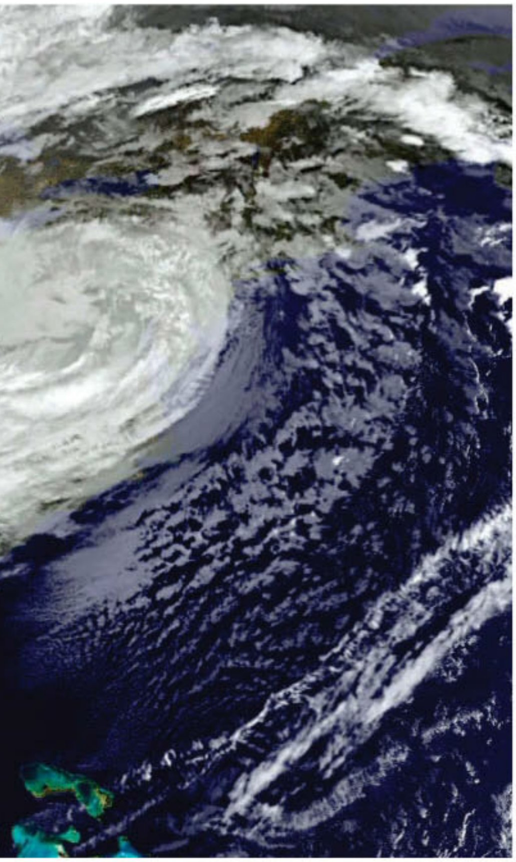
The position of the polar jet stream determines the weather at mid-latitudes in the northern hemisphere



climate change – including an analysis of different models developed for the latest assessment from the Intergovernmental Panel on Climate Change, published online in September 2013 – actually predict faster polar jet streams, and fewer blocking highs in winter, though more in summer, says Cattiaux. This would mean more summer heatwaves but fewer instances of persistent extreme winter cold. The lengthy review process for the IPCC report meant it was not able to include an analysis of Francis's more recent work. It says simply that "trends in the jet speed are uncertain".

The future of the weather for billions of people depends on who is right – in ways big and small. Sirpa Häkkinen of NASA's Goddard Space Flight Center in Greenbelt, Maryland, has argued that jet stream winds also help maintain ocean circulation patterns in the far North Atlantic. Currents there are directly driven by surface wind patterns, which are themselves driven by the jet stream. These include the overturning circulation, sometimes called the Global Conveyor, which maintains the Gulf Stream that keeps north-western Europe unusually warm for its latitude.

"The most important point about the jet stream is how chaotic it is on all timescales, from day-to-day changes to year-on-year and even decadal variability," says Cattiaux. The growing fear is that, although we cannot exactly predict how things will change, big changes are coming. Such sudden and visceral shifts in our day-to-day weather are more likely to bring home the reality of climate change than any gradual changes in average temperature. In some of the most heavily populated parts of the planet, we could be in for a bumpier ride than even climate modellers predict. ■



The jet stream conspired with tropical storm Sandy to bring devastation to the eastern US

CLEARING SKIES

Our future is looking less cloudy – and that's far from good news, explains Stephen Battersby

DAJ/GETTY

AMONG the ranks of fluffy clouds stretching across the summer sky, one catches your eye. There is something familiar in the shape. Is it a dog? A bear on its hind legs? Not quite. As the pale billows shift, the cloud spreads out something like a pair of wings. Aha – a guardian angel. A little lopsided, but somehow reassuring. Until another change catches the air. The wings melt away and the cloud shrinks. Slowly it takes on a form that is less comforting. Starker. More... skeletal.

As well as providing entertainment on a lazy day, cloud-watching has a more serious side. Clouds have a vital role that few people appreciate: their overall effect is as a global heat shield, reflecting sunlight that would otherwise bake the Earth and obliterate life.

Much depends on what happens to this heat shield as the planet warms. It might grow a little stronger, slowing the warming somewhat. Or it could weaken, meaning the world will warm even faster. This is a crucial question because it could mean the difference between a planet that is 3 °C hotter next century – very bad but probably survivable – or 6 °C – which would be catastrophic. To narrow this range of uncertainty we need to understand clouds much better.

In recent years, we have started to make progress. It is now clear, for instance, where climate scientists should be focusing their attention. "We are hot on the trail, in a way that we haven't been before," says Bjorn Stevens at the Max Planck Institute for Meteorology in Hamburg, Germany. That trail leads to Earth's tropical seas, where great expanses of low cloud exert a powerful influence over the climate of the entire planet.

"Clouds act as a global heat shield. Without them, the sun would obliterate life"

Like all clouds, they trap heat below them in the form of long-wave infrared radiation. This is why temperatures fall less on cloudy nights than on clear ones. But clouds also reflect some sunlight straight back into space and, less obviously, act as radiators, emitting infrared to space from their tops. So a cloud is a parasol, blanket and cooling fin all at once (see diagram, page 100).

The overall result depends on the height and type of clouds. Low clouds cool the planet: although they trap some heat, they also reflect a lot, and their fairly warm cloud tops emit a lot of heat to space. High clouds emit much less from their colder tops, and often reflect little too, so they help warm the planet.

Low cloud is more widespread than high, which is why clouds cool the planet overall. In fact, if you were to strip away all clouds, it might lead to a runaway greenhouse effect that would eventually boil away the oceans, according to calculations published in 2013 by Colin Goldblatt at the University of Victoria in British Columbia, Canada. That's not going to happen, but we do need to know how clouds will change in a warmer world.

The best way to find out, you might think, would be to look at how clouds have changed over the past century as the planet warmed by 1 °C. This turns out to be extremely tricky. If you have ever been mesmerised by writhing wisps of cloud, you will appreciate that they are rather hard to pin down.

Every approach to cloud observation has some shortcomings. Weather stations on land are no use for the more widespread and important ocean clouds. Observations from ships are patchy and subjective. Instrument-laden planes are scarce. Weather satellites give some insights, but drift and decaying orbits plague their data. And the dedicated climate satellites of NASA's Earth Observing System have only been watching clouds for a decade or so, not long enough to catch long-term trends.

Even if we did have a good global record of cloud behaviour, it might not be a reliable guide to what happens when the planet gets even warmer. As the temperature soars we might pass some threshold that produces big changes in cloud behaviour.

If we understood exactly how clouds work, we could predict future behaviour in a climate model. But cloud computing isn't easy. The inner workings of a cloud involve turbulent flows of air on scales ranging from a few kilometres to a few metres. This is invisibly small to global climate models, which slice the atmosphere into cubes a hundred kilometres wide. Specialised small-scale models can now capture eddies down to a hundred metres or so, but these cannot encompass large weather systems.

On even finer scales inside clouds, droplets of water and crystals of ice are colliding, coalescing, condensing and evaporating. Many of these processes – collectively › known as "microphysics" – are well understood, but not all of them. Zoom in even more, and you see that clouds cannot form without a fine mist of aerosols: airborne particles less than a micrometre across that act as nuclei around which water can condense or freeze. With more particles you may get a whiter, longer-lived cloud, making a better parasol.

Models cannot capture all of these processes, so they have to rely on approximations, such as the observed relationship between cloudiness and humidity, say, or temperature. These relationships can then be plugged in to the models. But as we have seen, observations are not perfect, so we have no universal relationship between all the properties of the atmosphere and the amount and type of cloud that you should get.

That gives modellers too many options. For example, cloud cover correlates well with the temperature difference between ground level and 3 kilometres up. But it correlates equally well with another measure that includes both temperature and humidity. Model results vary depending on which option is chosen. "They give completely different predictions for what happens when Earth warms up," says Steven Sherwood at the University of New South Wales in Sydney, Australia.

Despite these difficulties, there has been progress with some types of cloud. Models and observations agree that high clouds will, on average, be pushed higher still as temperatures rise. That makes their cloud tops even colder, so they become less effective at radiating heat. Meanwhile, storm tracks will probably shift towards the poles, where clouds reflect less solar heat. Both of these factors will act to amplify warming.

A much more important part of the global heat shield is found in the tropics and subtropics, where great blankets of low stratocumulus cloud stretch over much of the oceans on most days. Here the models clash. Some predict almost no change in these low clouds, others a sharp decline that amplifies global warming.

To work out which point to the real future, we need a better understanding of what might be going on above those warm tropical waters. "In general I find physical mechanisms to be more compelling than 'my model predicts X so it must be true'," says Peter Caldwell at the Lawrence Livermore National Laboratory in California. The past few years have seen a flurry of new mechanisms explored.

Some look like good news: they are "negative feedbacks" that act to slow warming, the warmer things get. For example, where warm, dry air descends towards tropical oceans as part of a global circulation pattern, it can trap sheets of low, cooling stratocumulus cloud. With warm air above and cooler air below – a temperature inversion – the air cannot rise and lose its moisture by raining. And as global temperatures rise, the warm downdrafts should get warmer, strengthening the inversion effect and increasing cloud cover on average.

Trapping more heat

At least, that is what observations and small-scale models suggest, Caldwell and his colleagues reported in 2013. But it is only one mechanism. "I think this negative feedback will be offset by a variety of positive feedbacks," says Caldwell. "I'm on the fence about whether stratocumulus will increase or decrease, though most of my colleagues seem to think it will decrease."

That is because they have realised several positive feedbacks could be at work. For one thing, the clouds could be starved of moisture. Low clouds get their moisture through a roundabout process: as heat radiates from the cloud tops, cold parcels of air form and sink down. This pushes up damp air from near the sea surface, which forms more cloud as it cools and condenses.

In 2009, two teams that included Caldwell and Stevens pointed out that rising greenhouse gas levels will trap more heat, reducing heat loss from the cloud tops. That means less cooling, less sinking air, less moisture dragged up and less cloud cover on average.

Or clouds could lose moisture to the dry air above. Even where a temperature inversion traps the clouds, there is some mixing between damp, cool air below and dry, warm air above. As Stevens and colleagues suggested in 2012, warming could drive stronger updrafts from below and increase this mixing, dissipating the vital water. The result would be reduced cloud cover and amplified warming.

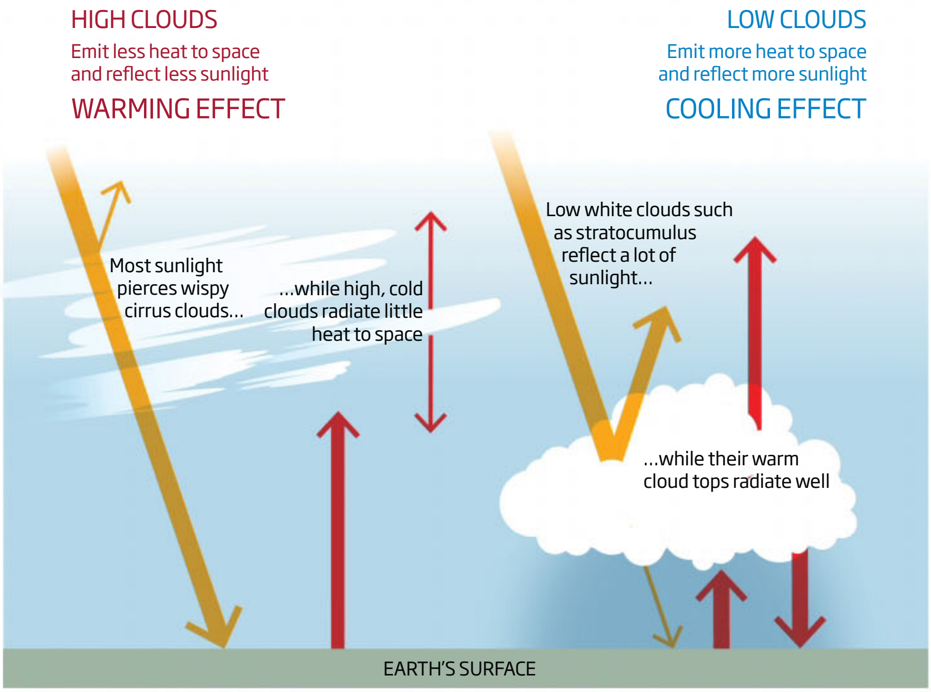
Even if mixing doesn't get stronger, there could still be more moisture loss to the dry air above. Warmer air can hold much more water vapour, so in a warmer world a given air current will carry more moisture away.

To find out how big this feedback could be, Sherwood's team looked at data from weather balloons to see how much mixing there is today. It turned out to be pretty vigorous – more than in many models. "Models that have more mixing are closer to the truth," says Sherwood.

Different models suggest that a doubling of CO_2 could lead to warming of anywhere between 1.5 °C and 4.5 °C in the short term – a figure known as climate sensitivity. But the

Earth's heat shield

Low clouds cool the planet, while high clouds help warm it. Because there are more low clouds, the overall effect is cooling, but climate change is likely to weaken this



ISMAELJORDA/GETTY

models with realistic mixing are the ones with greater sensitivity, Sherwood found. If they are to be trusted, then Earth's short-term sensitivity will be 3 °C to 4.5 °C.

"This work is a great step in the right direction, but I don't think it is definitive," says John Fasullo at the National Center for Atmospheric Research in Boulder, Colorado. One problem with Sherwood's approach, he says, is that observations of mixing are limited – relying on a scattering of weather balloons – so it may be difficult to confirm the theory.

Fasullo prefers to compare cloudiness directly with humidity, which can be measured globally by satellites. In 2012, he showed that models often overestimate the humidity in the subtropics. His finding was also bad news: the models with more realistic low humidity tended to predict greater warming.

These findings are casting some light on the great cloud conundrum, but it is still rather a dingy grey light, just hinting at which models might be most trustworthy. "Are the more 'successful' models getting the right answer for the right reasons?" asks Fasullo.

As computer power grows we can build models with finer resolution, but we won't reach some paradise of perfect modelling. Even ignoring the microphysics, important air movements are happening on scales as small as 5 or 10 metres. It will be several decades at least before global models can include such fine detail. So models must keep using approximations for this small-scale stuff, making it all the more important to test them against direct observations.

Feeding clouds

One answer may be to make the best of weather satellites. "For climate you need a stable observing network, but the weathersats that show clouds on the evening news were never intended to be stable in that way – if a sensor degrades or the orbit drifts a bit you can still see where a hurricane is," says Joel Norris at the Scripps Institution of Oceanography in San Diego, California. With a thin cloud layer, whether you see it all depends on the angle you look at it, so as satellites spiral closer to Earth, their record of cloudiness can be distorted. They can also move geographically so they are seeing a given spot later in the day, when there is typically more or less cloud.

To some extent these distortions can be corrected, and Norris is now working to do that with two of the main weathersat databases.

We need to watch not only the visible clouds, but also their invisible vaporous foodstuff. "Water vapour is the single most important variable," says Stevens. "If you ask how good are our global measurements – well, it's a crime, we are off by tens of per cent. But the great thing is we have some instruments now that can measure water vapour accurately." Raman lidars can fire a laser into the air and measure the spectrum of light scattered back by water molecules. "We need more of those – and also in space," says Stevens.

So we haven't mastered the science of clouds yet. But both observations and models suggest that far from coming to our rescue, clouds are going to suffer along with us. And many independent lines of evidence point to the same conclusion. Looking at past climates, for instance, cannot tell us how clouds behaved, but does reveal strong warming in response to rising greenhouse gas levels.

A slew of studies published in 2014 all concluded that the climate's sensitivity to CO_2 is at the higher end of the range. The forecast, then, is disturbingly clear and uncloudy. ■

Skyfall

Great rivers of water gush through the atmosphere. And when they dump their load, the results are catastrophic, says **Dana Mackenzie**

IN THE south-west of the UK, 2012 was the year that the weather played Scrooge to everybody's festive plans. In the five days leading up to Christmas, the seaside city of Plymouth got more rain than it usually gets in the whole of December. In Braunton, 80 kilometres to the north, the river Caen overwhelmed a recently completed flood-control project, inundating the town with water instead of shoppers. The main rail link connecting the region to the rest of the UK was cut off for six days. Even for an area more accustomed to wet than white Christmases, it was out of the ordinary.

That is nothing on the Christmas California endured 150 years ago. Starting on Christmas Eve 1861, Sacramento experienced a biblical 43 consecutive days of rain that left it submerged under 3 metres of water. The surrounding Central Valley became a lake 30 kilometres wide that did not recede for months.

Different times, different places. But there are similarities between the two cases beyond unusually soggy and cheerless Yuletides. California and the UK are both mid-latitude regions with an ocean-facing west coast. And the chances are the floods had a common cause: an atmospheric river.

Atmospheric rivers are vast, unbroken streams of water-laden air that can snake thousands of kilometres through the sky. Only recently identified and named, they are huge not just in geographical extent. "In terms of the water they dump as precipitation, atmospheric rivers are every bit as big and bad as hurricanes," says Michael Dettinger of the United States Geological Survey in La Jolla, California. Unlike hurricanes, they do not generate massive publicity, evacuations and early-warning efforts. Dettinger and others say this must change.

The effects of atmospheric rivers are nothing new. Residents of California have long talked about the "Pineapple Express", winter storms laden with warm water that originate around Hawaii. But atmospheric rivers were officially discovered on the other side of the country – in a computer printout. In 1998, Yong Zhu and Reginald Newell of the Massachusetts Institute of Technology were running a model of Earth's climate when they noticed that it showed that almost all of the water vapour travelling between the tropics and mid-latitudes was contained in narrow, intense bands.

This went against the grain. Severe weather was generally associated with the low-pressure centre of a storm system, an assumption reinforced by the satellite images available at the time. These images were recorded by monitoring Earth's infrared emissions, which are absorbed by water and other molecules on

It rained non-stop for 43 days in Sacramento starting in 1861

MATT CARDY/GETTY/CIMSS; LEFT: EUGENE HEPTING/CENTER FOR SACRAMENTO HISTORY

their passage through the atmosphere. They generally show blobby weather systems speckled with areas of more or less moisture. From this perspective, temperate zones were watered by a diffuse system of sprinklers – not the fire hose the model suggested.

As it turned out, 1998 was an El Niño year, and so an ideal time to settle the issue. This Pacific-wide phenomenon tends to bring unusually wet winters to the US west coast, and the US National Oceanic and Atmospheric Administration (NOAA) was planning to fly several sorties into storms over the Pacific, releasing expendable instruments called dropsondes. Like weather balloons in reverse, these beam back measurements of wind speed and water vapour as they fall.

They saw exactly what the model predicted: warm "conveyor belts" of moist air a few hundred kilometres across not at the centre of storm systems, but moving rapidly along their peripheries. The real surprise was how much water they transported – and how far it got. "One storm was conducting something like 20 per cent of all the water-vapour transport from the tropics to the poles for the whole northern hemisphere," says Dettinger. "That's the sort of thing that makes you stop and say, 'Whoa! What is *that* all about?'"

Rivers in the sky

The clincher came from weather satellites equipped with microwave imagers. Unlike infrared radiation, microwaves are not absorbed to the same extent by water vapour in the atmosphere, so they can punch through all the way from Earth's surface to the imaging satellite. The images revealed that, summed vertically through the atmosphere, the greatest quantities of water were found not in blobs, but long, thin ribbons extending thousands of kilometres. Atmospheric rivers had simply been hidden: looking for them using infrared was like using your eyes to discern the bottommost layer of water in a steaming bathtub.

So what causes atmospheric rivers? The short answer is we still do not know. To weather modellers they are simply an "emergent" phenomenon. Program in a few basic physical facts about the atmosphere, such as the conservation of matter and momentum, the distribution of incoming solar radiation, Earth's rotation and the thermal properties of water, and out they pop.

In the northern hemisphere, we generally become aware of an atmospheric river when a cyclone – an anticlockwise-rotating low-

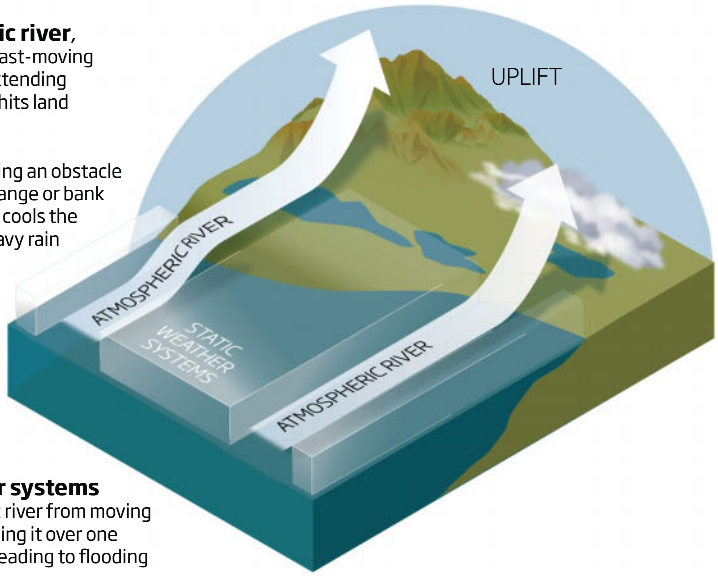
Three steps to inundation

Many instances of extreme flooding in temperate zones have a common cause: an atmospheric river getting stuck over one patch of land

1: An atmospheric river, a narrow channel of fast-moving moisture-laden air extending from warmer climes, hits land

2: Uplift occurs on encountering an obstacle such as a mountain range or bank of storm clouds. This cools the river and leads to heavy rain

3: Static weather systems stop the atmospheric river from moving along the coast, keeping it over one area for a long time, leading to flooding



pressure system – sweeps warm, moist air on to a coastline from the south and south-west. If winds are particularly strong about a kilometre up – a layer Marty Ralph at Scripps Institution of Oceanography in La Jolla, calls the river's "controlling layer" – vast quantities of water-laden air can pass over an area in a short time. If this stream hits mountainous coastal terrain, such as the Coast Range or the Sierra Nevada in California, it cools as it rises over the range, and its water vapour condenses into rain. "That's where we get our big precipitation from," says Dettinger.

For the UK it is a similar, though less extreme, story: because the country is further from the equator, the air is usually already cooler and holds less water vapour by the time it gets there. In 2011, David Lavers, then at the University of Reading, studied the 10 largest floods in four UK river basins over the past 40 years, including particularly devastating floods that hit Cumbria in November 2009. "We decided to reverse engineer the floods," says Lavers. "We looked at the largest impacts and asked what caused them." In almost every case, archived wind-speed measurements and water-vapour data suggested the presence of an atmospheric river.

If you know what to look for, it is easy to spot an atmospheric river in satellite microwave images: typically there are half a dozen of them snaking above Earth at any given time. Many rain themselves out over the ocean without ever making landfall, and a typical river conveys as much moisture as seven to 15 Mississippis – or one Amazon. In the most part they are unproblematic: winds move the river about like a garden sprinkler head, allowing it to distribute its moisture over a large area. California receives one-third to a half of its precipitation in this way. Things get dicier when surrounding weather systems cause a river to stall in one place. "Then you see a real problem," says Ralph, and one not just confined to mountainous coastlines, either (see "Tennessee blues", above right).

It is a problem that seems likely to grow. As far as we can tell, climate change has two opposing effects on atmospheric rivers. The temperature difference between the poles and the equator provides the ultimate energy source for mid-latitude storms. As the poles are warming quicker than mid-latitudes this temperature difference is getting smaller, and storms should weaken. But warmer air holds more water vapour, which could make atmospheric rivers even moister.

Receding snow line

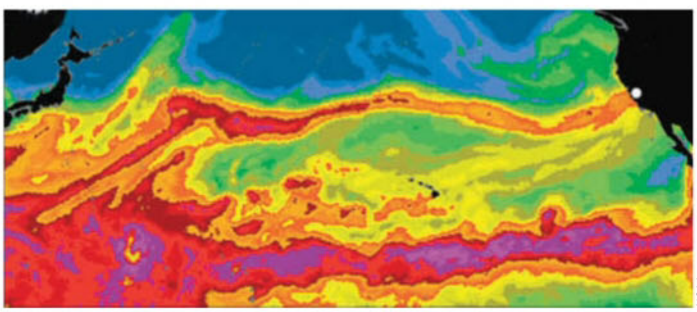
Dettinger has used the same sort of general climate model that first exposed atmospheric rivers to evaluate which effect will be stronger in the western US. It suggests that atmospheric rivers will in fact form as often or perhaps slightly more frequently than today – but they will be moister. The peak season for atmospheric rivers might also lengthen. Because the air will be warmer, the snow line will be higher, and some precipitation that would today fall as snow in the Sierra Nevada will fall as rain instead, increasing the immediate flood risk downstream in places like Sacramento.

Harsh experience suggests we should take note. The 1861-2 California flood killed thousands of people in an era when the state was much less densely populated than today, and it was by no means unique. Sediment deposits in the Sacramento river valley, near Santa Barbara on the Pacific coast and around San Francisco Bay provide evidence of comparable floods occurring in California roughly every 200 years.

Our ability to respond to a coming storm is currently limited. To react appropriately, we need to know how much rain will fall and in what river basins. But to create maps of water-vapour distribution and wind speed from microwave images, you need the background signal to be uniform – otherwise it is difficult to isolate which fluctuations are caused by atmospheric effects. While this is true over the wide expanses of the ocean, the varied nature of land cover currently makes reliable microwave sounding over land impossible.

Now NOAA, together with the California

This atmospheric river (upper red band) carried 38 centimetres of rain to California in 24 hours in October 2009



RUSTY RUSSELL/GETTY

A flood less ordinary: was Tennessee's inundation in 2010 a freak event?

TENNESSEE BLUES

On 1 and 2 May 2010, the city of Nashville, Tennessee, experienced its rainiest and third-rainiest days since weather records began there. This storm of storms dumped more than 30 centimetres of rain on the city itself, causing the Cumberland river to overflow into the streets. Almost 50 centimetres fell in some outlying areas. The cost of the damage totalled $2 billion, with 11 deaths in Nashville.

According to work done by Benjamin Moore of the US National Oceanic and Atmospheric Administration, this event was caused by an atmospheric river (see main story). The combination of a strong "Bermuda high" in the Atlantic Ocean and a low-pressure trough along the east coast of Mexico funnelled a jet of moist air from the Caribbean Sea. On hitting the south-eastern US, uplift was provided not by coastal mountains, but by a squall line of thunderstorms parked inland over Tennessee and Kentucky. The warmer tropical air was forced to rise over the top and release its massive load of water.

It seems to be an atypical atmospheric river: it did not dump its cargo on a hilly west coast, it was not winter, and there was no associated low-pressure cyclone. However, its combination of circumstances may be more common than we realise. Paul Dirmeyer and James Kinter of the Center for Ocean-Land-Atmosphere Studies at George Mason University in Fairfax, Virginia, have even dubbed it the "Maya Express" in homage to California's "Pineapple Express". Similar conditions, according to Moore, may have contributed to large-scale floods in the central US in 1993 and 2008 – and perhaps elsewhere.

Department of Water Resources and the Scripps Institution of Oceanography in La Jolla, is hoping to fill those gaps with four dedicated atmospheric river observatories positioned along the coast of California. The first observatory, at Bodega Bay north of San Francisco, was completed in 2013. Roughly the size of a dump truck, it contains a suite of standard weather instruments plus a "wind profiler" and a reconfigured GPS receiver. The profiler reflects radar off turbulence in the atmosphere to measure wind speeds at various altitudes, while the receiver mathematically inverts errors introduced into GPS signals by atmospheric water vapour to infer the amount of vapour the signal has passed through. "The instrumentation will provide real-time conditions," says California state climatologist Michael Anderson.

Each observatory costs roughly $750,000 – peanuts compared with the cost of flood damage. Lavers would like to see something similar in the UK. "If the observatories take off, that will be a great motivation to push them through here," he says.

But the observatories will give only a few hours' warning – enough to open dam gates or issue flood warnings, but not much more. Dettinger thinks California needs to be doing more offshore reconnaissance to give earlier warning, allowing the organisation of evacuations, for example. "We live off satellite imagery to a ridiculous extent," he says. "We've got the whole of the Pacific Ocean covered by only a couple of weather ships", plus a few permanent weather stations around Hawaii. The US east coast faces a similar problem to track hurricanes that approach from offshore, but in this case satellite images are supplemented by a fleet of "hurricane hunter" aircraft, which measure the intensity of storms and enable detailed predictions of their likely tracks.

"A typical atmospheric river conveys as much moisture as seven to 15 Mississippis – or one Amazon"

A first step towards something similar in the Pacific was taken by NOAA in the winter of 2011. In collaboration with NASA, a retired spy drone was flown into three storms, including one atmospheric river. The project was part research mission and part technology demonstration: NASA was looking for useful things to do with the drones, and wanted to prove that they could deploy dropsondes. Another monitoring campaign, called CalWater, was run in 2015, with observations at sea complemented by data from an array of rain and moisture sensors across the state. The main obstacle to further campaigns is money – and that means convincing the authorities that the technology helps. "We may have some more work to do, clearly demonstrating the impact of the observations on forecasts," says Gary Wick at NOAA.

One thing can be done without financial investment: raising public awareness. We now know the extent to which atmospheric rivers are responsible for the most extreme rainfall and the most severe floods, and are gradually getting a handle on how to spot them. When weather forecasters see a storm coming that is fuelled by an atmospheric river, they should warn the public of the flood danger, or "rattle some cages", as Dettinger puts it. It won't put an end to wet Christmases, but at least it will help Santa decide if he needs to put pontoons on his sleigh. ■

LARRY TOWELL/MAGNUM

SWAMPED

River deltas all over the world are sinking, bringing catastrophic floods ever more often. James Syvitski and Stephanie Higgins study why it's happening.

IN 2005, hurricane Katrina devastated the Mississippi river delta in Louisiana. Eighteen hundred people died and economic losses topped $100 billion. Three years later, tropical cyclone Nargis hit Burma. The storm surge penetrated more than 50 kilometres inland, killing 138,000 people as it ripped across the delta of the Irrawaddy river.

Other deltas have seen flooding that is less dramatic but has still had an enormous impact. In 2011, Thailand's capital city of Bangkok, which lies entirely within the delta of the Chao Phraya river, sat under metres of stagnant water for months, hitting the country's economy and affecting hard-disk prices around the world.

All told, 85 per cent of the world's major river deltas experienced severe flooding in the past decade or so. There is a reason for this: most deltas are sinking, and sinking fast. The immediate cause of the flooding in Bangkok was bad water management, but the problems were exacerbated by subsidence. The land on which the city is built has sunk by more than a metre, causing floodwaters to pool rather than

Hurricane Katrina caused major flooding and killed nearly 2000 people

drain away. So why are deltas sinking, and what can be done?

To understand the problem, we have to start by looking at how deltas form. Rivers carry vast amounts of sediment from the continents to the sea, and when this sediment is deposited faster than it is removed by waves and tides, land forms and vegetation starts to grow. This accumulation causes the river to split into a network of channels. Eventually, a broad, flat wetland forms – a delta. Some grow enormous. The Ganges delta in Bangladesh is three times the size of the Netherlands, and 150 million people farm and fish within its twisting tidal channels.

Rich soils and abundant streams make deltas highly fertile. There is also easy access to the ocean, and the land appears to be stable. All these factors made deltas tempting places for farms and settlements, which is why so many major cities sprang up on them: Shanghai, Bangkok, Rotterdam, Cairo, Buenos Aires, New Orleans and many others. Altogether, more than 500 million people live or work on a delta.

Unfortunately, this stability is an illusion. The peat, sediment and soils that make up deltas are loosely packed and as they become compacted, the surface sinks. If peat dries out, it can rot and subside even more quickly. Different types of sediment compact at different rates, but a good rule of thumb is that a delta will go down by about 3 millimetres every year. Once compacted, it cannot usually expand again.

In order for deltas to remain above sea level, then, they need a continuous supply of sediment. In natural deltas, this is delivered by annual flooding. The lowest-lying land floods first, and sediment deposited by the floodwaters rebuilds the ground. These deposits are thus the lifeblood of the delta; without them, it subsides.

"Shanghai, Bangkok and Jakarta have all sunk more than a metre in the past 50 years"

Before the industrial age, most human activities actually helped deltas grow. Farming, mining and logging increased soil erosion, and rivers carried this extra sediment to the coast, where much of it was deposited. Deltas like the Ebro in Spain grew higher and pushed further out into the sea. The Roman seaport of Amposta is now more than 20 kilometres inland from the river Ebro's mouth.

Destructive floods

Unfortunately, the situation on many deltas has changed dramatically. Levees, pumps and sluice gates now regulate when and how much a developed delta can flood. Canals fix rivers and streams in the same places for decades. Smaller distributary channels are choked off. These control systems block natural flood pulses, holding back the sediment that they would otherwise carry. Some dyke systems have existed for so long that the entire delta now lies below sea level – like that of the Po river in Italy, where streams have been held in the same location and prevented from flooding since the 17th century. The delta must now be continuously pumped to keep the land usable.

The longer a river levee system remains in place, the lower the land it protects from flooding becomes. As the surrounding land sinks, even more stress is placed on the levees. Given this vicious cycle, it is not surprising that even the best-engineered systems are beset by failures. Levees on the San Joaquin river delta in California, for example, breach every two to three years, temporarily salinating two-thirds of the state's drinking water. Small, regular water pulses have been eliminated in exchange for rarer but much more destructive floods.

Far upstream, sediment also gets trapped behind dams and in reservoirs. To study this, researchers at the University of Colorado developed a computer model that includes geological, climatic and human factors, along with sediment measurements from hundreds of rivers. They found that, on average, rivers in developing nations carry twice as much sediment as they would in more pristine settings, a result of increased human-induced erosion. Rivers in industrialised nations, however, now carry less than half of their original load, mainly because of blockage from dams.

Take the Mississippi. Its 40,000 dams ›

and reservoirs trap half of the river's sediment before the flow reaches the delta. The situation is even more extreme on other rivers. Dams trap 99 per cent of the Ebro's sediment, and the Nile, Indus and Yellow rivers similarly carry almost no sediment to the sea today.

Other rivers carry little sediment because their flow now runs dry for much of the year. Massive withdrawals of water for irrigation in the south-western US cause the Colorado river to run dry long before it reaches the ocean. The river's enormous delta, once a paradise of green lagoons, has become a barren wasteland at risk of inundation by the sea.

Rescuing these deltas would require withdrawing less water from rivers and either removing dams or redesigning them so that sediment can pass through. Hundreds of dams have been removed from US rivers in the past decade, but this was done because they were too old or no longer needed, rather than to restore sediment flow.

Similarly, because sedimentation is a major problem for dams the world over, designers and managers have long explored ways of limiting sediment build-up. Modern dams already have sluice gates (which open at the bottom) for allowing sediment through, particularly at times when rivers are carrying more of it. It is clear that the existing measures are not enough, however.

Even where sediment can move downstream, it needs to be deposited on sinking deltas through natural or controlled flooding. Some solutions are already being developed. Biologists are working with farmers to develop flood-tolerant varieties of common crops, so that deltas can be used for agriculture while flooding and sedimentation continue. Spanish geologists working on the Ebro delta are experimenting with adding river sediment directly to flooded fields.

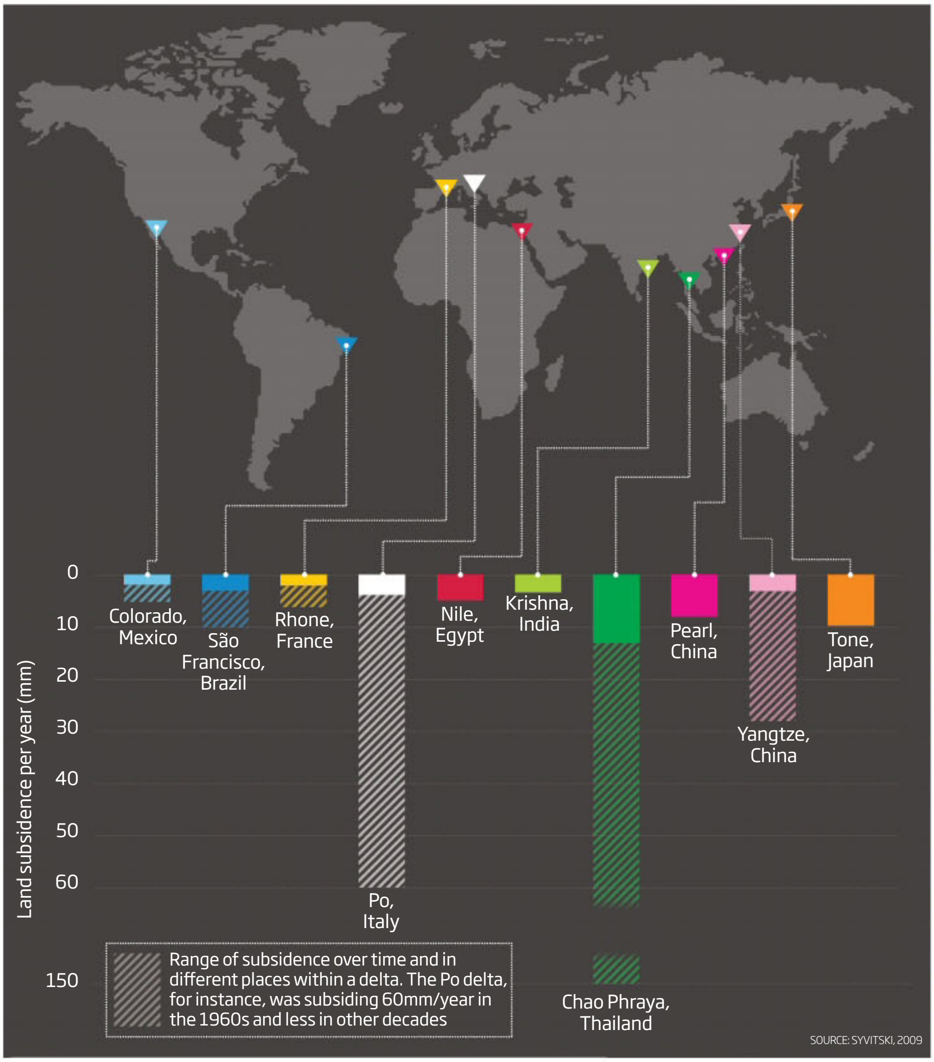
For deltas that are mostly used for farming, these techniques may be enough. Where they are covered with buildings and roads, however, the solution will be more difficult. Shanghai, Guangzhou, Bangkok and Jakarta have all sunk more than a metre in the past 50 years and they continue to subside. It may not be possible to simply add sediment to the ground in these densely populated areas.

In cities, subsidence is often exacerbated by another factor: the extraction of material from beneath the ground. If fluids like oil and groundwater are removed at high rates, the overlying land can sink. This is exactly what happened in Thailand. From the 1950s to the 1980s, water was sucked up at such a rate that buildings in Bangkok began to sag and crack. Stairways fell away from doors, highways warped and houses sank. So much salt water flowed from the ocean into the aquifer that in places the water was no longer drinkable.

The government reacted to the crisis by levying steep taxes on groundwater: 42 cents for every cubic metre used. Adjusted for the different income levels, this tax in the US would result in a $3 charge for a typical morning shower and $6 for a bath. The hefty fees worked – private water usage was halved. Recent measurements by Thailand's Department of Groundwater Resources show that sustainable rates have now been achieved, as shallow aquifers have refilled to 1988 levels. Subsidence appears to have slowed from 10 centimetres per year to just 1 or 2.

Sinking fast

Two-thirds of the world's major river deltas are subsiding. Below are the ones in greatest peril



The cost of extraction

Italy's Po delta has faced similar problems, due to the extraction of methane gas. Effective sea level rise on the delta was 6 cm per year in 1958, but decreased to less than 1 cm after methane removal stopped. Although water can be injected at the time of withdrawal to reduce subsidence, this technique can fail if subsurface layers dissolve.

For example, the THUMS Long Beach Company of California injects water into the Wilmington oil field at a level equivalent to 105 per cent of oil production. This has been

HIROYUKI MATSUMOTO/GETTY

NEWS PICTURES/REX

Deltas face many threats: dams have cut off the supply of fresh sediments, water or fossil-fuel extraction is causing dramatic subsidence in places, and sea level is rising

relatively successful: subsidence at the field has decreased from 38 cm per year to nearly zero since injection began. However, a similar attempt to balance production with injection in Norway did not work, because of the dissolution of underground chalk. Fluid injection has also been shown to produce hundreds of microearthquakes, and over long periods it can cause earthquakes of magnitude 4 or larger.

Groundwater will slowly seep back into collapsed aquifers even without injection, but it does not "reinflate" all the tiny spaces it used to occupy. The only way to fully recover sunken land is to add new material on top. If nothing is done, the land remains sunken, making it vulnerable to flooding. Low-lying land can be walled off and pumped to prevent flooding, but this is very expensive. Everyone tends to agree that we should build sea walls to protect cities, but even fairly "green" countries like the Netherlands argue about whether it is worth paying for sea walls to protect wetlands or nature reserves.

Subsidence as a result of fluid extraction is starting to be seen as a serious issue. Many of the world's deltas are hydrocarbon producers, including those of the Yukon, Lena, Irrawaddy, Po, Rhine, Burdekin, Red, Niger, Magdalena, Mahakam, Mackenzie, Yellow, Sacramento and Mississippi. Fish and shrimp farms, which often pump groundwater, are also booming on deltas. It can be difficult to predict the speed of subsidence. Complicated subsurface geology, variable extraction depths and delayed reactions mean that land does not always sink at the expected rate or even in the expected place. Moreover, there is much we don't know. Very few permanent GPS installations currently exist on river deltas and less than 10 per cent of the world's rivers are monitored for their sediment transport. Instead, we have to use computer models, historical maps and tide gauges to try to understand the causes of subsidence on any given delta. Most recently, it has become possible to make millimetre-scale measurements of ground motion using radars mounted on satellites.

"The coastline of the Chao Phraya delta in Thailand offers a glimpse of what the future holds for many"

In 2009, a group of researchers including one of us, James Syvitski, combined information from published studies, tide gauges and other sources to assess the state of 33 of the world's major river deltas. We found that 24 of them were sinking, some by several centimetres a year. This is why flooding is becoming ever more common. Even a few centimetres of subsidence can increase the risk of flooding from heavy rains or storm surges. Freshwater aquifers grow salty, wetlands are destroyed and low-lying land can turn into open ocean.

Not only is the land sinking, sea levels are also rising as a result of climate change. The observed rate of global sea-level rise is 3 mm per year, due to melting glaciers and ice sheets along with thermal expansion of the oceans as they warm. With global sea level predicted to rise by up to a metre by 2100, there are going to be major problems in coastal zones around the world. Yet in deltas, subsidence is actually a more pressing issue, as many are sinking faster than sea level is rising. For the inhabitants of deltas, though, what matters is effective sea level rise – the combination of higher seas and sinking land.

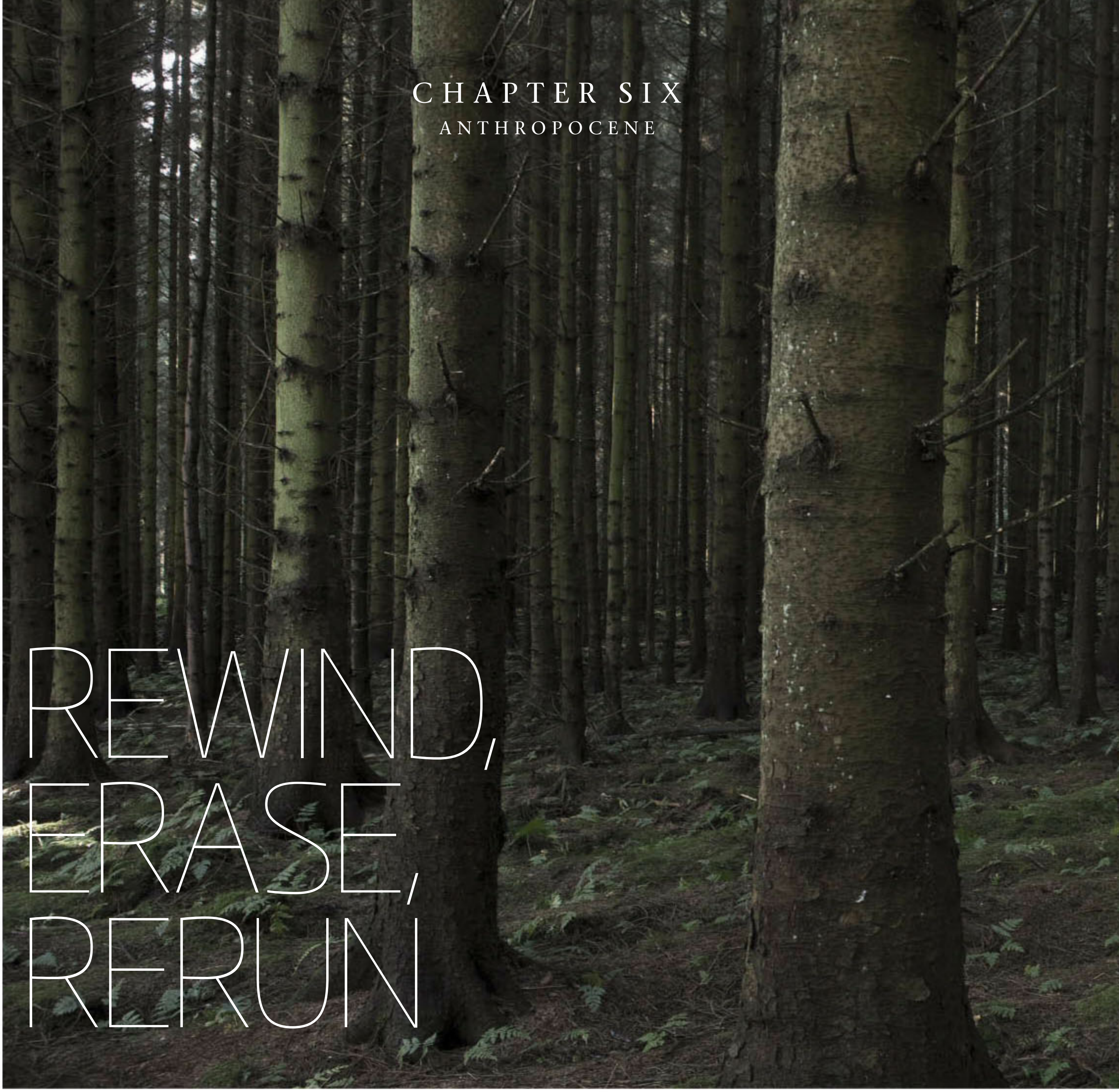
Nor will more dykes and dams help. A study of 48 deltas from around the world found that while those in wealthy countries can currently afford to reduce flood risks using engineering projects, those deltas are likely to see the largest risk increase in the long-term, as spiralling costs of energy hit construction.

The coastline of the Chao Phraya delta in Thailand offers a glimpse of what the future is likely to hold for many people. Here land is already being lost to the sea. In places, telephone poles protrude from the water more than a kilometre from the coast, marking where roads and houses have been lost. The Wat Khun Samut Trawat, a Buddhist temple once surrounded by roads, houses and a school, now stands alone on a tiny island hundreds of metres from the shore. Thick sea walls protect the temple from total inundation, but its floors are buried under mud, and saltwater laps against its lowest windows. Some of the families that lived near the temple a generation ago have moved five times to stay ahead of the waves. They will probably have to move again. ■

CHAPTER SIX

ANTHROPOCENE

REWIND, ERASE, RERUN



What was Earth like before humans, and would it still be like that today if we had never existed? Christopher Kemp investigates

IMAGINE for a moment that the last 125,000 years of Earth's history exist somewhere on a tape – a thick, old-fashioned ribbon loaded between two metal drums. With every second that passes, more tape slowly unspools from one drum and is wound onto the other. Now suppose it's possible to stop the tape, to intercede, and to reverse its direction. Rewind.

Gradually, with each turn of the drum, our existence is removed.

Every minute, an area of natural forest and woodland the size of 10 football fields is restored. At first, for each year that is regained, an area slightly larger than Denmark is reforested. It takes only about 150 years of this to restore most of what has been lost. At the same time, urban sprawl retreats like a concrete tide. Megacities shrink to cities and then dwindle into towns and villages, green swathes of pristine undeveloped land reappearing in their wake. The world's rivers are undammed. The sea floor is cleared of its wrecks and its tangled cables. The ozone layer is restored. The remains of most of the estimated 108 billion people who have ever lived are removed from the ground, and fossil fuels, precious stones and metals, and other mined materials are put back in. Tonnes of pollutants, including carbon and sulphur dioxide, are sucked out of the atmosphere.

ARMANDO FERRARI

Finally, we arrive at a point that seems incredibly distant to us: 125,000 years ago. In geological terms it might as well be yesterday, but the span of time between then and now represents the entirety of modern human existence. By running the tape backwards to this point, we have removed almost all human impact on Earth. What is it like?

A hundred-and-twenty-five thousand years ago, Earth was part way through the Eemian interglacial period – a 15,000-year-long temperate phase bookended by two much longer, colder glacials. Suddenly, it had become a warm and green world. In the northern hemisphere, continental ice sheets had retreated from as far south as Germany in Europe and Illinois in North America.

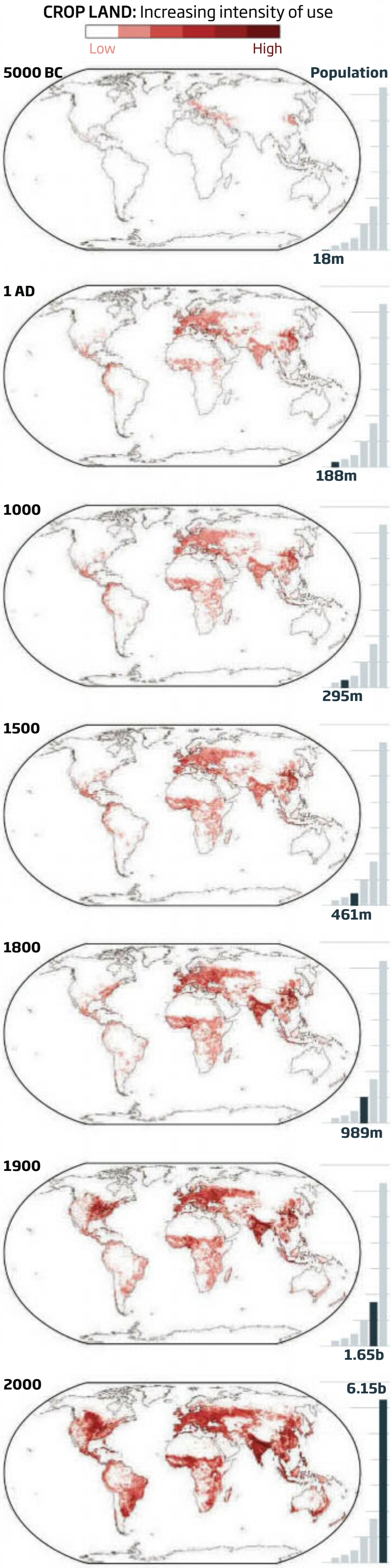
"It got a little bit warmer than at present, and sea levels were maybe a little bit higher at their maximum," says Ian Tattersall, emeritus curator of anthropology at the American Museum of Natural History in New York City.

One of the beneficiaries of this warm and stable climate was *Homo sapiens*. Our species had first appeared around 200,000 years ago in east Africa. By 125,000 years ago the population was probably somewhere between 10,000 and 100,000, surviving by foraging and hunting, and making its first forays out of its ancestral home.

But we were not alone. "There were at least three lineages of hominids around," says Tattersall, an expert in early human evolution. "There was *Homo sapiens* in Africa; there was the lineage of *Homo erectus* in eastern Asia, which later became extinct; and there were the Neanderthals in Europe."

Other human species too, both unknown and partly known to us, were struggling to survive elsewhere. "Who knows what was going on in Africa?" says Tattersall. "There were hominids in Africa that didn't look exactly like a modern *Homo sapiens*."

The world also would have been teeming ›



SOURCE: HISTORY DATABASE OF THE GLOBAL ENVIRONMENT (HYDE)/NETHERLANDS ENVIRONMENTAL ASSESSMENT AGENCY

with large animals – whales in the ocean, giant herds of herbivores on land. "I think if you could just teleport into this world, the thing you'd notice right away would be the megafauna," says environmental historian Jed Kaplan at the University of Lausanne's Institute of Earth Surface Dynamics in Switzerland. "You would find all of these massive herds of big animals roaming around all over the world," he says. "There would be woolly mammoths roaming the Arctic. For sure you would see things like bison. You would have big cats living in Europe, maybe horses in the Americas, certainly many more bears, wolves, and all of these kinds of herd animals."

Stepping outside nature

But then, without warning, everything changed. Or more precisely, humans changed first, and then so did the world. "The shit really didn't hit the fan until humans started behaving in a modern fashion, about 100,000 years ago," Tattersall says. "And it was after this that humans sort of stepped outside nature and found themselves in opposition to it, and started all the shenanigans that we're familiar with today."

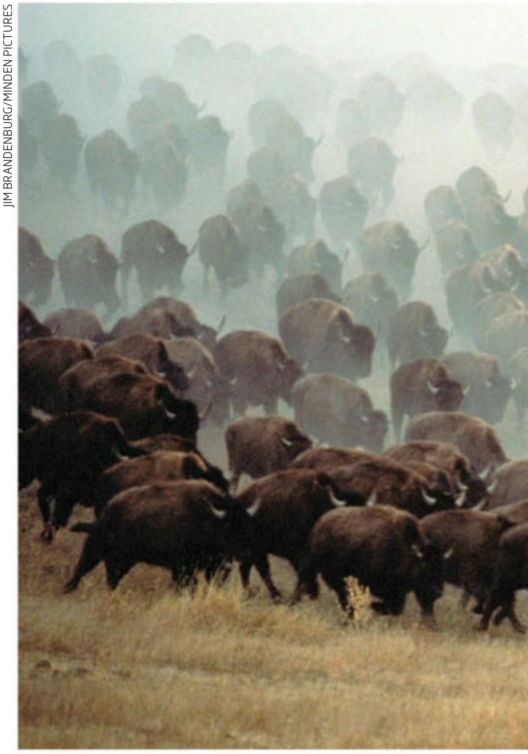
It is sobering to read even an incomplete list of the shenanigans that Tattersall is talking about. As recently as about 2000 BC, world population was counted in the tens of millions. By AD 1700, it was at about 600 million; it is now slightly more than 7 billion and grows by an estimated 220,000 people every day. And that's just the humans. According to the United Nations Food and Agriculture Organisation (FAO), the global cattle population is 1.4 billion, there are roughly a billion pigs and sheep, and 19 billion chickens worldwide at any one time, almost three for every person.

As befits our numbers, we consume energy like never before. In the 20th century alone, energy use grew 16-fold. According to an article published in 2009 in the *International Journal of Oil, Gas and Coal Technology*, since 1870, an estimated 944 billion barrels – or 135 billion tonnes – of oil have been extracted from beneath the Earth's surface. In 2011 alone, the US mined more than a billion tonnes of coal, and China three times as much.

We have also altered the landscape in untold ways. Together, agriculture and the use of fire have tamed and shaped the environment almost everywhere. In many regions, farmed land has replaced the natural vegetation. Between 30 and 50 per cent of the planet's land surface is used in one way or another by humans, and we are tapping more than half of the world's accessible fresh water.

Rice production, in particular, has flattened entire ecosystems. "People produce little dams," says Erle Ellis, an environmental

JIM BRANDENBURG/MINDEN PICTURES



scientist at the University of Maryland. "And that changes the whole sediment movement in a watershed. The goal is to create wetlands everywhere to grow rice. And that has flattened a lot of places. It's impressive."

In the modern world, we are left with few places that look the way they would if humans had not intervened. "There's very few landscapes that are really left, especially in Europe," says Kaplan. "There are hardly any forests where you find big dead trees just laying down on the floor. It's incredibly rare."

Ever since modern humans began to oppose the rest of nature, they moved, dispersing across the world like seeds in the wind, settling in the Near East 125,000 years ago, South Asia 50,000 years ago, Europe 43,000 years ago, Australia 40,000 years ago and the Americas between 30,000 and 15,000 years ago. The final significant, habitable land mass to be settled was New Zealand about 700 years ago.

Everywhere they went, humans took animals with them, some deliberately (dogs, cats, pigs) and others by accident (rats). The introduction of a non-native species

"Between 30 and 50 per cent of the planet's land surface is used in one way or another by humans"

The great plains were once biologically richer than the Serengeti

to a delicately balanced ecosystem can have irreversible effects, says Ellis. Especially rats. "They have a huge effect. Anything that nests on the ground or in any place where a rat can get to it – those species are toast."

We are also efficient killers in our own right, of course. Many species are known to have been hunted or persecuted to oblivion, most famously the dodo (last confirmed sighting in 1662). Also gone: Steller's sea cow (1768); the bluebuck (~1800); the Mauritius blue pigeon (1826); the great auk (1852); the sea mink (~1860); the Falkland Islands wolf (1876); the passenger pigeon (1914) and the Caribbean monk seal (1952). Many more species have disappeared on our watch. The human march across the globe was followed by wave after wave of megafauna extinctions. The causes are still debated, but many point the finger at us. "I really think that humans had a role in tipping a lot of these megafauna populations toward extinction," says Kaplan.

Fifteen thousand years ago, for example, humans were entering North America from Siberia. "There was an unprecedented pulse of extinction," says Bill Ruddiman, a climate scientist at the University of Virginia. "That requires something brand new, and humans were brand new."

"The American west, the plains, had a variety that was far richer than the Serengeti today," says Ruddiman. "It was an amazing place. Aside from mammoths and mastodons, there were sabre-toothed tigers, horses, camels, gigantic ground sloths – all kinds of animals that went extinct in a pretty brief interval. The best data on that suggests it happened about 15,000 years ago."

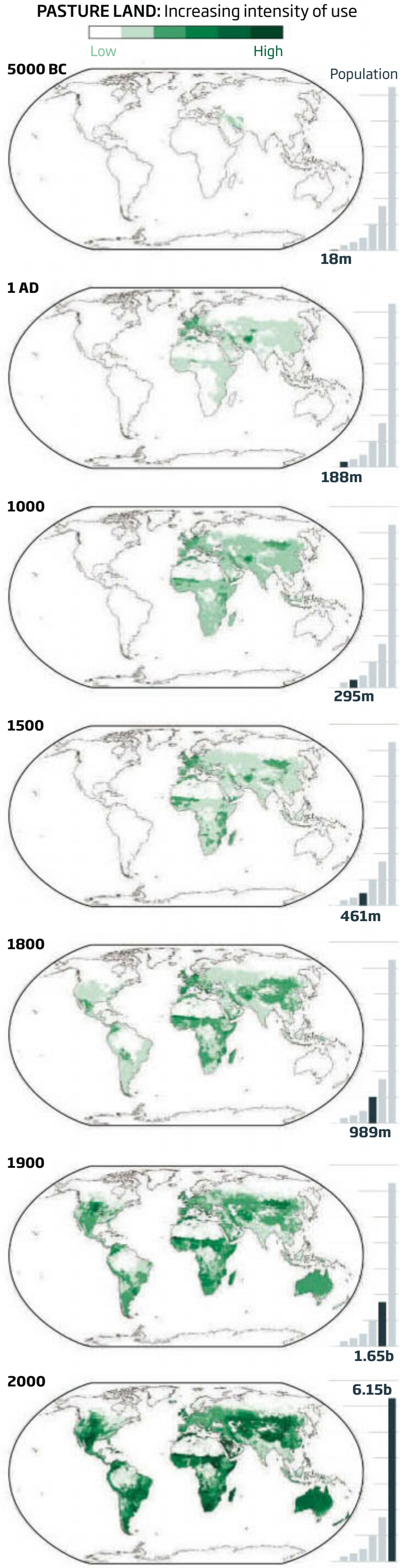
Today, wide open – and mostly empty – the American west looks vastly different from the way it did 125,000 years ago.

The removal of large animal species by humans has had effects on the landscape that are apparent almost everywhere. "A lot of land would be semi-open, kept partly open by these big herds of grazers and browsers and predators," says Kaplan. "It's important to keep in mind that landscape is also shaped by animals. These giant herds of bison would be trampling down little trees and keeping the landscape open, certainly not as much as people who are using fire, but definitely having an effect."

Watery world

We have also emptied the oceans. According to a 2010 report, the UK's fishing fleet works 17 times harder than it did in the 1880s to net the same amount of fish. The FAO estimates that more than half the world's coastal fisheries are overexploited.

Whaling has also changed the oceans beyond recognition. During the 20th century, several species were hunted to the brink of extinction, and populations have still not recovered. A controversial study published in *Science* claimed that pre-whaling populations were dramatically higher than previously thought. By this estimate there were once 1.5 million humpback whales, rather than the 100,000 estimated by the International Whaling Commission. It is a similar story for minke, bowhead and sperm whales.



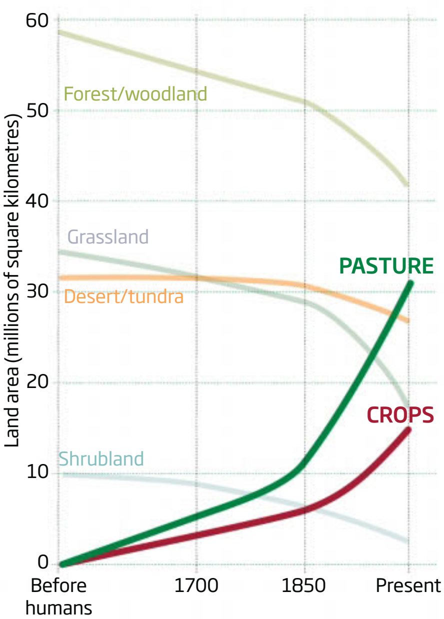
"Imagine that 125,000 years ago, our small band of ancestors in east Africa was wiped out. What next?"

We have also shifted the climate. In May 2013, atmospheric carbon dioxide levels topped 400 parts per million for the first time in millions of years; 125,000 years ago they were 275 parts per million. The increase comes partly from the burning of fossil fuels but also from the stripping of the world's forests, which have acted as an almost bottomless carbon sink for millions of years.

The impact is etched dramatically on Earth's ice. Across the world, glaciers are retreating and in some places have disappeared. The US National Snow and Ice Data Center at the University of Colorado in Boulder maintains an inventory of more than 130,000 glaciers around the world. Some are growing; many more are shrinking. Worldwide, for every glacier that is advancing, at least 10 are retreating. At its creation in 1910, Glacier National Park in Montana had an estimated 150 glaciers. Today there are about 30, all of which have shrunk. In 2009, the Chacaltaya glacier in Bolivia – once the location of the world's highest ski lift – disappeared. The polar ice sheets are breaking apart, calving city-size blocks of ice into the oceans. In November 2013, an iceberg the size of Singapore broke off the Pine Island glacier in Antarctica.

Land grab

Agriculture now occupies more than a third of the 135 million square kilometres of land on Earth



WILLIAM RADCLIFFE/SCIENCE FACTION/CORBIS

20th-century whaling profoundly altered the nature of the ocean ecosystem

By running the tape of time backwards, almost all of these human impacts on Earth are gone. Now, just for fun, let's do something else: let's remove *Homo sapiens*. Imagine that 125,000 years ago, our small band of ancestors in east Africa was wiped out by a catastrophe: a lethal virus, perhaps, or a natural disaster.

Now, let the tape run forward again. What would the world look like today if modern humans had never been here?

In some respects the answer is obvious: it would look a lot like the world of 125,000 years ago. "We would have a continuous biosphere – one that we can scarcely now imagine. That is, forest, savannahs and suchlike, extending across the Earth," says Jan Zalasiewicz, a geologist at the University of Leicester, UK. "No roads. No fields. No towns. Nothing like that." The land would teem with large animals, the seas with whales and fish.

But it wouldn't last, says Ruddiman. If humans had died out 125,000 years ago, we would now be entering another ice age. Glaciers would be growing and advancing. It's a controversial idea and it has earned Ruddiman his critics. But now, more than a decade since he first proposed it, many climate scientists agree with him.

"If you erase the human effect there would be considerably more sea ice and much more extensive tundra around the Arctic circle," he says. "Boreal forest would have retreated and, most dramatically of all, you would have growing ice sheets in a number of northern regions – the northern Rockies, the Canadian archipelago, parts of northern Siberia. It's the very early stages of an ice age. That's the single most dramatic change."

Or maybe not. Perhaps, in our absence, one of the other human species that was present – Neanderthals, *Homo erectus*, or an as-yet unidentified species – rises to prominence and begins to shape the world instead of us.

Tattersall is doubtful. "Having established themselves, would they have followed in our footsteps?" he says. "Would they have become an ersatz *Homo sapiens*, implying that there was some sort of inevitability on our having become what we became? I would guess no."

But there is a delicious counterpoint to this argument.

"There is this idea – convergent evolution – that if we didn't come along and do all this, somebody else would," says David Grinspoon, at the Planetary Science Institute in Washington DC. "There still would have been selective pressure for some other species to go through the same kind of development that we did, where there's this feedback between big brains, and language, and symbolic thought, and developing agriculture. If the scenario is literally that just *Homo sapiens* goes extinct but it's still the same general landscape, maybe something similar would have happened. It wouldn't have been identical because there's so much randomness, and it might have taken longer."

In short, perhaps it all would have happened anyway. Maybe this modern version of Earth, and our place in it, was unavoidable. Remove *Homo sapiens* from the equation, reforest the world and repopulate it with megafauna, and maybe in 100,000 years or so our greatest works, our advancements and our errors – or at least something like them – would still be the outcome.

"I wish I had a crystal ball, or an alternate-universe viewer," says Grinspoon. "It would be great to know." ■

DAWN of the PLASTICENE

Pleistocene, Holocene... what's next? Our love for plastics is leaving a lasting legacy, says Christina Reed

ONE million years from now, geologists exploring our planet's concrete-coated crust will uncover strange signs of civilisations past. "Look at this," one will exclaim, cracking open a rock to reveal a thin black disc covered in tiny ridges. "It's a fossil from the Plasticene."

Our addiction to plastics, combined with a reticence to recycle, means the stuff is already leaving its mark on our planet's geology. Of the 300 million tonnes of plastics produced annually, about a third is chucked away soon after use. Much is buried in landfill, where it will probably remain, but a huge amount ends up in the oceans. "All the plastics that have ever been made are already enough to wrap the whole world in plastic film," palaeobiologist Jan Zalasiewicz of the University of Leicester, UK, told a conference in Berlin, Germany in 2014. It sounds enough to asphyxiate the planet.

What will become of this debris? Landfill will stay buried until future generations rediscover it, but it's a different story for plastic that reaches the ocean. Some is washed up on beaches or eaten by wildlife. Most remains in the sea, where it breaks down into small fragments. However, our knowledge of its ultimate fate is hazy. We don't really know how much plastic pollution is choking the seas. Nor do we understand its potential impact on the health of sea creatures and those who eat them. Nor do we have any idea where the stuff will end up in the distant future – will plastic debris break down entirely or will it leave a permanent mark?

The scale of our plastic problem became clear in 1997, when US oceanographer Charles Moore came across a huge area of floating trash – now dubbed the "Great Pacific Garbage Patch" – as he sailed across the Pacific Ocean from Hawaii to California. It was soon found that other oceans contained similar concentrations of rubbish.

These patches are created by surface currents, or gyres, which meander from coast to coast in circular loops on either side of the equator – clockwise in the northern hemisphere and anticlockwise in the southern hemisphere. And just as noodles gather in the centre of a bowl of stirred soup, anything caught in these currents is likely to drift into the middle. The five biggest concentrations of marine debris are in the Indian Ocean, the North and South Pacific and North and South Atlantic (see map, page 117). In 2014 Moore reported finding one spot in the Pacific gyre where there was so much accumulated rubbish you could walk on it.

Most of the debris is plastic. "On a global basis, about 70 per cent of all the litter in the sea is plastic," says marine biologist Richard Thompson of Plymouth University, UK.

How much is that? To find out, an international team headed by Marcus Eriksen at the Five Gyres Institute in Santa Monica, California, gathered data on the amount of plastic caught in nets towed behind research ships on 24 expeditions over a period of six years. This was added to records from spotters who stood on the decks of these ships and counted every piece of plastic they observed. The team estimates that 5.25 trillion pieces of plastic, weighing more than 260,000 tonnes, are currently floating at sea. Most is big stuff like buckets, bottles, bags, disposable

Los Angeles rivers dump around 30 tonnes of plastic into the Pacific every day

"FOR SOME MICROBES, WASTE PLASTIC IS THE EQUIVALENT OF A HOTEL BUFFET TABLE"

In 2013 China produced 24.8 per cent of the world's plastics. Europe produced 20 per cent

packaging and polystyrene foam. The highest concentrations found were on the order of 10 kilograms of plastic – equivalent to about 800 water bottles – per square kilometre. Given the huge size of the oceans, this represents an incredible amount of trash.

What is most surprising, however, is that Eriksen and his team didn't find more plastic. According to PlasticsEurope, a plastics industry trade association, production increased from 1.5 million tonnes annually in the 1950s to 299 million tonnes in 2013. Given that it's often cheaper for manufacturers to produce virgin material than to buy and use recycled plastic, much of this material is thrown away after use. For example, in 2012, only 9 per cent of the 32 million tonnes of plastic waste generated in the US was recycled.

Eriksen's study found less than 0.1 per cent of the plastic produced each year. This is close to the result of a 1975 survey by the US National Academy of Sciences, which estimated that 0.1 per cent of global plastic production makes its way into the ocean annually – equivalent to about 300,000 tonnes this year.

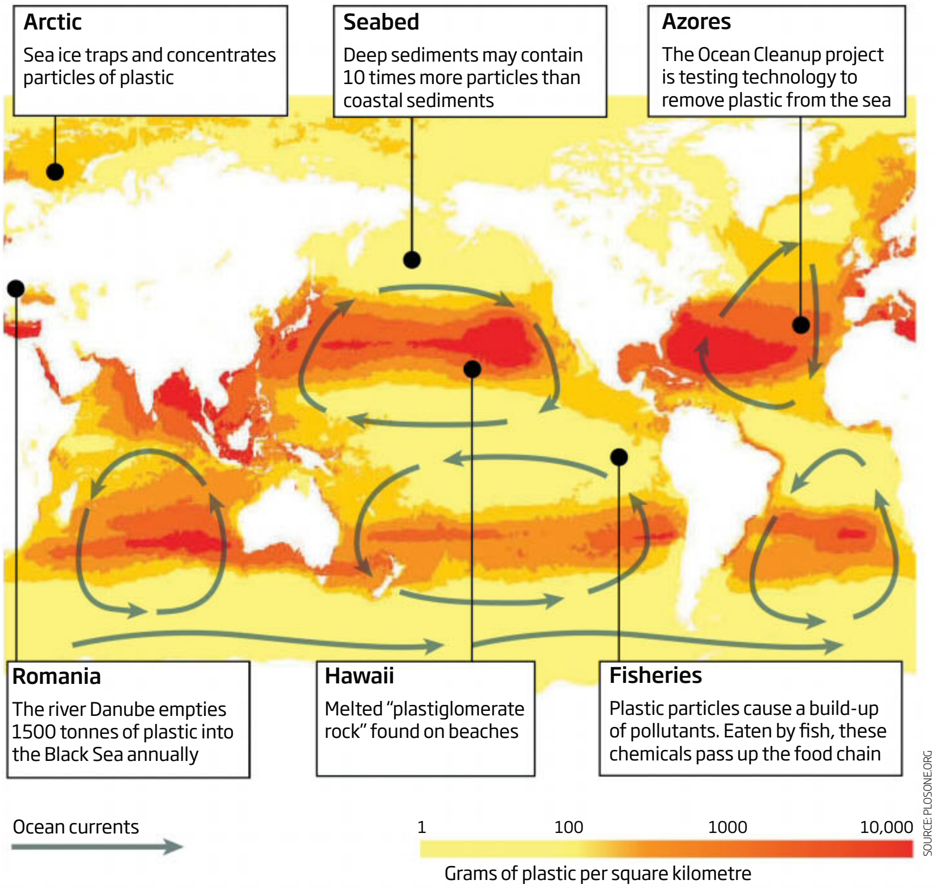
More surprisingly, the amount of plastic in the gyres doesn't seem to be changing. A team led by oceanographer Kara Lavender Law of the Sea Education Association in Woods Hole, Massachusetts, combed through decades of data recording plastic collected during research voyages in the North Atlantic and the Caribbean Sea, and found that the amount was fairly constant. "Despite a strong increase in discarded plastic, no trend was observed in plastic marine debris in the 22-year data set," they reported. "Where is all the plastic?" asks Law.

The answer could be that plastic breaks down more quickly than we thought, as the action of sunlight and waves degrades it into small fragments. The missing plastic may exist as a soup of tiny pieces suspended in the water column.

In July 2014, Andrés Cózar of the University of Cadiz in Spain, working with a team of international marine scientists, calculated the total amount of plastic fragments floating in the seas at between 7000 and 35,000 tonnes. Eriksen's team reckons there are 35,500 tonnes of plastic particles measuring less than 5 millimetres across. But both figures seem low – a million tonnes of these tiny pieces should have been found in the water.

Global garbage dump

Much of the ocean's plastic waste is found near heavily populated coastlines, but farther out, it is concentrated in five "gyres" in the Atlantic, Pacific and Indian oceans. Where most of it ends up is unclear



Through the net

There are a few possible explanations. Plastic particles less than a third of a millimetre across will slip through the trawl nets because the mesh size is too large, so a huge amount of plastic could have been overlooked.

Thompson believes that some plastic might also be locked up in ice. In June 2014, his team reported finding up to 234 particles of plastic per cubic metre of Arctic sea ice – several orders of magnitude higher than in the heavily contaminated waters of the gyres.

He suggests that as seawater turns to freshwater ice, it traps and concentrates small particles. Given that there are about 6 million square kilometres of sea ice, this could represent a huge reservoir of plastic. If the ice melts, this material will be released back into the sea.

More recently, Thompson's team has discovered another place where plastic is accumulating. In December 2014, the group published data showing that tiny pieces

E.ZETTLER, SEA EDUCATION ASSOCIATION

Buoyed up: floating plastic offers shelter to sea life and can create oases in the ocean

of plastic and other polymers, mostly in the form of fibres, are up to 10,000 times more abundant in deep-sea sediments in the Atlantic Ocean, Mediterranean Sea and Indian Ocean than in surface waters. Samples contained up to 800,000 particles per cubic metre. The number of samples – just 12 sediment cores taken from seven expeditions, and four coral samples – was small, but they found plastic debris everywhere they looked.

Could deep-sea sediments hold the key to the missing plastic? It seems likely, given that there are about 300 million square kilometres of seabed.

Some plastic particles are heavier than water and will sink, while others will become colonised by creatures such as phytoplankton, or clump together with other particles and drift downwards towards the seabed like falling snow. This process could be aided by ocean currents, Thompson says.

Confirming this model won't be easy. We don't know the density of minute particles of plastic in the sea, says Law, because we don't have a good way to measure anything there that is smaller than about 0.5 millimetres. But marine geochemist Tracy Mincer of the Woods Hole Oceanographic Institution has a solution. His group is using a special laser scanning microscope to investigate seawater. "We have just begun this work and are seeing plastics in the 2-20 micrometre range," he says.

There are similar gaps in our knowledge when it comes to understanding what impact this stuff is having on marine creatures. We know larger creatures like birds, turtles, fish and whales confuse plastic trash with food, and then choke to death or die of starvation as their stomachs become clogged. But the effect on smaller sea dwellers is far more complex.

For some microbes, plastic is the equivalent of a hotel buffet table. Any hard surface in the ocean becomes a collection plate for nutrients, says Mincer. This is why structures like oil rigs or sunken ships become oases of life.

Other species, too, are taking advantage of the floating debris. Across the Great Pacific Garbage Patch, the insect species *Halobates sericeus*, a type of water strider, deposits its eggs on the floating plastic. As plastic debris has increased in the Pacific, so too has these insects' reliance on it.

The river **Danube** releases **4.2** tonnes of plastic per day into the **Black Sea** or **1533** tonnes per year, which is **more than** the estimated total amount of plastic in the **North Atlantic gyre**

Eating **shellfish** can expose you to **11,000** pieces of **microplastic** every year

H. sericeus isn't alone. Erik Zettler of the Sea Education Association, working with Mincer and Linda Amaral-Zettler of the Marine Biological Laboratory in Woods Hole, discovered that the plastics are even providing an entirely new ecosystem – one Amaral-Zettler dubs the "plastisphere". Like the rhizosphere of microbes colonising roots, there is an entire "cast of characters that colonise plastic", says Mincer. The ones that are attracting most of his attention are bacterial strains called *Vibrio*. "These are very good at colonising surfaces and can be pathogenic as well," he says. There have been cases of people getting a hook caught in the hand while fishing at sea and coming down with *Vibrio* infections that are difficult to treat, he says.

Pathogenic *Vibrio* colonise the intestines of fish, empty the tissues of nutrients and salts, and break down blood cells to collect iron. Once excreted, they can attach themselves to a piece of plastic, regroup and wait to attack the next fish that mistakes their home for plankton.

Viruses might also find plastic useful. "We can't say confidently 'that is a virus', but we do see viral signals in the metagenomic data sets from plastic," says Mincer. It's not surprising, he says: there are far higher concentrations of viruses in the water column than there are microbial cells. "The more I look at genomic sequences, the more I tell my team to wash their hands and be careful," he says.

There are other reasons to worry about plastics. There is evidence that plastic microparticles are entering the food chain. *Vibrio*, for example, are bioluminescent, and can create a spectacular blue-green glow in the water. "During midnight tows in the summer, you frequently see the plastic glowing in the dark," says Mincer. The fact that plastic particles loaded with harmful

60 days: the **time** it takes for plastic to float from the **US east coast** to the **centre** of the **North Atlantic gyre**

ERWAN GLEMAREC/SOLENT NEWS/REX FEATURES

Round the bend: a new home is welcome, but waste plastic in the food chain is serious news

bacteria mimic food using bioluminescence "is diabolical in its own way", he says.

Microplastics aren't good news for fish. The particles can reduce the efficiency of food absorption, and as they break down, release additives such as phthalates and bisphenol A, which can mimic hormones, as well as toxic flame retardants. Plastics also act like sponges for chemicals in seawater, absorbing organic pollutants such as polychlorinated biphenyls, and pesticides such as DDT. Studies suggest that pollutants stuck to plastics can poison fish.

We might feel these effects too. According to environmental toxicologist Lisbeth Van Cauwenberghe of Ghent University in Belgium, eating shellfish can expose you to 11,000 pieces of microplastic each year. Her tests showed that commercially grown mussels contained an average of 0.36 microplastic particles per gram of tissue. Oysters contained slightly more. You would have to eat a lot of this seafood, says Van Cauwenberghe, "but marine microplastics could pose a threat to food safety".

So what will happen to all our discarded plastic in the long-term? Rocks on Kamilo beach, a remote spot in Hawaii, may hold one answer. Here hikers often burn plastic in campfires and the sand is now strewn with "plastiglomerates", a mix of sand and artificial materials, all glued together with melted plastic that has cooled and hardened. Although these have so far only been found in relatively small amounts, it is conceivable that similar "plasticene" deposits might form on beaches where lava flows run, or where forest fires and extreme temperatures occur, says geologist Patricia Corcoran at the University of Western Ontario in Canada. Corcoran and her colleagues have collected hundreds of fragments of this new "rock" and suggest it could eventually become embedded in the geological record.

Zalasiewicz agrees: "We are creating novel materials, which are very widespread in the environment. How do we know these will preserve?" Zalasiewicz works on fossilised plankton that leave a very small and delicate shell of organic polymers. "We know how they change when they enter the rock strata," he says: they lose hydrogen, nitrogen and oxygen, leaving carbon films, or become coated with iron sulphides or carbonates that leave fossil impressions in the strata. Similarly, as temperatures rise over time, pieces of buried plastic will begin to darken as the polymers break down, eventually releasing tiny amounts of oil and gas, and leaving a residue of brittle carbon. "On that basis, I see no problem in plastic drink bottles or CDs being preserved as fossils in the future – not exactly as they are, but as recognisable remnants," he says.

"What I would really like to see would be the preservation of vinyl long-playing records – good enough to preserve details of the grooves," says Zalasiewicz. And why not? Fossil worms preserved in 500-million-year-old Burgess Shale rocks show signs of fine grooves that would have created colours by refraction. These grooves are separated by less than a micrometre. Given that the grooves on LPs are around 20 times wider, there is a chance they, too, could survive, given the right conditions.

"That would mean fossilisation of the patterns of sounds," says Zalasiewicz – music locked up in the geological record. So plastic could leave more than one type of rock for future generations to discover. ■

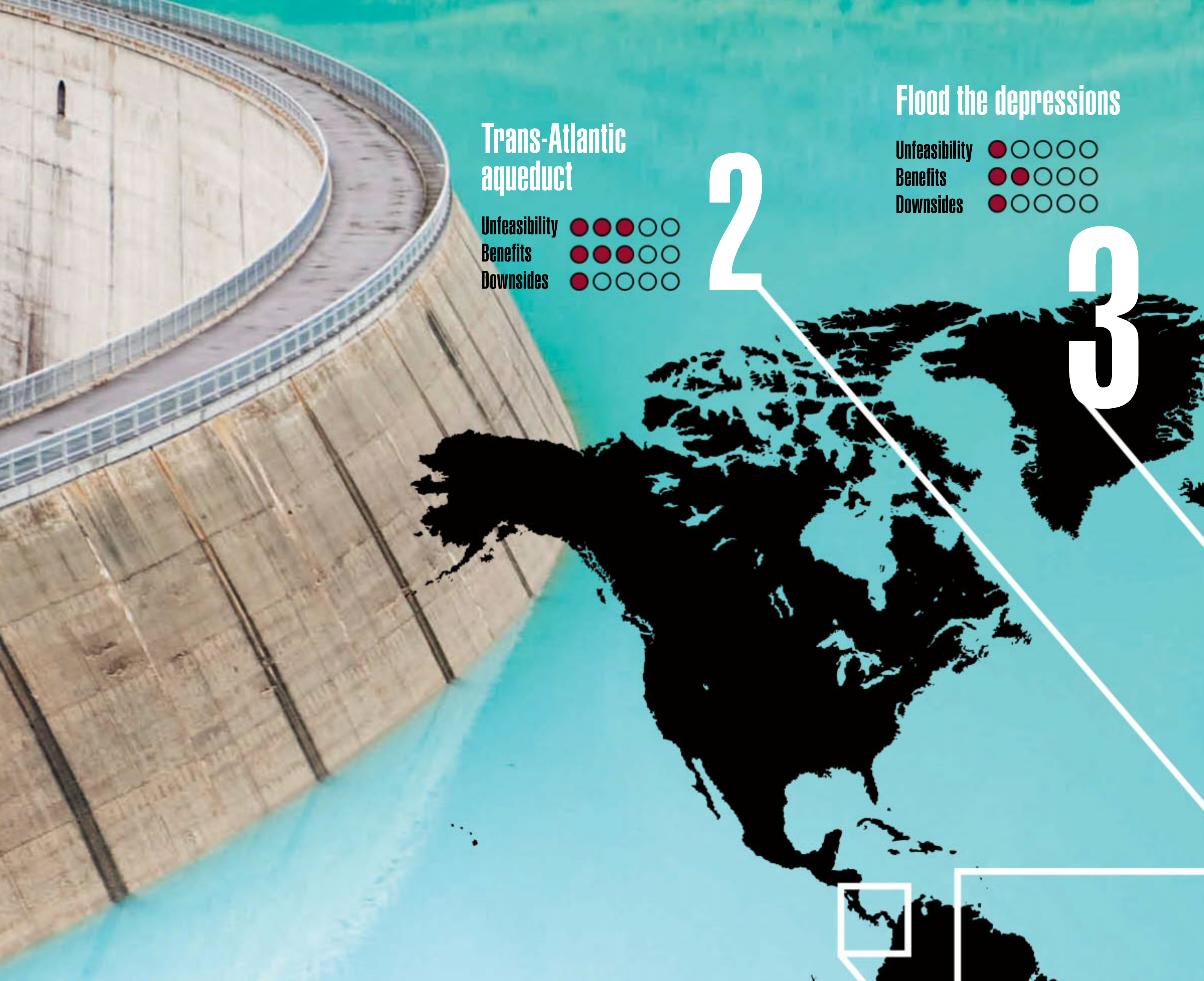
80 per cent of **marine litter** comes from **land**

STEMMING THE FLOW

Huge amounts of plastic enter the oceans via rivers. Major components of this waste are fibres from synthetic clothes released during washing. It also contains microbeads, which are tiny plastic spheres used in many cosmetics. Water treatment plants can't filter them out, so they all end up in rivers.

In 2014, the state of Illinois passed the world's first ban on microbeads, after studies showed that the tiny plastic particles are a common pollutant floating on the surface of the Great Lakes. US senator Kirsten Gillibrand is pushing for legislation that will ban microbeads in all US cosmetics. Some manufacturers have already acted: Unilever, Colgate-Palmolive, Procter & Gamble and Johnson & Johnson have all committed to eliminating these beads from their products.

Meanwhile, some groups are hoping to harvest plastic from the gyres. In 2014, an organisation called The Ocean Cleanup completed a trial of a floating boom system in the Atlantic near the Azores. Based on the results, the group estimates that floating debris in a single gyre could be cleared in five to 10 years without harming wildlife. The organisation is now raising funds for a pilot project that could begin in 2018.



We've joined oceans and tunnelled under the sea. But some engineers have much grander plans, as ***Michael Marshall*** *reports*

WORLD CHANGING

THEY said it would never happen. Yet preparations are under way for a massive new canal to link the Atlantic and Pacific oceans. Building the 278-kilometre-long canal through Nicaragua will require moving billions of tonnes of earth and cost at least $50 billion. If it is eventually completed, it will be wider, deeper and three times as long as the Panama Canal. Its backers claim it will be the biggest engineering project in history. But it is certainly not the biggest ever suggested. "All of us live in places that are engineered and designed," says mega-engineering expert Stanley Brunn of the University of Kentucky in Lexington. So it's natural to dream even bigger, he says.

That may be true. But some of the schemes sound like the plans of Bond villains, such as flooding California's Death Valley or nuking the isthmus of Panama. Others, like damming entire seas to generate hydroelectricity, are on a mind-boggling scale. Here are seven of the world's biggest schemes. Could we really go ahead with any of them? And should we?

ANGELIKA JAKOB/LUZ/EYEVINE


5
Dam the Indian Ocean
Unfeasibility ●●●○○
Benefits ●●○○○
Downsides ●●●●●
Join Asia and North America
4
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Relink the Pacific and Atlantic oceans
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Creating land
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Benefits ●●○○○
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1 Damming the Atlantic

It doesn't get much bigger than this. We could build a barrier across the Strait of Gibraltar (below), effectively turning the Atlantic into a huge dam reservoir. This was first proposed in the 1920s by German architect Herman Sörgel. With the flow of water into the Mediterranean reduced, the sea would begin to evaporate. Allowing it to fall by 200 metres would create 600,000 square kilometres of new land.

The environmental impacts of Atlantropa, as this plan is known, would of course be gargantuan. Perhaps most, er, damning of all, lowering the Med by 200 metres would raise sea level in the rest of the world by 1.35 metres. "It's impossible in terms of the politics," says Richard Cathcart, a real-estate adviser in Burbank, California, and a mega-projects enthusiast who has written several articles and books. "Academics are actually afraid to talk about big ideas," Cathcart says.

With sea level set to rise tens of metres over the coming centuries because of global warming, Cathcart thinks the idea of a dam across the Strait of Gibraltar is worth revisiting. Instead of lowering the Med, a dam could maintain it at its current level, saving low-lying farmland from the sea, as well as cities such as Venice and Alexandria. Egypt in particular would benefit. As things stand, rising waters will swamp large parts of the Nile delta and displace millions of people by 2100.

LTCE/GETTY

2 Trans-Atlantic aqueduct

Northern Africa could do with some more fresh water. The nearest potential source is the world's second largest river, the Congo, but it flows through a volatile, dangerous region. So why not tap the world's largest river, the Amazon, instead? All you'd need is a pipe. A very long pipe.

The idea of piping water all the way across the Atlantic has been around since at least 1993, when Heinrich Hemmer put it forward in *Speculations in Science and Technology,* a journal devoted to flights of fancy. He envisaged a pipe 4300 kilometres long, carrying 10,000 cubic metres of water per second, enough to irrigate 315,000 square kilometres.

There the matter rested until 2010, when Viorel Badescu, a physicist at the Polytechnic University of Bucharest in Romania, revisited the idea with Cathcart. They proposed to submerge a pipeline 100 metres below the surface, and anchor it to the seabed at regular intervals. The pipe would have to be at least 30 metres wide, and have up to 20 pumping stations to keep the water flowing. It would start off the coast of Brazil in the plume of fresh water from the Amazon - "water that has been discarded by the continent of South America", as Cathcart puts it. All in all, he estimates that the pipeline would cost about $20 trillion. Residents of the Sahara, start saving now.

"Underground nuclear explosions would do the trick"

It might be wise to start a bit smaller - perhaps by piping fresh water 2000 kilometres from lush Papua New Guinea to Queensland in Australia. In 2010, Australian businessman Fred Ariel announced plans for a feasibility study into a $30 billion pipeline. The Papua New Guinean government approved the idea in principle, but Queensland has said the plan is not under "active consideration".

3 Flood the depressions

In 1905, irrigation engineers in California accidentally flooded a depression that lay below sea level. The result was the Salton Sea, the largest lake in the state. There have been many proposals over the decades for flooding other low-lying areas.

The prime candidate is the Qattara depression in north-west Egypt, which lies as deep as 130 metres below sea level. It consists of 19,000 square kilometres of sand dunes, salt marshes and salt pans. The idea is to flood it with seawater from the Mediterranean, just 50 kilometres to the north. Generating electricity is the main motive: if water flows in at the same rate as it evaporates, generation could continue indefinitely. The "Qattara Sea" would become ever more saline, but surrounding areas might benefit from cooler, wetter weather.

The idea has been around since at least 1912, and the Egyptian government looked into it in the 1960s and 1970s. Few people live in the Qattara, so politically it is doable. The biggest problem is the sheer scale of the construction, which would require tunnels to go under a range of hills between the Mediterranean and the depression. One construction plan involved nuclear bombs. You may not be surprised that Egypt abandoned the idea.

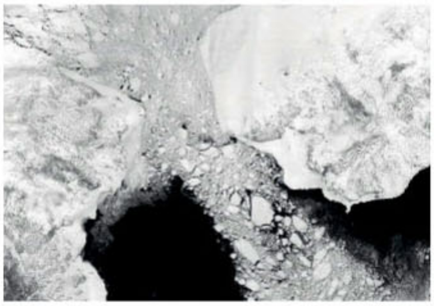
Interest in the idea has revived recently thanks to Desertec – a plan to build a vast solar power plant in North Africa. Magdi Ragheb, a nuclear engineer at the University of Illinois at Urbana-Champaign, has proposed storing energy from Desertec by pumping seawater through a pipeline to storage facilities on top of the hills. When more electricity is needed, this water would be allowed to run down into the depression, turning turbines as it went. There would be no need for tunnels.

Flooding areas like California's Death Valley would also help offset sea level rise caused by climate change. But it is not worth doing for this reason alone: even if we flooded all of the world's major depressions, it would barely make a difference.

The Salton Sea, meanwhile, is not a great advert. It did thrive for decades, but it is now drying out and dying. Most fish can no longer survive in the ever-saltier water, and frequent foul smells and toxic dust are driving human residents away.

Join Asia and North America

4



GEORGE RIGGS, NASA GSFC

The obvious place to link Asia and North America is at the Bering Strait (above), in between Russia's north-east corner and Alaska. At its narrowest point, the strait is just 82 kilometres across, and never more than 50 metres deep.

The idea of a bridge has been around since the 1890s. It would be the longest bridge over water, but not by a silly amount: the current record holder is the Qingdao-Haiwan bridge in China, which spans a 26-kilometre-wide stretch of water. But the Arctic conditions, especially the sea ice, pose a huge challenge. Oil drilling companies like Shell have struggled to even explore in the area.

That may be why Russia is more interested in a tunnel. In 2007, its government announced the TKM-World Link, a railway that would link Siberia to Alaska by way of a tunnel. Eight years later, there is still no sign of the tunnel being dug, and relations between Russia and the US have soured. But perhaps China will take the lead: in 2014 the *Beijing Times* reported that engineers there are hatching plans for a high-speed railway that would run from China to the contiguous US, via Russia, the Bering Strait, Alaska and Canada.

It may not be a recipe for more harmonious relationships, however. Twenty years after the Channel Tunnel physically linked it to the continent, the UK is considering breaking its political union with Europe.

Dam the Indian Ocean

5

Wherever there's a narrow bit of sea, someone has suggested installing concrete across it. The idea is usually to build a dam in a place where the water level on one side will drop because of evaporation. The resulting difference in height could be used to generate electricity.

There have been various proposals over the years but two stand out. In 2005, mega-engineering enthusiast Roelof Schuiling, a retired geochemist at Utrecht University in the Netherlands, suggested damming the Persian, or Arabian, Gulf where it opens into the Indian Ocean. At one point, the Strait of Hormuz, it narrows to just 39 kilometres across.

The idea is not to do this anytime soon, because the strait is an important shipping route for oil tankers. But when this trade declines as the oil runs out, Schuiling says, installing a hydroelectric dam and allowing the level of the Gulf to fall up to 35 metres could generate 2500 megawatts of electricity.

There is an even bigger proposal out there: a dam across the Red Sea just before it joins the Indian Ocean, across the Bab-el-Mandeb Strait between Yemen and Djibouti (below). That would require a dam wall 100 kilometres long, from the south-west tip of Yemen to either Djibouti or its northern neighbour Eritrea. Even Cathcart calls this "a little more wild". In 2007, he, Schuiling and their colleagues estimated it could generate around 50,000 megawatts of electricity.

These projects would lower local sea level and create more land. However, as with Atlantropa, they would cause sea level to rise even faster elsewhere. What's more, without any exchange with the Indian Ocean the water in the seas would become steadily saltier, eventually destroying their entire ecosystems.

EOSNAP/CHELYS

6

Creating land

Building artificial islands or peninsulas has become routine, with some astounding ones being made in Dubai, for example. But existing methods require deep quarries and deep pockets. Schuiling thinks there is a cheaper way to create land. He has shown that injecting sulphuric acid into limestone turns it into gypsum, causing it to swell to up to twice its original size. So where there is limestone close to the surface of the sea, new land could be created.

One such place is Adam's bridge, a narrow and shallow strip of shoals stretching for 35 kilometres between India and Sri Lanka. Schuiling thinks a land bridge could be created using his method for far less than the cost of a conventional bridge.

Relink the Pacific and Atlantic oceans

7

Destroying the Isthmus of Panama, the slender strip of land that joins North and South America, would reunite the Pacific and Atlantic oceans. Underground nuclear explosions would do the trick. With the land gone, the ocean current that once flowed around the equator would restart and, allegedly, stabilise the climate.

This idea is unlikely to be popular in Panama. What's more, some climate scientists think the closure of the gap 3 million years ago forced warm water in the tropical Atlantic to flow north, increasing humidity and snowfall in the Arctic and leading to the formation of the great northern ice sheets. If so, nuking the isthmus would hasten the loss of the Greenland ice sheet. ■

Earth: The comeback

If our civilisation collapsed in an orgy of runaway warming, could the planet recover? **Bob Holmes** finds out

WHEN Nobel prize-winning atmospheric chemist Paul Crutzen coined the word Anthropocene around 15 years ago, he gave birth to a powerful idea: that human activity is now affecting the Earth so profoundly that we are entering a new geological epoch.

The Anthropocene has yet to be officially accepted as a geological time period, but if it is, it may turn out to be the shortest – and the last. It is not hard to imagine the epoch ending just a few hundred years after it started, in an orgy of global warming and overconsumption.

Let's suppose that happens. Humanity's ever-expanding footprint on the natural world leads, in two or three hundred years, to ecological collapse and a mass extinction. Without fossil fuels to support agriculture, humanity would be in trouble. "A lot of things have to die, and a lot of those things are going to be people," says Tony Barnosky, a palaeontologist at the University of California, Berkeley. In this most pessimistic of scenarios, society would collapse, leaving just a few hundred thousand eking out a meagre existence in a new Stone Age.

Whether our species would survive is hard to predict, but what of the fate of Earth itself? It is often said that when we talk about "saving the planet" we are really talking about saving ourselves: the planet will be just fine without us. But would it? Or would an end-Anthropocene cataclysm damage it so badly that it becomes a sterile wasteland?

The only way to know is to look back into our planet's past. Neither abrupt global warming nor mass extinction are unique to the present day. Earth has been here before. So what can we expect this time?

Take greenhouse warming. Climatologists' biggest worry is the possibility that global warming could push the Earth past two tipping points that would make things dramatically worse. The first would be the thawing of carbon-rich peat locked in permafrost. As the Arctic warms, the peat could decompose and release trillions of tonnes of carbon into the atmosphere – perhaps exceeding the 3 trillion tonnes that humans could conceivably emit from fossil fuels. The second is the release of methane stored as hydrate in cold, deep ocean sediments. As the oceans warm and the methane – itself a potent greenhouse gas – enters the atmosphere, it contributes to still more warming and thus accelerates the breakdown of hydrates in a vicious circle.

"If we were to blow all the fossil fuels into the atmosphere, temperatures would go up to the point where both of these reservoirs of carbon would be released," says oceanographer David Archer of the University of Chicago. No one knows how catastrophic the resulting warming might be.

That's why climatologists are looking with increasing interest at a time 55 million years ago called the Palaeocene-Eocene thermal maximum, when temperatures rose by up to 9 °C in a few thousand years – roughly equivalent to the direst forecasts for present-day warming. "It's the most recent time when there was a really rapid warming," says Peter Wilf, a palaeobotanist at Pennsylvania State University in University Park. "And because it was fairly recent, there are a lot of rocks still around that record the event."

By measuring ocean sediments deposited ›

Would the post-human Earth resemble these mud pools in Iceland?

ANDY TAYLOR SMITH/CORBIS

"Recoveries from mass extinctions are geologically rapid, but from a human point of view grindingly long. We're talking about millions of years"

during the thermal maximum, geochemist James Zachos of the University of California, Santa Cruz, has found that the warming coincided with a huge spike in atmospheric CO_2. Between 5 and 9 trillion tonnes of carbon entered the atmosphere in no more than 20,000 years. Where could such a huge amount have come from?

Volcanic activity cannot account for the carbon spike, Zachos says. Instead, he blames peat decomposition, which would have happened not from melting permafrost – it was too warm for permafrost – but through climatic drying. The fossil record of plants from this time testifies to just such a drying episode.

Carbon spike

If Zachos and colleagues are right, then 55 million years ago Earth passed through a carbon crisis very much like the one feared today: a sudden spike in CO_2, followed by a runaway release of yet more greenhouse gases. What happened next may give us a glimpse of what to expect if our current crisis hits full force.

Geochemists have long known that when a pulse of CO_2 enters the air, much of it quickly dissolves in the upper layer of the ocean before gradually dispersing through deeper waters. Within a few centuries, an equilibrium is reached, with about 85 per cent of the CO_2 dissolved in the oceans and 15 per cent in the atmosphere. This CO_2 persists for tens or hundreds of thousands of years – what Archer believes will be the "long tail" of the Anthropocene. Until recently, though, climate modellers were a bit fuzzy on what this tail would look like.

"Until we had some case studies from the past, there was always some degree of uncertainty in the models," says Zachos. His studies are beginning to clear up these doubts. Carbonate rocks laid down on the sea floor during the carbon spike, for example, reveal that the oceans quickly became very acidic. But this extreme acidification lasted just 10,000 or 20,000 years, barely a blink of an eye by geological standards, after which the oceans returned to near-normal conditions for the next 150,000 years.

Even the stores of peat and methane hydrates must have regenerated within 2 million years, Zachos says, because at that time the planet underwent another, smaller carbon crisis, which must also have involved peat or methane hydrates. This suggests that the long tail of the Anthropocene is unlikely to last longer than 2 million years – still not long at all by geological standards.

However, today's carbon spike differs from that of the late Palaeocene in one important way: our planet is much cooler than it was back then, so warming is likely to have a more profound effect. During the late Palaeocene, the world was warm and largely ice-free. Now we have bright, shiny ice caps that reflect sunlight back into space. These will melt, giving way to dark, energy-absorbing rock and soil. And with all that meltwater, sea levels will rise and permafrost will thaw more rapidly, boosting warming still further.

This extra nudge could conceivably tip Earth out of its present cycle of glacials and interglacials and return it to an older, warmer state. "The Earth was ice-free for many millions of years. The current ice ages started only about 35 million years ago, so we might kick ourselves out of that," says Pieter Tans, an atmospheric scientist at the US National Oceanic and Atmospheric Administration in Boulder, Colorado.

Even so, the newly ice-free world would merely be reverting to a familiar state. On this reading of the evidence, even the most drastic climate catastrophe would have little chance of pushing Earth's physical systems into uncharted territory.

Not so, says James Hansen, formerly director of NASA's Goddard Institute for Space Studies, now at Columbia University in New York. He argues that past episodes are a poor guide to what will happen in the future, for the simple reason that the sun is brighter now than it was then. Add that to the mix and the release of methane hydrates could lead to catastrophic, unstoppable global warming – a so-called "Venus syndrome" that causes the oceans to boil away and dooms Earth to the fate of its broiling neighbour.

So much for Earth itself – what of life? If Hansen is right, Earth is heading for sterility. But if the lesser scenario plays out instead, it's a very different story.

Conservation biologists say we may already be in the midst of an extinction event that could potentially turn into one of the greatest mass extinctions ever – one that would alter the trajectory of evolution.

Oddly enough, the climatic turmoil of the thermal maximum led to very little loss of biodiversity. "Nobody has ever picked the Palaeocene-Eocene boundary as a major extinction interval. It's not even in the second tier," says Scott Wing, a palaeobotanist at the Smithsonian Institution in Washington DC. Instead, the fossil record shows that species simply migrated, following their preferred climate across the globe.

Today, of course, that is often not possible because roads, cities and fields have fragmented so many natural habitats. Polar and alpine species may find their habitat vanishes entirely, and this is not to mention all the other ways people imperil species.

"We're a perfect storm as far as biodiversity is concerned," says David Jablonski, a palaeontologist at the University of Chicago. "We're not just overhunting and overfishing. We're not just changing the chemistry of the atmosphere and acidifying the oceans. We're not just taking the large-bodied animals. We're doing all this stuff simultaneously." Even so, Jablonski thinks humans are unlikely to be capable of causing an extinction comparable to the one at the end of the Permian, 251 million years ago, when an estimated 96 per cent of all marine species and 70 per

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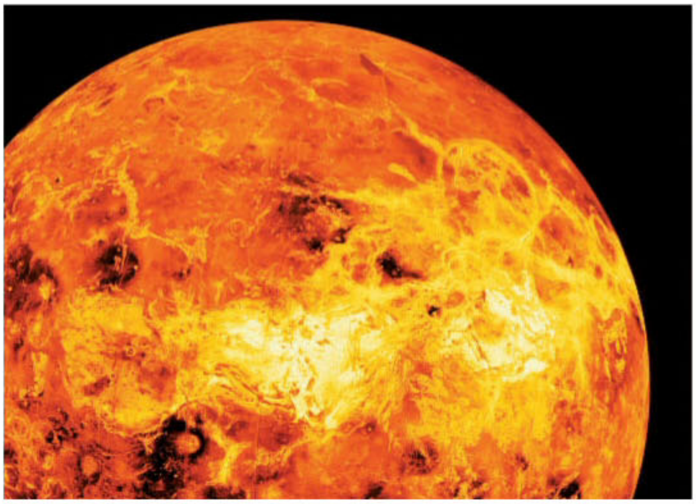

Some have warned of a "Venus syndrome" creating hell on Earth

KAZUYOSHI NOMACHI/CORBIS

Lake Natron in Tanzania is the kind of low-diversity environment that could become the norm

cent of terrestrial ones bit the dust.

Whether the Anthropocene mass extinction eventually ranks with the Permian or with lesser ones, it would still reshuffle the evolutionary deck. Once again, the past gives us some idea of what we could expect.

The fossil record tells us that every mass extinction plays out differently, because each has its own unique causes. However, there is one common factor: the species at greatest risk are those with the narrowest geographic ranges. Jablonski's studies of fossil marine snails show that species with planktonic larvae – which disperse widely – fare better than species with a more restricted distribution.

Cockroach world

Add to that massive habitat disturbances, says Jablonski, and a picture emerges of life after the Anthropocene extinction. Small body sizes, fast reproductive rates and an ability to exploit disturbed habitats will all prove advantageous. "It's a rats, weeds and cockroaches kind of world," says Jablonski.

The wave of extinctions is likely to sweep through species in a fairly predictable way. "First we would probably lose the species that are already endangered, then it would work its way down," says Barnosky. "Eventually it would hit some of the species that we don't consider at risk today – for example, many of the African herbivores that today seem to have healthy populations."

However, predictions about the fate of any particular species are almost impossible, as luck will also play a part. The survivors will probably be a more-or-less random selection of weedy plants and opportunistic animals, notes Doug Erwin, a palaeobiologist at the Smithsonian Institution.

If the Anthropocene does end with a mass extinction, the fossil record tells us a lot about what the recovery might look like. Whether the news is good or bad depends on your perspective. "Recoveries from mass extinctions are geologically rapid, but from a human point of view grindingly long. We're talking millions of years," says Jablonski.

Immediately after a mass extinction, the fossil evidence suggests that ecosystems go into a state of shock for several million years. For many millions of years after the Permian extinction, for example, marine environments the world over were dominated by the same 25 or 30 species. "It's pretty boring," says Erwin.

Something similar happened on land after the Cretaceous extinction. Pre-extinction plant fossils from western North America testify to flourishing ecosystems, with a variety of insects feeding on a wide assortment of plants. After the extinction, though, both plant and insect diversity drops dramatically, with some insect feeding methods vanishing almost completely.

After that, confusion reigns for 10 million years. There are fossil assemblages with only a few insects and plants, ones with many insects but few plants, others with many plants but few insects – just about everything except what ecologists would call "normal". "At no time did we have what I would call a healthy ecosystem, with diverse insects feeding on diverse plants," says Wilf. All the while biodiversity remains low, with few new species evolving. "You're just trying to hang on," says Erwin.

A study of marine fossil diversity bears this out. In 2000, James Kirchner of the University of California, Berkeley, and Anne Weil of Duke University in Durham, North Carolina, took a database of all known marine fossils and used it to work out how closely peaks of speciation follow peaks of extinction. "We went into this thinking, like everybody else, that when you have an extinction, you begin repopulating almost immediately," says Kirchner. Instead, they found that speciation peaks lagged about 10 million years behind extinction peaks. "We pretty much fell out of our chairs," he says.

In fact, for the first few million years after an extinction the speciation rate actually falls. "That suggests to us a sort of wounded biosphere. Extinction events don't just remove organisms from an ecosystem, leaving lots of opportunity for new species to diversify. Instead, what we think happens is that the niches themselves collapse, so you won't have new organisms emerging to occupy them. The niches themselves don't exist any more," says Kirchner.

Eventually, though, evolution wins the day, and after a few tens of millions of years biodiversity rebounds. Sometimes, as after the Ordovician mass extinction 440 million years ago, the new regime looks a lot like the old one. But more often a new world emerges. "You're not re-establishing the old chessboard, you're designing a whole new game," says Erwin.

In the Permian, the oceans were dominated by filter-feeding animals such as brachiopods and sea lilies, which lived their whole lives attached to the bottom. Predators were rare. All that changed after the extinction, leaving a more dynamic and richer ecosystem. "From my point of view, the end-Permian mass extinction was the best thing that ever happened to life," says Erwin.

In a perverse way, then, the bottom line is an encouraging one. Even if we manage to overpopulate and overconsume ourselves back to the Stone Age, the Earth will probably survive. Life will go on. By the time the long tail of the Anthropocene is over, what little was left of humanity will probably be gone. A new geological age will dawn. Shame there won't be anybody around to give it a name. ■


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