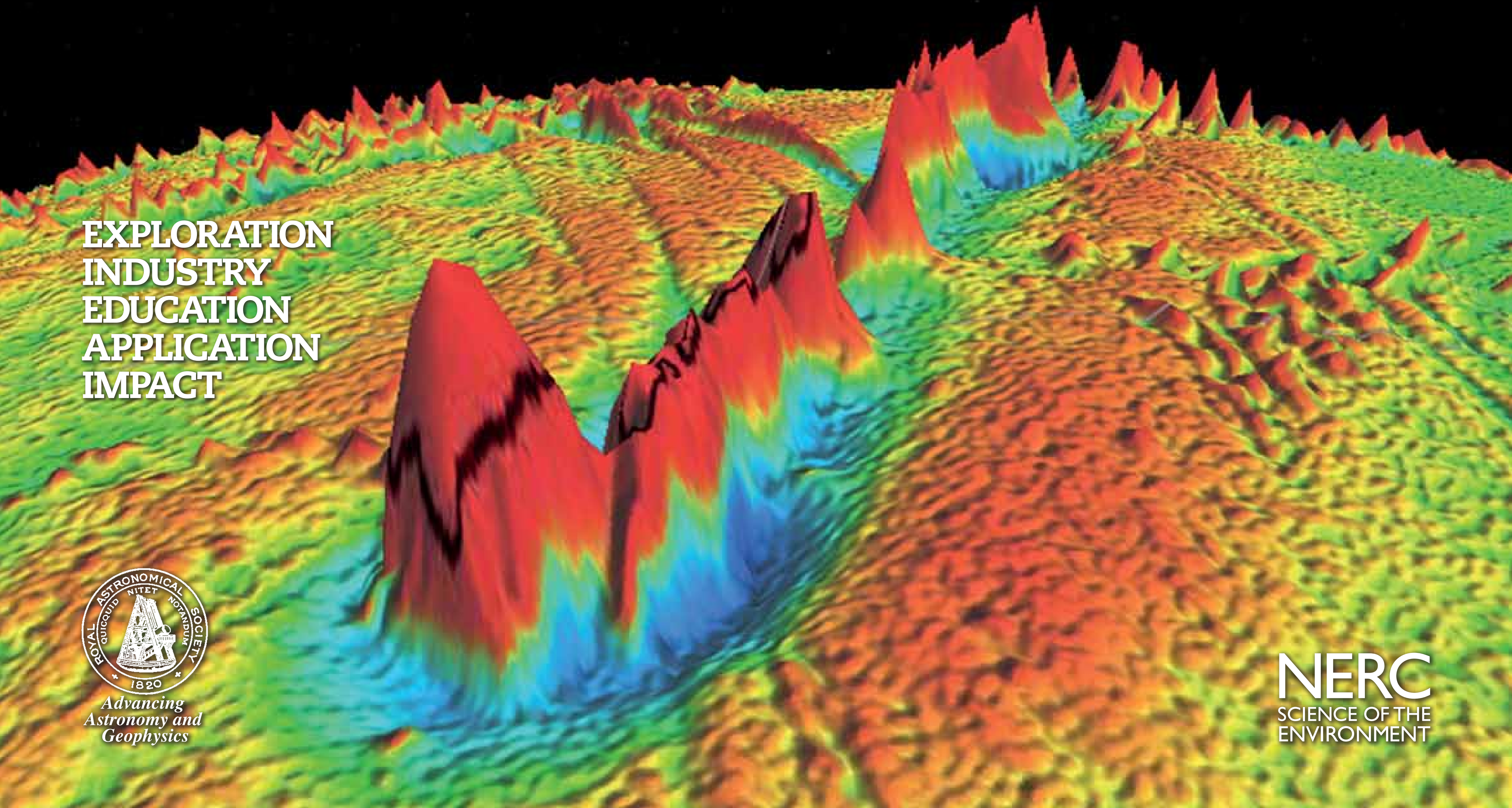
GOING UNDERGROUND: WHY GEOPHYSICS MATTERS



EXPLORATION
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IMPACT

ROYAL ASTRONOMICAL SOCIETY
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Advancing Astronomy and Geophysics

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GOING UNDERGROUND
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Cover:
The cover shows the free air gravity anomaly presented as topography on the curved Earth surface, looking east along the Hawaii chain of volcanic islands and sea mounts. The image illustrates the concept of flexural isostacy: the weight of the volcanic islands and seamounts (red peaks) warps the "elastic" oceanic crust downwards (adjacent blue troughs). The gravity field over the oceans is generated from processing the sea-surface topography mapped by satellite radar altimeters.

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FROM THE PRESIDENT OF THE ROYAL ASTRONOMICAL SOCIETY

It is a great pleasure to introduce this booklet on the wider economic and social impact of geophysics – the study of our changing planet and its place in space.

The most obvious thing about Earth sciences is that all of us live on and must share the same planet; not only is studying it humanly important, but it is also inevitably international in scope. That doesn't mean we Britons can leave it to others! UK researchers are – and need to be – world players, often taking leading roles in major international projects from studies of the Earth's interior to satellite missions that observe Earth from space. A developed country such as ours needs to undertake such science, not only to contribute to the general good of humanity, but also to ensure our own economic security.

The economic importance and impact of geophysics is self-evident. Outside the academic research sector, UK geophysics supports and is supported by a successful hydrocarbons industry thriving on all scales, from multinational players such as BP to small consultancies and specialist companies that make the sector as a whole flexible enough to make the best of a changing energy market. That industry needs more geophysicists, valuing them for their specialist skills, innovation and can-do attitudes.

At the same time, developments in geophysical imaging have revolutionized site surveys and made environmental investigation a growth sector on land and sea. Increased environmental awareness – driven, in large part, by growing scientific evidence of a changing climate from Earth observation satellites – has also boosted demand for remote monitoring of land, sea and air.

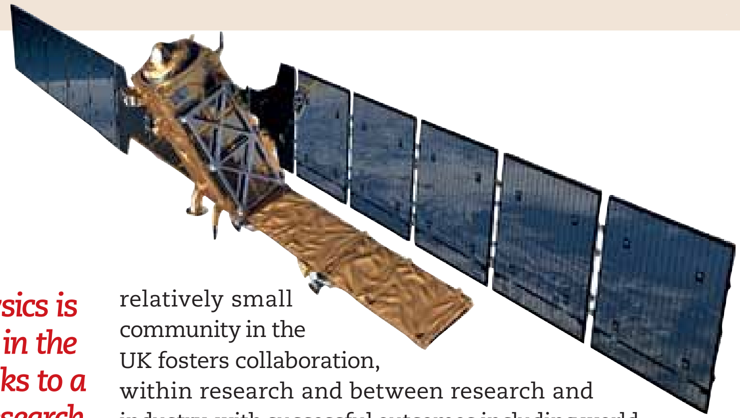
The UK geophysics community, while relatively small, benefits from close and active links with the international community and with industry – one of the reasons for its continual successful innovation. As Head of Earth Observation Strategy at the European Space Agency, I had the opportunity to work closely with the space industry and with the European Commission and other international bodies, trying to make a seamless pull-through from Earth science to applications relevant to managing our planet better. From that particular strategic viewpoint and now, as President of the Royal Astronomical Society, I can see that UK geophysics is very well placed to continue its success, boosting national prosperity and flying the research flag for the UK on the world stage.

"Geophysics is well placed to continue its success, boosting national prosperity and flying the research flag for the UK on the world stage"

I hope that you will enjoy reading this booklet and finding out more about geophysics in the UK and how it supports our society and economy.

Prof. David Southwood
President, Royal Astronomical Society
2012–2014

GEOPHYSICS: UNDERSTANDING THE EARTH

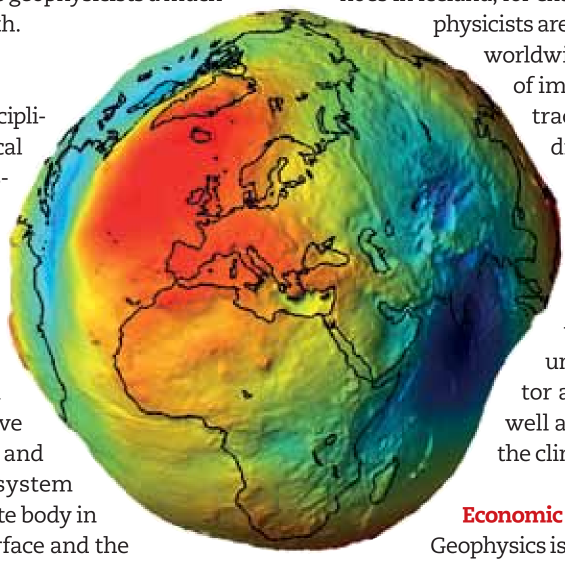


What is geophysics? What do geophysicists do? How does it help us in our everyday lives? And what part does the UK play in this inherently worldwide science? Read on to learn about the increasingly vital investigation of Earth and its environment, from the inner core, out to plate tectonics and the changing surface features and up into space.

Modern geophysics has flourished since the establishment of the theory of plate tectonics, some 50 years ago, yet the study of Earth has been part of broader scientific exploration for hundreds of years. What changed in the 20th century was a revolution in technology: instruments, data storage and analytical power have all improved beyond measure, giving today's geophysicists a much better and broader view of Earth.

Broad subject

Geophysics is a broad, multidisciplinary subject, covering all physical aspects of examining and measuring the Earth and its place in space. Government funding for geophysics research is administered largely through the Natural Environment Research Council (NERC). UK geophysicists are active in research, developing innovative methods to explore the Earth and discover how this complex system works. Our planet is an intricate body in which the deep layers, the surface and the climate and magnetic field interconnect. The deep Earth – the spinning mass of iron as hot as the surface of the Sun, and the slowly moving mantle rocks above – plays a part in driving the surface movements that we know as plate tectonics, but also affects our atmosphere and our interaction with the Sun, called space weather (pages 6–7). The Earth's constantly changing surface is now under scrutiny from satellites as well as on the ground; fieldwork and remote sensing together have shown how the subtler effects of plate movements work on human timescales (page 9). Exploration of the seas around the UK has shown how oceans form – and how those processes affect the eruption of volcanoes in Iceland, for example (page 5, 8). And UK geophysicists are investigating volcanic activity worldwide, finding reliable indicators of imminent eruption and ways to track the progress of their often disruptive plumes of ash (page 12). The effects of these natural phenomena are often hazardous to people nearby – but in today's interconnected world the effects can be felt worldwide. Geophysicists help to understand these events, monitor and mitigate their effects, as well as contributing to the study of the climate (page 13).



▲Global geophysics relies on satellite data such as the geoid – an accurate gravity map of the Earth – from GOCE data. Its bumps (red) and dips (blue) show how the rock mass varies at depth.

Economic growth

Geophysics is thriving in the UK. The oil and gas sector was worth £6billion to the UK in 2011, and it is growing fast (pages 14–15). In addition, the usefulness of geophysics for site investigation has made it an indispensible tool in construction, forensic science and archaeology, among many other sectors (pages 10–11).

Collaborative and multidisciplinary work is essential for success in geophysics. The relatively small community in the UK fosters collaboration, within research and between research and industry, with successful outcomes including world-leading roles for UK researchers. The British Geophysical Association (www.geophysics.org) represents academic geophysicists, under the umbrella of two learned societies, the Royal Astronomical Society (www.ras.org.uk) and the Geological Society of London (www.geolsoc.org.uk). Geophysics is also within the remit of the British Geological Survey (www.bgs.ac.uk), a national organization funded by the NERC that employs geophysicists to monitor the Earth and provide information to industry and business.

> "Geophysics is thriving in the UK, thanks to a strong research community allied with a powerful industry"

▲Big data about the Earth – collected with satellites and at ground level – makes geophysics a powerful tool for understanding our planet. It reveals both global and local rock structure, supporting safe and prosperous societies.▼

Education

Geophysics is thriving in the UK, thanks to a strong research community allied with a powerful industry. The subject inspires young people and the training is valued by employers. Geophysics education in the UK's universities is providing highly qualified people to support world-leading industries and businesses, amid a thriving entrepreneurial culture that supports successful companies in Britain. ■

EXPLODING IDEAS

Even a small volcanic eruption can have a big impact – as the 2010 Iceland eruption showed. UK researchers monitor active volcanoes and track plumes of ash, saving lives and supporting businesses worldwide.

Ash is pumped into the atmosphere during the explosive phase of the May 2010 Eyjafjallajökull eruption in Iceland, as seen from a farm 10km to the south of the volcano.

Volcanic eruptions are a risky business. During the 1995 eruption on Montserrat, British Geological Survey (BGS) and other UK volcanologists worked with the Montserrat Volcano Observatory to provide rigorous real-time risk assessment based on the consequences of the most likely eruption scenarios. As a result, they avoided wholesale evacuation of the island, allowing residents to keep their businesses where possible, while still saving lives.

Some of the world's active volcanoes are routinely monitored to track the movement of molten rock underground, together with tiltmeters to map how they bulge ahead of an eruption, for example. But this method does not show when an eruption is imminent. A team led by geophysicists from the University of Leeds have now found a way to predict an eruption on a timescale that allows those most at risk to take precautions or evacuate dangerous areas. The magma rising beneath volcanoes does so in pulses, each bringing the magma nearer the surface, like a cork moving closer and closer to the mouth of a bottle. The distinctive pulses of seismic signals are a reliable indicator of impending eruption.

Despite the fact that there are no active volcanoes in the UK, we can feel the effects of even quite small eruptions. The 2010 eruption of Eyjafjallajökull in Iceland grounded airline flights across Europe for days and disrupted travel for weeks. The problem was the plume of ash; when jets fly through ash, the tiny particles melt in the high temperatures and coat the turbine blades, effectively stopping the engines. In 2010, it proved difficult to track the ash in the atmosphere; NERC allocated funding to UK researchers to investigate not only how to map airborne ash, but also to find out what determines its distribution and density.

"Geophysicists have found a way to predict an eruption on a timescale that allows those most at risk to take precautions"

Iceland has an eruption every four years, on average, and Eyjafjallajökull was small – why did it have such an effect?

Tracking the ash

The answer came from space. Researchers working with data from satellites such as NASA's Modis (Moderate Resolution Imaging Spectrometer) were able to pinpoint ash from its absorption of infrared radiation. The IASI (Infrared Atmospheric Sounding Interferometer) on-board the European satellite EPS MetOp now offers much more sophisticated data, bringing better models that update in close to real time – much more useful for industry. Researchers from the University of Bristol are working with the UK Met Office to combine the plume models with meteorological modelling and help to bridge the gap between research and an operational service.

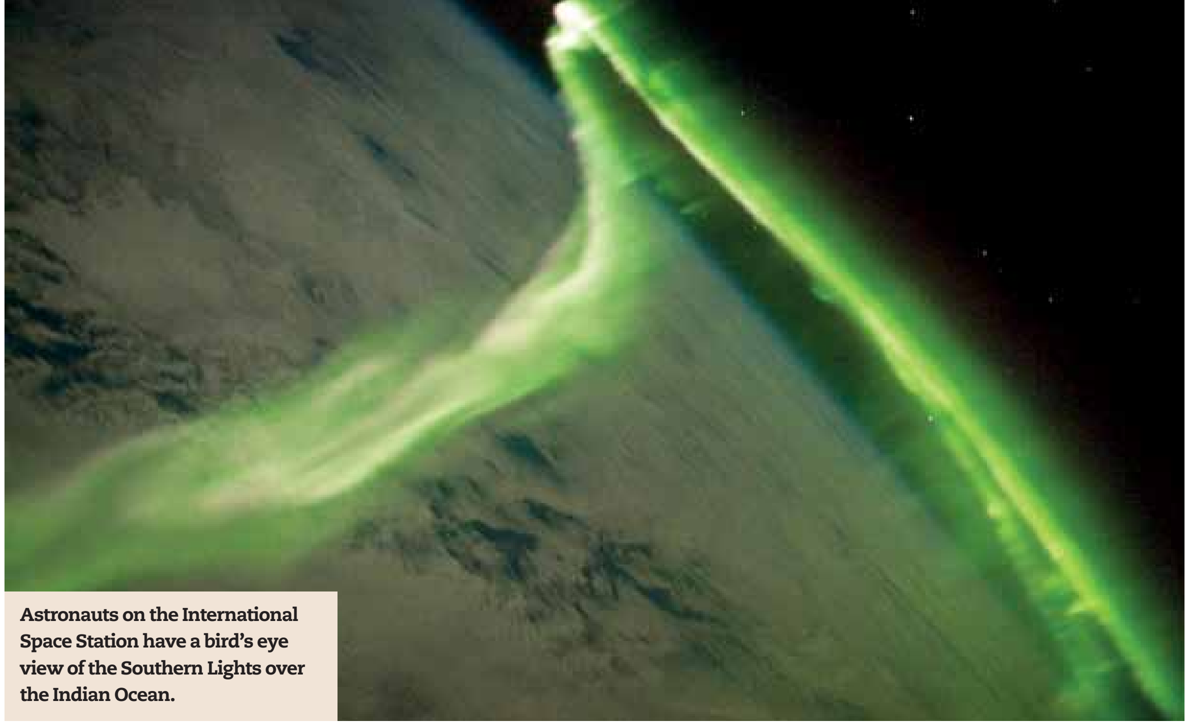
A key finding is that wind controls how and how far the ash spreads. In Iceland, tall plumes tend to send ash to the north, lower plumes to the south. Mathematical models using complex fluid dynamics are able to match eruptions as they progress. These models are freely available for research or operational use over the web and organizations including national research agencies are using them.

Geophysicists are also tackling the problem at source through the NERC-funded Vanaheim project, led by the National Centre for Atmospheric Sciences and involving nine UK institutions in an international effort to link data sources and learn scientific and organizational lessons from the 2010 Eyjafjallajökull eruption.

The European Commission has funded Futurevolc, an international collaboration using Iceland as a laboratory site for geophysical monitoring on the ground and from satellites, together with civil protection and advice. The BGS, the Met Office and the universities of Cambridge and Bristol are involved in this comprehensive approach to a problem that crosses borders in its effects on society. ■

FROM THE DEPTHS OF THE EARTH

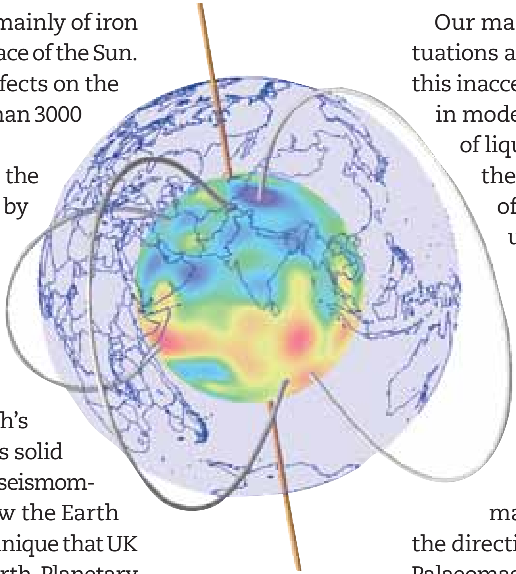
The deep Earth is utterly inaccessible, yet understanding our core and deep mantle is vital. Our magnetic field comes from the core and protects planet Earth from damaging solar storms. To minimize such effects on our increasingly technological society, we need to understand Earth all the way from its core up into the space around us.



Astronauts on the International Space Station have a bird's eye view of the Southern Lights over the Indian Ocean.

Earth's core is the size of Mars, is made mainly of iron and is as hot and inaccessible as the surface of the Sun. Researchers who need to study it use its effects on the surface to deduce what's happening more than 3000 kilometres below our feet.

Earth is cooling down: heat left over from the formation of the planet and that generated by radioactive minerals is carried to the surface by convection, ultimately giving rise to plate tectonics. Earthquakes set up waves that pass through the deep Earth, allowing seismologists to discover what the core is made of and how it is changing. This method has established that the inner part of Earth's core – a body about the size of the Moon – is solid and probably crystalline. Modern broadband seismometers also make it possible to examine how the Earth reverberates, like a bell, after a quake – a technique that UK researchers are using to explore the deep Earth. Planetary seismology is a strong field in the UK, with groups at the universities of Bristol, Cambridge, Edinburgh, Leeds, Liverpool and Oxford. Modelling the mineral structures present in the high-pressure, hot depths of Earth is a growing field where UK research is strong.



The magnetic field on the Earth's core shows complex patterns of polarity, with blue to the north, yellow south, in general.

Our magnetic field comes from the core, so its fluctuations and reversals offer clues to what is going on in this inaccessible region. UK geophysicists lead the world in modelling how the field originates – from the flow of liquid iron in the outer core, a mechanism called the geodynamo. Researchers at the universities of Cambridge, Edinburgh, Leeds and Liverpool use supercomputers to model magnetic fields with the properties of our field, now and in the past. Geomagnetic observatories worldwide measure the strength and orientation of the magnetic field; some have records going back more than a century. There are also longer-term readings to be found in nautical records, such as the logbooks of the ships of the East India Company. Over much longer timescales, magnetic minerals in rocks such as lava record the direction of the magnetic field when they solidified. Palaeomagnetic records of this type were pioneered in the UK and proved crucial in the establishment of the plate tectonics paradigm.

Monitoring the magnetic field

The British Geological Survey now monitors the magnetic field in the UK and tracks its response to outbursts from the Sun. Data from spacecraft such as NASA's Solar Dynamics Observatory – with cameras built in the UK – monitor the Sun's output in space and provide alerts when high-energy particles and radiation look likely to reach Earth. Such solar storms involve high-energy charged particles that are hazardous to human health and can damage the software and hardware of satellites. Satellites are also at risk from density changes in the upper atmosphere that alter their orbits. The electrical fields set up as a result of such magnetic disturbances induce currents in long-distance power lines; these can be enough to burn out transformers, with the risk of power cuts. It is the terrestrial magnetic field that protects both people and infrastructure; understanding how it responds to the Sun's activity – called space weather – is a key element of understanding the risk.

Britain is in a key geographical position to study the effects of space weather. The shape of Earth's magnetic field means that it is a less effective shield at the poles; this is why we see the Northern and Southern Lights at high latitudes. They arise from energetic particles striking molecules in the upper atmosphere; as the molecules lose this extra energy, they glow to form the aurora, a sign that solar particles are reaching Earth. The BGS issues alerts to

PLASMA POWER

The mixture of charged particles in the magnetosphere is in the form of plasma, a form of matter that is rare and difficult to study on Earth, but has the potential to provide power from nuclear fusion. UK researchers lead the world in the study of space plasma physics, with researchers providing instruments and leadership as well as working on plasma theory. Their work may also lead to practical protection for astronauts venturing out of low Earth orbit, who currently would have no protection from solar storms. A shield enveloping the spacecraft may be the solution and experiments at the Rutherford Appleton Laboratory in Oxfordshire have produced mini-magnetospheres with the potential to do just that, as pictured here.

commercial clients when solar activity will pose a problem. These include oil companies, who use the magnetic field as a reference frame for precision drilling, and the National Grid operators, who have to be alert for induced currents in power lines.

Solar wind effects in the atmosphere

Observations of the upper atmosphere from the surface of the Earth are carried out with powerful radar systems that map the movement of ions in the upper atmosphere, especially at the poles. The UK has been part of the SuperDARN network of high-frequency radars in northern Europe for 20 years. The radars allow researchers to study how our magnetic field interacts with the solar wind and to track effects in the middle levels of the atmosphere. Researchers from the universities of Central Lancashire, Leicester and St Andrews, Imperial College and University College London are particularly strong in these areas. Data from the polar regions are especially important; in the UK, the NERC runs the British Antarctic Survey (BAS) which deploys monitoring instruments in the Antarctic to help to understand the effects of space weather there, as well as monitoring atmospheric chemistry. It was BAS researchers who first found the ozone hole. ■

> *"Solar storms involve high-energy particles that are hazardous to human health and can damage satellites"*

The University of Leicester is sending its high-frequency radar systems round the world, including this one in Hankasalmi, Finland.

BOX-FRESH: EXPORTING HIGH-FREQUENCY RADAR

Mark Lester and his team at the University of Leicester have been building high-frequency (HF) radar systems for 20 years, initially for their own research. But the increasing worldwide concern about space weather has led to demand for their systems worldwide, for research and for wider markets interested in high-frequency communications and over-the-horizon radar systems.

The Leicester team has contributed significantly to the 33 HF radar systems established worldwide and has earned more than £2 million from exports to Japan, China and Russia.

The key to its success is that it provides specialized equipment, built for specific research purposes, but does so in a commercial fashion: the kit arrives ready for deployment, on time and on budget. It even comes in a shipping container that doubles as a base station, complete with desk and chair. It's not surprising that the Leicester team is bucking the trend and exporting electronics to Japan!

UNDER THE SEA

SAND GEOPHYSICS: SPECIALISTS AT SEA

If you want to know where to put an oil rig or a wind turbine at sea, you'll need a specialist geophysical survey company, and you'll probably find one among the UK's small and medium enterprises. According to Rob Morrow, one of three geophysicists behind SAND Geophysics, the flexibility of small companies is their key to success. "You've got to be ready to go to, say, Jordan, at three days' notice – and we can." SAND – Surface And Near-seabed Detection – uses specialist equipment developed at the National Oceanography Centre at the University of Southampton, in collaboration with GeoAcoustics Ltd. The 3D Chirp Sub-bottom Profiler produces detailed 3D images of the top few metres of seafloor over a few square metres at a time, picking out bedrock and objects just tens of centimetres across, buried in the sediment. SAND is concentrating on new offshore energy markets in the Mediterranean and the Middle East, where unexploded ordnance and complex seafloor environments pose particular problems.

Rob's marine geophysics degree at the University of Southampton has proved especially valuable. "A lot of contractors gained experience in the North Sea that they now use for siting wind farms," he says. "But UK geophysics degree programmes also started teaching the right things earlier than our world competitors, so we're ahead of the curve."

The seas hold the key to understanding the movement of the tectonic plates and the structure of the ocean floor around the UK.

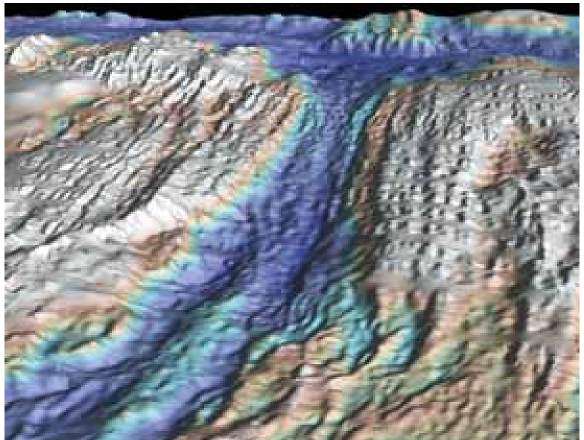
UK geophysicists have taken leading roles in international collaborations to map the seafloor and mid-ocean ridges worldwide. The discovery that these intriguing volcanic mountain chains hosted new ecosystems around hydrothermal vents, far from the light of the Sun, led to international collaborations such as Inter-ridge to investigate the seafloor and how these novel communities – possibly like the first life on Earth – survive and even thrive.

Ocean margins

But marine geophysics is also about the ocean margins. The UK lies at the western edge of Europe, where continental rocks meet the ocean floor. UK geophysicists have gained considerable insights into the rifting process and the deep architecture of the margin thanks to collaborations with the oil and gas industry. The British Institutes Reflection Profiling Syndicate in the 1980s was one of the first projects to combine industry techniques and equipment with academic teams, and produced deep seismic reflection profiles around the UK that showed structures such as the ancient line of collision between Scotland and England.

The deep ocean floor is a hostile environment that demands robust and often remote control or robotic instruments for exploration. UK researchers participate in international projects such as the European Consortium for Ocean Drilling and, through ECORD, the International Ocean Discovery Program, and work on national research vessels such as the RRS *Discovery*. Exploration of the deep sea uses both towed instruments and robotics, autonomous submarines carrying specialist instruments such as side-scan sonar. The National Oceanography Centre in Southampton designs, builds and operates dedicated instruments such as *Autosub*, an autonomous underwater vehicle able to explore beneath Arctic and Antarctic ice shelves, and *Isis*, a remotely operated vehicle able to work at depths of 6500m. These and other specialist devices are used alongside satellite information, such as ice-thickness data from ESA's Cryosat.

▲Shallow seas around the UK are preferred sites for windfarms; each turbine needs secure footings in the seafloor, located through geophysical surveying.



◀The Mid-Atlantic Ridge at 24°N, in a sonar image with purple showing the deep central valley, and tan the ridge on each side. This view is looking south towards the Kane Fracture Zone and the image covers about 16km width in the foreground.

Seeing new ocean crust

Side-scan sonar mapping of the Mid-Atlantic Ridge using such dedicated instruments has shown the details of how its volcanic structures gradually build new ocean crust – providing fundamental insights into the workings of our planet. Researchers from the universities of Cambridge, Durham, Edinburgh, Liverpool, Southampton and University College London have worked on the structure of ridges and margins around the UK. ■

A SHIFTING SURFACE

Field work and satellite data combine to show geophysicists how the surface of the Earth is continually adjusting to the stress of plate movements. The results reveal how the planet works on a human timescale, helping us to understand earthquake risk.

The plate tectonics revolution, 50 years ago, gave scientists a powerful new model for the surface of the Earth: a moving mosaic of rigid plates with earthquakes and volcanoes clustering at their edges. But it took geophysicists only a few years to realize that this is not the whole story. Dangerous earthquakes, in particular, can take place far from plate boundaries; devastating earthquakes killed tens of thousands of people in Iran (2003) Pakistan (2005), and China (2008).

The continental plates are not rigid and, as they move, large-scale but subtle distortion of the rocks leads to some of the most deadly earthquakes and most of the associated deaths. Devastating quakes can happen on previosuly unknown faults. This distortion, which takes place over many centuries, has been impossible to measure until recently. Now, new satellite technologies can track movements of the Earth's surface at the scale of millimetres, allowing geophysicists to evaluate the changing strain in a region on human timescales. This, in turn, brings better understanding of the threats to human lives and livelihoods.

Reshaping the surface

UK researchers lead the world in applying all the tools geophysics offers to understand the distortion of continental regions. The COMET consortium, including researchers from the universities of Oxford, Cambridge, Leeds, Bristol, Glasgow, Reading and University College London, has studied regions where devastating earthquakes arise within plates, focusing on the broad zone where the African, Arabian and Indian plates collide with Eurasia, known as the Alpine–Himalayan Belt. Here the team has combined seismology with satellite radar images, field mapping and historical trigonometric surveys in order to map ground distortions related to tectonic activity. The COMET team uses case studies of individual earthquakes, such as the 2009 L'Aquila earthquake (below right), to understand earthquake risk. Team members plan to use ESA's new Sentinel-1 satellite – due for launch in spring 2014 – for InSAR studies of how the continents deform through time, and how variation in the strength of the lithosphere affects surface deformation.

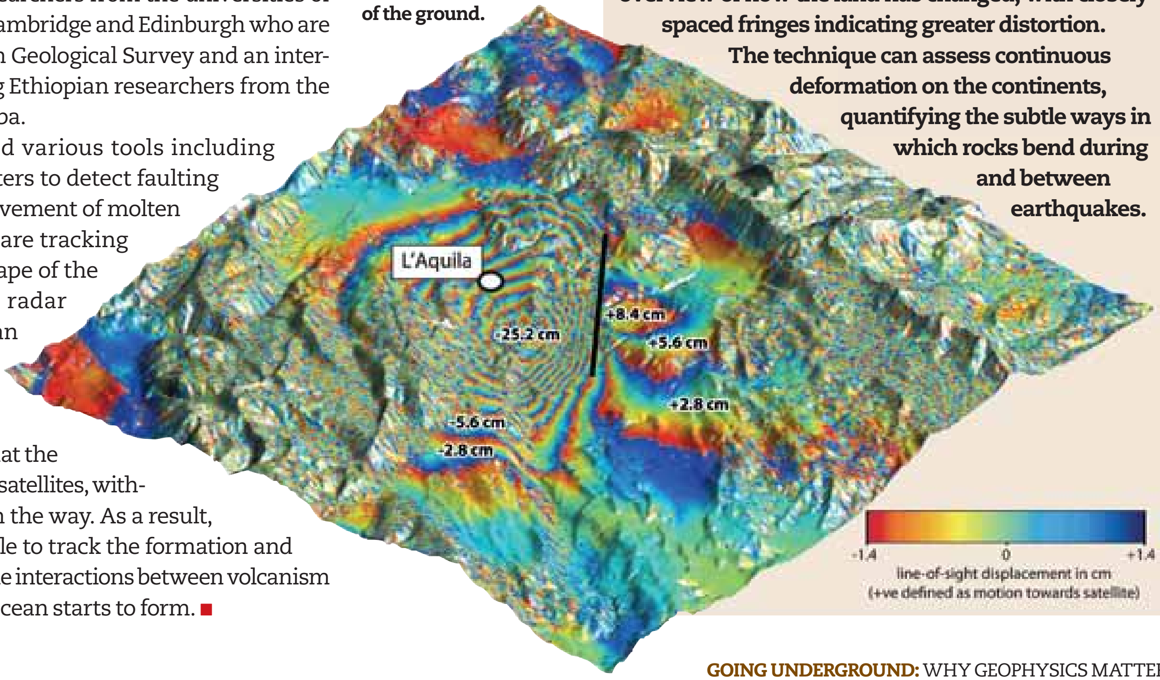
In Africa, UK geophysicists joined Ethiopian scientists and other members of an international team to study plate tectonics in action in Afar, where the East African Rift Valley meets the Arabian Sea, because all the signs are that a new ocean is forming there. This is a region where the African continental tectonic plate has been stretched so that it is thin and appears ready to break. The Afar Rift Project involves researchers from the universities of Bristol, Leeds, Oxford, Cambridge and Edinburgh who are working with the British Geological Survey and an international team including Ethiopian researchers from the University of Addis Ababa.

The teams have used various tools including networks of seismometers to detect faulting in the crust and the movement of molten rock underground and are tracking the distortion of the shape of the ground using satellite radar interferometry. Afar is an especially good place to use satellite interferometry because its desert climate means that the rocks are easily visible to satellites, without vegetation getting in the way. As a result, the teams have been able to track the formation and growth of fissures and the interactions between volcanism and tectonics as a new ocean starts to form. ■

In the East African Rift ▶ in Afar, deformation and volcanism interact to change the shape of the African continent.

INSIGHTS FROM INSAR

InSAR is a revolutionary technique in which an orbiting satellite uses radar to measure changes in the distance to the ground between one orbit and another. If the shape of the surface has changed, the distance differs; InSAR can detect displacements of a few millimetres. The maps use interference fringes to show the distortion – each full spectrum of colours marks a half-wavelength of difference, giving a quick overview of how the land has changed, with closely spaced fringes indicating greater distortion. The technique can assess continuous deformation on the continents, quantifying the subtle ways in which rocks bend during and between earthquakes.



▼Contours of surface deformation around the fault that moved in the L'Aquila earthquake in 2009, showing the town's position, close to the greatest movement of the ground.

In February 2013, a spoil heap at Hatfield Colliery slipped, closing the railway line for several months.

KEEPING THE TRAINS RUNNING

The UK's rail network runs on embankments and through cuttings, making the safe running of the trains reliant on avoiding landslips. This is where a British Geological Survey (BGS) project in collaboration with the track management authority Network Rail is making a difference. Engineered slopes such as road and rail cuttings are vulnerable to landslips when water lubricates subsurface layers, but the response depends on the individual subsurface structure. BGS researchers worked with Network Rail to bury measurement grids near vulnerable sections of track in order to monitor movement and warn of slippage before significant damage is done. A big problem was that the grid itself, embedded in the soil, moved during the monitoring. BGS researchers turned to medical imaging which used monitors that moved with the patient, and found that the software could be used to map the slip and identify danger signals: moisture in the ground and vegetation changes are important. The group is now developing the monitoring system to provide an automated system of alerts that should mean fewer hold-ups for rail passengers from landslides in the future.

SUPPORTING A SUSTAINABLE SOCIETY

From keeping train passengers happy, to minimizing the impact on the climate of burning fossil fuels, geophysics has tools to help solve many of our environmental problems.

The UK is a crowded area, with growing pressure on land, water and resources. Geophysics provides tools for resource exploration and extraction, but these and other tools are now widely used for time- and cost-efficient ground surveys. Methods using radar, electrical resistivity and magnetism can map foundations of demolished buildings, underground water, contaminated land and even archaeological sites. The BGS has a nationwide monitoring system to assess seismic risk for nuclear power plants, for example, and is pioneering high-resolution electrical impedance tomography to image the shallow subsurface, ideal for tracing tunnels and foundations.

"Geophysics can provide technologies that reduce the carbon released to the atmosphere from fossil fuels"

Environmental maps

The demand for geophysical surveys has brought a boom in companies offering this service, such as TerraDat, based in South Wales (see "TerraDat: Geophysics goes to work", page 11). But the British Geological Survey (BGS) is also involved, taking a leading role in strategic surveys of the UK, through the Tellus Project. This is a multidisciplinary mapping project, combining airborne geophysical surveys of features such as the magnetic field and electrical conductivity measurements on the ground. The result is a digital environmental map, identifying rock formations even beneath deep peat and soil sediments, mapping water flow and natural radiation and highlighting potential mineral deposits. For example, the results of the Tellus and Tellus Border surveys in border counties of the Republic of Ireland

and Northern Ireland have prompted renewed interest in mineral prospecting, resulting in the issue of new prospecting permits for precious and base metals in the area.

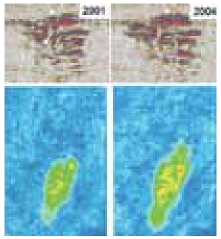
Tellus South West is now underway, including airborne geophysical and laser scanning surveys, carried out by the British Antarctic Survey, combined with geochemical and ecological surveys across southwest England. Survey data will contribute to the sustainable development and management of this region, where natural resource and development opportunities need to be balanced against the value of the landscape and coast for leisure and tourism.

A sustainable society needs energy, most of which we currently get from fossil fuels. While concern over the climate is driving the growth of renewable energy generation, the pace is slow. The UK will be using fossil fuels for decades to come; geophysics can support the development of technologies that reduce the carbon released to the atmosphere from fossil fuels.

Carbon capture

The principal method being tested to minimize the climate impact of fossil fuel use is long-term storage of greenhouse gases such as carbon dioxide: carbon capture and storage technology. A variety of experiments worldwide are testing storage technologies and assessing how they can hold carbon securely in the long term. Reservoir rocks that have trapped natural gas for millions of years are an obvious target for doing the same for greenhouse gases. BGS researchers are working with oil companies including Statoil to monitor the spread of the 11 million tonnes of carbon dioxide injected into rock at Sleipner in the North Sea since 1994. Seismic, gravity and electromagnetic surveys show the spread of the stored gas plume.

Monitoring is an essential part of any carbon capture scheme. Gas may escape to the surface through natural cracks and fissures; even small earthquakes may affect sealed reservoir structures and release the gas. Microseismic monitoring can pick up such earthquakes, as demonstrated by researchers from the University of Bristol using an array of seismometers placed by BP on the seafloor above the Valhall field in the North Sea. During hydraulic fracturing (fracking) of the reservoir, analysis techniques developed for investigating the core and mantle proved able to pick out earthquakes that were otherwise undetectable in the data. ■



Experimental carbon capture and storage: every year, about a million tonnes of the greenhouse gas CO_2 is pumped into rock at the Sleipner West field beneath the North Sea instead of being released into the atmosphere. These time-lapse seismic images show vertical slices (above) and maps of the expanding plume of CO_2 in 2001 and 2004.

TERRADAT: GEOPHYSICS GOES TO WORK

TerraDat was established in 1992 as a specialist and independent geophysical survey company, providing both contracting and consulting services to the geotechnical, civil engineering, mineral, hydrological and environmental industries. The company owns the largest range of geophysical survey equipment in the UK private sector and continues to expand its resources with every major advance in technology. For example, TerraDat uses magnetic gradiometry – mapping changes in the magnetic field arising from changes in materials in the subsurface – in order to produce 3D images of archaeological features. The visualization of data in 3D is an important aspect of TerraDat's work; for example, it uses airborne and ground-based laser scanning to produce digital models of the land surface and buildings for monitoring subsidence and to keep records of historical structures.

TerraDat's success comes from offering a high-quality service while promoting the wider use of geophysical science where appropriate; links with academic geophysics are part of its sucessful formula for helping clients all around the world.

Collecting data on the electrical resistivity of the ground, in order to make a three-dimensional map of the subsurface.

OUR DANGEROUS PLANET

Natural hazards harm those living close by, but can affect society worldwide. UK geophysicists work on the processes that underpin Earth hazards and on means to monitor and mitigate their effects.

While the UK does not have major seismic or volcanic risks, these are worldwide problems: the 2011 eruption of Eyjafjallajökull in Iceland interrupted travel across Europe for weeks, for example, and the aftermath of the great Tohoku earthquake in Japan, and its tsunami, spread around the world. UK geophysicists have contributed to understanding the mechanisms that drive earthquakes and volcanoes. Plate tectonics shows that most quakes happen at the edges of plates, but about 60% of the deaths result from earthquakes away from plate boundaries. This is a risk that UK researchers in the COMET research consortium are addressing across the Alpine–Himalayan belt.

UK researchers are also involved in understanding hazards such as flooding, drawing together data from satellites and geophysical observatories. Long-term surface movements – for example, the uplift of the northwestern UK after the end of the last Ice Age – combine with variations in ocean temperature and volume, including those coming from a changing climate. Geophysical modelling is a key part of protecting vulnerable infrastructure such as power stations in the UK.

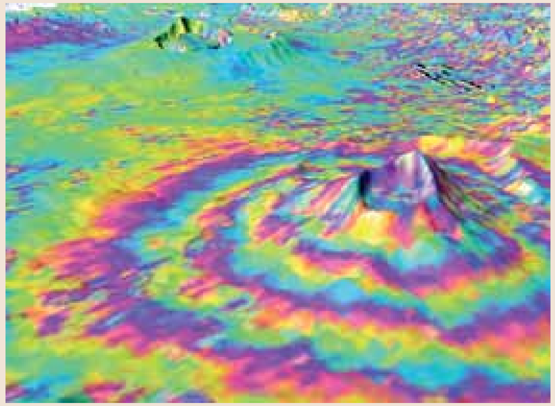
Risk assessment

Risk assessment is the key to minimizing the costs of natural hazards. The size of the tsunami generated by the great Tohoku earthquake in Japan in 2011 was much larger than had been expected, making the mitigation in place – sea walls, for example – ineffective, with devastating results, especially for the Fukushima nuclear power plant. The size of a tsunami depends on both the mechanisms of the quake and the way that tsunamis are generated. Geophysicists at the University of Southampton, for example, found that the nature of the seafloor sediments played a key role in the devastating earthquake and tsunami in Southeast Asia in 2004. The magnitude of the quake and, just as in Japan, the size of the resulting tsunami and its human and economic damage took governments and insurers by surprise. Geophysicists at the University of Cambridge have found that gravitational energy plays a part in quakes that generate large tsunamis, such as the great Tohoku quake. And researchers at University College London are working to improve the modelling of large earthquakes and tsunamis for insurance industry software using historical and archaeological data from the west coast of North America. ■

▲After the flood: the remains of Patong Beach in Thailand following the tsunami of 2004.

FINDING ACTIVE VOLCANOES

Few volcanoes worldwide are routinely monitored for signs of an impending eruption; networks of instruments on the ground are both costly and impractical for remote areas. Satellite technology offers a practical solution, by identifying the infrared radiation or the surface deformation that indicates hot rock close to the surface. A bulge of a few centimetres over the surface of a volcano can be detected by satellite radar interferometry (InSAR), for example by ESA's satellites Envisat and Sentinel. InSAR data from Kenya, collected by an international collaboration including UK researchers, found that four of the ten active volcanoes in the Rift Valley had had year-long episodes of bulging and sinking within an 11-year period. Three of the volcanoes showing these signs of life were in densely populated areas, within 100 km of the capital Nairobi. A wider study of volcanoes in 16 developing countries found that 384 out of 441 known to be active have essentially no monitoring; 65 of these pose a high risk to populated areas.



This satellite image of the Kenyan section of the Great Rift Valley reveals surface movements invisible to the naked eye. In the foreground, the Longonot Volcano shows uplift of around 9 cm, while the volcano in the background shows no displacement. The interferogram image was produced by the Envisat Advanced Synthetic Aperture Radar. Each complete set of coloured bands (or fringes) represents ground movement relative to the spacecraft of half a wavelength, which is 2.8 cm in the case of Envisat's ASAR.

EYES IN THE SKIES

Remote sensing is a crucial element in mapping and monitoring our planet and environment. Satellite data can show the shape of the Earth, map the oceans and track pollution.

Geodesy – measurement of the size and shape of the Earth, through its gravity field – has come into its own thanks to satellite technology. The Global Positioning System and laser ranging techniques have largely replaced traditional surveying techniques, but dedicated satellites such as ESA's GOCE mission have now produced precise gravity data. An accurate representation of the surface of the Earth is important for map-making as well as research and, in turn, allows more precise determination of orbits for other satellite missions. Satellite geodesy is also important in developing models of the Earth as a planet, and comparing it with other solar system bodies. Geodesy is necessarily an international field and UK geophysicists take leading roles in this research, in both instrument design and data analysis, in conjunction with the Natural Environment Research Council (NERC), the UK Space Agency and the European Space Agency (ESA).

Swarm of satellites

Satellite data are also important to complement ground-based observation of the magnetosphere and ionosphere. The launch of ESA's Swarm mission in November 2013 is providing researchers with new information on the Earth's magnetic field and core, using three satellites flying in constellation. UK industry played a part in many of the major components of the Swarm satellites, including their innovative batteries made by Oxfordshire company Enersys ABSL.

Earth-observation satellites monitor the planet using lasers and radars to probe the atmosphere and oceans, mapping such variables as sea-surface temperature and ice-sheet thickness. But satellite data also include environmental indicators such as air quality, things that have more commonly been measured at scattered locations on the ground. A University of Leicester project called CityScan has been developed to link these two datasets. CityScan uses the Compact Air Quality Spectrometer, an instrument developed by the university and Surrey Satellite Technology, to map pollutants such as nitrogen dioxide. These instruments were used in London during the 2012 Olympics, as part of a research initiative mapping London's urban atmosphere, involving researchers from across the UK, coordinated by the NERC's National Centre for Atmospheric Science.

◀ As part of the Clean Air For London project, Leicester's CitiScan spectrometers monitored air quality from London rooftops, in combination with satellite data.

Environmental monitoring

There are also important monitoring roles for geophysicists, overseeing operations and waste handling in the mining, hydrocarbons and nuclear power industries. Oil spills have proved damaging to wildlife and environments in the past; recovery strategies are essential as exploration moves into more extreme environments. Risk assessment is also crucial to public acceptance of new sources of hydrocarbons, such as shale gas. A consortium led by Heriot-Watt University to provide doctoral training has its focus on equipping the oil and gas industry with the skills to reduce environmental impact. Projects include developing best-practice guidelines for environmental impact, a decision-support tool to guide environmental monitoring, and a test to check for gas contamination of drinking water. ■

"Earth-observation satellites monitor the planet using lasers and radars to probe the atmosphere and oceans"

This 1970 US ▶ 10 kilotonne nuclear test (Baneberry) accidentally vented radioactive dust despite taking place at a depth of 270m; it was given body-wave magnitude 5.1 by the International Seismological Centre.

SEISMIC SECURITY

The techniques used to detect earthquakes can also pick up underground nuclear detonations – indeed, it can be challenging to tell the two apart. Geophysicists at the Atomic Weapons Establishment at Blacknest have taken the lead in forensic seismology internationally, developing methods to distinguish between shallow quakes and possible nuclear tests, in support of the 1996 Comprehensive Test Ban Treaty. The CTBT requires a monitoring system that can detect underground explosions of one kilotonne – this means instruments able to pick up a ground movement of just one millionth of a millimetre. AWE scientists work with international bodies to monitor Earth movements worldwide, and provide advice to government.

North Sea oil drove opportunities for UK business and industry.

GEOPHYSICS IN THE UK'S OIL AND GAS INDUSTRY

Commercial exploration of the North Sea for oil and gas began in earnest in 1964, bringing opportunities for UK business that have resulted in a thriving and successful industry that remains world-leading today. Large and small companies and the academic community together make the UK a global player in this field, known especially for expertise and innovation.

There are now more than 700 publicly limited companies in the UK in the oil and gas sector, employing 440,000 people and contributing £6bn a year to the UK balance of trade. As well as those technological companies directly involved in exploration and production, there is a strong services sector; Aberdeen is the global centre for many oilfield services companies. While world players such as BP have built their reputation in the UK, they work alongside many smaller independent companies and consultancies who are able to offer specialist services in niche marketplaces. And the sector is growing, with the 390 companies with 2011 revenues greater than £10m growing by an average of 17% – and most of that came from the 73 organizations with revenues greater than £100m that year. Growth looks set to continue, with 2012 investments in new projects in the UK up to more than £11bn, with more than 30 projects in the pipeline for this year.

Seismic surveys

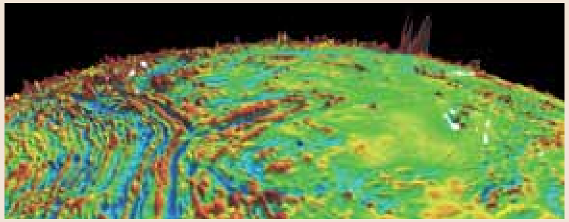
The exploration boom in the North Sea kick-started offshore exploration techniques, especially seismic surveying using vibrations in the subsurface to image rock structures. Oil revenues and collaboration between academia and industry through the 1970s onwards refined those techniques and led to the devleopment of innovative new ones. Now arrays of seismometers on the seafloor provide 3D images of the subsurface structure, and BP has pioneered the use of such arrays to monitor changes in reservoirs through time – so-called 4D seismic monitoring. Aeromagnetic surveys have been applied in hydrocarbon exploration, especially through the innovative techniques

GETECH: THE RIGHT STUFF

Getech is a company that provides tailored packages of geophysical information for companies interested in exploring for mineral or hydrocarbon resources. It began as a consultancy at the University of Leeds and floated on the London stock market in 2005; it now employs more than 70 people.

This success is based firmly in pioneering geophysical research. In 1986, a group of 10 oil companies sponsored geophysicists at the University of Leeds led by Derek Fairhead to provide gravity data for a region of Africa. The challenge was to provide the relevant information in a useable form, collecting data from various public and commercial sources, on paper or as computer records, some as raw data, some processed. Transforming this array of data sources into useful and useable information proved valuable – and Getech was born.

Getech moved from a consultancy basis to a more commercial footing and a management buy-out followed. The company diversified, moving into other data fields such as magnetic surveys, and won some big data contracts such as satellite gravity survey processing, that brought stability to the company and made possible more strategic planning. By 2005 Getech became part of the Alternative Investment Market on the London Stock Exchange and the company continued to grow. Now it provides industry clients with information across a much wider range of geoscience topics, such as geochemistry and palaeoclimate data, to meet the needs of customers. Geophysics is basically a means of imaging the Earth to obtain useful information – Getech has made a successful business out of organizing this specialized information for specialist customers.



◀Big data: there's no shortage of information about the Earth. What is in short supply – and therefore valuable – is organized and efficient access to geophysical datasets.

developed at the University of Edinburgh (see "MTEM: from academia to industry – and back again").

The relationship between academia and industry has been mutually beneficial. Geophysical research in universities has benefited from industry expertise and the opportunity to teach using commercially significant data. This relationship has had time to develop depth: in the 1980s, a major industry–academic collaboration – the British Institutes Research Profiling Syndicate – used state-of-the-art deep seismic profiling to reveal not only the ancient geological border between England and Scotland, but also the deep structure of the western margin of the UK. The exchange of information has led to major research advances that benefit the search for hydrocarbons worldwide. Despite modern commercial activity in the North Sea from the 1960s onwards, it was not until the 1980s that a fundamental theory underpinning the formation of the region was established, by academics from the University of Cambridge.

Fracking and other techniques

The UK's reputation for innovation continues. Despite many of the fields in the North Sea passing their peak production, they still contain plenty of hydrocarbons and extracting as much oil and gas as possible from existing fields is an area where UK companies excel. The techniques being developed to make the most of existing fields and their costly production infrastructure include pumping fluids into reservoir rocks in order to displace oil and gas, promoting fracturing in order to boost the permeability of a reservoir, and drilling horizontally within reservoirs in order to ease the flow. All these techniques, widely used in North Sea fields, mean that reservoirs considered unproductive just five or six years ago are now producing.

This is also the technology that makes possible the exploitation of shale gas reserves on land – known as fracking. There is strong government support for exploitation of these unconventional hydrocarbon sources, and the BGS has identified considerable potentially rich shale gas sources across the north of England. UK researchers in universities and in industry have world-leading expertise in understanding and controlling the fracking process, thanks to extensive experience in the North Sea and other fields. That same expertise will also ensure that this emerging industry operates responsibly. ■

"These techniques mean that reservoirs considered unproductive five or six years ago are now producing"

MTEM: FROM ACADEMIA TO INDUSTRY – AND BACK AGAIN

Aeromagnetic surveying is a staple tool in hydrocarbon and mineral exploration. Planes and satellites explore regions carrying sensors to pick up changes in the magnetic and gravitational fields that come from rocks in the subsurface, indicating likely locations for minerals or oil. In 2001, Anton Ziolkowski, Bruce Hobbs and David Wright of the University of Edinburgh invented a new electromagnetic method to detect subsea and underground hydrocarbons directly, without the need for drilling. In 2003, they founded MTEM Ltd to develop the technology to provide surveys for oil companies.

MTEM – Multichannel Transient ElectroMagnetic – applies techniques like those developed in seismic processing to electromagnetic surveys, resulting in significantly clearer imaging of the subsurface, including signals that directly identify gas in reservoirs. The initial ideas arose from research funded by the European Commission, Elf Petroleum and a NERC research studentship. With support from the University of Edinburgh and Scottish Enterprise, the project went on to gain venture capital funding and become the largest spin-out company from a Scottish university – and the second-largest university spin-off in the UK. MTEM Ltd was launched from the University of Edinburgh with £7.4m funding from HitecVision, Energy Ventures and Scottish Equity Partners; in June 2007, Petroleum Geo-Services bought MTEM for $275m.

This technology and its development as a commercial technique by MTEM has had a significant impact. Promising reservoirs identified by seismic surveys can now be evaluated to see if they contain hydrocarbons without drilling, reducing exploration costs for exploration companies. Closer to home, the company has employed people in Edinburgh, an estimated 200 man-years so far. And the project has returned £8.6m to the University of Edinburgh so far as a share of the sale to Petroleum GeoServices – funding 164 PhD studentships.

EXPLORING THE DEPTHS OF THE EARTH

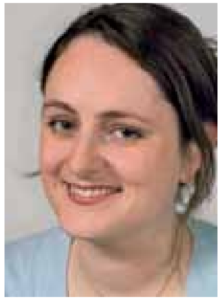
CAREERS

In her job at the University of Cambridge, Arwen Deuss has the best of both worlds: researching and collaborating on new science, and inspiring the scientists of tomorrow.

"It's a joy to go to work. Doing science, taking part in research, teaching students – it makes me very happy." These are the words of Arwen Deuss, Reader in Geophysics at the University of Cambridge, who uses the after-effects of earthquakes to find out what's going on in the Earth's mantle and core. "It's really exciting to discover something new," she says.

Her particular field is global seismology, analysing the way the planet oscillates after a major earthquake. "The whole Earth rings like a bell," she says. "If the Earth were the same everywhere, it would be as if the oscillations were in tune. Where they are out of tune, we know that we need to look more closely."

Global seismology took off in the 1980s, when a global network of seismometers good enough to record small signals from the core were put in place. The new data boosted wave seismology, for example, by identifying earthquake waves that had travelled through the deep mantle and core.



"It's really exciting to discover something new."

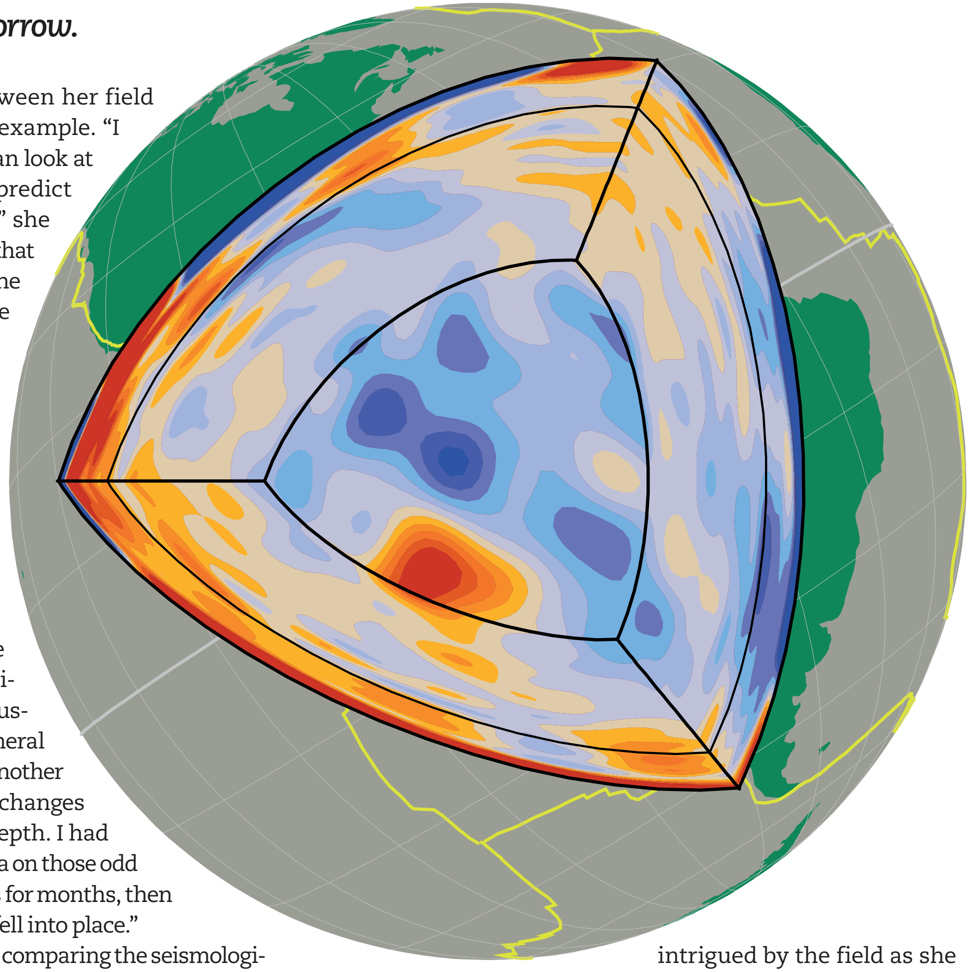
Model and real Earth

In this technique, geophysicists use models to predict when waves on different paths through the Earth should arrive at a seismometer. Early or late arrivals mean that the structure of the Earth differs from the model. A key finding was that the solid inner core, made mainly of iron, has a different structure in the north–south direction compared to the east–west, called anisotropy. Arwen says that the observations were incredibly clear: "Every arrival is 5 seconds faster in the north–south direction. When I looked at the data myself, I couldn't believe it was so simple." And you see the same thing in whole-Earth oscillations. "They were obviously out of tune, showing two frequencies, representing the two different, fast and slow, paths through the core."

Finding the same thing using two distinct methods is a sign that it is likely to be a feature of the Earth itself. The power of combining different techniques has led Arwen to develop links between her field and mineralogy, for example. "I wanted to see if we can look at the seismology and predict the mineral physics," she says. "And it turns out that it works both ways." The Earth is layered and one layer boundary – discontinuity – at 520 km depth in the mantle, arises because the dominant mineral, olivine, changes its structure under pressure. "We saw one 520 km discontinuity in one place, but in other places we saw a double discontinuity, which was confusing," says Arwen. "Mineral physicists knew that another mineral, garnet, also changes structure at 520 km depth. I had been looking at the data on those odd double discontinuities for months, then everything suddenly fell into place."

There's potential for comparing the seismological picture of the core with that gained by other methods. "It's very satisfying to make the links with mineral physics, back and forth," she says. "It would be really exciting to do it with models of the magnetic field, too, but that's for the future."

For now, Arwen is teaching undergraduate students about these discoveries and she finds that they are as intrigued by the field as she was. "I started out knowing I wanted to apply physics to something and I liked understanding the Earth. Now the physics students are pleased to find that the maths they have learnt, for example in quantum mechanics to describe the hydrogen atom, can also be applied to geophysics. They take on research projects in this area and many go on to careers in the field." ■



Networks of sensitive seismometers allow researchers to extract information from earthquake waves that have passed through the Earth's deep mantle and iron core, as shown in this global wave propagation model of the Earth.

HOW MUCH WILL A DISASTER COST?

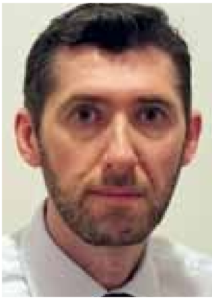
CAREERS

In a world at risk from earthquakes, volcanoes and other natural hazards, Ben Fox is a man who knows how much they cost. He puts his passion for geophysics to work to understand and explain the potential financial effects of such disasters, making a difference to how governments protect people.

"I like dragging ideas into the real world, applying knowledge where it can make a difference." So says Ben Fox, Financial Sector Specialist with the World Bank, who provides technical advice at government level on the potential economic consequences of natural disasters. Ben's special interest is in earthquakes, following undergraduate and postgraduate degrees at the University of Oxford.

"I've always been fascinatated by the natural world, so I chose physics, maths and geography at school, and Earth sciences for my degree," says Ben. "I then went into the financial sector in the City of London, but soon realized that it was not for me. So I went back to Oxford for a PhD in seismology, working on modelling earthquake depth." Afterwards, he took stock. "I found that it was the applications of the work that really appealed to me. I wanted to do something useful." He found it in the insurance business.

Natural hazards are big business for insurance companies, who use software to assess their potential economic risks. Initially, Ben joined a catastrophe model development company, Risk Management Solutions, before joining the reinsurance broker Aon Benfield as a Catastrophe Modelling Analyst. "I suppose I had gone from gamekeeper to poacher in a way," he says. "My team was testing commercially available software used in the insurance industry to see if the underlying science was sensible. These packages sell for millions of dollars and are used routinely to inform the underlying price of insurance and reinsurance contracts. We compared events modelled in the software to what actually happened, to see what economic consequences they modelled well, and what badly."



"My greatest professional pleasure is that it's real applied science"

The 2011 earthquake and tsunami in Japan is the costliest natural disaster in history according to the World Bank. It estimates the economic cost as $235bn.

Earthquake and tsunami

The Tohoku earthquake in Japan in 2011 confounded the models – its consequences were off the scale. The quake was larger than anticipated and the fires and tsunami damage, including at the Fukushima nuclear power plant, were far more extensive, long-lasting and costly than expected, as were the effects on the global supply chain

Ben now works for the World Bank, advising national governments on their potential risk from natural hazards. He identifies effective communication as a key part of this role. "I'm enjoying the challenge of talking to, for example, a minister of finance who's a lot smarter than me, but knows nothing about earthquakes," he says. "He's the person who needs to make decisions and it's my job to communicate the science effectively." So he is designing software conversation tools that incorporate the necessarily complex science but give comprehensible, relevant answers.

"In geophysics research you communicate very complex ideas to a wide range of audiences, and when you apply the work in other fields, you have to do so effectively." Geophysics research gave Ben the chance to learn scientific skills, as well as project and time management, from a very practical perspective, putting physics and maths straight to work on real-life problems. And that's something he continues to do today. "My greatest professional pleasure – and one of the reasons I sleep soundly at night – is that I can apply my knowledge about areas of science that I find fascinating in ways that help governments understand the risk to their populations and economies. It's real applied science." ■

PULLING TOGETHER

Launching one of 100 ocean-bottom seismometers into the Atlantic from NERC's RRS *Discovery* during the iSIMM project.

CAREERS

You don't have to choose between academia and industry, argues scientific advisor at Schlumberger Gould Research Phil Christie: the future lies in collaboration.

After more than 30 years in the oil business, Phil Christie is clear about the value of collaboration between academia and industry, in the right circumstances. "There's a lot that we can do best through collaboration with academic research," he says. "It's usually not something we do when we have a well-defined product or service about to enter the market. But for more adventurous, longer term or higher risk projects, or to work with researchers with decades of specialist experience, then we collaborate."

After a degree in theoretical physics at Oxford, Phil chose to get a job and see something of the world. He started work for Schlumberger as a wireline engineer and spent three years in West Africa, keeping the data – and the oil – flowing from boreholes. He then went to Cambridge for a PhD with Drum Matthews, using his Schlumberger experience in acoustics and electronics to build sea-bottom seismometers for profiling the crust and upper mantle beneath the North Sea. This was at a time when the mechanism for the formation of prospective basins within cratons was still speculative, although two models had been proposed. Phil, together with John Sclater at Cambridge, tested the models against the seismic structure and found that the McKenzie model of passive extension was the best fit for the heat flow and subsidence. They went on to model the sedimentation history of the region, developing methods now widely used in the North Sea and elsewhere. After his PhD and some postdoctoral work for the then National Coal Board, Phil went back to work for Schlumberger and, this time, stayed.

Sponsoring research

"Schlumberger is involved in direct collaborations with researchers, and as part of industry consortia in which several companies sponsor academic research and gain early access to the results," he says. A successful example is iSIMM, the integrated Seismic Imaging and Modelling of Margins project, run for four years jointly by Phil at Schlumberger Gould Research, Alan Roberts at Badley Geoscience Ltd and Profs Bob White and Nick Kusznir at the universities of Cambridge and Liverpool. This LINK project had eight industry partners and support, in cash or in kind, from NERC, EPSRC, WesternGeco and Schlumberger Research. Its goal was to develop a quantitative model for the development of rifted continental margins, using new seismic data from the Atlantic margin in a region where layers of an igneous rock, basalt, had formed during rifting. "Seismic profiling at the time was half-hearted about low-frequency data and conservatively used the higher frequencies to image just the sediments above the basalt layers," says Phil. "We felt sure that low frequencies would have more penetration and be able to 'see' below the basalt. This is what we tested and we proved it could be done."

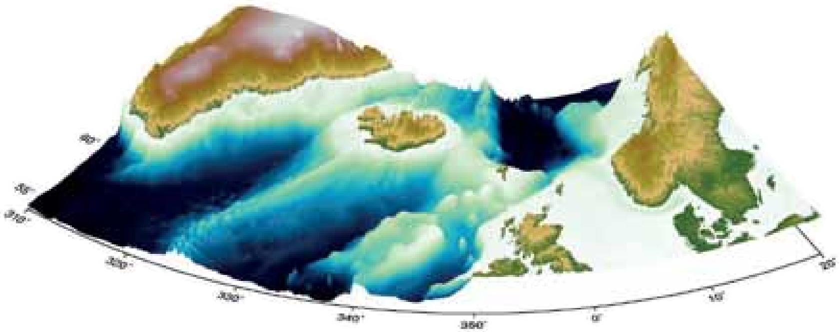
"This was high-risk science but it paid off with the best sub-basalt images of the time"

Their combination of 100 academic ocean-bottom seismometers with state-of-the-art marine seismic cables and processing brought the team an impressive amount of data along a 270km profile extending from the Laggan gas field into the Norwegian Sea at 64°N. This was high-risk science but it paid off with the best sub-basalt images of the time; iSIMM produced more than 50 peer-reviewed publications, two in *Nature*, plus nine PhDs and two postdocs.

Win–win

Throughout a career in which he has repeatedly bridged the gap between industry and research, Phil has found that all parties can benefit from collaborations such as iSIMM. Academic partners get access to industry-quality instruments, data and computer power, while funding bodies get more science for their money. And industry partners can undertake blue-sky research while spreading the costs and sharing the risk of failure. "It's a relatively low-cost way for companies to develop basic knowledge in relevant fields," says Phil. "And it's an excellent way for industry to be involved in the development of really good, well-trained people." ■

iSIMM investigated the ▼ Atlantic margin north of the UK and into the Norwegian Sea. The map shows the Atlantic Ocean across to Greenland, with deep water in deep blue.



KEEPING THE LIGHTS ON

CAREERS

***Ciarán Beggan** at the British Geological Survey in Edinburgh models the Earth's magnetic field and provides space-weather information tailored for clients in power generation and the oil industry, among others.*

"I spend half my time in the BGS Geomagnetism group on novel research into the Earth's magnetic field, tailoring our models of the field and its interaction with space weather. Our modelling gives our clients predictions of field behaviour in the future, and real-time measurements where that matters," says Ciarán Beggan. "For the other half I research the effects of space weather on power transmission, working with National Grid UK."

Real-time data make a difference for directional drilling, when oil companies want a borehole to follow a particular path; they use the Earth's magnetic field as a reference to guide and correct the drill. Where magnetic rocks are close to the borehole, they can distort the local magnetic field by 1° or more, a significant effect over a few hundred metres. "We provide a detailed map of how rock features change the field. But space-weather events make a difference, too, which is why companies sign up for our real-time alerts."

"This is a risk that needs to be understood – any problems could have a high impact on society and business"

Seeing the Earth's core

Ciarán has long been fascinated by space – that's what drew him to geophysics in the first place. His master's degree at the University of Edinburgh in remote sensing and planetary imaging involved computational physics. "I was really understanding how light travels through the atmosphere and what you're actually detecting when you take a photograph. It gave me a deep understanding of the difference between theory and measurement." He went on to a PhD on planetary geomagnetism, also at Edinburgh, exploring the Earth's core using satellite data and ground-based measurements. "I was fascinated by this Mars-sized liquid ball at the centre of the Earth, and the fact that we can 'see' it by measurements we take at the surface, 3000km above."

Ciarán's career keeps him at the interface between theory and measurement. His modelling work helps to keep the forecasts and nowcasts issued by the BGS as reliable as possible, but also feeds into geomagnetism research. BGS also responds to commercial need, which is how he came to work on the effects of geomagnetic storms on the UK power grid – a risk to power supply that has been appreciated only recently. "I'm working with the National Grid because this is a risk that needs to be understood – any problems could have a major impact on society."

Space-weather events can induce extra electrical currents in power lines, bringing the possibility of overload and damage to transformers. The BGS has been working in this field for some 15 years, because the effects of solar activity on power transmission depend on the conductivity of the rocks beneath the ground and the structure of the power network as well as on the nature and scale of the Sun's activity. "There's a need for fundamental understanding of how geomagnetic storms affect the field on Earth and how the grid responds," says Ciarán. "We've included in our model an improved understanding of the conductivity structure of the ground, based on BGS geological mapping. It works in Finland, where the power grid is relatively simple, and we're waiting to see how well it works in the UK."

The National Grid is complex, because it was made by combining six independent power grids. Its configuration – especially long unbroken lines – makes some parts more vulnerable to induced currents and, of course, the shape of the grid is changing. "It's not so much of a problem in cities such as London, where induced currents do not build up," he says. "The problem lies in long isolated lines, or at the end of lines such as at wind farms in remote areas."

Ciarán's geophysics research gave him a broad overview of how the Earth works, as well as the skills to focus on simple models as a first step. "You're in with a chance of doing something useful if you start with the bare minimum and gradually make it more complex," he says. "With induced currents we've gone from nothing to a website for the National Grid with near real-time predictions. That's going to help drive engineering solutions to this problem." ■

Giant solar flares (top) can produce space-weather events that affect the Earth's magnetic field and induce currents in power cables; modelling the effects on the National Grid could help to avoid power cuts.

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