GeoCam

EARTH SCIENCES ALUMNI MAGAZINE

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NEWS

Volcanic arcs recycle crustal carbon

FEATURE

Deep mysterious piles

RESEARCH

Unravelling the early evolution of animal life

UNIVERSITY OF CAMBRIDGE

Welcome

The turn of the year, be it calendar, lunar or academic, often provokes a moment of reflection, looking back to the past and forward to the future. In a way, the whole business of geosciences could be characterised in the same terms. Not only is the present the key to the past, the past can inform our future. It feels, increasingly, that there is a special urgency for Earth Sciences to help guide our futures. Over the last year, we have spent some time in the department reflecting on how our science can serve society more widely.

In our research, we are driven by our desire to understand the fundamental principles by which our planet works, and to make sense of our observations, be they in the field, the laboratory, or at the computer. It is delightful to see the recognition that members of the department have received in the form of various accolades, some recorded in these pages. We are all aware of the fundamental discoveries made in the realm of plate tectonics within our precincts just fifty years ago. But we are also acutely aware that humanity's needs and the long term (ok, geologically short term) 'health' of the planet are intertwined intimately. In that context, members of the department are understanding climate change, securing the resources that society depends upon, and making sense of old tectonic and volcanic hazards that may become new threats to society as urban centres expand.

One endeavour highlighted in this issue of *GeoCam* is the new partnership between industry and the department to tackle carbon capture and storage; the challenge of locking carbon from fossil fuel burning and cement manufacture back into the solid Earth. Another current challenge is how best to deal with the UK's legacy of spent nuclear fuel through deep geological disposal. A third research drive is on earthquake hazards across the Tethyan belt that runs from the Mediterranean to South West China, which has taken on a new dimension in the context of China's "Belt and Road" project. So, there are opportunities aplenty for our science to have impact; our looking forward is increasingly trying to chart that path to make the links between science and society.

Finally, we look back with a sense of great loss this year, as two members of the academic staff who pre-date the department's formation in 1980 passed away. Christine Kelsey helped engender a love of symmetry, crystalline materials, and atomistic wonder in me in my days as a young mineralogist. Alan Smith is remembered fondly for his wisdom and wit as well as the insights he provided in tectonics. Looking forward, we welcome on to the staff Owen Weller, who picks up the mantle of understanding tectonics in ancient Earth history, Oli Shorttle, who is developing a new understanding of the "geosciences" of exoplanets and Emilie Ringe who works at the nanometre length scale to understand the interactions between light and crystalline materials.

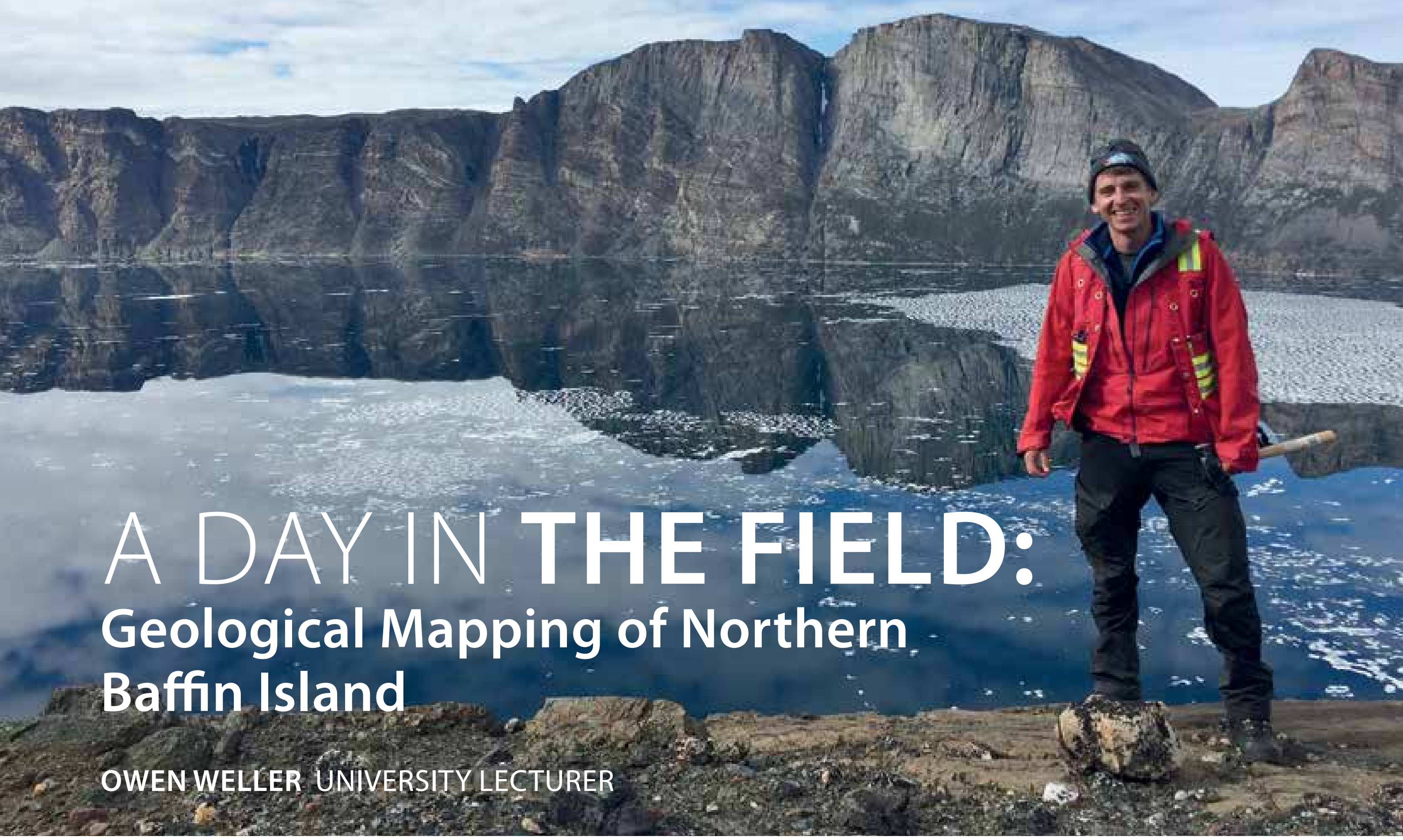
I hope you are able to visit the department at some stage in the coming year to catch up on our future vision, and to share in it.

Simon

Simon Redfern Head of Department

IN THIS ISSUE

COVER IMAGE: OWEN WELLER COLLECTING A FOLIATION MEASUREMENT IN THE MESOARCHEAN BASEMENT ORTHOGNEISS OF NORTHERN BAFFIN ISLAND, CANADA, WITH BYLOT ISLAND VISIBLE ACROSS ECLIPSE SOUND IN THE BACKDROP.



A DAY IN **THE FIELD:**
Geological Mapping of Northern Baffin Island

OWEN WELLER UNIVERSITY LECTURER

The Archean Eon (4–2.5 billion years ago) is one of the last great frontiers in our knowledge of the Earth. Plate tectonics is considered to have initiated during this time period, and large volumes of the continental crust formed, but fundamental questions remain regarding the timing, mechanisms and drivers of these transitions. Central to these debates is understanding the origin of a unique feature of Archean terranes: so-called 'granite-greenstone belts'. These are linear to circular arrays of volcano-sedimentary sequences that have been metamorphosed to greenschist facies, and located within large regions of gneissic granitoids. These enigmatic belts are particularly well exposed across northern Baffin Island in the eastern Canadian Arctic, so I visited this region last summer to conduct a targeted study of their formation.

Fieldwork in the High Arctic is logistically challenging. Thankfully, I was able to collaborate with the Geological Survey of Canada (GSC), my former employers, who are conducting a new bedrock mapping campaign in the region. Our fieldwork base was the predominantly Inuit community of Pond Inlet, which is located along the north shore of Baffin Island. Pond is renowned as one of the jewels of the Arctic; a series of snow-capped mountains with glaciers cascading off their margins form a picturesque backdrop. We arrived just as the sea ice was starting to break up, and it was fascinating to watch the mosaic of icebergs in the bay jostle and dissipate over the summer. The waters surrounding Pond Inlet are also nutrient rich, and we enjoyed regular sightings of various seals and whales, including most memorably a pod of narwhal.

EACH DAY, WHEN THE WEATHER PERMITTED SAFE TRAVEL BELOW A MINIMUM CEILING OF VISIBILITY, WE COMMUTED TO A DIFFERENT PART OF THE FIELD AREA VIA A BELL 407 HELICOPTER.

Using Cold War era air photos, we had pre-planned a series of ~10km foot traverses across features of interest. The helicopter would drop us at one end of the traverse, and leave a survival bag at the other, and our task was to walk between the two, recording observations into digital field tablets. In tandem with airborne gravity and magnetic surveys, our measurements are then compiled to produce modern geological maps of the region, which will be released as a series of 1:100 000 bedrock maps in both English and Inuktitut (the language of the Inuit) in April 2018.

Although the weather was inevitably challenging at times, and the latent threat of polar bears ever-present, it was a pleasure and a privilege to do research alongside affable colleagues from Canada in such a beautiful, fascinating and frontier region. The fieldwork was highly successful and I was able to collect a very promising sample suite for ongoing analysis in Cambridge. I would like to acknowledge the support of the NERC UK & Canada Arctic Partnership Bursary Programme, without which this exciting new collaboration would not have been possible. This fieldwork is hopefully just the tip of the research iceberg as I start my career at Cambridge, and indeed I will be visiting the Arctic again next summer to further investigate the start of plate tectonics on Earth.

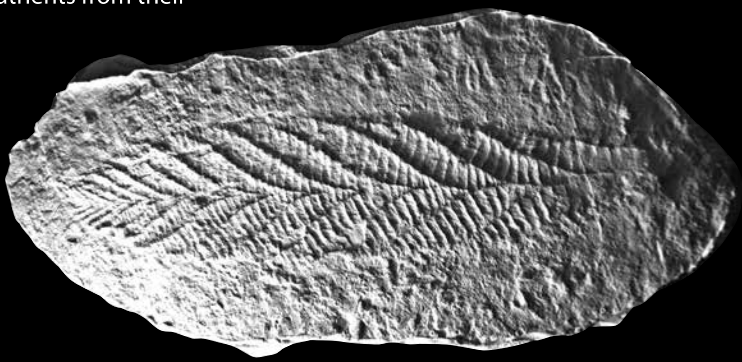
The 2017 field crew, including colleagues from the GSC, students, a GIS expert and a pilot.

BIG, SHAPE-SHIFTING ANIMALS FROM THE DAWN OF TIME

Why did life on Earth change from small to large when it did? Earth Sciences' Jennifer Hoyal Cuthill and Simon Conway Morris have determined how some of the first large organisms, known as rangeomorphs, were able to grow up to two metres in height, by changing their body size and shape as they extracted nutrients from their surrounding environment.

Their results could also help explain how life on Earth, which once consisted only of microscopic organisms, changed so that huge organisms like dinosaurs and blue whales could ultimately evolve.

Read more goo.gl/ho7FPt



RESEARCH **NEWS**

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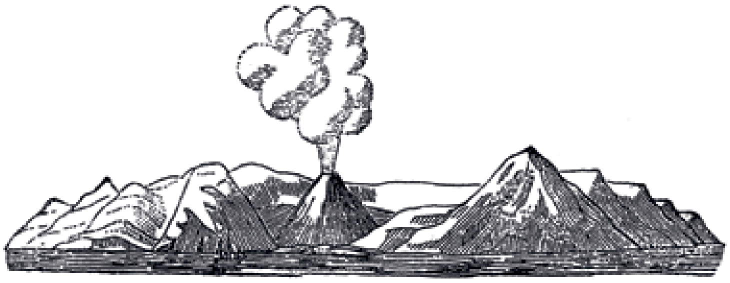
NEW STUDY SHAKES THE ROOTS OF THE DINOSAUR FAMILY TREE

More than a century of theory about the evolutionary history of dinosaurs has been turned on its head by the publication of new research from scientists at the University of Cambridge and Natural History Museum in London.

Cambridge's Matt Baron and David Norman, together with alumnus Paul Barrett of the Natural History Museum in London, have concluded that long-accepted familial groupings may in fact be wrong, leading to a radical reconfiguring of the dinosaur family tree. While analysing this tree the team arrived at another unexpected conclusion: that dinosaurs may have originated in the northern hemisphere rather than the southern, as current thinking goes.

Read more goo.gl/mxPTVD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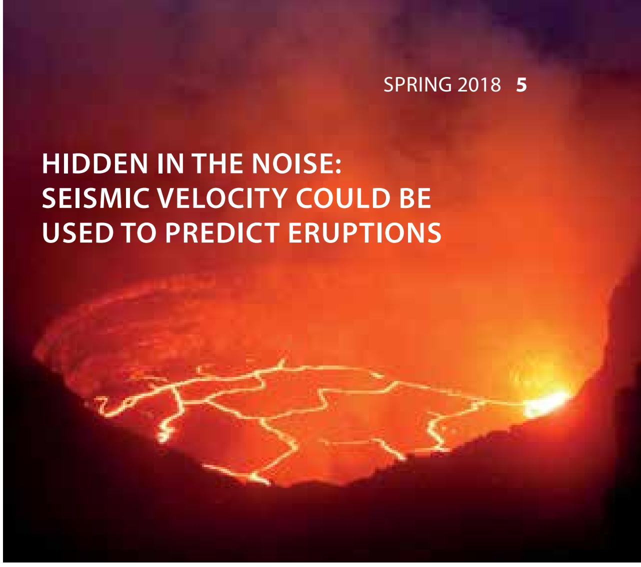
VOLCANIC ARCS RECYCLE CRUSTAL CARBON

Research by Earth Sciences' Marie Edmonds, Sasha Turchyn and Emily Mason has challenged fundamental assumptions about the role volcanoes play in cycling carbon between the deep Earth and the atmosphere.

The team have compiled a new global dataset of carbon and helium isotope compositions of volcanic gases released by over 80 arc volcanoes. Contrary to a carbon cycle paradigm, most volcanoes have a composition that is significantly offset from mantle values towards a shallow crustal carbonate signature. They also show that volcanoes with this signature (e.g. Mt Etna) emit the most CO_2. Through isotope mass balance calculations these results have the potential to change the way we interpret the long-term carbon isotope record and therefore estimates of oxygen concentrations in Earth's ancient atmosphere. This work extends and provides support to previous work that has shown that supercontinent aggregation and dispersal has the potential to modulate carbon dioxide concentrations in the atmosphere. Edmonds, Turchyn and Mason show that these tectonic processes have the potential to influence the carbon isotope record too.

Read more goo.gl/jtJv6a



HIDDEN IN THE NOISE: SEISMIC VELOCITY COULD BE USED TO PREDICT ERUPTIONS

Traditionally, volcano seismology is the study of small earthquakes at volcanoes, which occur when magma moves underground, forcing its way through solid rock. But many processes, such as 'silent' magma flow and pressurisation of magma reservoirs, can happen without generating earthquakes.

Seismic noise is the part of the seismogram usually ignored by seismologists, but just over ten years ago, it was recognised that there is useful information there, being recorded continuously.

A team of Cambridge researchers, led by research student Clare Donaldson, have used seismic noise and found that seismic velocity at Kīlauea in Hawai'i is correlated with deformation over a four-year period. The noise therefore reflects the pressurisation of the summit. The researchers anticipate that this method will be used at hundreds of active volcanoes around the world.

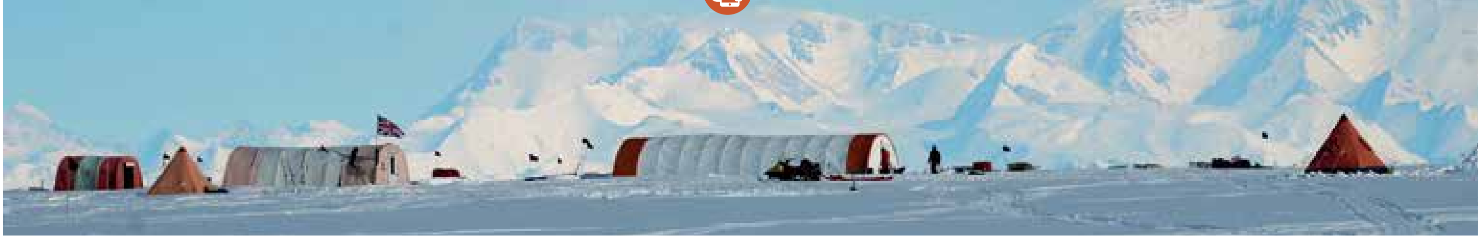
Read more goo.gl/N9bS47

EUROPEAN RESEARCH COUNCIL (ERC) PROJECT TO INVESTIGATE THE WARM CLIMATE STABILITY OF THE WEST ANTARCTIC ICE SHEET

Recent modelling studies predict that anthropogenic warming could lead to the loss of the West Antarctic Ice Sheet (WAIS) in the next few centuries, and a big rise in sea level. This new project aims to discover whether the WAIS was destroyed by similar warming in the last interglacial, as modelling and indirect evidence suggest.

The five-year ERC WACSWAIN project, led by Prof. Eric Wolff, will involve colleagues in the Department of Earth Sciences and at the British Antarctic Survey. During field seasons in the West Antarctic the team will drill two new ice cores. These will be analysed in Cambridge to understand past retreats of the ice sheet, allowing models for ice sheet cover on the continent over the past 130,000 years to be tested.

goo.gl/78tTxC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MIKE BICKLE, PROFESSOR OF TECTONICS
JEROME NEUFELD, UNIVERSITY LECTURER DAMTP AND EARTH SCIENCES

CARBON CAPTURE:

Universities and industry work together to tackle emissions

AN INTERNATIONAL COLLABORATION BETWEEN UNIVERSITIES AND INDUSTRY WILL FURTHER DEVELOP CARBON CAPTURE AND STORAGE TECHNOLOGY – ONE OF THE BEST HOPES FOR DRASTICALLY REDUCING CARBON EMISSIONS – SO THAT IT CAN BE DEPLOYED IN A WIDER RANGE OF SITES AROUND THE WORLD.

The world is not going carbon-free any time soon: that much is clear. Developed and developing countries alike rely on fossil fuels for transport, industry and power, all of which release CO_2 into the atmosphere. But as sea levels rise, 'unprecedented' weather events become commonplace and the polar ice caps melt, how can we balance our use of fossil fuels with the imperative to combat the catastrophic effects of climate change?

"Everything suggests that we won't be able to stop burning carbon-based fuels, particularly in rapidly developing countries like India and China," says Mike Bickle. "Along with increasing use of renewable energy and improved energy efficiency, one way to cope with fossil fuel use is carbon capture and storage – and there is no technical reason why it can't be deployed right now."

Carbon capture and storage (CCS) is a promising and practical solution to drastically reducing carbon emissions, but it has had a stilted development pathway to date. In 2015, the UK government cancelled a £1 billion competition for CCS technology six months before it was due to be awarded, citing high costs. Just one year later, a high-level advisory group appointed by ministers recommended that establishing a CCS industry in the UK now could save the government and consumers billions per year from the cost of meeting climate change targets.

CCS is the only way of mitigating the 20% of CO_2 emissions from industrial processes – such as cement manufacturing and steel making, for which there is no obvious alternative – to help meet the world's commitments to limit warming to below 2°C. It works by trapping the CO_2 emitted from burning fossil fuels, which is then cooled, liquefied and pumped deep underground into geological formations, saline aquifers or disused oil and gas fields. Results from lab-based tests, and from working CCS sites such as Sleipner in the North Sea, suggest that carbon can be safely stored underground in this way for 10,000 years or more.

"The big companies understand the science of climate change, and they understand that we've got to invest in technologies like CCS now, before it's too late," says Jerome Neufeld. "But it's a tricky business running an industry where nobody is charging for carbon."

"Everyone always wants the cheapest option, so without some form of carbon tax, it's going to be difficult to get CCS off the ground at the scale that's needed," says Bickle. "But if you look at the cost of electricity produced from gas or coal with CCS added, it's very similar to the cost of electricity from solar or wind. So if governments put a proper carbon charge in place, renewables and CCS would compete with each other on a relatively even playing field, and companies would have the economic incentive to invest in CCS."

Bickle and Neufeld are following discussions about CCS closely because, along with collaborators from Stanford and Melbourne Universities, they have recently started a new CCS project with the support of BHP, one of the world's largest mining and materials companies.

The three-year project will develop and improve methods for the long-term storage of CO_2, and will test them at Otway in southern Australia, one of the largest CCS test sites in the world. Using a mix of theoretical modelling and small-, medium- and large-scale experiments, the researchers hope to significantly increase the types of sites where CCS is possible, including in China and developing economies.

In most current CCS schemes, CO_2 is stored in porous underground rock formations with a thick layer of impermeable rock, such as shale, on top. The top layer provides the seal to ensure that the relatively light CO_2 will not escape.

The new research, which will support future large-scale CO_2 storage, will consider whether CO_2 could be effectively trapped without the top seal of impermeable rock, meaning that CCS could be deployed in a wider range of environments. Their research findings will be made publicly available to accelerate the broader deployment of CCS.

Mike Bickle taking part in a GPS-located drone survey of fossil CO_2 leakage from a natural CO_2 reservoir in Utah

"We are seeing a growing acknowledgement from industry, governments and society that to meet emissions reductions targets we are going to need to accelerate the use of this technology – we simply can't do it quickly enough without CCS across both power generation and industry," says BHP Vice President of Sustainability and Climate Change, Dr Fiona Wild. "We know CCS technology works and is proven. Our focus at BHP is on how we can help make sure the world has access to the information required to make it work at scale in a cost effective and timely way."

During the project, Stanford researchers will measure the rate at which porous rock can trap CO_2 using small-scale experiments on rock samples at reservoir conditions, while the Cambridge researchers will be using larger analogue models, in the order of metres or tens of metres. The Melbourne-based researchers will use large-scale numerical simulations of complex geological settings.

"One of the things this collaboration will really open up is the ability to deploy CCS almost anywhere," says Neufeld. "We know that CO_2 can be safely trapped in porous rock with a seal of shale on top, but the early results from Otway have shown that even without the impenetrable seal, CO_2 can be trapped just as effectively."

When CO_2 is pumped into underground saline aquifers, it is in a 'super-critical' phase: not quite a liquid and not quite a gas. The super-critical CO_2 is less dense than the salt water, and so has a tendency to seep upwards, but it's been found that surface tension between the salt water and the rock is quite effective at pinning the CO_2 in place so that it can't escape. This phenomenon, known as capillary trapping, is also observed when water is held in a sponge.

"The results from Otway show that if you inject CO_2 into a heterogeneous reservoir, it will mix with the salt water and capillary trapping will pin it there quite effectively, so it opens up a much broader range of potential carbon storage sites," says Bickle.

"However, we need to start deploying CCS now, and the biggest challenges we face are economics and policy. If these prevent us from doing anything until it's too late, and we're at a stage when we'd have to start capturing carbon directly from the atmosphere, it will be far more expensive. By not starting CCS now, we're building false economies."

Sarah Collins

This is an edited version of an article that first appeared in Research Horizons, Issue 34.

Deep Mysterious Piles

SANNE COTTAAR
UNIVERSITY LECTURER, GLOBAL SEISMOLOGY

THE COOLING OF THE PLANET DRIVES MANTLE CONVECTION AND PLATE TECTONICS. THE LOWERMOST HUNDREDS OF KILOMETRES OF THE MANTLE REPRESENT THE LOWER THERMAL BOUNDARY LAYER OF MANTLE CONVECTION. SEISMOLOGY PROVIDES INDIRECT OBSERVATIONS OF THIS LAYER, AND RESULTING IMAGES SHOW ITS HIGHLY HETEROGENEOUS NATURE.

The two largest heterogeneities have anomalously slow velocities and are named Large Low Velocity Provinces (LLVPs). Laterally they are the size of continents, covering roughly 30% of the core-mantle boundary, while vertically they extend hundreds of kilometres, and in places up to 2000 kilometres from the core-mantle boundary. The two LLVPs are antipodal, sitting beneath the Pacific and Africa. The LLVPs are surrounded by faster velocities, which are interpreted to be regions where subducting slabs pond on the core-mantle boundary and potentially where the high-pressure phase post-perovskite is stable due to colder temperatures. The LLVPs are often interpreted as compositionally distinct piles. Most volcanic hotspots at the surface overlie these two LLVPs, and anomalous geochemical signatures in their basalts could be explained by entrainment from the compositionally distinct piles.

Hints of the presence of LLVPs started to emerge from seismic tomographic studies of the lower mantle decades ago. Current global seismic tomographic efforts are improving the resolution of the lower mantle. However, seismic tomography always produces smoothed images, which are inherent to the inversion methodology. Corroborative observations come from body wave studies, which can target the boundaries of these features by studying waveform complexities with higher frequencies and thus higher resolution than tomographic studies. Body waves show the boundaries have sharp jumps in absolute velocity, and also show a change in anisotropic velocity. The former argues for a compositional change across the boundary, while the latter argues for a change in flow pattern, and both suggest the LLVP represents a mechanical boundary.

We have recently applied clustering analyses to look at the agreement on LLVPs across global tomographic models. This method clusters seismic tomographic profiles, and provides a fairly objective technique that groups distinctive areas in the tomographic model, the boundaries of which are sensitive to strong gradients in the model. Comparing the grouping across a number of models, in a 'vote map' shows remarkable consistency across shear velocity models in the suggested boundaries of the 'slow group' representing LLVPs or piles (Figure 1). This approach offers various new insights on LLVPs.

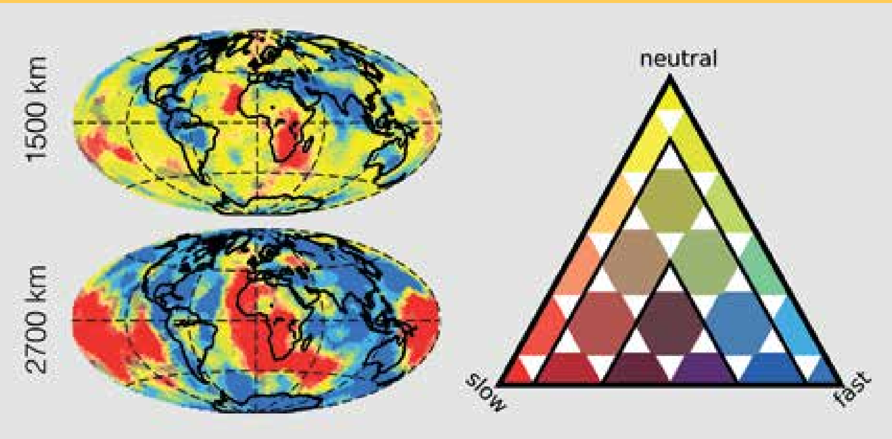

Figure 1:
Vote maps for three clusters ('slow,''fast,''neutral') and five global tomographic models are shown for 1500 and 2700km midpoint depths. The colour bar on the right is inspired by a ternary diagram. Bright red, blue, and yellow colours indicate all five models agree on the region being 'slow,' 'fast' or 'neutral,' respectively. Orange colours show disagreement between 'slow' and 'neutral,' while green colours show disagreement between 'fast' and 'neutral.' Darker and purple colours in the inner triangles show disagreement between 'fast' and 'slow' and mostly occur in regions of poor data coverage (e.g. the South Pacific). At 1500km, linear blue features are interpreted as subducted slabs, and circular red regions as regions where the LLVP extends high. At 2700, the two LLVPs, as well as several meso-scale features stand out of otherwise fast material.

Firstly, the analysis suggests LLVPs make up five to eight per cent of the entire mantle, which is around double the volume of any previous estimates. The African LLVP is about 30 per cent larger than the Pacific LLVP. Volume estimates of LLVPs are needed to assess their potential as a geochemical reservoir for trace elements, noble gases, and radioactive elements.

Secondly, the 'vote map' shows agreement on a highly variable morphology of the LLVPs, showing shallowly sloping edges to steep edges, and even an overhanging edge (on the east side of the African LLVP). The variable morphology could result from interaction with surrounding dynamics, including subducted slabs, and variability in composition and dynamics within the piles.

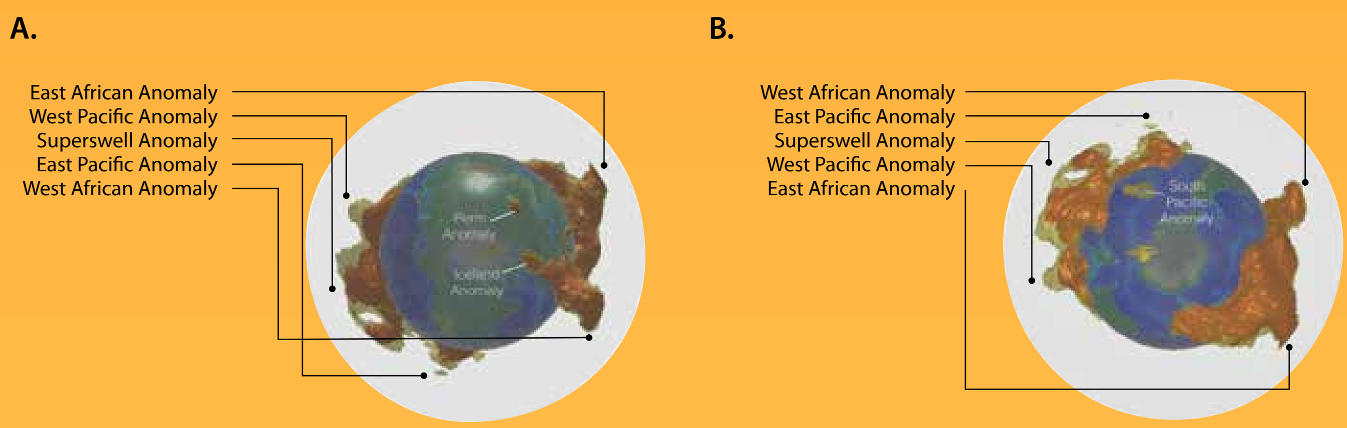

Figure 2:
Contour of the votes for the slow cluster are shown for a majority (transparent yellow) and for consensus (red) across all models. The anomalies are viewed a) from the North pole and b) from the South Pole, and include names we gave to 'subpiles' with the two main LLVPs and meso-scale piles outside. Surface topography is projected onto the CMB for reference.

Lastly, the 'vote map' shows agreement across the tomographic models for smaller lower velocity features outside of the two main LLVPs, which are on the order of 1000km in width (Figure 2). Such low velocity meso-scale features are difficult to interpret in individual tomographic models, but become more significant when seen across a number of models. Two of these features, one beneath the Ural Mountains in Russia, and one beneath the South Pacific are hundreds of kilometres high. Beneath Kamchatka there is a feature, which shows less agreement across the models, potentially because it might be thinner than 100km. The challenge and uncertainty remains if these meso-scale features are piles consisting of the same material as LLVPs, in this case meso-scale piles would need to be reproduced in any geodynamical scenario explaining the larger piles.

Many questions remain on the origin and dynamical role of LLVPs. Constraints on composition are weak, as the Vp/Vs ratio and density of LLVPs are poorly constrained. They could be a remnant of early Earth differentiation, potentially decreasing in size over time due to entrainment in mantle convection. An alternative scenario, in which LLVPs grow over time, is the accumulation of subducted basalt at the core-mantle boundary. In both cases, LLVPs are compositionally dense and thermally hot piles. The question remains to what degree the LLVPs are stable and to what degree they control the surrounding convection and the supercontinent cycle.

FURTHER READING:

Cottaar, Sanne, and Vedran Lekić. 2016. "Morphology of Seismically Slow Lower-Mantle Structures." *Geophys. J. Int.* 207 (2): 1122–36.

Cottaar, S, and B Romanowicz. 2013. "Observations of Changing Anisotropy across the Southern Margin of the African LLSVP." *Geophys. J. Int.* 195 (2): 1184–95.

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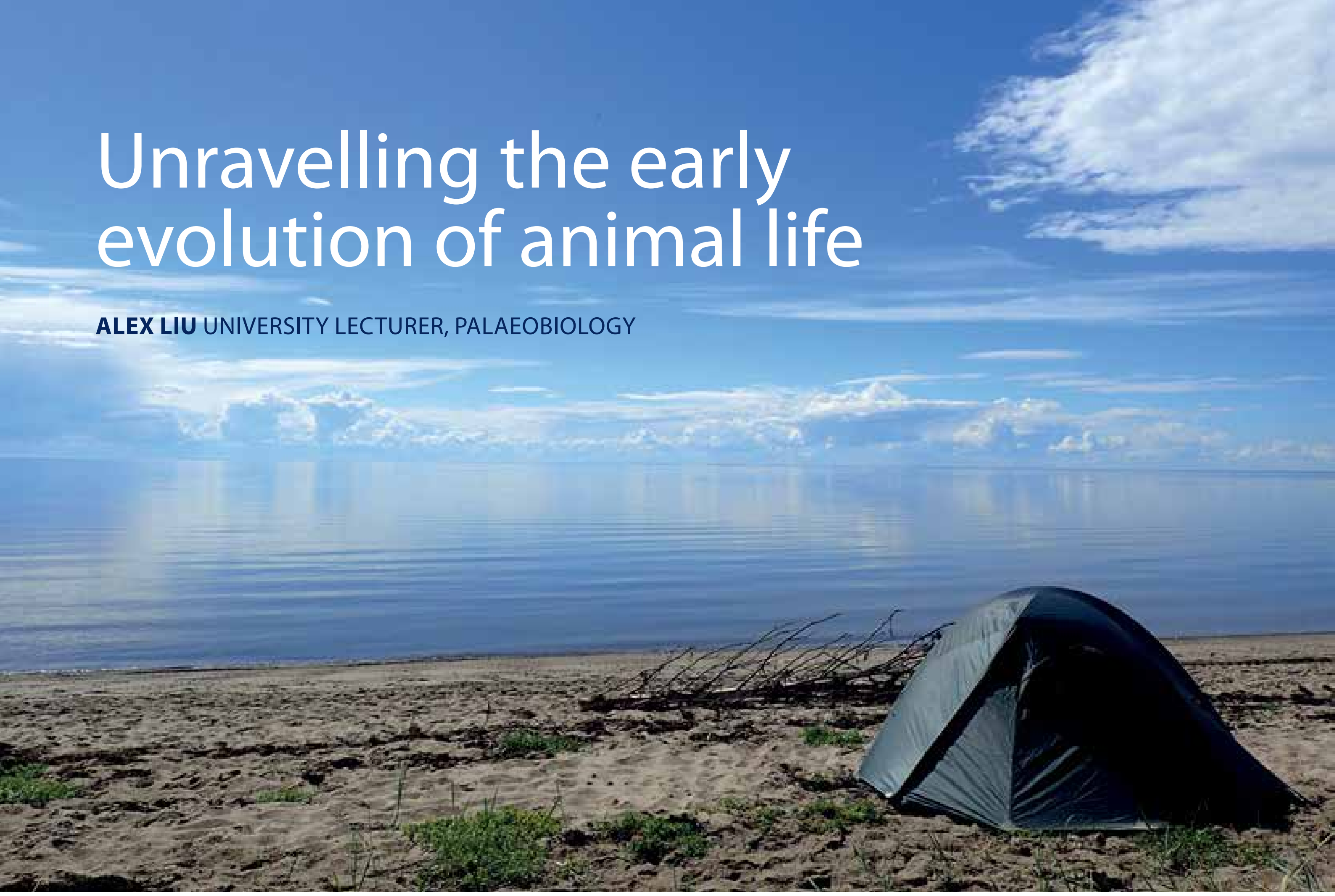
Unravelling the early evolution of animal life

ALEX LIU UNIVERSITY LECTURER, PALAEOBIOLOGY



A view of the White Sea from our Lyamtsa beachfront campsite.

The first diverse communities of large and complex organisms appeared in the global oceans in the late Ediacaran Period, some 570 million years ago. Researchers are gradually making progress in determining how these organisms, the Ediacaran biota, relate to modern taxa.

"Once you get home, you will forget the mosquitoes. I never remember the mosquitoes". I found those words hard to believe as I sat by the campfire amidst a swarm of blood-thirsty insects, on the second day of my fieldwork on the coast of the White Sea, Russia. Even though our trip leader Dima Grazhdankin (a post-doc in the department 2000–2005) was a seasoned visitor to the region, how such horrors could be forgotten when they seemed to occupy every waking moment was beyond comprehension.

We had travelled to the White Sea in search of Ediacaran macrofossils. The area is renowned for some of the most diverse and spectacularly preserved examples of the Ediacaran biota – a group of largely soft-bodied organisms that evolved ~40 million years before the Cambrian – anywhere in the world. Dima and I were working together to obtain both a better understanding of the stratigraphic distribution of Ediacaran fossils in the region, and to sample tuffs that could be dated to constrain the timing of their appearance. Dima had discovered many of the sections we would visit during his undergraduate research 20 years ago, and this was the first time he had returned since completing that research. I was to be one of the first non-Russians to ever see the sections.

It soon became apparent why, despite the fame of the White Sea fossils, so few people, Russian or otherwise, had studied them. Our journey involved driving through the city of Severodvinsk (until a few years ago completely closed to outsiders since it is home to Russia's nuclear submarines), travelling in the back of a large truck for 35km along a beach at low tide, and a 13km hike carrying 25kg packs through a swamp, during a thunderstorm. Each day we came under attack from mosquitoes, midges and horseflies, meaning we sweltered under our layers of protective clothing, and dreaded the call of nature. When we did find fossil localities, the specimens required excavation from gloopy, sticky muds and clays that soon had us all covered in a grey veneer.

Despite these hardships, the rewards we obtained were worth the effort. At one locality we unearthed six specimens of the iconic Ediacaran frond *Charnia masoni*, which are amongst the most exquisite ever collected. *Charnia* is one of the oldest of the Ediacaran biota, and these specimens reveal morphological features to a level of detail not achieved at other localities. In conjunction with studies that my PhD student Frances Dunn and I have conducted in Newfoundland (Canada), the new specimens suggest *Charnia* was likely to be an early animal. Other discoveries, including new taxa, new behaviours, and interesting palaeoecological relationships, demonstrate that the White Sea *Charnia* specimens shared their environment with protists, algae, and microbial communities. Together, our research has revealed that marine ecosystems were diverse, thriving habitats, many millions of years before the Cambrian Explosion.

The White Sea fieldwork enabled me to gain valuable first-hand knowledge and context from the region that will greatly inform my research into other global localities. I am interested in multiple aspects of Ediacaran palaeobiology, but it is becoming increasingly apparent that our best chance of elucidating the biology of these organisms is via comparison of specimens from different global localities, which are subject to different taphonomic and environmental conditions. Dima and I have already developed plans to expand our project further afield, to Siberia and Canada, to test hypotheses we developed in the White Sea. We hope that our collaboration will usher in a new era of Ediacaran research in Russia, enabling the wider scientific community to utilise and appreciate the fantastic palaeontological riches on offer in the region.

So now I am back home, was Dima right about the insects? It's clear that I am yet to forget them, but the lasting memories I will take from the trip are the positive ones: of beautiful scenery, fascinating culture, and spectacular fossils that made all of the suffering very worthwhile!

1. Partial specimen of the Ediacaran frondose organism Charnia masoni, from the Solza River. Specimens from this locality are exceptionally preserved in three dimensions, offering unprecedented insight into the original morphology of these organisms.
2. The field team, primarily from IPGG Novosibirsk. Expedition leader and former Cambridge JRF Dima Grazhdankin is second from left.
3. A fossil of the Ediacaran taxon Dickinsonia, recently confirmed as an early animal.
4. Brown bear tracks in the sand one morning, ~50m from our tents!
5. A typical excavation platform in the cliffs at Lyamtsa. Fossils were found on the bases of rare sandstone beds, such as the one at the base of the platform.

IN CONVERSATION WITH …
Nick Rawlinson

BP MCKENZIE CHAIR IN EARTH SCIENCES

GEOPHYSICIST PROFESSOR NICK RAWLINSON HAS RECENTLY MOVED TO CAMBRIDGE TO TAKE UP THE BP MCKENZIE CHAIR. DURING A CAREER IN AUSTRALIA AND THE UK HE HAS SPECIALISED IN OBSERVATIONAL AND THEORETICAL SEISMOLOGY. NICK DISCUSSED HIS LIFE AND WORK WITH GREG PALMER.

How did you get in to Earth Sciences?

When I finished high school I wanted to continue in music rather than science. I spent several years at the Melbourne University conservatorium playing trombone, but then I realised to be a performer you had to be the best of the best, and I wasn't up there. That was when I started doing science. I took an Earth Sciences course and started being slowly sucked in to this vortex of interesting research about the planet we live on.

What did you work on in your early career in Australia?

I did my final undergraduate year in applied mathematics at Monash University, but I specialised in geophysics. I stayed there for my PhD, on seismic imaging of Tasmania. Geoscience Australia circumnavigated Tasmania with a research vessel that fired airgun shots, which were recorded by land-based stations; this enabled me to build a 3D seismic image of the crust. At the end of my PhD I moved to the Australian National University in Canberra. I spent 12 years there, starting as a PostDoc and moving up to Senior Fellow. In fact I calculated almost to the day it was an eighth of a century – that's quite a long time.

Professor Nick Rawlinson in his Downing College study, portrait by Sara Rawlinson

Left: Deploying a broadband seismic station in western Tasmania as part of the TIGGER project.
Middle: Rolling hills in Gippsland, Victoria, where we deployed a number of short period stations as part of the WOMBAT array.
Right: Short period station deployed in outback NSW. Fence posts are an ideal place on which to mount a GPS receiver!

I started working on the more theoretical side of seismology, looking at things like geophysical inverse problems and numerical techniques for tracking seismic wave fronts. However they also had a very strong observational seismology group at ANU and hundreds of seismometers.

My main focus was the WOMBAT array: a transportable seismic array, similar in concept to USArray. However, as I tell everyone, WOMBAT came first, but on a shoestring budget. I spent several months every year in the field, in various parts of Australia, deploying these instruments. We'd simply turn up, knock on a door, and say "can we put an instrument on your property". I must have been to over 600 separate sites, and we collected a lot of good data.

You were at Aberdeen before moving to Cambridge. What brought you to the UK?

I'd been at ANU for 12 years so a change seemed like a good thing. One of the things I started looking at there was intraplate volcanism and high resolution images of the lithosphere. We demonstrated how volcanism can be related to plate motion and structure in the underside of the lithosphere interacting with the mantle underneath. Using another of our lithospheric maps we were able to identify the longest volcanic track on the planet, in Queensland. That was published in *Nature* and generated a lot of interest at the time.

What research do you have planned for the future?

I've got new things cooking up, one of which is getting back in to observational seismology. We're deploying a dense network of seismometers in North Borneo in February 2018. Offshore, in the South China Sea, the Chinese are going to deploy Ocean Bottom Seismometers at the same time.

Why that part of the world?

No one has done this kind of work in that part of South East Asia before. It has Mt Kinabalu, which is essentially a granite pluton which has emerged very rapidly in a few million years. There are also unique circular basins. On a topographic map they look like impact craters, but inside they are akin to a sedimentary basin. No one's really been able to explain how either feature formed. There is also a complex geological history of subduction, uplift, erosion, faulting, thrusting and seismic hazard in the area.

A trip to Borneo sounds like quite an adventure!

Deploying the instruments will be exciting. We'll use boats where the terrain gets rugged and the access is not so good. Out in the South China Sea there are a couple of Malaysian Islands and we're going to go out on fast launches to deploy a few stations on those. They should link up with the seismometers on the sea floor.

I visited one of the circular basins last summer. We're going to put one station on the inside and one station on the outside in order to try and get an understanding of what's actually underneath, and how it contrasts with the adjacent crust. Apparently there are a lot of ladders and climbing involved in getting inside. All the students coming with me are very excited by this adventure, but I haven't told them about the leeches yet. Borneo is well known for its leeches, and this place is wet, pristine jungle so it's going to be crawling with them…

We'll go back to service the seismometers after a few months, so we'll probably get our first data in mid 2018.

You're a fellow at Downing College. How are you finding college life?

When I moved here I thought it would be rather fitting to join them because my father went to Downing as an undergraduate in the 50s and 60s. It's good, though it has been pretty full on so far. When Ken McNamara retired he passed on his Director of Studies role and work to me. I'm sure after a year or two I'll get used to it. The students are all bright and interested so its not a hardship when you're dealing with people like that. We have formal dinners, wine tastings and concerts too – the food is good and the grounds are nice so I'm enjoying it.

What's been the hardest thing about moving to Cambridge?

The fact it is as flat as a pancake is a shame; everywhere else I've lived has been hilly. I found that pretty hard, so whenever we go on holiday we'll go to the Alps, or the Himalaya. My desktop background is a photo of the Cairngorms, to remind me there is such a thing as topography!

You can keep up-to-date with Nick's work in Borneo on the department website and social media.

Is there life beyond Earth (Sciences)?

KEV WONG (CORPUS 2014) SEDGWICK CLUB TREASURER & PART III STUDENT

POSTER BOARDS STAND TALL IN A CROWDED ROOM. FRIENDLY, FAMILIAR FACES EXCHANGE ADVICE OVER A GENEROUS KEG. CURIOUS MINDS EAGERLY WATCH AND LISTEN, BEFORE COLLECTING A HANDFUL OF FREE PENS FROM A NEARBY TABLE.

The Department of Earth Sciences' careers event at the end of Michaelmas term invites alumni and industry representatives to speak to a new generation of Natural Scientists about their life after graduation. Started in 2012 by the Sedgwick Club, this annual event has continued to grow, with more businesses, representatives, and undergraduates attending each year.

2017 was no exception; this year the department hosted nearly forty representatives from over twenty companies, covering a dozen career sectors.

So why does the Club do this? The Earth Sciences careers event stands out from other similar events at Cambridge. It is one of the few careers events that is organised by a student society, for example. It is also the only event that is organised for Earth Scientists, by Earth Scientists, with the blessing of the University Careers Service and the department (which covers the cost of refreshments to keep the conversation flowing).

It is important for Cambridge Earth Sciences undergraduates to see the wide range of career opportunities available with an Earth Sciences degree. After all, many of us did not join Cambridge to study the subject and do not have a career path in mind. I, for one, started my Natural Sciences degree as a chemist.

This is therefore especially true for first-year Natural Scientists. Many may be inspired, by the people they speak with and the hospitality of the department, to continue their studies and pursue a career involving Earth Sciences. A large proportion of the representatives they speak with will have had similar experiences; a quarter of the representatives at the event this year were alumni. Some alumni present only graduated last year!

An aim of the Sedgwick Club committee was to feature a wider range of careers at this year's event. We managed to accomplish this: the 2017 event featured not only representatives from sectors actively recruiting and employing Earth Scientists, but also alumni who work as lawyers, consultants and teachers.

We hope that future committees can expand the range of career representatives at the Event, to illustrate the wide number of opportunities available with an Earth Sciences degree. We intend to make this easier for our successors by making contacts with those who are interested in returning to our lovable department and sharing their wisdom.

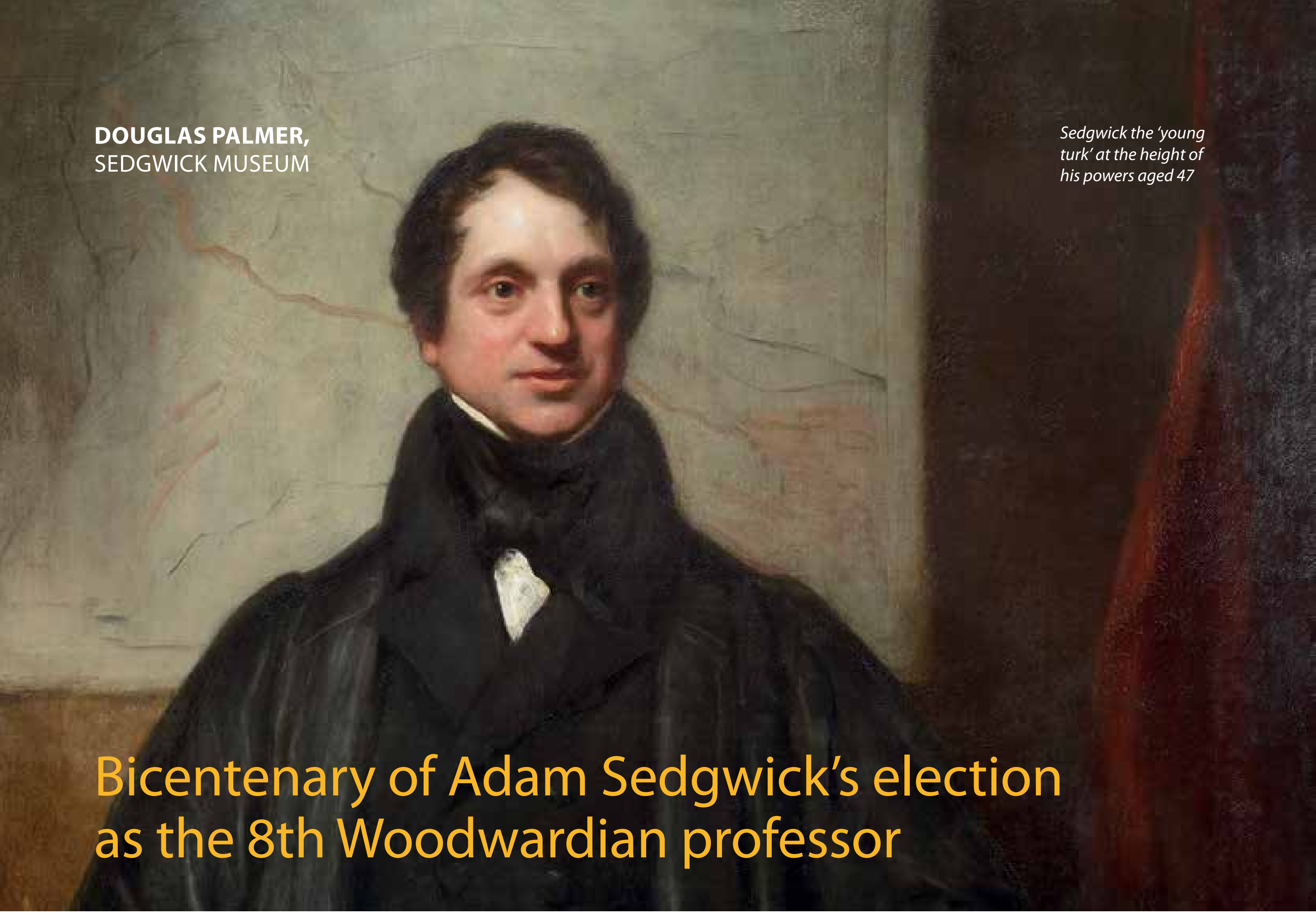
Contact the Sedgwick Club committee at sedgwickclub@gmail.com.

The Map Room

Earth Sciences Librarian Sarah Humbert is responsible for both of our libraries, on the Downing Site and at the Bullard Laboratories.

Stowed in the many drawers and cabinets of the Downing Site Map Room are tens of thousands of maps. Early hand-painted sheets by Smith, Sedgwick are Greenough are stored alongside recent maps of topography, solid and drift geology, bathymetry and more. The collection is unique and internationally significant. Historic maps are occasionally put on public display; most recently MacCulloch's 1832 geological map of Scotland was loaned to the University Library's *Landscapes Below* exhibition.

The room itself is particularly well-used by second-year undergraduates planning their mapping projects. A quick glance at a geological and topographic map of an area can be invaluable when determining where to map. Nowadays, once they have chosen an area, students will often download detailed digital files. The paper maps, though, are still available for reference.



DOUGLAS PALMER,
SEDGWICK MUSEUM

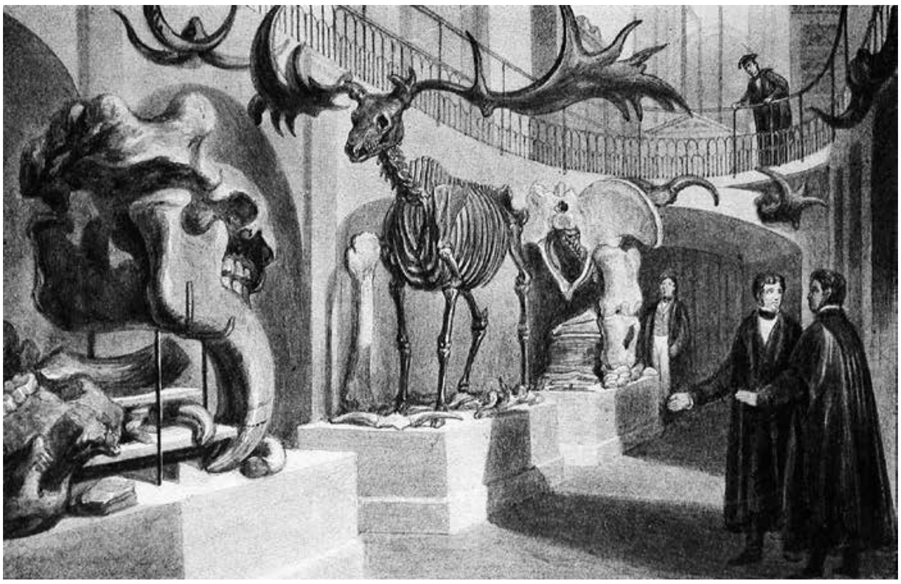
Sedgwick the 'young turk' at the height of his powers aged 47

Bicentenary of Adam Sedgwick's election as the 8th Woodwardian professor

In 1818 the recently ordained 33 year-old Adam Sedgwick (1785–1873) was elected to the Woodwardian professorship in the University of Cambridge. A Yorkshire schoolmaster's son, Sedgwick had entered Trinity College in 1804 and risen from being sizar*, scholar and fifth wrangler in 1808 to a fellowship in 1810. With little or no geological background, he was a surprising candidate for the Woodwardian chair. But he turned out to have been an inspired choice and went on to become one of the best known geologists of mid-19th century Britain.

There was however a personal cost to acceptance of the Woodwardian chair. As Sedgwick ruefully noted in 1858, 'Woodward put the ban of domestic sterility upon his Professor, but my Museum is in the place of wife and children'. Sedgwick's zeal as a lecturer, field geologist and collector was instrumental in promoting the science of geology within the University. Under Sedgwick, the Museum collections grew well beyond the core 11,000 specimens endowed by John Woodward in 1728. Sedgwick himself collected hundreds of specimens as well as buying collections and important specimens from the likes of Mary Anning. And, he pressurized the University authorities to provide more space for the collection.

When Queen Victoria and Prince Albert visited Cambridge in 1843, Sedgwick proudly showed them around his new Museum in the recently built Cockerell Building. The royal couple were suitably impressed by the plesiosaurs, ichthyosaurs and giant deer. When the Queen asked where one of the ichthyosaurs came from, Sedgwick replied that it was 'a delegate from the monsters of the lower world to greet Her Majesty on her arrival in the University'.



Sedgwick's Geology Museum in the Cockerell building c.1850

Right: Sedgwick statue in the Sedgwick Museum
Above: Declining years, Sedgwick at 82
Below: Segwick sketched in the field

From the start of his geological career Sedgwick had embarked upon field work across Britain; especially southwest England, then the Isle of Wight and the Lake District. By 1827 he was a prominent member of the geological elite in Britain becoming Vice-President of the Geological Society of London, meeting Cuvier, Humboldt and Laplace in Paris, geologising in Scotland with the young Murchison, visiting Lyell at his family home in Kinnordy and attending to his lecturing and ecclesiastical duties.

WITH LITTLE OR NO GEOLOGICAL BACKGROUND, HE WAS A SURPRISING CANDIDATE FOR THE WOODWARDIAN CHAIR. BUT HE TURNED OUT TO HAVE BEEN AN INSPIRED CHOICE AND WENT ON TO BECOME ONE OF THE BEST KNOWN GEOLOGISTS OF MID-19TH CENTURY BRITAIN.

From the early 1820s until the late 1840s Sedgwick was indefatigable in his pursuit of geological matters. His mapping in the Lake District, North Wales and Devon was a major achievement. In collaboration with Murchison he established the Cambrian and Devonian Systems. Although relationships with Murchison soured into one of the most notorious controversies of 19th century geology, Sedgwick's Cambrian emerged as an internationally recognized period of geological time.

In 1847 Prince Albert was elected Chancellor of the University of Cambridge. He appointed Sedgwick as a fellow reformer to be his secretary and in 1850 Sedgwick was appointed to the Royal Commission on University Reform. This work, his ecclesiastical duties and ill health meant that Sedgwick did little innovative geological work over the last two decades of his life. His geology was out of touch with the times. He viewed with dismay the publication of the 'Origin of Species' in 1859 by one of his most famous pupils. As he wrote to Darwin "You have deserted… the true method of induction".

The present Sedgwick Museum was opened in 1904 by King Edward VII as a memorial to Adam Sedgwick and to house the greatly enlarged collections.

The Sedwick Museum will mark the bicentenary with a number of events in May 2018: www.sedgwickmuseum.org

**Sizar – an undergraduate in receipt of financial help from the college in return for carrying out certain menial duties.*

RECENT NEWS & AWARDS

The Geological Record

01

Elizabeth Harper (Gonville & Caius 1983) has been appointed Acting Director of the Sedgwick Museum following the retirement of Dr Ken McNamara. Liz is an internationally renowned palaeontologist with an expertise in bivalve molluscs both fossil and living. She has a long association with the department, ever since she was an undergraduate, and her association with the Sedgwick Museum and its collections also dates back to her postgraduate research on post-Palaeozoic fossil bivalves.

02

Congratulations to **Richard Harrison** (Fitzwilliam 1990) who has been promoted to a Professorship. Richard's research combines state-of-the-art experimental techniques, including transmission microscopy, electron holography, neutron and X-ray scattering, together with atomistic and micromagnetic modelling, to study the fundamental properties of magnetic minerals at the nanometre scale. He is currently developing nanoscale methods to extract meaningful paleomagnetic information from meteorites.
www.esc.cam.ac.uk/nanopaleomag/

03

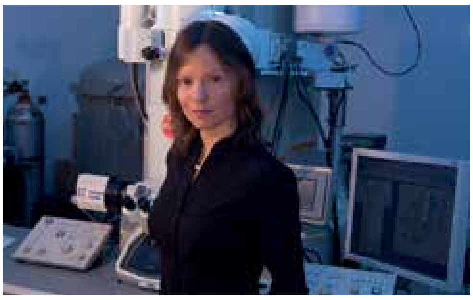
Andy Woods has been elected a Fellow of the Royal Society. Andy's research involves modelling fluid flow processes covering a wide range of phenomena from the dynamics of explosive volcanic eruptions, to geothermal power generation, carbon sequestration and oil recovery in heterogeneous porous rocks. His work on the dynamics of mixing in turbulent buoyant plumes and gravity currents has led to new insights about the ascent height of volcanic eruption columns and the run-out distance of ash flows, as well as constraints on the dynamics of hydrothermal and oil plumes in the deep sea. Andy has also developed a fundamental understanding of ventilation flows in buildings, developing strategies to minimise heat loss associated with low-energy natural ventilation.

04

Oliver Shorttle (Queens' 2005), Junior Research Fellow at Trinity College (2013–2018) returns from Caltech (2015–2016) as a University Lecturer in both Earth Sciences and the Institute of Astronomy. Oliver's work focuses on characterising the basic chemical and dynamic processes linking planetary interiors to their oceans and atmospheres, through a combination of fieldwork, geochemical analysis, and modelling. Working within the Institute of Astronomy Oliver is taking this geological insight to a new frontier, to characterise planets beyond our solar system and investigate their habitability.

05

Emilie Ringe returns to Cambridge from Rice University in Houston, Texas, as a University Lecturer, jointly appointed in Earth Sciences and Materials Sciences and Metallurgy. Emilie obtained her PhD in chemistry and materials sciences from Northwestern University in 2012, after which she joined Trinity Hall as the Gott Research Fellow and was awarded a Newton International Fellowship from the Royal Society. She worked in the electron microscopy group in Materials Science and Metallurgy, researching multi-metallic nanoparticles relevant for plasmonics and catalysis. In 2014 she joined the faculty at Rice University as an assistant professor, where she developed optical and electron microscopy tools to observe light-matter interactions in natural and synthetic materials.



06

Marian Holness (Clare 1983) has been elected the new incoming President of the Geochemistry, Petrology, Mineralogy and Volcanology division of The European Geosciences Union, EGU. Marian is Professor of Petrology and a Fellow of Trinity College.

CONGRATULATIONS TO OUR RESEARCHERS WHO HAVE RECENTLY WON AWARDS:

Award winning

Marie Edmonds (Jesus 1994) has been awarded the 2017 Wager Medal by the IAVCEI (International Association of Volcanology and Chemistry of the Earth's Interior) for outstanding contribution to volcanology. Marie joins a distinguished list of medal recipients: **www.iavcei.org/iavcei-awards/wager-medal.html**

David Hodell has been awarded the 2018 EGU (European Geosciences Union) Milankovich Medal for outstanding research in long term climatic changes and modeling. David is Director of the Godwin Laboratory for Palaeoclimate Research: **godwinlab.esc.cam.ac.uk/**

Helen Williams (Newnham 1994) has been selected as a Mineralogical Society Distinguished Lecturer for 2017–18 and will deliver a series of lectures on her work using non-traditional stable isotope systems: **www.minersoc.org/distinguished-lectures-17-18.html**

Ekhard Salje (former Head of Department 1998–2008) has been awarded the Werner Heisenberg Medal 2017.

Josh Einsle was awarded the EMAS Young Researcher Poster Prize at the European Microbeam Analysis Society meeting in May 2017. This was for his poster entitled "The potential for mineralogical mapping through machine learning."

Davide Novella was awarded the 'Angelo Bianchi' Prize of the Italian Society of Mineralogy and Petrology for young researchers in petrology.

Marie-Laure Pons has been awarded the Postdoctoral Medal of the GSL Geochemical Society.

Euan Mutch (Robinson 2014) was given an Exceptional Student Presentation Award at the recent IAVCEI Scientific Assembly in Portland, Oregon.

Pu Zhao (Lucy Cavendish 2011–2015) has been awarded the 2017 PANalytical Thesis Prize for a thesis entitled "The structure-property relations of zeolitic imidazolate framework 7 for carbon dioxide capture". This award recognises the best use of the techniques or methods of Physical Crystallography in a successfully examined PhD thesis.

OBITUARIES

Alan Smith 1937–2017

ALAN WAS MANY THINGS TO MANY MORE PEOPLE. IN REMEMBERING HIM I CAN ONLY SKETCH HIS WONDERFUL, QUIRKY CHARACTER. HE WAS OUR FRIEND AND EASY TO LOVE. AS A SCIENTIST HE WAS INSTRUMENTAL IN OUR UNDERSTANDING AS TO HOW THE PLANET TICKS.

Perhaps in the wider world he never quite received the full recognition he so richly deserved, but that was part of his natural modesty, a modesty that would regard the egocentric blowing of trumpets as slightly absurd, if not comic. And he had no lack of humour, not sly but subterranean, quietly observant of human quiddities, and he himself rejoicing in truly appalling puns – which I will not attempt to emulate.

Alan was a key catalyst in the scientific revolution that transformed geology from the study of a fixist planet, across which Darwin could safely potter, to the dynamic story of plate tectonics. So it was that he (along with Jim Everett and his mentor Teddy Bullard) put a rigour into the long-observed congruence of the western coastline of Africa and the now remote but corresponding shores of the Americas. He achieved this by employing a computer-aided fit that precisely matched the continental outlines at a particular bathymetry. This was one central link in the recognition of a planet composed of ever shifting plates and where oceans could close and open. Alan himself extended this work over many years, drawing on increasingly sophisticated computer technologies. In part this interest led to his almost equally important work on ophiolitic terranes, which again plate tectonics puts in an entirely new set of contexts. What, after all, could be more exciting than putting your hand on the Moho, well more or less.

His greatness as a scientist was the same ingredient as the whole man, a deep and abiding curiosity as to why the world is as it is. With a few blows of his geological hammer he could tell us how those mountains in northern Greece came to be there. Of course he had research teams, but again they were friends, not drones. As you heard the stories one sensed they were a pretty piratical crew, enjoying life to the hilt. Alan was always the leader and like all really original people he had a sort of X-ray vision, seeing the wholeness of things. But geology is perhaps unique because the evidence is so fragmentary and more often than not contradictory. Alan rejoiced in the struggle to understand, fully aware that truth is provisional and matters seldom simple.

He was always a comfortable companion. He desired the undramatic, the every-day, but never, never the hum-drum.

A drawing of Alan Smith by John Edwards, by permission of the Master and Fellows of St John's College, Cambridge

He embedded himself in the world, rather than skate over it. At conferences rather than heading for those soul-less mega-hotels with their corridors like nightmares, he'd ferret out some comfortable bed and breakfast and so treat some remote city as his home.

Science didn't stop when he retired, but he did other things. His garden flourished, albeit in a sort of disorganized Zen-like fashion with Alan taking quiet delight in his many horticultural successes. Also step-by-step, in short or long segments, he walked East Anglia, especially the coast-line where seemingly monotonous marshes, scudding skies and a heaving grey ocean revealed deeper secrets. It is hardly surprising that he became an increasingly skilled water-colourist, capturing landscapes with a limpid configuration of palates and imagination. Once he showed me a beautiful sketch of Bat Head in Dorset, waiting for me to spot how Turner-like he had rearranged the coast-line.

Alan was terrific on field-trips, especially around Anavra and helping us in Dorset. Chatting with the students, quietly quizzical as one or other of us was expostulating, or as we say in our Department "foaming". Alan was holistic, fascinated in what is meant by geological time – those endless wet Sundays – and how we might define the passing epochs. I have already alluded to his scientific stature, but apart from his contribution to tectonics it was here, in the development of internationally accepted time scales for the geological column, that he was truly pivotal. And this permeated Alan's career. With the usual suspects such matters as time scales and stratigraphic definitions are as dry-as-dust. Not with Alan, he was consumed by what it all meant.

Alan was a key catalyst in the scientific revolution that transformed geology from the study of a fixist planet, across which Darwin could safely potter, to the dynamic story of plate tectonics.

So classifications were of no great interest to him, but here I must note one crucial exception. It was he who defined the correct appellations for a gin and tonic, standards that I have good reason to believe now enjoy a world-wide currency. Note, please, that I exclude from all consideration that lamentable wetting of a glass one encounters in a pub. The bench-mark was, of course, the Smithy. If the tonic is in short supply we must turn to a Frogley, and then high in the stratosphere resides the almost tonic free G&T; I speak of course of the Churchill.

Alan was a man of infinite charm, and a most valued friend. We miss him now, and we will miss him for the remainder of our days. He was – and is – the Smith of Smiths.

Simon Conway Morris

This is a slightly extended version of the encomium read by Simon Conway Morris at Alan's funeral on Thursday 31 August, 2017.

Alan with colleagues on a field trip

Christine Kelsey 1931–2017

Formal group photograph of Girton Fellows in Eliza Baker Court in Girton taken in 1962 by Stearn and Sons. Christine is at the top left corner. Girton College archive reference: GCPH 6/1/6. Reproduced by kind permission of The Mistress and Fellows, Girton College, Cambridge.

Christine Kelsey read Natural Sciences at Girton College 1949–53 with an Exhibition in her third and fourth years. She was awarded a postgraduate research studentship in 1953 which enabled her to work on the structure of tobermorite 1953–56 (MA 1956, PhD 1958). Her paper "Crystal structure of tobermorite", co-authored with her PhD supervisor Helen Megaw, appeared in Nature in 1956. After 21 months of post-doctoral research in Canada, Christine returned to Cambridge as a University Demonstrator in the Department of Mineralogy and Petrology (1958–63). She became a University Lecturer (1963–80) in Mineralogy and Petrology, and subsequently in the Department of Earth Sciences following the merger of the Departments of Geology and Mineralogy & Petrology. She retired in 1998. Christine additionally held the office of Vice-Mistress of Girton College from 1987 to 1996.

Christine was one of the stalwarts of IA teaching in "Crystalline Materials", which became "Materials and Mineral Sciences" during her time, and was an ever present mainstay in the teaching of crystallography in Part IB and Part II.

She was married to Duncan McKie who was also a long-term University Lecturer in the Department of Mineralogy and Petrology. Their books, "Crystalline Solids" published by Taylor in 1974 and "Essentials of Crystallography" published by Blackwells in 1986, are classics familiar to generations of students as "McKie and McKie". Essentials of Crystallography still appears on reading lists for IA and IB NST students and is likely to continue to do so for many years to come.

Those of us who knew Christine only in the later stages of her career in Earth Sciences would not have been aware of the extent of her contributions to Girton College over a period of more than 40 years or of the fact that she acquired a rowing Blue in 1952. She will be remembered for her quiet dedication to many aspects of life in the University and for the kindness she unfailingly showed to everyone around her, students and staff alike.

Michael Carpenter

Thank you to our donors 2016–2017

We wish to thank alumni and friends who have generously made donations to the department in the last financial year. Every effort has been made to ensure the list is accurate; do contact us if you believe we have made an omission.

We would also like to thank all those who made a gift to the department anonymously.

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Learn more about what are our current students and researchers are up to

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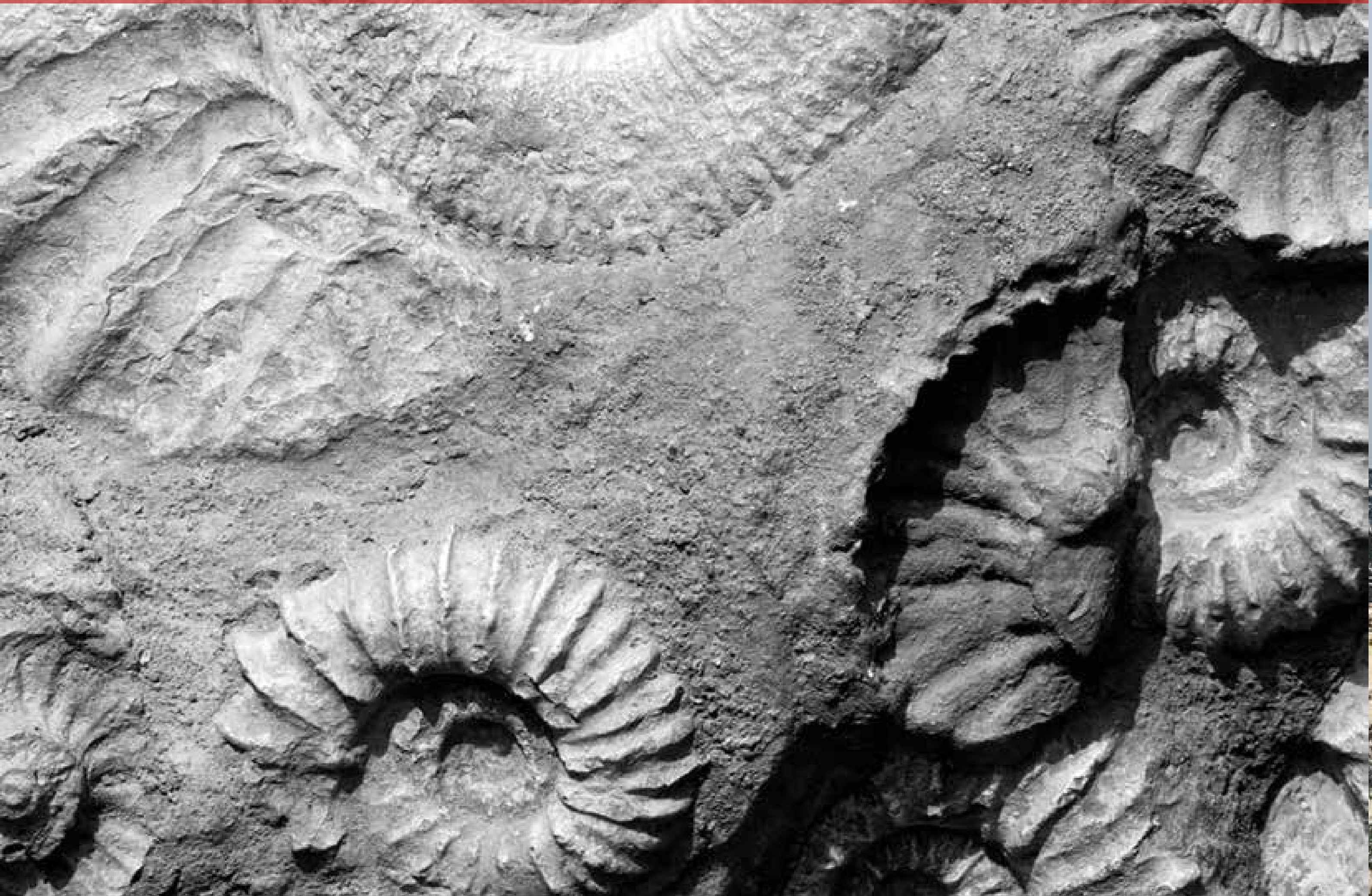
A gift in your will is a meaningful way to help the department flourish far into the future, and for you to be able to make a significant and lasting contribution. Such a gift can open up a world of opportunity for future students, researchers and academics, helping to provide the environment and tools they need to continue to achieve great things.



To learn more about the impact of a legacy, or for guidance on how to leave a gift to the department in your will, please contact:

Alison Holroyd, Alumni Co-ordinator
Department of Earth Sciences
Downing Street
Cambridge CB2 3EQ

T +44 (01223) 333442
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Alumni Day 2017 in pictures

flickr.com/photos/earthscicam/albums