CLIMATE CHANGE AND THE ENERGY TRANSITION

RESOURCES INDUSTRIES REIMAGINED
Framing perspectives for the energy transition

CRITICAL GEOSCIENCE
The vital role for our subject

GEOLOGICAL SOLUTIONS
Enhanced rock weathering and carbon mineralisation

PEOPLE POWER
Building trust to meet decarbonisation goals
JOIN THE GEOSCIENTIST TEAM!

Are you interested in producing compelling and engaging content for the global geoscience community? We are looking for passionate geoscience communicators to join our new volunteer Contributors Team.

YOUR ROLE
Over the course of a year, you will pitch and deliver three ~250-word-long articles that summarise important and exciting geoscientific research discoveries or industry developments. You will also produce one other article of your choice, be that an opinion piece, interview, short thought-piece, or feature, and this can take the form of a written article, video, audio or even drawn content.

The role is well suited to geoscientists who wish to develop their skills and experience in communicating complex scientific ideas in engaging and creative ways. We welcome applications from contributors at all career stages, with training in all areas of pure and applied geoscience, and with backgrounds in academia, industry or the public sector. The role is voluntary and remotely based, so applications from across the globe are welcomed.

We require a minimum commitment of twelve months, with the option to extend at the end of the term.

BENEFITS
This creative and rewarding role will allow you to:

- refine your scientific writing skills
- work with and receive feedback from an experienced team of editors
- build a portfolio of published work (in print and online)
- gain hands-on experience working with a respected professional society and on an established geoscientific publication with diverse readership and global reach
- expand your professional network

As a not-for-profit organisation, the Geological Society is unfortunately unable to offer payment for this role, but in addition to the above benefits you will also receive a free copy of Geoscientist each quarter, as well as complimentary registration to an online Society conference of your choice.

TO APPLY
Please email your CV and a one-page cover letter that outlines your area of geoscientific expertise and suitability for the role to geoscientist@geolsoc.org.uk (with the subject heading: Geoscientist Contributors Team).

To demonstrate your flare for science communication, please also include a ~250-word-long article that summarises a recently published geoscientific research paper in an engaging and accessible way. The article must be written in English and should be accompanied by a suggestion for an image or figure to illustrate the piece. You are welcome to recommend images from stock libraries (but please do not purchase the image—inclusion of the weblink is sufficient).

For more information, a full list of benefits and details on how to apply, please visit:
www.geoscientist.online/sections/editors-desk/contributors-team/

Closing date for applications: 4 October 2021
A CODE RED for humanity. This stark warning was issued by the UN Secretary General, António Guterres, on release of the latest report from the Intergovernmental Panel on Climate Change last month. The report suggests that Earth will likely breach the threshold of 1.5°C of warming (compared to pre-industrial levels) outlined in the Paris Agreement within the next two decades.

The 26th United Nations Climate Change Conference of the Parties (COP26), in Glasgow in November, marks the first iteration of the internationally agreed approach for nations to submit increasingly ambitious proposals to ratchet up their climate actions. Given the latest analysis, the meeting is seemingly a now-or-never moment.

To achieve the targets, geoscientists are vital

The report offers hope, however. We can avert catastrophe if we act fast to slash global emissions and remove CO₂ from the atmosphere. To achieve the targets, geoscientists are vital – a message that rings loud and clear in this autumn issue of our magazine on climate change and the energy transition.

Geoscience played an important role in identifying anthropogenic-induced climate change and placing the current changes within the context of past anomalies (p. 44), but geoscientists are essential for mitigation and restoration. We must now focus on the science-based solutions needed to meet the targets – solutions that include hydrogen and carbon capture and storage, renewable energy sources, as well as energy storage.

While the overriding message from those that have contributed to this edition is one of optimism, their hope is underlain by realism.

AMY WHITCHURCH, EXECUTIVE EDITOR
Geological Society’s Virtual Careers Days 2021
13-15 October 2021

An opportunity for geoscience undergraduates and postgraduates to find out the latest career developments and opportunities.

Over the course of 3 days, our dynamic programme will include presentations covering the varied areas of geology and academia. There will also be an opportunity to meet industry professionals for interview, CV and networking advice.

Registration is free, however pre-booking is essential due to numbers being limited. Delegates will receive a student manual and timetable.

#GSLCareers2021
@geolsoc

Contact information:
Becky.Goddard@geolsoc.org.uk
0207 432 0981
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IN EARLY NOVEMBER, Glasgow will host the 26th United Nations Climate Change Conference of the Parties (COP26) with the aim of accelerating global action towards the Paris Agreement and the UN Framework Convention on Climate Change.

The International Panel on Climate Change and governments around the world have highlighted the vital role of subsurface technologies and resources, such as carbon capture and storage, geothermal energy, energy storage in underground caverns to support future hydrogen economies, and compressed-air energy storage, for meeting net-zero targets. Demand for metals and materials to support the production of, for example, renewable technologies, batteries and electric vehicles, is also projected to increase substantially in the coming decades.

The Geological Society is working with the geoscience community, as well as decision makers and stakeholders outside the geosciences to understand and raise awareness of the various ways that geoscience will underpin the global decarbonisation goals. Visit our website to find out more: www.geolsoc.org.uk/COP26

Megan O’Donnell (Communications & Policy Officer) & Flo Bullough (Head of Policy and Engagement)

SPACESCAPES: POSTCARDS FROM OUR SOLAR SYSTEM
The Geological Society is hosting an outdoor, public exhibition that showcases the stunning landscapes and amazing geological features of our world and others.

Burlington House Courtyard, open 9am-6pm until 8 October, the exhibition is free and open to everyone. For more information, please visit: spacescapes.geolsoc.org.uk

GEOWEEK 2021
Chris King reports on GeoWeek 2021, which looked at what net zero by 2050 may mean for our regions.

GeoWeek 2021 launched in May with a virtual talk from the British Geological Survey’s Director, Karen Hanghøj, followed by a panel discussion. Then, in groups of six or less, or via self-guided tours, our GeoWeek leaders arranged for members of the public to attend field trips that promoted discussion of the impacts that the UK Government’s targets of achieving net-zero carbon emissions by 2050 might have on local areas.

A series of information and activity sheets on topics including climate mitigation, land management, blue hydrogen and renewable energy are available at: www.earthlearningidea.com

To take part in GeoWeek 2022, please visit: earth-science.org.uk/geoweek/
### Geological mapping – of our world and others

Lucy Williams delights in the magic of geological maps in anticipation of the upcoming William Smith meeting.

**WHO DOESN’T LOVE** a geological map? As an undergraduate, one of my best-loved classes was structural geology. We learnt how to ‘read’ a geological map, translate the 2D surface outcrop into cross-sections and delve into the unseen subsurface structure. Maps studied in the classroom were bought to life by visiting field locations and repeating the work carried out by geologists before us who generated the ‘works of art’ that are the geological maps of Great Britain… and beyond.

More recently, images of Mars acquired by NASA robots Curiosity and Perseverance are expanding our mapping capabilities into new/dimensions. Maps are fundamental to geology and were integral to some of the earliest discoveries in Earth sciences, as well as the latest breakthroughs. The Geological Society has collected geological maps since 1808. This treasure trove is one of the most comprehensive collections of geological maps in the world, and the inspiration for this year’s William Smith Meeting, Geological Mapping – of our world and others.

Join us for an international celebration of geological mapping that will explore the historical importance of maps, as well as their role in the future of our subject.

**William Smith Virtual Meeting 2021:** Geological Mapping – of our world and others – 19-21 October 2021

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### Martyn Millwood Hargrave to Support Oxford Net Zero

Martyn Millwood Hargrave, Chairman Emeritus and founder of Ikon Science (pictured, left), has joined Oxford University as a visiting professor in Earth Sciences to help define and advance future Earth science contributions towards carbon and geostorage of energy.

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### Gravestone geology on show

For geoscientists, almost any urban cemetery provides a valuable opportunity to carry out scientific fieldwork right on the doorstep and at no cost. A new exhibit, The Geology of Oxford Gravestones, highlights the geological features and social history revealed in Oxford’s graveyards. Curated by Nina Morgan and Philip Powell, geologists and honorary associates at the Oxford University Museum of Natural History, the exhibit is free and runs until 12 September at the Weston Library, Broad Street, Oxford.

For further information, please see: visit.bodleian.ox.ac.uk/event/geology-oxford-gravestones
Burlington House lease update

IN THE SPRING 2021 edition of Geoscientist, I explained the threats to the Society’s continued occupancy of Burlington House, caused mainly by the unaffordability of steeply rising rents. Work continues to find a long-term solution to this situation.

The political engagement campaign led by AprilSix on behalf of the Geological Society, Linnean Society, Royal Astronomical Society and Society of Antiquaries led to a Westminster Hall debate in early June. There is strong cross-party support for the Burlington House learned societies and the debate, led by Tim Loughton MP, was very successful in putting our case to the minister responsible, Eddie Hughes MP.

In a separate initiative, Sir David Attenborough wrote to the Prime Minister on behalf of the Geological Society, Linnean Society and Society of Antiquaries in early July. Sir David, an honorary fellow of these three societies, is a strong supporter of our case and his letter has since received positive media coverage. At the time of writing, there has been no signal of a significant change of policy from Government towards the learned societies.

In parallel, the ‘relocation options’ project, led by past-President David Shilston, continues its work to identify alternative accommodation options should the Society be forced to relocate. Recent work has focused on developing a statement of requirements for potential future accommodation, and discussions have taken place with several other organisations that have relocated in recent years to learn from their experiences.

The campaign has strong coverage on Twitter, and I will continue to keep the Fellowship updated on developments.

Richard Hughes (Executive Secretary)

SOCIETY’S AWARDS 2022: FINAL REMINDER TO NOMINATE!

FELLOWS OF THE SOCIETY are encouraged to submit nominations for the Society’s Awards for 2022.

The Geological Society is committed to seeing a sustained growth in the diversity of our awardees and to broadening the demographics of those put forward for our medals and funds. We are especially keen to receive nominations for the funds, which recognise excellent contributions by early career geoscientists.

All awards (except the President’s Award) have one standard nomination form. For guidance (including a downloadable pdf booklet) or to nominate, please visit: www.geolsoc.org.uk/About/Awards-Grants-and-Bursaries/Society-Awards

- Please send all nominations to the Awards Secretary: awards@geolsoc.org.uk
- Deadline: 23:59 on 30 September 2021

Trustees of the Geological Society of London 2021-2022

- Dr Michael Daly (President)
- Mrs Joanna Alexander
- Prof Mark Allen
- Ms Ruth Allington (President Designate)
- Dr Neil Frewin
- Dr Jennie Gilbert
- Dr Joel Gill (Secretary, Foreign and External Affairs)
- Dr Kathryn Goodenough
- Mr Martin Griffin
- Prof James Griffiths (Secretary, Professional Matters)
- Dr Michael Kehinde
- Mr Peter Loader
- Mr Andrew Moore
- Dr Keith Myers (Treasurer)
- Dr Amanda Owen
- Dr John Perry
- Mrs Sarah Scott
- Ms Gemma Sherwood
- Miss Jessica Smith (Vice President, Regional Groups)
- Prof Robin Strachan (Secretary, Publications)
- Miss Lucy Thomas
- Dr Alexander Whittaker (Secretary, Science)
- Mrs Lucy Williams

JOIN THE DEBATE

Has a news item got you thinking? We welcome readers’ letters and feedback. Share your views by emailing geoscientist@geolsoc.org.uk
Call for nominations to serve on Council

Would you consider standing for election to serve on Council and contribute to the Geological Society’s work – to influence its role as a respected voice serving science, the geoscience profession and society?

As a member of Council, you would play an active role in the delivery of the Society’s strategy to support and facilitate the communication of science through engagement with policymakers, the media and the public, as well as the certification of best practice in the profession.

The Society is committed to a diverse and inclusive Council. To ensure that Council better reflects the community it serves, we particularly welcome nominations from under-represented groups. We also warmly encourage nominations from candidates with trustee experience and/or knowledge of scholarly publishing or fundraising.

The 23 members of Council serve as trustees of the Society and are accountable to the Fellows, as well as other stakeholders and regulators, such as the Charity Commission. The principal responsibility of the trustees is to oversee the affairs of the Society and ensure it acts prudently in the management of its financial resources.

Council generally meets five times a year, usually on a Wednesday afternoon between 14:00-17:00. In addition, there is a one-day residential meeting, usually in late September, to discuss major strategic issues. Currently most meetings are held virtually, but moving forward we may offer a hybrid model.

All members of Council also serve on one of the standing committees (External Relations, Finance & Planning, Professional, Publications & Information, and Science). Standing committees usually meet three or four times a year, mainly virtually. We sometimes ask Council members to join other committees or short-term working groups. The typical time commitment is eight to ten days annually for ordinary members of Council.

For more details, to download the nomination form and to see the names of those members of Council due to retire at the AGM in June 2022, please visit: www.geolsoc.org.uk/councilllections

To request a form or to submit nominations, please email: christina.marron@geolsoc.org.uk or contact Christina Marron, Geological Society of London, Burlington House, Piccadilly, London W1J 0BG.

Deadline for nominations: 23:59 on 5 January 2022

Digital geoscience champion

The Society is seeking a volunteer Digital Geoscience Champion to work across our scientific themes and other activities. The individual will be responsible for ensuring that computational and numerical tools and techniques are embedded within our scientific outputs, such as our conferences and policy work.

For more information, please visit: www.geolsoc.org.uk/getinvolved

Deadline for expressions of interest: 15 September 2021

Research Grants: Applications are now open

The Geological Society awards a range of grants for a broad scope of research activities and we invite applications for the 2022 round. Only Fellows may apply and the application should be accompanied by supporting statement forms from two Fellows of the Society.

The Research Grants Committee meets once annually and can only consider complete applications on the appropriate forms.

For more information, please visit: www.geolsoc.org.uk/grants

Deadline: 23:59 on 8 February 2022

New Fellowship category structure for 2022

At the AGM on 25 June 2021, Council approved the proposal to introduce new Fellowship categories. The new approach uses a career-based categories model, rather than the previous age-based categories model.

Initially proposed in April 2021, we introduced these changes in response to the Fellowship Survey undertaken in 2018, the 2020 Strategic Options review and an online survey carried out in December 2020. Our aim is to modernise the Society, reduce barriers and stimulate growth, with the goal of becoming a fairer Society for all.

Further communication will go out to Fellows in due course.

For more details, to download the renewal process, please visit: www.geolsoc.org.uk/renewals
JOIN THE EXTERNAL RELATIONS COMMITTEE

THE GEOLOGICAL SOCIETY is looking for individuals to join its External Relations Committee, supporting the Society’s work on themes that include education, communications and outreach, policy, international engagement, geoconservation, and diversity, equality and inclusion.

To complement our existing membership, we are particularly keen to hear from those who consider themselves ‘early-career’, those from outside the UK, and those with experience and interests in science communication, international networks or policy. Applications should consist of no more than one side of A4 explaining relevant experience, and your motivation for joining this committee.

For more information, please visit www.geolsoc.org.uk/getinvolved or email Joel Gill (Secretary, Foreign and External Affairs) at joell@bgs.ac.uk
- Please send all applications to Alicia Newton (Director of Science and Communications): alicia.newton@geolsoc.org.uk
- Deadline for applications: 15 September 2021

PASS ON SOMETHING WONDERFUL

The past 18 months have prompted many of us to reflect on the things that matter most – family, friends and the causes close to our hearts. We’ve also been reminded of the value of planning for the future, to help look after the things we care about.

Remember A Charity Week, which runs from 6 to 12 September, is the perfect opportunity to consider passing on something wonderful by leaving a gift in your will.

After taking care of family and friends, even a small amount can make a huge impact. A gift in your will to the Geological Society could help us to advance Earth and planetary science for the benefit of humanity for generations to come.

To receive our information pack or find out more, please contact Jenny Boland, Head of Development on +44 (0) 20 7432 0960 or jenny.boland@geolsoc.org.uk

No inflationary increase in Fellowship fees for 2022

Typically, Fellowship fees increase annually in line with CPI. Whilst fees will rise for some Fellows following the changes to categories, in recognition of the challenges faced by many during the COVID pandemic, Council has agreed that there be no inflationary increase in Fellowship Fees for 2022.
Supporting you at every stage of your Earth science career

We’re evolving to become a fairer Society for all with our new career-based Fellowship categories model. Join us as we modernise the Society, reduce barriers and stimulate growth.

There are so many good reasons to be a member of the Geological Society;
• Connect and network within the Earth science community
• Advance your professional development opportunities
• Discounts on books and publications
• Attend conferences and events
• Access to journals and library services
• Add your voice to our advocacy for Earth science

Don’t forget to keep your ‘MyGSL’ details up to date, log in now, www.geolsoc.org.uk/info
NOTE: CHANGE OF MEETING FORMAT

Deep geological disposal of radioactive waste: The role of geoscience

Virtual meeting: Monday 27 and Tuesday 28 September 2021, 12 noon to 5.00 pm

A series of invited talks reviewing the critical role played by the geosphere in deep geological disposal of higher activity radioactive waste.

Programme includes

- Jon Gluyas (University of Durham, UK)
- Penny Harvey (University of Manchester, UK)
- Tim Vietor (Nagra, Switzerland)
- Neil Chapman (University of Sheffield, UK)
- Jonathan Turner (RWM, UK)
- Fiona McEvoy (Visiting Research Associate, BGS)
- Kaj Ahlbom (SKB, Sweden)
- Lukas Pollok (BGR, Germany)

- Discussion panel comprising a range of experts including: Professor Mike Daly, President, The Geological Society; Sir Keith O’Nions, FRS, Chair of BGS Board; Professor Cherry Tweed, Chief Scientific Advisor, RWM, Professor Julie West OBE

Details of registration (free) will be made available from the Yorkshire Geological Society website in August.

For further information about Yorkshire Geological Society events see http://www.yorksgeolsoc.org.uk/
On page 24 of this issue, Philip Ringrose highlights the importance of younger stratigraphy as we reimagine some geoscientific careers for the energy transition. Cenozoic, and particularly Quaternary and Anthropocene, deposits pose the biggest hazards to today's civil engineering projects. Knowledge of these deposits is invaluable for keeping on track projects with design lives that are required to last more than 120 years.

In the UK, there are important Cenozoic bedrock outcrops in the London Basin. Over the last two decades, the majority of the big infrastructure projects (such as Crossrail, High Speed Two, Thames Tideway, Lee Tunnel and the Lower Thames Crossing) were constructed in and on these deposits, furthering our knowledge of the London Basin enormously. The London Clay Formation is an excellent tunnelling medium due to its strength, low permeability and relative uniformity, but its limited extent restricted London’s tunnels to the north of the Thames. Recent advances in tunnelling techniques have allowed the Underground network to expand into south London and the much more variable Lambeth Group.

Quaternary deposits occur throughout the UK. Glacial till often contains water-bearing, granular materials that adversely impact slope stability. Its thickness can vary enormously across buried valleys, impacting pile design, and it can contain shear surfaces that lead to slope instability. Fluvio-glacial deposits form valuable aggregate resources—vital for use in concrete and drainage systems—but these can also vary in thickness and locally contain a lot of clay.

Relict Quaternary processes can continue to generate hazards. Cambering and valley bulging from over-eroded valleys can produce ground movements leading to voids and shear surfaces that can cause large settlements and slope instability. Periglacial processes can result in valleys containing soft, sheared material that can bring about slope instability or drift-filled hollows filled with water-bearing, coarse, granular materials that can lead to excavation instability, inundation, pile failure and settlement problems.

Anthropocene deposits potentially pose the biggest hazards. For example, prehistoric and historic mining has left partially backfilled mine-workings and quarries that result in loose backfill materials or voids.

An understanding of younger stratigraphy is essential for engineering geologists, argues Ursula Lawrence.
GEOSCIENTIST | AUTUMN 2021

VIEWPOINT

DEAR EDITORS,
In the spring issue of GeoScientist, to combat the decline in teaching and student numbers studying geology, Professor Ian Reid suggests that we should exploit the geography curriculum. This should be the answer, but I’m afraid it may be too late.

During revision of the major national curriculum over 20 years ago, human geographers won the battle over content. Scientific, physical geography, which covers geomorphology, basic geology, pedology, hydrology, biogeography, climatology and surveying, was relegated to ‘environment’. That is, only those elements that obviously relate to humans and environmental issues, such as climate change, erosion, deforestation and coastal management, were deemed sufficiently important to make the curriculum.

A few years ago, I was asked to take a field trip to the Dorset coast. I tried to teach real geomorphology, but the students weren’t interested in the fossils, landforms, processes or even the history of science. Instead, they only wanted to know about World Heritage, and the planning and economic aspects.

I tried to teach the mechanics of coastal erosion to which the students responded by asking, ‘Why don’t they do something about it?’ When I trained, a geomorphology student was the ‘they’ and many of us went into engineering geology (I am a William Smith medallist, for example – a geographer gratefully honoured by a different discipline!). Such a transition can only happen now for students studying at the few universities that maintain a decent geography degree, rather than jargonistic sociology.

Many geologists over the age of 40 will admit that they gained their first stimulus and field work from studying physical geography. I had the chance to study geology as a subsidiary subject, but when the curriculum revision decimated the subject, I had to ask (in desperation) the Science Curriculum Revision Panel to include some geomorphology.

I agree with Ian Reid that ‘environmental despoliation’ has won the battle. Real geography has gone. Our subject Societies have not fought the battle and now it is the turn of geology to feel the long-term consequences of the fatal human geography decision.

DENYS BRUNSDEN
Denys Brunsden OBE is Emeritus Professor at King’s College, London

DEAR EDITORS,
Professor Denys Brunsden rightfully highlights the role of the geography curriculum in providing an important gateway into geology for young people.

However, for those who are concerned that geomorphology’s place has been eroded there is significant reassurance to be found in the most recent reviews of the geography curriculum across the national curriculum, and at GCSE and A level.

For example, the geography national curriculum requires pupils to be taught about geological timescales and plate tectonics; rocks, weathering and soils; weather and climate; glaciation; hydrology; and coasts. At GCSE, geography pupils study geomorphic processes and landscapes with a focus on the UK. These studies should include how geomorphic processes operate at different scales, and in combination with geology, climate and human activity to influence our landscapes.

For those continuing to study geography at A level, their courses include four compulsory units – two human and two physical. The two physical units cover the carbon and water cycles, and landscape systems. In the latter, students will explore the characteristics of physical processes and patterns at a variety of spatial (landform to landscape) and temporal (seconds to millennia) scales.

Geographical fieldwork also plays an important role in bringing attention to hands-on geomorphology through its balanced coverage of aspects of physical and human
geography and is required from the primary years through to A level. The Royal Geographical Society worked closely with the respective review panels to strengthen the geography curriculum as a whole and enhance the place of physical geography.

And the data – in part – are encouraging, both in terms of uptake and who is now studying geography. For example, for GCSE geography candidate numbers have risen from 180,000 ten years ago to 268,000 in 2021. This growth has come from those pupils previously less likely to take geography (notably, disadvantaged pupils, Black, Asian and minority ethnic students, as well as those with lower prior attainment and studying in comprehensive schools). At A level, student numbers have been maintained with increased numbers of students going on to study geography at university. However, as the Royal Geographical Society’s Geography of geography: the evidence base report shows, the more diverse nature of GCSE students is not being carried on to A level or Higher Education. And the Royal Geographical Society recognises there is much more work to do to enable young people from all backgrounds to become inspired by the wonder and complexities of our human and physical worlds.

STEVE BRACE
Head of Education and Outdoor Learning, Royal Geographical Society (with the Institute of British Geographers, IBG)

TRE ALTAMIRA
@TRE_ALTAMIRA: The latest issue of @geoscientistmag features our findings on #subsidence caused by dewatering processes during work on the #Crossrail project (May 2012-May 2015) at the Limmo Peninsula in East London. #radarsatellite #InSAR

Mark
@MirelandMark: Coffee under control... Although @WadsworthFabian your article in @geoscientistmag has turned my morning coffee ritual into a daily science experiment!

Gareth Farr
@GarethFarr1: When the dog gets his picture in @geoscientistmag before you do:

Dr Kirstie Wright
@rocksandwiggles: Sunday morning reading of the @geoscientistmag and incredibly proud to see @JI_Farquharson and @scarlett_jazmin!! my coffee table never looked so good
#WriteHereWriteNow

The Flat Type
@theflattype: Some people I flattened on @geoscientistmag!
@geolsoc

Durham Volcanology
@Durham_Volc: “Coffee-making can be a daily mindful lesson in fluid- and thermodynamics.”
In the new Summer Issue of @geoscientistmag, our @WadsworthFabian muses with @JI_Farquharson on coffee as a microcosm of Earth Science!

Philip Benson
@RockMechLab_UoP: Smells good! Earth Science meets coffee with @WadsworthFabian and @JI_Farquharson in the summer issue of Geoscientist @geolsoc
Agricultural soil can be amended to increase rock weathering rates, which helps to remove CO₂.
To meet targets set in the Paris Agreement, we must stop emissions and actively strip carbon dioxide from the atmosphere. Rachael James and colleagues discuss two geological techniques – enhanced rock weathering and carbon mineralisation – that show promise for CO$_2$ removal.
Weathering and carbon mineralisation – and this is where geology can play a key role in addressing the climate emergency.

Geological processes and CO$_2$

Weathering is a natural geological process whereby atmospheric CO$_2$ dissolved in rainwater attacks rocks and soils, partly dissolving them (Eq. 1 and Eq. 2). The CO$_2$ is converted into hydrogen carbonate ions (alkalinity) that are eventually captured in the ocean where they are securely stored for more than 100,000 years. Some of the hydrogen carbonate ions may, under some circumstances, precipitate as carbonate minerals (carbon mineralisation) that are stable on timescales of more than 10,000 years (Eq. 3).
Note, however, that during precipitation of carbonates, half of the CO$_2$ captured by silicate minerals and all of the CO$_2$ captured by carbonate minerals is re-released back into the atmosphere (Eq. 3). Thus, carbon mineralisation of silicates is half as effective as mineral dissolution (weathering) for CO$_2$ removal, and dissolution and reprecipitation of carbonate minerals has no net impact on levels of atmospheric CO$_2$.

On a global scale, weathering removes about 1 Gt of CO$_2$ every year and plays a key role in the long-term regulation of Earth’s climate. However, natural weathering and carbon mineralisation take time. To remove significant volumes of CO$_2$ from the atmosphere by the end of the century, geologists are investigating ways to speed up these processes.

**Enhanced rock weathering**

Weathering rates are controlled by environmental factors – principally water availability and temperature, as well as the properties of the rocks or soils themselves, such as mineralogy, grain size, porosity and permeability. Enhanced rock weathering is a CO$_2$-removal strategy that amends agricultural soils with crushed calcium- and magnesium-rich silicate rocks and harnesses the photosynthetic energy of the crops to increase weathering rates.

**Modelling studies:** Initial model simulations of enhanced rock weathering (Taylor et al., 2016) indicated that application of 1–5 kg m$^{-2}$ per year of pulverised silicate rock (basalt and harzburgite) to all of the agricultural land located within 30° of the equator (~20 x 10$^6$ km$^2$) could lower levels of atmospheric CO$_2$ by between 30 and 300 ppm (depending on rock type and application rate) by the end of the century (Fig. 2). The model simulations also showed that enhanced rock weathering could increase delivery of alkalinity to the oceans to an extent sufficient to mitigate the effects of ocean acidification caused by uptake of anthropogenic CO$_2$.

A more recent study (Beerling et al., 2020) made a quantitative techno-economic assessment of the CO$_2$-removal capacity and costs for implementing enhanced rock weathering, constrained by the available agricultural land area and energy production. The model results showed that roll-out of enhanced rock weathering to between 10% and 50% of available agricultural land area in the world’s major economies, even taking into account emissions associated with crushing and transporting the pulverised rock, could contribute to the removal of between 0.5–2 Gt of CO$_2$ per year. This would equate to between 2.5% and...
40% of the amount required by 2100 to meet the Paris Agreement target, similar to quantities estimated for other CO₂ removal strategies, including bio-energy with carbon capture and storage, and direct air capture (Fuss et al., 2018).

Field studies: Before wide deployment, we need to confirm the efficacy of enhanced rock weathering as a CO₂-removal strategy using large-scale field trials on a wide range of agricultural soils and crop types, under different climatic regimes. The net amount of CO₂ removal will be reduced if pulverised rock is transported over long distances, so tests must also be undertaken using a variety of rock types, including those that may have lower-than-ideal CO₂-removal potential (Fig. 5). Moreover, we must develop methodologies for full greenhouse-gas budgeting, monitoring of crop and soil health, and robust, repeatable and relevant measurements for verifying CO₂ removal and security.

In support of this, the Leverhulme Centre for Climate Change Mitigation (www.lc3m.org) is conducting multi-year field trials of enhanced rock weathering in the UK, Malaysia, Australia and the US (Fig. 3). Crop types include maize (corn), miscanthus (a bioenergy crop), sugarbeet, sugarcane, oil palm, barley and peas, and soil type varies from slightly acidic (pH ~6) to basic (pH ~8). Pulverised rock was obtained from as close to the field sites as possible, and primarily consists of waste material from road aggregate mining – these wastes are too fine to be used for road building, so they are stockpiled at the mine sites.

The waste materials are silicate-rich and range in composition from relatively unweathered basalt to metabasalt. The trials are only in their early stages, but preliminary results indicate that dissolution products from weathering of the applied rock can be detected in soil waters within a few weeks of application, with higher soilwater alkalinity in plots amended with pulverised rock relative to control plots (that have not been amended with pulverised rock). The soil, soil waters and crops are also being monitored for heavy metal concentrations (such as arsenic, lead and chromium) to ensure the safety of enhanced rock weathering; no significant differences have been observed between any of the rock-amended and control plots to date.

Carbon mineralisation
Calcium, magnesium and hydrogen carbonate ions produced by weathering of silicate minerals (Eq. 1) can subsequently precipitate as carbonate minerals (Eq. 3). This process occurs naturally during weathering of ultramafic to mafic rocks, such as mantle peridotites and basalts. Peridotites undergo hydration (serpentinisation) and carbonation reactions at geologically relatively rapid rates at low temperature, as evidenced in the Oman ophiolite (Fig. 4). Mafic and ultramafic rocks have the potential to store tens of gigatonnes of CO₂ at the global scale (both onshore and offshore), but, in reality, the overall degree of carbonation also depends on the availability of CO₂ and the chemical conditions, such as pH, salinity, temperature, and pressure, as well as on the permeability of the storage formation.

Engineered carbon mineralisation is essential for effective CO₂ removal. It can be accomplished by (1) ex-situ mineralisation, whereby calcium- and/ or magnesium-rich silicate minerals...
are reacted with CO$_2$-rich fluid or gas in a reactor; (2) in-situ mineralisation, whereby CO$_2$ gas or CO$_2$-bearing fluids are injected into suitable subsurface reservoirs for geologic storage; and (3) surficial mineralisation with CO$_2$ from the air using mafic to ultramafic mine tailings or alkaline industrial waste material.

In-situ mineralisation has been tested at the field-scale, with pilot experiments in Iceland (CarbFix project) and the USA (Wallula Basalt Project). In Iceland, the geothermal company Reykjavik Energy and a consortium of research scientists, have injected ~230 tonnes of CO$_2$ dissolved in water into a highly permeable, fractured basalt reservoir at depths of 400 m to 800 m. By using novel chemical and isotopic tracers, the CarbFix experiment demonstrated rapid CO$_2$ mineralisation of more than 95% of the injected CO$_2$ within less than two years (Matter et al., 2016).

Since 2014, Reykjavik Energy has injected more than 20,000 tonnes of CO$_2$ into a basalt reservoir at about 2,000 m depth. Tracer results reveal nearly complete CO$_2$ mineralisation (Clark et al., 2020), but estimates of CO$_2$ uptake to date indicate that the CarbFix storage process may be limited by CO$_2$ supply. To increase the overall supply of CO$_2$ and to speed up mineralisation, carbon mineralisation can be combined with other CO$_2$-removal technologies, such as direct air capture, as demonstrated by the world’s first combined direct air capture mineralisation plant in Iceland (https://climeworks.com/orca).

Mine tailings as feedstock

The mining industry extracts tens of gigatonnes of rock material each year, generating large amounts of freshly exposed, reactive surface area that could be used both as feedstock for enhanced rock weathering and mineral carbonation.

Most common base metals (e.g., copper, lead, zinc, nickel) are profitably mined at concentrations as low as ~1% by mass, precious metals (gold, silver, platinum group metals) at parts per million levels, and diamonds at hundreds of parts per billion. So, most processed mine material is effectively “waste” that is stockpiled in dumps and tailings ponds. These mine tailings have been ground to clay-silt to sand-sized particles. Depending on the target metal, for every tonne of rock mined, around 60 to >99% becomes mine tailings.

Our recent assessment of the CO$_2$-removal potential of tailings from the mining of silicate mineral-hosted ore deposits is between 1.1 and 4.5 Gt of CO$_2$ per year via weathering and alkalinity generation, or approximately half that value (0.5–2.3 Gt of CO$_2$ per year) via
Climate Change

Mineral carbonation (Bullock et al., 2021). Ore deposits with the highest CO\textsubscript{2}\textsuperscript{-}removal capacity are those that are mined in high quantities and have an abundance of calcium- and magnesium-bearing silicate minerals. These include ores that are derived from mafic and ultramafic magmas, as well as some copper-bearing ores (Fig. 5). The former includes the platinum group metals and chromium-bearing ores. By contrast, mine tailings that contain high quantities of silica or sulphide minerals have low CO\textsubscript{2}\textsuperscript{-}removal potential.

Figure 5 shows only the CO\textsubscript{2}\textsuperscript{-}removal potential of different ore deposits and takes no account of reaction kinetics. Depending on particle size, only a few minerals are expected to weather on timescales of less than a decade (notably olivine, wollastonite and brucite) and these minerals are usually minor constituents of mine wastes. This means that new approaches will be required to unlock the full potential of mine waste as a feedstock for CO\textsubscript{2} removal. These approaches could include the acceleration of reaction kinetics through enhanced rock weathering with agriculture, or reaction with CO\textsubscript{2}\textsuperscript{-}-rich fluids and gases, as well as techniques that exploit microbial metabolisms that enhance mineral dissolution and/or carbonation.

As global mining operations are currently estimated to emit ~3.6 Gt CO\textsubscript{2}e per year (Azadi et al., 2020), and demand for raw materials continues to grow, implementation of effective CO\textsubscript{2}\textsuperscript{-}removal schemes at mine sites (combined with emissions-reduction technologies) is attractive because it would greatly improve the carbon footprint of the mining industry.

Outlook

There are potential barriers to the large-scale roll-out of the above methods. Such barriers include a lack of scientific knowledge, such as unknowns relating to the longer-term effects of rock application on soil quality, but also broader aspects including the public perception of the risks and benefits of these CO\textsubscript{2} removal techniques, as well as governance and ethical issues.

That said, farmers are used to applying fertilisers, such as lime, to their fields, so the enhanced weathering technique is compatible with agricultural practices. It may also bring important co-benefits for agriculture, such as improvements to crop yield, pest resistance, and increased plant nutritional quality that are key to catalysing farmer adoption. Furthermore, utilising mine waste as a feedstock has the benefit of creating a circular economy.

CO\textsubscript{2} removal via enhanced rock weathering and mineral carbonation clearly have the potential to make a significant contribution towards achieving the Paris Agreement targets and their cost is comparable to other CO\textsubscript{2} removal strategies (see Beerling et al., 2020 for a full evaluation). Both techniques essentially involve speeding up natural processes, and may be less controversial than engineered climate solutions, such as cloud seeding and solar radiation management.

Further Reading

A full list of further reading is available at geoscientist.online.

Energy Group Events

28 - 30 September 2021
The Geological Society, and Virtually, Zoom
https://www.geolsoc.org.uk/09-rescheduled-pg-petroleum-systems-modelling-2021

Petroleum Geology of the Southern South Atlantic
6 - 7 October 2021
The Geological Society, and Virtually, Zoom
https://www.geolsoc.org.uk/10-Energy-Group-Southern-South-Atlantic

8th UK Geothermal Symposium
17 November 2021
The Geological Society, and Virtually, Zoom
https://www.geolsoc.org.uk/11-EG-Geothermal

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Reimagining applied geoscience for the energy transition

Phil Ringrose offers some framing perspectives on what the energy transition may entail for practising geoscientists working in the Earth-resources industries.

WHAT WILL energy-transition geoscience look like? Is there such a thing as sustainable geoscience? And, perhaps more pressing for many, will there be a job for me as a practising geoscientist? These are among the most debated and challenging questions for the current generation of geoscientists, particularly those working in the extractive industries.

I recall when graduating with a degree in geology many years ago, the career advice was essentially to choose between gold, diamonds and oil – these being the main industry sectors that employed geologists at the time. A cliché perhaps – but reflecting the fundamentally exploitative nature of geosciences in the 20th century, with the hunt for energy and the exploitation of minerals and hydrocarbons forming a dominating umbrella for much of Earth science. Actually, I picked a fourth option and took a job as a consultant in environmental Earth sciences, only to discover that ‘environmental geoscience’ was itself closely connected with ‘exploitation geoscience’ since we mainly worked on geological aspects of nuclear waste disposal or clean-up of oil spills. Many academic geoscientists ‘sitting in their ivory towers’ also found it hard to isolate themselves from the exploitation mindset, since several geological disciplines, including igneous and metamorphic petrology or sedimentary basin systems analysis, received research funding motivated by the economic drivers from the mining and petroleum industries.

Now, with two decades of the 21st century behind us, the drive for a more sustainable approach to geoscience, and particularly the Earth-resource industries, is paramount and the urgency of responding to the climate-change challenge is the dominant Earth-science question. The energy transition is upon us – how do we respond?

A revised mindset

In recent years, many university departments have either discontinued or renamed their petroleum geology degree programmes and have reported difficulties in recruiting the next generation of students. Early- and mid-career geoscientists who were in demand a decade ago, especially in petroleum-related fields, are now finding the job market thin, particularly given the current economic slowdown caused by the double whammy of a global pandemic and a global climate crisis. The new Centre for Doctoral Training initiative (see page 34) is a good example of a proactive response to these challenges.

EMERGING TRENDS IN THE AGE OF DECARBONISATION

Some of the emerging trends for geoscience in the age of decarbonisation (based on Stephenson et al. 2019):

1. Energy storage for economies dominated by renewable energy systems, including thermal storage, compressed air storage and hydroelectric dam storage.
2. Carbon capture and storage (CCS), encompassing both CCS for net-zero-emission industries and as a vehicle for enabling negative emissions pathways.
3. Sourcing of raw materials (metals and rare-earth elements) to support the rapidly growing solar and wind power sectors and the associated demand for electrical batteries and power transmission systems.
4. The hydrogen economy, where water electrolysis or methane reforming are used to drive a new ‘green-molecule’ economy.
5. Nuclear energy, where geological disposal facilities for radioactive waste are successfully deployed to make existing and future nuclear power genuinely sustainable.

(NB: This review did not include other important careers in the field of applied geosciences such as the built environment, geohazards or applied environmental geology and engineering.)
ENERGY TRANSITION

A recent review of the emerging trends for geoscience in the age of decarbonisation (Stephenson et al. 2019; see box, previous page) provides a snapshot of some of the ways geoscience can contribute to international efforts to keep global warming well below 2°C and points to some of the likely focus areas for many geoscientists in the coming decades. This is a list driven by energy needs, and clearly many geoscientists will work on topics such as climate change, geohazards, and Earth processes.

Climate science and the United Nations Sustainable Development Goals (SDGs) are also important for framing the emerging demands for Earth science in our society and, arguably, geoscientists are uniquely well placed to understand what the SDGs will mean in practice. Our 2030 world will need more access to affordable and reliable energy (not less), significantly expanded renewable energy systems, new investments in infrastructure and a whole suite of upgraded technologies to supply modern, efficient and sustainable energy services for all – in developing countries as well as in mature economies. All of this will require new Earth resources and, most importantly, more intelligent and more sustainable ways of using those resources, including a lot more recycling. The exploitation mindset must be replaced by a sustainability mindset – where (paraphrasing complementary definitions of sustainability from the fields of environmental science, sociology and ecology) sustainable means without significant harm to the environment, including the atmosphere and climate system, and without damaging the long-term ecological balance, for future generations of humans and for other species. Quite a challenge!

Thinking differently is a precursor to behaving differently, and significant changes in behaviour must be a part of the energy transition, which itself is part of the fundamental change to a more sustainable and inclusive society. Three overarching themes emerge:

1. **A focus on younger stratigraphy** – with a stratigraphic bias towards the Quaternary and the Anthropocene.

2. **Different fluids in focus** – carbon dioxide, hydrogen and methane being high on the list.

3. **Environmental intelligence** – using space technology, geophysical sensing and geochemical tools to gather information about our planetary living space.

**Focus on younger stratigraphy**

All geoscientists will have learnt the geological column at some point in their education and then probably spent some time getting to know limited parts of it quite well. The Mesozoic often draws the most attention for petroleum geoscientists, while the Proterozoic and Palaeozoic are likely more important to mining geologists. One significant implication of the sustainability and climate-change challenge is the need to focus on very recent geological history – the Quaternary and Holocene.

The Anthropocene is now widely recognised as Earth’s most recent geological time period, marking the current phase of extensive human-influenced effects on Earth system processes. Although not yet officially approved as a formal subdivision of geological time, this period is critical for sustainable Earth science. It sits at the junction between understanding the recent geological past and forecasting possible Earth futures – scenarios that involve modelling the climate system, the hydrosphere, the oceans and the many geological processes involved.

Figure 1 shows an intentionally provocative re-scaling of geological time using the inverse log of time to illustrate how the understanding of present-day Earth processes is likely to be dominated
by the Holocene and Anthropocene timeframe. Certainly, climate change studies use a lot of information from the Cenozoic era and much less from the earlier geological record. Likewise, efforts to predict the availability of groundwater and surface water for human populations will tend to use recent (Holocene) records to calibrate forecasts for the next few decades. This concept is nicely captured in the 'geologic time spiral' (page 24).

The practical outworking of this modified timescale perspective is found in many of the energy transition activities. Building offshore windfarms typically involves foundation engineering of the top 100 m of substrate (typically Holocene and Pleistocene sediments). Acquiring minerals needed for the energy transition, hopefully in a responsible and sustainable manner, will also typically require much more focus on the near-surface environment and hydrogeological processes (even if the minerals themselves come from an ancient rock system). The growing activities in underground storage of CO₂ and H₂ generally focus on storage depths within the 1-3 km interval, with significant work needed on understanding the overburden of the uppermost 1 km.

Such studies on the shallower rock sequence often encounter a 'data gap' or at least a paucity of information for the overburden section. Many petroleum-related drilling and seismic surveys targeted the deep intervals, such that logging datasets and high-quality seismic imaging were lacking in the shallower intervals. Where shallow seismic imaging data are available (such as using broadband seismic acquisition datasets), the shallow sequences reveal much more complexity than previously imagined. For example, in the North Sea basin the top 500 m interval reveals an amazing network of glacial channel deposits from the Pleistocene glaciations (Fig. 2). Understanding these shallow glacial deposits has practical implications for the assessment of CO₂ containment systems (Landrø et al. 2019) as well as revealing new insights into the retreat of the British–Irish and Fennoscandian Ice Sheets (Bradwell et al. 2019). Another fascinating development in shallow marine geoscience has been the acceleration in understanding of the submerged Palaeolithic and Mesolithic settlements of the southern North Sea region – especially Dogger Land – provoked by the acquisition of new seismic and well data from offshore wind-farm developments (Bailey et al. 2008; Ward, 2014). I hadn’t quite appreciated how much the renewable energy boon would lead to a revolution in marine archaeology.

A different set of fluids

The study of multiphase flow in permeable rock media – an important branch of geoscience and applied physics – has for many decades been dominated by the study of petroleum-water systems. However, the last decade has seen a rapid expansion in the study of CO₂-brine systems and hydrogen-brine systems as important variants of the science of multiphase flow in rock media. We are therefore likely to see several bifurcations of multiphase flow analysis in the energy transition.

Insights from the much-studied oil-gas-water fluid systems are already being applied to CO₂-brine systems and hydrogen-brine systems, but new challenges are also emerging. CO₂ is much more reactive with the aqueous and mineral phases in the host-rock system; CO₂ dissolves in brine (making sparkling water) and can precipitate as carbonate minerals (a form of accelerated cementation). These processes contribute to an important principle in CO₂-storage projects, namely that the stored CO₂ generally becomes more secure as a function of time (Ringrose et al. 2021).

Figure 2: Imaging Upper Pleistocene glacial channels from shallow seismic data. Green channel object is ~ 500 m wide, ~12 km long and at a depth of ~200 m overlying a broad channel system in blue at ~400 m depth. From work reported by Furre et al. (2015) In: Third Sustainable Earth Sciences Conference and Exhibition 2015(1), 1-5, EAGE. (Image courtesy of Equinor.)
For hydrogen storage, which many argue will be essential in a renewable-energy-dominated world, there is a new set of geochemical reactions to concern us (Heinemann et al. 2021). For example, certain microorganisms frequently present in subsurface formations can be major hydrogen consumers, which can potentially lead to undesirable losses or technical challenges during a hydrogen storage project. However, by understanding the behaviour of 'bugs' over different ranges of temperature, salinity and acidity, these reactions can be controlled and managed. It does mean, however, that the biology of deep microorganisms will be an important theme in future geoscience.

Understanding these new fluid systems will bring novel and exciting challenges for geoscientists working on fluid-rock interactions and flow in permeable rock media. Although too broad to summarise here, perhaps figure 3 will provoke your interest. CO₂ in the subsurface becomes a liquid below a depth of ~800 m, and at those depths it behaves more like the olive-oil/water system than it does like the CO₂-sparkling wine system (Fig. 3).

There are of course many other factors controlling CO₂ in the subsurface that are not captured by this simple illustration (such as thermal effects on in situ phase behaviour), but it makes a good starting point for discussions at the bar.

Environmental intelligence and Earth monitoring systems

There is little doubt now that we live in an age of major environmental and climate-related challenges, which many would argue are at crisis levels. This concerns not only our response to human-induced global heating, but also how we address...
numerous other ecological impacts, such as loss of biodiversity, degradation of soils, loss of forested land and damage to water resources. The energy transition therefore involves both a rapid move to low/zero-emissions energy systems and a drive to use Earth resources without significant harm to the environment.

The sustainability mindset needs to be embedded in everything we do. For geoscientists this means a focus on monitoring and measuring the natural Earth system – the hydrosphere and biosphere, the marine and terrestrial environments, the shallow Earth and deep Earth system. The problem is often that the wider society lacks an appreciation of how important Earth resources are to modern life. Everybody wants ‘green’ but few really know what ‘green’ means in practice. As for us geoscientists, we must also admit that there is still much unknown about Earth process, especially longer-term processes. I am reminded of Emily Dickinson’s poem What mystery pervades a well! where she ponders the mysteries of ‘water […] from another world residing in a jar’ and writes:

But nature is a stranger yet;
The ones that cite her most
Have never passed her haunted house,
Nor simplified her ghost.

Even as a practising geoscientist, I agree with this sentiment – the natural world is still a stranger and those that cite her most need to do more to understand the ‘haunted house’.

This is where the ongoing revolution in remote sensing has a major role to play. Monitoring Earth’s surface by satellite and probing Earth’s interior using geophysical and geochemical sensing tools will be vital in the coming decades. A number of exciting and fast-moving innovations (see box, left) mean that geoscientists now have an unprecedented set of tools and methods to monitor Earth, and with the ‘sustainability mindset’ that we need to develop, we will have access to plenty of data to better understand the natural world.

So how should we re-imagine geoscience in the resource-utilisation professions? We are not here just to find resources and exploit them, we are available to help our society use Earth resources in a sustainable way. Every resource, including water, metals, minerals, hydrocarbons, porous storage units, and geothermal resources, needs a ‘Handle with Care’ label attached, and advanced, intelligent Earth-systems analysis must be integral to what we offer society. I find that exciting – I hope you do too.

Acknowledgements
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A list of further reading is available at geoscientistonline


definitions:
EN MOTHERN \| PERSPECTIVES

EXAMEN OF RECENT ADVANCES
IN EARTH MONITORING SYSTEMS

Illustration of the TerraSAR-X satellite
(by DLR, CC BY 3.0 via Wikimedia Commons)

- From space, we can now detect emissions of CO₂ and CH₄ with increasingly higher levels of accuracy and precision. For example, publicly available data is provided by the SCIAMACHY instrument on Envisat, AIRS on the Aqua satellite, the GOSAT and GOSAT-2 satellites, the OCO-2 satellite and the OCO-3 instrument mounted on the International Space Station. These satellites are important both for monitoring human-made emissions of greenhouse gases and for understanding natural emissions (from the oceans, terrestrial plants and volcanoes).

- Also from space, we can now measure mm-scale ground deformation on an almost daily basis. Interferometric synthetic aperture radar (InSAR) has in the last decade gone from a niche activity to a routine geodetic monitoring system. The satellites currently in operation include COSMO-Skymed and TerraSAR-X (in the X-Band) and Sentinel-1 and Radarsat-2 (in the C-band). Several nations now have complete InSAR coverage available for the public, allowing you to check subsidence or uplift around human-made structures and cities (Bischoff et al. 2020) or in relation to natural hazards such as landslides (Carla et al. 2019). The method can also be used to monitor pressure changes associated with CO₂ storage (Vasco et al. 2010).

- On Earth’s surface, most geoscientists are used to the value of seismic imaging to see what ‘lies beneath our feet’, but perhaps less aware of how the quality of those images has improved over the years. For example, broadband marine seismic acquisition can increase the usable frequencies from a few Hz up to 200 Hz (compared to conventional acquisition system typically between 8–80 Hz) leading to much better imaging of shallower and deeper features in the same survey. Furthermore, time-lapse seismic methods allow fluid movements and pressure changes in the subsurface to be detected with increasing levels of accuracy (Landrø 2001) and have been shown to be very suitable for monitoring CO₂-storage sites (Chadwick et al 2010).

- At and below Earth’s surface, fibre-optic sensing is opening up a whole new box of possibilities for monitoring. Fibre-optic cables are cheap and can be used for multiple purposes. For example, a standard telecommunication cable can be used to image the subsurface (Fig. 4; Taweesintananon et al. 2021) and to detect earthquakes (Lindsey et al 2017). Dedicated fibre-optic layouts, using surface and downhole fibre-optic cables can be used to monitor CO₂ storage sites (Harris et al 2017) or landslide hazards, and in some cases traffic noise can be used as the seismic source (Dou et al 2017).
The transition to net-zero carbon emissions requires innovative use of the subsurface. Colleagues from the Tectonic Studies Group argue that structural geologists have the knowledge and skills to effectively support the net-zero transition.

TECTONICS and structural geology have been at the core of Earth resource development for decades, helping to build and shape the world we live in today. Resource revolutions of the past, including mining of coal for the industrial revolution, the extraction of minerals and metals and the unlocking of hydrocarbons, were enabled and supported in large part by the know-how of tectonics and structural geologists. But many of these activities, and the developments that they have powered, have led to the climate and ecological crises that we face today. Given this, one might assume that structural geology will become obsolete in the net-zero carbon-circular economy of the future. On the 50th anniversary of the Tectonic Studies Group of the Geological Society, we look at some of the ways structural geologists will remain relevant, if not crucial, to the realisation of the net-zero carbon revolution.

A changing Earth
Our use of Earth resources is changing through necessity. As a society we have consumed, produced and polluted ourselves into a position where we must fundamentally change how we do business for the ecosystems that support us to survive. Climate scenarios modelled by the International Panel on Climate Change indicate that we can avoid the most dangerous impacts of climate change if we work hard to limit global temperature rise to 1.5°C above pre-industrial levels. To achieve this, we need to move to a ‘net-zero carbon’ world by 2040, and crucially, we must also reduce non-CO₂ greenhouse-gas emissions.

Action is required. We need to slash greenhouse-gas emissions, and deploy negative-emissions technologies to balance the books, while enabling sustainable global development, too. As a result, we will use the subsurface in innovative ways, such as fluid cycling through injection and storage, CO₂ disposal and waste management. Resource extraction will diversify and its environmental footprint will shrink. These new uses of the subsurface mean structural geological expertise will be in high demand.

Unlocking the future
Geological storage of CO₂ plays two roles in achieving net zero: reducing emissions from industry and enabling negative emissions, for example, by storing CO₂ captured from the atmosphere. Revived focus on hydrogen could see increased hydrogen geological storage, whether in engineered salt caverns or in porous rock formations. Other potential technologies include compressed air energy storage. The success of these technologies will require new data acquisition with reinterpretation of existing subsurface data, characterisation of the architecture of geological structures and subsurface fluid migration, as well as geomechanical approaches to characterise fault stability.

Growth in geothermal resource development is anticipated, in particular as a low-carbon solution for heating and cooling. Low-temperature resources, such as abandoned coal mines, can supply district heating, while higher temperature resources (‘hot rocks’) offer both heat and...
power options. The vast back catalogue of geoscience knowledge of coal systems, and the geological structures that partition them, is proving valuable to identify, assess and de-risk coal-mine geothermal energy. In higher energy systems, whether they be granite-hosted, fault-controlled reservoirs such as those in Cornwall, UK, hot sedimentary aquifers or active geothermal systems, we need structural geologists to carry out fracture mapping and modelling, as well as reservoir geomechanical analysis, characterisation, and model parameterisation. For this fledgling UK industry, structural geology know-how is essential to aid resource optimisation, operation and monitoring.

Constructing anything — whether wind turbines to generate energy, direct air capture units to remove CO₂, dams for hydroelectricity, or pipelines to create a connected CO₂ network — requires the expertise of engineering geologists who can assess ground stability, and here the understanding of geological structures is key. The need for critical raw materials will continue to rapidly increase to meet the demand of the growing green-technology revolution. Finding and extracting new deposits, optimising further utilisation of existing ones, and even reviving abandoned resources that may hold previously overlooked potential requires the expertise and skills of structural geologists who can understand the tectonic controls on fluid flow and mineralisation processes. Further, mining these metals will need to be more efficient and there are roles for structural geologists in mineral exploration and deposit modelling, resource estimation, 3D mine design and geotechnics.

Skills for the future

Structural geology skills and understanding are far from obsolete; they are key for delivering net zero. The past is the key to the present — and future. A range of net-zero solutions are grounded in the subsurface, meaning that structural geologists have a crucial role to play in the energy transition. Our market is evolving: while some traditional avenues will close, there are many new and exciting opportunities within our grasp. A successful transition depends on our realisation that the knowledge, understanding, approaches and data common in a traditional structural geologist’s wheelhouse translate to many developing and emerging industries. We do not need to reinvent the wheel, just adapt it with some new net-zero spokes. There is much to do — we face a period of innovation and adaptation to a new future that needs us if it is to succeed.

Despite the need for more structural geologists, there is a worrying downturn in student uptake of geoscience subjects. To avoid a future skills gap, we need advocacy to support uptake of Earth science in society and education in the years to come. Such advocacy must be coupled with action to break down barriers to inclusivity; diversity amongst the geoscience community is not only a matter of justice, but will support the innovative, cooperative and representative development needed for sustainable solutions.

Geoscientists are excellent at whole-systems integrated thinking. This approach is essential for a net-zero world, where a sustainable circular future is an integrated future, a ‘system of systems’ that combine to improve efficiencies, design out waste, and maximise benefits. We already see the vision of integrated geothermal power, heat, and metals production at United Downs in Cornwall, UK, a project that demonstrates the circular economy principles that must underpin the energy transition.

All net-zero solutions must be place-sensitive. Many of the approaches underpinned by geoscience are embedded in issues of social and environmental justice, and ignoring them will only propagate the negative impacts and public concern around the resource sector. Socio-scientific challenges are particularly prevalent for topics that are unfamiliar, uncertain, or emerging, and where change is needed fast — like most net-zero geoscience developments! So, we will need structural geologists who are comfortable integrating across disciplines, and who are able to communicate and collaborate with a range of stakeholders, including policy makers, the public and communities, so that our sustainable future will benefit everyone.

FURTHER READING

A full list of further reading is available at geoscientist.online.

• The Intergovernmental Panel on Climate Change Special Report: Global warming of 1.5 °C; www.ipcc.ch/sr15/
• The Tectonic Studies Group: http://tectonicstudiesgroup.org/
James Croll (1821–1890), a pioneer in palaeoclimatology, must be one of the few Geological Survey geologists to admit that he didn’t like geology. The son of a stonemason, Croll was born in 1821 near Little Whitefield in Perthshire. Largely self-educated, and suffering from ill health throughout his life, he worked as a wheelwright, a tea merchant, manager of a temperance hotel, and an insurance agent. Then, in 1859, he landed what he considered to be the ‘perfect job’ – as a janitor at the Museum of the Andersonian University in Glasgow.

The job gave him access to the university library and the opportunity ‘to study the sciences in something like a systematic form’ by teaching himself physics and astronomy. Early on he ‘conceived a distaste for geology, as involving too much consideration of details and not giving due prominence to principles’. Nevertheless, he became interested in the causes of glaciation and, in 1864, began publishing a series of papers arguing that changes in the eccentricity of Earth’s orbit were a key factor behind the glacial epochs that occurred periodically throughout geological time.

Mental arithmetic
Croll’s papers soon attracted the attention of scientists, including the mathematician Lord Kelvin (1824–1907) and geologists such as Andrew Ramsay (1814–1891), then head of the Geological Survey, and Archibald Geikie (1835–1924), director of the Survey’s Scottish branch, who offered Croll a job as a resident surveyor and clerk in the office at Edinburgh. Croll wasn’t keen to accept the offer, but finally agreed after receiving assurances that he would be allowed the time and resources to carry on with his own investigations.

But there was a hitch. To join the Survey, Croll needed to pass the civil service examination – and he failed the arithmetic and English papers. It was only after the intervention of Geikie and other eminent scientists that the ‘Lords of the Civil List … were induced,’ as Lord Kelvin has it, to accept Croll’s ‘great calculations regarding the eccentricity of the earth’s orbit and the precession of the equinoxes during the last 10 million years as sufficient evidence of his arithmetical capacity, and his book on The Philosophy of Theism and numerous papers published in the scientific journals as proof of his ability to write good English’. Croll joined the Survey in 1867 and remained until ill health forced his retirement in 1881.

Awards add up
During his time at the Survey, Croll’s publications (many summarised in his 1875 book, Climate and Time) proliferated and awards mounted up. In 1872, he was awarded the Balance of the Proceeds of the Wollaston Donation Fund by the Geological Society of London and, in 1876, was elected a Fellow of the Royal Society. By the time he died in 1890, his bibliography included 92 books and papers.

Nearly half a century later Milutin Milankovitch drew on Croll’s work to develop the concept of Milankovitch cycles to explain climate changes over geological time. Not a bad legacy for someone who failed an arithmetic test!
CONFERENCES & EVENTS

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https://www.geolsoc.org.uk/wsmith21

Year of Space - Mars – a new geological frontier
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Image: Laminated sandstones on Gullane beach © Milena Farajewicz
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“Geoscience is vital for meeting Paris Agreement obligations”

John Underhill discusses the criticality of geoscience for low-carbon sustainable solutions

"It’s a really exciting time for the geosciences. Earth science has been instrumental in documenting climate change and is pivotal in finding solutions that address it. Put simply, it is no longer about diagnosis, but mitigation and cure. Geoscience is vital for meeting the obligations embedded in the Paris Agreement."

John Underhill, a Professor at Heriot-Watt University, UK, views geoscience and the people who study and practice it as absolutely crucial as we seek to introduce measures that enable us to decarbonise, move towards a low-carbon sustainable future and address the United Nations’ Sustainable Development Goals.

“I have heard it said ‘the time for geological studies has passed, it is simply an engineering issue and we should just get on and do it’. While engineering is undoubtedly a major part of the solution, the fact that carbon dioxide has quite different physical and chemical properties from long-chained, inert hydrocarbons because it is small, nimble and highly reactive in the presence of water (when
it forms carbonic acid) means we cannot simply assume that we can re-use depleted oil-and-gas fields for a new purpose. Frankly, if the wrong geological sites are selected for subsurface storage of carbon dioxide or hydrogen, credibility will be lost and a vital technology will not be deployed at scale.

“The drive for electric cars, wind turbines, solar panels and new technologies will also have major consequences for our science. Such technology demands not only a step change in the amount of electricity needed, but also the mining of metals, critical minerals and essential raw materials like lithium, cobalt, titanium and the rare-earth elements. It is incumbent upon us to ensure that the optimal locations are selected that minimise environmental impacts of extraction, do not exploit local communities and are sustainable in the long-term.”

Holistic approach
John is particularly interested in the use of subsurface data to identify and critically evaluate safe sites for subsurface storage.

“I am committed to seeing the best and most appropriate use being made of the sea bed and subsurface geology as part of the net-zero agenda, ensuring the adverse environmental impacts are avoided.

“Despite the undoubtedly positive contribution of wind power to decarbonise the electricity system, wind farms have consequences that impact our ambition to do the same for other sectors and technologies. Since most offshore wind farms are fixed to the sea bed, it is much harder to visualise, characterise, monitor and, hence, utilise the subsurface that lies directly below them – an essential requirement if we are to locate and evaluate safe storage sites and monitor the CO₂ injection or hydrogen storage needed to decarbonise the UK’s industrial hubs. The occurrence of wind farms will affect our ability to build blue hydrogen capacity because this relies on a spatial association between a producing gas field supplying the methane feedstock, carbon store and hydrogen export route to shore (and storage).

“Holistic, joined-up thinking is needed to ensure the best and most appropriate use of the sea bed and subsurface geology. A collective failure to understand the dependencies and impacts that result from blanket wind farm coverage may rule out some or all of the other promising technologies and the UK’s pathway to net zero. A more judicious approach involving all the different regulatory bodies and various stakeholders is urgently required if the UK is to achieve the optimal outcome.”

Global population growth and increasing energy demands mean that oil and gas will remain in the energy mix – as highlighted by the Committee for Climate Change, who see a continued role for oil and gas in 2050 and beyond.

“While it may not be universally accepted that oil and gas should continue to be explored for and produced in the UK, it should be remembered that the basin’s indigenous supplies have a lower carbon footprint compared to the imports that would otherwise be needed to make up the shortfall. The reserves also provide the UK with energy security by reducing our reliance on other countries, and also mean we don’t simply transfer our carbon burden to them.”

Despite the undoubtedly positive contribution of wind power to decarbonise the electricity system, wind farms have consequences that impact our ambition to do the same for other sectors and technologies.
Skills shortage

To achieve our net-zero emissions targets requires a pipeline of talented people with the right skills to seek socially acceptable solutions. John believes that the association between geology and the extractive industries is too commonly made and feels it lessens the apparent attraction of Earth science to school children. He suggests we need a sustained effort to make geoscience a more visible, relevant and attractive subject, as well as more accessible to diverse communities.

“Our approach has shifted rapidly as universities seek to address an ongoing recruitment crisis. Many have or are re-designing their BSc and MSc courses; others have rebranded their department names. Likewise, the trends in research and available staff positions are changing to reflect net zero and the need to be relevant.

“Courses are populated with new content and there is an increasing awareness of the need to integrate topics like social license, public outreach, media communication and Government policy, as well as novel methods, such as virtual reality to augment fieldtrips through drone and laser technologies and artificial intelligence.”

John is Academic Executive Director of the UK Centre for Doctoral Training (CDT), GeoNetZero, a programme that undertakes research and training in geoscience and the low-carbon energy transition. The GeoNetZero CDT initiative seeks to build the next generation of geoscientists – those who will deliver a sustainable future as we undergo the energy transition. This academic-industry partnership is going from strength to strength with 32 PhD students recruited and a further 16 set to join next year. Involving 12 UK universities and with continued support from the Natural Environment Research Council, the CDT was the only entity named in the postgraduate training section of the UK Government’s North Sea Transition Deal, paving the way for further support for the programme.

Optimism and realism

John is hopeful about the UK’s decarbonisation goals and the role geoscience can play in getting us there, but his optimism is allied with a realism.

“I remain concerned that hype, wish fulfilment, confirmation bias and false drivers are in the mix. To determine the best subsurface solutions, reliable geoscientific input is essential. We must take a data-led, evidence-based approach, and articulate our science in a way that can inform opinion and lead to the right choices being made.

“I am also worried about polarised opinions and feel there is a need for a more nuanced view to be appreciated. We must gather, table and analyse the data to find the best and most appropriate solutions, those that ensure low-carbon energy security, aid our pathway towards a decarbonised world and alleviate all forms of poverty (including fuel poverty) for a just and fair transition. To achieve this, we must be open minded, be willing to test our assumptions, identify and eradicate biases, and be willing to ask and tolerate testing questions that challenge long-held dogma and beliefs. It is essential that there is an independent, robust test of the technologies and their potential deployment. To undertake such a forensic analysis takes time and is dependent upon data being collected or made available.

“It may be ironic, but the very same data acquired in the pursuit of fossil fuels (such as seismic, well and core data) provide an excellent foundation for repurposing and evaluating the subsurface for decarbonisation. Fortunately, these data have recently become available through the National Data Repository (NDR). Access and use of these data will extend the life of the mature North Sea basin and its re-emergence as a site where carbon storage, geothermal, wind and hydrogen can provide new low-carbon energy sources, and as a repository to help us decarbonise industrial hubs.

“The re-purposing of UK basins will require skilled geoscientists. While the number of jobs may initially be limited, the need for talent will increase if we are to understand and characterise new decarbonisation opportunities. There is a dual opportunity for experienced individuals to up-skill or re-skill and for young professionals, early career researchers, students and school children to have a sense of optimism that there is a vital role for them in geoscience as we strive to meet net-zero targets.”

JOHN UNDERHILL
Professor John Underhill is a Fellow of the Geological Society of London and Chartered Geologist, a Fellow of the Royal Society of Edinburgh, Professor of Geoscience and Energy Transition at Heriot-Watt University, Edinburgh, UK, as well as the Academic Executive Director of the UK’s GeoNetZero Centre for Doctoral Training
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Power to the people

Emily Cox suggests that to meet our decarbonisation goals, CO₂ removal technologies are needed at scale. Targets are no longer enough – we need significant financial support, as well as mechanisms that can systematically build trust and dialogue across all parts of society.

The CO₂ needs to be stored on very long timescales, but doing this doesn’t currently confer a financial benefit. More permanent CO₂ storage solutions need financial support, and currently there is no sufficient mechanism for doing that. We also need to remember that it is usually society who pays for this stuff (directly or indirectly), and therefore implementing these policies requires public buy-in. I’m not sure we’re doing enough to capitalise on the incredibly high level of support for addressing climate change.

Fighting misinformation

Misinformation and lack of trust is another concern that we must combat with public engagement.

In the UK, trust in scientists is quite high on average, but this average figure masks the emerging polarisation within it. I worry that people are being left behind – feeling as though no one cares about their concerns and being caught up by misinformation that appears more convincing and less distant than scientists do. For example, our work indicates that the controversy over fracking in the UK may have reduced people’s trust in subsurface energy technologies, which in turn might make it more difficult to develop and site techniques such as enhanced geothermal energy and carbon capture and storage.

Building engagement

A large and well-publicised national engagement process could help to improve transparency and trust. A great start would be a Citizen’s Assembly process for deciding the pathway we wish to take, including the role of CO₂-removal and geoscientific technologies within that, as well as the trade-offs people are willing to make, in a way that is perceived as fair, just and inclusive. But such an approach must commit to tangible action, because giving society a ‘pseudo voice’ is just as bad as giving no voice at all.

“I want the whole of society to have the opportunity to participate in this conversation. After all, we as a society determine policy mandates (through our votes), pay for innovation (through our taxes), create markets for new products, and will ultimately live alongside the technologies that we use to meet our decarbonisation goals.”

Emily Cox
Dr Emily Cox is a Research Associate at Cardiff University, UK, working on environmental policy and social psychology. She is an expert on public perceptions, policy and ethics of CO₂ removal technologies, including CO₂ sequestration via enhanced weathering.

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Richard Herrington, Head of Earth Sciences at the Natural History Museum, London, is optimistic that we can achieve the UK’s decarbonisation goals, but we must secure the materials we need for the mitigating technologies in a timely fashion. The rapidity of the energy transition means that mining new resources of commodities like lithium, graphite and cobalt, as well as traditional metals like copper, aluminium and iron for infrastructure, is inevitable.

Geoscientists are on the frontline of resource discovery, but also the responsible recovery of these resources and the design of a sustainable post-mining legacy, argues Richard Herrington.
“Any delay in their supply could mean that we won’t be able to build the electric vehicles, wind turbines and solar panels fast enough to hit the net-zero target in 2050. What the COVID pandemic has taught us is that supply chains for the things that we deem to be essential must be secured in advance. For the energy transition, metals and minerals are essential and geoscientists are key players to give us the expanded choice of supply that we need, thus securing sources for our industries.”

**Effective communication**

Effective communication of the essential role for mining in our greener future is critical.

“I think the public knows that science and technology are providing the answers to the net-zero challenges, but only a minority recognise that mining is part of the answer, too. There is the further challenge of where mining should take place. Done in the wrong places and by the wrong methods, mining could cause more problems than it is seeking to solve. We should develop mines where there is a positive impact to both the planet and its ecosystem, as well as the people involved. In some cases that might mean bringing mining ‘back home’ to old mining camps – Cornwall is a good example where mining could be an agent for good, but there are areas of potential in the UK and Europe where the mineral potential has not yet fully been evaluated.

“Very often, the geoscientist is the first person on the ground representing the company investigating the mineral potential, so there is a great responsibility on the shoulders of that scientist.”

**Revised approach**

Richard believes a new approach to mining is needed.

“A powerful book by Michael Braungart and William McDonough, entitled *Cradle to Cradle: Re-making the way we make things*, explores the idea that all things should be manufactured with the end-of-life re-use and re-purposing in mind from the start. I firmly believe that we should apply this philosophy to mining, which is a part of the manufacturing supply chain. Historically mining was viewed as a ‘cradle-to-grave’ business, often with a devastated site left as a legacy. Mining is a necessary ‘intervention’ to recover the minerals we need for a sustainable future, but we should design a mine in a ‘cradle-to-cradle’ fashion, so that the old mine site is left as a positive asset – maybe a solar or wind farm, a geo-park, a biodiversity oasis – in addition to delivering an economic and social benefit.

“Researchers at the Natural History Museum are developing methods and metrics that objectively measure biodiversity change due to human impacts, as well as investigating lower-impact mining techniques. I would love to see this tool applied to mining projects so that regulators can decide which projects have better eco-credentials. This may help when comparing the merits of mining in new frontiers, such as when considering deep-ocean mining, where we need to be able to quantify biodiversity impacts and compare those to the impact of comparable terrestrial mining operations for the critical metals we need.”

**Richard Herrington**

Professor Richard Herrington is Head of the Earth Sciences Department at the Natural History Museum, London, UK. He is also part of the NERC-funded LiFT project, which aims to understand how we can best source lithium resources for energy storage solutions, as well as the EU consortium project, CROCODILE, that looks at sourcing cobalt from European secondary supply.
The UK has some of the most ambitious climate-change targets in the world, and aims to become carbon neutral by 2050. While the targets will require an almighty effort to achieve, Gareth Johnson, a Research Fellow at the University of Strathclyde, UK, is optimistic that we will meet them.

“The public consciousness of climate change and net zero has increased considerably over the last decades and the UK Parliament has now put into law our net-zero targets. This is huge. We know the destination, and we know when we have to get there, so now we just have to work out how to do it — and there’s a lot of work underway across many sectors to figure that out.”

The role for geoscientists is clear — we won’t meet our net-zero targets without the materials, skills and experience the geoscience sector brings to the challenge.

“It’s actually hard for me to think about a technological development to meet our net-zero targets that doesn’t require geoscientists in some way. From geoscience educators making sure the next generation have the required skills, to geoscientists working on foundations for windfarms or energy storage schemes, the extraction of critical metals (such as for lithium-ion batteries or solar cells), or the energy provision or greenhouse-gas abatement sectors.

“There’s no shortage of demand for geoscientists. I’m convinced the future will be full of opportunities for geoscientists to make their mark and help get us to net zero.”

Scaling up

Gareth suggests it is the scale of the targets that present the greatest challenge, and this translates to everything from the size of the required workforce with the necessary skills, to the amount of resources and energy needed to enact the essential changes.

“To give a sense of the scale of just one component of the challenge, it is estimated that by 2050 we will need to inject somewhere in the range of 5 to 10 Gt of CO₂ into geological reservoirs every year. Globally we currently inject about 40 Mt (of which more than 75% is for enhanced oil recovery), so we’ll need to increase injection by two orders of magnitude in less than 30 years. But what does that look like? According to the International Energy Agency, oil production globally is currently about 4.5 Gt per year. So, by 2050 we need a carbon capture and storage industry that is, at a minimum, the size of the current oil industry, which took more than a century to develop to its present scale.”

New from old

Mine water offers one promising avenue as a geothermal energy source, and Gareth and his colleagues are embarking on a new project that would repurpose our old energy infrastructure for the new.

“We’re looking at the feasibility of using water stored within a number of old coal mines to provide heat for an industrial process that makes low-carbon plastics. It’s a nice story whereby the old carbon-extraction infrastructure and knowledge (we’ll be using the old coal-mine plans to develop our model) will be used to power a low-carbon future.”

With the United Nations Climate Change Conference of the Parties (COP26) in Glasgow in November, the UK has the opportunity to lead the world’s efforts to meet net zero, says Gareth Johnson.

GARETH JOHNSON
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Petroleum Geoscience is looking for a new Chief Editor!

The Geological Society of London (GSL) and European Association of Geoscientists and Engineers (EAGE) are looking for a new Chief Editor for their highly-respected, peer reviewed international journal, Petroleum Geoscience (PG) – to commence January 2022.

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Climate change in the geological record

The geological record captures multiple episodes of climate change. Dan Lunt and colleagues report on the use of past climate-change reconstructions and modelling to better understand the dynamics of the climate system and the range of possible impacts under current warming.

**Human-induced** climate change affects us all and has economic, sociological, political, and ecological consequences.

In 2019, the Geological Society and the UK Palaeoclimate Society jointly convened an expert working group to produce a statement on climate change. Led by Carrie Lear (Cardiff University, UK), the statement entitled “What the geological record tells us about our present and future climate” was published in the *Journal of the Geological Society* at the end of 2020. With the aim of exploring the themes laid out in the statement, which were centred around nine key questions, the Geological Society hosted a conference, *Climate Change in the Geological Record*, in May 2021.

**What does the geological record of climate change look like?**
The geological record provides evidence of huge swings in past climate (as discussed in a presentation by Jess Tierney, University of Arizona, USA). The extremes range from the cold Snowball Earth conditions that were prevalent about 700 million years ago, evidenced by glacially derived dropstones and striations found in many places around the globe, to the super-warmth of the early Eocene about 50 million years ago, evidenced by crocodile fossils in the Arctic, for example. However, even the fastest natural climatic transitions of the past, such as the Paleocene-Eocene Thermal Maximum about 55 million years ago, were slow compared with the current anthropogenic aberration.

**Why has climate changed in the past?**
On geological timescales, tectonic, orbital, solar and greenhouse gas forcings, determine climate change, as well as feedbacks between the climate, ice sheets and CO₂. However, when these processes are incorporated into climate models with quantitative representation, it becomes apparent that the observed geological record cannot be explained without a significant role for CO₂ (Paul Valdes, University of Bristol, UK).

**Is our current warming unusual?**
Analysis of the geological record indicates that it has been a long time since our planet has been as warm as it is today. Recent decades were likely warmer than all other decades during the past 2,000 years and probably warmer than any sustained period since the peak of the Last Interglacial, 125,000 years ago. Darrell Kaufman (Northern Arizona University, USA) showed that the Earth system is changing rapidly: since 1900, observed global mean sea level has risen at a rate unprecedented in at
least the last 2,500 years. Unlike previous naturally-occurring climate change, the effects of recent warming are occurring on top of other human-induced stressors, such as deforestation.

What does the geological record indicate about global versus regional change?
Drawing on examples from tropical Indian oceans during the Last Glacial Maximum 21,000 years ago, Kau Thirumalai (University of Arizona, USA) showed that clear non-linearities exist between global and regional climate, and that the geological record of past climates can provide perspective on future regional climate change and impacts. However, there is still much to learn about the mechanisms associated with past cold and warm climate states.

When Earth’s temperature changed in the past, what were the impacts?
Focusing primarily on marine ecosystem change, Daniela Schmidt (University of Bristol, UK) showed that, in general, species have migrated to maintain their optimum temperature during episodes of past climate change, for example, moving towards the poles during periods of global warming. Extreme events
State of the climate

There is hope to be gained in the recent rapid increase in the level of engagement with climate-change issues by the business community, corporate leaders and foundations, as well as governments and compound events of warming, acidification, and oxygen depletion have resulted in extinction and loss of ecosystems.

How does the geological record inform our quantification of how sensitive Earth is to CO2?
Past climates can provide important information to quantify Climate Sensitivity – a key policy-relevant metric (Anna von der Heydt, Utrecht University, Netherlands). However, some uncertainties make this challenging, such as the role of fast versus slow feedbacks, the dependence of sensitivity on background state, the degree of equilibrium in models versus the real world, and the need to account for tipping points.

Are there past climate analogues for the future?
Defining a palaeoclimate analogue as “An interval in Earth history that shares similar climatic conditions/characteristics to model simulations of future climate change”, Alan Haywood (University of Leeds, UK) presented examples where past climates can inform our understanding of future processes, for example, those associated with ice-sheet and sea-level change during the last deglaciation, atmospheric-circulation change during the Pliocene (~3 million years ago), and temperature changes during the Eocene.

How can the geological record be used to evaluate climate models?
Bette Otto-Bliesner (National Center for Atmospheric Research, USA) showed how climate models are usually evaluated by their performance compared to historical meteorological records from the last 150 years. However, comparison to the historical record does not “stress-test” the model over more extreme changes in CO2.

Using west-east gradients in tropical sea-surface temperatures during the Pliocene, and global mean temperatures during the Late Glacial Maximum, Bette showed how data from the geological record can test model outputs under more extreme climate conditions. Bette also highlighted that geological data have perhaps their greatest potential when used to develop models, not just evaluate them.

What is the role of geology in dealing with the climate emergency for a sustainable future?
To meet targets set by the Paris Agreement, it may be necessary to actively remove CO2 from the atmosphere. Rachael James (University of Southampton, UK) emphasised that geology can play a key role in speeding up natural processes of CO2 removal, for example enhancing carbonate formation by injecting CO2 into rocks containing high quantities of calcium and magnesium ions, or by enhancing rock weathering by applying calcium and magnesium-rich rocks to agricultural soil (see page 16). Rachael also noted that to meet the demand for battery storage and photovoltaics requires extraction of metals such as selenium, neodymium, and lithium – geologists clearly have an important role to play here.

Optimism for the future
Five upcoming scientists, Aidan Starr, Rebecca Orrison, Pam Vervoot, Rachel Brown, and Margot Cramwinckel, presented their exciting doctoral and postdoctoral research, supporting the Geological Society’s commitment to early career scientists.

Finally, in a plenary talk, Maureen Raymo (Colombia University, USA) presented the geological evidence for variations in the stability of the polar ice sheets and past sea-level change. During the Last Interglacial, for example, relatively small increases in temperature led to large changes in sea level. Future sea-level changes will not be the same everywhere, but the impacts will be felt from the largest cities to the smallest villages. Maureen emphasised the benefits of co-production of knowledge, whereby scientists work closely with local communities, for example when studying sea-level rise in Greenland, to aid progress and improve mitigation against the impacts of climate change. Despite the challenges we face, Maureen finished with some optimistic words for the future: Rates of change are crucial for understanding climate change in the geological record. There is hope to be gained in the recent rapid increase in the level of engagement with climate-change issues by the business community, corporate leaders and foundations, as well as governments – let’s hope that this is one rate that does continue to rise!  

DAN LUNT
Dan is a Professor of Climate Science at Bristol University, UK

MARY GAGEN
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BABETTE HOOGAKKER
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Charlie is Research Fellow at the University of Bristol, UK
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The energy transition

Achieving net-zero emissions requires interdisciplinary science solutions and effective stewardship of the planet. Rob Knipe and colleagues report on how geoscientists are reaching out and down to support the energy transition.

The transition towards a carbon-neutral economy is now a pressing international effort and geoscience will play a fundamental role in enabling the energy transition. Geoscientists are reaching out to combine knowledge of Earth processes and behaviours in the subsurface with the know-how of engineers, social scientists, policy makers and financiers to promote shared engagement, as well as to test and deploy the technologies that are urgently needed for a sustainable energy transition.

To facilitate discussions, the Geological Society has organised a series of webinars on the theme Geosciences and the Energy Transition.

The first event, held in April 2021, provided an overview of the various ways in which the geosciences can contribute to the energy transition and Sir Andrew Mackenzie FRS (Chair of Shell) provided a powerful overview of the geological challenges and the need to closely interact with other communities.

The second webinar, in June 2021 and reviewed in this report, focused on the use of the subsurface for energy transfer and carbon injection and storage. As well as considering the new understanding, plans and challenges associated with storing CO₂ in geological formations, discussions also touched on the economics required to achieve a net-zero/low-carbon world, as well as the critical issue of building public confidence – it is essential to understand public perceptions of different subsurface solutions for driving down carbon emissions.

Economics and policies
Paul Monks, Chief Scientific Adviser to the UK’s Department of Business, Energy and Industrial Strategy (BEIS), emphasised how essential geoscience is to the energy transition and outlined the major investment planned by the UK government to promote action. Support for scientific solutions, as well as their deployment, is — at last — high on the Government agenda, especially as COP26 approaches.

FUTURE MEETINGS
6-7 Sep 2021: Resources on a Finite Planet
26-27 Apr 2022: What does Geoscience need to do now for a sustainable transition to net zero?
For details, visit: www.geolsoc.org.uk/engtrans
Additionally, investment companies, such as Ernst and Young, now have dedicated teams to facilitate investment and advise policy makers on issues related to subsurface storage of CO₂ (as discussed by Graham Beal, Ernst and Young, UK).

Interestingly when the costs of different carbon capture approaches are considered over the timeframe of carbon drawdown, subsurface geological storage comes out cheapest in the long-term (~10,000 years), as noted in a presentation by Niall MacDowell (Imperial College London, UK) Stuart Haszeldine (University of Edinburgh, UK) and Jon Gibbins (University of Sheffield, UK).

Geological storage
The UK has an abundance of potential geological storage locations that could securely hold the UK’s carbon emissions. Engineers, geologists and industrial partners are combining efforts to optimise storage options, whether for hydrogen storage or CO₂ disposal.

Experience of CO₂ injection at some geological sites stretches back for more than 20 years, and geologists are sharing their knowledge of how to manage the operation of new injection sites. For example, Linda Stalker (CSIRO, Australia’s National Science Agency) shared the results from CO₂ field experiments, while Masoud Babaei (University of Manchester, UK) and Jon Gluyas (Durham University, UK) described a novel combination of CO₂ injection into the subsurface and recycling in a closed system for heat extraction and power generation.

A hydrogen economy is high on the list of priorities in the planning discussions of many countries. Geoscientists are working with engineers to assess the challenges of storing hydrogen in subsurface salt caverns, such as beneath the Cheshire basin, UK (as discussed by Alan Leadbetter, Storengy Ltd., UK), with the aim of supporting the power supply for near-by net-zero industrial clusters. At present, the hydrogen generation and storage for each industrial area is planned to link to a subsurface CO₂-storage site in offshore geological formations (reviewed by Katriona Edimann, University of Edinburgh, UK); hence an integrated ‘systems-within-systems’, as well as an innovative industrial and engineering decarbonisation approach is required, as stressed by Paul Monks (BEIS, UK), Nilay Shah (Imperial College London, UK) and Bryony Livesey (Industrial Strategy Challenge Fund, UK Research & Innovation).

Geothermal
The subsurface has untapped potential as a natural geothermal heat source. Abandoned coal mines full of warm water, that is largely unaffected by seasonal temperature variations, can be used for local heating requirements (Charlotte Adams, The Coal Authority, UK). Around 25% of all homes in the UK have been built in former coal mining areas, so several towns and cities are now assessing this future energy source.

The water deep in Cornish granites is even hotter and a new geothermal project to recover this ubiquitous subsurface resource to heat the ‘tropical rain forest’ at the Eden Project has recently been initiated (Lucy Cotton and Peter Ledingham, GeoScience Ltd, UK).

The volcanic geology of Iceland has provided geothermal heating for decades. Sandra Snaebjornsdottir and Bergur Sigfusson (Carbfix, Iceland) described how Iceland is now extending this innovation to new carbon-capture projects, whereby captured CO₂ is pumped into the subsurface to react with basalts to permanently fix the carbon by growing new minerals, thereby lowering emissions from geothermal.

Societal acceptability
The science behind these geological opportunities and solutions to support and enable the energy transition all require public confidence and social acceptability (Emily Cox, Cardiff University, UK; Gareth Johnson, University of Strathclyde, UK). At long last, there is the realisation in scientific communities that trust and acceptability of our ‘science solutions’ for future energy systems cannot be assumed.

Psychologists and social scientists, as well as public bodies, are not isolated from the geoscientists and engineers who are developing the technical solutions needed for the energy transition – and they never should have been. We are learning from past experience, such as our approaches to the communication and public perception of hydraulic fracturing, or fracking, for shale gas (Richard Davies, Newcastle University, UK and colleagues), as well as for radioactive waste disposal (Jonathan Turner, Nuclear Decommissioning Authority, UK). A notable example of a place sensitive and community connected development is coal mine geothermal, where heat from abandoned coal mines is being used to heat local homes.

Although there is still progress to be made, the growing interdisciplinary collaborations, with ever increasing interactions between geologists, engineers, social scientists, policy makers and financiers to meet the challenges of the energy transition, is an important, positive and absolutely necessary step.

The next webinar in the series (6-7 Sept), will include an introduction from Julian Kettle, a Vice President at Wood Mackenzie, and will assess the role of the geosciences for future mineral extraction, hydrocarbon stewardship, and the management of water resources during the energy transition. In addition to the technical challenges of sustainable and low-carbon resource management, we will discuss issues surrounding policy, investment and public awareness of the energy transition.
Have we passed peak core?

Extracting and analysing core samples is expensive. With pressure on budgets and the changing energy landscape, Lucy Williams and colleagues ask whether core continues to provide critical value to subsurface assessments.

Core has traditionally played a key role in the characterisation of conventional and unconventional hydrocarbon reservoirs, from exploration to mature production, because it provides the only means to observe and make measurements on actual reservoir rock. However, recent oil-industry downturns have driven many to question the value of routinely taking core, given the associated costs and potential risks to well operations. In tandem, advances in other reservoir visualisation techniques, such as seismic and borehole imaging, give weight to the contention that coring now represents a much less significant means of characterising reservoirs than it once did. In May 2021, the Geological Society’s Energy Group convened the virtual conference Core Values: The Role of Core in 21st Century Reservoir Characterisation to ask, ‘Does core have a future?’

Current state of play

Whilst coring is an expensive part of well-drilling operations, a great range of measurements and observations can be made on core, either directly or indirectly using artificial intelligence (AI). These measurements and observations allow us to calibrate our subsurface static and dynamic models (as discussed in a presentation by Nordine Sabaou, BHP, USA), and to quantify and reduce uncertainty and risk (as discussed by Mike Bowman, University of Manchester, UK and Patricio Desjardins, Shell, USA), thus enabling investment decisions to be made based on a fundamental understanding of the volume of hydrocarbons in place, as well as recovery factors.

The intrinsic value of core to the sedimentological and structural characterisation of reservoirs was demonstrated in a series of presentations (for example, by Bruce Levell, University of Oxford, UK; Martin Wells, BP, UK; Haakon Fossen, University of Bergen, Norway; Steve Laubach and Julia Gale, The University of Texas at Austin, USA). Additionally, the capacity for core samples to ‘ground truth’ a reservoir was exemplified by a series of presentations that compared borehole image studies both with and without core. The potential for successful outcomes in cases where core samples are not available depends on our understanding of the regional
geology, prospect maturity and nature of the reservoir (Adrian Neal, Badley Ashton, UK; Emma Jude, BP, UK). For depositionally complex reservoirs, core is indispensable even with excellent borehole-image coverage (Peter Gutteridge, Cambridge Carbonates Ltd, UK).

Understandably, geoscientists must justify the value core brings to a project and a coring campaign should be designed to address specific questions or challenges. The power of core is in its multi-disciplinary and evolving use throughout the lifecycle of a hydrocarbon field (Sean Kelly, EnQuest, UK). At the point of field discovery, the future value of core can be hard to predict and quantify. However, once the field is in production and performance deviates from predictions, or when trying to maximise the economic value of a field late into its life, we often revert to the core samples to seek answers and solutions. The ‘ground truth’ provided by core is currently irreplaceable in clastic reservoirs and, some may argue, more so in carbonate reservoirs (Anna Matthews, BP, UK), but the true value of core emerges when it is integrated with other datasets.

Legacy core

There is a growing awareness that the decommissioning of hydrocarbon fields in the North Sea is resulting in unwanted core finding its way into landfill and the question “Does legacy core have a future?” was a key theme at the conference. National core repositories are a veritable treasure trove of information, as exemplified by talks from Jeannine Honey at the USGS Core Research Center, and Mike Howe, at the British Geological Survey National Geological Repository (NGR). These institutions are under pressure to prove their value and reduce costs, despite their resources being available for education, geoheritage, research or commercial purposes at a fraction of the cost of drilling new core. Utilisation of these repositories spares money, time, and environmental impacts. Efforts are currently focused on harnessing the full scientific value of legacy collections, for use today and into the future in yet unrealised research and applications. The NGR is at the forefront of international endeavours to utilise digitalisation and the worldwide web to increase the impact of the collections and find solutions that turn a physical archive into an accessible digital resource for all.

The energy industry is transitioning to low-carbon solutions, placing a spotlight on the value of legacy core in assessing options to meet net-zero targets (as discussed in presentations from Richard Porter, Shell, The Netherlands; Richard Worden, University of Liverpool, UK; Samuel Krevor, Imperial College London, UK). Geothermal energy, hydrogen storage, carbon capture utilisation and storage, and subsurface waste disposal all require subsurface evaluation and share many similarities with traditional oil-and-gas prospects. Legacy core, augmented by the focused acquisition of new data to address the subtly different requirements of low-carbon technologies, provides a cost-effective solution. Given their current and future value we must ensure the ongoing survival of these national assets.

Analytical revolution

Traditional methods for core analysis use only a small fraction of the data available from core and developing technologies are enhancing the value of these samples. For example, AI has an increasingly important role in core characterisation, through cost-effective, automated, high-resolution, multi-sensor scanning technologies (Magret Damascckle, British Geological Survey; Paul Linton, TerraCore, USA; James Shreeve, Geotek, UK).

The huge volumes of data created by scanning technologies require robust database and visualisation platforms, but these methods can be applied to core samples in repositories worldwide and represent a revolution in our ability to understand the subsurface, to the wider benefit of industry and society beyond hydrocarbon extraction. Cloud-based software that allows multidisciplinary teams to virtually interrogate data at a range of scales already exists (Craig Lindsay, Core Specialist Services Ltd, UK), but will no doubt improve and hopefully become the bastion of not just large oil companies, but all those involved in the subsurface characterisation of porous media.

Bright future

Core alone cannot provide all the answers. However, when integrated with AI and complementary datasets, core samples provide the only mechanism to quantitatively ground-truth models and answer many field-development questions. To realise the full value of core, we must bridge the gap between analyses carried out using thin-section, seismic, and reservoir dynamic model data, using descriptive and interpretative schemes that allow data and understanding to cascade up and down the scales of investigation.

Some argue that we have reached or passed ‘peak core’. Others contend that core is not viewed by enough people – a visit to the core store is an opportunity not only for technical integration, but also team building across the geoscientific, engineering, management and commercial disciplines. In our view, the future for core looks bright. If available, we will always calibrate other datasets back to core. As challenges and needs change, and technologies evolve, the value of core is reinvented. We ask readers to consider if, as geoscientists, we are doing enough to promote the true value of core.

LUCY WILLIAMS
Lucy is a Development Geologist at Rockhopper Exploration plc and Orca Energy Group Inc.

ADRIAN NEAL
Adrian is a Deepwater Reservoir Geologist at Badley Ashton

MIKE ASHTON
Mike is Director of Ashton Geology

STEVE DEE
Steve is Structural Geology Advisor at BP

A Special Publication linked to the conference is in preparation.
SKYSEED

DETAILS
www.bookguild.co.uk

REVIEWED BY BRENT WILSON
How to review a novel without giving away the entire plot? I shall opt for providing the baseline scenario from which the plot develops, hoping to entice others to read this fascinating and exciting book, in which both the science and the personal lives of the central characters are intertwined believably.

In this work of fiction, which I hope does not prove prescient, ‘climate change’ has morphed into ‘climate breakdown’ as atmospheric carbon dioxide levels have risen to over 500 parts per million. Large swaths of western USA are now suffering drought. What can be done about it? What scenario will allow the world to continue using capitalism as business as usual?

The three protagonists, one in the military and two in academia, discover that a few governments have secretly seeded the atmosphere with nanobots that, capable of disassociating the carbon from CO₂ and accumulating it in pellet form, are also capable of replication. It is literally raining carbon. All goes well until a volcanic eruption in Guatemala throws into the stratosphere all the raw materials the nanobots need to replicate at an unanticipated rate. Global temperatures begin to fall precipitously, such that winter snowfall at temperate latitudes no longer fully melts in summer. Some communities become cut off, inducing a mass migration. What can be done about this?

Bill McGuire, one of Britain’s leading volcanologists, is a Professor Emeritus of Climate Hazards at University College, London. This is his first fiction book and it explores what may happen if humanity does not adequately address what is currently called ‘climate change’. As climate change leads to breakdown, Bill’s politicians panic and are wooed by dangerous and untested geo-engineering interferences. They do so in the hopes of reducing greenhouse-gas concentrations in the atmosphere, with such actions as carbon sequestration and alternative technologies no longer being adequate. The plot develops at a cracking pace, assassinations abounding.

Bill’s book acts as a clarion call to immediately reduce carbon emissions in every aspect of our lives, whether it be transport, agriculture, industrial production, waste disposal or how we heat our homes. His story does not seem far-fetched, if we consider the consequences of failing to address climate change with immediacy.

GERMAN MILITARY GEOLOGY AND FORTIFICATION OF THE BRITISH CHANNEL ISLANDS DURING WORLD WAR II

DETAILS
ISBN: 9783319227672 PRICE: £89.99
link.springer.com/

REVIEWED BY JUDY EHEN
The Channel Islands were the only part of Britain occupied by Germany during World War II. The islands, thought to be indefensible, were demilitarised by the British Government in the summer of 1940, with some of the population evacuated to mainland Britain. German occupation began thereafter. Because Germany feared recapture of the islands by Britain, protection against a potential invasion was crucial. German fortification concentrated on the three largest islands, Jersey, Guernsey and Alderney. Guernsey was the most heavily fortified, particularly on its north side, because of its nearness to mainland Britain.

Military geologists were heavily involved in the fortification of the islands, with at least 14 employed. Unlike the UK and the US, Germany employed large numbers of trained geologists, about 400 by the end of the war. Military geologists on the Channel Islands served in the Army and Air Force (Luftwaffe). Work for the Navy, primarily coastal defence structures, was most likely done by Army military geology teams. Later in the occupation, military geologists also provided support to Organisation Todt, the German construction agency.

The geography, the geological knowledge available at the time, and the historical fortifications are described in the early chapters of this book. The work of military geologists on each island between 1941 and 1943 is then discussed. At least 51 written reports and at least 26 thematic maps were prepared; these are preserved in archives in the US, the UK and Germany. Detailed descriptions of the German fortifications on each island are provided.

The main contribution of the military geologists dealt with ground water conditions and water supply for camps and batteries; they supervised drilling and mapped the locations of springs and wells. This was important because there is little surface water on the islands and the existing supply was unable to support the increased military population. In addition, new maps of the local geology, primarily Palaeozoic metamorphic and igneous rocks, were made and thematic military geology maps were prepared. They also provided advice on quarrying; sources of raw materials, especially aggregate for concrete; tunnelling; fuel and ammunition storage; site characterisation for batteries and other structures; anti-tank defences, especially on beaches; and airfield construction.

The book is lavishly illustrated with photographs of the fortifications, original drawings and sketch maps of the military works and historical military geology maps. Many examples of the German fortifications, particularly tunnels and observation posts, survive in the landscape today and some have been adapted for modern use, such as in museums.
the book perhaps reflects our own development of the understanding of the science of our planet and of key moments in the history of geology. Reading this certainly made me reflect on how I have developed mine.

Written in an engaging manner, this book will interest both laypeople and geologists. Gordon helps to clarify some of the key events that have broadened our understanding of the science, and she poses several important philosophical arguments, such as our understanding of the Anthropocene and how we may dispose of our nuclear waste legacy.

An intriguing and useful addition to the genre, I recommend this book wholeheartedly. It has allowed me to revisit my own thinking and helped me question several conventionally held beliefs.

POST-ARCHEAN GRANITIC ROCKS: PETROGENETIC PROCESSES AND TECTONIC ENVIRONMENTS

REVIEWED BY BERNARD ELGEY LEAKE

In 10 papers, this volume summarises much of frontier thinking about the varied origins and tectonic settings of granites, from the anatexitic of metasediments (S-type) to the dual origin I-type granites as either partial melts from lower-crustal igneous rocks or from fractionation of mantle-derived magmas, to the so-called anorogenic (A-type) granites that occur in a variety of tectonic settings. Granite classification and plotting schemes are reviewed, with the serious inherent drawbacks of the commonly used (even in this volume) Harker plots pointed out, but there is recognition of ‘inertia’ and unwillingness to change from familiar to new, even if more useful, plots. The innovative (for granites) accounts and open-access programmes of Mayne et al. enable the stable mineral phases and their Pressure-Temperature (P-T) stability fields to be calculated for variable P, T, and bulk compositions. This allows the determination of the compositions of melt batches generated by sequential melting of any pelite composition with other variables. Water is crucial in determining melt and crystallisation temperatures and the vital role of muscovite breakdown in providing water in melting pelites is emphasised. The water-fluxed and dehydration melting origins of granites and trondhjemites of southernmost Italy further emphasises this, as does the different production of magmatic and metasomatic trondhjemites by water-fluxed melting and subsolidus hydrous metasomatic destruction of alkali feldspars in already crystallised granite.

Accounts include the petrogenesis of leucogranites in collisional orogens; S-I-A granites in the Lachlan Orogen and A-types in Nigeria; the dual origin of I-types; granites and crustal heat; and laboratory experiments of fluid-fluxed melting, which after fractionation relates to Cordilleran batholiths above subduction zones.

Long-lived episodically constructed plutons formed by sequential magma injections giving zoned granites are well illustrated by the described ‘normally zoned’ mafic tonalitic–edged Sardinian Budduso body. This becomes more felsic inward but the quite common ‘reversely zoned’ bodies, requiring different tectonic conditions of emplacement, are not considered. The important roles of isotopes in identifying melt sources and their ages, as well as the ages of consolidation are not overlooked.

This is strongly recommended as a well-written and colour-illustrated volume, replete with significant advances in detailing geochemical modelling of granite magma genesis and crystallisation that others can use. There is less tectonic detail. The authors and editors should be congratulated on a volume of wide interest.
Chalk: all we need is a fracture log!
By Rory N. Mortimore

Chalk fracture logging is reviewed in the context of the broader geology needed to build conceptual ground models. Examples of drilling damaged core illustrate the many issues faced by core loggers including identification of marker beds (marl seams, hardgrounds, flint bands, fossil shell beds) and the 'interpretations' necessary to complete a fracture log. Stratabound fractures impart a special style of fracturing to each Chalk formation. Lithology is a key factor in development of fracture style where marl seams control inclined conjugate fracture sets, development of listric growth faults and interbed slides. Lateral changes in lithology and thickness and consequent controls on fracture evolution are related to intra-Chalk tectonic episodes and tectonic setting with onshore interpretations supported by offshore seismic profiles.

Read the full paper on the Lyell Collection: qjegh.lyellcollection.org/content/early/2021/07/20/qjegh2021-031

NEW!

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Edited by T. Aiża

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Geological Society publications online
DESMOND THOMAS DONOVAN was born on 16 June 1921 in Cheam, Surrey. After graduating from the University of Bristol in 1942, he was obliged, along with most science graduates that year, to join the Army, becoming 2nd Lieutenant Donovan in the Royal Electrical and Mechanical Engineers. After demobilisation in 1946, Desmond returned to Bristol, completing a PhD in 1951 on ‘The Ammonites of the Blue Lias of the Bristol District’.

Fieldwork and publications
In the 1950s, Desmond devoted much energy to fieldwork, mapping Bathonian Fullers Earth of the Cotswold Hills with WJ Arkell, providing consultancy services on water supply of the area and contributing to publications such as Geology of the Bristol District (BAAS, 1956) and Pevsner’s Buildings of England. Having written the geology introduction to the Somerset volume of Pevsner published in 1958, Desmond must have been unique in having also written the geological notes for the revised 2nd edition in 2014, 56 years later.

He often talked of summers over some 10 years spent in East Greenland, on expeditions led by the Danish geologist Lauge Koch. The team mapped, logged sections and collected ammonite faunas in many localities; work which was published in Meddelelser om Groenland in 1957. He also contributed to the first edition of the Kansas Treatise on Invertebrate Palaeontology (editing ‘L’ Ammonites).

At Bristol, Desmond met Lou Saward, also a geologist, who later became his wife. In 1962, he was appointed Professor of Geology at Hull University, during which time he worked on a major project mapping the floor of the North Sea. From 1966 to 1982, he held the Yates-Goldsmid Chair at University College London (UCL), overseeing the department and supervising several PhD studentships. During his time at UCL, his research interests in offshore geology and Jurassic stratigraphy continued apace.

Retirement
Desmond retired from UCL in 1982 and spent three years as honorary curator at the Wells and Mendip Museum in Somerset. He was active in geology and palaeontology until the end of his life, publishing on many topics. In the last years of his life, he could also indulge his passions for church and cathedral architecture and archaeology, and was consulted by many for his knowledge of building stone dating back to medieval times.

Desmond was a longstanding member of the University of Bristol Speleological Society and many natural history societies, including the Mendip Society, Bristol Naturalists Society, Bath Natural History Society, the Churches Conservation Trust and the Somerset Churches Trust. In later years, he was very pleased to be able to support the English Touring Opera and Friends of Music at the Wells Cathedral School.

Polymath
Desmond was an old-style polymath, a quiet and gentle man interested in and knowledgeable about many things, who never lost his curiosity and enthusiasm. His students appreciated the minimal interference in their research, but constant support when it was needed, including his taking pleasure in visiting their field areas. Recent visitors to his house in Wells will recall small trays of specimens awaiting measurement for statistical analysis, and excellent real coffee. His great intellectual ability was disguised with a very modest and unassuming manner, and a gentle sense of humour.

His children, Tom, Tessa and Dan, and his four granddaughters, visited regularly and reported that he read The Guardian daily and was working on geology and making lists of things to do right until his death, in his sleep, on 23 December 2019.

He will be greatly missed.

The full version of this obituary appears online.
DR WTC SOWERBUTTS, known to all as Bill, grew up on a small farm at Flamstead in Hertfordshire where he spent much of his childhood tending chickens, pigs and vegetables. He had an interest in geology from picking stones off the lane and fields and went on to graduate with a geology degree from Leicester University. He took part in the Geological Society Students' Instructional Tour to the Alps in 1965. Bill's PhD in geophysics from Newcastle University examined gravity and magnetic anomalies over the East African Rift.

Glasgow and Manchester
Bill’s first job was as a research assistant at Glasgow University undertaking geophysical surveys around Mull and Skye. In 1972, he secured a permanent job as a lecturer in geophysics at the University of Manchester, where he spent the rest of his career until retirement in 2000.

His early research focused on East Africa, making measurements by cycling round with a gravimeter on the back of a bike, resulting in two Nature papers. Bill was a pioneer in using shallow geophysics for site investigations, including to locate minshafts and archaeological structures, and he published on topics as diverse as locating pipeline joints and volcanic dykes. He also undertook geophysical surveys for energy companies across north-west England.

Innovation
Today Bill would be called an innovator – he designed some of the first mobile digital gravimeters and magnetometers connected to an Apple computer on a modified wheelbarrow, and starred on the front cover of Windfall magazine. He established a great practical teaching course where students had hands-on experience of using geophysical equipment. Bill was a quiet man who never sought the limelight but was always ready to help.

Bill was well ahead of his time in computer-aided learning, setting up a very early teaching computer cluster of Apple Macs at Manchester and developing 3D visualisation software. In 1992, he established the UK Earth Science Courseware Consortium as a non-profit-making organisation to develop, produce and distribute interactive courseware for use in Earth sciences teaching and learning. As chair of the Geological Society of London computing committee in the 1990s, Bill was a regular visitor to Burlington House.

Retirement
Bill continued to develop his interests in retirement, from making stone sculptures to woodturning. He was a lifelong vegetable gardener and organised lectures and excursions for the Cottage Garden Society. Bill was active in the garden until suffering a short period of ill health. He is survived by his wife Morven, daughter Alison, also a geologist, and two grandchildren.

Today Bill would be called an innovator – he designed some of the first mobile digital gravimeters and magnetometers.

IN MEMORY OF...
The Society notes with sadness the passing of:
• Allen, Philip A
• Angus, Alison Jane*
• Audley-Charles, Michael Geoffreys
• Bailey, Patrick Bernard Howard*
• Blakeway, Denis*
• Cooper, Bryan*
• Davis, Anthony*
• Dumpleton, Steve*
• Evans, Graham
• Head, Kenneth Harold*
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• Kettle, Clifton*
• Lurati, Matthias*
• Mason, Joseph Edwin*
• Petrie, Angus*
• Phillips, Richard
• Pulford, John*
• Ramsay, John Graham
• Rex, David
• Somervell, Adnan Ismail
• Somerville, Stanley Herbert*

Pictured, above: William Sowerbutts’ interest in geology began during his childhood on a farm
Lionel Lake was born in Fulham and evacuated to South Wales during World War II. His early education was disrupted, but he strove to address this as his career progressed. He was commissioned into the Royal Artillery for National Service in Northern Ireland (1953–1955) and completed a BSc in Geology through evening classes at Birkbeck College (1963).

Early contacts
Lionel joined Legrand, Sutcliffe & Gell in 1963, working on site investigations and foundations before taking a year out to complete the MSc course in soil mechanics and foundations at Imperial College London in 1967. At Imperial he met Noel Simons and established a strong rapport. He later completed his PhD under Noel’s guidance at Surrey University in 1975. Lionel also formed long-lasting contacts with other academics and senior practitioners who he often sought advice from in later years.

Lionel returned to his former employer for a further four years before joining Soil Mechanics Ltd and starting the transition from contracting to consultancy.

Senior roles and major projects
In 1973, Lionel joined Mott, Hay & Anderson in their Tunnels Department, but with the intention of strengthening geotechnical capability within the firm. In 1977, he was appointed Head of the newly formed Geotechnical Department and was responsible for establishing and growing his team of civil, mining, geotechnical engineers and engineering geologists. Lionel valued a diversity of skills and recognised the influence of geology upon all types of civil engineering projects. He was involved in investigations and various trials for the Channel Tunnel in 1973–76, 1978–79, as well as the successful scheme in 1986–94, and these formed some of his fondest memories.

Lionel contributed to major projects all over the world and, in 1979, became involved in radioactive waste management, carrying out research and development for various Government bodies. He was appointed a Director of Mott MacDonald Civil following the 1989 merger.

Professional excellence
Lionel recognised the importance of education and helped his team to achieve their professional potential. He set high standards and was Mott MacDonald’s group champion for professional excellence, convincing the Board to adopt this as one of the three tenets of their company ethos.

Lionel had an exceptional ability to write clear and concise reports, and helped many a graduate do the same. He believed in his staff, developing a robust framework for anticipated engineering behaviour, enabling them to spot something out of the ordinary.

Outside of a heavy workload, he gave time to many professional bodies, serving as a committee member at the British Geotechnical Society, Association of Geotechnical and Geoenvironmental Specialists, Ground Engineering Board, Construction Industry Research and Information Association, Engineering Council, EU advisory bodies, and Geotechnique. He was also an external examiner at Imperial College London and Visiting Professor of Geotechnics at the University of Newcastle upon Tyne and at Brighton. He retired from Mott MacDonald in 1994.

Lionel has two daughters by his first marriage and two sons by his second marriage to Pam. He was a keen sailor, loved classical music, and walking in the mountains with his family and their Bullmastiff dog. He will be sorely missed.

Contact
If you would like to contribute an obituary, please email the editor geoscientist@geolsoc.org.uk

Roll of Honour
Deceased Fellows for whom no obituary is forthcoming have their names and dates recorded in a Roll of Honour at www.geolsoc.org.uk/obituaries

Bold, recent additions to the list; * Fellows for whom no obituarist has been commissioned
Tell us about your work
I work at the interface between geoscience and international development, focusing on themes including sustainability, disaster risk reduction, and education for sustainable development.

By day, I work at the BGS supporting our international development programmes and delivering ‘multi-hazards’ research. By night and weekend, I lead the work of GfGD, a charity helping to mobilise and equip geoscientists to deliver the United Nations’ Sustainable Development Goals: a global plan to end poverty, improve social wellbeing and protect the planet.

What are you currently working on at the BGS?
I’m helping to review the impact of our recent international development programme. Starting in 2017, it involves three research platforms: integrated resource management in eastern Africa, resilient Asian cities, and global geological risk. We work with overseas partners to understand their needs, and co-design and deliver research, informatics, and outreach activities. We’re also exploring ways to share our learning with diverse groups within and beyond the geoscience community.

I’m also leading BGS’ contribution to a new interdisciplinary four-year research project: Multi-hazard and systemic framework for enhancing Risk-Informed Management and Decision-making in the EU (or MYRIAD-EU). Starting this autumn, the project aims to address multi-hazard risk management through the lens of sustainability challenges that cut across sectors, regions and hazards.

Tell us a little about GfGD?
After completing my undergraduate degree (in Natural Sciences at the University of Cambridge, UK), I supported a review of an NGO’s water programme in Tanzania, which highlighted that geoscience is not always integrated into planning and monitoring of such programmes, and that geoscientists working on them don’t always have the appropriate skills and training. In 2011, I founded GfGD (www.gfgd.org) to address these gaps. Our activities include research, policy engagement, and education and training. Later this year we’ll launch our new strategy, and set out plans to expand this work and opportunities to partner with us.

What advice would you give to someone hoping to work in your field?
Think strategically about how to use opportunities in your formal education, such as tailoring a dissertation to sustainability focused work, taking modules from other departments or seeking placements. Commit to diversity and inclusivity, ethical engagement and the building of respectful and meaningful partnerships. Invest time in building new skills and knowledge. Look at job adverts, read widely, including from the perspective of the social sciences, and look at reports coming out of the United Nations and associated agencies. Finally, network! Look out for events and talks at and outside of universities (particularly those in other departments). Organisations such as the Overseas Development Institute and the United Nations have free, virtual events.

What’s your favourite thing about your work?
I love the opportunity to meet and learn from people around the world, and their inspiring commitment to securing a sustainable future. We’re working together on activities that have the potential to make a real difference. At GfGD, we’re at the forefront of geoscience diplomacy, integrating our knowledge into global policy processes and providing a voice for geoscientists in forums where they wouldn’t otherwise be represented.

Pictured, above: Joel’s roles combine his passion for geosciences and sustainability through the lens of sustainability challenges that cut across sectors, regions and hazards.
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