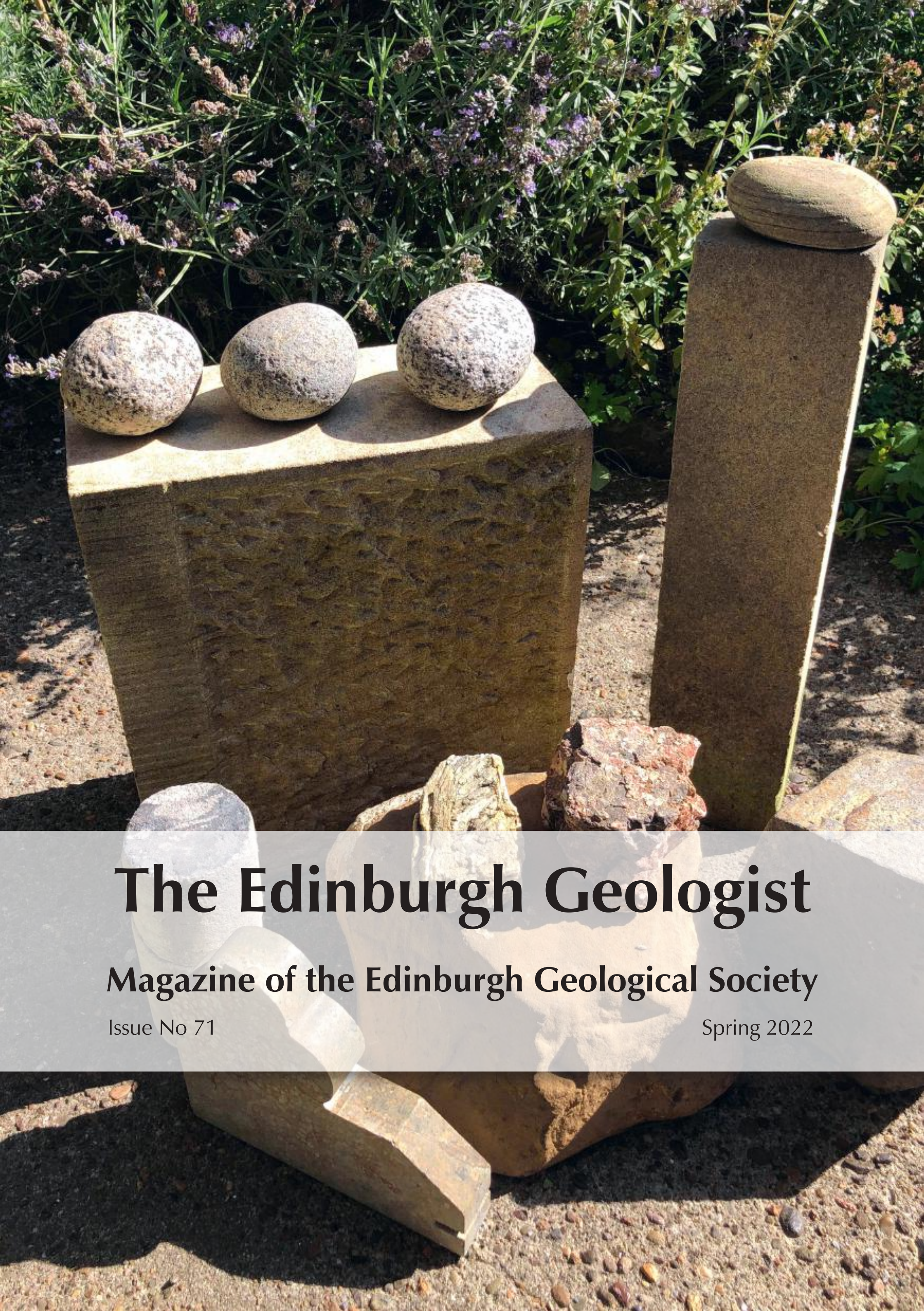

The Edinburgh Geologist

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Cover Illustration

Rocks and Stones: each one carries a story for geologists and poets. A photograph by Patrick Corbett, lead editor of 'Earth Lines' and convener of the Geopoetry 2020 meeting.

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Editor
Robert Gatliff
eg-editor@edinburghgeolsoc.org

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The Edinburgh Geological Society was founded in 1834 with the twin aims of stimulating public interest in geology and advancing geological knowledge. We organise a programme of lectures and excursions and also publish leaflets and excursion guides. For more information about the Society and membership, please visit www.edinburghgeolsoc.org.

Geology and society

By Robert Gatliff

In this edition Prof Stuart Haszeldine writes about the major contribution geology can make to limiting climate change by storing CO_2 in huge quantities in the subsurface. He also suggests underground hydrogen storage could be a key factor in developing a hydrogen economy. He shows how Scottish research institutions, together with some of the oil companies have led research into Carbon Capture & Storage (CCS) but our government have dragged their feet in supporting CO_2 projects.

We still have work to do to get geological solutions to be accepted by society. Similarly, universities are having to work harder to generate new applicants, and hence courses are changing towards environmental sciences with fewer traditional geoscience courses. One initiative, which EGS is supporting through a grant, is led by Amanda Owen (University of Glasgow), who writes about a project to encourage more girls into geoscience. This is so important as geology, although scattered through the 'curriculum for excellence', is no longer offered as a SQA geological qualification.

Last year a conference at the Geological Society of London highlighted that geology was one of the least ethnically diverse subjects at university. I suspect diversity amongst EGS membership is also limited. I hope EGS will continue to support education (such as Geobus, led by University of St Andrews) and diversity projects.

Our third author is member Paul Binns, who started out at BGS in Edinburgh before moving on to Shell. We all know the father of geology was James Hutton, but who knows about the active geologists before the Dark Ages? Read on for some pre-enlightenment enlightenment!

Encouraging links between science and the arts is another way to broaden awareness of geology, and our EGS member and geopoet, Patrick Corbett, put together our final article with extracts from 'Earth Lines', a new EGS publication edited by Patrick and others, and based on a geopoetry virtual meeting run by the Geological Society of London in 2020.

The Perils of Life on an Island Arc

From 1988 to 1990 your editor lived in Tonga and led the small geological department. The events of January of this year brought back many memories—of earthquakes, volcanic eruptions, and training for what to do if there were tsunami warnings. Luckily there were no tsunamis, only small eruptions and no large earthquakes, and the damaging events were tropical cyclones.

In the long-term, in addition to the geohazards, sea level rise is also critical to many of the islands. The generalised bathymetry shows the broad structure with the deep Tonga trench to the east, and a relatively narrow line of active and extinct volcanoes (the Tofua Arc) to the west (Fig. 1). Most people live on a series of Pliocene- Recent limestone islands in between these two features. The largest, Tongatapu, where around 75% of population live is predominantly low lying but reaches a maximum height of around 65 m (uplifted Pliocene reef limestones), surrounded by younger limestones. Many islands have a very fertile, up to 2 m thick, soil derived from ash falls. The soils provide a cover for a freshwater aquifer in the limestones. In the Nomuka Islands, Miocene volcaniclastics are exposed. Beneath the islands, the forearc basin has sediments up to 4km thick, predominantly volcaniclastics and turbidites with some limestone. The sediment thickness decreases towards the Trench, where Eocene basalts and limestones are exposed on the island of ʻEua. Large fringing reefs to the north of Tongatapu partially protected the capital, Nuku'alofa from the tsunami, but the low-lying inhabited islands to the east of the volcano in the Ha'apai and Nomuka Groups were less protected and suffered the most.

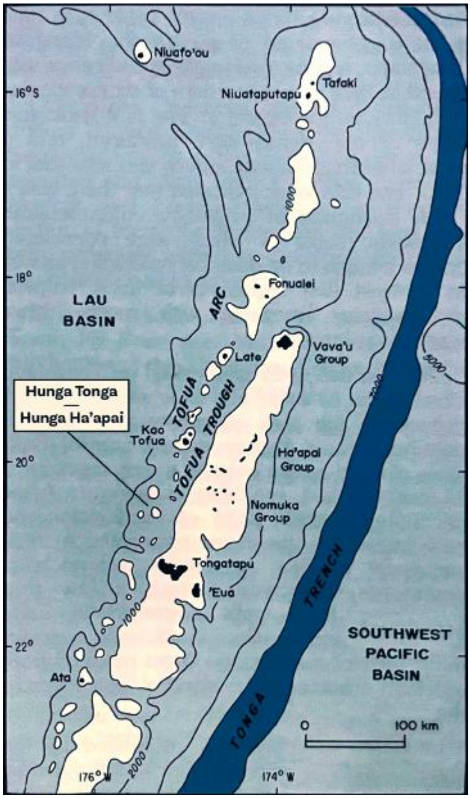


Fig 1 The Tonga Isles.

Scottish geology, climate and energy—selected activity at the University of Edinburgh

By Stuart Haszeldine, Professor of Carbon Capture and Storage, School of GeoSciences, University of Edinburgh

Summary

Scotland has been heavily involved in fossil fuel discovery and exploitation since the 1750's, but there is now disapproval of further extraction because CO_2 from combustion drives climate change. However, Scottish geology is still likely to provide valuable resources. Two key elements of research are a) to assess the fate of stored CO_2 over geological time—for at least the required 10,000 years and b) to provide secure storage in underground caverns or porespace of sandstones, including permanent storage for unwanted CO_2, and seasonal stores for hydrogen to replace methane. The University itself is also changing its energy supplies and behaviours—with an ambitious plan to attain 'NetZero' emissions by 2040.

The climate problem

Scotland can often be quick to claim credit for first exploitation of coal, in the 1219 charter at Newbattle Abbey, and 1291 at Pittencrieff (near Dunfermline), and with coal-fuelled industrial blast furnaces making iron at Wilsonstown (near Forth) during the Enlightenment from 1779. Employing hundreds of thousands of people—up to 10% of the population—across central Scotland until 2002, when the last deep mine closed at Longannet. That overlapped with the discovery of gas at the West Sole field beneath the southern North Sea in 1965, and first production of oil from the Argyll field in June 1975. In 2021 these two industries of fossil fuel extraction are visibly past their peak. But no bad thing, argue many advocates of renewable wind and tidal energy. Because now it's well understood that unprecedented rapid rates of fossil carbon conversion to CO_2, and associated leakages of methane, are a major cause of ocean acidification, greenhouse warming of earth's atmosphere, sea-level rise, and changing ecosystems. So each Scottish citizen carries one of the world's largest accumulated debts of carbon emissions.

Extraction of fossil carbon from underground and emissions to

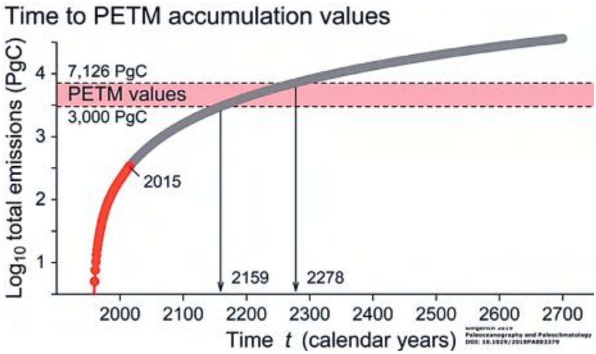


***Fig 1** Calculated global CO_2 emissions (red bar) from Paleocene-Eocene thermal maximum (as 1015 g Carbon), compared to graph of 21st Century more rapid release (Gingerich et al 2019).*

atmosphere have severely disturbed natural emissions since the start of commercial coal mining. Through computer simulation of Earth's natural carbon flows, it is apparent that timespans of 10,000 years are necessary for feedbacks and controls of the Earth's natural climate system to re-establish a pre-industrial equilibrium. In 270 years of extraction, since the first commercial coal mining in Scotland, humans have emitted fossil carbon some 10x faster than any known ancient rate calculated from geological records of natural emissions (Fig 1)—such as the Paleocene- Eocene thermal maximum. This means that very secure storage is needed for geological timescales, which is difficult when many citizens, regulators, policy advisers and politicians have only the vaguest concepts of timescales that long. This also means that most 'nature-based' and 're-wilding' remedies are too brief for carbon storage.

Political leadership, and its difficulties

Politically, successive governments in Scotland have established a cross-party consensus on Climate Transition, leading to the legally binding Climate Act (Scotland) 2008 which planned to decrease CO_2 emissions to 80% less than 1990; and the updated and more rigorous Climate Change Plan Update (2020) which commits to decrease emissions even further to reach NetZero in 2045, and 2050 in England (Fig.2). That's a leading ambition amongst the world's nations, which is further matched by a globally leading commitment to Just Transition — meaning fair and valued quality new employment for people moving out of the hydrocarbon industries. Unlike previous Transitions from coal, steel, or shipbuilding.

The first part of Scotland's transition out from centuries of coal, gas and

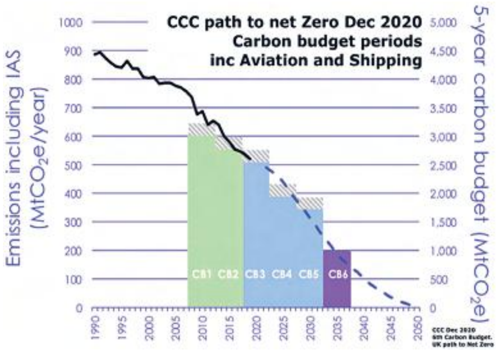


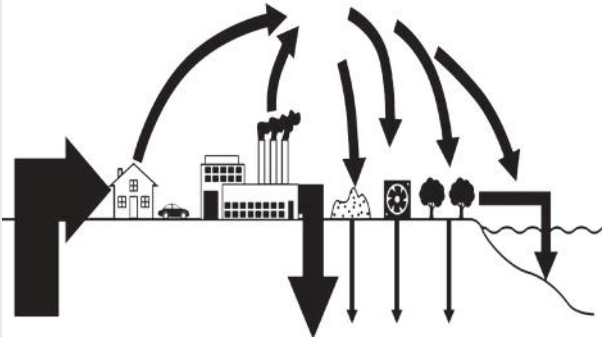
Fig 2 Pathway to Net Zero for UK (CCC2020).

oil has been the simplest—to close historic large emitters of fossil carbon gases—industries of steel, mining, and coal-powered and gas-fuelled electricity. These have become replaced by cleaner energies of onshore wind, offshore wind, hydro and tide generated electricity. But now the Transition becomes more complex, simply building more electricity generation does not lead to fewer carbon emissions. The Committee on Climate Change undertakes analysis and simulation of carbon and greenhouses gases across the whole UK economy, and a specific report on the Scottish progress to an interim target of 75% less emission in 2030 than 1999, and NetZero in 2045 (Fig 2). These reports—of the 6th carbon budget 2033–2037 for the UK, and annual Scottish progress reports, show that Scotland has not decreased emissions to meet targets in 2018 and 2019. The Committee report at the end of 2021 warns that these targets will be 'very difficult to meet' so that words for ambition and policies now need to be much more actively matched by practical actions and achievements. Some of those actions will involve changing vehicles from fossil petrol and diesel fuels, to electricity and hydrogen power. Heat delivery can no longer use carbon-rich methane as a fuel for dispersed combustion in millions of houses and businesses, but must switch to hydrogen, electricity, or geothermal extraction. To balance residual emissions at the point of NetZero in 2045, and to become a NetNegative emitter in perpetuity thereafter requires recapture and storage for some of the already emitted excess CO_2. Many of these actions for recapture and storage are expected to call on geological resources.

Decreasing emissions from fossil carbon conversion—carbon capture and storage

This remedy for excess emissions uses the concepts of carbon capture and storage (CCS). As far back as 1977 the Italian engineer and physicist Cesare Marchetti , proposed capture

Fig 3 Cartoon to show origins of fossil carbon, pathways to domestic or industry use, and multiple methods of CO2 storage by CCS, mineralisation, air capture, biomass or ocean (Haszeldine et al 2018).



of CO_2 and injection into the oceans to mitigate climate. Civil engineers and climate modellers then realised that emissions of climate warming CO_2 could be decreased by capturing and separating the flue gases on very large industrial facilities—such as coal or gas-fuelled power plant, oil refineries, cement works, steel making, petrochemical compounds or fertilizer making, and injecting liquid CO_2 into geological porespace (Fig 3). Since 2004, University of Edinburgh researchers have been collaborating with developers, industries, Governments and increasing numbers of colleagues in Scottish Universities and the British Geological Survey (BGS) to produce greater understanding of how tens of millions tonnes CO_2 can be captured, purified and securely geologically stored in microscopic porespace. The first evaluation of a CCS project in Scotland was a 1999 BP evaluation of the Grangemouth refinery to emplace CO_2 into the Forties oilfield and improve the efficiency of oil production. That was followed by a 2005 proposal to chemically split methane into hydrogen to be burned for electricity at Peterhead power plant and CO_2 to be piped offshore to improve oil production at Miller oilfield. But the Westminster government was not prepared to pay a subsidy to match the onshore wind subsidy for clean electricity—and the project lapsed. But both of these projects had suggested a potential to store CO_2 in depleted oil and gas fields. So in 2006 the combined Scottish talents at the University of Edinburgh (Stuart Haszeldine) and Heriot-Watt Universities (Adrian Todd and Eric MacKay), together with the BGS in Edinburgh (Maxine Akhurst and Martin Smith), gathered a consortium of some 20 industries to make the first systematic evaluation of CO_2 storage east and west offshore of the UK. That showed that the UK holds the geological potential to store 70Gt CO_2, equating to emissions from many decades, and possibly centuries of CO_2 emissions. That initial survey has been confirmed and further detailed by several subsequent projects between Crown Estate Scotland, Energy Technologies Institute, and BGS. This is now available as a world-leading database for researchers and storage developers.

Collaborations and innovative research on CO_2 storage still continue to improve the understanding, appraisal and monitoring of the geological conditions necessary for a store where CO_2 can be reliably contained. These assemblages are very well understood, and have many analogies with abundant oil and gas accumulations which have trapped fluids for many millions of years in duration. The fundamental features are an extensive porous and permeable reservoir sandstone at 1–4km deep, which can be accessed by drilling. That reservoir is typically the area of Edinburgh or Glasgow, and 20–100m thick, to be capable of receiving CO_2 injection though 1 to 10 boreholes simultaneously, for a project life of 10–50 years, which will store 10–500 Million tonnes of fluid CO_2. Overlying the storage reservoir, an impermeable mudrock is required to prevent buoyant leakage of CO_2, with lateral constraints to halt sideways seepage. And in addition it is necessary to reliably predict the buildup of fluid pressure during injection, and decrease of pressure during decades after project completion. Too much injection pressure can fracture the top seal or sideseal. The least secure retention of CO_2 is along legacy boreholes drilled for hydrocarbon extraction, and these need to be inspected and monitored for the quality of their continued sealing. Again techniques adapted from oil and gas can be reliably used to make seismic reflection images of the exact CO_2 location, or fluid pressures can be monitored at the borehole wellhead, and in unused aquifers above the operating reservoir.

Thanks to patient support from the Scottish Funding Council, the founding Universities have been able to expand the academic partnership through Scottish Carbon Capture and Storage, which now includes Aberdeen, Dundee, Edinburgh, Heriot-Watt, BGS, Strathclyde and Glasgow. Instead of wasting time and energy on competition between research groups, this has provided Scotland with a strong group of collaborators who have become sought-after partners in European science projects. SCCS maintains a database of current news updates, projects, academic publications and a global map of CO_2 storage

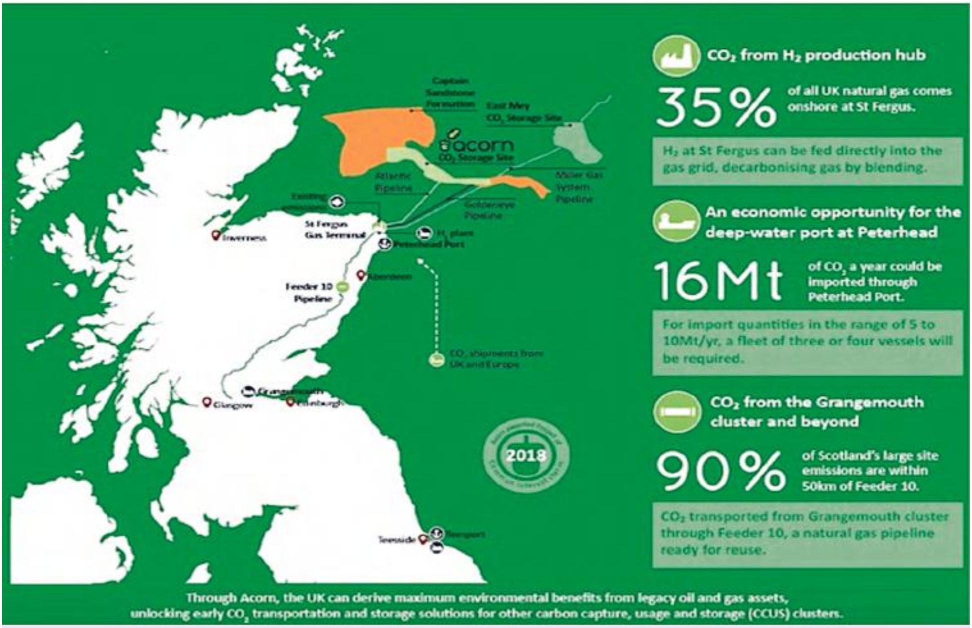


Fig 4 Outline principles of Acorn CCS project to capture CO_2 from all Scottish east coast and central belt industrial regions, transporting through re-purposed hydrocarbon industry pipes on land and undersea, to storage in the deepwater lower Cretaceous Captain sandstone www.theacornproject.uk.

investigations. Examples include the UK's first end-to-end project evaluations in CASSEM – investigating CO_2 storage beneath east Yorkshire and the Firth of Forth. The first investigation of CO_2 injection through multiple boreholes in MultiStore, and the first rapid calculator of CO_2 storage risk compiled a global database to calculate that 98% of CO_2 injected by CCS will be stored for at least 10,000yr. That makes CCS the most secure long duration storage method against global warming, and at large scale. The most recent CCS attempt to utilise this massive quantity of secure CO_2 storage offshore of Scotland, is the Acorn project. Funding negotiations are in progress between the Acorn CCS project at St Fergus and UK Government, to re-use an empty pipeline and feed CO_2 to storage offshore in the Cretaceous deepwater deposit of the Captain Sandstone (Fig 4); this was previously studied in the MultiStore collaboration. This Acorn project proposes to develop the

Peterhead deepwater port, so that shipping tankers can bring in CO_2 sourced from European countries to create a new environmental industry of secure CO_2 storage in Scottish porespace. After several years or decades, if CO_2 storage demand continues to increase, the Palaeocene Mey aquifer with Lista Formation mudrock seal, can be reached by a similar offshore pipe. Both of these offshore storage sites have been evaluated by the Universities of Edinburgh, Barcelona, Liverpool and SCCS collaborating with project developer Pale Blue Dot. This demonstrates the benefits of combining academic and industrial expertise, to build on the geological knowledge gained from decades of oil and gas exploration and development.

Switching chemical heat energy to hydrogen

About 80% of UK households use methane (North Sea Gas) for heating, and in 2020 about 37% of electricity supplied to the UK was generated by gas combustion providing heat to turbines. The depletion of UK indigenous gas resources, and the increase of imports, makes the UK vulnerable to European and global shortages of supply and market price changes as in 2022. To decrease carbon emissions from methane, which are too dispersed to capture from each household, and to produce more secure energy domestically for industry and surface transport, a switch to hydrogen is being developed at the same time as a switch to electricity. Both have strong positive attributes and both are likely to co-exist in 2030 onwards.

Geology can again play a role supplying hydrogen storage for heat supply. The quickest method to create about 10 million tonnes hydrogen per year for UK heating, is to split methane into CO_2 and H_2 using chemical industry processes of Steam Methane Reformers, and Auto Thermal Reformers. To avoid emissions the CO_2 must be transported and stored. This is an identical process to that described for CCS where CO_2 is stored for millennia in depleted oil fields, gas fields, or salt water filled porous aquifers. One good place to develop hydrogen manufacture and storage is at St Fergus where pipelines land about one third of UK gas, both imported from Norway and extracted from the North Sea. This can be converted to hydrogen by SMR and excess CO_2 sent offshore for secure and low cost storage (Fig 4).

But making hydrogen from imported methane is only an interim step, as that still requires insecure, and increasingly expensive imports with associated carbon emissions along the supply chain. The final step will be electrolysis of seawater using wind-powered electricity, to make hydrogen and oxygen directly. This method may be clean and green, but is currently about 10x more expensive than ATR hydrogen derived from methane, and so this will be a Transition dependent on the price charged for hydrogen. Even then, geology still has a role in storage—but this time the seasonal multi-month storage of hydrogen gas.

Scotland has a seasonal climate, so in winter there is need to provide space heating into domestic dwellings and business workspaces. Because the UK and Scotland have very poor buildings insulation, the demand for gas fuelled chemical energy in the winter can be 6x that of the summer. Historically that extra energy has been provided by extracting North Sea gas faster from natural gas fields. So the UK has only about three days gas storage, whereas countries such as France, Italy, or Germany,

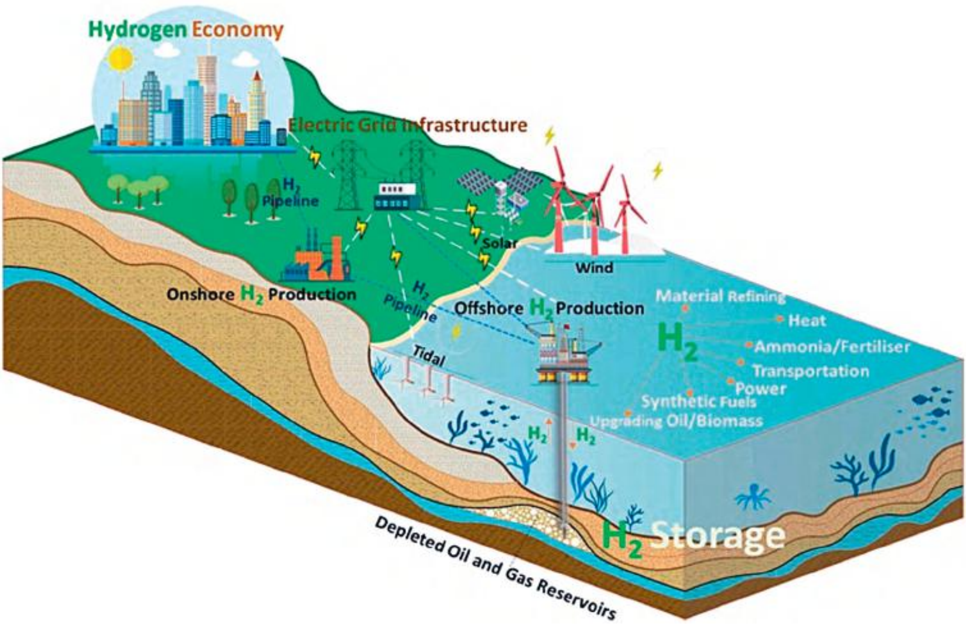


Fig 5 Outline principles of geological storage for hydrogen. Offshore locations are preferred due to lack of public opposition and because depleted gasfields exist which can provide large storage sites with evaporite or shale gas seals. (Hassanpouryouzband et al 2021)

where there is minimal domestic gas production have about 3 months. If hydrogen is to substitute for methane then large quantities of storage must be included on the gas network (Fig 5). Although methane is regularly stored in the sandstone porespace of depleted gasfields, and engineered salt caverns, that has never been attempted on a national network scale. The geological requirements are similar to those for CO_2 storage with CCS, but for timescales of months not millennia. At Edinburgh, a programme of laboratory work is underway, led by Katriona Edlmann, to measure the basic and fundamental properties of hydrogen in porous sandstones, and then in bedded salt plus sediment layers, and in diapir pure salt caverns. This is providing information such as geochemical reactivity with rock-forming minerals, capillary pressures of hydrogen to brine, and contact angles of hydrogen to rock-forming minerals. These measurements are enabling reservoir engineering software to be adapted to the physical and chemical properties of hydrogen gas, and will enable predictive modelling of the injectivity of hydrogen into, and recovery of hydrogen from a porous reservoir, and the physical or chemical interaction of hydrogen with engineered cushion gas, emplaced at low cost below the hydrogen. The cushion gas acts as a spring which is compressed during hydrogen injection, and then expands to push the hydrogen out of the storage site and into the network, to aid supplies in winter. University of Edinburgh has already surveyed the quantity of hydrogen storage available offshore of the UK, using the same CO_2Stored database which was established for permanent CO_2 storage. Depleted gas fields can supply 40x more storage than is necessary for hydrogen backup, because of the concentrated chemical energy. Whereas the same sites used for storage of compressed air (CAES) can supply only 15% of UK backup energy—because the energy density of compressed air is physical, whereas the energy density of hydrogen is chemical. New problems are emerging – such as the influence of microbes which consume hydrogen at temperatures below 120ºC and salinities less than 4x seawater—how important will that be? And, by extension, the desirable low cost and physical compression of CO_2 cushion gas with stored hydrogen has in several global localities induced mixing, which produces a microbial Sabatier reaction to form methane—which may be a contaminant rather than a fuel in a carbon-free hydrogen network. To predict the future, it does seem probable that the low cost of geological storage for hydrogen will be a very powerful addition to the security of a network system, and can out-compete electrical battery storage at grid scale by about 1,000x capacity duration. And the technology solution of geological storage for hydrogen can be very portable globally (Fig 5).

Direct Air Capture (DAC) and BioEnergyCCS

Additional to the conventional CCS to decrease current emissions, it is also possible to capture CO_2 from ambient air and return that carbon into secure geological storage deep underground. The purpose of these 'Negative Emissions' are to recapture some of the already emitted CO_2, to balance any continuing emissions of residual CO_2—which is the meaning of the Net in NetZero. That means activities such as fertilizers for agriculture, or hydrocarbons for aviation can choose to continue emissions, and can purchase verifiable offsets to recapture and store a quantity of CO_2 which balances or exceeds their own direct emissions. That can be achieved by two distinct capture methods.

The first is planting and growing trees; this is low cost, works with nature, and provides multiple ecosystem and flood control benefits. And this could (or perhaps should) be designed as a BioEnergy end point of use for the current enthusiasm for planting forests—which need to not just capture carbon, but must store that for 200 cycles of 50 year forests which do not suffer carbon losses by unplanned dieback from infestation, combustion from wildfire, or premature felling by people. The best methods for converting locally harvested wood to heat energy with clean flue gases are likely to be high temperature gasification, rather than low temperature combustion with unburned impure smoke and particles making CO_2 capture much more difficult. But in Scotland, trees are slow to grow, and may capture just 5–15 Mt CO_2/yr, whereas the minimum need is expected to be 10-30Mt CO_2/yr. Additional methods are needed.

A second method is engineered capture of CO_2 from air, for storage as solid carbonate minerals (Fig 6). This relies on solvents or adsorbtion capture in designed solids—similar to industrial sources. A difference being that regeneration of the capture material needs to be at lower energy use i.e. cooler temperatures or less pure CO_2. Unlike an industrial capture operation, this equipment can be positioned directly above a CO_2 storage site—which saves on compression and pipeline transport costs. A substantial expense is that a substantial energy feed is required,

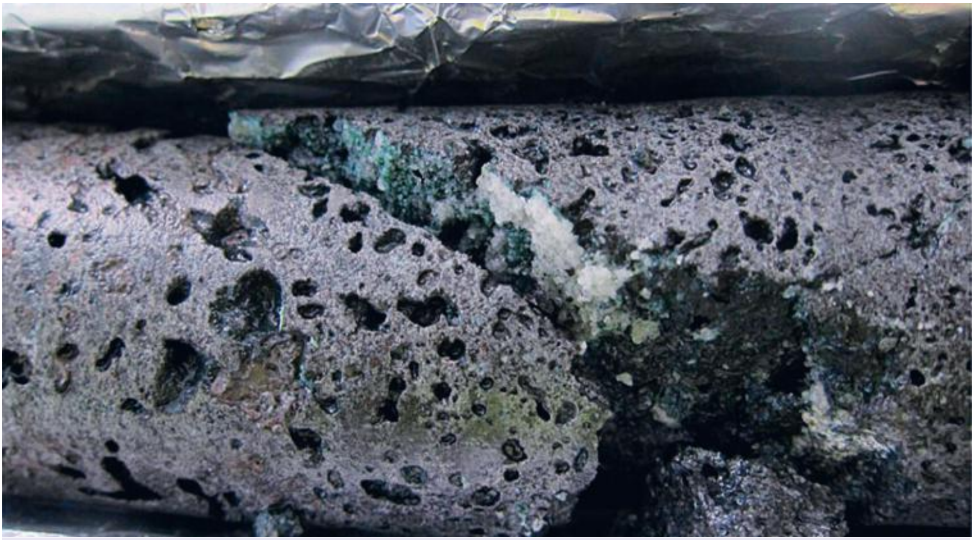


Fig 6 Basalt hyaloclastite core 4cm diameter from CarbFix site, showing natural mineralisation of calcite along flowing fractures in the geothermal system around Hengill (Gíslason et al 2018)

currently about 1,800kWhr to recapture 1Mt CO_2/yr That's roughly 300MW capacity from a 1 GW windfarm. A Scottish requirement for 15 Mt/yr CO_2 recapture is about 4500MW windfarm capacity, which is very large, but not impossible from the offshore wind resource of Scotland. Offshore wind resources have the potential to power air capture of CO_2 storage before 2040 and also provide immense export potential.

A pilot air capture project in Iceland also raises the possibility for storage to decrease in cost, as well as being more geographically close to capture sites. The CarbFix project has separated impure CO_2 from air, which is then dissolved in abundant local groundwater of low salinity, and injected through existing boreholes into geologically very young basalts. The aqueous CO_2 reacts with divalent cations (Mg, Ca) in basalts and precipitates carbonate solid minerals as a consequence. This engineered Iceland Spar forms within one month of injection and eliminates any CO_2 return to atmosphere. University of Edinburgh is undertaking investigations with Pale Blue Dot, to understand if DAC can be added onto the Acorn CO_2 storage cluster at St Fergus. Exploration is underway to identify suitable rocks in Scotland which may be able to act as geochemically reactive secure stores for CO_2.

What is the University of Edinburgh doing?

The University of Edinburgh is a billion pound per year corporation. Like many other large businesses, it is planning its pathway towards NetZero. And as a climate leader in teaching and research, the University plans to achieve Net Zero by 2040–5 years ahead of Scotland and 10 years ahead of the UK. How can this be achieved?

Crucially the University has appointed internal leaders who have job roles including a focus on changing well-established patterns of behaviour in energy and emissions. The Department of Social Responsibility and Sustainability led by David Gorman, is tasked with exactly that, both inside the University, amongst the University suppliers, and in the civic community of Edinburgh.

A first action has been to define the scope of work, the present position and the topics and issues. That journey started in 2015 and includes everything, from climate, through teaching, to food, travel and buildings. To briefly examine one narrow focus on climate change and emissions — one action has been to identify and inventory the University emissions within its own estate and activities e.g. buildings and energy supply (Scope 1), those it induces by its operations e.g. food consumption, travel to work, student field courses (Scope 2), and those which are produced as outputs from its business e.g. academic travel to conferences and meetings (Scope 3). By taking tens of small actions (timers on lights, draught excluders on doors, and some big actions (district heating CHP with piped heating water, double glazing throughout, strict travel emissions advice), the University has decreased

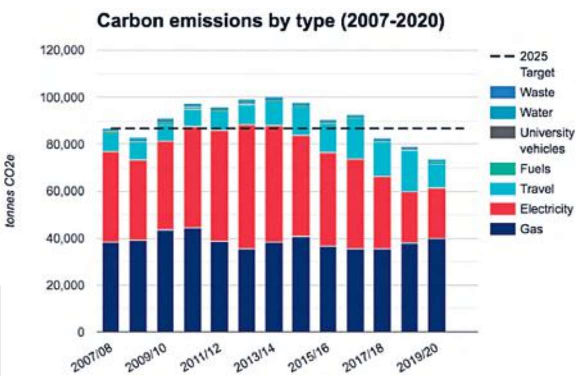
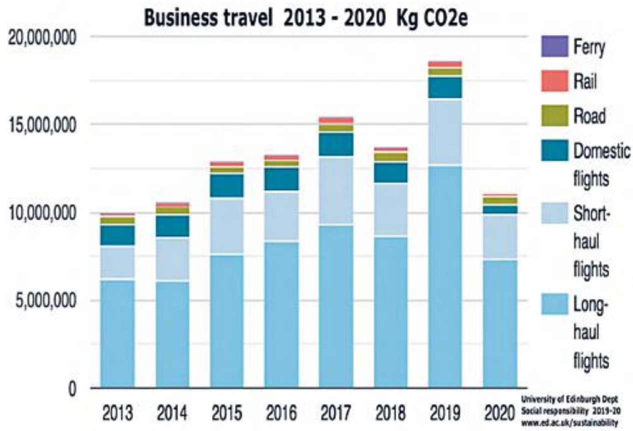


Fig 7 University of Edinburgh carbon emissions.

Fig 8 University of Edinburgh carbon emissions from travel.



its annual emissions by 15% since 2007 (Fig 7), even though student and staff numbers have approximately doubled; effectively a halving of emissions per person. Costs of decreasing emissions can be low. In 2019–20, a portfolio of 44 carbon and efficient energy projects were completed, generating £333,000 in cost savings and a reduction of 1,091 tonnes CO_2e. If the modifications have a 20 year life — that's just £15 per tonne saved. These multitude of achievements are reported comprehensively, annually. The target by 2025 is to decrease CO_2e emissions to 78t CO_2 per £M turnover. Looking 10 years ahead, it is clear that not all emissions can be avoided, and in particular there will still be residual emissions from travel (Fig 8). Those need to be offset by real and verifiable sequestration of an equivalent tonnage of carbon, so the University is purchasing land to grow a forest, allegedly in Highland Scotland, that aims to capture 1 Mt CO_2/yr — maybe with a 40 year life. The forest will also be a teaching resource for forestry, environmental and community research.

Conclusion

The geology of Scotland has provided abundant sources of fossil carbon extraction as a foundation for the Industrial Revolution from 1750. Now, as fossil fuel extraction wanes, the geology of Scotland can provide resources to inject and permanently store excess CO_2. Or can temporarily store valuable hydrogen, to act as reserves of low carbon chemical energy. These are both world-class resources which, with sufficient government support, can assist in a world-leading and Just energy Transition to NetZero emissions before 2045. That has to be matched by citizens and businesses actively investing to decrease their own carbon emissions.

Acknowledgements

The work described above has been, and continues to be, a remarkable collective effort between researchers at Edinburgh, in multiple Scottish Universities and BGS, in diverse energy and resource industries, and supported at its inception by Scottish Funding Council. Thanks to everybody involved for participating in the low carbon industrial revolution in Scotland. We have achieved progress. And provided global examples.

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Girls into geoscience: tackling gender and diversity in the geosciences

By Amanda Owen, University of Glasgow

This is a personal narrative of the Girls into Geoscience events organised by Girls into Geoscience: Scotland with views on increasing diversity, inclusivity and participation in the geosciences being those of the author.

It is well documented that there is a gender imbalance across STEM subject areas, with geosciences being no exception to this trend[1]. Understanding reasons for the gender imbalance is complex and can be observed from secondary school uptake of science subjects by females all the way through to the visibility of women in key positions in industry and academia. Although over the past few decade's improvements in the gender balance have been made, for example, an increase in the relative percentage of females in geoscience undergraduate enrolments or the appointment of Dr Karen Hanghøj as director of the British Geological Survey, there is still much more that needs to be done before any claims of balance can be made.

In addition to the centuries old backdrop of gender imbalance, recent recruitment into geoscience based programmes have also been declining, as was recently highlighted at the Geological Society: Future of Geoscience Summit held in June 2020[2]. Again, the reasons for such a decline are the result of a complex interplay of factors, such as public perception of the geosciences as well as declining visibility of the subject within school curriculums. Indeed, in Scotland there is a near complete absence of geology being offered as a Highers subject with the exception of a small handful of schools that offer A-level. Geoscience is a diverse subject that incorporates aspects of geography, biology, chemistry and physics with concepts relating to geosciences largely being taught within 'mainstream' subjects. As a result, students are being exposed to the geosciences but are not necessarily associating such topics as being 'Geoscience'. Recent work conducted by High School teacher Emma Wotherspoon from Gairloch High school has highlighted where geoscience appears and is being taught within the Scottish curriculum but highlights the lack of ownership of the subject[3]. It is thus imperative that action is taken to not only increase the diversity of the geosciences but to also ensure that geoscience is seen as an attractive subject to study and work within. As pointed out by MacMahon et al. (2021) '*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*' (p.31, Geoscientist, Autumn 2021[4]).

Girls into Geoscience is a grass-roots initiative that aims to increase the visibility of geosciences as a subject to study and pursue careers in for females. The initiative originates from the University of Plymouth, starting in 2014 led by Dr Jodie Fisher and Dr Sarah Boulton[5]. Since their first event, numbers of attendees have increased with over 60% of attendees saying they were more likely to consider studying geology after attending Girls into Geoscience[6]. Since initial conception at the University of Plymouth the initiative has grown to with Girls into Geoscience Scotland, Wales, Ireland and Girls into Geoscience Junior now organising events across the UK.

The Girls into Geoscience: Scotland initiative started in 2019, with an ethos that closely aligned with the original conception. All events, with the exception of Girls into Geoscience: Junior, are designed to bring together girls about to undertake/taking Highers (ages 14–17; S5–S6) with women from industry, government bodies and academia in order to highlight and promote the role geoscience has in our society and its potential to be an exciting and worthwhile subject and career to pursue for women. The Girls into Geoscience: Scotland team is based at the University of Glasgow and is composed of PhD students, professional support staff, early career lecturers through to professorial staff.

Events to date

The first Girls into Geoscience: Scotland event ran in person on August 1st 2019 at the University of Glasgow and attracted 25 students from a wide range of Scottish locations (from Aberdeen to Ayr) as well as locations as far south as Buxton, England. Women were chosen to be speakers and lead sessions with Jessica Smith (Engineering Geologist) from Atkins Global, Dr Anna Hicks (Volcanologist) from the British Geological Survey and Dr Amy Gilligan (Seismologist) from the University of Aberdeen all giving talks on their personal journeys from what made them passionate about geoscience from a young age and their career journeys to date. The talks took an innovative interactive approach, in which the participants handled seismometers, learnt about the role of geoscience in engineering solutions and the importance of science communication in natural disasters, all aimed to improve inquisitive based learning. After an informal lunch in which the Hunterian Museum laid out spectacular samples for the girls to interact with, the participants chose from a selection of hands-on workshops. These included making 'volcanoes in the lab', retrieving and interpreting their own sediment cores in 'Earth's past climates', studying meteorites from outer space and assessing changing landscapes. Feedback for the 2019 event was extremely positive, with 24 out of 25 participants stating that the event had made them more likely to consider studying geoscience related subjects in a range of Universities across Scotland.

With the successful running of the event in 2019, the team quickly started to organise the 2020 event. However, we sadly had to cancel the in-person event due to restrictions relating to the COVID-19 pandemic, but this didn't deter the organising committee, and with colleagues from Girls into Geoscience Plymouth, Girls into Geoscience: Wales and Girls into Geoscience: Ireland, a virtual offering encompassing all the aspects of our normal event, and more was put together. With inspiring speakers, stimulating Q and A panels (applying to university, student life and dealing with change, challenges and opportunities, life in the field), workshops (glaciers to natural hazards, and corals and climate to exploring Mars) and even virtual fieldtrips (from Cornwall to Siccar Point), the virtual event still enabled participants to connect with peers and females working in the geosciences. Taking away the physical component resulted in an increase in number of participations, with over 200 participants watching the talks and taking part in the Q&A sessions, workshops and virtual field trips. Feedback was overwhelmingly positive with comments such as '*the level of inspiration I felt from hearing women's careers, advice and stories and encouragement all relating to geoscience as an exciting science to study*' coming through post-event feedback forms.

Again, the on-going COVID-19 situation meant an in-person Girls into Geoscience 2021 event was not viable, and once again teams from across the UK came enthusiastically together to make the event happen virtually. This time, the event ran over two days, with virtual field trips on offer to Skye, the Yorkshire coast, Mars and the USA on Monday 28th June with career talks, Q&A and workshops running on Tuesday 29th June[7]. Again, a bumper number of participants was recorded with more the 90 girls

Siccar Point. Girls virtually took a field trip to this locality to learn about how we interpret past sedimentary environments and plate tectonics. You can access and undertake the field trip (as well as others) via: https://www.gla.ac.uk/schools/ges/community/girlsintogeoscience/digitalresources/

taking part at any one time, with many classes from schools across the UK tuning in for workshops and talks. Registrations came from across the entire UK as well as India, Morocco, USA and Egypt making this year's event truly global. Initial feedback forms again show the event to be a positive experience for those who attended, with statistics and follow up questionnaires being processed.

Looking Forward:

Inclusivity is a core value of this initiative. There is no doubt that the 2020 and 2021 online events increased not only the number of participants but the diversity of participants. As we start to plan successive events, and we all hope to see more events going back to an in-person format, it is important that learnings from outreach events that have taken place online will be taken into consideration. With previous and some current events going online, participants do not have the same need to travel, which is often a barrier to participation. Moving forward, we must ensure that such barriers are not again put up for place restricting the participation and visibility of geosciences. For events that do take place in person, funding provided by the Edinburgh Geological Society, The Geological Society and Atkins Global to Girls into Geoscience: Scotland are, and will continue to be, imperative to breaking down barriers through the provision of travel bursaries and lunches for in person events. Although online events have run extremely successfully, one must not forget that in-person events allow students to come to a university campus, interact with peers, current students and women working in geoscience and physical specimens and datasets that cannot be easily replicated online. There are clear advantages to both approaches and as we look forward it is hoped that future Girls into Geoscience: Scotland events take a hybrid approach to help increase participation and perceptions within the geosciences.

There is no single solution that will increase the diversity and inclusivity of the geosciences, but it is clear that holding such events that showcase the personal stories, highlight the diversity of topics and the fantastic and rewarding careers that can be had within geosciences can have a profound affect on young peoples choices. As closing remark from one participant: '*The event was amazing. It is so great to get involved with such a welcoming and positive community where silly questions can be asked with no judgement! Seeing such inspirational women who started their geoscience journey just as I am now is so motivating that I one day may be leading a talk like this and inspiring the next generation of geoscientists*'.

Finally, a personal thank you to all of those who help fund, and give up their time to take part in such events, running field trips, giving talks, answering Q&A sessions and helping with the organisation of the events. Without such volunteers these events cannot run and we as a community cannot engage with the wider public to showcase our fabulous subject. If anyone is interested in being involved with Girls into Geoscience:Scotland please contact amanda.owen@glasgow.ac.uk

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Progress in geology— discovery and controversy

By Paul Binns

Like all sciences, geology has progressed in various ways. Some controversies of global significance, such as continental drift, are ended by single piece of evidence. Others are settled gradually as evidence accumulates and opinions converge to a common view. Progress is also made as novel techniques open up a new fields. The optical microscope and radiometric dating are examples.

The Greeks and Romans were familiar with Mediterranean landscapes ranging from the volcanoes of Italy to the mountains and glaciers of the Alps. Their early naturalists recognised the great age of the earth and speculated about its history:

"… a place does not always remain land or sea throughout all time, but where there was dry land there comes to be sea, and where there is now sea, there one day comes to be dry land." … But the whole vital process of the earth takes place so gradually and in periods of time which are so immense compared with the length of our life that these changes are not observed." Aristotle (384 BC–322 BC) Meteorology, Book 1, Part 14.

For centuries after the fall of these Empires, the biblical view of creation was accepted in the West. In the Middle Ages, however, Arabs translated the literature of Greece and Rome and the development of science passed to the east (Geike, 1897, p.42). In particular, the Persian Ibn Sina (980–1037) made prescient contributions, associating the formation of mountains both with earthquakes and erosion and recognising the long periods of time involved (Al-Rawi, 2002). During the Renaissance in Italy, Leonardo da Vinci (1452–1519) and Nicholas Steno (1638–1686) made important and accurate observations relating to the origin of rocks and fossils. Steno's medical background, for example, led him to argue that the internal structure of fossils proved that they had been living animals and not, as had been argued, inorganic.

However, it was not until the 18th and 19th centuries that diverse observations came in from around the world, fuelling controversies as to the origin of the various rock types and the history of the earth. Fierce debates of global importance began!

The extent of geological time was a major controversy as geological evidence appeared to conflict with the Biblical account of creation. Attempts were made to reconcile the two. A French naturalist, Leclerc de Buffon (1707–1788) recognised that there was a history to be established. He interpreted the Biblical six days of creation as six periods of time (Geike, 1897, p.88–97) with remarkable prescience, and reportedly based on fossil evidence, he described the 'Sixth Epoch' as marking the separation of the continents of the *"Old and New Worlds"*. Even more remarkably he assigned a 'Seventh Epoch' *"to the commanding influence of man"* — an early exponent of the Anthropocene!

Writing in 1829, Andrew Ure (FRS, FGS, founder of the Andersonian Institute, forerunner of the University of Strathclyde), a little-known Scottish polymath, firmly supported the Biblical account but believed that there would be *"no truce between the combatants"* until the *"physical events appertaining to the creation and deluge, … are not discordant with the legitimate deductions of physical science"* (p.xiii, para 1). Ure goes on to describe diverse geological observations from as far afield as the Andes and the Himalayas.

James Hutton's (1726–1797) Siccar Point evidence for deep time was no accidental discovery. Hutton believed that evidence of an early world lay beneath *"secondary strata"* and the contact between them would reveal the relationship. With persistence he examined several contacts in Scotland but still sought a clearer one, which he believed to lie on the coast where the Lammermuir Hills come down to the sea. He was not disappointed when he landed at Siccar Point!

Less reported is Hutton's role in the controversy over the origin of igneous rocks. The forceful and charismatic Abraham Werner (1749–1817) headed a school of geology in the Freiberg Mining Academy. He asserted that the whole earth had once been covered by water from which rocks were precipitated. His theories were put forward dogmatically as truth, to be later scathingly dismissed by Geike (1897) as *"dogmatic assertions, of which every one is contradicted by … observation"* (Geike p.211). Werner's earliest 'precipitates' were rocks we now know as igneous and metamorphic.

With pointed reference to Hutton and Playfair one of Werner's followers wrote: *"We should form a very false conception of the Wernerian [knowledge of the earth] were we to believe it to have any* *reference to those monstrosities known under the name of Theories of the Earth …"* (Geike p.211).

Hutton and his followers, however, persisted in their belief of an igneous origin: *"… having been formed in the bowels of the earth, of melted matter poured into the rents and openings of the strata"* (Geike p.259). The debate raged on as observations came in from all over Europe. Hutton sought to prove an igneous origin, citing granite veins intruding schist in Glen Tilt and the dolerite wedged into the strata of Salisbury Crags.

Evidence in support of an igneous origin was also found in Portrush, Northern Ireland (Wilson, 2021). High temperatures from a sill had transformed Jurassic shales into hard rock. However, ammonites in the rock had survived. The 'basalt' with ammonites had been interpreted as igneous and taken as proof of crystalisation from sea water. Controversy followed. Geologists, including Edinburgh's Playfair, visited the outcrop and it eventually was accepted that the 'basalt' was indeed hornfels, a low-grade metamorphic rock.

Another 19th century controversy was the origin of glacial tills. Were they transported and eventually deposited from glaciers or dropped from melting icebergs? The work of Swiss geologist Jean Agassiz (1807–1873) proved glacial transport.

Perhaps the most significant controversy at the time followed the 1859 publication of Darwin's "On the origin of the Species". His many eminent critics maintained that species were *"immutable"*. Many generations are required for a species to adapt and the transitional forms, which Darwin's theory required, had not been recorded in the strata. Darwin responded by noting the imperfection of the geological record, quoting Charles Lyell's metaphor for the geological record as a book:

*"… written in a changing dialect; … we possess the last volume alone, … Of this volume, only here and there a short chapter has been preserved; and of each page, only here and there a few lines. Each word of the slowly changing language, … may represent the apparently abruptly changed forms of life, entombed in our consecutive, but widely separated, formations" (*Charles Darwin, On the Origin of Species, 1859, end chap. Ix).

James Croll in 1875 in his seminal book "Climate and Time" reviews controversies on the role of astronomical causes of climate going back to 1765 (Appendix p.528).

These include contributions from familiar names such as Lyell and Herschel. Changes in the orbit of the earth around the sun were, at the time, considered too small to have any effect. Croll thought otherwise - indirect effects had been overlooked and were important. He examined the various theories in detail, paving the way for Milankovitch's later work. This was not all though. In the last edition of The Edinburgh Geologist Mike Robinson writes of Croll's desire to learn. This is evident in his book which covers a range of topics including ocean currents, evidence for glaciation, the ice sheets in England and Europe, rates of erosion, the age of the sun and the cause of movement in glaciers.

All this begs the question—are there such controversies in Geology today which are of global importance? Plate tectonics has been accepted since the 1960s, following magnetic evidence. Geophysical techniques are providing stunning images of the sub-surface but, in a global perspective, are essentially filling in detail. Has the 'frontier' now moved to planetary geology? The images of the delta entering the Jezero Crater on Mars certainly suggests this.

Edinburgh played an early role in this with the analysis on the moon rock in the Grant Institute—which brings to mind another sort of geological controversy. Speaking in Edinburgh after his Apollo 17 return from the moon, geologist Harrison Schmitt's first slide showed an Apollo rocket blasting off—*"Geologists often argue with one another about how difficult is to get to their field areas"*.

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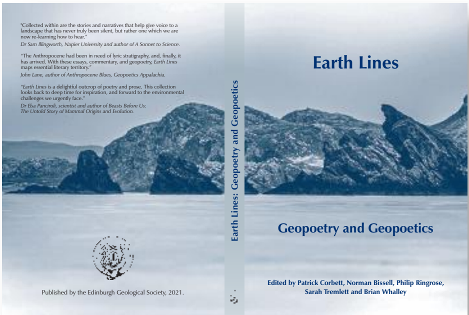
Book review

Earth Lines: Geopoetry and Geopoetics Edited by Patrick Corbett, Norman Bissell, Philip Ringrose, Sarah Tremlett and Brian Whalley, Published by Edinburgh Geological Society, 2021. Available via EGS website £15 non-members; £12 members.



“A new vista of wonder and entertainment for geologists and the wider world”

On 1st October 2021, the EGS published the volume *Earth Lines: Geopoetry and Geopoetics*. “The Anthropocene had been in need of lyric stratigraphy and, finally, it has arrived”, says John Lane, author of *Anthropocene Blues*. The volume is a compilation of all the contributions to Geopoetry 2020, an online meeting held under the organisation of the Geological Society of London. The publication of the material was later supported up by the Edinburgh Geological Society, for which the editors are grateful. “For anybody who doesn’t know much, if anything, about Geopoetry or Geopoetics, then this is a great place to start their inquest into the topic” said Cecilia Reid.

Geopoetry 2020 included a number of papers and poems presented or read by the authors. How to compile this into a volume with Geopoetry and Geopoetics in the title and what should be the difference? To help with the latter, Norman Bissell has provided a definition of each: Geopoetry regards geology as crucial to our understanding of the Earth and expresses places and the geoscience of them in poems; Geopoetics is a much broader concept and practice. It places the Earth at the centre of human experience and involves its creative expression in arts, sciences and thinking and combinations of them. The work gathered in this volume appears to lie on a continuum between these definitions.

The compilation challenge was solved by organising the material into five sections and the essays and poems are collected under these headings, although the division is not intended to be singularly restrictive.

Poetics of geoscience—the lines of the earth—in the broadest sense is what is captured and the reader is left to ponder on the appropriateness of the boundaries—if they exist even—between Geopoetry and Geopoetics. The sections are: Stratigraphy, Geological Processes, Geologists at Work, Geoidentity, and Geopoetics. I have included some lines from each section to give a flavour of the diversity without detracting from the volume or upsetting the poets (the latter point, I have to trust). Through these extracts, the reader can get a feel of the richness of imagery that comes with an appreciation of geology or the wonderment of geological mysteries.

Geological papers usually begin with stratigraphy, so we also started with Stuart Graham's "Old Boy"

Older than life the ancient dark whale
of Europe surfaces, his back just visible.

And compliment this with Sarah Acton's "Red Rock (Exmouth)" from her "Earth Shapers Poetry Cycle".

Rock is tired priestess, blesses migrations,
epic flights. From a seasonal point of view,
sees; proud land-thief is all sunspot
and no altar.

Geological and geomorphological processes are intertwined—the present is the key to the past. From Alina Haydar's "Streams wet the dry Land"

Streams wet the Dry land,
Wipe away the sand grains,
Then consign them to the Ocean bed.

to the sixth of Sila Thaus' "Source to Sink Haikus" we celebrate the cyclical process of erosion, transport and deposition.

Silent clay settles.
A calm, deep destination,
end and beginning.

Geologists at work feature in the class room, lecture theatre, laboratory or field. Geologists traditionally travel widely, often to exotic locations, as Andrew Abraham's "Field Boots" recalls

Having traversed the geologic column,
they have touched ancient volcanic arcs
and laid upon the exhumed roots of
mountain chains.

and to more prosaic locations as Nia Davies' "Rig Works: Oil rig gift shop" records.

oil rig exotic/rough neck occidental
Log jam ethic/yeh so it is/mud logger

If mindful of one's own Geoidentity, one can feel the impact of a place beneath one's feet, often a much loved and well frequented place, such as we find in Chris Jack's "Aeon of Ardverikie"

Standing in the river-gouged gorge,
Observing, mapping, eaten by midgies!
Amongst time-smashed ocean,
Psammites and schists;

or Jack Cooper's "The Testimony of the Rocks"

I watch the tide fall from Siccar Point
like a shallow breath from scarred lungs.

Geopoetry captures the wonder and spirit of the earth seen in various places—from the air as in Phil Ringrose's "Offshore Newfoundland"

But our future depends on using
our eyes in the sky, saying 'looking at you'
since these could bring sparkle, amazement and joy
back to the future.

and from the ground as in Claire Rinterknecht's "The Standing Stones of Stenness"

We created memories I now try to catch with my pencil.
They swirl around me, still caught in the Orkney wind.

The volume has many such Earth Lines to savour. In between the poems there are also reflective papers on aspects of the topic for those that want to understand the subject deeper or investigate important aspects of geoscience in poetry. The accompanying website, https://www.edinburghgeolsoc.org/earth-lines/, captures the voices of the poets reading some of the works in the volume or closely-related work. The book is illustrated with geologically-themed pictures or artwork to break up the text and reflect on the lines in the rock.

The authors are pleased that the volume has been 'blessed', as two of our more distinguished senior geological colleagues, Bryan Lovell and Dick Selley, have commented on the volume, respectively:

- "I keep it close by, and find more and more to enjoy and make me think" and,
- "In 2011, Bryan opened up a new vista of wonder and entertainment for geologists and the wider world".

This is a book to both enjoy and to be stimulated by and it builds on earlier works in the geosphere.

Professor Patrick Corbett
Heriot Watt University

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