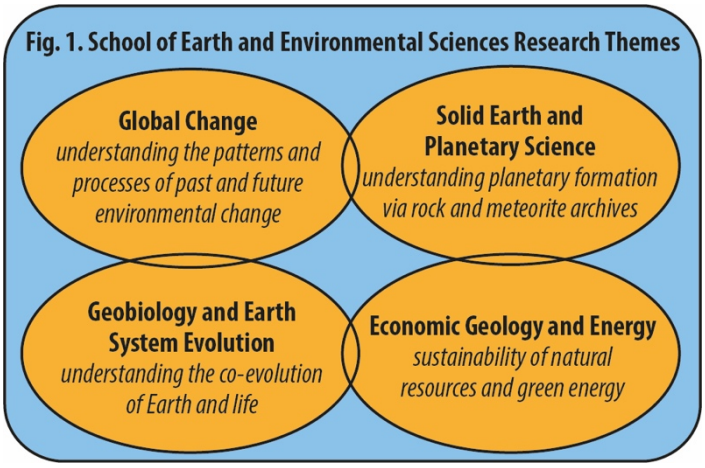
Institution: University of St Andrews

Unit of Assessment: UoA 07: Earth Systems and Environmental Sciences

Section 1. Unit context and structure, research and impact strategy

Research Aims and Achievements. In 2008, the RAE highlighted explicitly the quality of geoscience research within the then-combined School of Geography and Geosciences (in RAE2008 the School ranked 17 out of 49 programmes by UoA 32 Geography and Environmental Studies). To sustain and grow that potential, the existing six Geoscience staff crafted a strategy to leverage recognised excellence in field geology and igneous petrology with the aim of creating a standalone programme dedicated to curiosity-driven science underpinned by isotope geochemistry. The University adopted that strategy in Autumn 2010 and invested £1.3 M in the geosciences. The early phase of that strategy helped propel the School of Geography and Geoscience to No. 5 overall and No. 1 in Impact in REF2014 (UoA 17 Geography, Environmental Studies and Archaeology). Between 2010-17, Geosciences won £10.8M in competitive research income and tripled the size of its PhD-Research Fellow community (from 9 in 2010 to 28 in 2017). In recognition of those achievements, the University created the School of Earth and Environmental Sciences in 2017. The School now consists of 23 REF-returnable staff (20 at 1.0 FTE, 2 at 0.2 FTE, 1 at 0.5 FTE; total of 20.9 FTE staff), of whom 13 are within 10 years of obtaining their PhD and 6 are female. Our research community is thus built on strong support for early career Earth scientists, such as manageable teaching and admin loads for newer staff, and our inclusivity policies gained the School an Athena SWAN Bronze in September 2019.

Our research aims to deepen understanding of the processes and feedbacks that link Earth's interior to its surface and atmosphere. We study how those processes impact on and are influenced by human activities and use that knowledge to help underpin solutions to cope with future environmental change and steward sustainably Earth's resources. Our expertise defines overlapping clusters in isotope geochemistry, climate modelling, geobiology, field geology and planetary habitability integrated across four themes that bind our individual and collaborative research activities (Fig. 1), including support for several staff who are concentrating increasingly on applying geology and geophysics to heritage preservation. We use our chemical, biological and geological insights to gain better understanding of the origin of our solar system and its planetary bodies. Our research ethos is to inspire discovery and inquiry of bold hypotheses and undertake incisive testing via critical thinking and evidence-based assessment that is global in scope and impact. Our research is in keeping with a culture of Research Integrity and aims to become part of an open research environment where possible (see Institution-Level Environment Statement, ILES, 2.4 and 2.6).



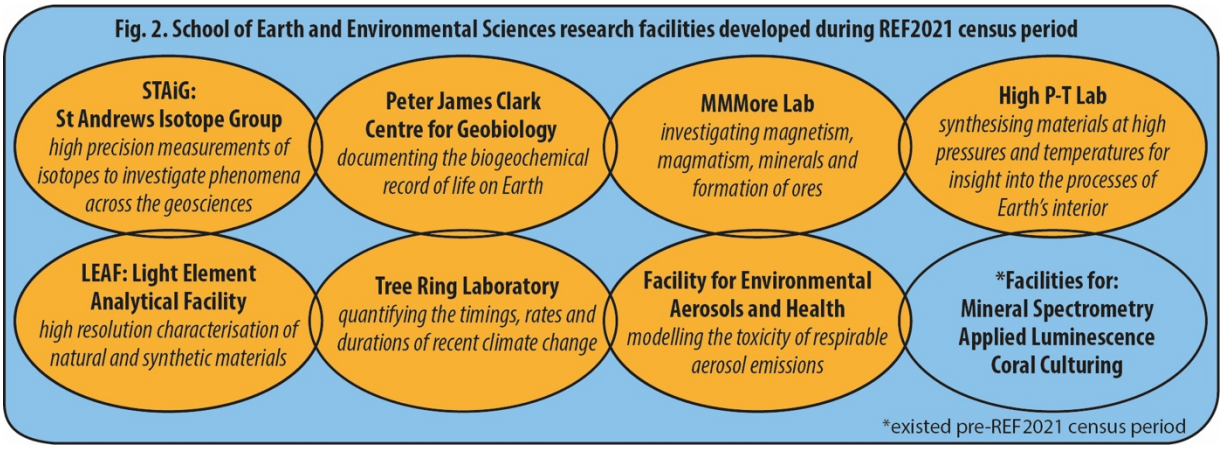
Our achievements are a testament to the success of our research and staffing strategy:

- creation, in January 2017, of an independent School of Earth and Environmental Sciences
- four independent Research Fellows proceeded to Lectureships [*Rae, Claire, Cousins, Stüeken*] and our UKRI Future Leaders Fellow [*Hutchison*] will transition to Lecturer
- during the REF2021 census period we attained an average of 18 peer-reviewed publications per REF-returnable staff
- £16.5M in competitive research income was won during the REF2021 census period
- establishment of four new research groups during the REF2021 census period:
    - *St Andrews Volcanic Eruptions and Impact Group* [*Burke, Byrne, Claire, Hutchison, Rae, Wilson*] integrates expertise in volcanology, geochemistry, (palaeo)climate

and atmospheric modelling to investigate large volcanic events and how climate and societies respond

- *Planetary Geodynamics Research Group* [*Finch, Gardiner, McCarthy, Mikhail, Savage, Steele, White*] integrates novel and non-traditional stable and radiogenic isotopes and chronometers, geodynamical modelling and petrology to investigate processes leading to the genesis of continental crust and geological evolution of rocky planetary bodies
- *Centre for Exoplanet Science* [*Claire, Cousins, Mikhail, Savage, Steele, Stüeken, Zerkle*] is an interdisciplinary centre combining expertise from the Schools of Earth and Environmental Sciences, Physics and Astronomy, Biology and Philosophy to study how planets and their atmospheres form in different galactic environments and the impact that finding life elsewhere would have on humankind
- *Climate Dynamics Group* [*Allison, Byrne, Burke, Rae, Wilson*] is a nascent group that addresses questions in atmospheric and climate modelling, genesis of monsoons, land-climate interactions, the water cycle and past and future climate change; this Group is central in coordinating the University's new initiative, the *St Andrews Network for Climate, Energy, Environment and Sustainability*

Our research traditionally championed field-based datasets and staff were recognised worldwide for expertise in field geology. Consequently, we implemented a strategy that focussed effort and resources on obtaining complementary expertise and cutting-edge analytical facilities in isotope geochemistry, geobiology, experimental petrology and geomagnetism (for a listing of specific equipment see Section 3). Hence, one of our most outstanding achievements during the REF2021 census period was bringing together a group of world-class researchers and creating seven state-of-the-art analytical facilities (Fig. 2). We now lead research in the conception, testing and constraining of models of Earth system functioning, from the Recent through to Deep Time and from Earth's oceans-atmosphere interface through to its interior. These include:



- The UK's only laboratory capable of measuring all four stable isotopes of sulphur using gas-source methods that incorporates a custom-built SF_6 line and innovative Curie point-pyrolysis technique; research differentiates sulphur isotope signals produced by thermochemical, atmospheric and metabolic pathways in mineral and organic materials to address questions about the composition and evolution of Earth's surface environments during pivotal periods in Earth system development [*Claire, Hutchison, Rose, Zerkle*].
- Clean room ICP-MS laboratory suite with one of the first collision cell MC-ICP-MS Sapphire in Europe, Neptune Plus MC-ICPMS, state-of-the-art QQQ ICP-MS and RESolution Excimer laser ablation with cryocell, including associated Class-100 clean rooms for sample preparation. Specialist applications include boron isotopes to reconstruct atmospheric CO_2, triple-sulphur isotopes to assess aerosols in ice cores and volcanic forcing of climate, and key metals (*e.g.* Cu, Ni, Si, Zn) in meteorites and terrestrial samples to probe questions about planetary habitability and solar system evolution [*Burke, Hutchison, Rae, Savage, Steele, Stüeken*].
- Laser ablation facility for elemental and isotopic analysis across the Periodic Table including capability for Nu Plasma MC-ICPMS and Agilent 7500 ICPMS with New Wave Deep-UV (193 nm) Excimer laser for *in situ* analyses of samples. Research foci include U-

Pb dating and Hf compositions of minerals to investigate early growth of continental crust, genesis of metal resources and elemental distributions in corals to probe biomineralisation processes and their elemental fingerprints [*Allison, Finch, Gardiner, Rae, Savage, Steele*].

- a state-of-the-art electron microscopy Light Element Analytical Facility run jointly with the School of Chemistry and designed to provide high-resolution, non-destructive analysis of a wide range of natural and synthetic materials with emphasis on the traditionally difficult light elements (Li through F); bespoke research foci include documenting distribution and speciation of nitrogen in geological substances to assess geosphere-atmosphere interactions, genesis and structure of crystals and light elements for energy sources, storage and industrial uses [*Finch, Hutchison, Mikhail, White*].
- the first out-of-phase magnetic susceptibility kappabridge in an academic institution for quantified separation of magnetic anisotropy tensors associated with ferromagnetic and paramagnetic mineral fabrics; this enables ascription of fluid/melt-flow events to magmatic and ore-forming processes, relative ages and distinct tectonic regimes [*McCarthy, Raub*]
- molecular biology and geomicrobiology labs for cultivation of environmental microorganisms under extreme conditions, including manipulation and visualisation of DNA from the environment; research focusses on understanding and characterising biogeochemical cycling and biosignatures in settings ranging from the hyperarid (Atacama) to high-latitude cryogenic salts as analogues of possible Martian and icy world habitats, respectively [*Claire, Cousins, Zerkle*].
- an experimental petrology lab equipped with a Rockland Piston Cylinder press capable of 0.5-4.5 GPa pressures and 100-2000°C temperatures to study solid-state, solid-fluid and fluid-fluid reactions, element partitioning, stable isotope fractionation and stability of carbon- and nitrogen-based molecules during differentiation of silicate melts and planetary bodies [*Mikhail, Savage, Stüeken, White*].
- a dendrochronology lab that has pioneered the Blue Intensity technique for late-Holocene palaeoclimate reconstruction and historical dating based on tree ring analysis; projects have spanned both the southern and northern hemispheres and the efficiency and inexpensiveness of the technique is enabling researchers in ODA-listed countries to undertake their own climate-change studies [*Wilson*]
- an aerosol chemistry laboratory supported by Cancer Research UK, a facility unique within the UK for generating and sampling respirable emissions across the full spectrum of nicotine-aerosolising methods, from combustion-generated smoke to medicinal nebulisers; LC-, GC- and ICPMS analyses of the emissions are used to model human toxicity and inform health policy makers and regulators [*Stephens*].

We have co-located our highest-maintenance mass spectrometry facilities and Class-100 clean labs in wings shared with the Schools of Chemistry and Biology (ILES, 4.2). This has helped foster interdisciplinary research that bridges the natural sciences and, as detailed below, is forging research and impact linkages with colleagues in Social Sciences and Arts and Humanities. Details of our analytical capabilities are discussed in Section 3.

Impact achievements. Our strategy for delivering research and impact places emphasis on activities that are interdisciplinary, span varying career stages for colleagues and weave together curiosity-driven science and applied research that achieves added value via our analytical capabilities. Our efforts have leveraged commercial contract work to cross-subsidise individual staff initiatives, help support PhD and MSc students, as well as Honours and MGeol dissertation research, and to underwrite research-led teaching programmes in the REE-resource, base-metal mining and renewable energy sectors. Our Impact achievements include:

- *Heritage resources and preservation* [*Bates, Kinnaird, Raub*]. We have pioneered novel combinations of geophysical remote sensing methods and adapted those for heritage preservation to better understand humankind's past through accurate reconstructions of the fragmentary records of ancient landscapes and cultures; our discoveries have informed UK and Scottish Government heritage policy, helped develop digital preservation techniques of artefacts ranging from 800,000-year-old human footprints to ancient Middle East temples, and guided development of better management protocols of UNESCO World Heritage sites in Nepal, Sri Lanka, Tanzania and the UK.

- *Natural resources and green energy* [*Bates, Claire, Finch, Gardiner, Hutchison, McCarthy, Prave, Rae, Raub, Steele, Stüeken, Wilson*]. Our isotope geochemistry and field geology strengths have fostered collaborations with the energy and mineral resource industries and governmental research and policy organisations that include:
    - base metal and critical element studies with First Quantum Minerals, Gemfields Pty Ltd, Kaz Minerals, 32 South, Nuna Minerals, Mkango Resources Ltd, SRK, Boliden Tara, British Geological Survey and Geological Survey of Denmark and Greenland
    - technological developments of analytical instrumentations with ThermoFisher Scientific and proof-of-concept work with NuPlasma
    - renewable energy and environmental assessment supported by the Scottish Funding Council, Fife Council, Scotland-Malawi Partnership and UKRI Global Challenges Research Fund with in-country partners in ODA-listed countries of Angola, Armenia, Ethiopia, Kazakhstan, Malawi, Peru, Rwanda and Tanzania.
- *Society and Health* [*Stephens*]. Initial research into environmental sources of toxins released during tobacco combustion (*e.g*. metals) was extended to all carcinogens in smoke and e-cigarette vapour but quantitative methodologies for comparing the risks of disease were lacking. During the REF2021 census period, a model of cancer risk dependence on aerosol chemistry was developed and emissions from each generic nicotine source were used to construct a *cancer potency spectrum*. The predicted risks were endorsed by Public Health England in its tobacco control policy and influenced a radical refocussing of long-term strategic business directions within all major “Big Tobacco" companies to a future of non-combustible smoke-free products.
- *Society-and-Science Outreach* [Cousins, *Finch, Gardiner, McCarthy, Rae, Raub, Savage, Stüeken*]. We coordinate and run a dynamic programme of educational impact through activities aimed at students of all ages and the general public. During the REF2021 period:
    - *GeoBus,* our mobile educational outreach project, delivered bespoke knowledge enrichment to >70,000 primary and secondary pupils in 278 schools throughout Scotland and northern England and leveraged £1.1M in funding from EPSRC, NERC, The Royal Society and industry sources including Shell, BP, Maersk and Verus Energy Ltd.
    - we delivered *c.* 300 *contact hours per annum* to the University’s summer school programmes (*e.g*. First Chances, Sutton Trust, Summer Academic Experience, Royal Society Masterclass) [*numerous staff*].
    - we brought on-line two taught MSc degree programmes, Geochemistry in 2017 [*Savage*] and, in 2020, Strategic Earth Resources [*Gardiner*] (restructured from our Mineral Resources MSc) with dissertation projects linked to industry partners (see list above); the former focusses on preparing students for further research whereas the latter provides fundamental geological knowledge and skills required for modern mineral exploration targeting and estimation, including economic, environmental and social aspects related to resource extraction and remediation.
- *Professional ‘good citizenship’ activities.* We commit to providing as broad an exchange of knowledge as possible across the geosciences with the wider scientific community outside St Andrews. These activities are supported by our operations budget supplemented by funding from professional societies and organisations; they include:
    - an annual international symposium, FRESH (Frontline RESearcH at St Andrews) developed thematically around emerging breakthroughs by School staff. For example, in 2018 *FRESH: Volcanic Impacts on Climate, Environment and Society* contributed to the research network foundational for the successful application and award of an UKRI Future Leaders Fellowship to *Hutchison*
    - hosting at least one professional international conference per year; examples include the annual conference for the Alfred P Sloan Foundation’s Deep Carbon Observatory in 2017 [*Mikhail*], the Geochemistry Group annual meeting in 2018 [*Burke, Rae, Savage*], and the annual Volcanic and Magmatic Studies Group (VMSG) meeting held in St Andrews in 2019 [*Mikhail*]; Astrobiology [*Cousins*, *Stüeken*], Metamorphic Studies Group [*White*] and Geological Society London sponsored Port Askaig Tillite [*Rose*] conferences were planned for 2020 but postponed due to the Covid-19 pandemic

- leadership on professional societies such as VMSG [*Gardiner, Mikhail*], Geochemistry Group [*Burke, Savage*] and Metamorphic Studies Group [*White*], European Association of Geochemistry [*Mikhail*], Tectonic Studies Group [*McCarthy*], Mining Institute of Scotland [*Prave*], Theme Leader for the Geological Society London's initiative *Energy and Materials Transition* [*Gardiner*], co-chair Election Committee for the Association of Tree-Ring Research [*Wilson*].

Research and Impact: future aims. Over the next decade, our main aims are to: (i) maintain a position at the leading-edge of research that addresses the Grand Challenges in Earth and environmental science, (ii) remain responsive to new breakthroughs and prospects to recruit top-level researchers, (iii) continue to refine our analytical facilities and (iv) be opportunistic in creating and capitalising on funding opportunities to link the Natural Sciences with the Social Sciences and Arts and Humanities. Our strategy will consolidate expertise and investment in:

- *Global Change research* [*Allison, Burke, Byrne, Finch, Hutchison, Rae, Wilson*]. We plan to advance research and impact along two main initiatives:
  - develop the next generation analysis of chemical fingerprints of global change with an overarching aim to improve understanding of Earth's climate forcing by CO_2 and volcanoes and the impact of an acidifying ocean on corals; the aim is to place ourselves as a world leader in analyses of key environmental archives, including corals, ice, trees and fossils
  - refine continental climate modelling using state-of-the-art GCMs that will interface with our efforts in constructing chemical fingerprints of environmental change; the aim is to deliver deeper understanding of the fundamental controls of changing precipitation patterns and temperature extremes.
- *Economic Geology research* [*Bates, Finch, Gardiner, McCarthy, Raub*]. We aim to expand applied research capabilities using our MMMOre Lab (Magnetism, Magmatism, Mineralogy, Ore) by integrating magneto-thermal characterisation of minerals, UAV- and satellite-based hyperspectral measurements and geochemical fingerprinting. We will use this capability to address the needs of the critical minerals industry, particularly in ODA-listed countries, via better predictive models for mineral resource estimation. This is made possible by a £100k investment split 1/3rd each between the School, University and PI funding [*McCarthy*] and includes provision for training to build in-country expertise.
- *Facility enhancement* [*Gardiner, Rae, Savage, Steele, Stüeken, White*]. We are establishing a multidisciplinary facility combining Laser Ablation-Laser Induced Breakdown Spectroscopy (LA-LIBS) with the next generation of collision cell multicollector ICP-MS and triple quadrupole ICP-MS for simultaneous *in situ* measurement of volatiles, ppb precision of isotopic ratios and trace elements and 3-D elemental mapping. This will underpin research characterising mineral archives with beta decay system geochronology (*e.g.* La-Ba) for 4-D tracing of ore-forming processes, tracking Hg accumulation in biosystems, constraining past atmosphere compositions with combined S, Hg and Se isotopes, and building models of planetary differentiation and volatile cycling. A £30k grant from the MIS Trust is helping refurbish this facility.
- *Earth System Evolution research* [*Burke, Claire, Hutchison, Magalhaes, Rae, Zerkle*]. We will capitalise on our capabilities to measure all four stable isotopes of sulphur on samples an order-of-magnitude smaller than required by standard fluorination methods. Using ERC funding we are automating sample preparation to enable an array of opportunities to examine high-resolution changes in atmospheric and biogeochemical sulphur cycling across Earth history. Noteworthy is that this facility is garnering requests worldwide for collaborative research.
- *Planetary Science research* [*Claire, Cousins, Mikhail, Savage, Steele, Stüeken, Zerkle*]. Understanding why our solar system is habitable and participating in the search for finding life elsewhere fuels our interest in expanding astrobiology and planetary habitability research via our on-going participation in the EU's ESA Mars Rover and NASA-UKSA-ESA missions and the UK Cosmochemistry Analysis Network (UK-CAN). Joint with colleagues across the UK and our interdisciplinary Centre for Exoplanet Science we will continue to develop methods that impact on technologies for the study of Mars, icy moons and planetary bodies throughout our Solar System.

- *Multidisciplinary initiatives* [*Bates, Burke, Byrne, Kinnaird, Prave, Rae, Raub, Wilson*]. Much of our research incorporates expertise from outside the conventional sphere of Earth science and here we highlight three initiatives that will be central in our interdisciplinary research and impact efforts to address the sharpest challenges in sustainability:
    - We are forging linkages with the School of Chemistry's Centre for Innovation in Energy Storage. Our aim is to establish a one-stop-shop combining R&D with state-of-the-art climate science, including potential for CCS/U industry-academia integration, to reveal how such technologies impact on environment. Supported by the Scottish Government's commitment to adopting materials, products and policy based on sustainable life cycle analysis, we are poised to leverage academic expertise within the wider Scottish technology and policy base to build toward a carbon-neutral economy in-line with governmental target dates.
    - We are coordinating efforts to develop an up-scalable model of a University-scope 'Digital Twin' focused on carbon-oriented operations across the University Estate, inclusive of its energy and innovation campus (Eden Campus)
    - We will strengthen our links with researchers in Anthropology, Art History, Archaeology, Classics, Computer Science and History to: (i) establish heritage preservation and protocols via novel digital geo-archaeological investigations using UAV-multispectral and land-marine geophysical survey methods supplemented by geochemical analysis and optically stimulated luminescence (OSL) dating and (ii) apply modern methods of climate science to refine and deepen understanding of the historical scope and scale of climate-human interactions.

Cogency between research strategies of the School of Earth and Environmental Sciences and University of St Andrews. The University of St Andrews has articulated an overarching research strategy aimed at encouraging activities categorised under four main themes: *Global St Andrews, World-leading St Andrews, Diverse St Andrews* and *Entrepreneurial St Andrews* (ILES, 2.5). In-line with the University's request to engage with those research activities, during the REF2021 census period we have:

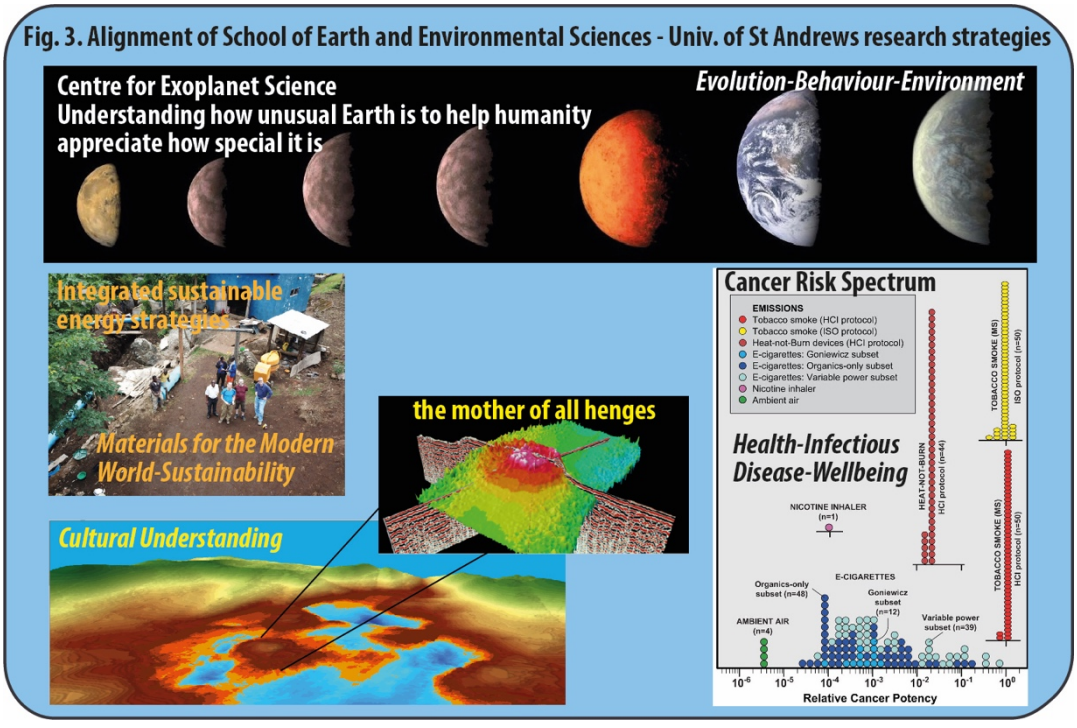
- hosted more than 20 visiting scholars from institutions in ODA-listed countries (Tanzania, Malawi, Armenia), the United States and Brazil with support from the Leverhulme Trust, The Carnegie Trust for the Universities of Scotland and by University of St Andrews Fellowships; their collaborative research activities during their tenure at St Andrews have led to 7 research outputs and 5 funding applications
- helped establish a UK-based renewable energy SME company (*TownRock Ltd*) and an analytical company dedicated to luminescence dating (*CERSA Luminescence*). *CERSA luminescence* has active commercial and research projects in 14 countries across 4 continents and underpins interdisciplinary research in fields as diverse as archaeology, classics, ecology, environmental science, geology, history and sociology.
- embedded consultancy skills training into research-led teaching such that our students availed themselves of secondment and internship opportunities with UK and Scottish governments and industry partners (see Postdoctoral-Postgraduate Community sections).

To motivate implementation of its strategy, the University highlighted four priority areas of research for which individual Schools were challenged to align as best as possible their own research strategies; these are: *Evolution-Behaviour-Environment, Materials for The Modern World-Sustainability, Cultural Understanding* and *Health-Infectious Disease-Wellbeing*. Our alignment to each of those priority areas includes (Fig. 3):

- *Evolution-Behaviour-Environment Priority Area* [*Allison, Burke, Byrne, Claire, Cousins, Finch, Mikhail, Rae, Savage, Steele, Stüeken, Zerkle*]. Our contributions to this area are via two main pathways:
    - building zero-carbon economies is a goal that cuts across national boundaries and we coordinate activities to address this challenge through our nascent Climate Dynamics Group and leadership in the University's interdisciplinary *Network for Climate, Energy, Environment and Sustainability*
    - knowledge of planetary habitability is central to understand life's origin and evolution on Earth and potentially elsewhere in the Universe; we engage in this

quest through the University's Centre for Exoplanet Science and collaborative research coordinated with the European and UK Space Agencies.

- *Materials for The Modern World-Sustainability Priority Area* [*Bates, Finch, Gardiner, Kinnaird, McCarthy, Raub*]. We engage in this priority area through two main avenues:
  - In November 2019 the University established its Environmental Sustainability Board (ESB) to coordinate the breadth of University activities and its estate in that area. *Byrne* co-chairs the ESB's Research Working Group with the aim to identify key initiatives and position the University as a leader in environmental sustainability research (Byrne recently secured £86k to begin making this vision a reality).
  - Our on-going Global Challenges Research Fund supported work is developing initiatives in green energy and resources, environmental change and natural hazards (earthquakes) in ODA-listed countries of Angola, Armenia, Ethiopia, Malawi, Nigeria, Rwanda, Tanzania and Vietnam.
- *Cultural Understanding Priority Area* [*Bates, Kinnaird, Raub*]. Our expertise in shallow marine and land-based geophysical surveying techniques, combined with OSL dating, underpins interdisciplinary collaborations between Earth sciences, archaeology, anthropology, computer science and sociology. This has led to Royal Society award-winning research in the reconstruction of marine (palaeo)landscapes (Doggerland, palaeo-English Channel) and new discoveries and documentation of UNESCO World Heritage sites such as at Stonehenge and Heart of Neolithic Orkney in the UK and Kilwa Kisimani and Leaky Lateoli in Tanzania.
- *Health-Wellbeing Priority Area* [*Stephens*]. Expertise in mineralogy and petrology led to novel application of geochemistry to identify and model vaporisation processes between minerals captured by tobacco leaf and the chemical components of e-cigarettes. This work defined a *cancer potency spectrum* for tobacco, now influential in policies of governments, health agencies and the tobacco industry worldwide.

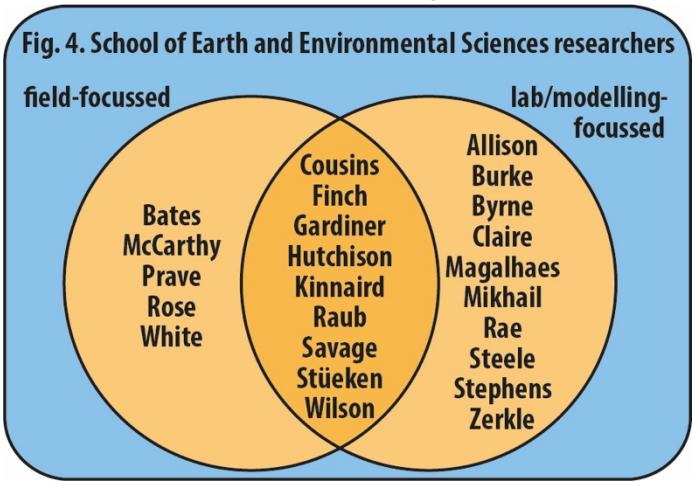


Section 2. People

Staffing Strategy and Development. Our staffing strategy was to build expertise in environmental, geochemical and planetary science to complement our traditional assets of field geology and petrology. By 2017, our strategy established a nuclei of isotope geochemistry and environmental change and strategic hiring providing expertise in geobiology and planetary habitability. We eschew like-for-like replacement and opt for targeting rising world-class researchers who bring added-value to our research. A key principle we insist upon is that a hire

must commit to our ethos to provide a diverse, inclusive environment of open-minded critical thinking aimed at promoting a scientifically literate and informed society (ILES, 3.2). Our approach has both broadened access to job opportunities and enabled recruited colleagues to best engage with and respond to evolving global research agendas across a variety of topics and themes, cogent with adapting needs to opportunities.

Understanding Earth system functioning requires integrating, analysing and interpreting data gleaned from geological archives, geochemical proxies and environmental modelling. To achieve that complementarity, the School has a healthy mix of field- and lab/modelling-focussed staff (Fig. 4): five are mainly field-based researchers, nine blend field- with lab/modelling-based studies and ten conduct primarily lab and desk/cloud-based modelling work integral to research that drives collaborations between multiple School colleagues and others across the Science Faculty. Staff reliant on computer modelling are supported by the University's centralised data storage resources and HPC assets available for funded projects within time-managed workflows. Our most computing-intensive colleague uses NERC HPC facilities for Global Climate Model scenarios. Other staff purchase cloud-computing services for image analysis projects.



Because fieldwork, analytical lab work and computing research carry different cost burdens, and because UKRI demand manage NERC standard grants, the School has self-managed NERC-targeted grant applications aiming to ensure primary users access to and management of our most cost-intensive analytical facilities. We support and encourage grant applications to the widest range of funders; for example, outside our natural NERC-funding framework colleagues have won ERC grants [*Claire, Rae*], AHRC funding [*Bates, Kinnaird*], support from charitable trusts [*numerous staff*], defence and government research contracts [*Bates*] as well as support from overseas research agencies [*Kinnaird, Rae, Savage, Wilson*] and industry [*Bates, Finch, Kinnaird, McCarthy, Prave, Rae, Raub].* We also pursue external funding to pump-prime NERC and ERC research programmes, examples include the International Continental Scientific Drilling Programme [*Prave, Rose*] and UK Space Agency and STFC [*Cousins, Mikhail, Stüeken*].

The School reserves part of its operations budget for targeted support of early career researchers, and we spend half of our direct-grant returns on research cross-subsidy. This ensures that all colleagues have sufficient funding to sustain active publication habits and for seed-corn support of fieldwork or analyses generating preliminary data motivating larger grant proposals. More than half of our successful NERC and ERC awards in the REF2021 census period drew on pre-application cross-subsidised support to collate preliminary data and build research networks.

State-of-the-art analytical facilities require ambitious and capable technical support. The University has supported hiring three Research Officers [*Kinnaird, Magalhaes, Steele*] and one permanent technical support staff [*Fischer*] in the REF2021 census period. Each has access to professional development opportunities that provide career promotion prospects, including shared use of equipment and research collaborations between the Schools of Earth and Environmental Sciences, Chemistry and Biology. One Research Officer [*Steele*] has received a competitive independent research grant (Carnegie Trust) to develop Ni-isotope methodology to examine the source of proto-planetary materials and investigate thermal events in the early Solar System. Another Research Officer [*Kinnaird*] has won £241k of grant income supporting our OSL laboratory. The third Research Officer [*Magalhaes*] won a start-up grant for investigating deep subsurface life in extreme environments and brings igneous petrology and stable isotopic fluid inclusion analysis expertise to our IR-MS labs. All three Research Officers have research independence written into their contracts.

All staff can access CPD courses through the University's professional staff development unit (OSDS: Organisational and Staff Development Services). For example, data obtained for the

School's AthenaSWAN 2019 application showed that between April 2017 through to October 2018 colleagues participated in 84 University-led professional development and training courses (ILES, 3.1). To further enhance research career pathway opportunities, we also encourage our Research Officers to supervise BSc Honours, MGeol, MSc and PhD student dissertations.

Postdoctoral Community. Currently, we have 14 Research Fellows (7 female, 7 male) and, spanning the REF2021 census period, 24 Research Fellows (12 male, 12 female) helped undertake the School's research activities, 8 bringing their own funding. Of these, 5 have been made permanent staff members in the School, 4 obtained permanent academic positions at other institutions, 3 won independent Research Fellowships (1 remaining within the School) and 3 have secured employment to their satisfaction. Fellows organise an early career support programme and an annual research retreat, supported by School operational funds, and contribute to School Council meetings, access University and School mentorship schemes and may co-supervise BSc Honours, MSc and PhD students.

To support activities bespoke to our Postdoctoral community, £5k/year is set aside from our operations budget for careers-related activities delivered by a diverse cross-section of School and external colleagues. Examples include:

- creation of an Early Career Researcher Forum, a congenial setting to provide information, support and insight about careers and research
- an annual two-day Fellow-led team building event held at The Burn, Glenesk, Scotland
- a programme for mental health and well-being run jointly with the University's Advice and Occupational Health Support Centre
- an *Early Career Researcher Grievance Policy* produced by the Research Fellow community and endorsed by School Council to help resolve issues-of-concern that could arise within the School
- day-long Careers Workshops such as: *How are Fellowship proposals reviewed?; So, you want to get a Fellowship?; Getting Published; How to write academic CV's and Cover Letters* (*n.b.*: these Workshops are also open to our PhD students)
- professional development activities in which Fellows organise Workshops open to the entire School community to share solutions to commonly faced issues and offer avenues of new learning ranging from teaching languages to analytical methods platforms

Postgraduate Community. The School is a member of NERC's IAPETUS2 (formerly IAPETUS) Doctoral Training Partnership (DTP; includes Durham, Glasgow, Heriot-Watt, Newcastle and Stirling Universities, and British Geological Survey and Centre for Ecology and Hydrology). Thirty-six PhD students (17 female, 19 male) have contributed to School activities during the REF2021 census period and support is divided approximately evenly between NERC (n=10: 9 IAPETUS DTP, 1 SoS RARE Consortium), University-sponsored awards [n=12, including 4 matched studentships triggered by NERC DTP awards] and School- or external-partner-funded non-UKRI awards (n=14). Within the REF2021 census period, 12 PhD students have graduated and likely *c.* 15 will do so by the close of REF2021. Twenty-three colleagues have (co)supervised at least 1 PhD student (average=3, max=8).

For University- and School-supported PhD studentships, the School commits £11.5k/student to match NERC's Research Training Support Grant (NERC RTSGs have ranged between £7-13k). DTP-supported PhD students can apply for competitive access to NERC Shared Instrument Facilities and 11 of 36 PhD students have won 12 in-kind grants exceeding £400k in net value to support analyses at those Facilities. IAPETUS2 students have access to reciprocal agreements made by five of the other fifteen DTPs to share skills training and networking opportunities. Further, the Scottish Alliance for Geoscience, Environment and Society (SAGES) allows IAPETUS2 DTP students access to its annual retreat, training programmes, international collaboration facilitation funds and industry/public-body placement schemes.

Across all funding avenues, eight of our thirty-six PhD students have pursued research activities aligned with industrial priorities (one formal NPIF studentship, two NERC-CASE studentships). Externally funded PhD studentships include two by the Nigerian State Oil Company, one by First Quantum Minerals, two by the Marine Alliance for Science and Technology for Scotland and five

by the UK Space Agency. All St Andrews planetary-science students and colleagues are members of the Scottish Planetary SciEnce Research NetwOrk (SPERO), which connects researchers with relevant analytical facilities across Scotland and accelerates promoting collaboration. Our interdisciplinary Centre for Exoplanet Science successfully funded one PhD student in 2018, two in 2019, and one in 2020, and each Science School member contributes between £3-5k/year to administer the Centre.

The University provides partial subsidy of Chinese Gov Scholarship Scheme studentships and other bespoke international and interdisciplinary studentships, as well as matched studentships triggered by its commitment to the NERC DTP consortium following initial, cross-consortium competitive awarding of standard DTP studentships. The University also subsidises tuition fees so that PhD student costs are similar, *i.e*. same base-level cost, no matter their country of origin, which helps contribute to the global reach of School research.

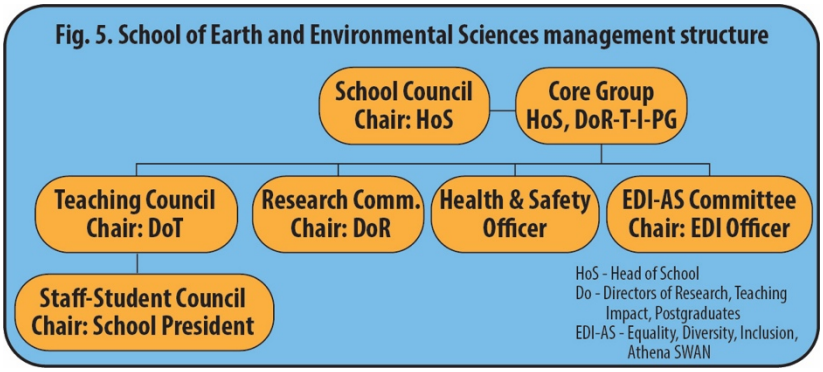
Postgraduate-Postdoctoral Community: professional development. The School uses its operations budget to support PhD students with grants up to £500 for travel and up to £1,000 for opportunistic research, subject to writing a 2-page proposal assessed, with feedback, by the School's Postgraduate Student Research Committee (consists of Directors of Research and Postgraduate Study and three rotating staff members). PhD students supported by the IAPETUS2 DTP have preferential access to bespoke training courses within the DTP and also to government secondments; one has taken up such a secondment, which led directly to employment and two non-DTP-funded students have taken up a St Andrews University funded secondment. Non-DTP PhD students have used School-supported RTSG and external, competitive student-sought support (*e.g*. Russell Trust, Society of Economic Geologists, Mineralogical Society, Mining Institute of Scotland Trust, Institute of Materials, Minerals and Mining) to gain professional development and skills training in areas as diverse as software engineering, UAV theory and practical operations, and to undertake research in industrial settings where the original studentship was not classified as CASE or NPIF.

School Community: Equality-Diversity-Inclusion (EDI). The School holds an Athena Swan-Bronze award. The 2019 application incorporated an array of statistics and survey data and the following summarises key aspects of our equality, diversity, inclusion and fairness policies; survey response was 100% for School staff and 95% for our postgraduate and postdoctoral communities:

- 100% of female and male colleagues believe the School is a welcoming workplace
- 93% of female and 95% of male colleagues believe the School handles EDI issues well
- 92% of female and male colleagues believe the School is well managed
- 88% of female and male colleagues believe decision-making is broad-based and that their views are listened to and influence policy
- 93% of female and 100% of male colleagues agreed that School social activities are welcoming to all
- 100% of staff agree that the School's leave policy is operating well for long-term issues
- since becoming an independent School, research seminars and career presentations have averaged 45% female speakers

The School has a relatively flat management structure (Fig. 5) designed to promote engagement and buy-in across the entire School community. Management decisions are made at monthly meetings of Core Group (Head of School, Directors of Impact, Postgraduate, Research, and Teaching, and Equality-Diversity-Inclusion and Health-and-Safety Officers; six males, two females) and these are open to all colleagues, barring when sensitive matters require confidentiality. School Council is the overarching decision-making body, chaired by the Head of School and comprised of all School staff and representatives from the various student bodies.

Workload is guided by the School's Workload Model (WLM), which is 100% transparent and open access to all academic staff; it is used solely as a management tool and is not used by Head of School for promotion purposes. The WLM is updated every semester and captures hour-by-hour data on teaching (lectures, practicals, fieldwork), admin (hours agreed by School Council) and



supervision. Colleagues are asked to examine the WLM and, if they feel their hours need to be revised, a conversation is held and mutual agreement reached with the Head of School and Director of Teaching. New hires and early career colleagues are given as much as possible reduced teaching loads in their first two years in order to build their research programmes.

For promotions, an informal mentoring scheme was instituted in 2016 for younger colleagues to discuss strategies with senior colleagues. In 2017, an internal promotion review committee was created to offer guidance to applicants via friendly review and constructive feedback prior to submitting applications to the University's promotion board. The committee is gender-balanced and includes a Professorial-level female colleague from the Science Faculty outside the School. Since these actions were instituted, our promotions success rate has improved such that every staff member in a research and education role has been promoted from where they were in 2014 to their current level: 10 of 10 promotions have been successful, of which 4 are female.

All colleagues are offered the opportunity for informal feedback on research grant applications by Head of School and Director of Research; several external senior colleagues act as friendly reviewers. We hold mock interviews for colleagues to hone their presentations in instances where panel interviews are required; in 2018-19 this included mock interviews for three Research Fellowships (1 female, 2 male), ERC Starting Grant (1 male) and two faculty positions (1 female, 1 male). We also financially support colleagues who need specialist training courses through application to the staff-training fund underwritten by our operations budget---obtaining such funds requires a short justification (a few paragraphs) and is assessed by Head of School and Director of Research; to date, all such requests have been approved. Directors of Research and Impact inform colleagues regularly about what funding opportunities are available (this information is provided by St Andrews' Research & Innovation Services and Business Development teams). Colleagues can also apply to the University's Caring Fund (ILES, 3.1) to attend external courses or seminars to help with costs associated with childcare or elderly parents up to £1k *per annum*.

Core Working hours are 10:00-16:00. In instances when childcare cannot be arranged, children are welcome to attend any and all meetings. All School social activities welcome families, inclusive of children, partners and parents alike. Our policy for staff leave follows HR guidelines, and we redistribute workload as fairly as possible guided by our WLM. School policy on flexible hours is to be as accommodating as possible. Colleagues provide a brief justification to Head of School and their Line Manager and all reasonable requests for flexi time are agreed.

Our recruitment process is discussed openly with all staff and all are invited to be involved in the shortlisting process. Meetings are organised during which applicants are ranked and feedback is provided to the interview panel members. In line with University policy, all shortlists are gender-inclusive and interview panels consist of both female and male members.

Section 3. Income, infrastructure and facilities

Income. The School has won £16.5M in research- and impact-related funding during the REF2021 census period. UKRI and Scottish Government Funding Councils account for about half of our competitively won grant income and 34% of those awards (n=35) are Impact specific. For the REF2021 census period, REF-returned staff averaged 1 grant award per year (166 awards over 5 years, 23 staff) with an average award of *c.* £700k per staff (median≈£300k). That income is broken down as follows:

Funding agency	Amount awarded (period 2014-20)	Total number of awards
UKRI		
NERC	£5.02M	55 (10 are Impact specific)
AHRC	£1.2M	
STFC	£338k	
EPSRC	£200k	
European Research Council		
ERC Starter Grant	£3.48M	2
Trusts, Foundations, Charities		
Carnegie Trust for Univ. of Scotland	£500k	11
Leverhulme Trust	£510k	4
various agencies	£450k	16 (3 are Impact specific)
Scottish Government		
Scottish Funding Council and Scottish Technology and Facilities Council	£1.4M	32 (20 are Impact Specific
Commercial contract work		
Various industry partners	£690k	11 (2 are Impact specific)
OSL Lab (*CERSA Luminescence*)	£241k	8
International Continental Scientific Drilling Program		
GRIND: Geological Research through Integrated Neoproterozoic Drilling	$600USD	1
GeoBus funding		
EPSRC, NERC, Royal Society, Verus, Shell	£1.1M	
NERC Instrument Facilities		
In-kind grants	£425k	10
Global Challenges Research Fund		
Staff research grants	£375k	16

Infrastructure and Facilities. Our facilities have evolved and grown in concert with our staffing strategy. Our goal is to have the capability to identify, trace and time processes in systems ranging from ocean and atmosphere circulation, biospheric evolution, terrestrial geodynamics, to planetary differentiation and formation of the solar system. As highlighted in Section 1, several of our labs are unique to the UK, being replicated in only a few institutions worldwide, and all are comparable to the best worldwide. The facilities underpin three main analytical clusters: isotope geochemistry, geobiology-astrobiology and materials characterisation with the following equipment:

- Nu instruments Sapphire CC-MC-ICP-MS; this is the newest generation of collision cell multi-collector inductively coupled plasma mass spectrometers able to perform kinetic and chemical reactions on ion beams allowing for removal of interferences (*e.g.* ^{40}Ar from ^{40}Ca) and thereby opening new avenues of research and transforming precision in isotope ratio mass spectrometry
- ThermoFisher Neptune MC-ICP-MS for measuring the isotope compositions of a wide range of elements at very low blank and sample mass and at ultra-high precision; a coupled gas chromatograph (GC) on the Neptune allows for measurement of isotope ratios in specific organic compounds
- Agilent 8900 QQQ-ICP-MS for measurement of elemental concentrations in solution and via laser ablation; includes collision cell and pre-cell mass filter to allow both simple reactions to eliminate interferences and mass shift analyses to insert elements of interest into a pre-cleaned mass range
- Two Class-100 metal-free clean rooms support much of the above mass spectrometry and enable meticulous preparation of materials; these labs maintain an over-pressured environment that prevents contamination of trace level samples and, notably, are some of the first in the world to be designed to be completely boron-free

- A RESOlution Excimer laser with cryocell can be coupled to the Neptune, Sapphire and 8900 QQQ-ICP-MS in any combination for analyses of a range of solid materials for geochronological and chemical tracing applications including analysis of frozen fluid inclusions in ice and tissues
- Two Thermo-Finnigan MAT-253 isotope-ratio mass spectrometers (IR-MS), one with custom-built fluorination manifold capable of measuring all four isotopes of sulphur and the other dedicated to measuring major carbon, nitrogen and sulphur isotopes, including nitrogen in ppm-levels with a custom-built tube cracker line
- A Trace 1310-ISQ GC-MS for characterisation of organic compounds in natural and synthetic samples and used in combination with custom-built lightning-discharge experiment equipment
- Dedicated laser ablation lab with a New Wave Deep-UV (193 nm) Excimer laser, coupled to an Agilent 7500a ICP-MS and a Nu-Plasma MC-ICP-MS for simultaneous *in situ* analysis of trace elements and radiogenic isotopes (U-Pb Lu-Hf) in a range of solid materials for geochronological and chemical tracing applications
- Cavity ringdown mass spectrometer capable of measuring all three isotopes of oxygen in natural water samples and nitrate minerals
- Delta+XP IR-MS with Gasbench II and TC/EA optimised for stable isotope measurements of carbon and oxygen in carbonates and for oxygen in various oxide minerals
- Thermo iCAP 6300 ICP-OES used for obtaining major and minor element compositions from a range of sample types, and one XRF spectrometer and one X-ray diffractometer for routine materials analyses
- Shimadzu 8040 Ultra Liquid Chromatography with triple quadrupole mass spectrometry for quantifying environmental organic compounds and determining reaction pathways
- Jeol JXA-iSP100 electron probe microanalyser (EPMA), Jeol JSM-F100 FEG electron microscope with a SXES detector (one of only 2 in the UK), JSM-IT200 electron microscope and Renishaw Confocal Raman Microscope for state-of-the-art non-destructive analyses of natural and synthetic substances
- out-of-phase magnetic susceptibility kappabridge capable of field-dependent, anisotropy tensor and thermal evolution analyses
- active shielding-housed thermal-, pulse-, and alternating field-demagnetisers supporting a spinner magnetometer as well as magnetic susceptibility apparatus optimised for whole or split drill cores, polished rock slabs and natural outcrops
- the UK's only time-resolved wavelength multiplexed spectrometer lab capable of *in situ* analysis of the energy state (luminescence) of minerals and high field strength and REE composition of igneous rocks
- luminescence dating lab with dedicated sample preparation facilities, containing DA-15 and DA-20 Risø OSL and TL readers for dating of sediment and heated materials, a miDose µdose unit for low-level environmental radioactivity measurements and portable OSL reader, two Ortec micronomads and 1 GF Instruments Gamma Surveyor Vario for measuring luminescence in the field
- experimental petrology lab for studying elemental partitioning and isotopic fractionation at pressure-temperature conditions simulating those in the upper mantle and lower crust
- a coral-culturing facility for controlled simulation of ocean-atmosphere chemistry to assess biogeochemical response to rising CO_2 and its impact on shallow-marine biodiversity
- a set of ion chromatography and electrochemistry columns and modules, and UV-VIS spectrophotometers, optimised for measuring concentrations of many cations and most anions abundant at trace levels in natural aqueous solutions and for measuring parameters of natural fluids relevant to carbonate saturation state
- imaging suite with Keyence VHX-30003-D digital super-resolution microscope, custom-built cathode-luminescence microscope and Olympus and Leica research microscopes
- three UAV drones, one capable of payloads up to 2 kg, outfitted with VIS-NIR hyperspectral cameras, a devoted high-performance geospatial analysis and 3-D reconstruction workstation and a portable UV-VIS-NIR spectrometer (TerraSpec)

- rock and mineral preparation suite with saws, thin-sectioning and magnetic separation equipment and a Wilfley table. Drill coring equipment includes a core-splitting saw with 4-m pass-through length and two Vibracorers capable of BQ collection to 10 m depths.

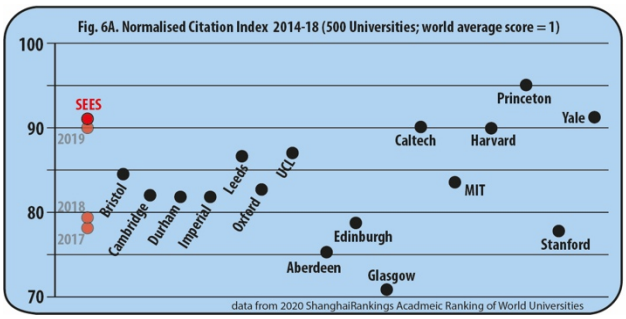
Our geobiology and astrobiology facilities are supplemented with field portable multimeters and aqueous sensors to determine compositions of natural waters, a wet chemical distillation line to support Fe speciation measurements in mudrocks and carbonates, and an environmental DNA and RNA laboratory for preparing and assessing genetic material and products *in vivo* and *in vitro* for metagenomic analysis.

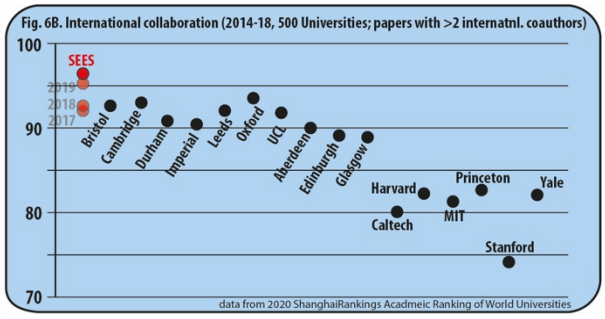
Environmental and geo-archaeological geophysical investigations make use of field electromagnetic conductivity, resistivity, induced polarisation and geomagnetic surveys together with drone-based and handheld hyper- and multi-spectral and magnetic susceptibility instrumentation. For nearshore marine survey the School has a 7m vessel, Swordsman, coded to 12 NM. We also benefit from NERC's geophysical shared instrument facility in Edinburgh. Students and staff can travel with any of our portable equipment to characterise rocks, cores and soils *in situ* or in curated archives.

We access collaboratively and, in some cases, co-manage additional equipment focused on solid material characterisation (XRD, laser diffraction granulometer) and physical chemistry (zeta potentiometer, differential calorimeter, thermal gravimeter). The School also pursues co-capitalisation of new analytical facilities through interdisciplinary avenues (ILES 4.2). Colleagues can access the University's electron microscope facility, which houses two TEMs, a SEM with FIB and EBSC capability, in addition to the EPMA and SXES-SEM listed above. Collaborations with the Schools of Chemistry and Physics & Astronomy focus on Magnetic Properties Measurement and Physical Properties Measurement systems (MPMS/PPMS), as well Nuclear Magnetic Remanence (NMR), to use atomic force and scanning tunnelling microscopy techniques to image crystal and mineral-cleavage faces.

Section 4. Collaboration and contribution to the research base, economy and society

REF-eligible staff collaborate actively with researchers in 31 UK universities, forty institutions in twenty-seven countries on five continents, ten Geological Surveys, twelve companies and thirteen governmental and parastatal organisations. The breadth of our international collaboration networks and partnerships can be ascertained objectively using two metric measures from the 2020 ShanghaiRanking's Academic Rankings of World Universities of 500 Earth Science departments and their publications between 2014-18. The two metrics (Fig. 6A-B), International Collaborations (papers with 2 or more international-based co-authors) and Category Normalised Citation Index, reveal that the School of Earth and Environmental Sciences (SEES) ranks with the top universities worldwide and has, year-on-year, continued to improve that ranking.





Within St Andrews, we help lead, (co)Chair and/or contribute to the:

- Centre for Exoplanet Science [*Claire, Cousins, Mikhail, Savage, Steele, Stüeken, Zerkle*]
- Centre for Archaeology, Technology and Cultural Heritage [*Bates, Kinnaird, Raub, Wilson*]
- Centre for Ancient Environmental Studies [*Bates, Kinnaird, Raub*]
- Centre for Innovation in Energy Storage [*Bates, Prave, Raub*]
- The Scottish Oceans Institute's Gatty Marine Laboratory [*Allison, Burke, Rae*]
- Steering Group for the University's nascent Institute of Engineering [*Raub*]

- St Andrews Environmental Sustainability Board and Research Group [*Bates, Byrne, Finch, Rae, Raub, Wilson*]
- St Andrews Network for Climate, Energy, Environment and Sustainability [*Byrne, Rae, Wilson, numerous staff from the Science and Arts & Humanities faculties*, ILES, 2.5]

Outside the University, our contributions to broad-based initiatives are diverse. Specific professional organisations, societies and government engagement includes:

- Scottish interdisciplinary pooling initiatives: Marine Alliance for Science and Technology for Scotland (MASTS) and Scottish Alliance for Geoscience, Environment and Society (SAGES) and Palaeoenvironmental and Archaeological Sciences Scotland [*Allison, Bates, Burke, Byrne, Hutchison, Rae, Wilson, Zerkle*]
- Royal Society of Edinburgh's Young Academy of Scotland [*Cousins, Rae*]
- a variety of expert consulting on environmental and health issues for the Scottish and UK governments [*Bates, Raub, Stephens*]
- leading Geological Society London's Energy and Materials Transition initiative [*Gardiner*]
- Shell's Brent Decommissioning Advisory Group [*Bates, Prave, Raub]*
- Scottish Carbon Capture and Storage organisation [*Bates, Prave, Raub*]
- European and UK Space Agencies [*Cousins*]
- NASA Virtual Planetary Lab [*Claire, Stüeken*]

We also contribute to national and international initiatives via the following:

- Our NERC- and GCRF-funded projects in Ethiopia and Malawi have involved studies in de-risking geothermal energy [*Bates, Hutchison, Raub, Robinson, Stephens*]. In 2016 the School won a competitive Stage 1 Feasibility grant through the Scottish Government's Low Carbon Infrastructure Transition Programme to explore the potential for turning the University's nearby Eden Campus into a geothermal heat demonstrator project (Robinson *et al*. 2016. *Geothermal Hot Sedimentary Aquifer Heat in Scotland, The Guardbridge Project*). Eden Campus is an industrial brownfield site that shares ecological and industrial challenge characteristics with other brownfield sites nationwide. Another example involves the UK-GEOS (Geothermal Observatories) programme to prove a low-enthalpy geothermal mine-water resource. For its preliminary studies, the BGS used 3-D models of coal mine works digitised by our BSc Geology Honours students who used legacy Coal Authority paper plans as part of this collaborative research activity.
- In support of the UK-Scottish Governments' Tay Cities deal, we contribute to a developing plan spearheaded by the School of Chemistry's Centre for Innovation in Energy Storage. We provide geological, geochemical and climate modelling expertise across climate change and resource systems topical to foci aimed at addressing the emerging challenges to the Circular/Zero-Carbon Economy. These challenges are faced by Universities globally and by UK and European industrial partners across a range of sectors. Our efforts intersect with an explicit £29.5M commitment by the UK Government to develop an energy and innovation R&D hub on the University's Eden Campus (ILES, 4.3).
- Our expertise in climate science will guide policy recommendations in the next Assessment Report (6th) of the Intergovernmental Panel on Climate Change for which two colleagues are contributing in chapters on past climates [*Rae*] and on cyclonic storm and global precipitation patterns [*Byrne*]. Although AR6 will be published in 2022, postdating the REF 2021 output period, research and impact activities contributing to and arising from its composition are ongoing. These activities support the UK and Scottish Governments' stake in and commitments under the Paris Climate Agreement, and they support both Governments' targets for renewable energy provision and a zero-carbon future.
- We contribute to St Andrews' portfolio of Scottish Government and variously UKRI-championed Global Challenge Research Fund activities via participation by 13 staff across 16 funded projects over the past four years. The University has established an internal GCRF Steering Group to identify best practices and build St Andrews' GCRF portfolio in ODA-compliant research, and a School colleague sits on that board [*Bates*]. We help guide the University's Environmental Sustainability Board (ESB) to develop an environmental sustainability strategy for the University over the entire scope of University activities; the

ESB's Research Working Group is co-chaired by another colleague [*Byrne*] and is tasked with identifying environmental/sustainability research cogent with University strategy.

- Our *GeoBus* mobile educational outreach programme delivers bespoke education and in-person sessions by multiple School staff and students to primary and secondary school pupils across Scotland (>70,000 individual pupils in 278 schools). It informs about future education and career track decisions and broadens access by delivering frontline research results and fun, hands-on exemplary activities to students crossing all scales of depravation and remoteness: 81% of visited schools are identified by the Scottish Government as being in Remote Small Towns or Rural Areas, 49% are in the top 25% of deprived catchments with 41% of those in the top 15%. *GeoBus'* resources have been downloaded in 79 countries and, as far as we know, it is one of the most-accessed University-driven in-person science educational outreach programmes anywhere.
- As detailed in our Impact Case Studies, active research programmes engage with initiatives that range from global medical science and technology policy and practice, to awareness and response to climate change and other natural hazards, to stewardship of Earth's natural resources. Cross-disciplinary partnerships between School staff, computer scientists, classicists and historians are making global impact in ODA countries in heritage resources, their preservation and management that address UN Sustainable Development goals. Further, our *Music Planet* initiative (established in 2017) brings together scientists, artists and musicians both within St Andrews and across the UK to create and design events that investigate the relationship between humans and their environment through the performing arts. Since its formation, over 100 artists have participated with academics to engage +3000 participants with inspirational stories about Earth history and our shared responsibility as stewards for Earth's future environment and biosphere.

In summary, the School's contributions to research and impact span from the fundamental to the applied. We have undertaken a trajectory that started post-RAE2008 in which geoscience research was incorporated within a School of Geography and Geoscience (SGG) that was ranked 17th in the UK. In 2010, six geoscience staff within that School were given quasi-autonomy to develop a strategy to create world-class geoscientific research and the implementation of that strategy contributed to propelling SGG to a ranking of 5th overall in REF2014. Since then, we have formed an independent School of Earth and Environmental Sciences comprised of 23 REF-returnable researchers whose shared vision is to ensure that we remain firmly within the cohort of the finest Earth and environmental science programmes worldwide.