Institution: University of Bristol
Unit of Assessment: 7: Earth Systems and Environmental Sciences
1. Unit context and structure, research and impact strategy

1.1.1 Unit context

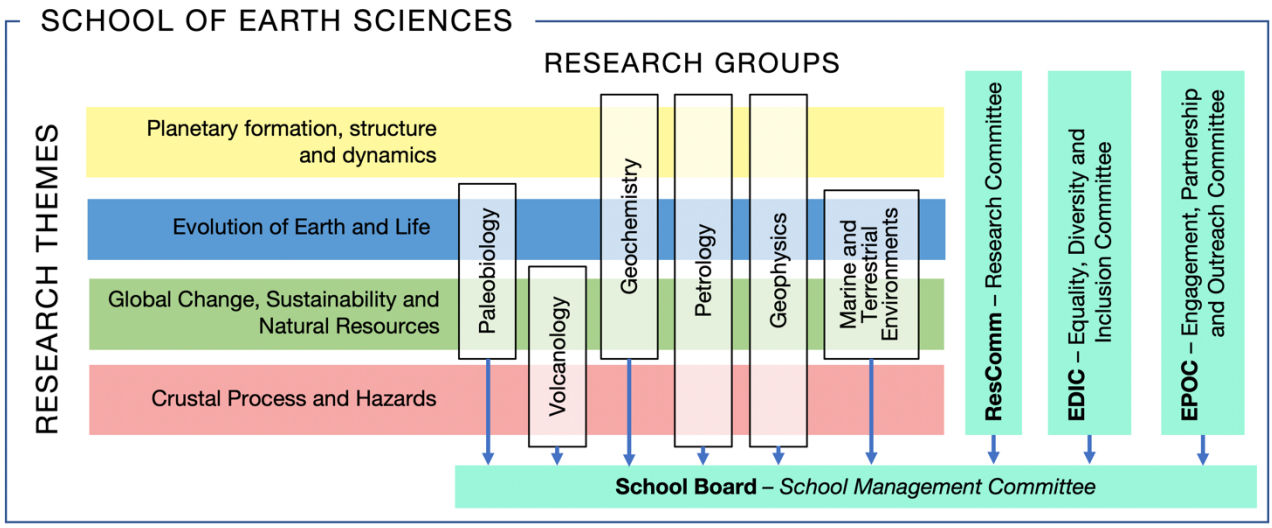
The School of Earth Sciences (ES) conducts world leading research in numerous aspects of our diverse discipline. We are committed to the essential role of the Earth Sciences in understanding our planet, its history, and our place on it, and our School is ideally placed to address the major resource, hazard and environmental challenges of the next century. To that end, we played a leading role in the creation of an Earth and environment centred University Vision and Strategy, with our School strategy enabling this by *supporting staff*; *investing in infrastructure*; and developing *interdisciplinary collaborations and strategic partnerships*. Consequently, the School continues to evolve and thrive, adding strategic capacity since REF2014 in economic geology, geophysics and environmental geosciences.
We aspire to be recognised for our consistent innovative, high-quality, high-impact research in an exceptionally collegial environment. Evidence of this in the REF period include:

- We are 15th in the 2020 QS World University list (from 29th in 2014). The citation impact of our papers is the best of any UK Earth Sciences department and 5th best in the world[1].
- Our equity-centred people strategy was central to the School achieving **Athena Swan Silver** (one of only three ES departments in the UK). We now have **near gender-parity at all staffing levels including Professor** and have led efforts to address racial and ethnic diversity in the discipline.
- Staff at all levels have received outstanding individual recognition:
    - At senior level, this includes **eight Fellows of the Royal Society** – five currently in post (Benton, Cashman, Donoghue, Elliott, Sparks), one Emeritus (Hawkesworth) and two departed to competitor institutions (Kendall, 2019, and Blundy, 2020). **Five** of these were awarded during this REF period.
    - Our submission also includes **five** staff who have held prestigious mid-career Fellowships, such as Leverhulme and Wolfson Research Merit Fellowships, during the REF period (Biggs, Cashman, Donoghue, Pancost, Schmidt).
    - We have hosted more than **30 Independent Early Career Fellows**, with **10** current Fellows as part of our submission. **>40%** of our permanent academic staff have been supported by such Fellowships with six holding them during the REF period.
- We have directly benefited from more than **£100M** of strategic investment into estates (including £63.8M for the Life Sciences building), capital and infrastructure, and brought in **£45M** of external research income (£1M/FTE), including £7M across the eight ERC grants active or awarded in the REF period.
- We have driven national and international policy on volcanic risk, aviation and hydraulic fracturing, and generated projected benefits of more than £100M for our partners. Bristol Earth Scientists play significant roles in UK science leadership, including leading and serving on committees for more than **60** research councils or professional bodies, and advising both UK and overseas governments.

[1] (CNCI parameter – Shanghai ARWU world subject ranking 2019)

This broad impact in policy, industry and public engagement, has been recognised with civic prizes including a **Queen's Anniversary Prize** for outstanding research into volcanic risk, and a **knighthood** to former volcanology group leader and SAGE member, Sir Steve Sparks. Celebrated public engagement schemes such as the Bristol Dinosaur Project have worked with civic partners to engage with over half a million members of the public and now centre engagement with marginalised groups.

1.1.2 Unit Structure



School Structure

Since REF 2014 we have refreshed our organisational structures, invested in our Groups and revised our Research Themes to strengthen core research areas while engaging with the dynamic evolution of our discipline. Our research structure and strategy remain guided by Research Committee (ResComm), and we established two new research-facing committees: the Equality, Diversity and Inclusion Committee (EDIC) which supports staff to thrive; and the Engagement, Partnership and Outreach Committee (EPOC) which coordinates our diverse collaborative activity. The Directors of all three serve on School Board (the School leadership committee).

The School's Research is organised into six **research groups** with international reputation: *Geochemistry*, *Geophysics*, *Palaeobiology*, *Petrology*, *Marine and Terrestrial Environments*, and *Volcanology*. These groups provide the infrastructure that enables our research to flourish (e.g., laboratories and equipment, §3.2), and operate as administrative units and frameworks for mentoring staff and students (§2.1), with the group leaders serving on School Board. Furthermore, environmental sustainability is a pillar of the University's Vision and the School is at the heart of the associated Earth/Environment-centred interdisciplinary research ecosystem, including the Cabot Institute for the Environment and the majority of Schools in the University (detailed in §4).

Complementing these internal operational structures, our intellectual strengths and ambitions are encapsulated in four cross-cutting, interdisciplinary **research themes**: *Global change, Natural Resources and Sustainability*; *Evolution of Earth and Life*; *Crustal Processes and Hazards*; and *Planetary Formation, Structure and Dynamics*. These encompass our collaborations within and beyond the School, and adapt and evolve over time.

1.2 Research Themes

Global change, natural resources and sustainability

Overview: Addressing the intersecting challenges of climate change, environmental degradation and sustainable resource provision is a priority for the School. We have long provided leadership in these areas, both within the discipline and beyond, including via the Cabot Insititute, but to expand and support that we have invested in three strategic appointments in biogeochemistry and geomicrobiology (Bryce, Byrne, Pancost) and >£4M in our world leading geochemistry, geomicrobiology and environmental mineralogy facilities (§3.2).

Highlights over the REF period:

- *Understanding the oceans.* Investment in our geochemistry infrastructure and a plethora of new samples and observations from Bristol-led research cruises yielded critical insights into changes in oceanic nutrient and carbon cycling, including interactions with the cryosphere and seafloor boundaries [Hawkins et al, 2018; Costa et al, 2020; Shlitzer et al, 2017], and the first observations of microplastics in deep sea organisms [Taylor et al, 2016].
- *New Technology for Sustainable Energy Infrastructure.* Through new appointments (Verdon), new partnerships, and technological innovation in applied geophysics, we made policy- and industry-facing impact via microseismic monitoring of energy (nuclear and gas) infrastructure [e.g., Kettlety et al, 2020]. This included critical contributions to the policy debate on hydraulic fracturing, and monitoring and regulation protocols for the UK fracking industry (Microseismic Impact Case Study).
- *Building industry partnerships to deliver crucial metal resources*. Large amounts of metals, and especially copper, are required to deliver a low-carbon future. We applied our fundamental expertise in crustal magmatism to the development of porphyry copper deposits from which 75% of the world's copper is derived [Matjuschkin et al, 2016]. This was the foundation for an expanding strategic relationship with BHP Billiton (Copper Impact Case Study).

Future Ambitions: We will accelerate the transformation of our industry engagement, shifting away from exploratory oil/gas research towards the sustainable extraction of critical metals, carbon capture and sequestration, resilient energy infrastructure and water and soil resources. This work will be conducted within an interdisciplinary context that recognises social justice, land rights and equity in collaboration with Social Sciences and Environmental Humanities colleagues.

Crustal Processes and Hazards

Overview: We conduct fundamental research into the physical and chemical processes controlling stress field and fluid flow within the crust, to mitigate the impacts of induced and natural hazards in the UK and developing countries. We have expanded this theme to include earthquakes and faulting, and the implications for natural and induced seismicity.

Highlights over the REF period:

- *Understanding magma in the crust.* Bristol scientists have made a paradigm shift from the classic geological concept of a magma-filled chamber to that of an inter-connected network

of partially crystalline, magmatic mush [e.g., Cashman et al, 2017]. This new understanding has widespread implications for applications spanning from eruption precursors to economic deposits (see Copper impact Case).

- *Volcanic and earthquake hazard in the developing world*. Responding to some of the most significant volcanic crises in recent years (Guatamala, Indonesia), we provided new insights into the drivers of volcanic unrest and models for volcanic hazards [Manzella et al, 2015] and reassessed global magnitude-frequency eruption relationships [Rougier et al, 2018]. Our success is enabled by the strong bilateral relationships with volcano observatories globally, and our leadership in the 2015 United Nations Global Assessment of Risk (GAR15), (see Volcanic Risk case study). Our expertise in earthquakes has been used to design new building regulations for developing countries through multidisciplinary Global Challenges Research Fund (GCRF) projects, including strong links with the British Geological Survey.
- *Volcano and Earthquake Monitoring from space.* To overcome the lack of monitoring of most active volcanoes, we developed novel approaches to satellite observations applying deep learning techniques to satellite radar images (InSAR), now being used to automate baseline volcano monitoring on a global scale [e.g., Biggs, 2014; Anantrasirichai, 2018]. We designed the first publicly funded, university-led CubeSat which will provide 3-D imaging of volcanic gas emissions. This success is enabled by strong links with Bristol's Engineering Departments, the UK and European Space Agencies and leadership roles in the Natural Environment Research Council (NERC) Centre for the Observation and Modelling of Earthquakes, Volcanoes and Tectonics (COMET).

Future ambitions: In the next few years we will bring modelling of multiphase systems and the new wealth of environmental data combined with recent advances in machine learning to bear on our understanding of dynamic crustal processes, including extending the scientific basis for both hazard management and resource exploration. We plan a cluster hire in the area of global hazard and risk centring volcanic, magmatic, tectonic and anthropogenic processes, and we will continue to leverage our strong collaborations in developing countries.

Evolution of Earth and Life

Overview: The School has traditional strengths in palaeobiology (recently ranked the best in the world[2]), palaeoclimate and the deep Earth. This is enriched by complementary strengths in Geographical Sciences and Biological Sciences, and recent cross-Faculty appointments. Our common interest in the long-term evolution of the Earth's linked interior, surface, atmosphere and biosphere drives collaborations and paradigm-shifting research in Earth history.

Highlights over the REF period:

- *Beyond Palaeontology.* We have developed paleobiology from a world-leading but isolated research group in Earth Sciences to a cross-faculty endeavour centred around innovative genomic, molecular and biomechanical approaches to understanding organismal evolution. This development thrived due to major investment from the University, including the new Life Sciences building and new posts with an evolutionary focus in the School of Biological Sciences (Harrison, Paps, Williams), reinforcing the two joint positions (Vinther, Pisani)

[2] The Center for World University Rankings (CWUR) 2017.

between our two Schools. Main advances include understanding display and camouflage behaviours in extinct birds and feathered dinosaurs (one of the 'top ten scientific discoveries of the decade'[3]) [e.g., Brown, 2017]; challenging timescales of organismal evolution using novel genomic and molecular methods to infer deep interrelationships of animals and plants [Dos Reis et al, 2015; Puttick et al, 2018]; and overturning ideas of the origin and form of mammals using tomographic reconstruction and biomechanical modelling [Gill et al, 2014].

- *Palaeoclimate.* We have built an innovative palaeoclimate community in partnership with Geographical Sciences (e.g. Valdes, Lunt), supported by investment in world-leading geochemistry facilities and HPC. We provided primary evidence that pCO_2 has likely not exceeded 450 ppm for the last 3 million years [Martinez-Boti, 2015] nor 1500 ppm for the past 50 million years [Anagnostou, 2016]. This contributed to the inclusion of palaeoclimate, including palaeoclimate-derived estimates of climate sensitivity, in IPCC assessments (with Schmidt as an IPCC Coordinating Lead Author, §4.2).
- *Understanding the deep volatile cycle.* We have driven research to understand the role of the deep Earth in the cycle of volatile elements over geological time, supported by continued investment in isotope mass spectrometry, high-pressure experimental facilities and HPC to support deep Earth seismology, as well as investment in staff (Lord, Irving). Under this programme we have, for example, revealed unexpected potential for deep reservoirs of carbon and hydrogen in the mid-mantle [Thomson et al, 2015; Walter et al, 2015].

Future Ambitions: Cross-faculty appointments create exciting new avenues for collaboration. These are further enabled by novel molecular insights into evolution and our analytical innovations that have expanded the "isotopic window" into the ancient Earth. Critical questions include determining the planetary drivers of Earth's carbon inventory and the ecological, biological and biogeochemical consequences of pCO_2 change.

Planetary formation, structure and dynamics

Overview: Planetary research in the School was a nascent area in REF2014 but has been strengthened by new appointments and our first Earth-Sciences-led STFC Consolidated grants with Physics colleagues (2014, 2017, 2020). The heart of this theme is our expertise in isotope geochemistry, atmospheric processes, mineral physics and seismology, allowing the investigation of the formation, interior structure and atmospheres of solar system bodies.

Selected REF period highlights

- *Measuring Marsquakes.* Since 2010 we have been part of the UK team developing the main SEIS instrument for the NASA InSight geophysics mission to Mars. We have capitalised on our key roles across the Science team, from pre-launch development and verification, through post-landing deployment and into the main scientific phase of the mission, including the observation of the first 'marsquakes' [Lognonne et al, 2020].
- *Probing the early solar system with next generation mass-spectrometry.* With our industrial partners, Thermo Fisher Scientific, we developed a one-of-a-kind prototype mass-spectrometer, Proteus (§3.2.2). This allowed us to develop novel isotopic techniques which

[3] https://www.smithsonianmag.com/science-nature/top-ten-scientific-discoveries-decade-180973873/

have shed new light on long-standing questions about the solar system's primordial radioactive inventory [Luu et al 2019; Gregory et al, 2020] and the fundamental role of silicate vapour loss during collisional accretion on the Earth's bulk composition [Hin et al, 2017].

- *Planetary atmospheres.* Members of the school are on the science teams of major missions to study planetary atmospheres, including Cassini-Huygens, Mars Reconnaissance Orbiter, and Trace Gas Orbiter, and co-led a recent ESA mission proposal to Titan. We have expanded our observational capability to include telescope observations, including the Herschel Space Telescope and the Atacama Large Millimeter Array which allowed us to show Titan's atmosphere is much colder than expected due to enhanced radiative cooling from trace gases [Teanby et al, 2017].

Future ambitions: By leveraging new STFC funding, new staff (Irving) and collaborations with Chemistry, Geography, Physics and Engineering we will tackle critical questions in planetary science, including: the nature and origin of pre-solar grains; seasonal drivers of planetary atmosphere dynamics; and the interior structure of Mars and Moon. Continued commercial collaboration on instrumental development will keep us in the vanguard of analytical capability.

1.3 Research Strategy

We remain deeply committed to our long-standing international strengths in volcanology, petrology, palaeobiology, geophysics, environmental sciences and geochemistry and have identified several areas of strategic interdisciplinary collaboration or investment to support, complement or expand on those. We have considerable achievements against the strategic goals identified in the 2014 Environment Statement and Impact Template (denoted by **REF2014** below) but they remain vital and relevant, complemented by new goals that anticipate the continued interdisciplinary evolution of the Earth Sciences.

(a) Academic Staff
Goals: Grow academic staff numbers in areas of strategic need **REF2014**.
Achievements (2014-2020):

- Our strategic appointment in Applied Geophysics (Verdon) has delivered >£100M of projected impact for our partners (Microseismic Case Study).
- We built a broad planetary theme including new Fellowships (Myhill, Susorney) and an academic (Irving).
- Appointment of core staff (Cooper, Bryce, Byrne, Pancost) has been the foundation for the new Global Change, Natural Resources and Sustainability Theme.

Ambitions (2021-2026):

- Appoint in new areas of strategic need, including interdisciplinary growth through joint appointments in areas such as Digital Environment, and a cluster hire in Volcanology/Petrology/Tectonics.
- Develop mechanisms to further integrate our pool of >80 esteemed visitors and partners into our academic body.

(b) Developing the Talent Pipeline

Goals: Continued growth of our postgraduate cohort with emphasis on overseas students [REF2014], improved support for postdoctoral research assistants (PDRA) and early career researchers (ECR).

Achievements (2014-2020):

- We have increased our postgraduate research (PGR) numbers over the REF period (average of 19 doctoral awards per year, compared to 15 for 2008-13, with an average PGR cohort size of 92, compared to 84), with an increased proportion of overseas students.
- Bristol was one of the first signatories of the Researcher Development Concordat, and we have brought in a new, bespoke mentoring system to support our PDRAs and Fellows (central to our Athena Swan Silver award).

Ambitions (2021-2026):

- Increase the (especially BAME) diversity of our early career researchers, for example by focussing on pathways to PGR programmes and support for Fellowships.
- Mitigate the impacts of Covid on ECRs and staff.

(c) Research Funding

Goal: Growth and diversification of our research funding base [REF2014].

Achievements (2014-2020):

- £44.8M of research funding income (50% increase over REF2014), doubling the amount of non-UKRI/EC funding.
- Highlights include a strategic partnership with BHP Billiton (£3.6M), leadership or partnership in interdisciplinary GCRF grants worth £6M, 20 strategic or large grants, and eight European Research Council (ERC) Awards.

Ambitions (2021-2026):

- Build further resilience to political and economic shocks through an adaptable research strategy. This includes engagement with the post-Covid green recovery and local/regional partnerships to capitalise on the 'Levelling-Up' agenda.
- Blue skies research remains critical to our ambition, and we aim to translate our success with ERC to schemes such as Future Leaders and Pushing the Frontiers.

(d) Research Infrastructure

Goal: Development of our research infrastructure [REF2014].

Achievements (2014-2020):

- We have directly benefited from >£100M of strategic School, University and external investment and commitments, including the £64M Life Sciences Building, £10M of High-Performance Computing capital, new CT and Radiocarbon AMS Facilities and over £5M of new mass spectrometry capacity.

Ambitions (2021-2026):

- Support areas of strategic need with cutting-edge facilities and nurture technological innovation. Specific targets include launching UoB-SAT in 2021 and new biogeochemical

imaging facilities. A new building for the geosciences is currently in the top tier of Bristol's strategic infrastructure priorities.

(e) Interdisciplinary and Multidisciplinary Research
Goal: Advocate, create and lead interdisciplinary structures within the University.
Achievements (2014-2020):

- We led in the creation of the Cabot Institute of the Environment (the first University of Bristol University Research Institute, URI, in 2010) and directed it from 2013-2018.
- Integration of our Palaeobiology group into the University's Life Sciences vision led to coordinated appointments with Biological Sciences.
- More than half of our core staff have funded collaborations with colleagues from other disciplines (>80 total).

Ambitions (2021-2026):

- Expand and deepen our engagement with the technology-focussed URIs (Jean Golding Institute and the nascent Digital Futures Institute).

(f) Building Research Staff Capacity
Goal: High workloads emerged as a key concern during this REF period. We expanded our strategy to address this, protecting the capacity of our research-facing staff with investment in our technical, administrative and teaching-focused teams.
Achievements (2014-2020):

- We have expanded core technical and administrative staff by 32% (now 22.2 FTE) to support research and impact.
- Two academic teaching staff (increasing from 1 to 3) have been appointed, relieving pressure on research.

Ambitions (2021-2026):

- Procure further support for public engagement, expanding on the success of the Bristol Dinosaur Project.
- Expand core technical support in the isotope geochemistry labs and in our newly refurbished geomicrobiology and biogeochemistry labs

1.4 Impact Strategy

Our School embraces the relevance of our research for broader societal impact, from inspiring a fascination for science through public engagement, to providing the scientific framework for local, national and international policy and nurturing industrial collaborations and academic consultancy.

(a) Partnerships
Goals: Strengthen and expand our critical partnerships[REF2014].
Achievements:

- Our Impact Case Studies highlight our work with the copper and aviation industries and global policy on volcanic risk and the UK policy on fracking. We host two large platforms for

long-term industrial engagement – the Bristol University Microseismicity Project and the BHP-funded Bristol PCD project.
- We work with the Knowledge Exchange Team to support emerging areas of impact through seedcorn funding (e.g., PolicyBristol, Cabot Institute), impact accelerators and innovation grants (19 over the REF period).
- The School is embedded in the University's Civic Agenda, with a long record of working with Bristol's cultural, environmental and racial equality sectors (e.g., partnering in the construction of Bristol's One City Plan).

Ambitions:

- Leverage strategic partnerships at university level and foster global partnerships.
- Enable analytical and experimental innovation, building on current relationships with Thermo-Fisher and Elementar (§3.2).

(b) Outward facing activities

Goals: Develop an external advisory network and integrate outward facing activities.

Achievements:

- Our Engagement, Partnerships and Outreach Committee provides an integrated, inclusive and strategic policy for impact, public engagement, outreach, careers and recruitment. New frameworks will leverage our industrial partnerships and alumni networks to provide internships and careers advice for PG students and inspire the next generation into the geosciences.
- Working with the Faculty of Science Partnership Office, we have developed a faculty-level scheme for the formal appointment of 'Industry' Professors and Fellows, which will form our external advisory board. The first appointment is John Thompson (UBC, Cornell) an expert in economic geology and resource sustainability.

Ambitions:

- Recruit 3-4 additional fellows and strategically add to our community of honorary staff with appointments from Bristol civic, government and industry partners. We will draw from and engage with this community to form a network of external advisors.

(c) Public engagement

Goals: Ensure public engagement is strategic, inclusive and sustainable.

Achievements:

- We have generated exemplar public engagement on a local scale, by engaging with civic authorities to host major events such as the DINOMANIA event at Bristol Zoo (350,000 visitors) and the William Smith Bicentenary Lectures (6000 visitors).
- Our staff feature in several BBC productions attracting a global audience (e.g., Attenborough and the Dragons, Sky at Night).
- Our outreach strategy has been pivoted towards widening participation through widely celebrated schemes such as the Bristol Dinosaur Project and Black and Green Ambassadors.

Ambitions:

- Increase the sustainability of our public engagement activities by providing centralized funding.
- Ensure our engagement reaches marginalised groups and contributes to the diversification of the Earth Sciences discipline
- Broaden our content to include current global issues including resource management and climate change.

1.5 Commitment to open research

Open access to publications and the data which underlie them is a core value held by the School. The Institutional Environment Statement (REF5a) outlines Bristol's commitment and broad approach to open access. The Director of Research is responsible for local strategic direction and monitoring open access. We regularly contribute to the development of community policy and systems. Examples include:

- A community white paper [Davies et al., 2017] which establishes standards for access to 3D and 4D fossil morphology data (a huge technical and organisational challenge).
- Creating a library of over 500,000 satellite interferometry images of volcanos [Anantrasirichai et al, 2018, https://comet.nerc.ac.uk/comet-lics-portal/; 40+ views per day] and developing a dedicated system for volcano deformation (https://comet.nerc.ac.uk/comet-volcano-portal/).
- Establishing a repository for protocols and standards for EPMA (UK-EPMA, planned to go online in 2021), and nascent data protocols for volcanic tephra.
- Contributed to the open science initiative of the Collaboratory for the Study of Earthquake Predictability (CSEP), including developing a Python toolkit.

Simple provision is not always enough, and we are pro-actively engaged in ensuring the accessibility of our science. For example, we developed a web-based tool for assessing the hazards associated with lahars (www.laharflow.bristol.ac.uk; users from >15 countries have run >3,200 hazard models since 2017) and ash clouds (www.plumerise.bris.ac.uk; 95,000 models since 2013). To enable the best of use these resources, we have provided training for volcano monitoring authorities, especially in developing countries in South and Central America and Asia.

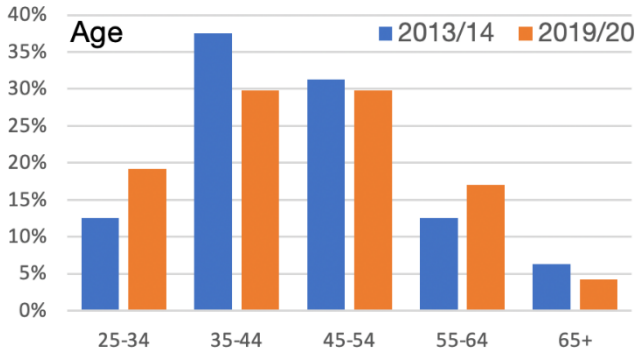
1.6 Research Integrity

We pride ourselves on adhering to the strictest standards of research integrity, following the processes and guidelines set down by the University, as outlined in REF5a. The review, mentoring and support structures outlined in §2.1 provide the primary mechanism for monitoring, training and advice of staff in this regard, and extra provisions and training are made for PGR students (§2.2).

2. People

2.1.1 Staffing Strategy

Recruitment strategy



Demographic profile of the School for the REF2014 and REF2021 submissions. The similarity demonstrates the effectiveness of our 'talent pipeline' and the future sustainability of the unit (nearly 80% of our submitted staff being >10 years from retirement, and 50% are below age 45).

Staffing and recruitment is a key component of our broader research strategy with three goals: **(a) consolidating and maintaining capacity in our core research areas, (b) building new capacity in strategic research areas** and **(c) building a diverse and inclusive community of scholars**. We have appointed five new academic staff to externally advertised posts during the REF period (Verdon, Melbourne, Bryce, Byrne, Irving), converted an externally-funded post to core-funded (Cooper), and recruited Pancost from the School of Chemistry (to Head of School). Our School is further enhanced by our honorary and emeritus staff (e.g., Aspinall, Hawkesworth, Thompson, Janis, Meredith), who collaborate with us on research and provide mentoring and guidance.

Our appointment process foregrounds equity and inclusivity (§2.3). We also appoint via proleptic lectureships, an approach based on mentoring and supporting ECRs to win Fellowships and thrive with them (**21%** of our submitted staff are ECR, including one on permanent contract). Previous proleptic appointments in the School have been promoted to Associate Professor (e.g., Buss, Hendry, Teanby) and Professor (e.g., Gottsmann, Rust, Schmidt, Wookey). Our approach has resulted in achieving near gender-parity at all levels (see §2.3), and ensured a strong international dimension (e.g., almost half our submitted staff were outside the UK before starting in Bristol). 9.5 FTE (21%) of our category A submitted staff are on non-permanent contracts, all but one of who are on research fellowships. As with the wider discipline, racial and ethnic diversity remains low; addressing this shapes our public engagement, student recruitment and staff appointment policies.

Staff supporting research

A core part of our Staff strategy is enabling academic staff to excel in research by providing strong technical and administrative support (32% increase since REF2014). Technical support now has a much clearer strategic focus, both at School and University level (§3.2). Additionally, the appointment of two teaching-only permanent academics has allowed more capacity to pursue research.

2.1.2 Staff development

Support and Review Structures

The University's Staff Review and Development (SRD) process requires the School to support all staff via a yearly review; this is a staff-led discussion about their ambitions and the support they

need to achieve them. In Earth Sciences, the Head of School conducts SRD for all permanent academic staff and senior research fellows. Informal mentoring is well-established through our research groups. Additionally, within the REF period we launched a formal mentoring scheme for academic staff at lecturer and senior lecturer level. This has received positive feedback (100% in a 2019 staff survey), and the scheme is being expanded. An additional specialised School committee provides targeted support for those seeking promotion.

Supporting and Rewarding Research

In line with updated University policy, we have developed a new, transparent workload model, to enable distribution of other activities and protect research time. This new model embodies the ethos that all academic staff share teaching and administrative duties and have an equal allocation of research time. It also recognises a broad range of research activity, including impact generation, public engagement and service to the scientific community (§4). Similarly, the criteria for promotion have recently been transformed to recognise and reward impact-generating (industrial, community and policy-facing) activities.

We support those who have achieved research excellence via external Fellowships (e.g., Leverhulme, Wolfson Research Merit; five held during the REF period). We provide further support via Bristol's University Research Fellowship Scheme. We also have an annual 'staff constraints' process, which alongside SRD allows us to adjust teaching load, liberating research time.

Stimulating Research and Impact Collaborations

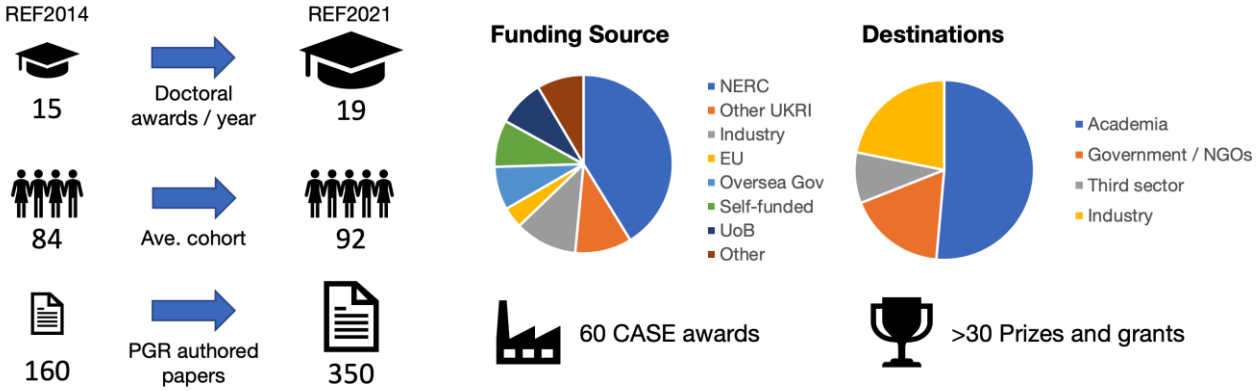
Research and impact excellence are driven by a bidirectional flow of people between other academic institutions, industrial partners and third sector organisations (more than **200 total visits** over the REF period). Many visits (up to 6 months) are funded by the University's Benjamin Meaker Fellowship scheme, bringing 32 Fellows to the School since 2014. Additional support for interdisciplinary collaborative visits comes from the URIs, including the Cabot Innovation Fund, and international partnership events. Members of the School have also hosted or organised numerous workshops and conferences aimed at external organisations. Honorary positions (>100 currently in post) are also a critical part of building collaborations.

Additional support for ECRs

Bristol was one of the first signatories of the Researcher Development Concordat and has developed a raft of policies to implement its principles (see REF5a). At School-level the >100 PDRAs employed over the REF period are championed by representatives who have been instrumental in ensuring the local adoption of the Concordat policies, such as the entitlement to spend 20% of their time on career development. These reps also organise and host a regular PDRA Forum and attend School Assemblies.

PDRAs are formally reviewed by their line manager, but extra support and mentoring is provided by eight senior academics in the School. This includes one of our Emeritus Professors (Hawkesworth), who the School has paid to support ECR career development. ECRs also have formal recourse for any pastoral issues through the School Research Director and Head of School. The PDRA Forum delivers co-created advice and training, for example around fellowship schemes, led and initiated by PDRAs. School support is augmented by the University's Research, Enterprise and Development (RED) Team and Bristol Clear (REF5a).

2.2 Research students



The PGR cohort over this REF period has been **larger, more diverse** and **more productive** than ever before. We have increased our PGR numbers over the REF period (average of **19 doctoral awards per year**, compared to 15 for 2008-13, with an average PGR cohort size of **92**, compared to 84), with a significant increase in overseas students. **18%** of our research students have identified as BAME, and **46%** as female (compared to subject national averages of **9%** and **43%** respectively for a similar period). More than **350** papers published in the REF period have PGR student authors (compared with 160 in REF2014). We have recently additionally formalised an MSc by Research programme, including interdisciplinary projects through the Cabot Institute.

Funding

Our students' funders represent the breadth of our research. Our largest cohort (35) are NERC-funded students through the GW4+ Doctoral Training Partnership (Bristol, Exeter, Cardiff and Bath), which includes formal partnerships with BGS, BAS, CEH, Met Office, NHM and PML and a further 28 associates drawn from industry, media and environmental agencies. More than 60 of our students were supported by CASE supplementary awards from, e.g., BGS, BHP, GNS Science, AWE and TerraDat UK Ltd. Moreover, we participate in other Bristol Doctoral Training Partnerships (DTP) and Centres for Doctoral Training (CDT) (funders include BBSRC and EPSRC), competitive international scholarship schemes subsidised by University agreements (CSC and Conacyt), and attract self-funded students (28 over the REF period).

Recruitment

The School of Earth Sciences receives over 100 applications for PGR study per year, with more than 50% coming from overseas. 42% (10 of 24) of PGR students registered in 2019-20 were overseas, compared to 15% (3 of 20) in 2015-16. For funded PhD studentships the ratio of applications to places averages 20:1. All PhD applications are centrally administered and are reviewed by at least two academic staff (who receive equality and diversity training), and protected characteristics are monitored at every stage of the process. DTPs use a panel of academics who review all candidates to ensure that the best students are selected.

Monitoring and Support

All students have at least two supervisors in the School, and often additional supervisors at external partners. There is an annual progress monitoring system in place. Each year, every student gives a research presentation, produces a report, and is interviewed by two independent members of academic staff who report on progress and surface any concerns (their own or the student's). Formal comments are recorded through an online Faculty system, and responses by

the student, supervisors, head of the graduate school and graduate Dean are incorporated. A range of additional support and monitoring measures (both informal and formal) can be invoked in order to bring projects back on track. Separate from the APM process, we have a School Graduate tutor who provides pastoral support to PGR students, and the University has also launched an extensive student well-being service.

Training and Development

Postgraduate support and training have been significantly enhanced over the REF period. At the heart of this is the Bristol Doctoral College (established in October 2013). This body (which includes dedicated facilities and study space for PGR students) provides a wide range of training and support for PGRs (technical skills, language support for overseas students, career development and finances). University Research Institutes offer complementary training in communications and policy engagement. The CDTs and DTPs offer specialised training, with the GW4+ NERC DTP providing a portfolio of **more than 500 courses** across the four partner universities. Furthermore, the School has organised and hosted several externally funded (e.g., NERC, British Geophysical Association) courses over the REF period, including Software Carpentry, GPS Processing and Fundamentals of EPMA available to internal and external PGRs and ECRs.

Outcomes

Our PGR students have been awarded more than **30** prizes and grants, including thesis prizes (e.g., the Linnean Society Irene Manton prize, the Greenwich Forum prize and the International Springer Thesis Award) and individual prizes (e.g., EMAS/IUMAS Young Scientist Award, Palaeontological Association's President's Prize). Destinations for our students include a diverse range of professional careers, with the majority continuing in science, across academic and non-academic careers.

2.3 Equality and diversity

Achievements in EDI

EDI has been at the heart of the School's priorities over the REF period, and our successes in gender inequality have been particularly noteworthy. **>40% of staff** (and research postgraduates) **at all career levels identify as female**. This includes **47% at professorial level** (c.f. 10% in REF2014, and against a national benchmark of 16%), with a low professorial gender pay gap relative to the sector (6.2 cf. 8.4% in 2019). These successes were enabled by a redesign of our policies and practices in EDI. We have created a standing EDI Committee (EDIC) which reports directly to the Head of School and Dean and participates in School Board, ensuring equal standing with Teaching and Research; going forward, EDIC has prioritised improving racial and ethnic diversity in the School and wider discipline.

Many School staff have taken on EDI leadership for the broader community, for example chairing EDI committees for EAG and the Society of Vertebrate Paleontology and serving on the Royal Society Forums on Research Culture and Diversity in UK Polar Science Initiative committee. Alongside gender equality, we have visibly committed to both race and LGBTQIA+ equality charters, the latter celebrated by, for example, the @palaeoiris 'queerlobite' initiative started by one of our PhD students. School-led efforts to widen BAME representation include the Black and Green Ambassadors programme (a public engagement project co-created by the School and Cabot Institute (under Pancost) with Ujima Radio and the Bristol Green Capital Partnership). The Award-winning Bristol Dinosaur Project (see §4.2.3) has refocused on Widening Participation (WP)

communities, via Faculty WP funding over the past four years (7800 students reached). The School launched in 2019 a Palaeobiology internship scheme specifically for BAME students. We recognise that Covid-19 has profound implications, especially on ECRs, those with caring responsibilities and those from marginalised groups. We have already started documenting these impacts, and will prioritise minimising career impacts in our future strategy.

EDI in Recruitment, Research Strategy and Policies

The University of Bristol provides and continues to improve a broad range of policies and support to enable its diverse research staff to thrive. This includes mandatory EDI and new anti-racist training for all staff. Representation in shortlists for School job vacancies of female and BAME candidates has risen from **40→47%** and **0→24%** respectively. We now require a diversity statement in applications, which is used in the shortlisting process. Finally, the workload model described in §2.1 provides a transparent, effective mechanism for supporting flexible and remote working, as well as providing parity for part-time staff. Crucially, all recruitment, workload allocation and research support processes are monitored by the EDI committee.

Caring leave

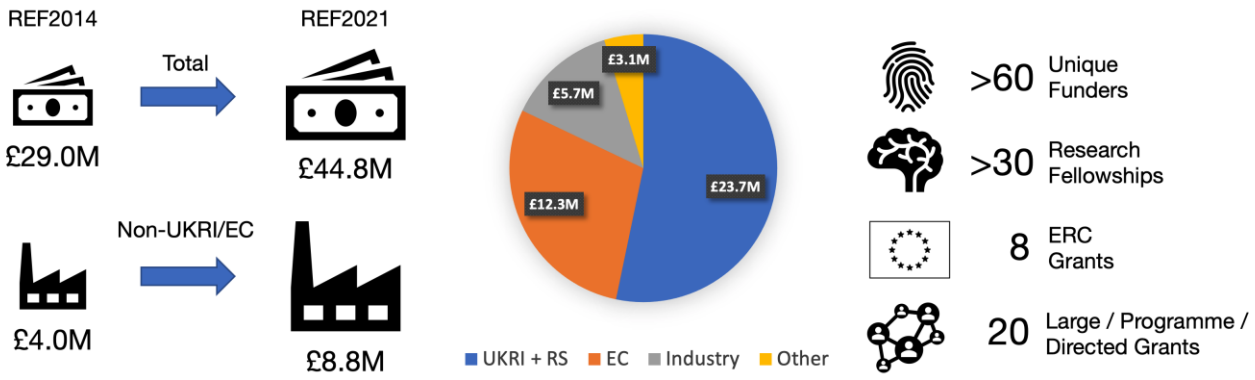
There is a range of support for individuals returning from caring leave (REF5a); indeed, members of the School have been instrumental in the development of these schemes. For example, two female Professors within the School championed the University's Returning Carers' Scheme, which provides funds to help re-establish a research programme after extended leave due to caring responsibilities.

EDI and the REF

The REF submission was constructed with the primary goal of presenting research excellence across the whole School. We contributed to the development of University's high-level code of conduct, and implemented it locally. This included explaining and supporting the process for assessing independence to staff, and the School's research committee provided a first port of call for informal advice for ECRs. Unconscious bias training was provided to the UoA coordinator, and this was used to design the necessary internal review and selection processes for outputs. Our list of submitted outputs reflects the diversity of our submitted staff; for example, >40% outputs are attributed to female authors. The administrative effort of preparing the REF submission (including impact cases) for the individuals involved is also formally recognised in our workload model.

3. Income, infrastructure and facilities

3.1 Research Income



Over this REF period we have won total direct research grant income of more than **£44.8M** (50% above REF2014 and more than triple RAE2008); this is >£1M/FTE. We have received **£3.5M** of UKRI in-kind income, double that of REF2014. We have continued investing in partnerships and interdisciplinary collaboration in this REF period, more than **doubling** the total from non-UKRI or European Commission sources compared to REF2014 (£8.8M vs £4.0M). We have pursued a strategy of developing our talent pipeline, hosting >**30 esteemed research fellowships**.
Our largest funders continue to be UKRI plus the Royal Society (**£23.7M**), and the EU (**£12.3M**), reflecting our continued commitment to fundamental research. These draw on our established strengths in Deep Earth (e.g., NERC Programme 'Deep Volatiles'), Palaeobiology (e.g., an ERC Advanced grant, two NERC 'Biosphere Evolution, Transitions & Resilience' thematic programme grants, and a NERC Large grant) and the understanding of volcanic hazard (e.g., three NERC Large/Programme grants). Additionally, we have expanded into planetary research, resulting in our first School-led STFC consolidated grants (2014, 2017, 2020), the CUBESAT, and UKSA Aurora support for the NASA InSight geophysics mission to Mars; and Life Sciences research funded by the MRC and Leverhulme with colleagues in the faculties of Health and Life Sciences.
Industrial and impact funding both enables and follows our successes in engagement. For example, we have received more than **£3M** in funding from the direct partners on our impact cases, such as BHP and EDF, and Earthquake hazard and other research has been further enabled by more than **£6M** funding to the School through ODA schemes.
Fellowships hosted over the REF period include Royal Society URF and Dorothy Hodgkins, NERC IRF, UKSA Aurora, Marie-Curie S, Leverhulme and RCE1851 schemes. We have hosted 8 Newton Fellows from countries including China, India, Israel and Spain.

3.2 Research infrastructure and facilities

World leading research activities require high quality organisational, physical and digital infrastructure to support it. The School has benefitted from more than **£100M** of investment and commitments in the REF period, including major upgrades to our estate, technical support, equipment and facilities.

3.2.1 Estate

The largest of our estate investments is the new **£63.8M Life Sciences building**, enabling our strategic aim to centre the paleobiology group in the University's interdisciplinary Life Sciences vision. This has enhanced and enlarged our the laboratory space and facilitated new collaborations as well as joint (Vinther, Pisani) and coordinated (Harrison, Paps and Williams) appointments. This new, research-facing space has enabled the development of new facilities, such as the £980k fossil imaging suite. The Wills Memorial laboratories have also seen major investment including a £2M refurbishment of our isotope geochemistry and experimental petrology facilities. Other space investments have included a new geophysics computing suite, a new geophysics field equipment facility, a programme of refurbishment of PGR offices, construction of a new Geomicrobiology Lab, and re-investment in our Biogeochemistry Labs.

3.2.2 Laboratories and technical support

We directly manage a portfolio of more than **£17M** of scientific equipment and infrastructure in the School across 14 laboratories, a rock-crushing lab and a dedicated workshop. Our in-house laboratories are supported by 11 FTE of technical support (a **>50% increase since 2014**, providing technical leads for all major laboratory spaces). This is enhanced by a new University-level commitment to improving the career framework for all technical staff, delivered by a new senior strategic position. Bristol was a founding signatory to the HE sector's 'Technician Commitment' in 2018. All of our laboratories have LEAF sustainability accreditation. Funding supporting the upgrade and maintenance for our laboratories comes from research grants, industrial partners and investment from the University.

Research infrastructure highlights during REF period
School Laboratories

- **Petrology** *(high-pressure, high-temperature experimentation and sample spectroscopy)* • New equipment including an advanced pulsed laser milling machine (£150k) • New technician (Goodes, appointed 2017).
- **Geophysical Laboratory** *(environmental, applied and global geophysics, geodesy, multispectral imaging)* • New equipment since 2014 includes lidar capability, electrical resistivity tomography, GPS receivers and additional seismic equipment (including picoseismic sensors for borehole imaging), totalling >£200k • £48k support for dedicated HPC • New technical lab manager (George, appointed 2018).
- **Electron Microbeam Laboratories** *(electron imaging and X-ray microanalysis)* • Central focus of UK training for EPMA receiving £165K from NERC and £23K from EMAS to support advanced training courses for post-graduates and early career researchers • Facility staff (Kearns, Buse) have co-authored 12 peer-reviewed papers on new refinements to SEM/EPMA techniques.
- **Isotope Spectrometry** *(high-precision isotopic measurement)* • Delivery of the Proteus Collision-Cell Multi-Collector ICP-MS Proteus, co-developed with Themo-Fisher (see below) • New state of the art clean lab (£750k).
- **Geological Fluid Mechanics Laboratory** *(experimental modelling of viscous, explosive and granular volcanic flows)* • Comprehensive refurbishment of the University's science and engineering fluids labs including a £200k refit of our GFM laboratories • New multiphase materials characterisation capability including £58k for particle size analysis

instrumentation.

- **Biogeochemistry and Geomicrobiology Laboratories** *(growth and characterization of microorganisms, water and soil analysis)* • £120K of investment in the infrastructure allowing reorganisation for geomicrobiology • new Mossbauer spectroscopic instrumentation and anaerobic growth and handling facilities • Increased coordination with other Schools (e.g., Geography, Chemistry); these labs are now part of a University-wide suite of microbiological facilities.
- **Palaeontology** *(molecular biology including DNA/RNA extraction, fossil X-ray tomography / microscopy)* • New active X-ray tomography facility and imaging suite (£980k) • New Palaeobiology Lab Manager (Davies).

Co-maintained (with Chemistry)

- **Organic Geochemistry** *(wet chemistry preparation and organic mass-spectrometry)* • UK's first GC-Orbitrap installed in 2018 • Inclusion as a node of the NERC National Environmental Isotope Facility.
- **Bristol Radiocarbon AMS** *(radiocarbon determination of organics)* • A newly established £1.9M resource specializing in methods for radiocarbon determination of gases, solid and dissolved organics from diverse environmental matrices. The Labs are supported by one manager and 3 technical staff (not included in the Earth Sciences technical staff totalled above).

Experimental facility support for impact activity

The following facilities have been critical to the delivery of our impact strategy, including our impact cases:

- The experimental Petrology laboratories, used in partnership with BHP Billiton, were critical to research into porphyry copper deposits for the Copper impact case.
- Measurements of the effects of airborne ash on jet engines were also undertaken in the experimental petrology laboratories; part of the work done in partnership with Rolls-Royce in the Aviation impact case.
- Picoseismic equipment in the Geophysics Facility – acquired in partnership with KeirBAM – were used to make site measurements at Hinkley Point instrumental to the Microseismic impact case.
- Ground-based multispectral imaging equipment from the Geophysics Facility and InSAR data from multiple space agencies were used to provide monitoring in the Volcanic Risk impact case.

Development of novel equipment

Methodological and technological innovation has been enabled by the growth of our technical team and a dedicated workshop (1.5 FTE). A step change for our innovation has been industry partnership: development of next generation technology through co-operative design between experienced instrument users and instrument manufacturers. Such a partnership was realised in an ERC Advanced grant (Elliott) to develop a novel mass-spectrometer for the Bristol Isotope Laboratory in collaboration with Thermo-Fisher Scientific (resulting in a joint patent). A new tri-bid instrument – Proteus – was built by Thermo and delivered to Bristol for testing, further development and frontier scientific research (§1.2). The next generation of this machine will be developed over the next 5 years, again in partnership with Thermo-Fisher Scientific and funded by a second ERC Advanced Grant to Elliott. These machines also have significant potential

applications beyond the Earth Sciences, for example in medical research. Other novel equipment includes the world's only high temperature GC-IRMS system, developed in partnership with ElementarUK as part of an ERC Grant, and the SEIS instrument package deployed on the surface of Mars in 2018 by the NASA InSight mission.

3.2.3 Central University Facilities

A central tenet of Bristol's research strategy is to amalgamate research equipment capability into centralised facilities where possible. This has a host of advantages, including expertise and continuity of support, quality of supporting estate and infrastructure and maximising leverage for investment. Facilities benefitting the School include the **Interface Analysis Centre**, the new **Satellite Lab and Ground Station**, the nascent **National Soil-Foundation-Structure Interaction (NSFSI) Laboratory** and the **Advanced Computing Research Centre (ACRC)**. Highlight developments in this REF period include:

- A £12M capital investment will develop the **NSFSI Laboratory** to include unique earthquake testing equipment, with a deep test pit and large-volume data storage. This facility has significant potential for our work in earthquake hazard under the 'Crustal Processes and Hazards' theme.
- The University has invested £16M over the last decade (£10M since 2014) in **high-performance computing** and **robust research data storage** through the **ACRC** over the last decade with committed to investment of £2M/year for the next ten years.
- The GW4 in partnership with the Met. Office and ESPRC, has built Isambard – the largest Arm-architecture based supercomputer in Europe – which was brought online in 2018 at a cost of £3.0M, and a further £4.1M was awarded in 2020 to significantly increase the capability of this machine. Support to port research codes to the new Arm architecture has been provided to the School (Wookey) through ACRC.

3.2.4 Usage and Leadership of National and International Facilities

Over the REF period we have used more than **20** different national and international facilities (including synchrotrons, analytical facilities, and research ships and bases) and we are closely involved in developing the next generation of these facilities. For example, Hendry is the science lead for the Net Zero Oceanographic Capability (NZOC) project, scoping future low carbon oceanographic research capability for the UK. Other examples include developing new high-pressure beamlines for the proposed Diamond Light Source II (Lord) and planning the design and deployment of the UKArray seismic project (Wookey). We take leadership and advisory roles in the facilities through membership of steering and access committees (NERC Ion Microprobe Facility, Cashman; NERC Isotope Facility, Robinson; NERC Geophysics and Geodesy, Biggs; UK Seismic Array, Wookey; Global Seismic Network organisation, Irving; Diamond Light Source, Buss, Lord; ESRF, Lord; Comprehensive Institute for Geodynamics, Irving; National Oceanography Centre Association, Marine Facilities Planning Group, NERC Cruise Programme Review Group, Hendry).

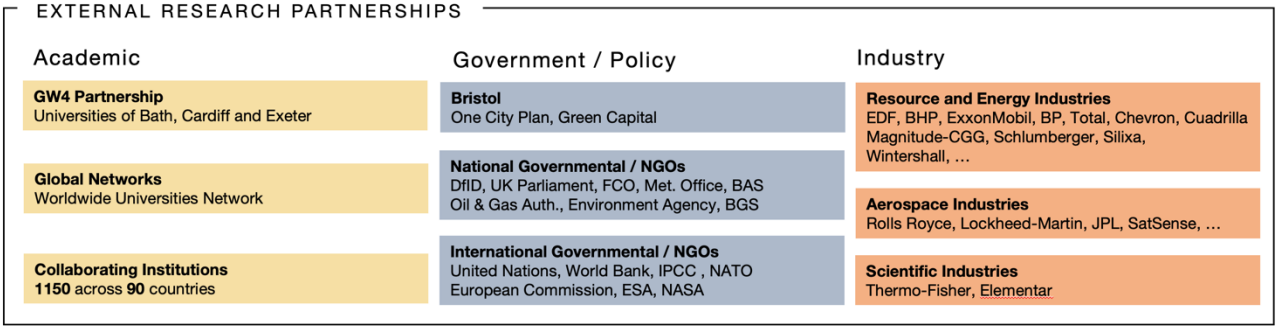
3.2.5 Organisational Infrastructure

Our research and impact activity is supported by broader University infrastructure. These include the University Research Institutes (URIs; REF5a and §4.1). Professional services to support research include Research and Enterprise Development (RED) and the Science Faculty

Partnership Office. They foster strategic partnerships, including with EDF, Rothamsted Research, ATI and the UK Met Office, providing access to new collaborations, funding and PGRs. Second, they have won and administered innovation funds enabling the development of new technology, collaborations and industry partnerships (§4.2), Third, they have pioneered partnership and investment with the southwest England tech sector, initially through the award-winning 'Bristol is Open' collaboration and more recently through a Research England partnership grant worth £100M that will support the University Digital Futures vision and be vital to our Digital Environment strategy.

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

4.1 Research Collaborations, Networks and Partnerships



Collaboration and partnership are integral to the success of the School. We have co-authored papers with >1150 institutions from 90 countries, with 73% of publications including international partners. Our broad, deep network of relationships is fostered by a wealth of schemes supporting bilateral research visits (>200 lasting a week or longer). In total, the School has hosted more than 100 honorary staff including academic, industrial and other partners, plus short visits from notable policy figures such as Dame Julia Slingo, Sir John Beddington and Christiana Figueres, as well as three MPs, both of Bristol's elected Mayors and many Councillors. We have hosted 63 Collaborative Awards in Science and engineering (CASE) funded studentships, all of whom have spent at least 3 months working directly with their CASE partners.

Our goal to lead multidisciplinary research teams has led to collaborations with >80% of the other Schools within the University, supported by the University Research Institutes (URIs): Cabot (environment), Jean Golding (data), Elizabeth Blackwell (health), Brigstow (21st century living) and Digital Futures (digital society). In particular, the School has taken on strategic leadership roles within the Cabot Institute for the Environment, including Director (Pancost 2013-2018); Associate Director (Biggs, 2021-2024) and Theme Leads. Seedcorn funding from the URIs, the International Strategy Fund, Institute for Advanced Studies, GW4+ and Policy Bristol (19 in total) has incubated challenge-led, multidisciplinary partnerships and paved the way for much larger projects.

The GCRF has been a key opportunity to develop new partnerships, and the School has taken on leadership roles within the University Steering Group. We have received over £6M in funding to carry out significant capacity building projects in 9 ODA countries and hosted 10 ODA-related Fellows (incl. 8 Newton Fellows). Highlights include a new collaboration between Earth Sciences and Civil Engineering focussed on improving resilience to earthquakes funded by GCRF-EPSRC, and an expansion into hydro-metrological hazards in SE Asia through the NERC Shear programme. Bristol's role in the £19M GCRF Urban Disaster Risk Hub 'Tomorrow's Cities' links the Schools of Earth Sciences, Civil Engineering and Sociology, Politics and International Studies.

4.2 Environment for engagement

The School is increasingly using our world-leading research to benefit the environment, economy and society, hosting two major long-running platforms for industrial engagement (§4.2.1), influencing environmental policy (§4.2.2) and emphasising widening participation and sustainability in public engagement (§4.2.3). The School/Faculty/University has fostered these through 1) forming an Engagement, Partnerships and Outreach Committee (EPOC), chaired by the School Impact Director (SID); 2) appointing a School Public Engagement Officer (from professional services) to co-ordinate outreach activities with an emphasis on widening participation; and 3) forming the Science Faculty Partnership Office, led by a member of the School.
The School's policy for the strategic appointment of Honorary Staff has built a thriving community of around 100 partners, representing all career stages, from academia, government, industry and civil society and over 20 countries. The appointment of our Aegis Professor in Sustainable Resources (see §1.4b) is the first step towards developing an External Advisory Network. The School's Impact Director (Watson 2012-2016; Biggs 2016-2021) has nurtured nascent impact activities, working with the RED Knowledge Exchange Team to develop 16 successful bids for translation activities and impact accelerators. Impact Accelerator funding has been particularly key for ECRs wishing to explore careers associated with the industrial application of their research.

4.2.1 Industrial engagement

The RED Partnerships Team, with the URIs, establish and oversee university-wide systems that support the development and growth of industry partnerships; of direct relevance to the School, this includes an umbrella agreement with BHP and multidisciplinary relationships with AWE, EDF and Rolls Royce. UoB's burgeoning relationship with the Met Office funded 8 studentships in this School and was formalised through competitive entry to the Met Office Academic Partnership (MOAP) in 2020 with two members of the School joining the board. The cross-Faculty SW Nuclear Hub acts as a focus of activity for several School research groups.
At School level, the newly formed Global Change, Natural Resources and Sustainability Research Theme (§1.2) integrates and expands our industrial engagement, hosting two multi-phase platforms for engagement with established industries while nurturing 'green energy' and 'blue economy' initiatives. These collaborative hubs provide internships and studentships, attract talented ECRs, and have leveraged over £3M in additional funding including CASE sponsorship for 6 PhD studentships. During this REF period, School staff have filed patents in economic geology (see the Copper impact case study) and the development of novel scientific instruments (Proteus, §3.2.2) supported by the RED Commercialisation Team and founded three SMEs: FATHOM (Neal), Outer Limits Geophysics (Kendall, Verdon) and Seagrown (Robinson).

Hydrocarbon Industry and Regulators: The Bristol University Microseismicity Project (BUMPS) began in 2009 with a focus on safe gas extraction and is now entering Phase 5, with a focus on Carbon Capture and Storage and forecasting induced seismicity. More details are provided in the Microseismic impact case study.

Sustainable Mineral Resources: The Bristol PCD partnership with the world's largest mining company, BHP, leverages our expertise to find the resources needed for green energy. The partnership is now entering Phase 3 (Total > £4M) and has led to a spin-off project 'Mine The

Brine' (now entering Phase 2) and NERC strategic funding (FAMOS) to engage with a consortium of 11 mining companies. More details are provided in the Copper impact case study.

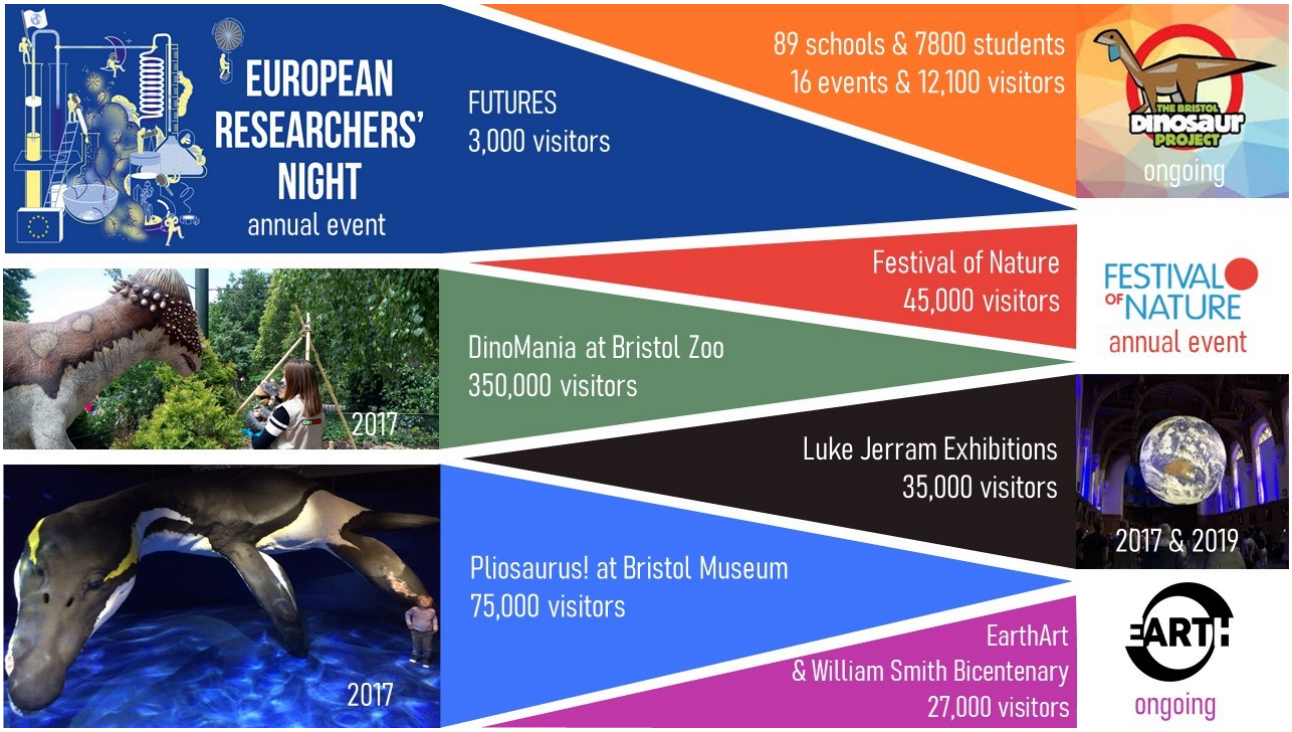
Instrument Development: The School uses its expertise in analytical innovation to develop scientific instruments in partnership with major technology companies, including a novel mass-spectrometer with Thermo Fischer Scientific, a high temperature GC-IRMS system with ElementarUK, Distributed Fibre-Optic Sensing Systems with Silixa, and a Martian seismometer with NASA (§3.2.2).

The Blue and Green Economy: Bristol researchers (Robinson) are involved in setting up the UKs first large scale macroalgae cultivation site, SeaGrown, as the first step in developing an exciting new marine industry for the UK (https://www.seagrown.co.uk/). Other collaborations around the terrestrial food/soil/water system include Alltech, Wessex Water and BGS, DEFRA, Rothamsted Research and Bristol City Council.

4.2.2 Engagement with policy makers

The research excellence of members of the School has led to their invitation to engage across a wide range of governmental and regulatory bodies including the UN, World Bank, IPCC, European Commission, NATO, DfID, UK Parliament, FCO and Bristol City Council. The School's research informs policy on environmental issues including climate, marine, polar and energy policy and plays a critical role in supporting the city's environmental movement. Pancost supported Bristol City Council to become one of the first major cities in the world to declare a Climate Emergency and adopt the UN Sustainable Development Goals. Schmidt is coordinating lead author for IPCC AR6 and was lead author of IPCC AR5, through which she has provided advice to the UK Parliament. Hendry shapes the UK polar and marine science strategy through various national committees and recently co-authored an FCO-funded policy briefing on UK impacts of a changing arctic. Bristol scientists work closely with the regulators of the UK's nascent fracking industry (see Microseismic impact case study) and with the Environment Agency, Natural England and Wessex Water to meet EU Directives on Urban Waste Water Treatment, Habitats and Water.
Our research into natural hazards is used to inform and advise international policy throughout the disaster risk reduction cycle, and Bristol scientists co-authored the UN Global Assessment of Risk (see Volcanic Risk impact case study) and NATO guidance on safe military operations in hostile environments (see Aviation impact case study). The FCO/FCDO has directly funded our response to natural disasters around the world including for the 2018 eruption of Fuego, Guatemala (see Volcanic Risk impact case study) and cyclones Idai and Kenneth (work shortlisted for the 2019 THE Research Project of the Year). Most recently, Bristol's world-leading expertise in managing volcanic risks has been applied to the pandemic through the NIHR-UKRI-funded COVID-19 rapid response initiative 'COVID-19 Mapping and Mitigation in Schools (CoMMinS)'. This work will input into the Scientific Pandemic Influenza Group on Modelling, which gives expert advice to SAGE.

4.2.3 Public engagement



Sharing our passion, understanding and concerns for our planet is at the heart of the School's community and underpins our public engagement and outreach efforts. Critically, we recognise that public engagement must centre marginalised groups, and we have re-focussed towards those. Our staff deliver workshops in their local schools, offer public talks, are active on social media, and advise media, policy, cultural and non-commercial organisations, and businesses. In total, we estimate that the School has contributed to events that have attracted over half a million visitors. Our staff assume a range of leadership roles with local organisations including Bristol Zoo and the Green Capital Partnership, and include a year-long secondment as Senior Curator at Bristol County Council. Beyond the city, our staff have appeared in several BBC productions, including 'Attenborough and the Sea Dragons' and 'Astronauts: Do You Have What It Takes?', Jeff Bridges' film 'Living in the Future's Past' and long-running series including Sky at Night, BBC Breakfast, Inside Science and News at Ten. TEDx talks by Robinson and Benton have accumulated over 1.7 million views. Benton is a leading non-fiction author with 3000-4000 copies of his palaeontology books sold per year. We are developing our individual collaborations into sustainable partnerships by supporting staff and students through training and remunerating contributions by students to larger events.

4.3 Leadership in the broader research base

Invitations to fellowships of learned societies and civic prizes

- Sir Steve Sparks was appointed to Knight Batchelor in recognition of his career contributions.
- Five new Fellows of the Royal Society (Benton, Cashman, Donoghue, Elliott, Kendall) making a total of seven.
- National Academy of Sciences (Cashman).
- Academia Europeae (Gottsmann).

- Royal Society of London (Elliott).
- Royal Irish Academy (Hawkesworth).
- Geochemical Society and European Association of Geochemistry (Elliott, Pancost).
- Chinese Academy of Sciences (Distinguished Scientist, Hawkesworth).
- Royal Society for Chemistry (Pancost).
- Royal Society for Biology (Schmidt).

Prizes and medals

- Vetlesen Prize (Sparks), known as 'the highest prize in Geology'.
- The Queen's Anniversary prize (Volcanology Group).
- GeolSoc Murchison (Elliott, Blundy) and Bigsby (Rayfield) medals.
- AGU Norman L. Bowen Award (Elliott).
- EGU Jean Baptiste Lamarck (Benton) and Robert Bunsen (Hawkesworth) medals.
- EAG Ringwood (Blundy) and Houtermans (Hendry) medals.
- Pal. Assoc. President's Medal (Donoghue, Rayfield).
- Zoological Society of London Scientific Medal (Rayfield).
- Leverhulme Trust prize (Biggs).
- Over a dozen more prizes and distinguished lecturer awards.

Leadership in the science community

Members of the school have served on more than **60 committees, advisory/working groups and panels** for national and international bodies. Highlights include:

- **Funding Bodies:** REF2021 UoA7 Panel (Donoghue); NERC Science Committee (Pancost) and nine other UKRI committees; Royal Society Council (Sparks, Hawkesworth) and eight other RS committees.
- **Local, National and Overseas Governments:** Beyond our strong civic engagement members of the School are called on to provide expert advice to governmental bodies. Examples at national level include Sparks' membership of Science Advisory Group for Emergencies (SAGE) and the Montserrat FCO Scientific Advisory Committee, and the independent review of the National Geological Screening (tasked with identifying sites for the geological disposal of nuclear waste) was chaired by Hawkesworth. Overseas examples include INSIVUMEH the Guatemala Scientific advisory group (Watson) and the Worksafe New Zealand panel into the White Island Volcanic disaster (Sparks).
- **Professional bodies and other organisations:** President and Vice-President of the Society of Vertebrate Palaeontology (Rayfield), Vice President of the Palaeontological Association (Rayfield), Board of directors and Council Leadership Team of the American Geophysical Union (Riker) and steering committees, working groups and prize panels for **30** more such organisations including professional bodies (e.g., International Science Council, EAGE, MinSoc, Leverhulme Trust), research institutes (e.g., Royal Netherlands Institute for Sea Research, Southern Californian Research Centre) and museums (e.g., NHM; Museum National d'Histoire Naturelle, Paris; Humboldt Museum of Natural History, Berlin).

Funding body decision panels

Members of the School have served on panels for more than **20** different funding bodies in the UK and overseas, including for UKRI (NERC, STFC, UKSA), the Royal Society (e.g., UR and DH Fellowships, Grants), ERC (Starting (Chair), Consolidator and Advanced grants panels),

Leverhulme, Royal Astronomical Society, GeolSoc, ESA, NASA, NATO, DFG and the US National Academy and NSF. Members of the school review grants across an even broader range of bodies.

Editorship of major international journals

Members of the School have served as chief editor for four journals (EPSL, JVGR, Physics and Chemistry of the Earth and Elements) and on the editorial board of **>45** other journals as well as regularly reviewing across an even broader range of publications.

Organisation and participation in major conferences

Members of the School have organised or session-chaired more than **200** conferences and workshops, and given more than **400** keynote talks or invited lectures.