Institution: University of Oxford

Unit of Assessment: 7 – Earth Systems and Environmental Sciences

1. Unit context and structure, research and impact strategy

1.0 Overview

We are submitting 42 staff (40.95 FTE), drawn from the Department of Earth Sciences (**DoES**) (35.95 FTE) and Oxford University Museum of Natural History (**OUMNH**) (5.00 FTE).

Our research links fundamental curiosity-driven questions about how the Earth and other planets work today and in the distant past with pre-eminent societal challenges, such as rapid environmental change and sustainable natural resources. Our ethos is based in quantitative science using field and laboratory observations, physical and mathematical analysis, and knowledge transfer with cognate disciplines.

Attracting and nurturing outstanding talent is central to all our goals. The appointment of 12 new faculty, six from outside the UK, during the REF period has been an outstanding opportunity to reinforce our strength in some areas and to create new capability in others. The appointment of Jon Blundy FRS (Royal Society Research Chair) invigorates our Planetary Science theme. Mike Kendall FRS (Chair of Geophysics) strengthens our study of the deep Earth and anchors a new initiative in cryosphere research. The internal promotion of Ros Rickaby (Chair of Geology) represents an intensified focus on the interface between biology, geology, and the environment.

We have diversified our funding base since the last REF, securing the largest number of ERC awards in Earth System Science (PE10) of any single-site institute in Europe, and strengthening links with natural resource industries. Our research-to-policy approach is highlighted by Gideon Henderson's appointment as DEFRA Chief Scientific Advisor (**CSA**). OUMNH provides outstanding opportunities to engage the public in our research; with 800,000 visitors annually, it is the most visited university science museum worldwide.

We place great value on supporting and promoting our community through national and international funding bodies, editorships, and learned societies. The latter is exemplified by Alex Halliday's role as Vice-President of the Royal Society. Our scientists have also received significant recognition across career stages, including three awards presented by Heads of State.

1.1 Context and structure

Oxford UoA7 spans two distinct sections of the University: DoES forms part of the Mathematical, Physical, and Life Sciences (**MPLS**) Division; and OUMNH sits within Oxford's Gardens, Libraries, and Museums, a grouping of six internationally significant research collections. The DoES Head of Department (**HoD**) and OUMNH Director each sit on the other's governing committees, ensuring strategic cohesion.

Inspiring research leadership in our faculty and researchers at all career stages is a core tenet. This is built on the principles of academic freedom and independence. We encourage development of collaborative networks between our researchers, across Oxford departments, and with national/international partners from academia, industry, and the third sector. Enabling agility to address timely scientific problems in novel ways is a key aim of our research environment. While we do not have formal groups, research falls into six broad themes (Figure 1), with many researchers active in more than one area.

Figure 1: Primary research theme affiliation of REF-returned research staff
(including Visiting Professors and grant-holding Emeritus Professors, not REF-returned)

Geophysics and geodynamics
Katz
Kendall *
May *^
Nissen-Meyer
Sigloch
Stevens *

Planetary evolution and materials
Ballentine (HoD)
Barling *^
Blundy *
Bryson *
Marquardt *
Nichols *
Wade *^
(*Wood*)

Oceanography, climate and palaeoenvironment
Bouman
Henderson
Holdship ^
Johnson
Khatiwala
Porcelli
Rickaby
Robinson

Palaeobiology and evolution

DoES	OUMNH
Anderson *$	Dunn *$
Benson	Murdock *$
Cosmidis *	Pérez-de la Fuente *$
Parry *$	Rahman
Saupe *	Smith [Director]
Shillito *$	

Geodesy, tectonics, volcanology & hazards
Cassidy *$
Hawthorne *
MacNiocaill
Mather
Palin *
Pyle
Searle
Walker
(*Watts*)

Earth resources
Cartwright
Foschi *$
(Daly)
(Idiz)
(Levell)
(St-Onge)
(Robb)

**Recruited in REF period* $*Independent Research Fellows* ^*Small Research Facility Manager*

1.2 Research strategy and developments since 2014

We provide fundamental scientific understanding of the processes that shape the Earth and our environment. We inform society's influencers and policymakers and find solutions to some of the most pressing global challenges. This is achieved with three interdependent approaches, reflecting the inherently multidisciplinary nature of Earth sciences:

- Observations of Earth and other planets
- Laboratory analysis, imaging, and experiments
- Mathematical analysis and numerical modelling of planetary processes

Key aspects of our research strategy include:

- Using **recruitment or promotion** of faculty to review (via faculty-wide discussion) our research emphasis and to **identify new and emerging fields of cutting-edge research**, and faculty with **cross disciplinary interests**. For example, promotion of Rickaby (to the Chair in Geology) represented a shift in emphasis at senior level towards the interface of life and the planetary system.
- Sustaining **vibrant areas** of the discipline, illustrated by the recruitment of Marquardt, Bryson, Nichols, and Blundy (plus Barling and Wade to lead analytical facilities) to rebuild our strength in planetary science.
- Investing **in innovations in instrumentation**. Examples include a Brillouin Spectroscopy system to probe high PT mineral properties (Marquardt), and our new Oxford Centre of Quantum Palaeomagnetism (Bryson, Nichols, MacNiocaill).

- Building and maintaining a **cutting-edge analytical capability** by appointing permanent senior independent research fellows (**IRF**) as facility managers (Wade, Barling, May, Holdship).
- Attracting and training excellent postgraduate research (**PGR**) students and post-doctoral researchers (**PDRAs**) (**§2.1**).
- Developing **international connections, networks, and collaborations** within academia and to reach out to other stakeholders (**§1.4**, **§4.1**, **§4.2**).

1.2.1 Theme foci and key developments during the REF period

i. Geophysics and geodynamics

We seek to understand the structure and dynamics of Earth's interior; the response of the lithosphere to loading; the mechanics of earthquakes; the fluid dynamics of geological materials; and the physical behaviour of the cryosphere. Analysis of observational data relies on application of rigorous mathematical techniques and high-performance computing.

Since 2014: Appointing Kendall as Chair in Geophysics delivered on our 2014 objective to maintain leadership in the field (*vice* Woodhouse), strengthening deep Earth studies and new applications to resource and sustainability. Recruitment of Stevens adds new strategic capability in Cryosphere Geophysics. We have strengthened our computing resources by creating a permanent IRF post in advanced research computing (May).

ii. Planetary evolution and materials

Study of the chemical, isotopic, magnetic, and mineralogical behaviour of planetary materials enables us to make cutting-edge discoveries in the formation, structure, and evolution of Earth and planets.

Since 2014: New appointments have brought expertise in igneous planetary materials (Blundy) and deep planetary mineralogy (Marquardt). Recruitment of Bryson and Nichols (planetary magnetic materials) to join MacNiocaill (tectonics) created the new Oxford Centre for Quantum Palaeomagnetism. The theme links strongly to Oxford Physics' exoplanets group and has been further strengthened through the creation of two permanent IRF posts (Wade and Barling) to support cross-theme surface and isotope analysis, respectively. This theme hosted four NERC IRFs in-period.

iii. Oceanography, climate and palaeoenvironment

We address the fundamental workings of the climate system and carbon cycle. New insights are achieved with remote and *in situ* observation, analysis, and modelling of the biology, chemistry, and physics of Earth's water and its record preserved in sediments. Strong networks – within Oxford, nationally, and internationally – contribute to solutions that mitigate the changing climate.

Since 2014: As planned, we have strengthened links with Oxford's leading social scientists, including in the Environmental Change Institute and the Smith School of Enterprise and the Environment, and continued to build on our links with Physics, Maths, and Zoology, and externally (e.g., the Met Office). Johnson has led the Oxford Climate Research Network since 2019. This theme hosted four IRFs. Henderson retains a 20% post following appointment as DEFRA CSA in Sept 2019.

iv. Palaeobiology and evolution

We aim to understand the processes governing biotic change on long timescales, including major evolutionary transitions, such as the origin and early evolution of animals, and how biodiversity responds to environmental change. We approach this by assessing the assembly of Earth's extant and extinct biodiversity, studied in a rigorous phylogenetic and mathematical framework.

Since 2014: Our UoA-wide vision to grow capacity in this area has led to significant expansion of research in OUMNH, returning five researchers in REF2021 (cf. 2.5 in REF2014). This theme attracted seven externally-funded IRFs during the REF period and four-internally funded IRFs awarded against cross-disciplinary competition. In DoES, recruitment of Cosmidis (Geobiology) brings expertise at the biological/mineral interface. Appointment of Saupe strengthens research in life-climate interactions.

v. Geodesy, tectonics, volcanology and related hazards

We address the fundamental physical and chemical processes governing tectonics and volcanism and their impacts from planetary-scale evolution to local, regional, and global hazards and risk. Our research advances via techniques and applications in Earth Observation, laboratory experiments and analyses, field observation, data analysis, and modelling.

Since 2014: Oxford remains a key member of **COMET** (Centre for Observation and Modelling of Earthquakes, Volcanoes, and Tectonics), providing a multi-institute interdisciplinary environment. We both advance the science and, as a 2014 goal, have increasing emphasis on providing societal advice on the impact of volcanic eruptions and earthquakes (**§4.2.1**). We have sustained strength with the recruitment of Hawthorne and Palin and one NERC IRF (Cassidy).

vi. Earth Resources

The occurrence of resources and their environmentally-secure development forms the focus of this grouping. Closely aligned topics are the science challenges in water resource security, geological CO_2 sequestration, and nuclear waste disposal.

Since 2014: Key aims were to expand industry links and to grow work on CO_2 sequestration. We have increased the number of industry Visiting Professors from two to five (**§3.1**), and doubled the number of major industry research contracts (**§4.2.3**). Contracts with the US Geological Survey (**USGS**) and the Canadian Nuclear Waste Management Authority open up new opportunities to apply our science to groundwater security and nuclear waste disposal.

1.2.2 Future objectives

- **Climate change and its mitigation** is, and will remain, one of the greatest challenges for our society this century. We will continue to lead the Oxford Climate Research Network (Johnson) and advance our understanding of the underpinning processes important for climate and mitigation of impacts. Our direction of travel is shown in work funded by the Oxford Martin School, which in turn led to a partnership (Kendall, Rickaby) in a University-wide strategic programme, *Oxford Net Zero*, to tackle the urgent zero emissions challenge.

- **Cryosphere Geophysics** is an environmentally-critical and timely field of study. Recent appointments (Kendall, Stevens) join Katz, and we will use this newly-established critical mass to build strategic links with the DoES Climate theme and with complementary groups in Oxford Physics, Maths, and Geography.

- Our investment in **geobiology** (Cosmidis) builds on new (Saupe) and existing expertise in **palaeobiology**, and promotion of Rickaby to Chair of Geology. A new building for the Department of Zoology (under construction) includes space designated for cross-disciplinary activity and represents a strategic opportunity to build on our already strong research links with biological sciences. This new dimension will advance knowledge of life–Earth interactions and links with biomaterials and climate mitigation groups.

- **Planetary Sciences** and exoplanet research is a growing strength in Oxford (e.g., the in-period appointment by Physics of Pierrehumbert as Halley Professor) and we continue to explore opportunities for a cross-disciplinary PhD programme. Within **Geodesy**, **tectonics and volcanology** and **Geophysics**, we have programmes developing our

understanding of processes operating on other planets. We have rebuilt strength in Planetary sciences (Bryson, Marquardt, Nichols). We will exploit our leadership in microanalytical techniques and investment in the Oxford Centre for Quantum Palaeomagnetism to develop cross-over applications (e.g., Fe isotopes) between planetary science, tectonics, microgeobiology, materials science, and medicine.

- Responsible use of **Earth resources** is a defining societal challenge. We will capitalise on the expertise of, and recruit new, Visiting Professors; and apply curiosity-driven research to challenges in the resource industry and third sector. For example, application of new paradigms in our understanding of crustal magmatism enables novel ways of recovering metals from volcanic systems (Blundy). We will continue expansion into the new sectors of water resource and anthropogenic waste disposal established in the last REF period (Ballentine). New appointments in Geophysics (Kendall) and Tectonics (Palin) further extend our capability in resource and sustainability.

1.3 Impact Strategy

Our strategy for realising impact from our research has four strands:

- **Applying our research to improve policy**: We engage with national governments and international bodies. We leverage our leadership of, or participation in, existing internal or national networks and create key routes to impact for our work across climate, natural hazards, defence, and sustainable resource use. This approach has: provided key science-to-policy stepping-stones leading to two of our submitted impact case studies; positioned Henderson to step into the DEFRA CSA role; and supported policy-making bodies in a further eight examples of wider impact (**§4.2.1**).

- **Enhancing the socio-economic benefit of research through Public Engagement with Research (PER)**: Engagement of the public with contemporary Earth sciences research is core to our ethos, with Pyle appointed as MPLS PER champion, and enhanced through the expertise and extensive visitor base of OUMNH. The Museum has held three interdisciplinary Earth sciences exhibitions since 2014: one (First Animals) forms an impact case study. Other activities include a major Bodleian Library exhibition (*Volcanoes*, Pyle), a Royal Society Summer Exhibition (Rickaby), participation in regional science festivals (16 in-period), short films, mobile exhibitions, and online media (**§4.2.2**).

- **Developing effective, long-term engagement with industry and third sector partners:** We have expanded our industry Visiting Professor scheme and doubled the number of active industry partners with 13 major research contracts worth nearly £4m (**§4.2.3**). We have established a strategic collaborative partnership with the UK Oil and Gas Onshore Library – *Beneath Britain* – to host the entire UK onshore reflection seismic archive and widen use of these data by UK universities: 18 projects have been supported since its foundation in 2018.

- **Promoting commercialisation of research outcomes**: Oxford University Innovation (**OUI**) supported ten projects registering new intellectual property from the UoA (from new seismic techniques for oil and gas discovery to advances in analytical techniques) and filed six patents. We increased consultancy activity, with 11 personal and ten department contracts (including advising a start-up company in Tanzania (Ballentine), which announced the discovery of a major helium resource province in 2016). We secured £170k of pump-priming support for a technology spin-out company.

Relationship to case studies: Two (Henderson, England) illustrate our work in **science-to-policy**; one (Rahman) describes **public engagement** impacts through a major OUMNH exhibition; and one (Cartwright) the **commercialisation of research** through our long-term engagement with industry and third sector partners.

1.4 Interdisciplinarity and International Research

Earth sciences is an inherently interdisciplinary field. Our researchers lead or participate in Oxford-wide networks in Climate, Energy, Biodiversity, and Water; and in interdisciplinary events and programmes run by the Oxford Martin School (e.g., 'Climate Change and our Oceans', jointly organised with Physics). Most of our major grants (e.g., ERC, NERC 'Geotraces', NERC 'Volatiles') involve international partners: 81 of our submitted 102 outputs include at least one non-UK co-author (see also **§4.1**, **§4.2**).

1.5 Open research

We engage with University and national initiatives to promote open scholarship and research. Our librarians (**§3.2.4**) support researchers to ensure compliance with institutional Open Access policy. An e-Newsletter includes a monthly list of all publications deposited into the Oxford Research Archive. Data generated comply with the data policy of their funder, e.g., NERC data repository. All numerical ocean and climate model data generated are submitted to nationally managed, accessible archives (CEDAS). Rock samples are catalogued and added to the OUMNH searchable collection. Open, digitised OUMNH and seismic research collections are detailed in **§3.2.4**; and examples of open-source software used in national facilities in **§3.3**.

1.6 Research integrity

Researchers adhere to the University's *Academic Integrity in Research: Code of Practice and Procedure* and research policies. Research Integrity is embedded within the induction programme for all new researchers, also including plagiarism, data security, and data storage. We encourage participation in the MPLS Division's course on Research Integrity, which covers good practice in research, how University researchers can meet their responsibilities, and the key principles and practices of good research conduct.

2. People

2.1 Staff

The DoES research community comprises 35.95 FTE academics (Prof or Associate Prof (**AP**)) and independent Category A researchers submitted to the REF, as well as 41 PDRAs, 60 PGR students, five Visiting Professors, and two active Emeritus Professors (holding major grants). These are supported by 27.1 FTE administrative and technical support staff. OUMNH is submitting its Director and four IRFs to this UoA. During the period, DoES and OUMNH hosted a total of 17 IRFs, of whom 13 were externally funded.

We seek to attract the best researchers at all career stages, support their scientific development, develop their international profile, and enable them to lead at the frontiers of their discipline; both here and by progressing to prestigious roles elsewhere. Early-career researchers (**ECR**) are a valued component of our research effort: 27% of our submitted outputs have a PGR student or PDRA as lead author. Examples of success since 2014 include: recruitment of Blundy, who brought his Royal Society Professorship to Oxford; promotion of Rickaby, against international competition, to the Chair of Geology (the first woman to hold the post); and the moves of Halliday to become Director of the Earth Institute at Columbia, and Tosca to Cambridge as Chair of Mineralogy.

2.1.1 Recruitment

The DoES has seen a significant change in the demographics of its permanent academic staff, appointing 12 new Profs/APs and four permanent research fellows. Six of these appointments were from outside the UK (five from the US, one from Germany). This balanced 12.8 faculty who left in-period, mostly due to retirement (nine). People re-investment has focussed on junior

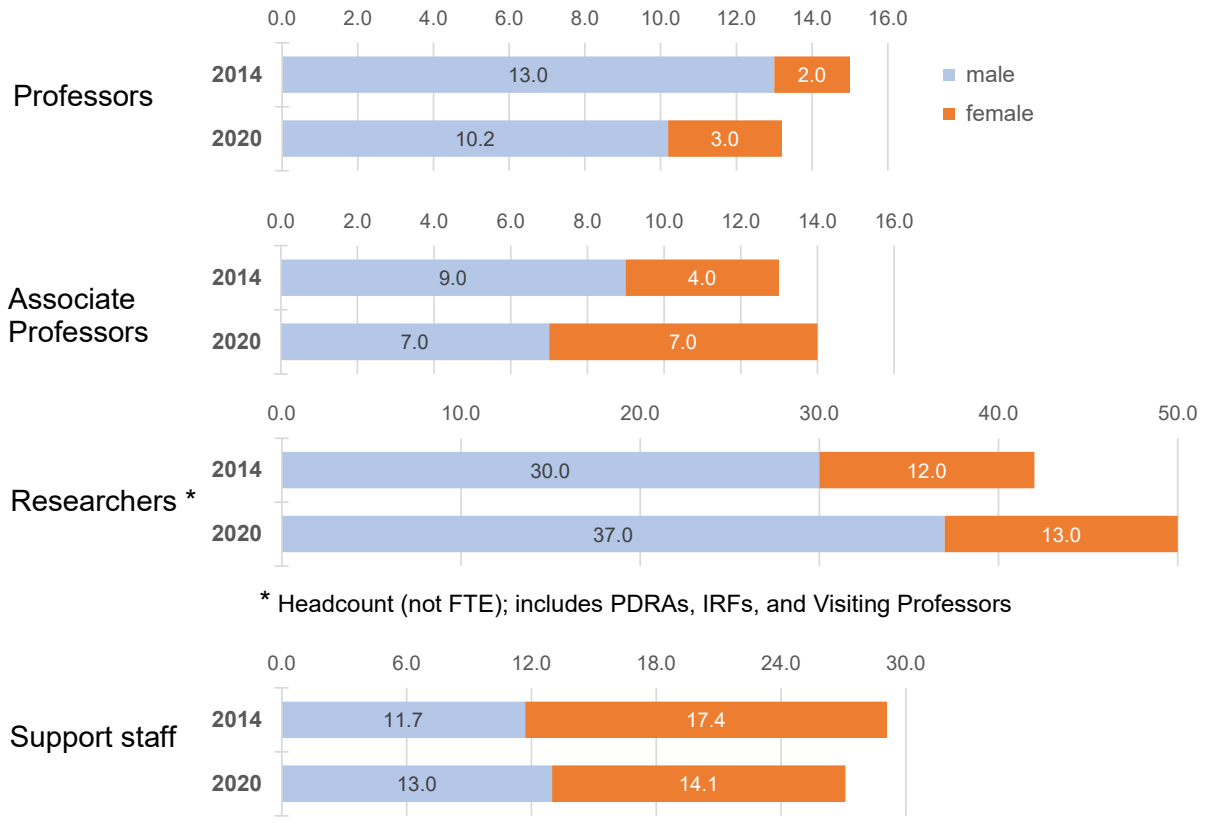
faculty with 10/12 appointed at AP level. The total number of DoES researchers – including permanent research fellows, IRFs, and Visiting Profs – increased over the period from 42 to 50.

All academic posts are recruited by international open competition, with broadly-defined advertising criteria to attract a wide pool of high-quality applicants. Appointment strategy is discussed by the whole faculty.

Diversity plays a major role in the search process: we use faculty discussion and targeted solicitations to encourage strong and diverse fields; all appointment panel members receive unconscious bias training; panel gender balance is maximized; and 'stop and review' is triggered in the case of a single-gender shortlist, in line with University policy. This strategy has **improved the gender balance** amongst DoES Profs/APs: 37% are female (50% in our AP body), compared to 21% (30% APs) in 2014 (Figure 2). At 7% in our Prof/AP body, we recognise the need to do more in terms of BAME representation (**§2.3**).

We have invested £1.45m since 2014 in start-up packages for new DoES faculty in the form of laboratory/field instrumentation and computing needs. We have used internal sources to match-fund two Leverhulme Trust Fellows in OUMNH; and to provide small grant support to IRFs (four awards in period - £6k to £25k).

Figure 2: DoES staff breakdown by gender



* Headcount (not FTE); includes PDRAs, IRFs, and Visiting Professors

PDRAs and IRFs are recruited internationally. 61% come from abroad, 34% are female. We mentor all fellowship applications, hold an open information day, and offer proposal reviews and practice interviews.

We have fully adopted the principles of the Concordat to support the career development of researchers and implement these through its Code of Practice. This includes formal inductions and welcome sessions run by the University. A tailored welcome pack and induction is provided for all staff on appointment. Salaries meet equal pay requirements and Fixed-Term Employees

Regulations. Since 2017, the University has been an accredited Living Wage foundation employer.

2.1.2 Career development

Faculty: All early-career faculty have reduced teaching and administration loads during their first three years. Each is assigned a senior faculty mentor for their five-year probation period (an additional year's probation has been offered to everyone impacted by COVID-19). Reviews, after two years and at end of probation, are conducted in accordance with the University Code of Practice for the Employment and Career Development of Research Staff. This includes reports on teaching, research, and service, and provides formal supportive feedback to the individual. No faculty have failed probation in the last three REF periods.

Faculty are offered an annual appraisal with the HoD to discuss career growth, aspirations, recognition, and promotion (**§2.1.4**). The HoD maintains an overview of faculty workload with the Associate Head of Department (**AHoD**) (Teaching) to balance teaching (including field teaching, examining and tutorial load) and service (administration and management in the department and University).

PDRAs and IRFs: On appointment, a choice of mentors is offered to IRFs and PDRAs, in the case of PDRAs to complement the support they get from their PI. We have an established system of reviews for all fixed-term research staff at the mid-point and end of their one-year probation period.

Termly meetings between the PDRA/IRF body and the AHoD (Research) allow concerns and suggestions for improving department processes and collegiality to be raised. One exemplar outcome is our highly-valued annual fellowship day for PhDs, PDRAs, and IRFs which includes presentations from IRFs and faculty to highlight opportunities and best practice in preparing for academic job applications and interviews.

Of known (62 of 74) PDRA/IRF destinations, 41% went on to a further PDRA or IRF post, 28% to a faculty position, and 31% to industry or the third sector.

2.1.3 Research and Impact Leave

Faculty sabbatical leave for career development accrues at one term's leave for every six of qualifying service. All faculty support colleagues to take this leave by covering their duties. Research activities undertaken include paper, book and grant writing, extended fieldwork, course development, and visits to other institutes. Impact activities include design of exhibits (e.g., Pyle, *Volcanoes* exhibition, 2017), public lectures and other public engagement activities, as well as report writing for NGOs or other organisations (e.g., Henderson, Royal Society Report, *Future ocean resources, metal-rich minerals and genetics*). 13 faculty took sabbaticals in-period, totalling 27 terms of leave.

2.1.4 Reward, recognition, and promotion

An annual Recognition of Distinction exercise enables Associate Professors to apply for full professorial title (and a small pay increment), informed by international peer review. Six faculty (four male, two female) were awarded title in-period. Academic salary progression is via the Professorial Merit Pay scheme, every two years. The HoD actively encourages those who fit the promotion or salary progression criteria to apply, especially amongst under-represented groups. Out-of-round recognition can occur through retention awards (pay and/or title enhancement), and stipends for major leadership roles. 17 awards across all categories were made in-period.

Recognition of excellence for support staff is either through promotion/regrading (one promotion to an IRF was awarded in-period) or through the award of AP or Professor title to permanent

IRFs who engage in teaching. The latter offers a clear career progression route for IRFs who lead our research facilities: one Associate Professor title was awarded in-period.

2.2 Research Students

2.2.1 Recruitment and funding

We admitted an average of 16.7 PhD students per year, with ~2/3 recruited via competitively-awarded cohort-based programmes funded by NERC. Since 2014, the main route has been the NERC-Oxford DTP in Environmental Research (PI: Pyle, UoA7) but also includes the Oil and Gas CDT led by Heriot Watt. Within the Oxford DTP, we accept students from all three 'streams' – 'Biodiversity, ecology, and evolutionary processes'; 'Physical climate system'; 'Dynamic Earth, surface processes, and natural hazards' – further illustrating the interdisciplinary nature of our research. Other students are funded by STFC, ERC, industry, foreign national government grants, one full international scholarship each year from Oxford's flagship Clarendon Fund, and two annual 50% college scholarships. The ratio of applications to places averaged 3.3 to 1.

2.2.2 Training, support, and mentoring mechanisms

All PhD students have a minimum of two Oxford-based supervisors to provide a safety net. The Division and University offer an extensive range of training enrichment, including in advanced presentation skills, connecting with industry, scientific writing, time management, communication of research, and public engagement. The focus of the NERC-Oxford DTP on cohort-led learning in Year 1 engenders an immediate network of peers, and exposure to faculty across the MPLS and Social Sciences Divisions for support and collaboration (nine departments participate); as well as opportunities to engage with 22 external partners (including the Met Office, National Oceanography Centre, and Natural History Museum, London).

PhD students and supervisors each provide progress reports four times annually. Reports that flag issues (or null returns) are brought to the attention of the Director of Graduate Studies for follow-up.

All PhD students are members of a college and are assigned a college academic for pastoral support to provide an additional contact point in case of physical, mental, or personal issues. Students with a disability, long-term physical or mental health condition, or a specific learning difficulty have access to the University Disability Advisory Service, a team of specialist advisors trained to facilitate study. We have faculty and support staff trained in mental health first aid, and in harassment, signposted in the student's handbook and advertised via posters throughout the department.

2.2.3 PhD Student Progression, Completion, and Destinations

Student progression occurs in two stages before completion: within their first four terms and after seven terms. Progression at each stage requires a report, presentation (in a student-led two day mini-conference open to all researchers), and an interview with the Director/Deputy Director of Graduate Studies and a faculty member in a related field.

In-period, 117 PhD students have been based in and graduated from the DoES (equating to 99.59 FTE once adjusted to reflect interdisciplinary co-supervision across UoAs). PhD students have access to a wide range of DoES, OUMNH, University, MPLS Division, and DTP workshops and career support. 76%, 89% and 91% of DoES students submitted their thesis within 49, 60 and 72 months respectively and were awarded a PhD. Two students received an MSc, one sadly died, and the remainder withdrew.

Destinations: 65% of PhD graduates took up a PDRA/IRF position, 8% went on to further study (e.g., PGCE training), and 27% into graduate employment (including the insurance industry; as

data scientists; international resource companies; and the Civil Service). 55% of the PDRA posts (i.e. 37.5% of graduates) were abroad, predominantly at top North American institutes (e.g., Carnegie, Columbia, Princeton, Smithsonian, Toronto), but notably also across Europe and Japan.

2.3 Equality and Diversity

We believe that a fair, inclusive, and diverse department environment underpins all our other goals. We recognise that we still have work to do in this area, especially in terms of BAME representation, and encourage a culture of proactive discussion to identify actions that widen participation through both recruitment and retention.

The Workplace and Equality Committee (**WEC**) is an integral part of the DoES structure. Meeting termly, and with representation from all parts of the community, the WEC implements actions to build and support diversity within the workplace. A variety of formal and ad hoc staff and student groups feed into the WEC including an annual online staff survey and reports from moderated focus groups with support staff, PhD, and PDRA/IRF bodies.

DoES holds an Athena SWAN Bronze award (2016); OUMNH is applying in April 2021. Improvement in the DoES faculty gender balance has been detailed (**§2.1.1**). Similar efforts have been made to tackle the gender gap amongst our student body, and we now have a 50:50 male:female balance in both our undergraduate (**UG**) and PGR populations.

We have a Stonewall Ally on the staff and consult with LGBTQ+ representatives to ensure any issues are identified and rectified, and support provided where needed. Allies and Harassment advisers are fully trained and signposted on posters, in staff handbooks, e-bulletins, and online.

We are working to tackle BAME under-representation in Earth Sciences found at all levels from undergraduate to professor. Supported by our Communications and Outreach Officer (1FTE), we have focussed UG recruitment since 2018 on geographical locations with broader ethnic diversity and helped to pilot the Oxford UNIQ residential summer school to introduce students from non-traditional backgrounds to higher education. UG intake in both 2019 and 2020 was 20% BAME, up from <10% in previous years.

An internal DoES graduate student-led report and faculty reply prompted an Oxford-organised national discussion of BAME representation within the discipline (June 2020). The online panel included Oxford students and faculty as well as senior representatives from the Geological and Royal Astronomical Societies. The event attracted 225 participants from 39 UK and 17 international institutes. Recommendations from this process have informed UK Head of Earth Sciences and Geological Society London discussions to address diversity within UK Earth sciences.

2.3.1 Flexible working

Meetings and seminars are scheduled in core hours to allow for family commitments. Childcare responsibilities are surveyed and proactively taken into consideration when scheduling teaching hours. Flexible working is offered to all staff when possible, exemplified pre-COVID by some staff working from home part of the week to minimise commuting and others shifting temporarily to part-time working to balance domestic responsibilities.

2.3.2 Support for carers, returning staff, and staff with protected characteristics

Carers are encouraged to disclose their responsibilities, in confidence, to managers or other colleagues. Support to enable a positive work-life balance includes flexible working (**§2.3.1**), and additional time off to deal with domestic emergencies. There is a short-term carers' leave scheme, options to take a career break of up to 12 months, and access to emergency back-up

childcare and adult care. A Returning Carer's Fund offers small grants to support staff returning to research, or who require support to maintain their research group during a period of leave. In-period, 16 researchers took paternity leave, six maternity leave, and three shared parental leave.

The University Disability Advisory Service assists in assessing need and identifying reasonable workplace adjustments (e.g., standing desks for several individuals, a quieter environment for an individual with Autism Spectrum Disorder); and, together with the University Occupational Health Service, provides additional support and advice for students/staff with mental ill-health. Mental health workshops are a termly event. DoES has trained Mental Health First Aiders on the staff.

2.3.3 Staff and student wellbeing

Our relatively small size makes for an informal, friendly community: people know and support each other, professionally and socially; and visitors often comment favourably on an environment that is seen as inclusive and welcoming.

DoES runs a variety of events to foster the sense of community and to promote network building across groups and career stages. These include daily coffee breaks in the Researchers Common Room, and a weekly 'Brown Bag Lunch' with discussion of emerging research topics. Weekly social gatherings in the common room and an annual Christmas party are run by the postgraduate students; and a Summer BBQ brings all staff together. We hold regular discussion sessions for PDRAs, as well as periodic focus groups and surveys.

During the COVID-19 pandemic, we have sought to maintain a regular series of online events and bulletins, from coffee mornings to HoD briefings, and twice-weekly Yoga classes to maintain morale and cohesion amongst our community. A communications group, with members from across DoES, co-ordinates regular faculty 'check-ins' with all staff and graduate students, with follow-up by senior faculty or HR when needed.

2.3.4 E&D and the REF submission

In line with the University Code of Practice, quality was the primary selection criterion for outputs. We held a workshop (2019) to train faculty and IRFs across DoES and OUMNH to promote reviewer consistency. Outputs nominated by eligible staff were reviewed internally twice (and again if the two reviews differed significantly); an external moderator calibrated a subset of outputs. We monitored the gender balance of our Outputs submission after internal ranking. From a Category A staff population split 72% male / 28% female, the submitted outputs are attributed 63% male / 37% female.

3. Income, infrastructure, and facilities

3.1 Funding strategy and profile

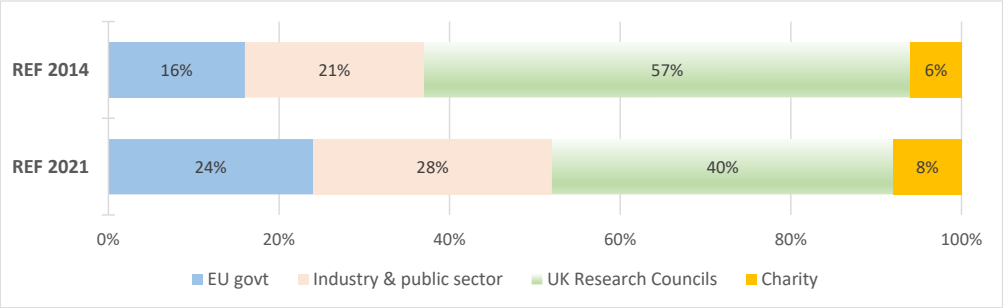
NERC and the hydrocarbon/extractive industries were our main UK government and industrial funding sources in the last REF. With NERC responsive mode funding decreasing in real terms, key objectives in this REF period have been to widen our funding base (Figure 3) and to enhance proposal competitiveness.

In-period, over 44 sponsors have contributed £43.5m research income. These include four UKRI councils (EPSRC, BBSRC, STFC, NERC), the ERC, industry (e.g., Petrobras, Schlumberger, Shell, Exxon-Mobil, Total, Statoil, BHP Billington), government (e.g., DfID, BEIS, DECC) and third sector (e.g., USGS, Canadian Nuclear Waste Management Organisation, British Geological Survey, NATO).

Part of our strategy has been hosting Visiting Professors (a formal title awarded by the University) who are leaders from the hydrocarbon (Daly, Levell, Idiz) and mineral (Robb) sectors, and the Canadian National Geological Survey (St-Onge). They advise on our external-facing research strategy, and contribute to research proposals, teaching and supervision of UG and PGR student research projects, and career advice.

Our strategy has been successful: since 2014, the number of significant research contracts (>£100k) with industry or the third sector has increased to 13. Consequently, industry funding represented 28% of external grant income during the period compared to 21% in REF2014. The other two principal funding sources were EU Government (24%, up from 16%) and decreasing reliance on UKRI (40%, down from 57%).

Figure 3 Comparison of funding sources, REF2021 *vs* REF2014 [1]



3.1.1 Research funding, research outputs, and impact

In-period, we have been awarded 75 external grants of between £100k and £1.8m in value, as well as many smaller awards. Of particular note, since 2014 Oxford won seven ERC grants from PE10 (Earth Systems Sciences), bringing the total to date to 15, the highest number of PE10 awards to any single-site institute in Europe. Another ERC Starting Grant Award was awarded from LS8 (Ecology, Evolution and Environmental Biology).

Awards supported >1,900 publications across our themes, many in leading subject journals. 149 were in the *Nature*/*Science*/*PNAS* publication groups, alone attracting >4,300 citations.

Selected ERC awards and exemplar outputs illustrate how external funding enables high-quality training and research (see **§4.1** and **§4.2** for impacts from grants).

- **GRACE: Starting Grant** (2008-15, Rickaby). Training three PDRAs, a major output shows the specificity of the enzyme RuBisCO, the most abundant enzyme on Earth catalyzing the fixation of CO_2, provides a potential pathway to genetically engineer more efficient RuBisCOs. (REF output: Poudel et al., 2020).
- **NOBLE: Advanced Grant** (2011-17, Ballentine). Supporting three PDRAs, research identified and quantified halogen recycling into the terrestrial mantle, re-set the chondritic reference database for halogens, and shows wet accretion to be a viable mechanism to account for the distribution of terrestrial halogens. (Two REF outputs: Chavrit et al., 2016; Clay et al., 2017).
- **ISMAGIC: Starting Grant** (2012-17, Katz). Training one PhD student, two PDRAs, and collaborating with Langmuir and Huybers (Harvard) and Hirschmann (Minnesota). Three REF outputs (Crowley et al., 2014; Cerpa et al., 2019; Keller et al., 2017) show that

[1] REF 2021 figures exclude a £5.4m deferred capital accounting adjustment (from UK charities) relating to the DoES building, completed in 2010.

fluctuations in sea level drive variations in mid-ocean ridge magmatism and indicate that mantle carbon promotes channelised melt transport at mid-ocean ridges.

- **DEEPTIME: Starting Grant** (2015-21, Sigloch). Training two PhD students, two PDRAs and engaging three international partner institutes. 2 REF outputs (Hoseini et al., 2020; Sigloch et al., 2017) show that the deformation and sinking of subducted lithosphere follows more systematic patterns than commonly perceived in geodynamics and that the complexities of mantle processes are dominated by shallow paleo-trench geometries.
- **TEMPO: ERC Starting Grant** (2016-21, Benson). Two REF outputs (Benson et al., 2014a, 2014b) provided the foundation for this grant which has to date trained seven PDRAs and established major patterns of dinosaur and bird evolution. This includes body sizes, multiple transitions to quadrupedality in sauropodomorphs, and the evolution of vision and hearing modalities and nocturnality in theropods and birds.
- **APPELS: Consolidator Grant** (2016-21, Rickaby). Training one PhD and three PDRAs, this produced two REF outputs (Lu et al., 2018; Shafiee et al., 2019). The latter shows that the marine ammonia oxidising archaea (AOA), organisms that catalyse the nitrogen resource availability for eukaryotes, have some of the highest Fe requirements of all marine plankton such that AOA growth in surface waters may be Fe limited.

3.1.2 Research Facilitation, Finance Support and Communication

In DoES, pre-award support is provided by the Research Committee and a full-time Research Facilitator (1 FTE). An internal peer review process is arranged for applications of all types and sizes, including feedback from faculty, and practice proposal presentations and interviews. This approach has contributed directly to the ERC funding success described above. The DoES finance team (4.7 FTE) provides project management, purchasing, and accounting support; whilst a Communications and Outreach Officer ensures high-profile research is promoted through print and online channels. Visiting Professors and other networks across Oxford, and externally, help to promote research impact. Links with alumni, many in industry, are maintained via social media, on-site events, and an annual magazine outlining our key research news.

In OUMNH, the Research & Impact team (2 FTE) manages grant applications to, and awards from, research councils and trusts. 12.6 FTE public engagement staff manage research communication.

3.2 Facilities

The DoES occupies a purpose-designed building opened in 2010, close to the Grade I listed OUMNH built in 1860. UoA7 researchers also make use of analytical facilities (including AMS, XRD, BET, and TEM) in adjacent departments: Physics, the School of Geography and Environment, and the Research Laboratory for Archaeology & the History of Art (**RLAHA**). The latter houses one of two NERC ^{14}C dating facilities and, with a common interest in improving chronology, provides a key partnership for DoES (e.g., climate group: Henderson, Rickaby).

A suite of nine small research facilities (**SRFs**), run by technicians or scientists on permanent contracts (9.0 FTE), underpins and supports research across the UoA. The SRFs are complemented by a range of specialist labs run by individual academics or groups of academics.

3.2.1 Small Research Facilities (SRFs)

SRFs provide continuity of specialist knowledge, training to students and staff at all levels, and analytical technique development. Our submitted Category A staff include four SRF managers who have been appointed at (or promoted to) IRF level and have their own independent research programmes (Barling, May, Wade, Holdship).

Recognising the value of the SRF model, we have increased the number of SRFs from six to nine during the REF period:

- (**NEW**) Research Computing SRF (software sustainability and best practice development, HPC use)
- (**NEW**) Clean Chemistry Suite
- (**NEW**) Mass Spectrometry Suite (MC-ICPMS and TIMS)
- Trace Element Analysis
- Stable Isotope Analysis
- SEM and Electron Probe (Surface Microanalysis)
- Geofacilities (optical microscopy, rock cutting/crushing, thin sections)
- Organismal imaging (multi-plane focus-stacking micrography, photomicrography and tomography workstations)
- Workshop (High precision materials machining)

The Clean Chemistry and Mass Spectrometry (**MS**) Suites were created by consolidating individual faculty clean labs and MS equipment into a shared SRF provision. This model has improved access, flexibility, and funding continuity to maintain the technical expertise in these areas. Similarly, research support for programming and computational hardware in the department had previously been kept within different faculty groups in geophysics; consolidation as an SRF now facilitates shared access for our researchers.

Prioritization of access and oversight of the SRFs is undertaken by the Department's Research Committee, chaired by AHoD (Research). An SRF manager sub-committee provides a forum to feed into the Research Committee, identify common operational issues, and develop strategic plans for future provision. Unfunded research staff and students can apply for SRF access through the Research Committee to complete research outputs or pump-prime grant proposals.

Continued investment ensures that our SRFs provide the support required for research. For example, the Electron Microprobe was procured in-period through a NERC capital grant (£500k plus £83k internal funds). The DoES has recently invested in a CNC lathe, Vertical Milling Machine, and CAD capabilities, enabling a step-change in, for example, design and construction of precision high-pressure in-vacuum crushing equipment installed in the Noble Gas Isotope Laboratory. The analytical SRFs are used routinely by other cognate disciplines (Materials, Geography, RLAHA) and external users to augment funds raised by internal SRF charges. For example, our workshop SRF has constructed seven high-pressure piston cylinders for materials research at institutes around the world (£420k total turnover).

3.2.2 Faculty-run laboratories

Faculty labs are managed by individuals or by groups of faculty. All faculty have access to secure laboratory bench-top analytical space, as needed. Some have extensively equipped laboratory space, fully funded by their research programmes and engaging other faculty through collaborative effort:

- (**NEW**) **Centre for Quantum Palaeomagnetism** (MacNiocaill, Bryson, Nichols) is centered on a dual steel-shielded magnetic field-free room containing a 2G magnetometer with extensive demagnetization and related equipment. Orders have been placed in this REF period for an upgrade to include a **new generation of quantum diamond microscope** to support the recent recruitment of Bryson and Nichols.
- (**NEW**) In 2020, DoES established new laboratory space for **geophysics field equipment testing**, calibration, and maintenance (Kendall, Stevens).

- (**NEW**) Noble Gas Isotope Laboratory (Ballentine), **a state-of-the-art isotope laboratory** commissioned in this REF period containing four static sector gas mass spectrometers, peripheral equipment and supported by 1.0 FTE laboratory manager fully funded through research income.
- (**NEW**) **Experimental sedimentary geochemistry laboratory**, including XRD and supported by 0.5 FTE lab manager; originally for Tosca, and currently being extended to include biogeochemistry (Cosmidis).
- **Experimental Petrology Laboratory** (established by Wood; oversight now transferred to Blundy) investigates high-pressure mineralogy with two piston-cylinders and a multi-anvil apparatus for high-pressure experiments, together with tube furnaces and related analytical facilities.
- The **Shell Geoscience Laboratory** (Cartwright) for subsurface geological interpretation of petrophysical and geophysical data. This consists of six high-specification seismic interpretation workstations (operating Schlumberger's Geoframe and Petrel Software (~US$20m), and IHS's Kingdom software), two RAID arrays providing 24Tb of storage, and two servers with 32Gb of RAM.
- Other laboratory space includes a **marine bio-culturing** lab (Rickaby, Henderson), **palaeo-3D imaging/visualization** lab (Saupe, Benson, Smith), **volcanology** lab (Mather, Pyle), and **sedimentary geochemistry analysis** (Robinson, Mather).

3.2.3 Computing

IT provision in DoES is overseen by the IT Committee. Our researchers have access to high-quality computing infrastructure locally (supported by two full-time computer officers) and at University level. Since 2014, DoES has replaced seven discrete servers and multiple disc systems with three physical servers and two-disc systems and an off-site back-up repository to allow for disaster recovery and business continuity (£65k) and extensive switch/network upgrades (£80k).

Our researchers make extensive use of the central Oxford Advanced Research Computing (**ARC**) facilities, which host and support scientific computing platforms. Katz chaired the ARC Executive Committee (2013-16). The Research Computing SRF manager supports researchers to make optimal use of time on ARC.

Palaeobiology is also supported by high-performance computing facilities for 3D visualisation, statistical analysis, and modelling; and complemented by the proximity of the OUMNH world-class research collections.

3.2.4 Collections and library provision

OUMNH houses a collection of 7 million geological and zoological specimens, designated by Arts Council England as of national and international importance for research and engagement. The collections are fully accessible for research by UoA members and the international research community through the newly updated Collections Online portal. They are supported by 22.9 FTE specialist staff (at July 2020) and over 6,000 specimens are loaned globally each year for research. Museum facilities also comprise a palaeontological preparation laboratory and conservation suite, plus imaging facilities that include SEM and 3D laser scanning.

Both DoES and OUMNH house libraries that are available to members of the UoA (supported by 1.62 FTE librarians) and which contain the main Earth science journals, and provide important historical collections, a designated archive, maps, and other special publications. Oxford invests ~£100k/yr on journals and e-resources in Earth sciences, through the Radcliffe Science Library. Almost all journals relevant to our research are now available by electronic subscription. We host *Beneath Britain,* the largest archive of 3D seismic data in academia (see **§1.3**).

3.3 Use of collaborative or national facilities

We use UK national and international facilities extensively across all research themes. Below we detail exemplar activities and outcomes of peer reviewed or competitively funded access:

Synchrotron Radiation Light Sources:

Researchers used the **UK Diamond Light Source** to calibrate volcanic Br degassing (Pyle); visualise key early fossils and fish bone microstructures (Benson); image some of the oldest fossil green algae and Burgess shale fossils to show the importance of clays to fossilisation (Anderson); and used S-near-edge XANES measurements of experimental glasses to underpin our understanding of sulphur speciation and solubility in silicate melts (Wood). The **BESSY synchrotron, Berlin**, and **ALS synchrotron, Berkeley**, were used to determine the relationship between meteorite cooling, core crystallisation and magnetic field generation, developing the thermal and structural history of the first planetary bodies in our solar system (Bryson). Use of the **German Synchrotron Radiation Facility DESY** enabled four PhD students to develop an atomistic understanding of the role of water in controlling elastic properties in high-pressure MgFe-silicates at deep planetary pressures (Marquardt). The **Canadian Light Source, Saskatoon**, and **Stanford Synchrotron Radiation Light Source** showed inorganic formation mechanisms of carbon/sulphur microstructures resembling microbial structures being used as biosignatures, winning a Canadian Light Source award for this work (Cosmidis). The **ISIS Neutron & Muon Source** has shown how neutron tomography can resolve internal structures in fossils that are invisible to X-ray-based imaging (Rahman).

Supercomputing:

US NSF-funded Yellowstone and Cheyenne supercomputers and **Swiss National Supercomputing Centre** enabled Khatiwala to run simulations using his 3D model of ocean circulation and biogeochemistry to identify key processes controlling oceanic zinc distribution; revise global carbon fluxes from oceanic riverine and carbon transport; and build a global reconstruction of historical ocean heat storage and transport. **Archer** (NERC supercomputer) has been used to develop a novel numerical method (AxiSEM3D) that simulates global seismic wave propagation in realistic aspherical 3D earth models. This underpins 11 Oxford papers as well as community users through an open-source interface (Nissen-Meyer).

Research Ships:

The **RRS Discovery (NOC)** was used to retrieve ocean bottom seismometers and magnetometers which produced observational evidence for a reverse rupture earthquake mechanism, predicted theoretically but never observed before (Kendall). The **RRS James Clark Ross (NERC)** and **UiT Research Vessel FF Helmer Hansen** were employed over four cruises to quantify bio-optical models that quantitatively link glider and satellite observations – used to track the increasing dominance of *Phaeocystis* in the Barents Sea, a marine phytoplankton that can function at a wide range of temperatures and salinities (Bouman, **§4.2.1**).

National instrument pools:

Polar GNSS receivers **(US NSF Geodetic Instrument Pool)** on the Greenland Ice Sheet, Ross Ice Shelf and George VI Ice Shelf have identified stress coupling between neighbouring supraglacial lakes during rapid drainage (Stevens). Reftek data loggers and seismometers **(NERC Geophysical Equipment Pool)** in the Antarctic Rutford Ice Stream have generated new seismic icequake datasets, with papers now in review (Kendall).

Other Facility Use:

The **NERC Ion probe in Edinburgh** was used by Pyle, Mather, Cassidy, and Wood to support four PDRAs and three PhD student projects. One outcome showed for the first time the effect of oxygen fugacity on halogen volatility in magmatic systems (Wood). The **BGS core repository** supported work detailing the processes controlling the termination of Oceanic Anoxic Event 2 from reconstructed Southern Hemisphere sea-surface temperatures (Robinson).

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

4.1 Collaborations, networks, and partnerships

National and international collaboration underpins our research. Of our 102 submitted outputs, 94 have co-authors external to Oxford: 57 with other UK authors; 41 from elsewhere in Europe; and 66 from wider international institutes.

Examples of effective partnerships in-period include:

- The Oxford-led NERC consortium (PI: Ballentine) 'Mantle volatiles: processes, reservoirs and fluxes' (2014-21) brought together 21 co-PIs, ten UK HEIs and international partners and supported seven PDRAs and eight PhD studentships. The Oxford team included six faculty and three PDRAs. This consortium has made major advances through 84 publications (25 with an Oxford author, 45 with international partners); extended the UK network through five 'all-hands' meetings, including two with two related consortia (a NERC funded programme with Ballentine/Mather sitting on the management board); and established a major new sample resource from a multinational expedition to Kamchatka, Russia.
- Mather and Pyle contribute to the NERC large grant 'Rift Volcanism: Past, Present and Future' (2014-21) with six UK HEIs and five international project partners. The Oxford component supported one PDRA (now faculty in Brussels); resulted in 13 publications; and contributed Oxford expertise to hazard elicitations run by the BGS for the World Bank (2015), and to a report for the BGS Earth Hazards and Observatories Programme. A joint Oxford/Kenya GCRF workshop (Kenya, 2018), involving the UK and six African countries, catalysed new collaborations in Kenya between academics, industry (hydrothermal energy), and government.
- Other examples include participation in **OSNAP** (Johnson), a £50m international programme to observe the ocean overturning circulation at subpolar latitudes in the North Atlantic and its £2m follow-up, **SNAPDRAGON** (PI: Johnson); **COMET** (Mather, Pyle, Walker, Hawthorne) brings together world-leading scientists from 11 UK institutes working closely with the National Centre for Earth Observation, European Space Agency (**ESA**), and other international partners (**§4.2.1** and **§4.2.4**); and **Geotraces** (Henderson), an international research programme focussed on biogeochemical cycles in the oceans, involving 15 international partners, and active participation of >30 countries (with data freely available online).

4.2 Relationships with key external stakeholders and audiences, and wider impact

Our research contributes to the wider economy and society and has impact through informing government environmental policy, public engagement, and in support of industry (**§1.3**).

4.2.1 Applying our research to improve policy

We highlight our impact on policy by presenting examples in four areas:

Climate, Oceans, and Conservation

- Henderson chaired the Royal Society working group Ocean Resources; co-chaired the Foreign and Commonwealth Office (**FCO**) international meeting on *Environmental and Legal Implications of Deep-sea Mining*; presented evidence to the House of Commons Environmental Audit Committee on *Sustainable Seas* (2018); and served on the expert advisory group for the 2018 Government Office for Science report, *Foresight Future of the Sea*.

- Rickaby was a co-author on the UN Joint Group of Experts on the Scientific Aspects of Marine Environmental Protection report, *High level review of a wide range of proposed marine geoengineering techniques* (2019).
- Bouman contributed to a series of reports, roadmaps, and workshops to improve satellite ocean colour products and algal bloom detection (ESA, IOCCG, NASA, DEFRA / Environment Agency).
- Saupe initiated a series of workshops in sub-Saharan Africa (2019) on biodiversity data collection/analysis, involving policymakers to discuss implementation of sustainable development goals. This has increased capacity to make effective conservation decisions in >10 African nations.

Natural Hazards

- Walker consults via the World Bank in the design of a new country-wide seismic hazard assessment for the Kyrgyz republic.
- Pyle/Mather contributed to a working paper on the impacts of volcanic ash to the UN Office for Disaster Risk Reduction global assessment report (2019 - GAR19). Mather hosted and presented advice on funding Earth observation research for monitoring volcanoes to the Cabinet Office, Government of Japan (2016). (Also See **§4.2.4**)
- Novel seismic techniques developed by Nissen-Meyer have been used to develop decision-making processes associated with tsunamis (GNS New Zealand representation to government leading to NZ$20m warning network) and earthquakes (Southern California Earthquake Center).

Defence

[Text removed for publication]

Resources and Sustainability

- Through a Royal Society/Royal Academy of Engineering working group, Cartwright contributed to appraising shale gas research applicable for the UK.
- Ballentine worked with the UN International Atomic Energy Authority (2016) to co-author a paper on *State-of-the-Art and Emerging Approaches to Identify Fracking Derived Gases and Associated Contaminants in Aquifers* and applies this approach with the USGS (2018) to protect groundwater resources in California.
- Kendall contributed to a joint US-UK (NERC-NSF) workshop on improving Understanding of Potential Environmental Impacts Associated with Unconventional Hydrocarbons (2015) and provided consultancy to the UK Oil and Gas Authority on induced seismicity from shale gas stimulation (2019-20).

4.2.2 Public Engagement with Research (PER)

Our PER activities have helped to **enrich research**, **establish new collaborations**, **and promote diversity in the discipline.**

Pyle was the first MPLS Division Academic Champion for PER (2017-20); Mather (Royal Society Rosalind Franklin Lecture, 2019; Darwin College Lectures, 2020) and Rickaby (Royal Society Summer Science Exhibition, 2019; and short films, 'Adaptability', 2015 and 'Hay Levels', 2017) are visible female role models for Earth science students. Other activities include *Being Human* (2016), *Curiosity Carnival* (2017), the *Oxford Science Festival* (annually) and *Super Science Saturday* (twice yearly). Since 2014, Oxford's online science engagement platform *Oxford Sparks* has produced eight science podcasts and seven videos (with associated resources for schools) based on our research.

Specialist public engagement staff in OUMNH (12.6 FTE) interface between research and public audiences. OUMNH receives 800,000 visitors annually, the highest number to any university science museum globally. The museum's Contemporary Science & Society series included three exhibitions with a significant Earth science component: *Handwritten in Stone*, 44,298 visitors (Searle); *Bacterial World*, 174,805 visitors (Anderson); and *First Animals*, 219,000 visitors (Dunn, Murdock, Rahman, Smith; impact case study).

The NERC/ESRC-funded project 'STREVA' produced a mobile volcano simulation which toured seven venues over 20 days, attracting over 5,000 visitors. A spin-off card game, 'Volcano Top Trumps', became commercially available in 2015 and has been adopted by teachers in the UK and internationally. These provided the inspiration for follow-on AHRC-funded research projects engaging directly with communities in the Caribbean.

In 2017, Pyle curated the first science-led exhibition, *Volcanoes*, in Oxford's Bodleian Libraries and produced an accompanying book. Over three months this received 55,000 visitors and featured in 100 items of press coverage reaching ~200 million people.

Researchers from the UoA have also led efforts to recognise global geological heritage sites, with OUMNH involved in the new Discovery UNESCO Global Geopark (Newfoundland, Canada, 2020); and Searle helping develop proposals for UNESCO World Heritage status GeoPark sites and SSSI across Oman.

4.2.3 Links with Industry and the Third Sector

The application of geochemical tracer approaches has found particular success. The noble gas laboratory (Ballentine) has applied isotope tracing of subsurface fluid systems to projects funded by: the **UK Department of Energy and Climate Change** to determine the long-term performance of geological seals for carbon capture and storage applications; **ExxonMobil**, showing that a significant portion of CO_2 injected into depleted oilfields can be microbially converted to methane, and must be considered when making a safety case for anthropogenic CO_2 burial; **Total** oil company to determine the commercial viability of natural subsurface hydrogen sources; and the **Canadian Nuclear Waste Management Organisation** to determine the geological history of fluid movement through proposed nuclear waste disposal sites.

Two projects with **Shell**: i) develop the use of isotope tracers in determining past surface depositional environments (Henderson/Cartwright); and ii) determine the natural flux of hydrocarbons from geological trapping structures into the environment, showing an under-recognised source of natural greenhouse gas emissions (IRF, Foschi). **BP Exploration Ltd** (Cartwright) funded work on depositional control on UK shale gas resources; and **Saudi Aramco** commissioned work on predictive models for subsurface fracture systems critical for subsurface fluid migration (Cartwright).

Other major contracts from **Hanno Resources** informed metal ore exploration strategy (Robb) and the **Abu Dhabi National Oil Company** to build an understanding of the controls on collision tectonics and ophiolite emplacement (Watts).

4.2.4 Responsiveness to national and international events

Our long-term international collaborations with scientists and practitioners in disaster management – in particular through COMET, 'Earthquakes Without Frontiers', and 'STREVA' – has built capacity to respond to rapidly emerging events. For example, we provided scientific advice, analysis and data following volcanic eruptions in Chile (Calbuco, 2015; NERC Urgency Grant, Pyle), Indonesia (Krakatoa, 2018; NERC Urgency Grant, Cassidy) and the Caribbean (St Vincent, 2020). Immediately following the 2015 Nepal earthquake, we provided information to SAGE and COBR that guided response and subsequent monitoring of the risks (England). Via

solicited collaboration with the USGS/Hawaiian Volcano Observatory we provided key analyses on island-wide air quality impacts of the 2018 eruption and 2020 activity (Mather).

4.3 Contribution to the sustainability of the discipline and indicators of recognition

The collective strength of DoES has been consistently recognised in the **QS World University Rankings** with Oxford placed in the top five institutes globally in the Earth and Marine Sciences category since 2015.

Individually, our academics play a vigorous role in promoting and supporting the sustainability of the UK and international science community. Activities are recognised and encouraged as a component of promotion or salary cases.

4.3.1 Learned Societies and Recognition

Our members operate at the highest level in National Academies (Royal Society) and Science Societies as Presidents, Vice-Presidents, and Board Members. They lead the organisation of major international conferences and sit on the committees that award the major medals recognising international excellence. They also receive recognition for their own work through prestigious national and international awards.

Major Learned Society Leadership

Ballentine	Vice-President, President, and Past President, European Association of Geochemistry (**EAG**) (2012-18) (4,000 members) Elected, Board of Directors, American Geophysical Union (**AGU**) (2017-20) (55,000 members)
Daly	President, Geological Society London (2020-22)
Halliday	Vice-President and Physical Secretary, Royal Society (2014-17)
Henderson	Chair, Royal Society Global Environmental Research Committee Member, Royal Society Science Policy Expert Advisory Committee Chair, Joint Royal Society/Royal Academy of Engineering Working Group on Greenhouse Gas Removal Technologies Chair, Royal Society Working Group on Future Ocean Resources
Mather	Board of Directors, Geochemical Society (**GS**) (2017-19) (6,000 members)
Rickaby	President, Challenger Society (2020-22)
Smith	President, Palaeontological Association (2016-18) Co-Chair, University Museums Group UK (2014-17) National Museum Directors Council (2013-18)

Other Significant Society Roles

Ballentine	Chair or member of awards committees (2012-18): - GS/EAG: Fellowships; Gast Lectureship - GS: Goldschmidt Medal - EAG: Science Innovation Medal; Houtermans Medal
England	Geological Society of America, Arthur Day Medal Committee
Saupe	Joint Association for Women Geoscientists /Paleontological Society, Awards Committee
Kendall	AGU, Fellows Committee (2017-18) Royal Society, Fellows Committee (2019-present) 2020 Kuwait Prize (Earth Sciences), Selection Panel member Royal Society 2020 Young People's Book Prize, Judging Panel chair

Rahman	Palaeontological Association, Council member (2014-17)
Smith	Geological Society London, Awards Committee and Grants Committee
Murdock	Geological Society London, Science Committee member, and Early Career Network
Rahman	Palaeontological Association, Awards Committee

Major Conference or Meeting Leadership

Ballentine	Goldschmidt Conferences (2009,11,13,15) (3-5,000 attendees), Chair, Co-Chair, or Host Deep Carbon Observatory (DCO) International Conference, St Andrews (2018) (300 attendees), Chair
Katz	Earth2Earth UK-wide geoscience seminar series, co-founder, https://earth2earthseminar.com/index.html
Mather	Goldschmidt conference, Theme Chair (2016, 2019) and scientific organising committee (2021) DCO International Conference, St Andrews (2018), organising committee
Saupe	Geological Society of America, Technical Program Representative British Ecological Society Meeting, 'Crossing the Palaeoecology-Ecology Gap', Co-Chair Royal Society Hooke Discussion Meeting, Co-organiser
Tosca	Mineralogical Society of Great Britain & Ireland, 2015 Euroclay Meeting, Organising Committee

Selected Recognition

Awards Presented by Head of State

Ballentine	ENI Award (2016), Sergio Mattarella, President of Italy
Halliday	Knight Bachelor (2019), HM Queen Elizabeth II
Smith	Polar Medal (2017), HM Queen Elizabeth II

Major Learned Society Awards

Blundy	Royal Society Research Professor (2020)
Cartwright	AAPG, Grover E Murray Medal (2014)
England	Royal Astronomical Society, Gold Medal (2016) AGU, Bucher Medal (2018)
Mather	Royal Society, Rosalind Franklin Award and Lecture (2018)
Parsons	EGU, Augustus Love Medal (2017)
Rickaby	Geological Society of London, Lyell Medal (2017)
COMET	Royal Astronomical Society, group achievement award (2018) (Mather/Walker/Pyle/Parsons/England/Hawthorne)

Early Career Awards

Cosmidis	Canadian Light Source, Young Investigator Award (2018) French Society of Mineralogy and Crystallography (SFMC) and the French Geological Society (SGF), Best Doctoral Thesis (2014)
Marquardt	Bavarian Academy of Sciences, Selected member (Young Scholars' Programme) (2016) German Science Foundation, Emmy Noether Award (2014)

Saupe	*Proceedings Royal Society B*, Best Associate Editor (2018 and 2019) Association for Women Geoscientists, Outstanding Service Award (2015) Erasmus S. Haworth Distinguished Graduate Award, University of Kansas (2014)
Stevens	AGU, *Geophysical Research Letters*, Citation for Excellence in Refereeing (2018) United States Antarctic Service Medal (2017) AGU Hydrology Section, Horton Research Grant Award (2015)

National Academy-level Fellowships

- Seven Fellows of the Royal Society (FRS) were UoA members in-period, with two elected in this period: Kendall, Watts.
- Seven Fellows of the AGU were UoA members in-period: Ballentine, Kendall, Rickaby, England, Halliday, Parsons, Watts, Wood.
- Fellow of CIFAR (Canadian Institute for Advanced Research): Ballentine

4.3.2 Selected Journal Editorships

All returned staff referee publications. Our researchers play a significant role in supporting the science community through editorial roles:

Mather	Co-Editor-in-Chief, *Earth and Planetary Science Letters* (2014-19)
Nissen-Meyer	Topical Editor, *Solid Earth* (EGU)
Pyle	Board of Editors, *Geological Research Journal*
Rahman	Editor, Paleontological Society Short Course on Virtual Paleontology Editor, *Palaeontology* Editor, *Papers in Palaeontology*
Robinson	Guest Editor, *Sedimentology*
Saupe	Editor, *Journal of Biogeography* Associate Editor, *Proceedings of the Royal Society B* Guest Editor, *Philosophical Transactions of the Royal Society B* Guest Editor, *Palaeobiology Journal*
Tosca	Editorial Board, *Geochimica et Cosmochimica Acta* (Elsevier) Editorial Board, *Sedimentology* (Wiley)

4.3.3 Support of, and Engagement with, Science Funding Bodies

We help shape UK science funding policy through extensive engagement with the UKRI NERC funding body at the highest strategic level and on operational committees. The UoA plays a substantive role in the decision-making that results in disbursement of research funds nationally and internationally (e.g., ERC).

<u>Membership of NERC Advisory Councils</u>

England	Science Innovation and Strategy Board (2012-15)
Henderson	Member of Council (2018-present)
Kendall	Science Innovation and Strategy Board (2011-14)
Mather	Science Committee (2017-22) Chair, Large Infrastructure Evaluation Committee (2017-18) Chair, Evaluation of the UK IODP Subscription (2018)

	Panel member, NERC IODP Subscription Renewal Assessment (2018) Science Committee Recruitment Panel (2019)
Nissen-Meyer	High-performance Computing Steering Committee (2018-current)
Pyle	CDT Panel - smart and autonomous observation (2015)

Membership of UK Research Council Grant Panels

Hawthorne	NERC Standard Grant Panel Member (2019)
Katz	NERC Standard Grant Panel Member (2013-2018)
Pyle	Diamond Light Source, Beam-time Allocation Panel (2015-2019) Royal Society, Future Leaders, Africa, in Research (FLAIR) Fellowships (2018-21) UKRI, Future Leader Fellowships (2018-21) Royal Society, Leverhulme Trust Senior Research Fellowships Panel
Rahman	Science and Technology Facilities Council (**STFC**) Engineering Facility Access Panel, ISIS (2018)
Robinson	Large grants sift panel (2016) Large grants interview panel (2017) NERC-NSFC (China) Biosphere Evolution, Transitions & Resilience Panel (Beijing) (2016) Independent Research Fellowships Panel (2019) UK IODP Knowledge Coordination Call Panel (2019)

Membership of International Research Councils or Institutes

Ballentine	European Research Council, PE10 Grants Panel (Advanced Grants) (2016-current)
Henderson	Academia Sinica, International Advisory Board for Earth Sciences (2017-20) Earth Observatory of Singapore, Science Advisory Board (2020-22)
Kendall	European Research Council PE10, Grants Panel (Consolidator Grants) (2019) Norwegian Research Council, Panel Member (2017-20)
MacNiocaill	Norwegian Research Council, Panel Member (2015-current)
Mather	International Continental Drilling Programme Science Advisory Group (2019-22)