Institution: University of Oxford

Unit of assessment: UoA 7 (Earth Systems and Environmental Sciences)

a. Overview

The UoA conducts research across a broad range of earth sciences to tackle fundamental problems at the forefront of the discipline, and address intellectual challenges relevant to society. The ethos is of quantitative science, based on observations in the field and laboratory, linking strongly to cognate disciplines.

This submission returns 35 staff from the Department of Earth Sciences (DoES) and 3 from the Oxford University Museum of Natural History (OU-MNH). The UoA is also home to 58 post-doctoral scientists and ≈65 graduate students. In 2012/13 it had a turn-over of £9.4m with a research-grant expenditure of £4.2M.

Major developments in the UoA since RAE2008 include:
- The appointment of 11 new faculty members to DoES, increasing faculty numbers to 31 (the largest the department has been in its 200-year history).
- The rehousing of DoES in an acclaimed custom-designed new building, dramatically improving the quality and quantity of laboratory, office, and interaction space.
- Successfully applying for an Athena Swan Silver Award, in the process fully reviewing and improving provision for the support of staff.
- Increasing research-grant expenditure by 52%, with a significant diversification of funding sources to Europe (e.g. 5 ERC awards) and industry.

b. Research strategy

Our research seeks to understand the processes that shape the Earth and our environment. The focus is on fundamental research at the forefront of the subject to address uncertainty or ignorance. This research is often curiosity-driven: asking critical questions and searching for new routes to understand the Earth and other planets. Research also addresses challenges facing society: recognising that the earth sciences have a continuing role in satisfying society's need for resources, but must also provide understanding of environmental change and the consequences of resource use. We seek to provide the data and fundamental science to underpin society's decisions about management of our changing environment.

The UoA pursues its research through three inter-dependent approaches:
- Observation in the field (ranging from traditional geological and oceanographic techniques, to modern geophysical methods such as seismic, acoustic, and satellite earth observation)
- Analysis and measurement of samples (from traditional rock/mineral observation to advanced analytical approaches, including analysis of field samples and those from laboratory experiments that mimic earth processes)
- Mathematical analysis and numerical modelling of the Earth and its processes (including fluid dynamics, statistical analysis, and complex modelling of Earth systems)

A key strategy is to maintain strength in each of these approaches and a balance between them. This balance, coupled to an open and collaborative research environment, leads to a highly productive environment for the pursuit of world-leading research.

Earth sciences is a highly interdisciplinary subject, as reflected by our academics who have a range of complementary expertise spanning biology, chemistry, maths, physics, and geology. It is an explicit strategy of DoES to maintain strong links to cognate departments, through networking, joint funding, studentships, and seminars. There are substantial links to Physics, Zoology, Geography and Archaeology; growing links to Maths, Engineering, and Chemistry; and an increasing range of interactions with social-science subjects to inform policy questions.

Research is guided by the vision of individual faculty, informed by interaction with Oxford University colleagues and by substantial networks of international collaborators. Research is not separated into formal groups, and interactions between researchers are very diverse, but it is helpful to divide the research of the UoA into six overlapping areas:

i. Geophysics and geodynamics

Research seeks to understand the structure and dynamics of Earth's interior; the response of the lithosphere to loading; the mechanics of earthquakes; and the fluid dynamics of geological materials. Work relies on analysis of observational data and on application of rigorous mathematical techniques and high-performance computing.

Developments and highlights since 2008: Two new Lecturers in seismology (Nissen-Meyer; Sigloch) propagate existing strength in this key area, and fulfil a strategic goal from RAE2008 of proleptic appointment to geophysics posts. Appointments in Physics, Maths and Engineering Departments provide complementary geophysical fluid dynamics (GFD) expertise. Research on coupling between climate and volcanism resulted in an ERC grant and major NSF project (Katz).

Future strategy: Geophysics is a long-standing strength of the UoA, and continues to offer potential for fundamental new discovery. We will capitalise on GFD expertise across the university by strengthening existing mathematical-geoscience networks, and continue to ensure sufficient computer power to remain at the forefront of seismology. Retirement of the Professor of Geophysics (Woodhouse) in 2016 will enable appointment to a new Chair in Geophysics, maintaining research excellence and international standing in geophysics.

ii. Planetary evolution and materials

We study the origin and internal development of the Earth and other terrestrial planets, and the chemical and mineralogical behaviour of planetary materials, with significant expertise in the application of isotope geochemistry and experimental mineralogy.

Developments and highlights since 2008: Appointment of Ballentine to the Geochemistry Chair brings world-leading expertise in gas geochemistry. His work on differentiation history of the mantle, crust and exosphere dovetails with existing DoES research. A new Lecturer (Hansen) and NERC Research Fellow (Wade) strengthen experimental mineralogy. Research impact is indicated by 6 papers in *Nature* or *Science* (Ballentine, Halliday, Wade, Wood) on the accretion and evolution of Earth and Martian atmospheres and on the formation of Earth's core; and by the award of three advanced ERC grants (Ballentine, Halliday, Wood). Planetary science is complemented by growth of the subject within Physics (e.g. Aigrain, Thatte, Balbus).

Future strategy: We will grow research into (a) isotopic variations in moderately volatile elements to constrain the origin of the Moon, (b) core formation processes using fractionation of siderophile elements, (c) volatile accretion and loss using noble gases and (d) the physics of rock deformation at high pressures.

iii. Oceanography, climate and palaeoenvironment

Observation, analysis and modelling of the biology, chemistry and physics of the ocean system integrates with study of the past from sediments and elsewhere (e.g. cave deposits) to assess the operation of the climate system in varied modes, and at a range of timescales.

Developments and highlights since 2008: Continued expansion of climate science was a strategic goal from RAE2008 and has been achieved by appointment of two Lecturers in Earth Sciences (Khatiwala, Robinson), three in Physics (Zanna, Woolings, Wells), and by closer integration of research across the university through the Oxford Climate Network. Successes include insights into rapid sea-level changes (e.g. papers in *Nature* and *Science*), and an ERC award (Rickaby) to use novel genetic approaches to assess past CO_2. Such successes have attracted independent research fellows to the UoA (e.g. Homoky, Hoogakker, Vaks).

Future strategy: To make use of the university's broad strength to maximize scientific discovery in climate-science, and to see this science more effectively translated to policy. Links to Physics, Zoology and Maths will grow and interactions increase with the university's leading social scientists, including those in the Environmental Change Institute and new Blavatnik School of Government.

iv. Palaeobiology and evolution

Research assesses the assembly of modern biodiversity, using deep time and extant data, studied in a rigorous mathematical framework, and focusing on groups with well-constrained phylogenies and rich fossil records (e.g. vertebrates, arthropods, foraminifera). We aim to understand the processes governing evolutionary change on long timescales, and the patterns

of biodiversity during changing climatic regimes.

Developments and highlights since 2008: An area of significant growth with the hiring of new permanent (Friedman, Benson) and fixed-term (Lloyd) Lecturers, and two independent fellows (Aze, Legg). Research has led to 8 papers in *Nature* or *Science*, and NERC- and Leverhulme-funded initiatives to quantify evolutionary patterns, dissect the relationship between the palaeontological and stratigraphic records, and integrate fossil and genetic datasets.

Future strategy: The shared vision of DoES and OU-MNH (under a new Director; Smith) provides a platform for continued growth of palaeobiology. New research links with Zoology will allow the development of cross-over between techniques used for extinct and extant organisms.

v. Geodesy, tectonics, volcanology and related hazards

Our research advances techniques and applications in Earth Observation (EO), and integrates these with field measurements and modeling to improve understanding of the processes causing earthquakes and volcanoes, both on land and at sea.

Developments and highlights since 2008: Appointment of a new permanent Lecturer (Walker) has strengthened field tectonics. Key findings include assessment of the causes and impacts of volcanic activity (e.g. 2008 Chaitén; 2011 Santorini), and of major earthquakes both past (AD 365 Crete) and recent (2009 L'Aquila; 2010/11 Christchurch; 2011 Van), as well as the impact of seamount subduction on megathrust earthquakes.

Future strategy: Continued fundamental science will complement increasing work on the societal impacts of volcanic eruptions and earthquakes. Forthcoming faculty appointments will replace retiring geophysicists with interests in this area, recognizing the continued importance of tectonics for the broad Earth Sciences. Pre-appointment to the Chair of Geophysics allows flexibility to appoint at a senior level.

vi. Earth resources

Resource exploration continues to offer fundamental scientific challenges with obvious societal relevance. Collaborative research with industry assesses the distribution of resources in sedimentary basins; unconventional hydrocarbons; hydrocarbon migration and flow; the tectonic evolution of rifted continental margins and cratonic basins; and geological CO_2 sequestration.

Developments and highlights since 2008: This area has seen significant expansion since RAE2008. Investment from Shell International (£5.2M) funded the appointment of a dedicated Professor (Cartwright); the new Chair in Geochemistry (Ballentine) pursues research in basin fluids and CO_2 sequestration; and Visiting Professorships have been awarded to senior exploration geologists from industry (Daly, BP; Levell, Shell).

Future strategy: Use our research skills to further build collaboration with industry globally to tackle fundamental questions relevant to the origin, stratigraphic architecture, fluid flow and thermal and maturation history of sedimentary basins in diverse tectonic settings. Capitalise on new expertise across the university to better assess and develop models for CO_2 sequestration.

c. People

Staffing strategy and appointments

Our strategy is to recruit and retain the most-talented earth scientists and provide them with world-class facilities and a vibrant intellectual environment to support their research aspirations.

In identifying subject areas for new appointments, we ensure the continuity of core aspects of the earth sciences (e.g. field-geology, stratigraphy, petrology, geochemistry, geophysics), but also seek new areas where there is potential for significant discovery, looking for links with existing research. We maintain a balance of expertise in the three forms of research: field, analytical, and mathematical (Section B). In the OU-MNH, an additional strategy is to appoint those who will make active use of the extensive 'designated' collections.

Appointment strategy is discussed by the Department Committee which involves all academics. This discussion is informed by interaction with other departments, both in pursuit of agreed strategies (e.g. expansion of climate with Physics; and of mathematical geosciences with Mathematics), and through the university recruitment process, which requires a panel member from another department.

Eleven new academics appointed 2008-2013 have enabled the UoA to meet its strategic goals: strengthening climate science; establishing critical mass in palaeobiology; maintaining strength in geophysics in the face of forthcoming retirements; and protecting the base of core geological expertise. Three academics have left during the period: Hesselbo to a Chair at Exeter; Lamb to Wellington (NZ); and Worthington to retirement. The net 35% expansion from 23 to 31 academics brings the DoES to its largest ever size. To maintain a coherent research atmosphere, further expansion of academic staff is not envisaged in the coming years, but the replacement of those close to retirement will enable continued appointment to important subject areas, and the renewal of ideas and energy.

The UoA hosts 42 Post-Doctoral Research Assistants supported on grants. These PDRAs underpin research, so recruitment and retention of the very best young researchers is critical. All positions are advertised internationally and interviewed by a panel including a trained chair.

Career development

All new academics are provided with mentors to provide help and practical advice, and with start-up funds to help establish research. Teaching loads are reduced for the first year, and administrative burdens kept to a minimum during the first 5 years. After two years, academics have an interim review of their teaching and research, which identifies and provides any additional support needed. In the fifth year there is a full review covering all aspects of the post, before appointment to retirement age.

All academic staff are invited to an appraisal annually, providing an opportunity to reflect on their career development. Ensuring that individuals have sufficient time to pursue excellent research, is an important aspect of these appraisals. The University's sabbatical leave policy is helpful in this regard, allowing for extended periods of research, free from other commitments.

The University runs a "Recognition of Distinction" exercise, through which academics may apply for the title of Professor. Promotion is based on performance across the full academic job description and DoES encourages and supports applications. Four academics (Khatiwala, Pyle, Rickaby, Searle) were awarded the title of professor during the REF period.

All members of the academic staff sit on The Department Committee, which meets termly and provides a forum for discussion of DoES policy and strategy. This forum ensures that all academics are engaged with the strategic evolution of the department. The Research Committee, supported by two DoES Research Facilitators, reviews all research proposals prior to submission, with the aim of increasing success rates to ensure that the research ambitions of faculty can be met. The Research Facilitators also provide support in identifying possible sources of funding, and preparing budgets and papers for proposal submission.

Limited institutional research funding is provided to all academics each year, with this sum increasing with successful research proposals. This policy incentivizes writing of proposals, and provides a small amount of funding to initiate new research. Funding for larger projects (typically up to £100k) can be sought competitively within the university through the John Fell Fund, which supports pump-priming and interdisciplinary research, particularly for new faculty.

Oxford University has enthusiastically endorsed the principles of the Concordat, and has implemented them through its own Code of Practice. This has been fully adopted by DoES, which offers: formal induction for new researchers; welcome sessions run by the university; mid-point and final probationary review meetings for all contract research staff; and salaries that meet with equal-pay requirements and Fixed-Term Employees Regulations. These policies are supported by a full-time DoES HR Officer, who ensures the introduction and operation of best practice for career development. PDRAs select an academic mentor outside their immediate research project to offer an impartial source of research and career advice.

A wide range of personal and career development courses are offered by the university and staff are encouraged to develop their skills. Courses include: Career Review & Planning; Job Search & Interview Skills; Teaching Skills; computing and IT courses, training in leadership and management skills, and the Oxford Language Centre (Academic Writing, Advanced Communication Skills, English and foreign language courses).

The DoES offers a vibrant and supportive environment for academic study and networking. Leading scientists from around the world are invited to speak at the weekly seminar series. A

second weekly seminar consists of a short research presentation from a member of DoES or OU-MNH and the sharing of news. Individual research groups also hold focused seminars, and there is a wide range of relevant seminars elsewhere in the university. News is also shared by a monthly e-newsletter sent to all DoES staff. Networking is facilitated by a number of pleasant social spaces in the new building, particularly the top-floor common room, which is used throughout the day for informal research meetings, and hosts a catered coffee time every morning. Graduate students organize a weekly event for all staff following the external seminar.

Research fellowships

Independent researchers are an important part of the intellectual environment. We encourage applications to such positions where proposed research links to that in the UoA, and support the career development of these Fellows, recognizing that they are the academic leaders of the future. We mentor applications for fellowships, with draft proposals reviewed by the Research Committee and practice talks and interviews offered in preparation for the external assessment.

Independent fellows hosted in the UoA (2008-2013) include: 16 NERC Fellows; 4 Royal Society URFs; 3 Marie Curie individual fellowships; 2 Newton Fellows; 1 ESA Fellow; and 1 US-NSF Overseas Fellow. In addition, a number of institutionally funded Research Fellowships are available across the university. These are awarded based on a research proposal, and are designed to establish recipients in an independent research career (e.g. by including financial research support). The UoA has hosted 4 such fellows during the REF period (e.g. Aze; Legg).

Fellows are encouraged to apply for faculty positions that arise (e.g. Walker: now faculty, previously URF) or to seek additional funding to continue their research in the UoA (e.g. Vaks: now PI on external grants, previously NERC Fellow). Fellows conduct high-quality research, as demonstrated by the leading institutes in which they take up faculty positions on departure; in the UK (Biggs, Bristol; Williams and Humphreys, Durham; Prytulak, Imperial; Pogge von Strandman, UCL), and overseas (Pett-Ridge, Oregon; West, University of Southern California; Neilson, WHOI; Knudsen, Aarhus; Siebert, AWI Kiel).

International appointments and visitors

All recruiting is international in scope and advertised positions attract applicants from leading institutes around the globe. Of the 11 new faculty members, 3 were previously at US institutes (Stanford, Columbia, Chicago) and 2 from European institutes (ETH, Munich). Of all staff returned to REF, more than half were at an overseas institute immediately before joining the UoA. Our PDRA community is also strongly international, containing at least 14 nationalities.

The UoA welcomes many distinguished international scientists for extended visits, with the depth and breadth of our research expertise attracting them to the UoA. Examples in the REF period include: Langmuir (Harvard); Fukahata (Kyoto); Bar-Matthews (Jerusalem); Measures (Hawaii); Margulis (Amherst); Takei (Tokyo); and Zhong (Boulder). We also host a large number of shorter visits from overseas, including speakers in the departmental seminar series, or in prestigious Visiting Lecturer schemes (e.g. Elkins-Tanton, DTM, as an Astor Lecturer).

Support of equality and diversity

DoES is proud to have been awarded Athena Swan Silver status (2012). This award recognises commitment to advancing women's careers in science. We were the first Earth Sciences department, and remain one of only two (with Imperial), to receive this level of award. Practices recognized by the award include flexible working hours around family commitments, scheduling meetings and seminars to core hours to ease child-care, and mentoring schemes. These augment wider university policies such as generous maternity and paternity allowances, nursery schemes, and the requirement for gender representation on all appointing panels.

Staff participate in centrally run training schemes, including "Springboard" - a programme encouraging women to set and achieve career goals. Two academics (Mather, Rickaby) have also taken part in a university-wide scheme (Ad Feminam) exploring the role of focused mentoring in addressing the under-representation of women in academic leadership positions.

The DoES Workplace and Equality Committee meets termly and includes representatives of all sectors of staff. This committee ensures a good working environment for all, regardless of gender, race or religion. It is supported by the HR Officer, who sees that recommendations are put into practise and maintained.

Research students

DoES has admitted between 11 and 18 doctoral students per year (2008-13). The graduate admission strategy focuses on the academic excellence and potential of the student rather than on the project. This policy will continue in a new Doctoral Training Partnership programme following the award of 24 Ph.D. studentships per year to the University of Oxford by NERC.

Within DoES, responsibility for graduate matters rests with a Director of Graduate Studies (DGS) and is considered by the Teaching Committee. The most important interaction is between student and supervisor, and it is common for graduates to have more than one supervisor. A Code of Practice outlining the responsibilities of supervisors and students is provided to new students. All new students attend induction sessions, covering academic, resource, safety, and administrative issues. DoES training includes scientific writing, teaching, first-aid and safety, in addition to training on procedures and equipment specific to laboratories or research groups. Advice and a wide range of other information is provided in a Graduate Handbook. Graduates also select an academic mentor, separate from their supervisor, who offers advice about training and career development. Additional training is provided centrally by the Graduate Academic Programme, which offers courses in many aspects of computing, personal and professional development; language skills; career-development; and enterprise and entrepreneurial skills.

Graduate students are encouraged to engage in teaching through demonstration in practical classes, in the field, and in tutorials. Virtually all students play some role in such teaching. They are also encouraged to attend departmental seminars to broaden their interests and contacts.

Student progress is monitored with a university-wide on-line reporting system. Students provide a termly self-assessment, and supervisors are required to submit a report on progress. There is specific provision for recording training and for flagging concerns about progress. Reports are monitored by the DGS so that appropriate action can be taken when concerns are noted.

Students undergo two stages of course progression. The first - Transfer of Status to D.Phil. - takes place at the end of the third term of study, and involves submission of a report covering progress and future plans, a presentation, statements of support from supervisor, college and the DGS, and an interview with a panel consisting of the DGS, the academic mentor, and one other member of the faculty or research staff. The second - Confirmation of Status - follows a similar course, with a report and proposed thesis outline, a presentation, panel interview, and support statements. These progression exercises are organised as mini-conferences, highlighting presentation skills, and introducing D.Phil. research to new students.

The success of the graduate programme is demonstrated by subsequent employment: 65% of completing graduates (2008/13) went on to post-doctorial positions, while ≈10% went straight to a faculty or teaching position; and ≈20% into industry jobs that used their research training.

d. Income, infrastructure and facilities

Specialist infrastructure and facilities

Buildings and space: The Earth Sciences Department is housed in a custom-designed 7100 m^2 building, completed in 2010 at a cost of £37M. Funding for this strategic expansion and modernisation was provided by the University, with donations totalling £6.2M from philanthropic sources. Design of the building involved extensive consultation with members of DoES and focused on providing state-of-the-art research and teaching facilities. One of the building's two wings is dedicated to laboratories and teaching, with specialist spaces designed and serviced for a wide variety of laboratory equipment. The building is located in Oxford University's Science Area, within 150m of the main science library and cognate departments including Physics, Chemistry and Geography. All DoES personnel are hosted in this building, which provides a conducive environment for interaction, including well-appointed communal spaces and meeting rooms. The OU-MNH is adjacent to DoES and provides 1000 m^2 of space dedicated to research and to relevant sample collections, with 2250 m^2 for displays and education facilities.

Specialist laboratories and analytical equipment: Analytical geochemistry is a particular strength and a complete floor of the laboratory wing is dedicated to mass spectrometers (MS). These include five multi-collector ICP MS, one of which is a large-geometry machine unique in the UK (Nu-1700). Institutional funding (£350k) has recently allowed purchase of a new MC-ICP-MS to replace the oldest such instrument with an improved model. DoES also hosts four single-

collector ICP-MS instruments, a thermal ionisation MS and two gas-source MS for stable-isotope analysis. Samples are prepared in a specialist 280 m^2 metal-free clean-laboratory designed to provide extremely clean conditions for preparation of samples. A new (2013) laboratory is dedicated to noble-gas geochemistry including three new MS and an extensive range of peripherals. This lab was equipped with ERC funding (Ballentine) and £810k of institutional start-up support to the Chair of Geochemistry.

There are also specialist laboratories designed and equipped for marine bio-culturing, high-pressure mineralogy, palaeomagnetic research, and micro/macro palaeonotology. The palaeomagnetism laboratory, for instance, is centred on a dual steel-shielded field-free room containing a 2-G magnetometer with extensive demagnetization and related equipment. The high-pressure mineralogy laboratory hosts two piston-cylinder apparatuses; a multianvil apparatus; vertical tube furnaces; and analytical facilities. A new laboratory is being refurbished and equipped for research into rock deformation (Hansen) at a cost of £115k.

Significant funding for specialised analytical equipment has been raised from external sources to augment that from institutional support. Successful ERC grants have purchased equipment including a new laser-ablation ICP-MS (Wood, 2011), and an experimental geophysical fluid dynamics laboratory (Katz, 2012). Funding from Shell has enabled purchase of a Rock Eval pyrolysis instrument (Jenkyns, 2012) to identify the type and maturity of organic matter and detect petroleum potential in sediments.

Research facilities: DoES runs six Small Research Facilities (SRF), supporting its research and that in other departments. These are: Trace Element Analysis; Stable Isotope Analysis; SEM and Electron Probe; Department Workshop; Scientific Drafting; Rock-Cutting and Thin-Section Lab. Each is managed and run by expert technicians (total 8 FTE) on long-term contracts to provide continuity of specialist knowledge. Continued investment ensures that these SRFs can provide the support required for research. Funding is sought from external sources by major users, to augment funds raised by charges for SRF usage (which include a charge for depreciation). For instance, purchase of a new SEM (2013) was possible via joint funding from Shell and from SRF usage charges. This SEM significantly upgrades analytical capability (e.g. large sample chamber and electron backscatter diffraction). DoES has also invested ≈£150k to purchase or renovate equipment in the Rock Cutting (e.g. resin impregnation) and Workshop (e.g. CAD) SRFs. A future strategic goal is to increase provision of electron-probe access. Matching funding schemes operated by the university will enable competitive proposals to be written to external funders for this equipment.

Computing: DoES is well equipped for computing, both through its own network, and extensive resources in the wider university. The DoES network consists of ≈50 servers, supporting ≈220 Windows and Mac desktops and 40 UNIX/Linux desktop clients. In addition, there is a 136-node UNIX cluster for seismology. DoES computing is supported by 2 full-time computer officers. DoES makes extensive use of the Oxford Supercomputing Centre (www.osc.ox.ac.uk; OSC) which hosts and supports scientific computing platforms. A DoES member (Katz) chairs the OSC Executive Committee (2013-2016).

DoES houses the Shell Geoscience Laboratory 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, and IHS's Kingdom software), two RAID arrays providing 24Tb of storage, and two servers with 32Gb of RAM. Hard and software was installed in 2013 with £130k provided by Shell and more than £7M of in-kind support from Schlumberger's provision of software.

Library resources: The DoES library is continuously available to members of the department, contains the main earth-science journals, as well as maps and other special publications, and is supported by a 0.82FTE librarian. The University's Radcliffe Science Library is a world-class resource for journals and books in earth sciences which, in addition to being a legal deposit library, spends ~£100k/yr on journals and electronic resources specifically for earth sciences. Essentially all journals relevant to our research are available by electronic subscription. Theses and other outputs are stored in a robust digital archive (Oxford Research Archive), which is also used to help ensure fulfillment of Open Access requirements (along with dedicated University funding for such publication).

Museum services: Palaeontology is supported by OU-MNH collections, which are 'Designated' for their national and international significance; there are over 350,000 specimens, with 2,257 type and 12,029 cited specimens. In addition, there are internationally significant mineral and petrology collections, with 30,000 and 50,000 specimens respectively. Museum facilities include a newly refurbished palaeontological preparation laboratory (2012) and conservation suite (2013), plus imaging facilities that include SEM and 3D laser scanning.

Use of facilities outside the Department: A wealth of other analytical facilities are available in cognate departments and used for our research (e.g. AMS, XRD, BET, TEM). The DIAMOND light-source is only 16 miles away and is used frequently (e.g. Pyle, Friedman, Wood), helped by a dedicated Oxford University DIAMOND Research Facilitator. DoES researchers make extensive use of other national infrastructure, including a range of NERC Analytical Facilities, ISIS, and the NERC ships (including three cruises led from DoES during the REF period).

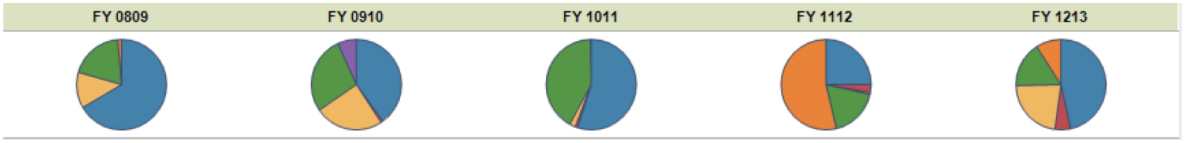
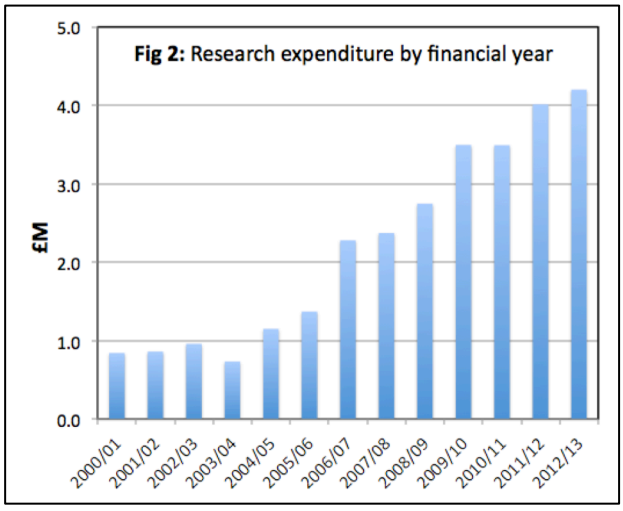


Fig 1: *Evolving portfolio of awarded DoES research funding: Blue (RC); Green (EU, including ERC); Yellow (UK Government); Orange (industry); Purple (Charities).*

Research funding portfolio

A key strategic goal of DoES has been to diversify sources of research income to smooth inevitable variability of income from individual sources and to defend against vulnerability from over-reliance on research-council funding. This goal has been successfully met during the REF period. The Research Councils (including the Royal Society) continue to be an important source of funds (between £2.4M and £3.9M per year) but they provided only 45% of total research awards during the REF period. Other major funding has come from Europe (ERC and FP-7 Mobility), the UK Government, and industry (Fig 1). A large grant (£5.2M) from Shell, for a portfolio of research on sedimentary basins, is a particular success, but this represents part of a systematic effort to increase industrial funding for relevant fundamental research. Funding has also been received from BP (Watts); Statoil and Exxon (Ballentine), Petrobras (Jenkyns), and other companies (Perenco, GETECH), plus institutes (ADPIRC) and national surveys. Industrial funding is seen as an important, but not dominant, source of UoA research funding in the future.

The growth of research funding is seen in annual research expenditure (Fig. 2). Significant and consistent growth from a base of <£1M prior to 2004/05 includes an increase of 52% from £2.7M in 2008/09 to £4.2M in 2012/13. This growth reflects both the diversification of funding sources, and the dynamic research culture in the UoA. Growth is expected to continue as recent appointments ramp up research efforts and approach funding levels of established staff.



Consultancies and professional services

All academic staff are encouraged to undertake consulting, and permitted to undertake paid contracts up to 30 days per year without loss of salary. Oxford University Consulting provides a framework within which staff can undertake such consulting, handling legal and administrative aspects, and many staff also have relationships directly with companies and policy makers. Department members have consulted across a wide range of subject areas, particularly related to our research themes on Hazards and Earth Resources, consulting to companies including: Arch Re; BP; Chevron; De Beers; Exxon-Mobil; GETECH; Ove Arup; Petrobras, Shell; and Statoil.

e. Collaboration and contribution to the discipline or research base

Research collaborations

UoA researchers work with an extensive network of collaborators, made clear from publication metrics. Of publications from DoES listed on Scopus (2008/13) 14% include an author from another Oxford University department; 54% from another UK institute; and 74% from an overseas institute (with at least 65 different countries represented). The DoES is involved in many national and international programmes, including:

IODP: Oxford faculty contribute to management and oversight of *The Integrated Ocean Drilling Programme* with three serving on the UK-IODP Steering Committee during the REF period (Henderson, Jenkyns, Robinson) and two on international IODP panels (Jenkyns, Robinson). Significant DoES research has arisen through international IODP collaboration.

ICDP: The UK became a member of the *International Continental Drilling Programme* in 2012. UoA researchers (Jenkyns, MacNiocaill) are involved in a proposal aiming to establish a global standard for Early Jurassic Earth history. An ICDP-funded international workshop held in Oxford in 2013 was the first such UK-led event in the programme's history.

GEOTRACES: UoA scientists play leading roles in this marine chemistry programme (www.geotraces.org/). The programme was led (2006-2012) by Henderson and UoA faculty lead UK contributions (Bouman, Henderson; Marshal from Physics), including a NERC Consortium and two research cruises involving scientists from 11 UK and 4 overseas institutes.

MetTrans: Oxford University is the lead institution for MetTrans, an EU-funded Marie Curie Training Network involving 13 partners (including 3 from industry) from 6 countries. MetTrans trains 12 PhD students in advanced isotopic and experimental techniques, tackling a range of problems related to the migration of metals in the environment.

NCEO: The Geohazards theme (www.nceo.ac.uk/research_geohazards.php) within the *National Centre for Earth Observation* grew from an Oxford-led consortium – COMET – which expanded its remit during the REF period from earthquakes and tectonics to include volcanoes. Five UoA faculty contribute to this collaboration of 7 UK universities, providing its Director from 2008-13, and continuing to provide two of three Deputy Directors (Mather, Walker).

NERC Programmes: DoES scientists have been funded participants in many NERC Research Programmes including: Ocean Acidification (Rickaby); RAPID-WATCH (Johnson); Arctic (Bouman); QUEST (Henderson; Hoogakker; Rickaby), Co-evolution of life and the planet (Robinson); and IODP (Henderson, Robinson).

Interdisciplinary research

The breadth of excellence across Oxford University enables high-quality inter-department research. Collaborations include those with Zoology (e.g. a co-organised research cruise studying seamount geology and biology); Physics (e.g. co-supervision of climate and oceanography graduates; joint grants; collaboration on volcanic inputs to the atmosphere); and Archaeology (e.g. co-supervision of graduates on climate and human evolution/migration; shared use of stable isotope and geochronology facilities). Growing links includes those to Chemistry (e.g. isotope tracing of enzyme function); Maths (e.g. ice sheet modelling); and Engineering (e.g. geological CO_2 sequestration; geoengineering). Additional interdisciplinary activity occurs though The Oxford Martin School (www.oxfordmartin.ox.ac.uk/) which directs funding towards major societal problems of the 21st Century. Three scientists have been involved in the School during the REF period (Bouman, Henderson, Rickaby) researching oceanography, the carbon cycle and geoengineering. The Oxford Networks for the Environment (www.one.ox.ac.uk/) also fosters environmental collaborations across the University.

Our research is increasingly linking explicitly with that in the social sciences to propagate policy influence from new scientific understanding, and to guide the direction of further research. Particular examples of such work are our role in two NERC funded consortia:

Earthquakes without Frontiers: (EwF; ewf.nerc.ac.uk/) a 5-year, £3M project that brings together physical and social scientists from 6 UK universities with the Overseas Development Institute (ODI), the British Geological Survey (BGS) and collaborators in China, Greece, Kazakhstan, Kyrgyzstan, India, Iran, Italy, Nepal, and Turkey. This consortium aims to understand the vulnerabilities of communities to earthquake hazards in the Alpine-Himalayan belt, and to

communicate new knowledge to policy makers. The project developed from sustained research collaborations between Oxford University and overseas agencies and involves 4 UoA scientists.

Strengthening Resilience in Volcanic Areas: (STREVA; streva.ac.uk/) a 5-year, £3M project linking physical and social scientists from 4 UK universities, with ODI, BGS and volcano observatories in the West Indies, Ecuador and Colombia. STREVA aims to advance tools for volcano forecasting, and understand factors influencing resilience in communities around volcanoes. Oxford's contribution builds on long-term collaborations with observatory partners.

Interaction with research users

The DoES has strong and growing links to research users, and a significant fraction of research is guided by the needs of policy makers and industry. Close interaction with senior oil professionals identified new areas for research in stratigraphy, geophysics and geochemistry, helping to initiate research in the Cretaceous of the South Atlantic (PetroBras); Brazilian cratonic basins (BP); and the isotope chemistry of oils (PetroBras) and sediments (Shell). Such interaction also identified further potential for industry-relevant discovery in geophysics and basin structure and led to the appointment of the new Shell Professor of Geoscience (Cartwright). Similar interactions with those in the mining industry has led to field work in areas of mineral potential, which also provide challenging fundamental science questions.

Oxford University became a formal partner to the Met Office in 2013. This partnership is a mechanism for the Met Office to incorporate new academic research into its climate models and policies, and to indicate (and fund) research to address specific scientific challenges. An important component of the Oxford link is in physical oceanography, building directly on joint Earth-Sciences/Physics research leadership in this discipline, which recognised the need for improved physical oceanographic understanding in UK climate science.

Leadership in the academic community

Prizes: 5 fellows of the Royal Society (Halliday, Henderson, England, Wood, and Woodhouse), and 9 fellows of the American Geophysical Union (AGU). Many medals and awards, including: 4 Leverhulme Prizes (Rickaby, Mather, Katz, Friedman) making Oxford University the largest recipient of prizes in the Earth Sciences category; 2 Young Scientist Awards of the European Geosciences Union (EGU) (Rickaby, Katz); the Macelwane Medal (Rickaby), Hess Medal (Wood), and Daly Lecture (Halliday) of AGU; the Urey Medal of the European Association of Geochemistry (EAG) (Halliday); the Holmes, Love, and Gutenberg medals of EGU (Watts, England, Woodhouse); the Gast Lecture of the Geochemical Society (Rickaby); the Gold Medal of the Royal Astronomical Society (Woodhouse); the Bigsby and Silver Medals of the Geological Society (Ballentine, Cartwright); the Pettijohn Medal of SEPM (Jenkyns); the Taylor and Francis Prize of the Society of Vertebrate Paleontology (Friedman); the Laurence Sloss Award of GSA (Jenkyns); the Distinguished Educator Award of AAPG (Cartwright); the Fellowship Award of the Challenger Society (Johnson); and the UNESCO/L'Oréal Women in Science Award (Mather).

Editorships: Earth and Planetary Sciences Letters (Henderson); Geological Magazine (Pyle); GeoResL (Pyle); Journal of the Geol. Soc. (MacNiocaill); Palaeontology (Benson); Proceedings of the Geologists Association (Watts); Treatise of Geophysics (Watts); Zootaxa (Benson). Plus more than 12 associate editorships on a range of journals.

Service on boards/councils: Examples of wide service have included: **NERC:** Council (Halliday); Chair (England) and member (Henderson) Science and Innovation Strategy Board; Evaluation of Centres (Parsons); 8 members of the Peer Review College. **Royal Society:** Council (Halliday); Sectional Committees (Henderson, Woodhouse, Wood); Research Grants Committee (Halliday); Travel Grants Committee (Mather, Robinson, Walker); International Exchange Committee (Mather). **Science programmes:** Chair of Review of US-NSF MARGINS (Watts); IODP ECORD Committee and Proposal Evaluation Panel (Robinson); Chair, UK Volcanology and Magmatic Studies Group (Pyle); Co-Lead Petroleum Industry consortium CAPROCKS (Cartwright). **Societies:** President, EAG (Halliday; Ballentine); President, AGU VGP Section (Halliday, Wood); Tectonophysics Section (Watts). **Conference leadership:** Chairs of Organising and Science Committees of the Goldschmidt Conference (Ballentine, Wood); organising committee for the Royal Society conference, "Tomorrow's Giants" (Mather).