Institution: University of Bristol

Unit of Assessment: 7 – Earth Systems and Environmental Sciences

a. Overview. The School of Earth Sciences is internationally recognised for leadership across a range of disciplines, realised through a vibrant, research-intensive environment. Our research activity thrives through a collegial atmosphere among a team of world-class researchers with diverse scientific backgrounds, a broad and successful portfolio of funding sources, the creation and maintenance of state-of-the-art research facilities, the ability to attract and engage with the best young researchers, and excellent Faculty and University support.

The School is organised functionally into six Research Groups each with a distinct, international reputation: *Environment, Geochemistry, Geophysics, Palaeobiology, Petrology,* and *Volcanology.* The Groups provide the infrastructure that enables our research to flourish (e.g. laboratories and equipment), and operate as administrative units and frameworks for mentoring staff and students. Interactions among the Groups provide the nuclei for collaborative, interdisciplinary research.

The School's research activity is focussed around six broad Research Themes addressing fundamental scientific questions in areas where we are well placed to make world-leading contributions. The breadth of the Themes reveals the scale of our ambition and achievement, and embraces an explicit recognition that cutting-edge research often transcends traditional discipline boundaries, and may benefit from an interdisciplinary approach. The Themes, which evolved from those presented in RAE2008, are: (1) *Earth Surface Processes; (2) Dynamics and Architecture of the Solid Earth; (3) Evolution of Biodiversity and Morphology; (4) Planetary Formation, Structure and Dynamics; (5) Crustal Magmatism, Volcanism and Geological Risk;* and *(6) Resources and Reservoirs.*

The quality of the Research Environment is evinced by research output during the REF period amounting to over one thousand peer-reviewed articles in ISI-recognised journals; these articles already have more than 10,000 citations. A total of 71 letters, articles and commentaries were published in *Science and Nature*-group journals alone – equivalent to one every 31 days. Beyond this fundamental academic impact, our research has led to tangible societal impacts ranging from government policy on volcanic ash hazards to new prospecting tools for natural resources.

b. Research strategy. The School's guiding philosophy is that research success cannot be manufactured by top-down imposition of research directives. Rather, it relies on provision of an environment (e.g. expertise, infrastructure, collegiality) that facilitates identification of the key questions, the untrammelled pursuit of the most exciting ideas, and the dissemination of output in the highest quality international journals. While maintaining strengths in core earth sciences disciplines, we identify and respond quickly to areas of emerging research that typically cross-cut traditional boundaries, as exemplified by our Research Themes. Development and implementation of this strategy is the responsibility of the School's eight-person Research Committee, comprising the Head of School (HoS), and representative Professors, Readers, Lecturers and Research Fellows. The Research Committee is supported by a 0.5 FTE administrator.

b.1 Basic Elements. The ten guiding principles of our research strategy are: **(1)** Create and sustain a collegial, collaborative research environment that enables us to mobilise collectively and rapidly as new opportunities arise; **(2)** Be aware of, and engage in, emergent areas of strategic importance and new policy and technology developments, including those identified by RCUK and other bodies; **(3)** Work with industry to identify areas of basic and applied research in which cooperative alliances can be formed; **(4)** Recruit staff with outstanding international research reputations to maintain leadership, and award "proleptic" positions to the very best Fellows to ensure retention of talent; **(5)** Maintain a high international and national profile, and reputation for excellence, which attracts world-class researchers and distinguished visitors; **(6)** Recruit the best UK and overseas students for our PhD programme to ensure continued growth of our PhD cohort; **(7)** Engage MSc students and 4th year undergraduates in research projects likely to lead to publication, thereby fostering close links between students and research staff; **(8)** Maintain a diverse portfolio of external funders and provide institutional support for preparation of research proposals; **(9)** Maintain cutting edge equipment through University-led infrastructure bids for which

our strong research income provides leveraged support; **(10)** Promote a culture of publishing our findings in the very best journals.

b.2 Summary of Research Themes. The following are brief descriptions of the six Research Themes, lists of participating Category A personnel, and selected Theme highlights as evidence of success within the REF period. The themes have evolved from those identified strategically in RAE2008: *Chemical Differentiation and the Early Solar System; Subduction; Crustal Magmatism and Volcanism; Atmospheres and Climate;* and *Evolutionary Morphology and the Tree of Life.*

Earth Surface Processes [Buss, Foster, Hendry, Hendy, Hornibrook, Naafs, Parkinson, Robinson, Schmidt, Sherman, Siddall, Whitaker] quantifies all aspects of environmental change on the past, present and future Earth, and the processes that lead to these changes. Investigations cover the oceans, cryosphere, terrestrial biosphere and soils, with an emphasis on understanding interactions between the carbon cycle, climate and environment at all timescales: **(1)** Considerable advances have been made in understanding natural and anthropogenic climate-forcing, including novel and improved quantifications of past and present carbon exchange between land, ocean and atmosphere, as well as the impact of ocean acidification on ecosystems [Burke & Robinson **Science** 2012; Le Quere et al. **Nature Geo.** 2009; Pangala et al. **New Phytol.** 2013; Prentice et al. **GBC** 2011; Foster et al. **PNAS** 2013; Krief et al. **GCA** 2010]; **(2)** Improved understanding of mechanisms behind millennial to centennial scale variability in the climate system [Hönisch et al. **Science** 2009; Hendry et al. **Geology** 2012; Lam et al. **Nature Geo.** 2013; Naafs et al. **Nature Geo.** 2012]; **(3)** Developed new ways to use paleo sea-level data to more accurately reconstruct past, and predict future, sea-level change [Rohling et al. **Nature Geo.** 2008; 2009]; **(4)** Major funding successes include assessing drivers for natural abrupt climate change (ERC grant €2M) and solar radiation management for mitigating climate change (SPICE, RCUK £1.6 M).

Dynamics and Architecture of the Solid Earth [Blundy, Brooker, Dhuime, Elliott, Helffrich, Kendall, Kohn, Lord, Parkinson, Schumacher, Walter, Wookey] focuses on the origin, composition, structure and evolution of Earth's interior using geochemistry, experimental petrology, mineral physics, seismology, and theory: **(1)** New constraints on the composition, structure and dynamics of Earth's core, and a new generation of integrated models on the role of Core-Mantle Boundary dynamics in the long-term evolution of the planet [Helffrich & Kaneshima **Nature** 2010; Wookey & Helffrich **Nature** 2008; Lord et al. **EPSL** 2009; Ammann et al. **Nature** 2010; Nowacki et al. **Nature** 2010]; **(2)** Seismic and isotopic constraints on the formation of continental crust and roots and the onset of plate tectonics, and new insight into processes occurring during continental rifting [Bastow et al. **Geology** 2011; Thompson et al. **EPSL** 2010, 2011; Pawlak et al. **GJI** 2011; Rychert et al. **Nature Geo.** 2012; Dhuime et al. **Science** 2012; Hammond et al. **Geology** 2013; Ferguson et al. **Nature** 2013]; **(3)** Discovering a link between subducted sedimentary mélanges and chemical components seen in arc magmas, and investigations of inclusions in diamonds as evidence for deep mantle recycling of crustal materials [Marschall & Schumacher **Nature Geo.** 2012; Walter et al. **Nature** 2008; Walter et al. **Science** 2011]; **(4)** Identification of unradiogenic isotopes of Pb in the upper mantle and a possible solution to the "Lead Paradox" [Burton et al. **Nature Geo.** 2012].

Planetary Formation, Structure and Dynamics [Coath, Elliott, Helffrich, Teanby, Walter, Wookey] focuses on the accretional origins of the terrestrial planets and their subsequent evolution, using isotopic analysis of meteorites, numerical simulations of accretion processes, laboratory experiments to understand early planetary evolution, and remote sensing of present day planetary atmospheres and interiors: **(1)** Testing designs for a seismometer for NASA's Mars InSight mission, following work on the potential of meteor impacts as a source of events for a seismic mission [STFC grants to Teanby and Wookey; Teanby & Wookey, **PEPI** 2011]; **(2)** First observation of a reversal of Titan's atmospheric circulation [Teanby et al. **Nature** 2012]; **(3)** Determined oxygen isotopic composition of the solar system from material collected during the Genesis mission, using the MegaSIMS instrument, with ion-optics designed by Coath [McKeegan et al. **Science** 2011]; **(4)** Used novel isotopes systems (Ti, W and Ni) to test a model of thermal processing of pre-solar material in the early solar system, confirm the 'Late Veneer' hypothesis, and identify a stellar heritage for solar materials from type II supernovae [Trinquier et al. **Science** 2009; Willbold et al. **Nature** 2011; Steele et al. **Astrophys. J.** 2012].

Evolution of Biodiversity and Morphology [Benton, Cunningham, Donoghue, Kearns, Pisani, Rayfield, Schmidt, Vinther] focuses on the evolutionary assembly of organism bodyplans, establishment of biodiversity over geological timescales, and the relationship between phylogeny, and crises and diversifications in Earth history: **(1)** Used large-scale phylogenetics, coupled with molecular and anatomical data from living and fossil organisms, to resolve debates over the architecture of the Tree of Life and the timescale of evolutionary history [Heimberg et al. **PNAS** 2010; Erwin et al. **Science** 2011]; **(2)** Elucidated the evolutionary assembly of the jawed vertebrate bodyplan, and showed that the origin of vertebrates was associated with an explosion in non-coding regulators of gene expression that control development of vertebrate-specific anatomy [Anderson et al. **Nature** 2011; Rücklin et al. **Nature** 2012]; **(3)** Used novel techniques to identify first evidence for colour patterns in dinosaurs and other taxa, and provided evidence for the use of feathers in visual display, insulation and flight [Clarke et al. **Science** 2010; Li et al. **Science** 2010; Li et al. **Science** 2012; Vinther **Biol. Lett.** 2008**;** Zhang et al. **Nature** 2010]; **(4)** Quantified the effect of intrinsic and extrinsic drivers on diversity and morphological variance, and the importance of environmental rate of change on extinctions [Brusatte et al. **Science** 2008; Ridgwell & Schmidt **Nature Geo.** 2010; Benton et al. **Science** 2009].

Crustal Magmatism, Volcanism and Geological Risk [Annen, Aspinall, Biggs, Blundy, Brooker, Cashman, Gottsmann, Kendall, Mader, Phillips, Rust, Sparks, Watson, Werner] focuses on understanding magmatism from the Moho to the surface, combining field geology, petrology, geochemistry, physical volcanology and thermodynamic modelling, and on the analysis of associated hazards and risks, including formalised use of expert judgement in decision-making. The theme has strong links to the University's cross-disciplinary Cabot Institute. **(1)** Improved understanding of explosive volcanic eruptions by integrating a global database with studies of the formation, transport and deposition of volcanic materials, coupled with novel approaches to hazard and risk assessment [Deligne et al. **JGR** 2010; Bamber & Aspinall **Nature Climate Change**; Sparks ERC Advanced grant "VOLDIES"]; **(2)** Pioneered new techniques to study the evolution and architecture of sub-volcanic magma reservoirs, and forecast eruptions using geophysical observations, field, experimental and petrological studies, and modelling [Saunders et al. **Science** 2012; Del Potro et al. **GRL** 2013**;** Melekhova et al. **Nature Geo.** 2013; Parks et al. **Nature Geo.** 2012; Blundy, ERC Advanced grant "CRITMAG"]; **(3)** Modelled the rheology of multiphase geomaterials relevant to magmatic and volcanic processes by combining analogue experiments, experiments on natural samples, and theory [Rust & Cashman **JGR** 2011; Mueller et al. **GRL** 2011]; **(4)** Pioneered research into the feasibility of changing global temperatures by simulating input of volcanic particles to the stratosphere [Pope et al. **Nature Climate Change** 2012].

Resources and Reservoirs [Blundy, Buss, Cooper, Huppert, Kendall, Scott, Sherman, Verdon, Whitaker, Wookey] focuses on developing fundamental understanding of processes to better evaluate and predict natural resources, and to mitigate environmental impacts of exploitation by imaging and modelling reservoirs and ore bodies, including conventional and unconventional petroleum settings and the subsurface storage of CO_2. High-pressure experiments and thermodynamics are used to better understand hydrothermal ore and diamond deposits. By linking molecular-level geochemistry with innovative technologies for interface analysis, new approaches to environmental remediation are developed: **(1)** Pioneered use of passive seismic monitoring in oil and other reservoirs to better exploit microseismic data, resulting in better understanding of fracture characterisation and geomechanical responses to reservoir production [de Meersman et al. **Geophys.** 2009; Angus et al. **Geophys. Prosp.** 2010; Chambers et al. **Geophys. Prosp.** 2010]; **(2)** Studied geophysical aspects of CO_2 sequestration, including seismic imaging of CO_2 injection sites, long term seismic monitoring of storage, and mathematical models and experiments [Neufeld et al. **GRL** 2010; Verdon et al. **EPSL** 2011; Verdon et al. **PNAS** 2013]; **(3)** Integration of laboratory experiments with *ab initio* computer simulations and synchrotron X-ray spectroscopy to elucidate fundamental controls on trace metals in aquatic environments and hydrothermal fluids [Sherman et al. **GCA** 2008; Mei et al. **GCA** 2013]; **(4)** Development of a novel (and patented) process for manufacturing water filters using nanomaterials [Scott et al. **J. Hazardous Mat.** 2010].

b.4. Strategic changes since RAE2008 and future aims. Reflecting on RAE2008 allowed us to further develop, and modify, our Research Strategy during the REF period. While our philosophy

remains that individual staff pursuing their own ideas leads our research, we recognised the need for an overarching strategy that provides the basis for growth and success, resulting in the strategic elements codified in **b.1** and **c.1**. The current Themes (see **b.2**) have evolved from those in RAE2008, consistent with the responsive nature of our Research Strategy and our ability to identify and pursue important science questions. For example, *Subduction* was identified as a Theme in RAE2008, and while several staff members still pursue research in this area, subduction per se was judged too specific, and the diversity of projects are now better placed within *Dynamics and Architecture of the Solid Earth*, *Crustal Magmatism, Volcanism and Geological Risk* and *Resources and Reservoirs.* The lastTheme is new since RAE2008, and is a good example of actively pursuing new opportunities; it underpins our recent successes in obtaining industry funding for research into reservoir imaging and modelling, porphyry copper deposits, and nanomaterials. The number of Research Groups changed from five to six, as Geophysics and Petrology separated from the Deep Earth Group of RAE2008; a functional mitosis arising from growth in the Geophysics group and very different equipment needs. These groups maintain strong research links through the *Dynamics and Architecture of the Solid Earth* Theme.

The School has grown considerably during the REF period, and in the sections below we provide comparisons, where appropriate, of the School's current position relative to RAE2008. The School's future research ambition is simply to remain one of the world's top earth sciences research centres. We aspire to be further recognised, e.g. by a top ten position in the QS World University (Earth and Marine Science) rankings (currently 29th), as somewhere that consistently produces innovative, high-quality, high-impact research in an exceptionally collegial environment, such that we are a magnet to the best researchers. Specific aims for 2014-19 include: (1) Growth and diversification of our research funding base with emphasis on the industrial sector; (2) Continued growth of our postgraduate cohort with emphasis on overseas students; (3) Further development of our research infrastructure through University-led bids; (4) Growth in academic staff numbers in areas of strategic need (e.g. geodynamics, tectonics, applied geophysics).

c. People: Since RAE2008, the School has grown from 28.7 to 33.5 FTE core-funded academic staff, including 13 professors (11.1 FTE), of whom 3 are FRS (Blundy, Huppert, Sparks). Post-doctoral researchers are critical to our enterprise: we have 4 Royal Society URFs, 1 AXA Chair, 5 NERC Fellows, 2 RCUK Fellows, 1 STFC Fellow, 6 Marie Curie Fellows, 1 Rubicon Fellow, 1 AXA Fellow and 30 other externally-funded Research Associates. The age and gender profile of the School is actively monitored; of 44.28 Category A researchers submitted, 10 are designated early-career researchers and 32% are women, including 2 Professors and 5 Readers. Of 14 hires in the REF period 43% are women. 58% of PhD students are female. Non-academic staff (9.8 FTE administrative, 7 FTE technical) provide essential support to teaching and research.

c.1 Staffing strategy. Our strategy is designed to be responsive, flexible, and with the ultimate goal of recruiting outstanding researchers in the wide range of disciplines necessary to deliver world-class science across our Research Themes. To achieve this goal we have developed the following strategy: **(1)** We recruit new staff in order to respond to emerging scientific initiatives and to maintain critical mass in the various Research Groups; **(2)** We target new joint appointments between Earth Sciences and other Faculty Schools; currently we have three [Hendy, Pisani, Vinther] held jointly with Biological Sciences and one [Huppert] with Maths, emphasising the University's commitment to 'omics-based' research; **(3)** We recruit via the University's "Exceptional Talent" route whereby world-class researchers [e.g. Cashman] are 'head-hunted' on the grounds that (a) they can support their own salary in the long term through external research revenue, and (b) there is a high strategic value to their appointment; **(4**) We make proleptic appointments, to begin upon termination of the fellowship, to outstanding research fellows, such as URF or RCUK; **(5)** We secure externally funded positions; we currently hold such positions in volcanology (AXA Chair - Cashman) and economic geology (BHP Billiton Lectureship - Cooper)**.**

Since RAE2008 we have recruited new staff in earth observation (Biggs), crustal weathering (Buss), planetary atmospheres (Teanby), global sea-level (Siddall), ocean geochemistry and palaeoclimate (Hendry, Hendy, Parkinson, Robinson), seismology (Werner, Wookey), volcanology (Cashman), phlyogenomics (Pisane, Vinther) and economic geology (Cooper).

c.1.1 Staff Development: A Management Committee consisting of the HoS, School Manager,

Director of Teaching, Director of Research, Head of Graduate School and a junior academic staff member provides strategic advice on policy issues and ensures continual review of staff support and development. Each staff member, including research fellows, is assigned a mentor to help guide research activity and review career development. The University has a new Staff Review and Development process making it mandatory for each staff member to undergo a yearly review by senior Professorial staff. The HoS has reviewed all staff individually since 2008. We follow well-established University policies on staff induction, staff review and promotions. The University's HR division provides ample support and training opportunities in leadership and management, personal and career development, work and family, sustainability, health and safety, and more.

c.2 Research Groups: Each staff member is assigned to a primary Research Group, although many staff are affiliated with more than one group. Each Group has frequent meetings, organises reading groups, or has informal research fora, often with external speakers. The Group leader's principal role is to co-ordinate activity within and among Groups, and discuss collaborative research opportunities. Many Groups have overlapping needs in terms of space, expertise and resources, and individuals are not constrained by their perceived research area. The Research Groups with assignments (current group leaders underlined) are:

Environment [Buss, Foster, Hendy, Hornibrook, Naafs, Siddall, Whitaker] focuses on climatic, chemical and ecological change on land and in the ocean using biogeochemistry, isotope geochemistry, modelling and biology. This Group is at the forefront of developing, calibrating, and interpreting quantitative proxies on timescales from decades to millions of years for the effects of global change on element cycling and ecology in the ocean and on land.

Geochemistry [Coath, Dhuime, Elliott, Hendry, Parkinson, Robinson, Scott, Sherman] applies theoretical and analytical work to global problems in environmental chemistry, geochemistry and cosmochemistry. The Group has harnessed new plasma and laser technologies to develop world-beating laboratories for the analysis of novel isotopic systems. Development of a unique, collision cell mass-spectrometer (ERC Advanced Grant 'ISONEB' to Elliott) is an exciting future prospect.

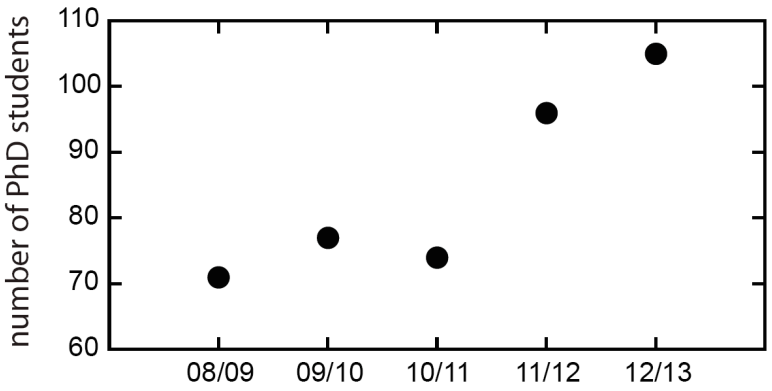
Geophysics [Biggs, Helffrich, Huppert, Kendall, Teanby, Verdon, Werner, Wookey] has world-leading expertise in seismology, gravity, GPS, and satellite/spacecraft observation. Members address problems at the scale of planetary atmospheres, hydrocarbon reservoirs, volcanoes, tectonics and Earth's mantle and core. They have deployed portable seismic and geodetic networks in some of the harshest conditions on Earth, from the Canadian Arctic to Afar, Ethiopia.

Palaeobiology [Benton, Cunningham, Donoghue, Kearns, Pisani, Rayfield, Schmidt, Vinther] covers a breadth of time scales and organismal groups to understand biological evolution on Earth with a particular emphasis on the evolution of form and function. Research combines observational studies of fossils with pioneering developments in biomechanical modelling, X-ray tomography, in situ (geo)chemistry, phylogenetics and molecular biological techniques.

Petrology [Blundy, Brooker, Cooper, Kohn, Lord, Schumacher, Walter] uses a combination of high-pressure and high-temperature experiments, petrology, geochemistry, and mineral physics to attack a wide range of problems in the solid Earth. State-of-the-art experimental and analytical facilities permit exploration of conditions ranging from the core to the surface.

Volcanology [Annen, Aspinall, Cashman, Gottsmann, Mader, Phillips, Rust, Sparks, Watson] includes experts in physical volcanology, fluid dynamics, volcano geophysics and probabilistic risk, and combines volcanological and geophysical field studies with analogue and numerical modelling. The hire of Cashman ensures the continuation of this group as one of the strongest in the world.

c.3 Research students. Postgraduate students are essential to the research success of the School. They provide raw talent, new ideas, and much of the vitality and work necessary to carry through the research ambitions of our staff. Therefore, attracting the very best home and international students is a strategic priority. In addition to NERC algorithm awards (currently 6 per year), we have secured funding through other research organisations, industry, overseas scholarships and the University of Bristol scholarship scheme. Very recently, the School led a successful bid for a NERC Doctoral Training Partnership ("*GW4+*"). This is the first major research initiative to be led by the Great Western Four alliance of research-intensive universities (Bristol, Exeter, Cardiff and Bath), and involves further partnership with six major UK research organisations (BGS, BAS, CEH, Met Office, NHM and PML), and 28 associates drawn from industry, media and environmental agencies; Blundy is Chair designate of *GW4+*. NERC awarded *GW4+* 28 studentships, making it the largest NERC-funded DTP in the UK; GW4 universities



themselves provided an additional 10 studentships, demonstrating the alliance's dedication to supporting earth and environmental sciences research and training.

There are currently 134 postgraduates; 105 registered for PhDs, and 29 on one of our two MSc programmes (18 in *Palaeobiology*; 11 in *Volcanology*). The ratio of PhD students to staff eligible to supervise (per University regulations) has risen from 2.0 to 2.9 over the REF period. Part of our Research Strategy is to increase PhD student numbers through active recruitment, and by increasing our funding base. The graph above shows that this strategy has been effective during the REF period, and we expect to grow at a similar rate over the next five years. Since RAE2008, MSc and MSci research projects have produced 23 first-author papers and 12 secondary-author papers in international journals. 75 PhD students have graduated and have authored or co-authored 125 publications in international journals. PhD students are recruited via open competition to projects identified by staff members and advertised on our web page each year. Applications are centrally administered and a panel interviews short-listed candidates. Awards are made primarily on the basis of applicant quality, with some strategic oversight to avoid over-concentration in certain areas, and to ensure that new staff have access to PhD students as they begin to grow their research teams.

c.3.1 Postgraduate support. Three academic administrative posts and a School postgraduate administrator support PG students. The Director of Graduate Studies oversees the PG community, with a dedicated academic member of staff acting as Graduate Tutor responsible for PG training and pastoral support. Each PhD student is assigned two supervisors. All academic staff are responsible for Annual Progress Monitoring via reports and meetings with students. This includes a formal annual report and panel interview and a research presentation to the School in Year 2. The PG community has two representatives to liaise with the PG administration team and attend the Faculty Graduate Studies Committee. A School Graduate Forum meeting is held three times a year, enabling students to discuss their training with the postgraduate team in an informal environment. MSc students send representatives to the Staff Student Consultative Committee.

Students are embedded in the Research Groups, which provide the necessary support in terms of facilities and guidance, and hands-on training. PhD students are encouraged to attend advanced level undergraduate courses. Bespoke PG training courses are provided, e.g. in electron microbeams or statistical methods. The University provides additional courses on topics as diverse as time management, computer programming and foreign languages. It is our policy that all research costs for use of centralised facilities, such as electron microbeam analysis or rock cutting, are borne by the School such that no student is disadvantaged for budgetary reasons.

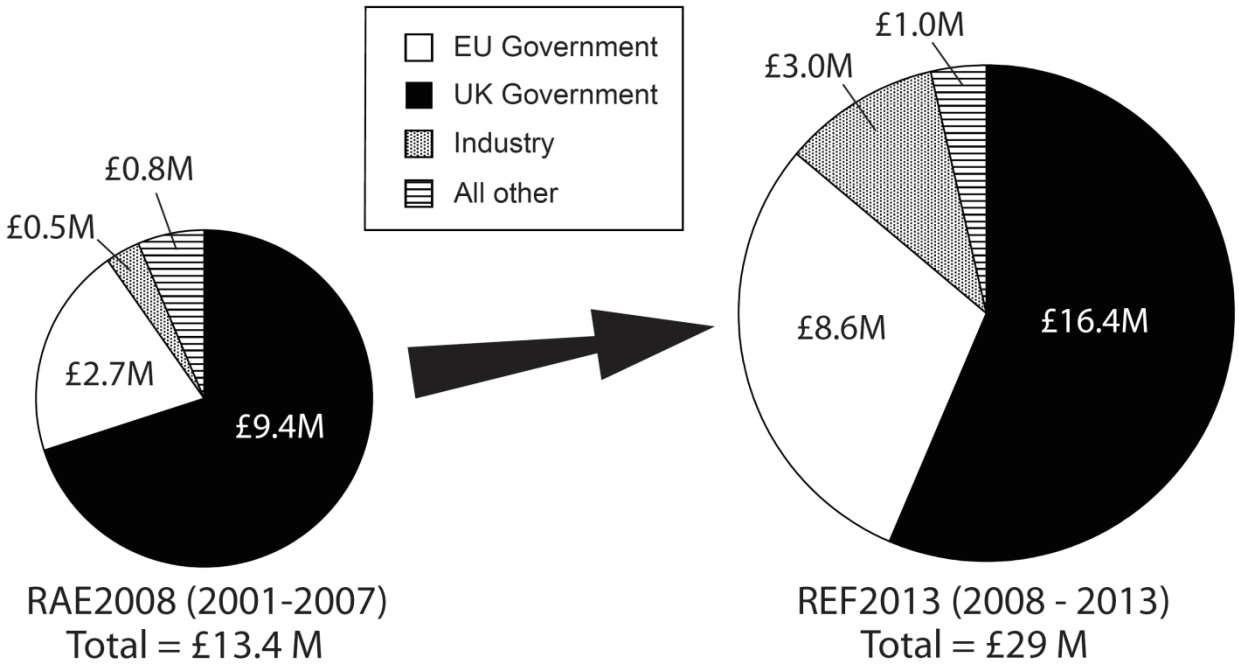
PhD students are required to present their research annually to their Research Groups. The PhD community organises a School-wide PG seminar series in which students present research to their peers. Our PhD students organise an annual Natural Systems and Processes poster session, attended by over 100 PG students from the Faculties of Science and Engineering. PhD students are strongly encouraged to demonstrate in undergraduate practical and field classes; they receive appropriate training in teaching and learning, and fieldwork safety. Demonstrating allocations are based on a knowledge- and skills-based audit of incoming PhD students carried out by the Graduate Tutor and Fieldwork Coordinator.

The accomplishments and destinations of PG students who graduated in the REF period are too numerous for an exhaustive list, but highlights include: permanent academic appointments at Exeter, Harvard, Imperial, St. Andrews, and UCL; postdoctoral Fellowships at CalTech, Berkeley, Columbia, ETH Zurich, Minnesota, NASA, Oxford, UCLA and UCL among many others; numerous prestigious Fellowship awards (NERC, BBSRC, 1851, Leverhulme, Marie Curie); permanent jobs in industry including Npower, Rolls Royce, and Nu Instruments; and editorial positions at Cambridge University Press and the Institute of Physics.

d. Income, infrastructure and facilities

d.1 Research funding. In the REF period we have obtained ~£29M of research funding, including ~£16M from UK governmental sources, ~£9M from EU governmental sources including three ERC Advanced Grants, and ~£3M from industrial sources. Our principal sources of external research funding are RCUK (especially NERC) and the ERC. We have been particularly successful at winning ERC Advanced Grants (Sparks, Blundy, Elliott), and Starting Grants (Robinson, Wookey). These large awards have resulted in the purchase of major new pieces of analytical equipment, as well as recruitment of PhD students and post-doctoral associates. Our success rate in securing NERC Standard Grants is above the national average and submission rates are impressively high, made easier through the institutional support for preparing and costing proposals.

Following RAE2008, the School recognised that over-reliance on a small number of sponsors creates vulnerability. The figure below illustrates how we have broadened our funding portfolio since RAE2008 while increasing income (expressed as spend) by a factor of more than two. We have made the most notable gains in securing EU and industry funding. Particular successes with industry include the award of an AXA Chair in Volcanology (Cashman) and a £1.8M award from BHP Billiton for a new research initiative in porphyry copper deposits (Sparks, Blundy, Rust); this illustrates the effectiveness of our Research Strategy in that collective strengths in geochemistry, volcanology and petrology allowed us to successfully bid for industrial funding in an area of research for which we are not traditionally known. We have also expanded our portfolio in the energy sector; the School hosts and participates in a number of joint industry projects sponsored by petroleum companies (e.g. *BUMPS*, Kendall, £840k; *IRT-MODE*, Whitaker, £750k), and Shell sponsored a study to use novel isotope systems to trace hydrocarbon provenance (~£700k, Elliott). Work related to environmental radionuclide pollution and geological disposal of nuclear waste has attracted funding from Sellafield, AWE, NDA, Royal Society and EPSRC. The School has also received more than £4M of in-kind research income through its extensive use of UK and international facilities (e.g. DIAMOND, ESRF, APS, ALS, Soleil, and SLS synchrotrons; NERC Edinburgh Ion-microprobe Facility).



The School keeps abreast of new research initiatives via regular postings from the University's Research Enterprise and Development (RED) office and by our involvement in research organisation committees, such as NERC, Royal Society and ERC. RED provides support for the costing and preparation of research grant applications and contracts, as well as mock interviews for fellowship applicants, and this support greatly enhances our efficiency in securing external funding. Each staff member typically is involved in one to three research grant applications per year. The level of support provided ensures that the gulf between developing a new concept and applying for funding is minimised and does not constitute an impediment to curiosity-led science.

d.2 Infrastructure and Facilities. We have exceptionally well-equipped and maintained laboratories; these are the predominant, but not exclusive, domain of Research Groups and it is instructive to describe them in terms of what they do, rather than to whom they "belong". Since RAE2008 the University has been supportive in refurbishing research space, including over £3M to refurbish Palaeontology, Geochemistry, and Geophysical Fluid Dynamics laboratory space, and funding for capital equipment purchases, including portable seismograph, viscometer, ion mill, FTIR microscope and ion chromatographs. This strong University support is, in large part, a consequence of our strong external funding successes and perceived research excellence.

Experimental Petrology facilities comprise seven rapid-quench hydrothermal cold-seal pressure vessels, one rapid-quench externally-heated gas-pressure vessel, two controlled-atmosphere furnaces, four 250-ton piston-cylinder and two 1000-ton multi-anvil presses, eight diamond-anvil cells (DACs) with laser-heating and spectroradiometry, and two externally-heated DACs. The facility is overseen by a Laboratory Manager (Brooker); ***Geophysical*** field equipment includes 8 Guralp and Nanometrics broadband seismometers with data loggers, Lacoste-Romberg, Scintrex and Burris gravimeters. Shallow surveying equipment includes a 24-channel seismograph, Geonics EM-31 and EM-61s, Mala and PulseEKKO GPR systems, an Abem resistivity system, a Geometrics proton-precession magnetometer and TopCon EDM. The group also operates GPS equipment including Leica, TopCon and Trimble receivers. Dedicated computing facilities include a 720 CPU Linux compute cluster, and several task-specific high capability servers; ***Microbeam Analysis*** comprises two electron microprobes (JEOL JXA8530F, Cameca SX100), analytical SEM (Hitachi 3500N), Technoorg Linda ion mill, Thermo iN10MX FTIR mapping microscope, and Horiba T64000 confocal micro-Raman spectrometer. The JXA8530F is the first high spatial resolution, field emission gun microprobe in any UK HEI, and was purchased via Blundy's ERC Advanced Grant; ***Isotope Spectrometry*** laboratories are undergoing major upgrades with University support for new clean labs and ERC Advanced Grant (Elliott) support to build a next-generation mass spectrometer, in collaboration with Thermo-Finnigan. The laboratories also house two Neptune multi-collector ICP-MS, a Triton multi-collector TIMS, an Element 2 magnetic sector ICP-MS (all Thermo-Finnagan), excimer laser-ablation, and clean labs; ***Aqueous Geochemistry*** laboratories have equipment for experiments under controlled temperature and atmospheric composition, plus analytical capabilities including ICP-AES, UV-Vis spectroscopy, potentiometry and voltammetry; ***Fluid Mechanics*** laboratories include high-speed cine and videography, digital image processing, rotational and oscillatory rheometry, custom-designed tanks and flumes, and a cold room; ***Biogeochemistry*** laboratories, which are linked to the NERC Organic Geochemistry Unit in the School of Chemistry, include gas and ion chromatographs, reduction gas analyzer, liquid scintillation counter, stable isotope mass spectrometer, constant temperature rooms and microbiology instrumentation; ***Palaeontology*** laboratory (completely refurbished in 2012) hosts fossil preparation equipment, digital imaging microscopes, histology labs, workstations for computed tomography, finite elements analysis and morphometry, a marine culture facility, and a molecular laboratory for amplifying, cloning and examining gene expression.

Ensuring that facilities are properly funded and staffed remains a priority. Of particular importance is our dedicated workshop, essential to the successful design, construction and operation of our equipment base, notably in experimental petrology and geophysical fluid dynamics.

d.3 Library Facilities The Wills Library contains over 22,000 books and journals, online subscriptions to over 10,700 journals across all disciplines, and a dedicated Subject Librarian. The library is located in the same building as Earth Sciences and has recently undergone a major £1M refurbishment, completed in 2013.

e. Collaboration or contribution to the discipline or research base

e.1 Collaborations. The School has strong links with other schools within the University and beyond. We have been particularly successful in securing research funding as a participant in large grants involving consortia in the UK and overseas. Within the REF period we have been involved in the following large-scale, multidisciplinary research programmes:
EU Funded Collaborations. *MED-SUV* and *FUTUREVOLC* are European supersite projects integrating monitoring, data interpretation and decison-making capacity (Gottsmann, Phillips); *VUELCO* involves ten partners in Europe and Latin America, aimed at linking volcano monitoring

to hazard response strategies (Gottsmann); *Crystal2Plate* includes 7 partner organisations and is a training and career development platform for early stage and experienced scientists in geodynamics, geochemistry, petrology, fluid mechanics and seismology (Kendall); *EPOCA* has 32 partners in ten European countries with the goal to advance understanding of the biological, ecological, biogeochemical, and societal implications of ocean acidification (Hendy, Schmidt).

RCUK Funded Collaborations. *STREVA* has 8 partners in the UK and West Indies looking at volcanic hazards from a geological and social sciences perspective (Sparks); the Afar Rift Consortium involves 8 partners in UK, Ethiopia and USA to investigate rifting in north-east Africa using geophysics, geodesy, volcanology and petrology (Kendall, Blundy); *UK Ocean Acidification Research Program* aims to reduce uncertainties in predictions of response to ocean acidification to develop mitigation and adaptation strategies (Schmidt); *VOILA* is a NERC Large Grant involving 5 UK HEIs to investigate volatile recycling beneath the Lesser Antilles (Blundy, Kendall).

Industry Collaborations including Industry Technology Facilitator (ITF). *IPEGG* conducts coupled fluid flow – geomechanical modelling to predict reservoir behaviour and seismic properties during production (Kendall); *IRT-MODE* is an ITF-funded consortium that integrates numerical modelling of reactive transport with observational data to assess diagenetic modification of reservoir-quality in fractured carbonates (Whitaker); *FRACGAS* (ITF) investigates improved hydraulic fracture stimulation of tight gas reservoirs using finite element modelling and microseismic monitoring (Kendall); *GESER* (ITF) investigates enhanced, integrated geomechanics-seismic models of improved lifecycle performance of tight gas sand reservoirs (Kendall); Passive seismic monitoring of CO_2 injection: Weyburn phase II, Petroleum Research Technology Council (Kendall).

Other Internationally Funded Collaborations. *Deep Carbon Observatory* is a Sloan Foundation-funded initiative to advance knowledge of carbon in the deep Earth (Kohn, Walter); *InSight,* is a NASA/ESA-funded mission to study Mars' interior using seismology, scheduled for launch in 2016 (Teanby, Wookey); *NASA Astrobiology Institute* studies environmental, ecological and genetic factors underpinning complex life, its evolution, preservation and detection on Earth and beyond (Pisani).

e.1.1 Interdisciplinary Groups in which School Members have Leadership Roles:

The Bristol Biogeochemistry Research Centre (BBRC) is an interdisciplinary venture bringing together researchers from across the University to address cutting edge questions involving atmosphere/biosphere/geosphere interactions in close collaboration with the Schools of Geography and Chemistry [Buss, Cunningham, Donoghue, Hornibrook].

Bristol Life Sciences is a hub for interdisciplinary research housed in a new £65M building (to be completed late 2013) with state of the art research facilities in biology, palaeobiology, and medicine. This will be home to the Palaeobiology Group from 2014. The vision is underpinned by new joint appointments between Schools and draws together evolutionary biology researchers from Biological Sciences, Chemistry, Computer Science, and Earth Sciences.

The Bristol Isotope Group (BIG) is a collective (Archaeology, Earth Sciences, Chemistry), hosted in Earth Sciences, that uses isotope measurements to investigate a wide range of natural processes, from planetary evolution to environmental change and archaeology [Coath, Elliott, Hendry, Hendy, Parkinson, Robinson].

The Cabot Institute carries out fundamental and responsive research on risks and uncertainty in a changing environment. Interests include natural hazards, resilience and governance, food and energy security, and the changing urban environment [Blundy, Cashman, Foster, Gottsmann, Hendry, Hendy, Kendall, Mader, Schmidt, Scott, Sparks, Robinson, Rust, Whitaker].

Centre for Environmental Flows brings together experts in the applications of fluid dynamics to environmental and geoscience problems, drawn from Earth Sciences, Geography, Civil Engineering and Mathematics [Huppert, Mader, Phillips, Rust, Sparks].

Interface Analysis Centre (IAC) researches materials and material surfaces of all types, including activities in nanoscience and nuclear materials. This involves industrial and fundamental research through state of the art in situ analysis [Donoghue, Schmidt, Scott, Rayfield, Walter, Whitaker].

e.2 Contribution to the discipline or research base. A high level of service to the UK science community and beyond is a hallmark of the School and a further indication of our collegiality. Staff serve on many national and international panels, demonstrating a leadership role within. Examples include: *HMG Blackett Group* (Aspinall); *French ANR* (Annen); *HMG Science Advisory Group for*

Emergencies - Volcanic Ash (Aspinall, Sparks, Watson); *IAEA International Safety Centre* and *Working Group on Probabilistic Seismic Hazard Assessment* (Aspinall); *HMG Scientific Advisory Committee on Montserrat Volcanic Activity* (Aspinall, Cashman, Sparks); *European Association of Geochemistry Council* (Elliott, Walter); *HMG Home Office Mathematical Modelling Group* and *Chemical, Biological, Radiological, Nuclear Substances Advisory Group* (Huppert); *European Microbeam Analysis Society Board* (Kearns); *NERC Radioactivity and the Environment Expert Group* and *Science Innovation Strategy Board* (Kendall); *In Salah CO_2 storage project advisory board* (Kendall); *IPCC, Working Group II, Lead Author* (Schmidt); *ICSU Panel on Man-made and Natural Hazards* (Sparks); *Earth Observatory of Singapore Board* (Sparks); *AGU Board and Council* (Sparks); *Nuclear Decommissioning Agency Technical Advisory Panel* (Sparks); *NERC Training Awards Review Committee* (Sparks); *Advisory Board for Mathematics Education,* Chair (Sparks); *NASA ASTER and MODIS science teams* (Watson); *Diamond Light Source Review Panel* (Walter); *NERC Peer Review College* (Blundy, Donoghue, Elliott, Hornibrook, Kendall, Rust, Schmidt, Walter, Wookey).

Further leadership is evinced by presidency and vice-presidency of major scholarly organisations within the REF period: *Palaeontological Association*, *International Palaeontological Association*, and *Geologists' Association* (Benton); *British Geophysical Association* and *Royal Astronomical Society* (Kendall); *Volcanology, Geochemistry and Petrology section of AGU* (Sparks).

Editorship of major international journals is a demanding, but important task. We currently boast Senior Editors on: *Contributions to Mineralogy and Petrology* (Blundy); *Earth and Planetary Science Letters* (Elliott); *Geophysical Journal International* (Kendall); *Physics of the Earth and Planetary Interiors* (Helffrich); *Geochimica et Cosmochimica Acta* (Hornibrook); *Journal of Geophysical Research* (Walter). Invitation to editorial boards is also a clear demonstration of research standing and we have members on several major international journals: *Bulletin of Volcanology* (Phillips); *Chemical Geology* (Elliott, Sherman); *Earth and Planetary Science Letters* (Rust, Schmidt); *European Journal of Mineralogy* (Kohn); *Evolution and Development* (Donoghue); *Evolutionary Biology* (Pisani); *Geochemical Transactions* (Sherman); *Geochimica et Cosmochimica Acta* (Hornibrook); *Geology* (Blundy, Siddall); *Journal of Geophysical Research* (Walter); *Journal of Sedimentary Research* (Whitaker); *Journal of the Geological Society* (Blundy, Donoghue); *Journal of the Physics and Chemistry of the Earth* (Gottsmann); *Journal of Vertebrate Paleontology* (Rayfield); *Journal of Volcanology and Geothermal Research* (Gottsmann, Mader); *Lethaia* (Benton); *Marine Micropalaeontology* (Schmidt), *Organisms, Diversity & Evolution* (Donoghue); Paleoceanography (Schmidt), *Palaeogeography, Palaeoclimatology, Palaeoecology* (Benton); *Palaeontology* (Donoghue); *Physics of the Earth and Planetary Interiors* (Helffrich); *Proceedings of the Royal Society, Series B: Biological Sciences* (Donoghue); *Transactions, Royal Society of Edinburgh* (Benton, Donoghue).

International recognition of our staff via awards and medals and election to learned societies over the REF period provides a robust barometer of international reputation and standing:

- CBE for services to environmental sciences (Sparks)
- Election to FRS (Blundy); FRSE (Benton); Academia Europea (Blundy, Sparks); American Academy of Arts and Sciences (Cashman); Fellowship of AGU (Cashman, Kendall).
- Major international awards include: *The Geological Society's William Smith Medal* (Aspinall), *Wollaston Medal* (Sparks), *President's Award* (Robinson), *Murchison Fund* (Rust), *Lyell Fund* (Rayfield, Schmidt) and *Wollaston Fund* (Wookey); *Paleontological Society's Schuchert Award* (Donoghue), *Sylvester Bradley Award* (Vinther) and *Hodson Award* (Rayfield, Vinther); *Royal Society's Bakerian Prize* (Huppert) and *Wolfson Research Merit Awards* (Blundy, Cashman, Donoghue); *Philip Leverhulme Prize* (Robinson, Teanby); *IAVCEI Thorarinsson Medal* (Sparks) and *Wager Medal* (Gottsmann); *AGU Kuno Award* (Rust); *Joseph Priestley Award* (Sparks); *Princeton University Hess Fellowship* (Werner); *Caltech Kliegel Lecturer* and *Moore Scholar* (Blundy); *Challenger Fellowship Award* (Robinson, Hendry); *Royal Astronomical Society Fowler Award* (Wookey), *Winton Capital Award* (Biggs) and *Keith Runcorn Prize* (Verdon); Distinguished Lecturer for *AAPG* (Whitaker), *Mineralogical Society of America* (Cashman) and *European Association of Geochemistry* (Elliott); *Springer Thesis Awards* (Ramalho, Verdon, Nowacki); *SEDI Doornbos Memorial Prize* (Wookey); *Antarctic Service Medal* (Hendry).