Institution: University of Cambridge

Unit of Assessment: B 07 - Earth Systems and Environmental Sciences

a. OVERVIEW: The Department of Earth Sciences sits within the University's School of Physical Sciences; this encompasses the physical and mathematical sciences and fosters **strong multi-disciplinary collaboration** in research. Much of our most effective and cited work has involved significant collaboration within Cambridge, nationally and internationally. Many of the major advances to which we have contributed occurred at the boundaries between disciplines; such as marine geophysics and seismology (plate tectonics), earthquakes and stratigraphy (extensional basins), petrology, fluid mechanics and geochemistry (hydrothermal plumes, physical volcanology and melting), marine sedimentology and isotope geochemistry (climatic cycles), and solid-state physics, petrology and mineralogy (encapsulation of hazardous materials).

We continue to attract a large group of independent research fellows (8) and post-graduate students (80) who make vital contributions to our vibrant research culture. The uniquely integrated Natural Science Tripos teaching structure in Cambridge enables us to **attract a significant number of biologists, physicists and mathematicians into Earth Sciences** as undergraduates and as PhD students (section c.ii.2). We also attract excellent research students from other UK departments and institutions worldwide. We have **strong collaborative links with industry** (especially through hosting the BP Institute), which exploits our fundamental research advances and employs many of our students and young research workers, provides access to important data, and has facilitated the design and construction of novel instrumentation. Our **flexible structure and lack of rigid group boundaries** encourages creativity and new initiatives with a high degree of intra- and inter-departmental collaboration.

b. RESEARCH STRATEGY: Our goal is to carry out **fundamental innovative research** to make major advances in the Earth Sciences. Our strategy is to maintain strength in several key areas so that we can apply a **broad-ranging interdisciplinary approach** to a wide spectrum of problems in Earth Sciences, ranging from geophysics, geodynamics, petrology, volcanism, climate change and palaeobiology to the physics and fundamental properties of materials. This strategy is reinforced through **interdisciplinary research centres** which we were instrumental in setting up ─ notably the Cambridge BP Institute with the partner Departments of Applied Mathematics and Theoretical Physics (DAMTP), Chemistry, Engineering, and Chemical Engineering, and the Institute of Theoretical Geophysics (ITG) with DAMTP.

Overall **strategic leadership** is provided by a Head of Department (HoD) who is elected for a minimum of five years, with possible extension for a further 5 years. This provides a highly stable leadership structure with overall strategic direction developed by interaction between the HoD and the Department Advisory Committee, whose membership is evenly balanced between professorial and more junior members of staff and covers all of the major research areas. The strategy is reviewed annually by discussion with the Head of the School of Physical Sciences (SPS) and feeds into the longer-term plan of the SPS which is then reviewed by the PVCs for research, planning and resources and the University's Research Policy Committee.

The HoD, with the Advisory Committee, **monitors the Department's progress** in several ways and provides feedback through the bi-annual Department Meeting. The University Research Office provides statistical data on research grant income and success rates, and the department has a database of all research grant submissions with their outcomes so that we can retrieve statistical information on individuals or the unit as a whole. We have a record of publications by all department members for over 30 years; in the period 2008-13 this includes 1150 peer-reviewed publications, with 77 contributions to Nature or Science. We produce a Research Handbook, summarising the activities of all staff who are active in research. The Department's Advisory Committee regularly reviews this information and a summary is tabled at Department meetings. Academic staff can access most of this management information on-line.

b.i ***Evaluation of strategy from RAE 2008:*** For the 2008 RAE our long-term research priorities were focused in the 3 areas below, with the following consequent developments:

b.i.1. Geodynamics, seismology and mantle structure. We are active in a number of new initiatives in which we aim to set the agenda in the general area of geophysics and tectonics. The international impact of this work, in both academia and the commercial environment, has been recognised by the recent award of the ***Royal Society's Copley Medal*** *(McKenzie)*, a ***Leverhulme Prize*** *(Deuss)*, and the endowment of two new posts by industry (section d.i). The appointment of four new young university lecturers in tectonics & geodynamics *(Copley)*, geophysics *(Rudge)*, fluid

dynamics *(Neufeld)* and theoretical geophysics *(Al-Attar)* and the forthcoming appointment to a new chair in Quantitative Earth Sciences have reinforced our links with DAMTP and the BP Institute (BPI). To support this work we have invested in a new fluid-dynamics lab, an extensive set of seismometers and new computational facilities.

b.i.2 Climate change, environmental impact studies and energy provision. New initiatives have included testing the ice-volume-threshold hypothesis for millennial-scale climate variability and using sulphur isotopes to understand the coupling of carbon and sulphur biogeochemical cycles (*Turchyn*). New appointments of a Palaeoclimatologist to the ***Woodwardian Professorship*** *(Hodell), a* ***Royal Society Research Professor*** *(Wolff)*, who brings ice-core expertise to the department and University climate groups, and a university lecturer in Palaeoclimatology-Palaeoceanography *(Skinner)* have been reinforced by several postdoctoral appointments, including a Herchel-Smith Research Fellow and 5 other postdocs funded by 2 ERC awards totalling over £3.75M. We have carried out a £1M+ expansion, refurbishment and re-equipping of the palaeoclimate labs (section d.ii).

The Department is central to the University's strategic initiative in climate science which has led to the formation of the **Cambridge Centre for Climate Science (CCfCS)**, linking the world-class cross-department strengths in Earth Sciences, DAMTP, Chemistry, Geography (including the Scott Polar Research Institute) and Plant Sciences with the British Antarctic Survey. The CCfCS focuses on the fundamental scientific processes underlying climate science. Field and laboratory measurements, together with theory and modelling, explore the causes and consequences of rapid climate changes in the past, developing a basis for understanding our present climate and providing input to our collaboration with the climate-modelling community.

Our work on climate systems includes research on **carbon sequestration** (led by *Bickle*) which is intended to improve our understanding of the fate of CO_2 stored for long periods in geological reservoirs. This research is supported by a £730k grant from DECC and a £3M NERC-funded consortium hosted by this department (CRIUS, running from 2008-2014), as well as industry-funded modelling and monitoring projects concerned with multi-phase flow of CO_2 and brines in reservoirs, together with colleagues in DAMTP and BPI.

b.i.3 Palaeobiology, deep structure of the evolution of life. A major focus on the Precambrian-Cambrian transition, particularly on soft-bodied fossils and microfossils, has generated a wealth of new insights into Cambrian and Ediacaran palaeobiology and ecology, including the central importance of the rise of animals. This area has been strengthened by 3 new University Research Fellows and over £1.5M funding from the Templeton Foundation (to *Conway-Morris*) and RCUK.

b.i.4 Infrastructure. The amalgamation of smaller departments to form the present Department of Earth Sciences in 1980 left us occupying two sites separated by 2km. The University is currently developing a 250 acre site in **NW Cambridge** and the importance attached to the future of Earth Sciences is demonstrated by the inclusion in the masterplan of land contiguous with the BP Institute for consolidation and expansion of the Department of Earth Sciences. This will allow the whole Department to be located together on one site, thereby stimulating intellectual activity, reinforcing a sense of common purpose, and ending the vulnerability of the present split site.

b.ii ***Major long-term research priorities.*** Our work can be loosely grouped into the five thematic areas below. We emphasize that our research transcends traditional scientific boundaries and there is considerable overlap between these areas, but these groupings provide an effective way of distributing responsibility for teaching, mentoring and providing support for grant applications. An FRS is involved in each of these areas, helping to provide research leadership, strategic guidance and vision.

b.ii.1 Petrology and Volcanic Studies. Natural hazards form one focus in this area, with a growing group of researchers working on the environmental effects of modern and past volcanism. We aim to investigate how magma differentiation and degassing relate to atmospheric loading in both basaltic and silicic volcanoes, using thermodynamic and fluid-dynamic models to interpret our observations. Modelling and observation of deeper mantle conditions will include investigation of peridotite melting, the geochemistry of large-volume well-mixed basaltic eruptions, and the link between these processes and mantle convection.

b.ii.2 Geophysics, Geodynamics and Tectonics. We will investigate a very broad spectrum of structural, tectonic and geodynamical processes using quantitative physical models closely integrated with space-based (GPS, radar imaging) and Earth-based (seismology, gravity,

petrology) observations as well as the increased resolution of geophysical imaging technologies. Fundamental targets include the structure and rheology of the lithosphere, the influence of mantle convection on the stratigraphic record, magma movement in the crust, and the thermal and compositional state of the Earth's deep interior. We anticipate a greater use of fluid-mechanical methods across this research area, linked to related advances in petrology, geochemistry and mineral sciences. Both natural hazards and energy-related themes are involved here, with substantial support from the hydrocarbon industry as well as RCUK.

b.ii.3 Mineral sciences*.* Our expertise on the properties of minerals and fluids at a fundamental level will play a significant part in taking forward research on radioactive waste management and CCS. We also anticipate significant developments in understanding the magnetic behaviour of small particles and the properties of domain boundaries. This area is supported by industry, RCUK and a £2M ERC award *(Harrison)*. The recent installation of facilities unique to the UK include a laboratory for NanoPalaeoMagnetism and a Resonant Ultrasound Spectroscopy facility (*Carpenter*, section d.ii), these will allow us to move into new areas of research including domain-boundary engineering and extraterrestrial magnetism. These developments will support our existing strengths in dielectric-ferroelectric and magnetic properties (3 of the 8 'highlighted' papers for 2012 in these sections of the Journal of Condensed Matter were from this Department).

b.ii.4 Climate Change and Earth-Ocean-Atmosphere Systems*. A* large group is involved in research into the impact of changing ocean-carbonate saturation on marine calcifying organisms and the processes controlling atmospheric CO_2 on million-year time scales. This research uses a range of new techniques including foraminiferal boron-isotope ratios and B/Ca to reconstruct changes in seawater pH, which is being applied as a proxy for pCO_2 reconstruction in the Plio-Pleistocene, particularly to glacial-interglacial transitions. By combining numerical modelling with observational data we will investigate feedbacks regulating carbon burial and oxidation in the subsurface deep biosphere and resolve the long term sinks of carbon from the surface of the planet. In the area of CCS a small-scale CO_2 injection experiment will use fluid and gas geochemistry to constrain short-term fluid-mineral reactions and two-phase flow behaviour during CO_2 storage and injection for enhanced oil recovery. Additional use of Sr-isotope and chemical fluxes to determine permeability and mineralogy at depth will help evaluate the viability of this process as a factor in climate-change mitigation.

b.ii.5 Palaeobiology, palaeoecology and evolution. Under the general theme of the interaction between biota and environment we will work in four frontier areas: 1. Research in Neoproterozoic-Cambrian palaeobiology will lead to significant multidisciplinary advances in understanding the causes (and consequences) of the modern biosphere and the origins of major animal groups. 2. Work on Mesozoic ecosystems will extend to investigation of key anatomical transitions in vertebrate evolution such as the origin of birds, and secondary adaptation to life in water. 3. In collaboration with mineral scientists, we will investigate unique patterns of biomineralization in shell-forming organisms. 4. The nature of organic complexity and occupation of biological hyperspace and their bearing on evolutionary thinking.

c. PEOPLE

c.i.1 Staffing strategy. The identification and recruitment of the highest-quality, most able and creative researchers internationally, followed by their retention, mentoring, encouragement and support through provision of the highest-quality facilities is the cornerstone of both the University's and the Department's staffing strategy. Our academic staff have backgrounds ranging from solid-state physics to zoology and many are involved in more than one subject area. The **age profile** is well balanced: over 30% are under 40 years. Over the next 5 years we anticipate refilling 5 posts which will fall vacant by retirements and since 2008 we have been able to **refill all vacancies** arising from retirement or resignation by excellent new appointments. The Department and the School recognise the importance of, and deliver, start-up packages to attract the very best staff from an international pool; these new appointments have refreshed our strategic areas and ensured critical intellectual mass in each one. The new **Royal Society Research Professor** and the endowment by one of our industrial associates of a **new chair in Quantitative Earth Sciences** connected with tectonics and geophysics (which we are in the process of filling) will further strengthen research leadership. The University has acknowledged the Department's overall performance by prioritizing the upgrading of our infrastructure and experimental facilities through £2M of internally-competitive funding over this period.

We now have 34 academic staff, 42 research fellows and postdocs, 10 Computer and

Technical Officers to support key research facilities, and 46 administrative and technical support staff. 15% of our postdocs hold personal independent research fellowships from the Royal Society, RCUK, EU (Marie-Curie) or elsewhere. The others are funded from RCUK, EU or industrial research grants. Distinguished active **Emeritus academic staff** and **collaborators retired from senior positions in industry** contribute significantly to the Department's vitality through their research, experience and ambassadorial roles, fostering commercial interactions and attracting visits from leading international figures. The Department's reputation, unique research facilities and international research collections, combined with opportunities for collaboration, attract visitors of stature; each year we welcome many short-term visitors and 12-15 **overseas academic visitors** staying for a month or more, including some on Leverhulme or British Council funded fellowships or long term sabbaticals, These all add to the overall vitality**.**

c.i.2 ***Staff development.*** All **new academic staff** receive an intensive induction at both departmental and University level, and as a minimum take part in the *University's professional development programme* for probationer University lecturers. All junior appointments must complete a period of *probation* during which they receive mentoring and support. They are encouraged to attend existing lectures in the Department, to familiarise themselves with the student audience, and are not normally expected to lecture in their first year. When they do begin teaching, it is usually in their own specialism to 3rd and 4th year students. They are also encouraged to attend relevant university training courses, and the Department runs its own training for supervising and demonstrating.

An annual exercise is conducted by a **University promotions committee** to consider applications for promotion of academic staff to the office of Professor, Reader or Senior Lecturer. Decisions are made according to clearly advertised criteria. The Head of Department provides personal and individual advice and guidance to staff applying for promotion. In 2012-13 two staff were promoted to professorships (1 female) and two to readerships (2 female). Academic staff are entitled to **paid sabbatical leave** to encourage their research at the rate of one term for every six terms of service, up to a maximum of three terms at any one time; typically 3 staff/year take a term or more sabbatical leave. Additional periods of sabbatical leave are available to those whose research plans have been disrupted by carrying heavy administrative loads e.g as Head of Department. Staff are also entitled to generous sick and maternity leave with the opportunity for a graduated return. The support of **Early Career Researchers** (including postdocs) is driven by the ***Code of Practice for Research Development***. They are introduced to teaching through 4th-year seminars, field courses and guest lectures, depending on their expertise. University support and development schemes for research students are mirrored by similar schemes for ECR, and include development opportunities provided by the *Centre for Entrepreneurial Learning* and similar groups. 'Postdocs Of Cambridge' is a University Society for ECR, and an organised active social group within the department also provides an informal support structure as well as opportunities for induction and networking.

An **appraisal system**, based on the University's, reviews all staff on completion of their probation and at least every two years thereafter. It consists of: self-assessment by the staff member; assessment by the reviewer; a face-to-face discussion of progress, training and development needs, and plans for the next review period; and creation of a written action plan.

c.i.3 ***Equality and Diversity.*** At undergraduate, postgraduate and postdoc level our gender distribution is very close to 50%. The overall proportion of female academic staff has increased from 6% to 15% over the past 20 years. In 2013 75% of the senior academic staff promotions in the Department were female and currently the proportion of female academic staff at Reader level or above is the same as the proportion at more junior levels. Returning Carers can apply for additional University funds as a contribution towards research costs, travel or technical support to help them quickly re-establish their research profiles; two department members have been helped in this way since the scheme was introduced in 2012. Options for career breaks or secondments are also available and part-time working to support staff at various stages in their career development. We follow all of the University policies and procedures on equal opportunities, disability, and dignity@work. In recognition of these provisions for its staff, the University has received a number of awards including being ranked 11th (the highest for a UK HEI) on the Stonewall list (in 2012 and 2013) and winning the inaugural Employee Engagement award from the Employers Network for Equality and Inclusion (2012). The University has made a submission to renew its bronze Athena SWAN award and the Department aims to achieve a bronze award of its

own by 2014.

c.ii.1 Research students. Our research student community is flourishing and diverse, numbering at any one time over 80 postgraduates within their 4-year research period. Most are studying for PhDs, typically 4-5 are registered for an MPhil by research. Research students' projects range across the whole spectrum of the Earth Sciences, and a number are jointly supervised with other departments including DAMTP, Chemistry and Materials Science. Some projects are devised and tailored with prospective students. We aim to provide a stimulating training environment backed up by excellent research facilities; the Advisory Committee scrutinizes rigorously all studentship projects to ensure scientific viability, sound training for the student, and that all required facilities are available. We are the lead partner in the successful Cambridge NERC DTP submission which involves 7 University departments and the British Antarctic Survey, we are also a partner in a pending EPSRC CDT (in Nuclear Technology).

c.ii.2 Postgraduate recruitment. Some 100-120 high-quality applications are made each year from those with first degrees in earth sciences, physics, chemistry, mathematics, materials science and biological sciences. About **50% of the applications are from the UK**, with a growing overseas proportion. Short-listed prospective students are invited to visit us for a full day, to discuss their potential projects with supervisors and to be interviewed separately by a panel of four members of staff. Taking into account comments from potential supervisors, the panel ranks candidates by ability and research potential irrespective of field, and offers are made on this basis. **Overseas students** are admitted on the basis of paper submission, references and interviews by telephone or Skype. Where possible we seek assessments through academics personally-known to us in their home country.

We typically admit 15-25 students each year, of whom about **30% are from overseas**. We supplement the 20% of our intake funded by RCUK quota studentships, by others supported in a variety of ways. An endowed department fund supports one PhD student every 2 years at the same level as RCUK. The rest are funded from research grants, special scholarships and overseas foundations, or by industry (20%). Over 30% of our intake has first degrees in subjects other than Earth Sciences, strongly enhancing a culture of interdisciplinary research. Their introduction and absorption into Earth Sciences is nurtured through attending a carefully selected set of undergraduate lectures and by involving them as participants in fieldwork at all levels.

We regularly consult with our long-term **industrial partners** who support these recruitment strategies, recruit many of our students into their organisations on graduation and frequently fund research studentships here, including many involving students without a traditional geological background. They also contribute significantly to the sustainability of our field-based research training by providing funds to support training in field skills.

c.ii.3 Postgraduate Training and Support. Graduate students are assessed on entry to determine whether they should attend further courses in mathematics and sciences, computing, statistics or some of our specialist advanced undergraduate courses. In addition, they benefit greatly from exposure to a wealth of ideas, stimulating environment, exceptional Departmental facilities, and the **large and active community of fellow** postgraduates - both within the Department and in the college environment.

Students are strongly encouraged to attend **Department seminars** covering the whole range of the Earth Sciences, in order to widen perspectives, expose them to argument and debate, and to develop sound critical judgment. In term there are about four such seminars per week, ranging from the specialist to general and interdisciplinary, many delivered by speakers of international stature (in the first 9 months of 2013, 50% of the 50 speakers were from overseas).

Skills Training is provided in the form of generic courses by the University, additional courses for Earth Science research students provided by the Department, and training embedded in the research environment. Students also benefit from a business training course run by the BP Institute, from contacts with our Industrial Associates, and from the enterprise culture of the Department. Overseas students must meet the University's stringent language requirements on admission, but the Department arranges extra tuition if language difficulties persist. **Teaching experience** is a valued part of postgraduate education. Graduate students develop their skills by demonstrating in laboratories and on field courses. The more experienced give supervisions to small groups of undergraduates, usually after having attended University-provided courses for supervisors, reinforced by the Department's own written guidelines and subject-specific guidelines. We attach a high priority to students **attending international meetings,** and give training in oral

and poster presentations. In these ways they are encouraged to recognize that the communication of science is an important part of research. **Department travel funds** allow us to provide a £150pa travel allowance to every postgraduate, regardless of other support, to help meet the cost of attending conferences or fieldwork. Their success in winning over **25 best-poster prizes** or similar awards, at national and international conferences since 2008, provides a clear demonstration of the quality of the student intake.

c.ii.4 Postgraduate progress monitoring. The Department follows the ***University Code of Practice for Research Students***. Supervisors are required to submit termly reports using the on-line **Cambridge Graduate Supervision Reporting System.** Each student is assigned two academic staff members as '**Friends**', in addition to their supervisor. Students are required to write a report on the aims of their project, a description of their work, results so far, and outline plans for the next stages at the end of year 1. The Friends hold a viva with the student and then report to the supervisor and submit a **formal assessment** to the **Graduate Affairs Committee (GAC)**, which consists of three graduate tutors who cover the Department's main teaching and research areas. If progress is satisfactory, the student is registered for the PhD degree with the Board of Graduate Studies. If there are major concerns, meetings will be held with the supervisor and GAC, the student may be required to must submit a further report for assessment later in the year. The students submit a first draft of a thesis plan at the end of year 2 which is also reviewed by the Friends. The GAC maintains a **'watch list'** of any students whose progress may be less satisfactory, requesting regular reports from their supervisors so that potential problems can be dealt with at an early stage. The GAC also closely monitors progress towards **planned submission dates** of students in their fourth year.

Seminars are given by students in their second and third year, and are well attended by staff, post-docs and the student cohort. They provide a valuable indication of progress and training for conference presentations. We provide video equipment so they can be recorded for self-appraisal or professional feedback. By the end of the second year we expect all students to have made at least one presentation and a record of these is kept in order to monitor this policy.

The graduate **student cohort is mutually supportive**, and rapidly gains a camaraderie through relationships developed on field trips, laboratory demonstrating, meeting together over coffee and at regularly-organised meals out. The graduates independently organise a weekly social focus, preceded by a graduate talk in which students inform each other of their research in a supportive setting to gain invaluable feedback. Three graduate students attend the non-reserved agenda of the GAC to provide feedback on graduate concerns. The **success of our overall strategy** is reflected by the high completion rates (over 85% of students complete their PhD within 4 years), many graduate publications, best-paper and best-poster awards at conferences (see c.ii.3), as well as by the employment rate and destination of the students. As would be expected in a Department with an excellent research base, our PhD students often complete outstanding research, and the publication of several papers in high-profile peer-reviewed journals before submission of a thesis is common. A recent survey of the careers of our alumni shows that 45% of our postgraduates go on to academic careers and many have become leaders in academia, research institutes, industry and government, worldwide.

d. INCOME, INFRASTRUCTURE AND FACILITIES

d.i Income. The Department currently holds over **80 research grants with a total value of c. £22M**. Research grant expenditure in 2012/13 was over £3.9M. We have worked hard to diversify the sources of our research funding; at present c.**40% is provided by RCUK** and **30% from EU-funded** projects (amounting to c. £7.5M, including ERC Advanced awards to *Elderfield* and *Hodell*, Consolidator award to *Harrison*, and Starter award to *Deuss* and *Turchyn*). Research grant income from **industrial collaborations** has been between 12-20% over each of the previous 4 years, amounting to over £2M during this period. Industry has also provided free use of geophysical seismic imaging and analysis and has provided ship time, high-quality datasets and commercial software packages for data handling, which helps make this research area less vulnerable to changes in research council funding.

In 2010 **major endowments to fund academic staff** positions included £3.93M to the BP Institute to support an extra Lectureship and provide administrative support and £4.35M to fund the BP Foundation McKenzie Professor of Earth Sciences, which will strengthen research leadership in tectonics and geophysics. We also receive regular **un-hypothecated donations** from industry; in 2012-13 these were in excess of £120k. These donations allow us to respond rapidly to

opportunities for leveraging further financial support for our research programme. Over the past 5 years we received a number of other generous targeted **bequests and donations**, including a £3M endowment to support the work of the Sedgwick Museum of Earth Sciences and an additional bequest in excess of £100,000 to support research in palaeontology.

We regularly use **national and international facilities** with high notional costs for ship-time, neutron scattering (RAL), synchrotron X-ray diffraction (Grenoble), and international nuclear-licensed sites (PNNL and Karlsruhe). Over 2008-13 these averaged £380k pa with equipment loans from the NERC Geophysical equipment pool amounting to £150-200k pa.

d.ii ***Specialist infrastructure and facilities.*** We have an exceptional research environment with state-of-the-art experimental facilities that include a number of unique systems developed in-house to approach specific problems in entirely new ways. The University has demonstrated its commitment to our work by providing funds to develop our **facilities for climate research;** since 2008 these have included an XRF core scanner (£270k), three different mass spectrometers for stable isotope analysis (£840k) and a Neptune multi-collector ICPMS for more specialist applications (£760k). To optimize performance we have recently spent over £200k refurbishing our isotope-geochemistry laboratories and associated facilities.

The Godwin Laboratory is a self-contained part of the Department with its own dedicated suite of mass spectrometers, and is one of the World leaders in the fields of Palaeoclimatology, Palaeoceanography and stable-isotope analysis. In 2010 three new high-precision mass spectrometers increased the lab's total to 9, supported by various preparation systems, a cavity ring-down water-isotope analyser, and a sediment- and sample-processing facility. The Godwin has its own permanent support staff and plays a key role in collaborations between researchers in Cambridge and other Institutions, as well as providing a service supplying consistently high-quality isotope measurements to researchers within other parts of the University, elsewhere in the UK and throughout the World.

We have established a **Resonant Ultrasound Spectroscopy** (RUS) National Facility, purchased through the EPSRC (£214k). The unique capabilities of this instrument allow examination of strain coupling and dynamic properties of microstructures, such as transformation twin walls in ferroelastic materials and boundaries between polar nano regions in relaxors. It has been used to explore how the propagation of seismic waves, controlled by the elastic constants of silicates and oxides in the mantle and of molten and crystalline Ni-Fe alloy in the core, are influenced by the microstructure of the material through which the seismic energy travels. A new laboratory for **NanoPalaeoMagnetism** (ERC funded), includes a magnetically shielded room housing a high-resolution scanning magnetic microscope capable of spatially-resolved palaeomagnetic measurements at submicron length scales. This facility will be used to explore palaeomagnetic signals acquired by meteorites during the formation of the solar system.

We have invested in **facilities for handling radioactive materials** to support research on spent nuclear fuel management. Our two NMR spectrometers play an important part in this work, as do other modern instrumental facilities vital to other areas of mineral science research, including several different diffractometers in our well-equipped XRD lab, which allow high-quality measurements of strain and lattice parameters under conditions up to 1400^{o}C, under ambient conditions, and on air-sensitive samples.

We have recently spent c. £100k renewing equipment in our mineral separation and rock crushing facility and have other excellent **facilities for petrological work,** including an electron micro-probe which is also used by other departments in the University and further afield, a laser ablation ICPMS, and a Raman system. These facilities are supported by permanent staff.

The Sedgwick Museum of Earth Sciences is an integral part of the Department. It is an international research and training facility, providing a major resource for scientific study and teaching. Visitor numbers have risen from 60,000pa to 90,000pa since 2008, so it has a prominent role in communication with the public. It is internationally renowned for the great scientific and historic importance of its collections, which include all the 1500 rocks collected by Darwin during the *Beagle* voyage. In its role as a safe international repository for rock specimens it has received four major systematic collections (of almost 10,000 rocks) in the last 10 years. Its collections contain:

- *over 10,000 palaeontological type-specimens,* as well as more than 30,000 referred and figured specimens documenting UK biodiversity over the last half billion years.
- *The Harker Collection,* consisting of more than 165,000 specimens of igneous, metamorphic

and sedimentary rocks acquired from almost every part of the world since 1850.

- *The Documentary Archive,* which includes: the original manuscript of Scilla's 17th century book (the first ever on the meaning of fossils) and his related collection; the entire Woodward archive (documenting the oldest known intact geological collection and the founding of the world's first professorship of Geology); material related to many of the greatest geological contributions of the 19th, 20th and 21st centuries (most recently from Sir Edward Bullard, Harry Whittington and Brian Harland).

During the past 5 years over £750k has been spent on museum development (with a £500k HLF grant for work focussing on the *Beagle* voyage and the influence of geology on development of Darwin's ideas on evolution). Access improvements, partly funded by the Wolfson Foundation, have helped to improve access to the rest of the Department. New endowment income (section d.i) has provided the museum with funds to develop some of its work into the future and provide support for the permanent appointment of an archivist responsible for the museum's holdings in this area.

The **University Library** provides all members of the University with access, from anywhere in the world, to over 21,000 full-text electronic journals and a growing collection of electronic books. It is a legal deposit (copyright) library which houses over two million volumes on open shelves. Income from the Department's endowment funds contributes to the University's Journal Coordination Scheme to support subscription to overseas journals in specific subject areas. The **Department library** complements these holdings; its collections include over 40,000 maps and a breadth of historical material which continues to be important for active research in many areas of the Earth Sciences and forms a valuable resource for colleagues in cognate disciplines.

d.iii ***Consultancies and professional services.*** Our staff regularly provide consultancy to a variety of businesses ranging from engineering and hazards (e.g. Arup; reviewing earthquake hazard for BP's proposed expansion of a refinery site in Azerbaijan) and frequently to companies related to the oil industry (including BP, Schlumberger and Tullow).

e. COLLABORATION AND CONTRIBUTION TO THE DISCIPLINE OR RESEARCH BASE

e.i ***Collaboration.*** We are fully engaged with a wide range of international collaborative research programmes and our staff fulfill leadership roles in many; e.g. *Wolff* who is co-chair of IPICS, the International Ice Core coordinating body, *Bickle* who chairs the overall Science Plan Writing Committee of the **International Ocean Drilling Program** (IODP). Four others have served on IODP panels at the international or national level including the Science Steering and Advisory Panel and the UK Scientific Advisory Panel, over 40 department members have some involvement with IODP, 13 have participated in ODP/IODP expeditions.

Since 2008 our staff have led, or participated in 19 EU Framework projects in **Europe** and several collaborative projects with the British Antarctic Survey**.** We are involved in many on-going **RCUK**-funded collaborative projects including CRIUS (on carbon capture and storage, *Bickle*), COMET and Earthquakes Without Frontiers (on natural hazards, *Jackson*), and Refine (on nuclear waste management, *Farnan*). Over 50% of the research outputs we have submitted to the REF involve **co-authors from overseas**, providing a further indication of the level of international collaboration. Collaborative research, in association with 8 different multi-national and smaller **companies,** is currently supported by 15 grants amounting to £2.4M. This work covers a variety of energy-related projects. Many of these contribute to the University's **Energy Strategic Initiative** which seeks to utilise the University's range of expertise through cross-disciplinary projects to tackle the grand technical and intellectual challenges in energy that require integration of science, technology and policy research. Examples of these projects include:

- Sub-basalt seismic imaging, with Schlumberger and a consortium of multi-national oil companies *(White, RS).*
- Extending understanding of the evolution, origin and structure of sedimentary basins and continental margins, particularly with BP *(White, NJ).*
- Interdisciplinary work on natural ventilation systems, in conjunction with colleagues in Architecture. A spin-out company (Breathing Buildings) has resulted from department work in this area *(Woods).*
- A range of fluid-dynamical projects connected with issues including enhanced oil recovery and understanding oil spills *(Woods).*
- Work with the Nuclear Decommissioning Authority and AWE connected with nuclear waste management *(Farnan).*

- A range of projects connected with the quantifying the risks of CO_2 leakage from CCS schemes *(Bickle, Neufeld, Woods).*

The BP Institute continues to undertake a variety of scientifically exciting projects which have arisen from regular contacts with scientists in both BP and a variety of other companies. As a consequence of close interactions with BP, our staff have acted in an advisory capacity on the Macondo Gulf oil spill *(Woods)* and have sat on BP's Technology Advisory Council *(McKenzie),* which is made up of senior technology executives from industry and academia.

Our culture of interdisciplinary research is fostered by several active **collaborative local networks**, including:

- *The Cambridge Centre for Climate Science* (section b.i.2), promoting research across 6 University Departments and the British Antarctic Survey.
- *The Quaternary Discussion Group,* connecting researchers in Earth Sciences, Geography, Archaeology, Zoology, Chemistry and the British Antarctic Survey.
- *The Cambridge Volcanology Group*, spanning 9 departments including Earth Sciences, Geography, Chemistry and DAMTP
- *The Cambridge Centre for Carbon Capture and Storage*, linking research activities carried out across eight departments and research groups at the University.

To support these collaborations the Department continues to host many **national and international conferences,** ranging from international meetings with over 400 delegates to smaller workshops. Within the past 2 years we have coordinated 10 major meetings. All contribute to the vitality of the research environment; in addition, the interactions and the opportunity to see the breadth and depth of our work have subsequently led many delegates to arrange return visits and sabbaticals in order to collaborate with our staff. These meetings also help us to attract excellent postgraduates and postdocs, thereby contributing to the sustainability of our research. Over the past five years staff members have also been invited as speakers at over 100 international conferences and have been invited **keynote speakers** at 40 international conferences held overseas over this period. We have a dedicated **Research Grants Officer** who supports staff in developing new programmes and managing existing research programmes. She is supported by the University Research Office and interacts with research facilitators in the School and with University research analysts, whose remit embraces the development of research across the University and encouraging interdisciplinary research.

e.ii ***Contribution to the discipline.*** Our staff are fully engaged with the research community beyond the Department at all levels. In the **international arena** our staff hold key strategic positions such as Chair of the IODP Science Plan Writing Committee. Several have served on the review boards of overseas and UK Earth Science institutions, including the Universities of Uppsala and Bremen, Nanyang Technological University of Singapore, Deutsche Forschungs Gemeinschaft, the Paul Scherrer Institute (Switzerland) and UCL. They have also participated in Appointment Committees and as PhD examiners for several overseas institutions.

At a **national level** our staff play a significant role in the UK research councils. In addition to membership of both the NERC & EPSRC Peer Review Colleges, these roles have included chairing the Evaluation Panel of the NERC Earth System Science theme, chairing the Programme Advisory Group of the NERC Ocean Acidification research programme, membership of NERC's Science & Innovation Strategy Board and Training Advisory Group and of the Royal Society's Global Environmental Research Committee. They make important contributions to the dissemination of science as members of the **Editorial Boards** of 12 different peer-reviewed journals and act as reviewing or advisory editors to many more. The contributions of our staff to the subject have been recognised by many **prizes** during the past 5 years, including international awards from AGU *(Holland)* and the French Academy of Science *(Galy)*, and election to membership or fellowship of learned societies. Our staff include 7 Fellows of the Royal Society (*Bickle, Conway-Morris, Elderfield, Jackson, Salje, White, Wolff*).

Our staff contribute substantially to the strategic direction of the discipline by serving on the Councils of international scientific bodies including the Mineralogical Society of America, the International Glaciological Society and the Geological Society of London. They also act in an advisory capacity on scientific matters to a range of **governmental and commercial bodies**. Since 2008 these have included representation on the Board of the Parliamentary Office for Science and Technology *(Salje)* and BP's Technology Advisory Council *(McKenzie).*