Institution: University of Bristol

Unit of Assessment: 7 – Earth Systems and Environmental Sciences

a. Context

The School's six Research Themes address broad fundamental questions in: *Earth Surface Processes; Dynamics and Architecture of the Solid Earth; Evolution of Biodiversity and Morphology; Planetary Formation, Structure and Dynamics; Crustal Magmatism, Volcanism and Geological Risk;* and *Resources and Reservoirs*. Themes are delivered by the six interacting Research Groups (see REF5). This research drives a broad spectrum of impact, with beneficiaries ranging from policy advice and public engagement on climate change, ecosystems, natural hazards and risk, to close interaction with commercial entities exploiting reservoirs and resources. In several areas of our activity (e.g. management of hazardous nuclear wastes) we have non-academic partners directly engaged in the research.

In the REF period, the School has directly advised the governments of the UK (HMG), Montserrat and Greece, national institutions (e.g. Atomic Weapons Establishment, Met Office), and a plethora of private companies (e.g. Rio Tinto, De Beers, Exxon-Mobil, BP, Rolls-Royce, Shell, AXA, BHP Billiton). Our value to the latter two companies is evidenced by financial support for a three-year AXA Chair in Volcanology (Cashman) and BHP Billiton Lectureship in Economic Geology (Cooper). Both posts originate from our strong research links with these companies, are designed to foster collaboration and, explicitly, generate socio-economic impact through knowledge transfer.

Strong public engagement activity underpins all areas of research in the School and operates at all levels, from local schools to national broadcast media. We are actively engaged with the public, policy makers and industry through social media. Our Twitter feed is followed by over 600 people, the School's Facebook page is 'liked' by over 700 and the Palaeobiology Group's by 256; our LinkedIn alumni page has nearly 250 members. The School's young researchers have also produced highly acclaimed blogs and Twitter pages including: *Between a rock and a hard place*, an official EGU blog devised and run by our PhD students (over 10,000 views in the final five months before the end of the REF impact period) and *Frack-Land* and *TheFracDoctor* – a blog (5,000 hits per month) and Twitter page (460 followers) run by NERC Fellow Verdon. Research-led outreach activities have connected the School with tens of thousands of members of the general public, supported by, and working with, *STEMNet* (Science, Technology, Engineering and Mathematics Network), the Heritage Lottery Fund, Bristol City Council, the Centre for Public Engagement, and many museums and schools across the South West.

b. Approach to impact

The key to world-class impact is world-class research. Consequently, our primary approach to impact is the prosecution of first-rate science. Traditionally, research-intensive universities and schools have defined 'impact' as a directive process, where knowledge is accrued within the school and information is broadcast to stakeholders. In contrast, we have developed two distinct impact-generating mechanisms: **proactive** (problem-solving-led) and **reactive** (reputation-led). Impact beneficiaries via either mechanism fall into three broad categories: government, commercial entities, and the public. We interact with beneficiaries rather differently; typically, though not always, proactively with companies and the public, and reactively with governments.

Proactive impact arises as members of the School identify and focus upon scientific questions (or "grand challenges") with socio-economic impact. Challenges range from educational issues (such as the promotion of Earth Science in schools) to resource-oriented problem solving (such as the development of techniques to monitor geological reservoirs - see *Reservoirs Under Stress* case study). Once a challenge has been identified and a preliminary route to tackling it formulated, beneficiaries are approached and, through direct engagement, we explore joint interests in the research process. Many of our successful impact case studies originate from such dialogue, because the potential end-users of the research are involved at a relatively early stage.

Proactive impact in the private sector tends to lead to collaboration supported by research funding. In several cases a deep understanding of physical processes and analysis is applied to either software or hardware development, where most of the technical expertise, at least initially, is provided by the School. Once commercial significance or viability has been demonstrated, there is an informal transfer of intellectual property to the company. These interactions often build on strong, well-developed personal relationships. For example, two of the three Rolls-Royce

employees Sparks and Watson regularly interact with when discussing volcanic ash impacts on jet engines (2010-present) are alumni of the school, one a former MSci student (Beth Erland, 2000-2003) and the other a PhD student and later post-doctoral researcher (Fred Witham, 2005-2011).

A key aspect of the School's approach to impact is our ability to identify important challenges and potential solutions. Challenges can arise either through informal interactions with industry, education or media, or through national initiatives championed by RCUK or learned societies. Awareness of new problems and a flexibility to tackle these beyond their scientific "comfort zone" characterise School staff. Examples include recent work on the physical volcanology of kimberlites and implications for diamond exploration (*Kimberlite Diamonds* case study), a NERC Catalyst Grant (Blundy and Sherman) to explore collaborations with the mining industry in strategic metals exploration, and the porphyry copper deposit (PCD) research initiative. The latter resulted from informal interaction with senior staff at BHP Billiton, who identified porphyry copper mineralization as a major challenge for exploration. The well-known association of PCDs with volcanoes played into the existing research strengths of the School and, in consequence, a scoping study was proposed and commissioned by BHP Billiton. This brought School members with diverse research skills (petrology, volcanology, fluid dynamics, geochemistry, tectonics) together to focus on a topic of major economic importance, despite ore geology not being a traditional School strength. In 2012, BHP Billiton put £1.8M into a four-year research project. Although this work is too immature to feature as a case study for REF2014, it highlights an approach to impact that currently not only funds one lecturer, two post-docs and three PhD students, but also engages undergraduate students, with potential to lead to graduate recruitment, further reinforcing impact feedback.

Proactive impact can also involve public engagement. Promoting best practice in science delivery within schools is a key impact route. Several Research Groups have long-standing relationships with local schools, Bristol Zoo, Bristol Museum and Art Gallery, and the @Bristol science centre. Our aim is to inform and inspire the public by communicating not only knowledge and passion, but also the results of research activity. For example, GCSE and A-level Geography feature focus topics around Montserrat Volcano (*Volcanic Risk Reduction* case study) that arise directly from research carried out in the School since 1995. Another example is the *Bristol Dinosaur Project*, a major, open-access educational initiative funded by the Heritage Lottery Fund (£300k; 2008-2013). The project identified the potential of dinosaurs as a vehicle for engaging children in science education, and capitalised on the underpinning research of Benton and others to secure Lottery Funding for a programme of public engagement and aspiration-raising. Since 2012, *Bristol Dinosaur Project* has reached over 12,000 school pupils in 115 UK schools, and a further 12,224 children and adults at events such as the Festival of Nature. The project was awarded the 2011 STEM award for the best engagement project in the South West and was one of seven shortlisted (out of 900 national entries) for the National Lottery Awards.

Reactive impact arises from our reputation for research excellence across a wide range of disciplines; by creating a visible, high standard of research, the School acts as a beacon for industry and other organisations to seek out and establish collaborations. The process is driven by stakeholder needs and can require members of the School to be highly responsive. The recent Icelandic volcanic ash crisis is an example (*Volcanic Ash* case study). Impact can then be achieved through policy makers instigating change in established guidelines or practices and is based on our individual or collective expertise. Several School members have achieved this though national committees such as NERC *Science Innovation and Strategy Board* - Sparks (2005-2009) and Kendall (2011-present), HMG *Scientific Advisory Group for Emergencies* - Sparks, Aspinall, Watson (April/May 2010), the *International Atomic Energy Agency* - Aspinall (2007-present), the *Nuclear Decommissioning Agency* - Sparks (2000-2008) and the *Volcanic Ash Observations Review Group* - Watson and Sparks (2011-present). School members also have *ad hoc* advisory roles for HMG, including the *Department of Energy and Climate Change (DECC)* - Watson (2011-2012) and the *Home Office Chemical, Biological, Radiological, Nuclear Substances Advisory Group* – Huppert (2005-present). Aspinall is frequently called upon for his expertise in expert elicitation to advise the HMG on low-probability, high-consequence events, e.g. natural hazards impacting on nuclear power stations (2010), and on emergent issues such as leukaemia risk for the *Public Health Agency of Canada* (2009-2010). When interacting with HMG, School members often discuss ideas that require a synoptic perspective and an understanding of the political sensitivities, as well as deep, domain-specific knowledge, particularly around crisis risk

management and climate change. School members not only provide scientific advice but also highlight uncertainties and knowledge gaps within their fields. For example, Sparks chairs the independent Advisory Committee for Mathematics Education (2012-2015) that aims to influence HMG strategy and policies with a view to improving the outcomes of post-16 mathematics teaching and learning in England.

Another consequence of reactive impact is public engagement on local and national radio and TV, science festivals and national events. Within the REF period members of the School (Blundy, Rust, Phillips) featured prominently on *Volcano Live* a four-part BBC TV documentary series on volcanoes (July 2012), and Donoghue, Rayfield and Benton have advised the BBC on a number of science documentaries, including the Emmy Award-winning *First Life* with David Attenborough, and, more recently, *Rise of the Continents* (June 2013). In addition, the School has a traditionally strong showing at British Science Association festival and at the Royal Society's Summer Science Exhibition (three times in the last four years). At a more specialised level, School members frequently write *News and Views* articles in *Nature,* commenting on recent high-profile scientific discoveries; there have been seven such articles in the REF period alone. It is not simply senior academic staff who engage in public outreach. Four PhD students and postdoctoral researchers participated in "*I'm a scientist get me out of here*", an X-Factor style competition for scientists, with school children as judges; in 2012 Verdon came second in a year which saw 1895 students register to take part from 44 UK schools. In addition, the School has 45 STEMNet ambassadors who have run their own volcano and earthquake workshops in local schools.

The recognition that both impact mechanisms (proactive and reactive) are an important driver and metric for our research is critical to the School's research strategy. This requires continued commitment from within the School, driven by the Head of School, the Research Committee and the School's Impact Director. For example, a workshop on developing collaborative relationships that might yield socio-economic impact, led by Sparks, was a key part of the School's annual strategy away-day meeting in January 2010.

There is continued development of a University-wide impact strategy, with strategic oversight from Research Enterprise Development (RED). Various support systems at School and University level help to design pathways to impact. At School level (1) researchers discuss impact specific to their discipline within their Groups and Themes; (2) the Research Committee is concerned with managing research output, including academic and socio-economic impact; and (3) the Impact Director has strategic oversight over impact development. At University level, staff attend training and personal development seminars and workshops to improve understanding of the commercialisation of research, and more effective communication; these are often provided by the University, but also given by external experts such as the NERC Knowledge and Innovation Manager (May 2012). Those involved in more controversial research have undertaken RCUK media training with the direct result of being better able to communicate their research and its context more clearly. The University recognises excellence in impact through the Vice Chancellor's Impact Awards and provides competitive pump-priming funds to initiate such activities. One example is the award of £5k to Watson and Rougier (Maths) to examine the Met Office dispersal model used to forecast ash abundances and used by the Civil Aviation Authority (and European equivalents) to manage airspace during volcanic crises (*Volcanic Ash* case study). This initial research idea subsequently fed into two NERC-funded consortia (VANAHEIM and CREDIBLE, total £5.5M), and delivered two CASE PhD studentships with the Met Office.

c. Strategy and plans

The scientific challenges that the school addresses are important, timely and globally relevant. As a School with broad interests in climate, natural hazards and risk, and natural resources, we will continue to have significant interaction with climate policy makers (IPCC, DECC), industry (mining, nuclear, oil and gas, reinsurance) and hazard managers (*Government Office for Science*, *Department for Transport*, *Office for Nuclear Regulation* and the *US Nuclear Regulatory Council*). We are also developing strategic regional collaborations with other HEIs, for example via the Great Western Four strategic alliance of research-intensive universities (Bristol, Bath, Cardiff and Exeter), and research organisations (ROs), which promise effective mechanisms for impact.

The School's funding stream has diversified significantly since RAE2008 (see REF5), reflecting an increased emphasis on interdisciplinarity and applied earth sciences, and, with that opportunity, we plan to address three key impact objectives over the next five to ten years:

1. Strengthen and develop current collaborations with beneficiaries
Our research strategy has created the opportunity to work closely with exploration companies from various sectors, providing them with access to the latest data handling and modelling techniques as well as innovative thinking about long-standing problems. As well as consolidating established collaborations, we are currently building new relationships with the Atomic Weapons Establishment around interpreting infrasound and seismic data, the Met Office and Rolls-Royce about measurement and modelling of volcanic ash, and with @Bristol on public outreach relating to both academic (e.g. volcanology, palaeobiology) and more applied (e.g. recycling) subjects. Our strategy for building key partnerships emphasises development of trust and mutual confidence, often built via sponsorship of PhD students (e.g. AXA, Met Office, BAS, BGS, South West Water, Golder Associates, Rio Tinto, AWE) and co-publication of research papers.

2. Pursue exciting new research with societal benefits
As with our work on porphyry coppers, we will continue to explore and develop research with high socio-economic leverage. For example, shale gas extraction through hydraulic fracturing has the potential for vast societal impact, but is associated with risk and uncertainty. The School of Earth Sciences is uniquely positioned to approach the problem holistically. We have expertise in microseismicity (Kendall, Wookey, Verdon, – e.g. *BUMPS*, an industry-funded consortium), including seismometers deployed on site in Balcombe; Carbon Capture and Storage (NERC-funded projects of Verdon and Kendall); methane detection from leakage (NERC-funded projects of Hornibrook and Watson) and reactive transport (e.g. industry-funded projects such as *Bristol Carbonates Consortium* and *CARB3D+* - Whitaker) and contaminant remediation (Scott). Through building an evidence base, and via interactions with strategic industrial partners like Cuadrilla, we can respond reactively to need but also proactively seek to collaborate.

3. Further development of impact delivery mechanisms
In 2013 Bristol led a successful bid for *GW4+*, the UK's largest, NERC-funded Doctoral Training Partnership (DTP). *GW4+* involves the Great Western Four universities, six major UK ROs (British Geological Survey, British Antarctic Survey, Natural History Museum, Centre for Ecology and Hydrology, Plymouth Marine Laboratory and the Met Office), and 28 associate partners drawn from earth and environmental science employers across a wide range of activity: science-policy interface (*Welsh Government*, *Cynnal Cymru*, *National Resource Wales*, *Food and Environment Research Agency*, *Centre for Environment, Fisheries and Aquaculture Science*, *Animal Health and Veterinary Laboratories Agency*, *Cornwall Council*); environmental science (*Environment Agency*, *Marine Biological Association*, *National Nuclear Laboratory*); science communication and engagement (*National Museum of Wales*, *National Botanic Garden of Wales*, *Taylor and Francis Publishing*); industry (*Astra Zeneca*, *Thermo-Fisher Scientific*, *Willis Insurance*, *URS Corporation*, *Syngenta*, *Southwest Water*, *Sellafield*, *Shell*, *BHP Billiton*, *Unilever*); and NGOs (RSPB). All associate partners are, consequently, stake-holders in PhD student training and have agreed, through memoranda of understanding, to provide CASE support and workplace secondments to interested students in their second or third years. This explicit DTP impact mechanism will not only expose PhD students to potential employers, but will also engender impact opportunities through closer collaborations between the School and many new potential beneficiaries.

d. Relationship to case studies
Our five case studies have been chosen to represent both the breadth and strength of our impact, and to showcase clear pull-through from research activities within the School. Each case study involves both the proactive and reactive mechanisms of impact generation and how these have been used in concert to maximise impact. Selecting one case study as an example, *Volcanic Ash* clearly demonstrates that the Volcanology Group was approached at the onset of the Icelandic ash crisis because of its strong reputation for research into physical volcanology, fluid dynamics, expert elicitation and remote sensing. Since April 2010, we have strengthened relationships with key partners such as Rolls-Royce, the Met Office and the BGS to undertake appropriate, high impact research. We are producing research tools, such as the *PlumeRise* mathematical model, that other researchers and decision makers can use, and designing CASE studentships aimed at reducing uncertainty in source parameters for dispersal models; both these efforts were proactive in the sense that they were designed as a function of beneficiary need, in collaboration, with socio-economic impact as the leitmotif. Similar relationships can be found in our other four case studies.