Institution: University of Glasgow

Unit of Assessment: B7 Earth Systems and Environmental Sciences

a. Overview

This submission integrates researchers from the School of Geographical and Earth Sciences (**GES**) in the University of Glasgow (**UoG**), and the Scottish Universities Environmental Research Centre (**SUERC**). The School of GES was formed in 2010 from the Department of GES following restructuring of the UoG, and is one of 7 Schools within the new College of Science and Engineering (**CoSE**). SUERC is a specialist research facility that is integrated into the CoSE and works closely with GES. The 36 GES and SUERC staff returned to UoA7 all belong to the Earth Systems Research Group (**ESRG**). The joint Research and Knowledge Transfer Committee is responsible for ESRG strategy and policy. It reports to GES and SUERC executives and the CoSE research committee.

The activities of the ESRG are described via 4 process-based themes: (i) surface; (ii) shallow crust; (iii) Earth-life; (iv) extraterrestrial and mantle. Each group member has a primary affiliation, and many people work across several themes. Those named in plain text are Category A or C staff listed in REF1, whereas people in *italics* are non-submitted staff (postdoctoral researchers or people that have retired/moved) who have contributed to our work over the assessment period.

The ESRG undertakes world-leading research in a range of areas including $^{40}Ar/^{39}Ar$ dating, biodiversity, climate proxies, cosmogenic nuclide analysis, earthquake hazards, environmental carbon, tectonics, and water pollution. Over the assessment period our work has been enabled by:

- Funding by 6 research councils; UK and overseas government agencies; industry; and charities. Research expenditure since RAE 2008 is £18.8M (excluding £0.9M from the SAGES pool);
- Strategic recruitment of 10 academic staff members, a 176% increase in PhD students to 47 FTE, and a 37% increase in postdoctoral researchers to 31.5 FTE;
- Enhancement of our world-class analytical infrastructure by the installation of a second accelerator mass spectrometer, 3 stable isotope and 2 noble gas mass spectrometers, and opening of new laboratories dedicated to materials characterisation, biomarker analysis and ocean acidification.

b. Research Strategy

In RAE 2008 we outlined our strategy to use interdisciplinary approaches to tackle major questions concerning Earth processes and their interactions at different spatial and temporal scales. Particular foci were: (i) thermochronology; (ii) landscape evolution; (iii) Quaternary palaeoclimatology; (iv) biotic response to environmental change; (v) biomineralization; and (vi) digital geoscience. Our strategic goals were achieved by enhancing the quality of our research outputs, and increasing ESRG capability through growth of income, investing in new staff, PhD students and equipment, and strengthening links with research users (e.g. UK government agencies; resource exploration companies). Over the review period we have also targeted support to research that was highlighted by the RAE panel as world leading, namely isotope geochemistry, accelerator mass spectrometry and studies of surface tectonics. At the same time we have diversified our portfolio by responding to new challenges in Earth, environmental and planetary science, and their connections to biology and engineering. Some of the evidence of the success of our strategy is listed in Table 1.

Table 1 Metrics demonstrating the success of our research strategy

Metric	REF 2014	RAE 2008	Increase from RAE 2008
Mean annual publication output*	127	98	30%
Papers in *Science,* the *Nature* titles and *PNAS*,*	21	5	320%
Total research expenditure	£18.8M	£14.7M	28%
PhD students	47 FTE	17 FTE	176%
Postdoctoral researchers	31.5 FTE	23 FTE	37%

*Does not double count co-authored papers. Our 760 papers since RAE 2008 have 5300 citations.

An important feature of our research over the assessment period has been our leading role in the **SAGES** (Scottish Alliance for Geoscience, Environment and Society) research pool. This 5 year initiative was established in 2008 with £22M of funding from the Scottish Funding Council (SFC)

and academic partners. It was designed to help research groups including the ESRG to compete globally by strategic investment in new posts and equipment, building a sustainable graduate school, and facilitating collaboration.

b1. Achievement of our research strategy

Our **surface** processes research has been enabled by £4.6M of support including 5 NERC consortium and programme grants. We have continued to set the agenda in quantifying landscape ages and rates of erosion and sedimentation using in-situ cosmogenic isotopes, and this work has been enhanced by the recruitment of Rood. We have pioneered applications of ^{14}C in environmental reconstruction, which has been supported by the strategic hire of Ascough, and research on freshwater carbon dynamics has been catalysed by SAGES, with strong stakeholder links developed through the NERC-funded CLAD network. With the appointment of Coveney and Li we have created a powerful geomatics and space geodesy capability for analysis of tectonically and climatically driven landscape evolution using InSAR and LiDAR.

The **shallow crust** theme has been supported by £2.6M of grant funding including awards from NERC, 2 Marie Curie Initial Training Networks (ITNs) and international industry. We have pioneered development and application of the (U+Th)/He technique for quantifying rates and timescales of denudation in combination with apatite fission track analysis, and this capability has been enhanced through the recruitment of Persano. The appointment of D. Brown and Koehn has expanded our shallow tectonics work into volcanic processes and stress analysis using rock microstructures. We have driven international efforts in high precision geochronology, and applied $^{40}Ar/^{39}Ar$ to reveal rates and durations of processes in deep time including high precision correlation of the Chicxulub impact with end-Cretaceous mass extinction.

Earth-life processes research has been supported by £2.4M from sources including the Royal Society of Edinburgh (RSE) via independent fellows Kamenos and McGowan, RCUK (BBSRC, EPSRC, NERC, MRC) and the Leverhulme Trust. Our strategic focus on biomineralization along with the recruitment of Phoenix and Toney has led to advances including: validation and application of marine invertebrate and biomarker climate proxies; pioneering use of microfluidic lab-on-a-chip technologies to probe the molecular controls on calcite crystallization; and development of microbial technologies for radioactive waste storage via the EPSRC BANDD consortium. We have also undertaken agenda-setting research into the responses of biotic communities to environmental change at the present-day and in deep time by application of novel statistical and isotopic tools.

Extraterrestrial and mantle research activity has increased sharply with £2.0M of funding from NERC, the UK Space Agency, and STFC (including a £1M consolidated award to ESRG). By combining mineral, chemical and isotopic tracers with high precision chronometers we have explored the chronology of aqueous activity in asteroids and the crust of Mars, and the nature and composition of the deep Earth.

b2. Future objectives

Our £7.1M portfolio of active research grants, which includes **5 NERC consortium and programme awards** and **2 Marie Curie ITNs**, gives us the ability to pursue our current programme and the confidence that our new strategy will succeed. Many of the strategic objectives listed below are underpinned by the unique array of chronometers at our disposal (i.e. ^{14}C; $^{40}Ar/^{39}Ar$; (U+Th)/He; cosmogenic nuclides; environmental radioactivity; fission track analysis; luminescence; ^{210}Pb; U-series), which enable us to quantify the decadal to billion year timescales and rates of geological and environmental processes to the highest precision. We will continue to invest in the areas of research excellence outlined above, and develop new opportunities through our analytical facilities, collaborative networks, and UoG interdisciplinary research initiatives. The following are new components of our strategy:

Our work on **climate change** will utilise the marine and terrestrial proxies that we have developed and validated (e.g. calcareous algae, corals, biomarkers) together with a new capability to measure clumped isotopes using a recently purchased £1.2M ThermoFisher 253 Ultra mass spectrometer. A particular focus will be on cryospheric melt, sea level rise and its impact on coastal and marine processes, resources and management. We will also investigate the drivers of Holocene and Anthropocene climate change in the North Atlantic.

Our work on **environmental hazards** will include monitoring and predicting gas efflux and co-seismic ground deformation. This research will capitalise on our work on environmental sensors that is supported by UoG interdisciplinary networks with computer scientists, engineers and statisticians, and recent funding for radionuclides in the environment via the NERC RATE Programme. Our partnership in the NERC consortium 'Looking Inside the Continents from Space' will enable growth of our capability in remote sensing of natural hazards and environmental change. Our geomatics and geodesy expertise will be consolidated into a new Earth Observation centre that will also collaborate closely with stakeholders on the stability of infrastructure (e.g. dams and bridges).

Hydrocarbon exploration and geothermal power will be the principal emphasis of our **energy and natural resources** work. We will exploit our expertise in isotopic analysis of major gases (CO_2, CH_4, H_2O) and trace gases (He, Ne, Ar), as well as ^{14}C, ^{222}Rn, and organic geochemistry, to fingerprint the source and mobility of gases and dissolved constituents in the crust for carbon capture and storage, tracing the source of unconventional hydrocarbons and quantifying geothermal resources. This emphasis also draws on our capability in crustal fluids and geodynamic modelling, collaborations with statisticians and civil engineers within the CoSE, and current funding from international industry. The analytical facilities at SUERC are being integrated to provide a 'one-stop shop' focused on the geochemistry of crustal fluids.

The 6 STFC and UK Space Agency grants that we currently hold give us a strong platform from which to develop our work on **extraterrestrial chronologies**. The three strands of this research will be: (i) understanding the properties and evolution of primitive asteroids in preparation for sample return missions by NASA, and the European and Japanese space agencies; (ii) developing instruments for in-situ $^{40}Ar/^{39}Ar$ dating of the Martian crust (utilising funding currently in place from the UK Space Agency 'Crest' initiative); (iii) exploring the history of H_2O, CO_2 and organic molecules on Mars via meteorites and terrestrial analogues.

c. People, including:

I. Staffing strategy and staff development

c1.1. Staff strategy. Our return of 36 people is an increase of 2 on RAE 2008. These 36 currently work alongside 31.5 FTE postdoctoral researchers and 47 FTE PhD students. Our staff strategy has been to sustainably grow and strengthen core research areas, including those identified as world leading by the RAE panel, by:

- Appointing internationally renowned scientists and attracting researchers with personal fellowships;
- Recruiting skilled instrumentalists to enhance our analytical capabilities, and scientists with a track record of interdisciplinary research to support our collaborative ethos.

Furthermore we have sought to nurture researchers of the highest calibre by:

- Rewarding success via promotion, research leave and return of a proportion of grant overheads;
- Managing their research time effectively using a robust performance and development process;
- Employing 6 University Teachers to ease their lecture and administration loads.

The ESRG staff returned comprises 13 Professors, 5 Readers, 5 Senior Lecturers, 10 Lecturers and 3 Research Fellows. Two thirds are under 50, thus making for a grade and age profile that is ideal for driving our programme forward. Ten appointments were made during the assessment period as 'new blood' positions or following retirement. We recruited early career scientists with outstanding technical skills and leadership potential from the UK, continental Europe and the USA, and from institutions including Brown University, Lawrence Livermore, Mainz and UCL (Table 2).

Table 2 Strategic staff appointments phased over the assessment period

Name	Theme	Current grade	Name	Theme	Current grade
Ascough	Surface	Lecturer	Li	Surface	Senior lecturer
D. Brown	Shallow crust	Lecturer	Persano	Shallow crust	Lecturer
Coveney	Surface	Lecturer	Phoenix	Earth-life	Reader
Kamenos	Earth-life	Lecturer	Rood	Surface	Lecturer
Koehn	Shallow crust	Senior lecturer	Toney	Earth-life	Lecturer

These people were attracted to the ESRG by its reputation for excellent research and world-class analytical infrastructure. The same factors have been a draw for independent fellows (Table 3).

Table 3 Research fellows with funding won in open competition

Name	Funding	Duration
Balthasar	Volkswagen Stiftung	2009-2012
Ishitani	Japan Society for the Promotion of Science	2013-2015
Kamenos*	RSE/Scottish Government	2008-2013
McGowan	RSE /Scottish Government co-funded by Marie Curie	2009-2014
Morgan	Marie Curie Intra-European Fellowship	2011-2013
Muñoz-Salinas	Marie Curie Intra-European Fellowship	2009-2011
Persano*	RSE/British Petroleum	2006-2008
Phoenix*	RCUK	2005-2010
Wright	Historic Scotland	2012-2013

*As a consequence of their exceptional research performance, independent fellows Kamenos, Persano and Phoenix have been appointed to GES staff.

c1.2. Staff development. Our strategy for staff development as described below follows the **Concordat for Career Development of Researchers** that was implemented by the UoG in 2009. As an acknowledgement of its commitment to supporting its staff, the UoG received the 'HR Excellence in Research' award from the European Commission in 2010. All staff have an annual performance and development review that is tailored to their career stage and conducted by senior academics. It guides professional and personal development, and considers progress against previous objectives and appropriate performance criteria. This process also sets objectives for the following year that are consistent with our strategic goals, and the reviews give staff the opportunity to discuss promotion or research leave. Over the assessment period 7 members of ESRG have had paid research leave and one third have been promoted: 6 to Professor, 3 to Reader, 3 to Senior Lecturer. At professorial level outstanding performance normally ensures a pay award. Professorial pay zones have been externally assessed since 2012, and this transparency has largely corrected previous gender and other inequalities so that pay parity in the UoG is amongst the best in the sector. For example, following implementation of these procedures 31% of the female professorial population moved to a higher salary level.

We place particular emphasis on helping our early career researchers (ECRs) develop independent careers. For their first 3 years, each ECR is paired with an experienced academic mentor. They have light teaching and administration loads, and undertake the UoG Postgraduate Certificate in Academic Practice that includes research skills training. ECRs have priority in applications to the ESRG research committee for funding for conference attendance, equipment purchase and networking. They can also apply to the CoSE equipment fund, which has been augmented by an EPSRC award, with ESRG staff receiving £68k over the last 2 years. Both ESRG and the CoSE run research proposal workshops for ECRs and PhD students, and each person who completes the ESRG course is given £1.5k for proposal development. ECRs receive feedback on research grant applications, and senior academics provide mock fellowship interviews.

The CoSE supports and contributes to the **RSE Scottish Crucible**, which is focused on developing the careers of ECRs. This residential leadership and development programme is based on the UK-wide Crucible training scheme established by the National Endowment for Science, Technology and the Arts (NESTA). Three of our ECRs have won places, and on completion of the programme each was awarded £5k to develop research ideas together with ECRs from other Scottish institutions. The CoSE has a parallel Crucible programme for new staff that is designed to enhance their research skills and to nurture an interdisciplinary community of scientists and engineers. The programme has sessions ranging from ‘pitch’ training to publishing in high impact journals. Eight members of ESRG have so far participated in the CoSE Crucible and it has successfully stimulated new interdisciplinary research activity, for example a £100k grant from the UK Space Agency to Phoenix in collaboration with an ECR from the School of Engineering.

Our **contract staff** contribute substantially to ESRG research, and are supported in the transition to permanent posts. Senior academics provide mentoring and training, and help with preparation of proposals. The contract staff have low-cost access to equipment and technical support, and are given the opportunity to develop academic skills via undergraduate teaching and PhD student co-

supervision. The UoG provides career guidance and workshops on applying for grants and jobs.

International visitors are a major contributor to the vibrancy of our research culture. Annual visitor numbers of 80-100 over the assessment period reflect our historically strong collaborative research ethos. Typically 10-20 researchers per year stay for over 1 month to be trained in specific techniques and to work together with ESRG staff. Visitors speak at the weekly seminar series, and the high degree of participation by researchers and PhD students produces a lively and collaborative atmosphere. ESRG members have undertaken research visits to universities overseas (e.g. Dalhousie, Canada; Hokkiado and Tsukuba, Japan; Melbourne, Australia; Pierre et Marie Curie, France; Yale, USA; University College Dublin, Ireland), some via prestigious awards (e.g. Hansom is visiting Professor at the University of Canterbury, New Zealand). GES has also recently entered into formal collaborations with Shenzhen, Sun Yat Sen and Wuhan universities that will include regular exchanges of researchers and PhD students.

c1.3. Equality and diversity. The vigour of the ESRG has also been enhanced by the influx of new staff members and researchers, and the commensurate increase in our diversity. 36% of our academic staff were born outside the UK and 25% are female, including two Professors, one of whom is the Head of GES. The UoG is committed to promoting equality in all its activities and aims to provide an environment free from discrimination and unfair treatment. In 2007 it established the Scottish higher education sector's first dedicated Equality & Diversity Unit. All ESRG staff have completed online training courses. The 'Equality and Diversity Essentials' course outlines the key legislation of the **Equality Act 2010**, the protected characteristics and types of discrimination and harassment. 'Managing Diversity' looks at the benefits of managing diverse teams, and how to challenge unacceptable behaviour. The UoG joined the **Athena Swan Charter** in August 2011 and its action plan outlines the steps that it will take to advance women in STEMM disciplines, female academics in non-STEMM disciplines and other female staff. It has also set a key performance indicator in its strategy 'Glasgow 2020: A Global vision' to increase the percentage of women in senior administration and Professorial posts. The University was awarded Athena SWAN Institutional Bronze in 2013, and GES applied for Athena SWAN Bronze in November 2013. Appropriate mentors for female staff in GES and SUERC are arranged by Toney, who is on the European board of the **Earth Science Women's Network**, which is sponsored by the European Geophysical Union.

c. II. Research students

The ESRG PhD students are trained in a stimulating and challenging environment that is central to the group's dynamism and the attainment of its strategic objectives. The 176% increase in PhD student FTEs relative to RAE 2008 demonstrates the success of our strategy for growth. The studentships have been funded from sources including: American Chemical Society; Boliden Tara Mines; Carnegie Trust; Eni Exploration & Production; Historic Scotland; Leverhulme Trust; MASTS research pool; RCUK; SAGES; Thermo Fisher Scientific; the UK Space Agency; and overseas governments. With support from the UoG's international office we are developing joint PhDs with overseas organisations, and a current GES student is 50-50 jointly enrolled and supervised at Macquarie University; we also have PhD student exchanges with Wuhan University.

Our PhD students are based at GES or SUERC and are all members of the CoSE Graduate School; they may also be affiliated with the Graduate Schools of the SAGES or MASTS pools, or one of our Marie Curie ITNs. The CoSE Graduate School oversees student training, monitors and refines best practice in recruitment, progression and examination, ensuring compliance with the QA Code of Conduct. Its **Research Student Code of Practice** emphasises the University's expectations of its students and staff and the high level of support they will receive. The admissions procedure for PhD training is rigorous and demonstrates equality of opportunity. All studentships are awarded competitively and on the basis of excellence. The demand for places is high, and as a consequence our PhD student cohort is diverse, with 53% coming from overseas, and 32% from outside Europe.

Each student has their own workspace with a computer, and is assigned a primary and one or more secondary supervisors. In line with the **Researcher Development Framework**, students undertake transferable skills courses via a campus-wide programme in which the UoG invests £300k/yr. Courses include academic writing, project management and public engagement, some of which are delivered by employers. These training packages were shortlisted for Times Higher

Education awards in 2010. The CoSE Graduate School spends £85k/yr on training to complement the courses provided centrally, for example scientific writing and applied statistics. ESRG students are expected to participate in at least 1 national and 1 international conference per year, for which they can receive financial support from the UoG (typically £500 to £1500/yr) to supplement their scholarship funds. They are also encouraged to apply for external funding for conferences, fieldwork and visits to other laboratories, and to contribute to publications. Over the assessment period our students have obtained £26k in grants and published 43 papers.

Student progression is carefully tracked, and we have a rigorous monitoring procedure. All students produce an annual report that is assessed through a mini-viva held by senior ESRG staff. Where progress is acceptable the student moves to the next year of study; if progress is deemed unsatisfactory, remedial action is taken following discussion with supervisors. Just before their annual progression vivas, the ESRG PhD students organise a 2 day conference at which they present their research to fellow students, academic staff and industrial partners.

The success of our training is highlighted by the 2013 **Postgraduate Research Experience Survey**, which found that 83% of our PhD students are satisfied with their experience. ESRG students have also won prizes including: British Society for Geomorphology's Chorley Award (2009); Anglo American Environmental Geochemistry Poster Prize (2009); BGS BUFI Science Festival Poster Prize (2009); Royal Scottish Geographical Society University Medal (2010); Historic Scotland research showcase award (2011); Landscape Research Group best PhD thesis in practical science and planning (2013); Institute of Physics Environmental Physics Group writing prize (2013). The skills that they obtain equip them well for research careers, as shown by destinations of recent graduates that include: BMT-WBM Brisbane; Centre for Advanced Bioanalysis GmbH, Austria; GFZ Potsdam; Universities of Cologne, Durham, Edinburgh, Leeds.

d. Income, infrastructure and facilities

d1. Research grant portfolio

The success of our programmes has been underpinned by a growth of income and a diversification of funding sources. Our £18.8M of research expenditure is an increase of 28% on RAE 2008, and we have been awarded £11.4M of new research grants over the assessment period. Those in excess of £50k have come from RCUK (AHRC; BBSRC; EPSRC; MRC; NERC; STFC), UK charities (Leverhulme Trust; RSE), government agencies (European Commission; Historic Scotland; UK Space Agency), and international industry (e.g. Boliden Tara Mines Ltd; German Society for Petroleum & Coal Science; Eni Exploration & Production; Volkswagen Stiftung).

d1.1. Plans for future research funding. Our £7.1M portfolio of active grants gives us a strong platform from which to develop our research strategy, and we will continue to grow income by: (i) proactively engaging with funders, in particular non-academic users of our research; and (ii) supporting staff to seek funding, especially ECRs. In order to meet our research objectives, we have 4 priority income targets.

(1) Industry and government agencies will be an important source of income to support all of our strategic goals. The innovation centres that are currently being established by the SFC are an exciting opportunity. The UoG leads the £10M **Centre for Sensor & Imaging Systems** (CENSIS), which is an ideal route to support our work on environmental sensors and Earth observation. GES and SUERC are also co-applicants in a proposal for an **Oil and Gas Innovation Centre**, which has been well received by SFC and if funded will support industry partnerships in energy research.

(2) RCUK will continue to be an important source of support, and the grants that we have won from 6 of the research councils since 2008 give us confidence that this target is achievable. We will seek to support our Earth and environmental science objectives through **NERC** via the 3 grand challenges of its forthcoming strategy (making the most of natural resources; resilience to environmental hazards; managing environmental change), and through the new Doctoral Training Partnerships and Centres. For our environmental hazards work we will apply for funding from **ESPRC**, including the Sensors and Instrumentation portfolio. The **STFC** Roadmap and **UK Space Agency** Civil Space Strategy both highlight Solar System exploration as an investment target and so they will be an ideal means of supporting our extraterrestrial chronologies research.

(3) We will build on our recent success with Marie Curie Fellowships and ITNs by applying for funding through the societal challenges of **Horizon 2020** including: (i) Food security, sustainable

agriculture, marine and maritime research, bio-economy; (ii) Secure, clean and efficient energy; (iii) Climate action, resource efficiency and raw materials. We will also seek support for our strategic objectives via the Excellent Science Pillar (European Research Council grants) and by helping researchers to obtain funding from Marie Sklodowska-Curie actions to work in GES and SUERC.

(4) The world-leading research infrastructure available to the ESRG, coupled with the diversity of our expertise, will enable us to become a major hub of PhD training. An early sign of success is the increase of PhD student numbers to the current cohort of 47 FTE. We plan further growth through our membership of 2 NERC Doctoral Training Partnerships (E3 and IAPETUS) and a NERC Centre for Doctoral Training in Oil & Gas, and by exploiting links with Chinese universities and other overseas governments that support our programme (e.g. Azerbaijan, Brazil).

d1.2. Consultancies and professional services. Our analytical infrastructure and expertise is extensively used for contract research. This work has predominantly been in the fields of archaeological surveys, radioactive waste disposal, radiometric surveying and food security. ESRG members also provide expert advice on natural hazards, environmental change and pollution to bodies including: Centre for Ecology and Hydrology; Chinese government; DEFRA; International Atomic Energy Agency; Jet Propulsion Laboratory; Nuclear Decommissioning Authority (UK); Oxfam; Scottish Government Science Panel for unconventional gas; UN Environment Programme.

d2. Research infrastructure – provision and investment

We have an extensive research infrastructure that enables us to address a very wide range of research questions. The support of 33.5 FTE technicians means that this equipment is well maintained and reliable, and that PhD students, ECRs and visitors receive comprehensive and consistent training. Our analytical equipment includes: 15 magnetic sector mass spectrometers for stable, radiogenic and noble gas isotope determinations; 2 accelerator mass spectrometers for quantification of very low abundance isotopes; 3 ICP-based instruments; and an array of continuous flow isotope ratio mass spectrometers for compound-specific isotope analysis of organic material. We have an extensive suite of α, β and γ counting laboratories and a powerful concentration of equipment and expertise for luminescence dating. The (U+Th)/He and fission-track laboratories, with integrated mineral separation facilities, provide the full complement of low temperature thermochronometers, and we have dedicated laboratories for sample preparation for cosmogenic nuclide analysis. The Bio-Earth laboratory houses incubators, an anaerobic chamber and pressure vessels enabling simulation of conditions from the Earth's surface to the deep biosphere. It is also equipped with fluorometers, spectrometers, optode systems and protein analytical facilities for monitoring the responses of marine biota to global change. Facilities for research on nutrient losses from terrestrial landscapes include sensor sondes, analysers for aquatic CO_2 efflux, and measurements of all dissolved carbon species. Our near-shore research vessel is equipped with GNSS-linked echo sounders. Precision survey equipment for quantifying changing Earth surface morphology includes LiDAR, dGPS, GNSS, terrestrial laser scanners and a Swinglet aerial drone.

Over the review period we have invested **over £1M** in magnetic sector mass spectrometers for stable isotopes (two ThermoScientific Delta V; ThermoScientific 253) and noble gas isotopes (ThermoScientific Helix-SFT), as well as elemental analysers. We have also recently purchased a **£1.2M ThermoScientific 253 Ultra** high-resolution stable isotope mass spectrometer, which will place us on a par with CalTech alone in ability to measure **clumped isotopes**. Three new facilities were opened in 2010 with funding from the UoG (£0.6M), SAGES (£0.3M) and research grants:

- The **BECS** (Biomarkers for Environmental and Climate Science) laboratory is dedicated to palaeoclimate work, and is one of the few biomarker facilities worldwide to use advanced chemical ionisation methods for compound specific measurements;
- **ISAAC** (Imaging, Spectroscopy and Analysis Centre) houses 2 field-emission SEMs, microscopes for Raman spectroscopy, cathodoluminescence imaging and fluid inclusion analysis, an atomic absorption spectrometer, and a fully equipped thin section laboratory;
- The **Marine Mesocosm Facility** has 128 remotely monitored microcosms for exploring the impacts on marine biotic and geochemical systems of global change linked to CO_2. Our scientific dive team also gives us the capability to study marine organisms in-situ.

We host and manage **5 national NERC Facilities** that are embedded within the SUERC laboratories: Argon Isotope; Cosmogenic Isotope Analysis; Isotope Community Support; Life

Science Mass Spectrometry; Radiocarbon (Environment). The accelerator mass spectrometry laboratory is, in addition, a Recognised Facility. ESRG members have won £0.6M of in-kind support for access to NERC facilities. We have also been awarded 6 shifts at the Swiss Light Source (£30k in-kind), 18 shifts at Diamond, and access to the EPSRC-BBSRC NRM Facility. ESRG researchers and PhD students have access to UoG facilities, through collaboration or via funded projects, which include: the Kelvin Nanocharacterisation Centre and James Watt Nanofabrication Centre (specialising in materials analysis and manipulation); Glasgow Experimental Magnetic Resonance Imaging Centre; School of Engineering hydraulics laboratories; ScotGrid (high-performance computing); and the Hunterian (one of the leading university museums in the UK).

d2.1. Planned infrastructure investments. In order to maximise the benefits of our work together, GES and SUERC would like to move to a single location, and this is being actively explored. In 2013 the UoG acquired the 14 acre **Western Infirmary site**, next to the current campus, initiating its biggest redevelopment since 1870. The UoG will invest up to £750M in this project and space will be available in the Science and Engineering quarter for a building to house GES and SUERC.

e. Collaboration and contribution to the discipline or research base

e1. Research collaborations and their links to ESRG activity

ESRG staff are involved in a series of UK and international research networks as leader or partner:

- **Amazonica** (Amazon Integrated Carbon Analysis; co-I Waldron, 2008-2014). A collaboration between organisations in the UK, USA and Brazil; the UK part is funded by a £3M NERC consortium grant. It aims to quantify the carbon balance of the Amazon Basin.
- **BANDD** (Biogeochemical Application in Nuclear Disposal and Decommissioning; co-I Phoenix, 2009-2013). A £1.8M EPSRC consortium of 7 UK organisations who are pioneering microbial technologies to tackle contamination in nuclear decommissioning and waste disposal.
- **BRITICE-CHRONO** (co-Is Fabel & Freeman, 2012-2017). A £2.5M NERC consortium of 10 UK organisations whose goals are to understand evolution of the collapsing British-Irish Ice Sheet.
- **CLAD** (Carbon Landscapes and Drainage; PI Waldron, 2009-2013). A £183k NERC-funded knowledge transfer network addressing carbon storage and loss from peatlands.
- **FlowTrans** (PI Koehn, 2013-2016). A €4.1M Marie Curie ITN of 8 universities with 6 industry partners whose goals are to train researchers to understand flow in transforming porous media.
- **FRACS** (PI Koehn, 2010-2015). A consortium of 9 academic institutions funded by €1M from the German Society for Petroleum and Coal Science that advises industry partners on the fluid flow characteristics of heterogeneous, fractured and resealed reservoirs.
- **LICS** (Looking Inside the Continents from Space; co-I Li, 2013-2018). A £2.8M NERC consortium of 7 UK organisations whose goals are to create models of seismic hazards and the physical processes deforming the continents.
- **LO-RISE** (Long-Lived Radionuclides in the Surface Environment; co-Is Cook & Xu, 2013-2017). A £2.6M collaboration of 8 partners funded under the NERC RATE programme, which aims to understand the speciation and transport of long-lived radionuclides in the environment.
- **MEDGATE** (co-I Ellam, 2012-2015). A £2.2M Marie Curie ITN with 10 academic, commercial and public partners that is exploring Mediterranean-Atlantic connections between 10 and 5 Ma.
- **Ordovician Palaeogeography & Palaeoclimate** (co-I Owen, 2004-2009). International Geoscience Programme Project 503. Co-led by Owen, with 260 members from 35 countries.
- **TREE** (TRansfer – Exposure – Effects; co-I Freeman, 2013-2018). A collaboration of 7 UK partners supported by £2.51M from the NERC RATE programme. Its aims are to integrate the science needed to underpin radioactivity assessments for humans and wildlife.
- **VMRC** (Volcanic Margins Research Consortium; co-I D. Brown). A network of 6 UK organisations providing the petroleum industry with training and research expertise relevant to resource exploration at volcanic margins.

e1.1. Link between research collaborations and strategy. The BANDD, FRACS and VMRC consortia, and the FlowTrans ITN, are all direct outcomes of our strategy to appoint staff with multidisciplinary and industry focused research interests (i.e. D. Brown, Koehn and Phoenix). These networks have also led to 'energy and natural resources' becoming one of the 4 objectives of our research strategy, and 'energy' being one of our 2 impact nodes (see REF3a). Our NERC consortium grants (BRITICE-CHRONO; LICS) and the 2 projects supported by the RATE

programme (LO-RISE; TREE) will run until 2017-2018 and will be important in driving and enabling research for our 'environmental hazards' objective.

e2. Support for interdisciplinary research

Restructuring of the UoG in 2010 created a fertile environment for interdisciplinary research, and the diverse research interests and collaborative ethos of the ESRG have enabled it to capitalise successfully on the opportunity. The new CoSE established a series of interdisciplinary research themes, and ESRG has received PhD studentship and seed-corn funding via the Sensor Systems and Space themes. The innovative interdisciplinary research of the ESRG has also been supported by the UoG through its **Kelvin-Smith** (K-S) programme. We have hosted a K-S research fellow in technical art history (with the School of Culture and Creative Arts), and 9 PhD studentships, which are partnerships with the Adam Smith Business School, the Institute of Biodiversity, Animal Health and Comparative Medicine, and the Schools of Chemistry, Computing Science, Engineering, Interdisciplinary Studies, Mathematics and Statistics, Medicine, and Molecular Biology. The 3 K-S studentships that have been completed to date have been very successful in generating research outputs and follow-on activity. The students have published 5 papers, in journals including *Environmental Science & Technology and Integrative Biology*, and the collaborations developed by their work have yielded £1.4M of new grant income from BBSRC, EPSRC, NERC and MRC. The strong interdisciplinary emphasis of ESRG has also enabled our partnership in many of the networks listed above (e.g. LO-RISE and TREE) in addition to smaller projects such as £30k funding from the AHRC/EPSRC Science and Heritage Programme (co-I Lee) for a research cluster focused on landscapes, archaeology and the built heritage. The 5 NERC Facilities that we host are also beacons of inter-disciplinarity with substantial activity across the (NERC-defined) sectors of Earth; Marine; Terrestrial and Freshwater; and Polar science.

e3. Academic leadership

ESRG staff have been instrumental in building and coordinating SAGES, which consists of over 200 researchers working across 4 themes. Bishop and *Fallick* co-led SAGES as it was developed, Hoey is the SAGES Director and previously served as Science Director and Executive Committee co-chair; this latter role is now undertaken by Cusack. Ellam is a member of the SAGES executive committee, Bishop was leader of the 80-member Theme 1 until 2009, and Waldron is co-leader of the 60-member Theme 2. The excellence of ESRG research has been recognised by external awards. We have 3 Fellows of the RSE, and Cusack and Ellam were both elected during the assessment period. Other awards are: Edinburgh Geological Society Clough Memorial Award (D. Brown, 2008) and Clough Medal (*Fallick*, 2013); Erskine Fellowship, University of Canterbury, New Zealand (Hansom, 2009); Fellow of the Geological Society of America (Bishop, 2011); Geological Society William Smith Medal (*Shipton*, 2010); Mineralogical Society Distinguished Lecturer (*Fallick*, 2009-10; Ellam, 2012-13); Royal Society of Chemistry Becquerel Medal (MacKenzie, 2012); RSE Saltire Society's Scottish Science Award (Cusack, 2008).

National leadership by ESRG is demonstrated by our prominent role in NERC through membership of the: Science Innovation & Strategy Board (Bishop); expert group of the £7.5M Security of Supply of Mineral Resources programme (Boyce); Space Geodesy Facilities Steering Committee (Li); Science Advisory Group of the £7.5M Resource Recovery from Waste programme (Boyce); and Peer Review College (R. Brown; Boyce; Li; McGill; Owen; Phoenix; Stuart). Lee was a member of the STFC Astronomy Grants Panel, *Fallick* was chair of the BGS Advisory Committee, and Toney is on the National Science Foundation Low-Temperature Geochemistry panel. We have also provided expert advice to overseas research funders including: Chinese Academy of Sciences; European Commission; German Research Foundation; Italian Science Commission; and NASA.

Service to the community by ESRG members includes membership of the editorial boards of 26 international journals, for example: *Chemical Geology; Geology; Journal of Structural Geology; Lethaia; Mineralium Deposita; Nature Scientific Reports; Palaeontology; Quaternary Geochronology.* ESRG members have delivered 32 keynote and plenary lectures (18 international; 14 UK) and 51 invited talks (35 international; 14 UK) to conferences including the AGU fall meeting, EGU, Goldschmidt and Gordon Research Conference on Biomineralization. We were also the principal organisers of: Palaeontological Association Annual Conference (2008); Geodiversity: why it matters (2010); 2010 Volcanic and Magmatic Studies Group Annual Meeting; 12th International Conference in Thermochronology (2010).