Institution: University of Manchester (UoM)

Unit of Assessment: UoA7 Earth Systems and Environmental Sciences

a. Overview: UoA7 research is based in the School of Earth, Atmospheric & Environmental Sciences (SEAES). Addressing broad, multidisciplinary challenges, we have led major advances in the REF period across atmospheric processes, hydrocarbon exploration, planetary degassing, mineralogical and biogeochemical controls in the Earth's critical zone, and the biochemistry of extinct species.

Key Achievements since 2008:

- Internationally-leading discoveries across the breadth of our activities in high profile journals (16 in *Science, Nature or PNAS*);
- 48% increase in research awards to more than £36M, consistently high RCUK income and a broad range of international collaborations with research activities on every continent;
- 18 major prizes to our staff, 2 prestigious senior fellowships and presidency of 3 learned societies, including only the second non-US president of the Mineralogical Society of America in nearly 100 years;
- Substantial impact on economic output and societal challenges through our outreach and industrial collaboration (e.g. major joint industrial awards worth > £6.5M in petroleum geoscience in sub-surface prediction with e.g. BP, ExxonMobil, Shell, Statoil).

Our success in addressing the complexity and cross-disciplinarity of the major UoA7 challenges, has followed from restructuring our research activities into three interconnected research groups through which we manage our research and training programmes, and physical infrastructure:

- Planetary and Earth Science (**PES**), **16** returned staff,
- Molecular Environmental Science (**MES**) **12** returned staff,
- Atmospheric Science (**AS**) **16** returned staff,

UoA7 hosts 60 Postdoctoral researchers (50 in 2008), with 10 Fellows (3 with guaranteed faculty positions), supported by 7 experimental officers, 8 research technicians and 19 other support staff. We currently have 79 PhD students, with 103 graduating since 2008.

b. Research strategy: Our principal goal is to solve key multidisciplinary challenges in Earth and Atmospheric Science by developing and deploying strong cross-cutting physical and biological science skills and expertise. We also aim to enhance the international impact of our research, by publishing in high-profile journals (leading to 16 papers in Science, Nature and PNAS in the REF period); develop an exemplary knowledge transfer record; deliver significant public-engagement activities; and exploit our high-quality research capability to produce the best environment for postgraduate training (see details in later sections). This vision aligns closely with the Manchester 2020 strategic plan.

Our research combines geosciences, physics, chemistry and biology to provide improved quantification of applied and fundamental Earth processes and their evolution over time. Major societal challenges addressed include:

- safe disposal of nuclear waste
- securing our energy future
- protection of the earth's critical zone
- improvement of regional weather, air quality and climate prediction

while fundamental research foci include:

- formation and evolution of the Earth and solar system
- evolution, biomechanics, taphonomy and palaeobiology of vertebrates
- aerosol and cloud processes and reactive trace gases in the atmosphere

Strategic management and development: We engage actively with our RCUK and industrial funders. We help our funders to define their key research questions and strategic priorities (through research programme management and board and panel membership wherever possible), thereby ensuring alignment between our core research activities and societal interests. This process has highlighted the societal grand challenges noted above and emphasised the need for

an increasingly multidisciplinary approach. Consequently, in 2011, we restructured several smaller discipline-specific activities into 3 larger interdisciplinary research groups, each with substantial critical mass: **Planetary and Earth Science** (**PES**), **Molecular Environmental Science** group (**MES**) and **Atmospheric Sciences (AS**). The Head of each group is an internationally renowned researcher who develops research strategies, fosters links between different research activities and identifies new opportunities. Each group has an annual general meeting with the School Executive to review performance, identify new opportunities, and pinpoint research needs. As a consequence, we have developed and delivered enabling strategies around staffing, postgraduate training, funding, infrastructure and user engagement (see sections below).

By cutting across traditional School, Faculty and University boundaries, we have been able to deliver important activities and achievements. For example, the BNFL-funded Research Centre for Radwaste and Decommissioning (**RCRD**) is led from **MES** and is a key component of Manchester's Dalton Nuclear Institute. It brings together nuclear and environmental expertise from across EPS in line with UoM's 'Nuclear' strategy. Water@Manchester, co-led from UoA7, is a network for water-related research across the University and external research, government and industry organisations. The **MES** Geomicrobiology group is one of the largest of its kind in Europe and draws on expertise from the physical and biosciences. Our palaeontology research links EPS and the Faculty of Life Sciences (**FLS)** with **MES** and **PES**. This group has developed successful *de novo* transdisciplinary research themes in the fields of biochemistry, taphonomy and the locomotion of extinct and extant vertebrates. In particular, state of the art x-ray nano and microtomography, high-performance computing, and synchrotron-based imaging techniques, have produced high profile (*Science, PNAS, Nature Comms*) insights into palaeobiology. **MES** and **PES** are both key contributors to an EPS Faculty energy theme, with inputs to hydrocarbon exploration and nuclear life-cycle. **AS** research makes extensive use of analytical facilities provided by **MES**. All of our activities have contributed to the continuation and expansion of synchrotron-based research since 2008, addressing radionuclide behaviour, biomineralisation reactions, palaeontology and atmospheric science amongst others. This has been delivered at 8 synchrotrons, including the Stanford Synchrotron Radiation Light Source, the Advanced Light Source (LBNL, Berkeley), the Canadian Light Source, ESRF and ANKA (Karlsruhe).

Whilst our research crosses multiple boundaries, our detailed research strategy is built around three core research areas, **PES**, **MES**, **AS**:

1. The goals of **Planetary and Earth Science** (**PES**) are: to extend our understanding of the fundamental processes driving the formation and evolution of the Earth and the solar system, to elucidate mechanisms operating in the Earth´s subsurface and to enable identification and efficient and sustainable extraction of vital resources. The broad grouping across three discrete areas of geosciences within **PES** enables these goals to be effectively tackled by shared, interdisciplinary approaches to developing and applying novel quantitative techniques. Achievements include: development of the world´s most sensitive instruments for Xe and Kr analysis and of sub-micron spatial resolution TOF-SIMS instruments, resulting in the award of aliquots of the most important extra-terrestrial samples available, e.g., sample return missions Genesis (Solar wind - NASA), Stardust (Cometary Material - NASA) and Hayabusa (Asteroid Itokawa - JAXA); pioneering of halogen analysis as noble gases after neutron irradiation, resulting in award of ERC funds to understand the Earth´s halogen cycles through studies of natural and synthetic samples; quantitative microscopic and macroscopic understanding of complex hydrocarbon reservoirs, leading to substantial partnerships with global oil exploration companies; elucidating the form of submarine and subaerial erosion by discovering remarkable geological and oceanographic flows using geophysical data collected by ourselves and industry. As a result, our geomorphology expertise has been recognised by participation in the IODP site survey panel, and staffing drilling expedition and site survey work.

Our overall interdisciplinary strategy has allowed us to build collaborations among the various specialisations within the new **PES** group and beyond. For example, we have combined fracture analysis, petrophysics and multi-scale imaging to understand efficient extraction of gas reserves from unconventional reservoirs. We have combined expertise in imaging from within and outside of **PES** on remote-sensing analysis of planetary surfaces, to target participation in space missions. With STFC funding, we embedded our expertise in noble gas cosmochemistry within the UK cosmochemical analytical network, further enhancing our ability to bid for rare aliquots. We have developed links with petroleum engineers in the School of Chemical Engineering and are exploiting advanced materials characterisation with the School of Materials Science (tomography) to achieve understanding of, and an industry-facing route to, enhanced petroleum recovery.

2. The goal of **Molecular Environmental Science** (**MES**) is to gain molecular-scale understanding of globally-relevant environmental processes by using cutting-edge tools from the physical and biological sciences. MES was formed from the merger of two research groups (Mineral Physics and Geochemistry / Geomicrobiology) and their co-location in the Williamson Research Centre for Molecular Environmental Science (WRC). As a result, we have developed substantial (multi-million £) cross-disciplinary molecular-scale research projects in RCUK (NERC/EPSRC/BBSRC), EU and industrial priority areas. Specifically, integration of **MES** expertise has ensured continued growth in research focussed on molecular-scale mineralogical and biogeochemical controls in the earth's critical zone. This has delivered a fundamental understanding of important biogeochemical processes, including identification of: (a) critical controls on the mobility of arsenic and other toxic metals in groundwater (poisoning tens of millions worldwide) and improved understanding of the routes of arsenic uptake and health impacts on vulnerable populations in Asia (*Nature Sci. Rep.*); (b) the rate and extent of climate change-related carbon cycling in Arctic (*Nature*) and upland areas has also been studied with major implications for global climate change; and (c) the development of environmental biotechnological processes including harnessing microbial nanoparticle biomineralisation for remediation of metal- and organic-contaminated soils, a major concern in the UK and overseas. Leadership of the RCRD has underpinned significant expansion in radionuclide biogeochemistry research, delivering the first comprehensive biocycling studies for key radionuclides at nuclear facilities, including contaminated land and high pH (nearfield) geodisposal systems, supporting international remediation and radwaste disposal initiatives. Palaeontological research has also leapt forward since 2008, benefitting from links between **MES** and the FLS to produce major advances in interpreting fossil biochemistry.

3. The goal of **Atmospheric Sciences (AS**) is to deliver quantitative understanding in multidisciplinary atmospheric process-scale research, based on detailed field and laboratory observations and numerical modelling. Since 2008, we have consolidated our well-established strengths in atmospheric aerosol, cloud, surface atmosphere exchange and ultra-violet radiation and have expanded to encompass remote sensing and extended capabilities in atmospheric dynamics and gas phase measurements. We have driven process-scale studies through large research programmes and NERC responsive mode consortia, of which 6 were led from **AS** in the REF period. The group hosts 9 NERC National Centre for Atmospheric Science (NCAS) scientists, and the NCAS Directorate of Observations is run from **AS**, ensuring strong strategic alignment with NERC science. **AS** has continued extensive participation in both large-scale and focussed field experiments from airborne, shipborne and ground-based platforms across the planet, using substantially-extended state-of-the-science instrumentation. Laboratory and modelling capabilities have been similarly enhanced allowing coupled multidisciplinary studies of atmospheric radiation, dynamics and composition of relevance to weather, climate and air quality.

These developments have allowed us to address multi-faceted atmospheric processes, such as: quantification of the global extent of sub-micron organic aerosol (*Science*); quantification and improved understanding of the role of the Criegee radical in the atmosphere (*Science* x 2); a much clearer quantitative understanding of the role of organic vapours and aerosol on cloud formation (*Nature Geoscience*); identification of a substantial contribution of isoprene to tropical organic aerosol; elucidation of the role of secondary ice in the interaction between mixed phase cloud and dynamics in storm systems; and, the development of a new description of the frontal occlusion process in mid-latitude cyclones. A recent development has been the use of a mass budget approach to measure regional scale methane emissions using aircraft. Each finding demonstrates the success of our research strategy and the culmination of extensive activity. Moreover, each has acted as pump priming for substantial new international partnerships and activities funded by NERC and the EU. For example, we have a newly developed focus on atmospheric processes in tropical and polar regions, and major mid-latitude storm systems.

Future Strategic Plan: Our interdisciplinary, focussed research structure will allow us to expand our RCUK funding base and deliver additional growth through complementary funding from industry and overseas partners. Recent new appointments in petroleum will drive continued growth in this area and, in support of cross-Faculty links in petroleum exploration, we will appoint at the interfaces between the sub-specialisations within **PES**, and between **PES** and the wider University. The resulting research synergies will leverage major funding opportunities to address global challenges in carbonate and shale reservoirs, and in stratigraphic prediction. We will exploit **PES** expertise in isotopic analysis more widely in addressing environmental and geological problems by expanding into the areas of the design of nuclear waste disposal, resource identification and quantifying recent climate change. We will also target greater involvement in exploration missions

through broadening the scope of our planetary science activity, supported by new and recent (Busemann, Joy) appointments. In **AS**, we will grow integrative modelling activity to complement our world-leading process based activities. We will ensure continuity and growth in the established area of cloud microphysics, in aerosol-cloud-dynamics-radiation interactions and in remote sensing activities as our new appointments develop. In **MES**, we will establish growth in genomics to complement our existing strength in geomicrobiology. Our mineralogical activities will increase as new staff (Shaw and Coker) become established. Water@Manchester – a newly established major cross disciplinary theme – will allow our staff to lead in the area of water quality. As a cross-disciplinary activity, we will continue to inform the environmental science programme development at the UK's Diamond Light Source (DLS), where our staff have major involvement with the UoM strategic investment in the tomography beamline. Our leadership or participation in three of the 8 EPS Faculty cross-disciplinary thematic research areas (those of Energy (hydrocarbon resources and nuclear), Imaging, Atmospheric Science and Gas Phase Measurement) will ensure further strategic alignment with our RCUK and industrial partners. Overall, the continued expansion of our research areas and funding portfolio will enable enhanced academic output volume whilst also building upon our exceptional output quality. Similarly, the increasing alignment of our research with industrial and societal requirements will ensure increased non-academic impact that we will exploit through our new research support structure.

c. People: I. Staffing strategy and staff development: To realise our research goals (see above), we have based our staffing strategy on: 1. recruitment of world leading researchers; 2. recruitment and development of excellent young academic staff; 3. supporting research work of staff; 4. development of staff at all levels; 5. encouragement and support of external Fellowships; 6. PDRA career development; 7. supporting staff equality and diversity; 8 expansion of our international profile.

(1) Recruitment of world-leading researchers in targeted key areas: Strong academic leadership provides strategic direction for our fundamental, multidisciplinary and applied research areas and the linkages between them. Over the REF period we have strengthened **PES** through appointments of Flint (Prof. - predictive stratigraphy in fluvial, shallow and deep marine sedimentary systems and reservoirs), Taylor (Prof. - fine-grained clastics) and Huuse (Reader - seismic imaging of sub-surface structure and fluid flow). We appointed Morris in 2010 as BNFL Research Chair in Geological Disposal to lead the RCRD, contributing to a strengthening of **MES** alongside appointment of Shaw (Reader - mineralogy with nuclear, petroleum and environmental applications). We strengthened and extended the range of **AS** through appointment of Schultz (Reader, 2010, Prof. from 2012 - synoptic meteorology).

(2) Recruitment and development of excellent young academic staff: The **UoA** has attracted five prestigious, externally-funded tenure-track fellows since 2008. In **PES**, Busemann (isotope cosmochemistry) will become a senior lecturer after his STFC Advanced Research Fellowship in 2017 and Joy (planetary science) will become a senior lecturer in 2015 after her Leverhulme Fellowship. Coker (L'Oreal Fellowship 2012) has been appointed in **MES** as a lecturer in mineralogy and geomicrobiology. Allen will bring remote-sensing expertise to **AS** beyond the end of his NERC Fellowship in 2015. Mecklenburgh (rock mechanics) became a lecturer in **PES** in 2011 following University and NERC Fellowships. In **PES**, we appointed Schroeder (2011) in the area of petroleum reservoir and regional exploration studies. Junior appointments immediately before the REF period have developed successfully; in **PES**, Hollis (2007) has developed two major carbonate industrial consortia; Brocklehurst (2007, **PES**), Connolly (2006, **AS**), Robinson (2005, **MES**) and van Dongen (2007, **MES**) have been promoted to SL in the REF period.

(3) Supporting staff research work: The school reviews all academic staff contributions (research, teaching and "citizenship") annually, with individual and line manager agreeing immediate goals and a plan of activities (including training and development) for the next year in line with an agreed School workload model. In addition, formal Performance and Development Reviews have been strongly encouraged and provided to all academic and research staff on request. Our fellows and new lecturers are provided with a dedicated period of time to focus primarily on research; duration varying according to individual needs. They are assigned a senior academic mentor who provides guidance and acts as a 'critical friend' during establishment of their research group and securing of funding. Probationary staff are provided with some starting funds to initiate their research and they meet with the Head of School once a month.

(4) Development of staff at all levels: Support programmes are targeted at all staff groups. Senior management training is provided through the UoM HeadStart programme (2 attendees since 2009). All new junior academic staff attend the New Academics Programme (NAP) and

completion is required to pass probation. NAP covers the 'essentials' of an academic career, with teaching accredited by the Higher Education Academy (HEA). Twelve academics have commenced NAP since 2008, with 4 completions (now accredited as Fellows of the HEA). Promotion is supported through training courses delivered by senior EPS academics and through mentoring by line managers and senior academics. The school Promotions Committee recommends cases to Faculty, with a pre-meeting to provide feedback to develop each case. Since 2008 we have had 7 promotions to senior lectureship (Brocklehurst 2012, Connolly 2012, Jones 2012, Robinson 2012, Van Dongen 2012, Hodgetts 2009, Covey-Crump 2008); 1 promotion to Reader (Manning, 2012) and 10 promotions to Professor (Redfern, 2008; Gallagher, McFiggans, 2009; Gilmour, 2010; Lyon, 2011; Percival, Polya, Schultz, Webb, 2012, Wogelius, 2013). A seminar series and annual development event is available for technical staff. Staff surveys are used across the University biannually and are used to develop the working experience of staff via the development of action plans at the School, Faculty and University level.

(5) Fellowships: Staff at all levels are encouraged to apply for externally-funded personal Fellowships and are supported through workload adjustments. In addition to the five held by our younger staff (Allen, NERC; Busemann, STFC; Coker, L'Oreal; Joy, Leverhulme; Mecklenburgh, NERC) mentioned in section (2) above, two senior staff have won prestigious externally-funded Fellowships: Lloyd, Royal Society Industrial Fellowship (2010-14); Manning, STFC Science in Society Fellowship (2013-15).

(6) PDRA career development: UoM holds the European Commission HR Excellence award for its support of PDRA research staff who, through implementation of the Concordat to Support the Careers of Researchers, have a dedicated programme of workshops, information sessions, coaching and mentoring (with academic staff member, Coker, as our local PDRA mentor). These are all mapped onto Vitae's nationally recognised Researcher Development Framework. In UoA7, 31% of PDRAs engaged with the training and development programme in 2010/11. There is PDRA representation on all major School committees and on the School Board. PDRAs are members of the Research Staff Development Working Group (RSDWG) that meets quarterly to review the implementation of the Concordat. Implementation is evaluated in the biennial Careers of Researcher Online Survey (CROS) with over 50% UoA7 staff returns this year. Analysis demonstrates progress in staff induction, staff development support and the sense of equity of treatment with other staff.

(7) Supporting staff equality and diversity: Our 'Dignity at Work' policy outlines what all staff and students should expect in their dealings with UoM. An Equality and Diversity Leadership Team of senior academics and professional support staff explore factors that affect women and minority groups in EPS, implementing measures and targets to address any problems. Our local plan develops from this framework. The School Executive reviews the plan twice a year, ensuring that all staff have received Equality and Diversity training and that recruitment and promotion processes follow University guidelines for gender balance, which is reflected in membership of decision-making committees. We are pro-active in offering and encouraging flexible working and identifying role models.

(8) International Staff Appointments, Visitors and Sabbaticals: Our unit is an international community and we have enriched the international flavour of our research since 2008 as is reflected in our broader staff profile (86 home, 20 overseas in 2008-9 and 89 home, 37 overseas in 2012-13 from 15 different nations). 41% of our research staff and 16% of our academic staff originate from outside the UK, and. Reflecting the strong international profile of the school, 27% of our research students across the REF period were from overseas and 4 of the 11 academic appointments made during the period were from outside the UK.

Continual revitalisation of research activities has occurred since 2008 through our vibrant sabbatical programme. During the REF period, 14 staff have been on sabbatical, visiting international universities and research institutes (e.g. Berkeley Advanced Light Source, Stanford) and to industry (e.g. Chevron, Aerodyne Research Inc.). This has resulted in extensive collaborative projects and outputs, including two *Science* papers from Percival and one from Wogelius and Manning from working on US synchrotron facilities.

Our active visitor exchange programme enables our staff to benefit from support to initiate international contact and collaboration and world-leading researchers to benefit from our research environment. Across the REF period, 175 researchers (111 home, 64 overseas, with 12 Professorial and 55 from industry) held visiting positions in the School. These include visitors from international universities (e.g. Bilbao, Bergen, Patras) and from a wide range of commercial

organisations (e.g. BP, Diamond Light Source, Met Office).

II. Research students Our RCUK-funded PhD student registrations have shown a steady rise across the REF period (38 in 2008/9 to 48 in 12/13) reflecting our increase in RCUK funding and we have maintained the percentage of PhD funding from industrial (15.5%) and international (10%) sources. 103 PhD students have completed across the REF period, 40 funded through RCUK (30 NERC) with a 4-year completion rate of 99% with RCUK-eligible allowances. We have developed a successful strategy for enhancing the quality of our PhD students throughout the period as outlined below.

(1) Funding and recruitment of PhD students: The number of registered postgraduate (PGR) students has grown over the past three years, by a combination of: increasing industrially-funded PGR students, particularly in petroleum and nuclear research; significantly increased investment of University and Faculty recruitment through the President's and Dean's scholarship awards; and recruitment of excellent international students through targeted initiatives (CONACyT (Mexico), Science without Borders (Brazil)). This enhanced attractiveness of our PhD programmes over the REF period has ensured that we increasingly attract the highest calibre of home and international applicants (exemplified by 37 student prizes at National and International conferences). Since 2008, 55% of PhD students received RCUK funding, 21% of home students are industrially-funded (including CASE) and 13% of overseas students receive industrial sponsorship. Our major PhD sponsors include BP, Met Office, National Nuclear Laboratory, Schlumberger, Shell, Statoil, Total, DIAMOND, British Council, Chevron, NDA, Maersk and Petroleum Development Oman. We receive STFC studentships in cosmochemistry and isotopes. We lead a NERC Doctoral Training Programme with the University of Liverpool, and the NERC National Oceanographic Centre (Liverpool), which will fund 60 new PhD students over the next 5 years. The University has also won new funding to continue the successful EPSRC DTC in nuclear research, which provides training for UoA7 research students in this area.

(2) Postgraduate Research Management: We have robust mechanisms for developing and monitoring PGR students during their research study. A senior academic member of staff is dedicated to managing recruitment, progress monitoring, and ensuring that our supervisory teams are maintaining consistently high levels of student supervision. PhD project titles and outlines are solicited annually, are advertised widely and are available online. Applicants for RCUK-funded programmes are selected primarily according to academic excellence and largely allocated to their chosen projects, with balance transparently negotiated across the UoA7 research portfolio and eligible supervisors. Supervisor research and supervisory track record are recognised in the project selection process.

(3) Supervision: to ensure a high standard of student supervision and supervisor continuity, at least 2 academic staff supervise each student, and each student is allocated an advisor with whom they can independently and confidentially discuss their progress. Supervisors are monitored for successful student thesis submission within four years of registration and PhD award within five. NAP includes training on the role of the supervisory team, student recruitment and selection, co-supervision, engagement with 'eProg' (see below), project management, research teams and networks, and student support. New staff are mentored through first PhD supervision by an experienced staff member and must have a student successfully complete before assuming full main supervisor responsibility. Supervisory teams are encouraged to support supervisory best practice and encourage excellence in supervision by junior staff.

(4) Progression monitoring and training: One of the best examples of integrated PGR student training and progression management in the UK, the online student progression platform, 'eProg' (marketed to the HE sector as 'Progress Platform') was implemented across UoM in 2010 for all PhD students. eProg integrates progression monitoring, skills training provision and management, personal/career development, feedback mechanisms and recording of personal achievement**.** Students mutually agree targets with their supervisory team during progression meetings and the student's portfolio of skills and record of achievement is documented through the system. Training requirements are satisfied by a number of methods. We provide transferable skills and career management training through a very extensive graduate training programme drawing based on the Vitae Researcher Development Framework (RDF) as well as student-specific training courses. UoA7 PhD students participate in a wide range of subject specific summer schools in their early training, before exposure to National and International conferences as they progress. They organise their own annual conference, raising sponsorship, organising the agenda, inviting external keynote speakers and selecting abstracts for talks and posters. All UoA7 PhD students are encouraged to communicate their science through public engagement and communication events

(e.g., Manchester Science Fair and the Astra Zeneca Teaching Trust).

d. Income: during the REF period, we have diversified the UoA7 funding portfolio in order to maintain and expand research income. Total research award value has been over £36.4M (averaging £6.1M per annum) since 2008 (compared with £24.6M, excl. JIF over the previous RAE period). Around £4M per annum of this has been secured through RCUK awards (previously £1.7M pa), with £780K from industry (previously £670K pa) and around £750K from the EU pa (previously £220K pa). SEAES is consistently in the top tier of UK Earth Sciences departments for NERC funding and nationally the most successful (£4.8M) in 2011/12.

Funding Highlights: Of particular strategic benefit to UoA7, the STFC Rolling (now Consolidated) Grant of £2M in 2009 and £1.3M in 2012 underpins Isotope Geochemistry and Cosmochemistry research. Funding since 2008 of £3.65M from NERC National Centre for Atmospheric Science (NCAS) underpins the **AS** contribution to National Capability. Our strategic alignment with **RCUK** themes (described in section e) is demonstrated by ten new NERC **Research Programmes (RP)** projects worth £4.4M (11 further RP projects active over the REF period, funded pre-2008 and worth £2.8M to UoA7). We have led further NERC and EPSRC **Consortium Grants** worth £4.1M to UoA7 (and significantly more to the research community) over the REF period, demonstrating leadership in substantial research efforts with additional participation in consortia (worth £2.2M to UoA7), illustrating broad collaboration. Four further NERC consortia were active over the REF period, funded prior to 2008 worth £2.4M to UoM.

Our **EU project awards** totalling 4.47M across the REF period demonstrates clear European leadership for a range of infrastructural, research and training consortia. **MES** and **AS** staff are involved in EU projects worth £1.45M commencing since 2008, with further EU Projects funded prior to 2008 but active over the REF period. Ballentine led an ERC advanced grant with **PES** staff, 2011-16 (£2.2M) and, after his departure, half remains in UoA7.

Since 2008, the income from 6 prestigious **Personal Fellowships** has totalled almost £900K: Lloyd, Royal Society Industrial Fellowship (2010-14); Joy, Leverhulme Early Career Fellowship (2012-15); Allen, NERC Postdoctoral Fellowship (2011-14); Busemann, STFC Advanced Fellowship (2009-12); Manning, STFC Science in Society Fellowship (2013-15).

Industrial funding has grown substantially over the REF period, particularly from the energy sector. Our hydrocarbon exploration activities in **PES** have led to contracts worth almost £6.5M from the oil industry (Anadarko, Aramco, BP, Conoco, ExxonMobil, GDF, Maersk, Petrobras, Shell, Statoil, Total, Tullow and VNG amongst others). £1.06M of the BNFL Endowment funds the Chair for Morris as head of the RCRD. Additional nuclear industry KTP and research funding has been secured from Areva, NNL and Sellafield worth around £550K. Tesco and Rolls-Royce have provided research funding in sustainability and atmospheric science worth £590K and we secured £159K KTP funding in collaboration with Arvia focused on wastewater treatment technology.

Income in Kind: Synchrotron beamline access corresponds to almost £5.4M over the REF period. As the largest UK university user, **AS** scientists have participated in around £3.3M worth of research flying (leading c. £1M) per year on the joint Met Office / NERC FAAM BAe 146 aircraft worth £19.8M over the REF period (costed at EUFAR Transnational Access rate).

Consultancies and Professional Services: whilst such activities play a minor part in our funding portfolio, effective engagement of UoA7 staff with industrial partners at a fundamental level and with government department end-users ensures profitable recognition of our expertise by “customers” for our research. Where possible, we convert consultancy relationships into collaborative research activities, such as **PES** hydrocarbon exploration collaborations with the oil industry, **MES** work with the nuclear industry on radwaste geodisposal and contaminated land remediation, ongoing **AS** particulate matter contracted activities for Defra under a rolling Framework agreement and **AS** emergency response atmospheric monitoring for the Environment Agency in a research sub-contract.

Future funding and sustainability: This successful diversification of our funding portfolio ensures no single points of failure in our income. Strategic emphases on growing our RCUK relationships through programme management and strategy board membership and careful fostering of large industrial partnerships ensures that these income streams are persistent and reliable. Clear alignment of our research activities with societal and commercial challenges ensures that we are well placed for security in future funding.

Infrastructure Major research infrastructure developments have occurred throughout the period, with substantial investments in laboratory space and equipment in the Williamson Centre (**MES**), the Isotopes and Cosmochemistry group (**PES**) and **AS**. Hydrocarbon Exploration (**PES**)

and **AS** Research computing facilities have been funded in the "Redqueen" HPC cluster (£60K).

Physical Infrastructure: The University has invested £750m in new build and refurbishment since 2004 and now plans a further £1bn investment to 2023. The first phase of this (£700m to 2018) will see all UoM engineering relocated close to UoA7. We are housed in two adjacent buildings in the centre of the Manchester campus, with major refurbishments planned to both. **AS** activities have been located in the Simon Building since 2007 and its main research laboratories have been fully commissioned across the REF period. The neighbouring Williamson Building, home for our **PES** and **MES** groups, received a major external refurbishment in 2012 costing £3.24M. A further major refurbishment of the Williamson building interior will take place before 2020 and the Simon exterior in the next 4 years.

Since 2008 we have developed the research areas for radwaste, geodisposal and geomicrobiology (**MES**), and isotopic geoscience and petroleum geoscience (**PES**). In 2009, a £1.4M BNFL endowment helped support the development of the RCRD with laboratory and office space, and new Environmental Radiochemistry labs, unique in UK Earth Science. Bionanomineralogy, molecular ecology and geomicrobiology facilities also opened during the REF period following a £700K strategic Faculty investment. £150K investment in geochemistry laboratories has created space for new instrument development and enhanced our capability for halogen and isotope geochemistry research. We have invested in petroleum geoscience facilities to accommodate our new chair of stratigraphy (Flint) and his substantial research group. Further expansion of the RCRD and environmental geochemistry and mineralogy laboratories is planned for 2014-18.

Research Support Infrastructure: In 2011/12, UoA7 appointed a research support manager as part of the development of an integrated EPS Research Support Services (RSS) delivery team. This enables an effective and integrated service to maximise delivery and exploitation of high quality research. Managers offer expert advice and services from funding opportunity awareness through to delivery of research activities. RSS employs six cross-Faculty Research Support Officers to improve administrative support to external funding bids and subsequent projects and an additional four senior research finance posts.

Facilities: Our research benefits from an excellent range of state-of–the-art analytical and experimental facilities, supported and developed through a combination of University and external funding. We have procured equipment funded through Research Grants worth £1.64M over the REF period. The range of instrumentation and equipment we maintain and the uplift since 2008 is too extensive to list but highlights by research area are: **PES** have developed new capabilities in ToF-SIMS (Time-of-flight secondary ion mass spectrometry) and RIMS (resonance ionisation mass spectrometry) for Krypton analysis, while dedicated labs house state-of-the-art commercial noble gas mass spectrometers. Alongside this, a neutral atmosphere facility has been developed for extraterrestrial samples, increasing competitiveness in seeking access to returned samples. Funding has been secured for a Zoller+Frölich Imager unit and LiDAR surveying equipment to support palaeontology. Industry has funded enhancements in computer hardware and software and for petrophysics (laboratory measurement of porosity, permeability, petrography, mineralogy). A high temperature torsion rig has been acquired to study rock deformation. The **MES** group draws on the excellent range of facilities available in the Williamson Research Centre for Molecular Environmental Science to provide a comprehensive suite of high resolution electron and X-ray microscopy, advanced separation and mass spectrometry facilities for mineralogical, geochemical and surface analysis. Additional dedicated laboratories for geomicrobiology, molecular ecology, radionuclide biogeochemistry, organic geochemistry and mineralogical studies ensure the **MES** group have access to uniquely comprehensive suite of analytical facilities. **AS**: A major cloud chamber facility, funded prior to the REF period, has been commissioned since 2008 and is now fully operational, enhanced by the development of next generation cloud physics scattering and imaging instruments during the REF period. We have continued to invest in novel online aerosol instrumentation (including single black carbon particle incandescence and high resolution aerosol mass spectrometry instruments) and aerosol chamber developments since 2008 and driven major expansion in laboratory and field reactive trace gas instruments (e.g.CIMS, chemical ionisation mass spectrometry) supplementing comprehensive existing state-of-the-science capability. Likely the biggest atmospheric science instrumentation investment in the country (largely from NERC RM funding in addition to NCAS infrastructural investment worth around £2M since 2008), it is world-leading in scale and capability.

UoM Facilities: UoA7 additionally draws on University facilities across a range of disciplines including the Manchester X-ray Imaging Facility, one of the world's most comprehensive 3D X-ray imaging capabilities, and extensive high resolution electron optical facilities in Materials Science.

MES staff use facilities in the Centre for Radiochemistry Research in the School of Chemistry, Wolfson Molecular Imaging Centre (WMIC) in Materials and the extensive environmental proteomic, genomic, post-genomic and synthetic biology tools within the FLS Faculty and Manchester's Institute of Biotechnology.

e. Collaboration or contribution to the discipline or research base: In order to address the multi-disciplinary challenges of Earth System and Environmental Science research, we conduct much of our research through large-scale collaboration. Indeed, participation in prestigious large-scale national and international consortia, and other forms of collaboration, is our primary mode of operation and this been has recognised in the construction of our UoA7 and Faculty research support infrastructure. Collaboration operates on all scales: between researchers across areas and the school; cross-Faculty facilitated by EPS thematic initiatives; across the University; with other UK and International Universities; and, with Government departments, NGOs and Industrial partners. The larger the collaboration, generally the more cross-disciplinary the study. The school and University structures encourage and foster smooth establishment of such relationships. Our Research Support Staff are extremely experienced in administering large-scale collaborations and UoA7 researchers in managing them.

RCUK collaborations: Clear evidence for alignment with NERC thematic strategy is provided by the lead or participating roles of UoA7 staff in numerous national collaborations commencing funding through the 10 **NERC Thematic Programmes** across the REF period as well as continuing to work in the REF period on 11 programme consortia funded prior to 2008 (8 led from UoA7 at UoM). NERC strategy continues to be influenced in aerosols, clouds and environmental nuclear research by our staff, through leadership of the Aerosols & Clouds programme and participation in the steering committee of the Radioactivity and the Environment (RATE) research programme. UoA7 staff lead substantial community research efforts in **NERC Consortium Grants** in the area of nuclear biogeochemistry (Biogeochemical Gradients and RADionuclide transport, BIGRAD and the newly funded RATE programme Lo-RISE), pollution and climate impacts of biomass burning emissions (South American Biomass Burning Analysis; SAMBBA) and impacts of aerosols and clouds on the South-East Pacific (VAMOS Ocean-Cloud-Atmosphere-Land Study UK; VOCALS-UK) in each case involving international partners and end-users of the research (e.g. Sellafield, Met Office). We further participate in consortia funded in the REF period, investigating the near-field Eyjafjallajokull volcanic plume, ocean micronutrient cycles, oceanographic and seismic heat dissipation and alteration by hydrothermal fluids at an axial ridge, the fate of CO_2 in geological reservoirs for modelling geological carbon storage and the role of night-time chemistry in controlling the atmospheric oxidising capacity.

International collaborations are extensively funded through EU programmes (Integrated Projects, Networks of Infrastructures and International Training Networks) and UoA7 researchers have been investigators in across the REF period. These cover areas as diverse as airborne platforms for atmospheric measurements from dedicated research aircraft and the commercial fleet, water treatment by integrating nano- and membrane technologies, chamber infrastructures for atmospheric processes and nanotechnological remediation processes. We are developing partnerships with university departments in China, Brazil, USA and India to ensure continued international research leadership. For example, a UoM memorandum of understanding with the Sao Paulo Research Council (FAPESP) has driven joint programmes in atmospheric and petroleum research in Sao Paulo. We have established relationships with many universities in the USA to access unique paleaontological specimens and synchrotron facilities. We work closely with NASA and associated institutes to play an integral role in analysis of inter-planetary samples (see section b) and we have developed joint US-UK multi-institute atmospheric sciences programmes. Consortia in India with ISSc are developing through the NERC-MoES MoU and associated programmes. Our links with Nanjing University of Information Science and Technology (NUIST) involve their staff working in Manchester for 12 month periods, embedded in our research teams, leading to deeper collaborations on their return to China. These initiatives are closely linked to PT and PGR programmes to foster broader, stronger and longer lasting partnerships in the future.

Industrial and government collaboration is exemplified by the integration of industrial partners (NNL, Sellafield, BNFL) within our **MES** nuclear research strategy including substantial knowledge exchange activities, both embedded and through explicit specific activities. We provide leadership of the Hydrocarbon Exploration and Development capability for the Manchester Energy institute, which has built strategic relationships with leading energy companies on all continents (e.g., BP, TOTAL, Statoil, Shell, Petrobras, ExxonMobil). Significant tripartite research projects with other Universities and an industrial partner illustrate our effective engagement with end users

for **PES** hydrocarbon exploration research. We have developed partnerships with Government Agencies, **AS** providing Atmospheric Incident Emergency Response standby for the Environment Agency, holding a Defra Framework Agreement to provide policy-related evidence for atmospheric particulate material and developing cloud and aerosol treatments in Met Office forecast models.

Leadership roles in Research Councils / EU: Our staff perform key leadership roles in research councils. Vaughan (G.) was a member of NERC Science and Innovation Strategy Board (SISB; 2009-2012). UoA staff are extensively involved in Research Programme direction and management (Lloyd, Livens, Coe, McFiggans) and NCAS management (Vaughan (G.) and Coe). Across the UoA, we have strong EU Expert panel and extensive peer review college membership.

Leadership roles in Industry: Examples of the range of industrial liaison activity are given by Bowman (using deep industry experience to promote University of Manchester Energy related research and related activities as Member of Advisory Board, Dana Petroleum and of ENEGI Oil TRACS Associate Member Petrochemical Engineers Society of GB), Vaughan, G. (member of Met Office Scientific Advisory Committee (MOSAC) 2005-present), Lloyd (as Senior Visiting Research Fellow, National Nuclear Laboratory, acts to promote **MES** nuclear environmental research).

Roles within Learned Societies or Professional bodies: Our broad involvement with learned societies is illustrated by the presidency in the REF period of the American Mineralogical Society (Vaughan, D., 2013), the Royal Meteorological Society (Vaughan, G., 2006-08), Petroleum Exploration Society of Great Britain (Bowman, 2012), Commission Internationale d'Eclairage (CIE; International Commission on Illumination, Webb, 2012-), Mineralogical Society of Great Britain and Ireland (Pattrick, 2010-11). In addition, numerous Fellowships and memberships of Advisory Boards and normal memberships of all major learned societies in our field ensures both broad dissemination and familiarity with current developments our fields.

National or International advisory board membership; Our contribution to the direction of international research is exemplified by the following advisory board and review panel membership in addition to numerous reviews of international and national proposals: DFG panels, 2008, 2010, 2011, 2012 (McFiggans and Vaughan, G.), Norwegian Research Council, 2010 (McFiggans and Redfern), EU Expert panel, 2008-present (McFiggans), regular panel reviews for NASA (Gilmour), International panel for Petromacs (Norwegian petroleum industry research body, Flint), Finnish Academy of Sciences Review Panel member 2008, 2010, 2012; US DoE Atmospheric Radiation Measurement Science Board member 2010 to present; US DoE Brookhaven National Laboratory Atmospheric System Research review panel member 2010 (Coe), External review, Forschungszentrum Juelich,. Germany ii) External review for Institut de Chimie Separative, CEA Marcoule (Livens), Nuclear Decommissioning Authority (NDA) panel member for review (2010) of UK research on reactivity of radioactive waste glass, Italian Ministry of Education, University and Research (MIUR) panel member 2011 (Wogelius),

Conference roles: Overall conference chair: European Aerosol Conference 2011 (Coe), Faraday Discussions 165, 2013 (McFiggans), RSC Gas Kinetics, 2012 (Percival), International Association of Sedimentologists 2013 (Jones), Chair, International Advisory Committee, Actinides 2009 (Morris), numerous Theme and session chair responsibilities. Plenary & Invited Keynotes, too numerous to mention, but commensurate with a School of the size and vitality of SEAES

Editorships, Associate Editorships Editorial Board Membership of most major journals in our field (e.g. Applied Geochemistry, Atmospheric Chemistry & Pysics, Atmospheric Science Letters, Geomorphology, Quarterly Journal of the Royal Met. Soc., J. Geol. Soc. London, J. Soils and Sediments, J. Metamorphic Petrology, Marine and Petroleum Geology).

Esteem Indicators: In addition to the prestigious personal Fellowships listed in section d), there are many further noteworthy indicators of research excellence. Garwood (category C submission) declined a Leverhulme Early Career Fellowship in favour of an 1851 Research Fellowship to study the origin and early evolution of insects. In addition to his NERC Fellowship, Allen was awarded a Royal Society Westminster Pairing Fellowship (Oct 2012), a prestigious exchange with John Leech MP to facilitate methods of communication between science and policy-making. Joy was awarded the Royal Astronomical Society's Winton Capital Geophysics Prize 2013. Wogelius was awarded a Blaustein Fellowship Award as Visiting Professor in Earth Sciences for Stanford University, a prestigious, competitive appointment. The recognition of Manchester's expertise in the Structural and Petrological Science area has been made through the award of the 2012 Louis Neel Medal to Rutter by the EGU. In 2012, Percival was awarded the David A. Shirley Award for Outstanding scientific achievement at the Berkeley Advanced Light Source.