Bristol and Oxford Passive Seismic Research Consortium

Using Passive Seismic to Monitor and Image Subsurface Industries

A Proposal from the universities of Bristol and Oxford

We propose a 3-year research project to investigate the use of passive seismic methods to monitor and image subsurface fluid injection. The primary intended application of our proposed research is for monitoring of carbon sequestration sites (CCS), hydrogen and natural gas storage, and deep geothermal energy. Our research will also have applicability to hydraulic fracturing and conventional hydrocarbon extraction, to subsurface mining, and to natural phenomena such as the monitoring of volcanoes and glaciers.

This consortium-funded project will emphasise fundamental research and knowledge transfer. The consortium will be based between the School of Earth Sciences at the University of Bristol, and the Department of Earth Sciences at the University of Oxford. It represents a continuation of the previous Bristol University Microseismicity Project (BUMPS) research consortium, but with a shift in focus that recognises the enormous potential opportunities offered by the effective use of all kinds of passive seismic data (not just microseismic).

The proposed research will cover the following overarching topics:

1. **Novel acquisition technologies:**
   Acquiring and processing passive seismic data using cost-effective monitoring solutions such as nodal arrays, fibre-optic DAS, and ocean-bottom sensors.
2. **Novel methods for processing large volumes of data:**
   What roles can machine learning play in the handling of passive seismic data? For event detection? For noise removal? For imaging?
3. **Passive seismic acquisition in challenging settings:**
   How can we acquire useful data to monitor operations in challenging settings, for example offshore CCS sites, geothermal sites in urban settings, sites in challenging terrain? Developing tools for robust and accurate feasibility studies for array design.
4. **Passive seismic for reservoir imaging:**
   How can we use passive seismic data as a cost-effective alternative to 4D controlled source seismic reflection to image the long-term behaviour of reservoirs. Imaging using seismic events (seismic tomography, anisotropy) and ambient noise interferometry.

Sponsorship will be £30k per year per sponsor, and will provide funding for postdoctoral researchers, PhD students, computing, travel and consumables. The project will produce a range of deliverables including regular sponsors meetings, a password protected website for sponsors, a complete set of reports and presentations, and algorithms developed in the course of the project.

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Introduction

The means by which societies produce and store energy is changing. The twin challenges posed by climate change and energy security are driving major shifts in the technologies used to heat our homes and power our industries. The new technologies being developed to meet these challenges, such as CCS, geothermal energy, and hydrogen storage, pose new challenges for subsurface geophysical monitoring.

As this energy transition progresses, hydrocarbons will continue to be a key part of our energy mix. Indeed, many countries are seeking to expand their domestic hydrocarbon production capabilities in order to meet national energy security challenges. However, increased public environmental awareness is driving new pressures for subsurface monitoring of both conventional and unconventional hydrocarbon extraction projects to meeting stringent regulatory compliance.

The use of passive seismic monitoring for subsurface imaging and characterisation offers enormous potential to meet these new monitoring challenges. Characterisation of microseismic event sources offers insights into the dynamic subsurface state of stress, and into the geomechanical perturbations and movements of fluids caused by subsurface operations. Detection of microseismicity also provides the only means available with which to identify and characterise the potential for incipient induced seismicity, which has posed a major challenge for various subsurface industries and resulted in the wholesale cancellation of major projects.

Seismic waveforms recorded by passive arrays offer the opportunity to characterise the properties of the rocks (and the fractures and fluids within those rocks) through which the seismic energy has propagated. Event where no microseismicity is detected, ambient seismic noise can also be used to image the properties of rocks around passive seismic arrays. These capabilities offer a cost-effective alternative to repeat 4D active-source seismic monitoring of long-term projects.

In recent years, there have been major changes in how passive seismic data can be acquired, including the use of fibre-optic DAS, and autonomous nodal arrays. Microseismic datasets have grown exponentially in size, with even a few weeks of monitoring now producing terabytes of raw data as instrument numbers and recording frequencies increase. However, passive seismic data must be processed rapidly (i.e., in near real-time) so that observations can be used to support operational decision-making.

This project will cover a range of research themes concerned with better exploiting passive seismic data acquired to monitor CCS, gas storage, deep geothermal energy, hydraulic fracturing and conventional hydrocarbon extraction. Our research will investigate the use of passive seismic data for microseismic monitoring and reservoir imaging, using a broad range of acquisition methods. It is a consortium-funded endeavour, emphasising fundamental research and knowledge transfer. The consortium is jointly based in the Schools of Earth Sciences at the University of Bristol and the University of Oxford, with collaboration with the British Geological Survey.

This first phase of our consortium (2001-2004) was based at the University of Leeds (LUMPS), and focused on borehole passive monitoring to refine event locations and image seismic anisotropy. After a hiatus, the consortium restarted in 2010 at the University of Bristol (BUMPS), where technique development continued, including the use of surface arrays, and the emphasis shifted to the monitoring of hydraulic stimulation. The third stage addressed a number of key questions regarding geomechanics, mechanisms for fluid migration, reservoir integrity and fracture characterisation. Later phases have seen a significant emphasis on induced seismicity, regulatory monitoring and public engagement, and rapid developments in monitoring for regulatory compliance, especially in the UK context, necessitating more accurate assessment of event magnitudes and source parameters. New processing methods for sparse arrays and anisotropy analysis have also been developed, and the start of using DAS in recording microseismicity.

Science Questions

In the next phase of the consortium, we aim to address a combination of key questions that are especially relevant to the upcoming challenges and opportunities for passive seismic monitoring that we described above.

SQ1. Novel acquisition technologies:
Recent technological advancements in instrumentation have led to notable changes in how passive seismic data is acquired. This includes the use of DAS arrays (both downhole and across the surface) and autonomous nodal arrays, for example. These systems offer advantages in terms of numbers of stations (and monitoring density) and deployment cost. However, different systems pose their own challenges in terms of event detection and seismic imaging. A key focus of the BOPS project will be on developing a better understanding of the advantages and limitations of novel methods of passive seismic acquisition in order to develop cost-effective monitoring and imaging solutions, with a particular focus on data acquisition in challenging settings (see SQ3).

SQ2. Novel methods for processing large volumes of data:
As passive seismic arrays increase in density and sampling rate, real-time processing of data streams has become more challenging. Machine learning (ML) has demonstrated potential for seismic event detection in tectonic settings, but applications to industrial settings have been limited to date – just re-purposing of ML algorithms trained on tectonic data. Clearly there is immense scope for developing bespoke ML algorithms for microseismic event detection in industrial settings.

Whereas existing ML algorithms are trained on single station recordings (data from each recording station is treated as a discrete entity, e.g., Lapins et al., 2021), in industrial settings the possibility exists to treat data from closely spaced stations (whether downhole geophone strings; DAS arrays, or dense surface arrays) as a single, multi-dimensional entity. Rather than ML models being trained on an individual trace-by-trace basis (or at most, on individual 3-component recordings), machine learning algorithms could be trained using entire multi-dimensional datasets, thereby becoming able to take advantage of relationships between phase arrivals on different stations in order to identify and pick events.

BUMPS has pioneered the development of machine learning for microseismic event detection using seismometers (e.g., Lapins et al., 2021) and using DAS arrays (e.g., Stork et al., 2020). We have previously led the development of array-based processing methods for microseismic event detection, including with downhole geophones (e.g., de Meersman et al., 2006), surface arrays (e.g., Chambers et al., 2010), and DAS arrays (Verdon et al., 2020). In this phase we will use this experience to develop array-based ML methods for microseismic event detection.

In addition to ML models for seismic event detection, we will also explore the potential offered by machine learning for other passive seismic processing steps, including the modelling (and subsequent elimination) of unwanted noise sources, and in microseismic source mechanism characterisation.

SQ3. Feasibility assessments for passive seismic acquisition in challenging settings:
The need to monitor CCS sites will require the development of capabilities for passive seismic monitoring of offshore installations. A range of potential monitoring solutions, from OBSs or sea-bed installations, arrays placed on nearby landmasses, and DAS arrays, have been envisaged. Likewise, geothermal projects may be sited in peri-urban areas where deployment of monitoring instruments may be very restricted.

In either case, cost-effective monitoring solutions are required that find an appropriate trade-off between deployment cost and monitoring performance. Methods for robust and accurate feasibility studies are therefore needed to inform the design of monitoring arrays, and act as a realistic guide to expectations with respect to what different kinds of monitoring array will be able to deliver. These array design methods should incorporate a full understanding of the latest acquisition technologies, and in particular their typical signal-to-noise levels and instrument responses (see SQ1 above), and processing methods (see SQ2) such that realistic, up-to-date assessments of monitoring performance are made.

SQ4. Passive seismic for reservoir imaging:
Some new industries require long term monitoring. For example, CCS projects must guarantee storage integrity long after shut-in. While reflection seismic imaging is probably the most powerful geophysical tool available to the industry, it may not be cost-effective to re-acquire repeat active surveys over long periods of time. For geothermal projects in igneous rocks, the lack of horizontal reflectors renders reflection seismic ineffective for imaging subsurface structures.

Passive seismic imaging offers an attractive alternative with which to characterise the properties of the subsurface rock mass, and in particular any variations in fluid saturations and fracture networks that produce changes in seismic properties. Passive seismic imaging can be achieved in a range of ways, including observations of seismic anisotropy, seismic velocities, and seismic attenuation, using detected microseismic events, with tomographic methods used to constrain the spatial distributions of any observed changes. Where no microseismicity occurs, ambient noise can be used to monitor changes in seismic properties around monitoring arrays. To date, the BUMPS project has pioneered the use of passive reservoir imaging using both microseismic sources (e.g., Wuestefeld et al., 2010; Al-Harrasi et al., 2011; Hudson et al., 2022) and ambient noise (e.g., Stork et al., 2018).

In this phase we aim to develop these methods for application to novel methods of microseismic acquisition such as DAS and nodal monitoring arrays, where we anticipate that high station density will produce significant improvements in imaging quality. In addition to passive seismic and ambient noise imaging, there is scope to investigate the potential role of combined active and passive seismic monitoring, whereby permanent instruments (whether downhole or buried in the shallow subsurface) record continuous passive seismic data, tracking the temporal evolution of fluids and the rock mass in between repeat active source surveys using the same fixed instruments.

Personnel

The project coordinators will be Dr James Verdon (https://geophysics.gly.bris.ac.uk/ ~gljpv/index.html) at the University of Bristol and Professor Michael Kendall (https://johnmichaelkendall.com) at the University of Oxford.

James Verdon is a Senior Lecturer in Applied Geophysics in the School of Earth Sciences, and currently leads the BUMPS project. He was a Co-I on the Fast-MODE project, which pioneered the use of fibre-optic DAS arrays for microseismic monitoring in oilfields. He is currently a Co-I on the SeisGreen project, a NERC Large Grant investigating the geomechanics of induced seismicity associated with net zero technologies. James has collected and analyses passive seismic data from a range of large CCS sites including Weyburn and In Salah. His work has included the use of microseismic data to calibrate geomechanical models, the use of microseismic observations to identify the growth of fractures into caprocks, and assessment of induced seismicity hazard at CCS sites. In 2010 he was awarded the Keith Runcorn Prize by the British Geophysical Association for best doctoral thesis. He is an internationally-recognised expert in microseismicity and induced seismicity, and has regularly advised governments, regulators and operators on microseismic monitoring and the management of induced seismicity risks.

Mike Kendall holds the Chair in Geophysics at the University of Oxford and is the Head of the Department of Earth Sciences. Mike is a Fellow of the Royal Society, the Royal Society of Canada and a Fellow of the American Geophysical Union; between 2009 – 2014 served as the President of the British Geophysical Association. Mike's research interests cover pure and applied seismology across a range of scales. He has led seismic field experiments in a range of settings, including the installation of ocean-bottom seismometers to monitor the mid-Atlantic Ridge, and the use of fibre-optic arrays to monitor ice-quakes in Antarctica. Mike founded the BUMPS research consortium, and has a strong track record in monitoring of CCS sites. He recently served on the Working Group for the Royal Society report on CCS. He served on the Scientific Advisory Board for the In Salah CCS project, and the Eden Geothermal Porject (Cornwall). He is a research provider to the FRS operated by CMC-Canada, and has analysed and interpreted passive seismic data from the Weyburn and Aquistore CCS sites. He is an Investigator in the Digimon and SHARP projects, funded under the "Accelerating CCS Technology" (ACT) program specifically to develop the science to underpin the monitoring of CCS sites.

Other permanent academic staff involved with related work include Professors Max Werner and James Wookey. Post-docs involved in the project include Drs Tom Kettlety, Tom Hudson, Antony Butcher, German Rodriguez-Pradilla, Sacha Lapins, Joanna Holmgren, and Jose Bayona. Previous phases of the BUMPS project have trained over 20 PhD students and supported over 10 postdoctoral researchers, many of which have either continued in academia doing geophysical research, or gone on to industry positions in microseismic monitoring (including with past BUMPS sponsors).

Datasets

In previous phases of BUMPS, we have worked with passive seismic datasets from some of the largest CCS projects in the world, including Weyburn, In Salah, and Aquistore. We have also worked with geothermal datasets, including Aluto (the largest geothermal plant in Ethiopia) and the United Downs and Eden Project deep geothermal sites in the UK. We have access to a broad range of datasets from oil and gas fields, including offshore and onshore, conventional and unconventional. We have also acquired a range of datasets monitoring relevant natural phenomena, such as Antarctic glaciers, and active volcanic settings.

The data we work with comes from many instrument types, including: DAS, geophones, nodes, OBSs, and broadband seismometers; many different deployment types, including: surface, shallow and deep boreholes; and array types, from single, sparse stations to dense, large-N array networks.

We have access to a range of instrument types to acquire new data during the course of the project, including a pool of three-component seismometers and nodal stations. In addition, we have access to a varied instrument pool through the NERC-run Geophysical Equipment Facility – SEIS-UK, and we have access to InSAR data at academic rates.

Having access to a large number of different types of datasets, we are able to select and use the appropriate datasets to advance different scientific developments and ideas, and to test novel techniques under a wider range of different conditions. In addition to existing datasets, we are happy to work with sponsors using their passive seismic datasets – we often find that collaborations of this nature maximise the value of our research consortia.

Funding

The proposed phase will last three years. The requested funding is £30K per year per industry sponsor. This represents excellent value for money as many of the involved personnel do not need salary support. The funding will primarily provide salary for postdoctoral and PhD positions. The rest of the funding will be used for travel, consumables and equipment (primarily the computational architecture to support the large volumes of data involved). Complementary funding will be sought from government funding agencies such as the UK Natural Environment Research Council (NERC) and the Department of Business, Energy and Industrial Strategy (BEIS).

Synergies

Bristol and Oxford are involved in a range of complementary research programs – funded by both industry and research councils. These synergies add significant value to the proposed project, enabling collaborations to develop between researchers working on related and complementary research topics. Current synergies include:

- **Seisgreen:** A NERC Large Grant project running for 5 years (from 2022), studying induced seismicity in the context of net-zero energy technologies. The project incorporates analogue lab rock physics experiments, numerical geomechanical simulation, seismological observations, risk assessment, and social science to learn how to manage and mitigate induced seismicity hazard.
- **SHARP-Storage:** A consortium grant funded by ACT-3, running for 4 years (from 2021) studying the geomechanics of CCS. The overall aim is to increase the accuracy of subsurface CO_2 storage containment risk management through the improvement and integration of subsurface stress models, rock mechanical failure and seismicity observations
- **Oxford Net Zero** is an interdisciplinary research initiative which recruits research fellows from partner institutions from around the world to track progress, align standards and inform effective solutions in climate science, law, policy, economics, clean energy, transport, land and food systems and Greenhouse Gas Removal.

Past collaborations have included:

- **UKUH:** Large consortium project investigating the potential for UK shale gas. BUMPS researchers contributed to three research packages, including assessing the potential resource; investigating impacts on the overburden (including fault reactivation), and assessments of induced seismicity risk. Funded by the UK Natural Environment Research Council (NERC) from 2018 – 2022.
- **FAST-MoDE:** Innovation grant developing the use of DAS for microseismic monitoring, with a particular focus on machine learning for event detection. Funded by NERC from 2018 – 2019.
- **Digimon:** Consortium developing the use of DAS for real-time monitoring of CO_2 storage sites. Funded by Accelerating CCS Technologies (ACT-2) from 2019 – 2022.
- **Dynamic UK Ground Motion Maps:** Demonstrator project developing InSAR-based UK-wide ground displacement databases. Funded by NERC from 2019 – 2020.
- **MORE:** Knowledge exchange grant implementing microseismic monitoring technologies for regulators and operators. Funded by NERC from 2014 – 2015.
- **FRACGAS** and **GESER:** Consortium projects developing numerical geomechanical methods to simulate hydraulic fracturing in tight reservoirs. ITF-coordinated project with a range of industrial sponsors, running from 2010 – 2016.
- **Still or Sparkling:** Partnership grant with BP using microseismic monitoring to evaluate CO_2 storage integrity at the In Salah CCS site. Funded by NERC from 2011 – 2014.

Deliverables

The primary deliverable for this project is knowledge transfer of research findings, guidelines and algorithms for the best exploitation of passive seismic data. This will come in the following forms:

- A password-protected website for the consortium
- Annual sponsors meetings; visits to sponsors when needed
- Presentations and talks
- Progress reports
- Comprehensive final report
- All publications in industry and academic journals
- Access to consulting
- Access to software; primarily Matlab and Python code and algorithms.

Track Record

BOPS is a continuation of the long-running Bristol University Microseismicity Project (BUMPS). The change in name is a recognition both of the broadening of our research base to include the University of Oxford, and of the need to broaden our focus to include all the ways in which passive seismic data can be utilised (i.e., not just microseismicity).

Since 2011, BOPS personnel have produced over 100 papers in leading scientific journals, and a large number of EAGE and SEG extended abstracts. We are regularly invited to give keynote talks at meetings, workshops and institutions, and have co-organized a number of international conferences and workshops.

In addition to our academic contributions, we are often asked to advise policy-makers and regulators regarding effective monitoring of subsurface industries, and we have also engaged in numerous outreach and public communication of science activities, including TV and radio interviews and public debates.

The preceding BUMPS project has pioneered the use of many techniques in microseismic analysis, including:

- Methods for rapid manual processing of downhole DAS microseismic data (Verdon et al., 2020).
- Machine learning (image-recognition) based methods for detection of microseismic events in DAS data (e.g., Stork et al., 2020).
- Methods to forecast induced seismicity magnitudes during hydraulic fracturing (Verdon et al., 2018). These methods have been applied in operationally to hydraulic fracturing at the UK Preston New Road site in 2018/19 (Clarke et al., 2019; Kettlety et al., 2021).
- Using DAS to monitor 'cryo'seismicity and acquire passive seismic images of Antarctic glaciers (Hudson et al., 2021).
- Deep learning methods to detect and pick microseismic events (e.g., Lapins et al., 2021)
- Mapping variations in rock and fluid properties at geothermal sites using using tomographic methods (e.g., Wilks et al., 2020).
- Migration techniques to image small events using surface sensors (e.g., Chambers et al., 2010; Verdon et al., 2016).
- Automated seismic anisotropy workflows (Teanby et al., 2004; Wuestefeld et al., 2010), including techniques to use seismic anisotropy to characterise fracture networks (Verdon and Kendall, 2011), and frequency-dependent methods to image the length-scale of fractures (Al-Harrasi et al., 2011; Baird et al., 2013).
- Signal extraction and polarisation analysis methods to better constrain source-receiver azimuths (De Meersman et al., 2006), including dip-based analysis to resolve 180-degree ambiguities in downhole event locations (Jones et al., 2010).
- Using piezo-electric sensors to image rock wall stability in large construction projects (Butcher et al., 2021).