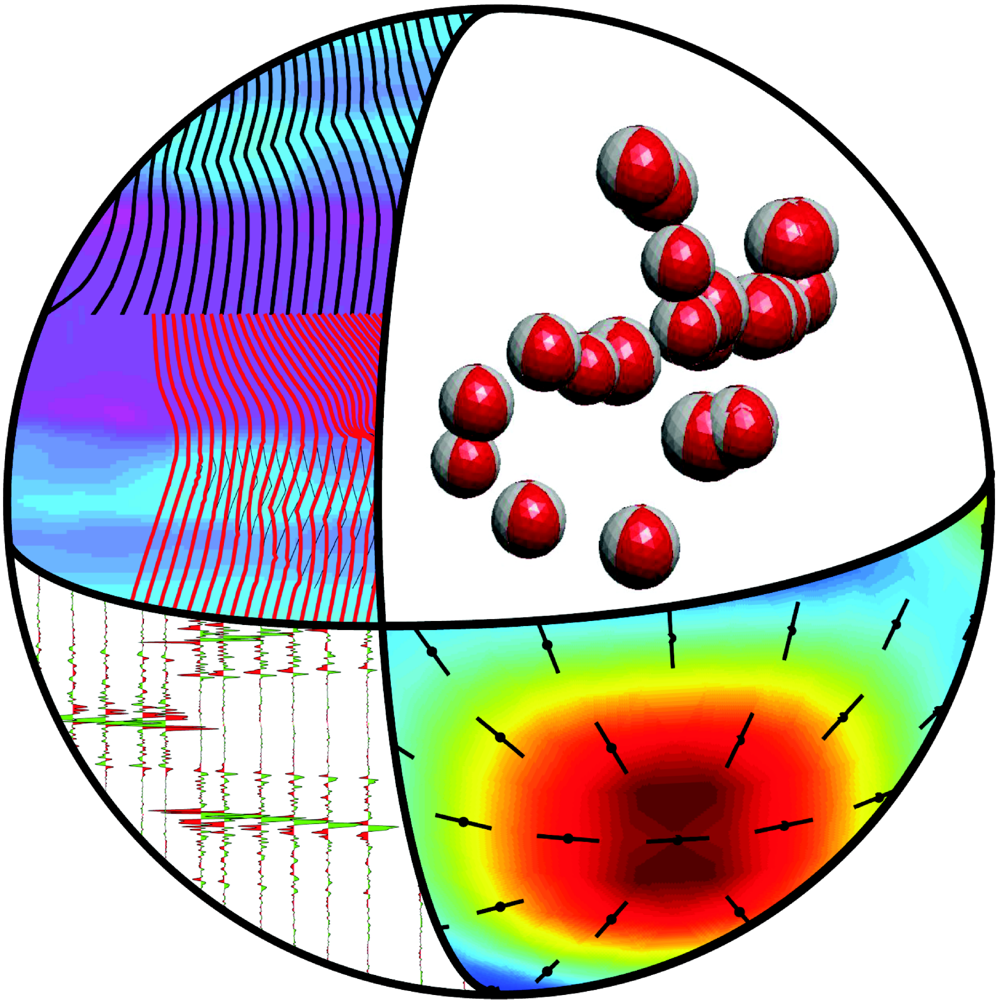
Bristol University Microseismicity Projects

Phase II Proposal



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Bristol University Microseismicity Projects (BUMPS) – Phase II

A Proposal from the Department of Earth Sciences, University of Bristol

Here we propose a 3-year research project to investigate natural and induced microearthquakes in localised regions such as hydrocarbon reservoirs or mining settings. This consortium-funded project will emphasise fundamental research and knowledge transfer. The consortium will be based in the Department of Earth Sciences at the University of Bristol, with collaboration with members of the School of the Earth and Environment at the University of Leeds. The project is the continuation of a successful first phase, which was based at the University of Leeds. Activities envisaged in the scope of this project fall into the following work packages:

Event location and characterisation. Accurate source locations are crucial to any analysis of microseismic data. Techniques for improving source locations including enhanced polarisation analysis, co-inversion with velocity models and using data from surface sensors will be explored. Source characterisation also provides important information and this work package aims to continue the development of inversions for moment tensors and focal mechanisms, including feasibility studies.

Studies of seismic anisotropy. Seismic anisotropy provides valuable information about lithology, fracturing and permeability; it also has profound effects on wave propagation. This phase of the project will continue the development of techniques for measuring, interpreting and accounting for seismic anisotropy in microseismic data. Some of the proposed activities include developing shear-wave splitting tomography, and incorporating frequency information to infer additional properties (e.g., fluid properties and fracture dimensions).

Exploiting the wider wavetrain. Most work to date has focussed on direct P- and S- waves from microseismic sources. Other phases such as head-waves, reflections and conversions also potentially provide valuable information, such as further constraints on location and velocity models. The project will explore methods for isolating and utilising such phases.

Improved utilisation of microseismic data. It is widely recognised that microseismic data are underutilised, not only because they are only rarely measured, but also because more work is needed to investigate potential uses of the data. Applications that we will consider include: monitoring fracture stimulation, CO_2 sequestration, reservoir compartmentalisation, and temporal variations in the stress field. A poorly understood but key element is the link to the geomechanical behaviour of a geological setting. Drawing on experience from other projects, we will develop a better understanding of how microseismic data can be better used to ground-truth geomechanical models. This will lead to an improved understanding of issues such as fracture properties, top seal characterisation, and the identification of high risk areas for future drilling. Initial studies have also highlighted the possibility of obtaining data on the stress orientation and magnitude from microseismic data. We will also investigate and identify key uncertainties/inaccuracies associated with the estimation of stress from microseismic data.

Sponsorship will be £20K per year per sponsor, and will provide funding for postdoc salaries, PhD students, computing, travel and consumables. The project will produce a range of deliverables including regular sponsors meetings, password protected web resources for sponsors, a complete set of reports and presentations, and algorithms developed in the course of the project. The project is expected to start in January, 2009.

Enquiries can be directed to:

Professor Michael Kendall
Department of Earth Sciences, University of Bristol,
Wills Memorial Building, Queens Road
Bristol, BS8 1RJ, UK
gljmk@bristol.ac.uk
+44 (0)117 331 5126 (tel); +44 (0) 117 925 3385 (fax)
http://www1.gly.bris.ac.uk/∼jmk/BUMPS/bumps_home.html

Proposal for Phase II

The passive monitoring of microearthquakes can provide a cheap and effective means for monitoring spatial and temporal variations in sub-surface properties. These microseismic events will occur naturally due to regional tectonic stresses, but can be also induced through exploitation activities such as hydraulic stimulation, enhanced petroleum recovery and fluid extraction, and underground mining. Such monitoring offers insights into the dynamic state of stress – invaluable information for developing effective strategies for drilling, injection, fracturing and production programs.

This project covers a wide range of research themes concerned with understanding and exploiting natural and induced microearthquakes in localised regions such as hydrocarbon or mining settings. It is a consortium-funded endeavour emphasising fundamental research and knowledge transfer. The consortium is based in the Department of Earth Sciences at the University of Bristol, with collaboration with members of the School of the Earth and Environment at the University of Leeds. It is the continuation of a successful first phase originally based at the University of Leeds.

Work Packages

Below outlines a series of proposed work packages, intended to provide an overview of the research programme. It is not intended to be an exhaustive list of activities, one which may be modified as the project progresses, both by the results of the research and feedback from the sponsors.

Event location and characterisation

Accurate source locations are crucial to any analysis of microseismic data. Phase I developed tools for refining locations by improving polarisation measurements. There are several avenues to further improve this line of research which will be explored in Phase II. Polarisation filtering has proven useful in the analysis of various phases in teleseismic data. We will investigate the application of such techniques to microseismic data, as well as the further identification and use of multiplets. This has obvious relevance to standard applications, such as frac-monitoring.

Event locations — especially where only an array in a single well is available — can be particularly sensitive to the velocity model chosen. Models derived from reflection data are often employed, but these usually lack S-wave information and true depths. Well-log derived models may have S-wave speeds and depths but are very localised, and measured using high frequencies. Anisotropic information is also not currently used, which may significantly affect the accuracy of locations. We propose to explore the sensitivity of locations to the vagaries of velocity models. Another possibility, however, is to adopt the approach applied to seismogenic studies of regional earthquakes and treat the velocity model as well as the locations as a inverse problem. This should improve the coherence of source locations, and perhaps additional useful imaging information.

The availability of permanent surface sensors (or arrays) is also improving (*Chambers, et al.*, 2008). These have a great deal of potential to aid in the accurate location of microseismic events; however, such arrays usually lie at considerable distances from events, and are located in noisier environments (e.g., sea floor). The project aims to establish thresholds for detectability, and explore the influence of surface array design, instrument capability and processing techniques, including noise reduction methods.

One of the most appealing applications of microseismic monitoring is the estimation of the stress field. Such information can be derived from knowledge of earthquake source mechanisms. The evaluation of focal mechansisms and stress tensor inversions are common methods of analysis in conventional earthquake analysis. We will apply such methods to microseismic datasets that are appropriate for such analysis. In the past, we have developed a range of techniques for extracting focal mechanisms from high frequency, noisy datasets, including those based on analyses of first motions, particle motions, amplitude ratios and waveforms by Rayleigh mode summation.

To date, studies of microseismicity in economic contexts have focussed on brittle failure style earthquakes. However, where there is significant fluid movement there are likely be other seismic events with a quite different frequency and character (as is observed in volcanic and hydrothermal systems). If events of this style can be measured, they are likely to provide very different information to faulting earthquakes. With the inclusion of broader band surface sensors at some fields, detecting and locating these events may be feasible. We will explore the possibility of identifying such events using forward modelling, and look for these in those data with appropriate instrumentation.

Seismic anisotropy

Seismic anisotropy refers to a directional dependence in velocities and results from the preferred alignment of crystals, inclusions, cracks and layers. Such order in a medium results from past and present deformational and depositional processes and, as such, offers insights into the dynamic nature of the Earth. In hydrocarbon settings, applications include interpretations of fracture alignment, the stress field, paleo-flow directions and lithology. The first phase of this project made a large contribution in this field, pioneering the measurement and interpretation of anisotropy from microseismic datasets using shear-wave splitting. This will continue in Phase II. For example, frac-monitoring is probably the most wide–spread application of passive seismic monitoring, but the generally only involves locating events. We will explore other means of monitoring anisotropy associated with stimulation, such as tracking shear-wave splitting.

Seismic anisotropy has a cumulative effect on waveforms, and if a wave traverses several regions of anisotropy separating the effects of these is difficult. In global seismology several groups (including Bristol) have begun to develop methodologies for shear-wave splitting tomography. These have been used successfully to understand anisotropy in subduction zones, and it is proposed that these methodologies can be applied to many microseismic datasets. This has huge potential for detailed anisotropic mapping of reservoirs, and also for interpretation of anisotropy in more physical terms.

A feature of many of the available microseismic datasets is their richness in frequency content. For example, the Ekofisk dataset contains signal at frequencies up to 500 Hz. The shear-wave splitting for data in different bandwidths can be analysed (or inverted tomographically) separately and the variation of anisotropy with frequency can be inverted for parameters such as fracture size, crack density and aspect ratio. We also aim to continue the work piloted in phase I to study the attenuation anisotropy in microseismic datasets. This is at an early stage, and requires observation in more datasets and validation of a theoretical model in order to better understand this phenomenon.

Exploiting the wider wavetrain

Exploitation of data from microearthquakes to date has focussed on primary arrivals: the direct P- and S-wave. There are, however, other seismic phases associated with such events which can provide valuable information. In settings with strong layering effects, for examples, interfaces waves can be a significant feature in the wavetrain. If these can be identified, they can be incorporated in inversions for the source location and velocity model. They potentially also pollute primary arrivals, so might be a good candidate for removal with polarisation filtering.

As well as direct and refracted waves, the microseismic wavetrain will also include conversions and reflections. These might also yield usable data. The former, for example, are used in teleseismic studies to infer near receiver structure (receiver functions). It is possible that — by analogy — conversions in the coda of primary arrivals in microseismic data might be similarly employed to study vertical features such as faults. Employing array techniques such as slant stacking of microseismic events might also allow the observation of scattered energy or reflected energy.

Developing modelling capability

Much of the effort outlined in the above is underpinned by the capacity to accurately and efficiently forward model seismic wave propagation in contexts appropriate to microseismic data. The modelling techniques required are dependent on the particular problem, for some problems (such as event location) detailed waveforms are not required; for others, frequency effects maybe very important. A great deal of forward modelling expertise and software already exists in the group, some of which has already been applied to microseismic problems. For example, we have developed tools for 3D ray tracing in fully anisotropic heterogeneous media. Recently, we have developed a wavefront construction method, which is used in locating events using 4D-time-migration. This method can be extended to anisotropic models, if necesssary. We also have experience with finite-frequency waveform methods, including 1-way wave equation solutions for fully anisotropic media and full-waveform methods for acoustic models. The research problems we aim to address in this phase of the project require will involve extending and adapting several modelling techniques.

Geomechanics

The project benefits from related research done at Leeds and Bristol on the geomechanical response of reservoirs to changes in fluids and stress. The ITF brokered projects IPEGG and GESER are collaborative endeavours between the Universities of Leeds and Bristol and Rockfield Software in Swansea. IPEGG aims to couple flow and geomechanical modelling to predict reservoir behaviour (i.e. stress changes, compaction, fault reactivation) and seismic properties during production. The focus of the GESER project is using geomechanical modelling and sesmic properties to better exploit tight gas reservoirs. We will draw on experience from these project to better understand how microseismic data can be better used to ground truth geomechanical models. This will lead to a better understanding of such things as fracture properties, top seal characterisation, identification of high risk areas for future drilling, reservoir compartmentalisation, etc.. We will also consider the link between microseismicity and geomechanics in the context of CO_2 sequestration.

Personnel

The project coordinator will be Professor Michael Kendall. Other Bristol personnel directly involved will include Dr James Wookey, Dr Kit Chambers and Dr Andreas Wuestefeld. Other members of the seismology group may contribute as appropriate. The primary collaborator at Leeds are Dr Doug Angus and Prof Quentin Fisher. All members of the group have extensive experience in looking at microseismic data, and several were involved in the first phase of the project (MK, JW, QF).

Proposed Datasets

The project has access to a wide range of microseismic datasets. These are from a range of environments including onshore and offshore hydrocarbon reservoirs and mining operations, and include both incidental and induced seismicity (from hydraulic fracturing and CO_2 injection). They also include a range of instrument coverage and geometries, and some include surface sensors. This wide range of datasets will allow us to test techniques developed under a wide range of conditions. We are also open to suggestions of other datasets which the sponsors can provide.

Synergies

The groups at Bristol and Leeds are also involved in a range of complementary research — funded by both industry and research councils — which add significant value to the proposed project. Some of these include: IPEGG (Integrating Petroleum Engineering, Geomechanics and Geophysics; an ITF consortium focussing on linking geomechanical models with reservoir simulations and seismic observables), GESER (geomechanical-seismic modelling of tight–gas sand reservoirs) and BCOG (Bristol CO_2 Group; part of a consortium studying the monitoring of CO_2 sequestration). Additional contributions will be available from project work from the Exploration Geophysics MSc course at Leeds and undergraduates at Bristol.

Funding

The proposed phase will last three years. The requested funding is £20K per year per industry sponsor. This represents excellent value for money as many of the involved personnel do not need salary support and the University charges relatively low overheads on salary. The funding will primarily provide salary for postdoctoral and PhD positions. Some may also be used for administrative support as required. 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 Trade and Industry (DTI).

Deliverables

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

- A password-protected website for the consortium (similar to that developed for the SAIL project at Leeds – http://www1.gly.bris.ac.uk/∼jmk/newsail/secure/sponsors.html).
- Regular sponsors meetings (every 6–9 months).
- Presentations and talks
- Progress reports
- Comprehensive final report

Summary of Phase I

What follows is a brief summary of some of the achievements of phase I of the project, including references to published work. More detail can be provided on request.

Passive seismic monitoring is a relatively new tool for studying hydrocarbon reservoirs. Until recently such experiments have focused primarily on the logistics of acquiring the data and locating microseismic events. Early experiments have shown the potential for monitoring faulting and fracturing (*Jones and Stewart*, 1997; *Maxwell and Urbancic*, 2002). The broad aim of this Microseismicity Project was to investigate and develop new approaches to further exploit this new technology.

Phase I of the Leeds Microseismicity Project began in May, 2001 and lasted 3 years. The consortium sponsors were ABB Offshore Systems (Rosemanowes, UK), BP (Stavanger, Norway), Schlumberger Cambridge Research (UK) and Shell Exploration and Production (Aberdeen, UK). Further funding came from a ROPA grant awarded by the UK Natural Environment Research Council (NERC).

Phase I primarily concentrated on microseismic data collected at Valhall, although some analysis of a similar dataset from the Ekofisk field was completed. The Valhall field is an overpressured, undersaturated chalk reservoir in the Norwegian sector of the North Sea. The field was discovered in 1975 and went into production in 1982. The original estimate of recoverable oil was 250 MM BO, however this has already been far exceeded (*Kristiansen, et al.*, 2000). Since first production, the seafloor has subsided over 4m due to compaction of the chalk. Despite the obvious environmental impact and drilling complications, this compaction has enhanced oil recovery from the reservoir through lithic drive (*Kristiansen, et al.*, 2000). However, borehole breakout is an expensive problem in this part of the North Sea. This partially motivated a pilot experiment to explore the utility of passive seismic monitoring to study faulting, micro-fracturing and stress build-up in the reservoir.

In June 1997, 6 three-component seismometers were deployed in an abandoned well near the crest of the field. The sensors were spaced vertically at 20m intervals between depths of 2100m and 2200m. Over 500 events were detected in the 2 month experiment, 324 of which could be located (*Dyer and Jones*, 1998).

A focus of Phase I of the project was on measuring and interpreting shear-wave splitting in microseismic datasets to evaluate anisotropy. Our approach is based on a methodology introduced for analysing splitting in teleseismic earthquake data (*Silver and Chan*, 1991). The Valhall dataset was analysed manually, with 117 events showing reliable results (*Teanby, et al.*, 2004a). The interpretation of the splitting results was based on extensive modelling. A ray based approach using the ATRAK software (*Guest and Kendall*, 1993) was used to construct synthetic seismograms. The modelling showed two plausible causes for the anisotropy. One model comprises vertical fractures in an inherently anisotropic siltstone with VTI symmetry: the net result an orthorhombic symmetry. The second interpretation appeals to models of anisotropic poro-elasticity (*Crampin and Zatsepin*, 1997). Here high pore-pressure and uniaxial stresses orient a network of vertical micro-cracks.

Although the number of events recorded in the Valhall dataset is large compared to that recorded in more conventional earthquake experiments, it is clear that microseismic datasets will soon be orders of magnitude larger. Data are now being acquired by more permanent sensor installations in more than one borehole. A similar experiment to Valhall was acquired at the nearby Ekofisk field. Here an 18 day experiment recorded over 1600 events on a similar 6-tool string of 3-component sensors. Given the large amounts of data recorded in microseismic experiments, an emphasis of the Microseismicity Project is on the development of more automated methods for analysing the data.

Microseismic data are in general often acquired by arrays of sensors in a borehole. A work package in Phase I exploited such array acquisition to improve travel-time picks and particle-motion analysis. Both are required when data are acquired in a single borehole. We developed a new method for semi-automating travel-time picking (*de Meersman, et al.*, 2004). Hodogram analysis was performed with multi-station, weighted, complex principal-component-analysis (PCA). Previously these steps had been done manually. The results from the semi-automated analysis showed systematic differences with the manual picks. They also revealed relative misorientations in the tools. The refined source locations showed more realistic tighter clustering and more linear distributions.

Another significant development with regard to automation was a methodology for automating shear-wave splitting analysis (*Teanby, et al.*, 2004b). The time consuming part of conventional splitting analysis is picking the time window for the analysis. In the automated analysis the splitting is done for a large number of time windows straddling the picked shear-wave arrival time. A cluster analysis is then used to find those measurements that are stable over a range of windows. The final result is based on the cluster with the lowest error and variance. The result is a more objective estimate of the splitting parameters and the ability to quickly analyse large datasets. A manual quality control step is still required, but this is a relatively quick process. The automated splitting method has been applied to both the Valhall and Ekofisk datasets, the latter producing nearly 10 000 shear-wave splitting measurements.

Another component of Phase I was an investigation of the frequency-dependent nature of shear-wave splitting. In Phase I we presented a simple method for the analysis of attenuation anisotropy and applied it to the Valhall data (*Carter and Kendall*, 2004). A comparison of the relative frequency content of fast and slow shear-waves provides a convenient measure of attenuation anisotropy due to aligned fractures or cracks. It should be more sensitive to fracture-content than velocity anisotropy. We also investigated the size of fractures by investigating how the magnitude of shear-wave splitting varies with frequency. Following the the methodology of *Maultzsch, et al.* (2003) we estimated the fractures or cracks responsible for the anisotropy to be on the order of centimetres in size or smaller.

One of the initial aims of Phase I was to relate the measured anisotropy to both lithologic and fracture properties via petrofabric analysis of reservoir and overburden rocks. Unfortunately, it was difficult to obtain core samples from Valhall. The overburden within which the microseismic data were acquired is a poorly lithified siltstone with some limestone stringers. Drilling cuttings were provided by BP, but this only rendered a few samples large enough to do any petrofabric analysis. As these were fine-grained and small samples, X-ray texture goniometry was used to determine the preferred orientations of micas and chlorite in the siltstone. The analysis showed that these minerals generate a VTI anisotropy with nearly 10% P-wave anisotropy and a maximum of nearly 10% shear-wave splitting in the horizontal plane. As these minerals constitute nearly 30% of the rock, the whole-rock anisotropy values were estimated to be roughly 3%. This is based on the assumption that the remaining minerals (primarily quartz) are randomly oriented (*Valcke*, 2006). The stratigraphy in the vicinity of the microseismic experiment is essentially horizontal. Earlier Valhall work on AVOA (*Hall and Kendall*, 2003) and converted-wave amplitude ratios (*Granger, et al.*, 2000) cannot be explained with this intrinsic VTI anisotropy. It is these observations, and the modelling presented by *Teanby, et al.* (2004a), that lead to arguments for an orthorhombic medium due to vertically aligned fractures in a layered VTI rock.

Phase I included a complete set of reports, presentations and papers. Some software was also provided to sponsors, including notes on the modelling and data analysis procedure.

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