EDINBURGH ANISOTROPY PROJECT
APPLIED SEISMIC ANISOTROPY

7TH PHASE RESEARCH PROGRAMME
2006-2009
THE EDINBURGH ANISOTROPY PROJECT
APPLIED SEISMIC ANISOTROPY
7TH PHASE RESEARCH PROGRAMME 2006-2009

EXEUCIVE SUMMARY

The Edinburgh Anisotropy Project (EAP) conducts research into applied seismic anisotropy, and how to utilize such information for the understanding of hydrocarbon reservoirs. EAP is supported by a consortium of major oil, service and software companies. The EAP research programme is guided by industry requirements and is primarily focused on fracture characterization and anisotropy imaging. The programme covers a wide variety of topics including data processing, interpretation, modelling and acquisition design, as well as fundamental wave propagation issues.

EAP was established in July 1988 with seventeen years of experience in seismic anisotropy. EAP has organised its research programme in three-year phases. The project is now in its 6th Phase, which ends in June 2006.

The 7th Phase Research Programme (2006-09)

The programme proposed for the 7th Phase is a continuation of the 6th Phase, but with a particular emphasis on frequency-dependent anisotropy, arising from discussions with sponsors. The programme has three components:

- **AVD technology for fracture characterization**
  Extension of traditional AVD (attributes versus direction) methods to exploit frequency-dependent anisotropy for robust fracture density information together with fluid saturation and dominant scale length

- **Converted-wave analysis for improved imaging of reservoir structure**
  Extension of current converted-wave imaging tools (e.g. CXtools) to account for diodic converted-wave effects and further development of depth-imaging tools for building a common anisotropic earth model

- **Anisotropic rock physics for analysing frequency-dependent anisotropy**
  Progress towards gaining more insights into the information content of frequency-dependent anisotropy through experimental studies, calibrated theoretical developments and analysis of time-lapse VSP data

An important aspect of EAP research is that the development of theory, methodology and algorithms is combined with application to real data, supplied by the sponsors, to demonstrate the value of the technology produced.
Deliverables and Technology Transfer

- Research results in the form of annual reports, technical papers and software releases
- Courses on applied seismic anisotropy, tailored to individual sponsor’s requirements
- Special consultancy and joint studies of company-specific anisotropy-related issues
- PhD research studentships

EAP believes in maintaining close links with each member of the consortium so that the technology developed is transferred efficiently, and the research programme remains dynamic and evolutionary.

Fees

For the 7th Phase the annual fees will be set at a flat rate of £31k.

For new sponsors there is, in addition to the annual subscription, a joining fee of £30k, or £10k plus some negotiable equivalent in the form of software or data.

Meetings

The main annual EAP Technical and Business Meeting is held in Edinburgh, usually immediately following the annual EAGE conference. A further meeting is held at the annual SEG conference.

Consortium members

EAP is currently sponsored by eighteen service and oil companies and one software company: Agip, BG, BGP, BP, Chevron, CNPC, ConocoPhillips, ExxonMobil, GX Technology, KerrMcGee, Marathon, Norsk Hydro, PDVSA, Schlumberger, Shell, SinoPec, Total, Veritas DGC and Landmark.

Project Resources

Staff: A team of 5 scientific staff and 6 PhD students (see Appendix A).

Computing: a 24-node PC cluster, Sun Ultrasparc/Sparc Workstations, Intel-Based destop PCs, Terabyte Raid System For Data Storage.

Datasets: EAP benefits from access to datasets supplied by the sponsors. A list of the datasets available to the project during the 6th Phase is given in Appendix B.

Further Information

Enquiries about EAP activities and membership details should be addressed to:

Professor Xiang-Yang Li, Technical Director
Edinburgh Anisotropy Project, British Geological Survey,
Murchison House, West Mains Road, Edinburgh  EH9 3LA,  UK
Tel: +44 (0)131 667 1000/Fax: +44 (0)131 667 1877/E-mail: xyl@bgs.ac.uk

Further information can also be found at http://www.eap.bgs.ac.uk
7th PHASE RESEARCH PROGRAMME

Introduction

During the 6th Phase (2003-2006), we have focused on consolidating our ideas and findings for technology transfer. This led to the release of three software packages, i.e. *CXtools* for converted-wave imaging, *RU* for rock physics and fracture modelling, and *GeoLab* for depth model building and imaging. Major progress has been made in the following areas in the past five years:

- **Converted-waves analysis**
  - New theories and algorithms for converted-wave imaging are consolidated into *CXtools*, which makes it possible to perform anisotropic imaging with high accuracy but low cost
  - A number of successful case studies (e.g. Lomond 2D 4C data, Afflect 3D 4C data)
  - Ideas for decoupled migration to perform multiwave type prestack depth imaging

- **Fracture characterization**
  - Frequency-dependent P- and S-wave attributes to characterize fluid saturation and dominant scale length
  - A number of successful case studies (e.g. Clair and Emilio 3D 4C data)

- **Time-lapse seismic data analysis**
  - Improved dynamic rock physical model with multi-scale fluid flow
  - Ideas of frequency-dependent time-lapse anisotropy for discriminating the effects of pore pressure and saturation

These developments have been endorsed and well received by all sponsors. During this Phase, EAP has also attracted a record number of sponsors, which encourages us to continue developing our work through real data applications during the next phase from 2006 to 2009, with a primary focus on integrated studies and the delivery of user-friendly tools.

EAP activities seek to address the needs of industry (**fractures, converted waves, imaging in complex areas**), while retaining a component of basic strategic science for future developments (**frequency-dependent anisotropy, fluid flow**). It is EAP’s intention to achieve a healthy balance between applied and basic research as well as ‘blue-sky’ research.

In addition to the industrial sponsorship, every year EAP also receives matching funds from the Natural Environment Research Council through its science budget. This provides great value for money for EAP’s members. From time to time EAP also receives government grants through competitive tender and review exercises. These matching funds and research grants enable us to carry out more basic and curiosity-driven research. As a whole, EAP research builds on a solid foundation of theoretical expertise and field-data analysis in seismic anisotropy developed over the past seventeen years. The following sections describe the major components of the 7th Phase programme.
Interest in converted-waves was rekindled by the emergence of 4C OBC technology in the mid 1990’s. Since then, more than a decade has elapsed. Despite an intensive effort in research and development of the converted-wave technology, the anticipated breakthrough into a mainstream technology has still to be realized. A general consensus is that the processing and interpretation of converted-wave data appears to lag behind the corresponding acquisition technology that has evolved from analogue phones to digital sensors, from line receivers to point receivers, from dragged cables to permanently installed trench-buried systems. The difficulties in processing the converted waves lie in two main areas. In onshore applications, the near-surface is still the main obstacle for obtaining high-quality and high resolution converted-wave data; whilst offshore, converted-wave imaging suffers from the wide occurrence of anisotropy in marine sediments together with the asymmetric raypaths and the diodic velocity effects due to shallow inhomogeneities, which has even made the data acquired with permanently installed systems un-interpretable. Due to these problems, there is a general lack of user-friendly and reliable tools for processing and interpreting the converted-waves.

Since the onset of Phase 5 (2000-03), we have made significant progress in bridging the above gap for converted-wave imaging. During Phase 5 (2003-03), we have developed a common theoretical framework to describe the converted-wave behaviour in anisotropic media in terms of converted-wavefield attributes. This paved the way for the use of standard procedures such as semblance analysis and Kirchhoff summation to implement converted-wave anisotropic processing with high accuracy but low cost. During Phase 6 (2003-06), we extended the previous developments into 3D-4C data for both anisotropic imaging and parameter estimation, and consolidated our achievement into an user-friendly software, referred to as **CXtools**. Using this tool, we have reprocessed a number of 2D and 3D-4C dataset from the North Sea, and in each case, a substantially improved subsurface image was obtained that has made significant impact on the development of the relevant oilfield.

During Phase 7, our emphasis is to extend **CXtools** to account for the diodic converted-wave effects and further development of our depth-imaging tools for building a common anisotropic earth model, and our aim is to fill the wide acknowledged gap in converted-wave processing with **CXtools**.

**Areas of interest and deliverables for the 7th Phase:**
- diodic decomposition for 3D 4C data;
- the corresponding depth imaging work flows using PP-independent PS imaging approach;
- decoupled migration and associated work flows for anisotropic inversion;
- conversion point signature from 3D 4C data;
- anisotropic estimation in TTI media;
- case studies of 3D-4C data from permanently installed systems in the North Sea;
- user-friendly fully-documented algorithms/software for PC cluster.

**Datasets available for the 7th Phase:**
- Valhall LoFS (Life of Field Seismic) 3D-4C data, North Sea;
- BG 4C data
- Shenli 3D-3C data, Yellow River Delta
Research developments

- Diodic PS decomposition for building a common earth model from 3D-4C data
- Anisotropic estimation in orthorhombic or TTI media
- Optimizing anisotropic depth model through a prestack time migration
- Case studies of 3D 4C seismic data
- User-friendly algorithms and software

CXtools for anisotropic model building

The Affleck 3D-4C experience (courtesy of KerrMcGee): (a) Reprocessed by EAP using the Cxtools; and (b) conventional isotropic processing.
AVD technology for fracture characterization

EAP has pioneered the use of seismic anisotropy for characterization of natural fractured reservoirs. Currently, we are extending our expertise to go beyond what the conventional anisotropy concept for fracture imaging can offer by developing innovative methods to evaluate the dominant scale length from 3D VSP, 3D surface and 3D 4C-OBC seismic data. Our new theories and methods allow the seismic response across a broad band of seismic frequencies to be computed, making it possible to observe and analyse the directional spectral/dispersion/attenuation variation and frequency-dependent anisotropy in seismic data and then to invert these variations for the properties of the fracture distribution. This will require advanced techniques for extracting spectral/dispersion and attenuation characteristics from seismic data using, for example, multi-instantaneous attribute analysis and modern spectral decomposition techniques.

EAP is also developing advanced numerical methods to simulate wave propagation in media with discrete fracture systems using the discrete dynamic rock physics model, which allows us to develop inversion techniques to obtain information about discrete formation or meso-scale fractures. The work so far focused on 2D will be extended to 3D with an aim to develop a discrete fracture network (DFN) model by using seismic anisotropy attributes as inputs to combine with other geological/geophysical data.

Areas of interest and deliverables for the 7th Phase:

- Characteristics of directional dispersion/spectral/attenuation variations in P- and converted-wave data and their applications for determining fracture properties such as the dominant scale length, and fluid saturation;
- Generation of realistic fracture networks and patterns at the meso-scale for seismic modelling, and computation of 3D synthetic VSP and reflection dataset using realistic reservoir models with discrete fracture distributions;
- Analysis and inversion procedure to quantify fracture size and fracture porosity (storability) from 3D VSP, 3D surface and 3D-4C OBC data including both synthetic and real data;
- Multi-Attribute Analysis, including coherency analysis, multi-component instantaneous polarization analysis, and spectral decomposition of seismic data to reveal anomalies that are related subsurface fracture distributions;
- Comprehensive software packages for fracture modelling and seismic imaging including enhanced 3D modelling capability to simulate seismic wave propagation in fractured media and software to extract information on fracture properties (size/storability, density, orientations, and fluid properties).

Datasets available for the 7th Phase:

- Emilio 3D 4C seismic dataset
- The Clair field OBC data and associated VSPs
- Physical modeling 3D datasets (CNPC Key Labs)
- Wind River 3D surface data.
Fracture characterization

Research developments

- Analysis of P-wave attenuation anisotropy/shear-wave splitting
- Dominant scale length and fluid saturation from 3D-4C seismic
- Techniques for modeling the seismic response of large fractures
- Multi-scale decomposition and attributes analysis
- Analysis procedures/user-friendly algorithms & software

Azimuthal frequency anomalies in 3D seismic data

Wind River Basin (Queen and Lynn 2003)

Frequency-independent  Frequency-dependent  Perpendicular  Parallel
Anisotropic rock physics for frequency-dependent anisotropy

Frequency-dependent geophysical properties have attracted more and more interests from the research communities and the industry, which potentially links the subsurface seismic response to permeability and the dominant scale length of the heterogeneities in the subsurface. The situation regarding this subject is comparable to that of research on seismic anisotropy in the 80’s: the potential is high yet more work needs to be done towards both the understanding of the phenomenon and its implications.

During the 6th Phase, we have developed a dynamic rock physical model accounting for changes in both pore pressure and saturation. A range of observable effects was predicted, including the frequency dependence of shear-wave time delays, differential attenuation between fast and slow shear-waves and P-wave attenuation anisotropy. We have analysed a series of VSP datasets in order to evaluate these effects, including multicomponent VSPs, walkway VSPs and time-lapse VSPs. These studies have confirmed that these effects are detectable in field data and can be related to fracture properties such as dominant scale length and fluid saturation, using robust modelling and inversion procedures.

Phase 7 will develop these ideas across a spectrum of activities, encompassing further theoretical development, laboratory calibration, development of processing techniques and application to field data. The goal of the research will be to use the modern ideas in spectral decomposition and poroelastic theory to establish a robust link between seismic anisotropy and the petrophysical properties of rock, particularly the anisotropic variation of permeability. We will continue to analyse VSP surveys including time-lapse VSP data, to consolidate our understanding, but the new direction of Phase 7 will be the emphasis on applying our ideas to surface seismic data.

Areas of interest and deliverables for the 6th phase

- improved rock physics models, calibrated against field and laboratory data, which relate the frequency dependent anisotropic response to fracturing, fluid saturation and stress state;
- finite difference modeling for wave propagation through a discrete fracture network, to establish the effect of scattering from fractures of different sizes on the anisotropic response;
- use of attenuation measurements for reservoir characterisation, in particular a comprehensive theory for interpretation of azimuthal AVO in the presence of frequency dependent anisotropy;
- Analysis of time-lapse multi-azimuth VSP data to establish the relationship between the anisotropic seismic response and pressure and saturation variations.
- a fully tested comprehensive rock physics subroutine library

Datasets available for the 6th Phase:

- Laboratory measurements of synthetic fractured rocks with known fracture geometries
- Multi-azimuths VSPs from the Wyoming Basin
- Time lapse 3D VSPs from Weyburn
- Time lapse VSPs from Quarnalam/PDO.
APPENDIX A – PROJECT PERSONNEL

The EAP team presently comprises five members of BGS staff, a senior consultant in the University of Edinburgh, and six PhD Students. It also benefits from its close association with BGS staff working in other areas of seismology, and associated academic staff in the University of Edinburgh.

EAP Staff

Technical director: Professor Xiang-Yang Li (Multicomponent seismology)

Principal Geophysicist: Dr. Enru Liu (Associate director and Fracture imaging)

Senior Geophysicists:
- Dr. Hengchang Dai (Anisotropic imaging)
- Dr. Mark Chapman (Rock physics model and fluid-rock interaction)

Senior Consultant: Professor Stuart Crampin (Fundamentals of anisotropy) (University of Edinburgh)

Associated Staff

Senior Seismologist: Dr David Booth (Project support)

Technical Engineer: Mr Brian Bainbridge (Technical and computing support)

Associated Academics

University of Edinburgh: Professor Ian Main (Rock Physics)
- Dr Roger Scrutton (Log data interpretation)
- Dr Andrew Curtis (Exploration seismology)

EAP Students

Jinghua Zhang (4C seismic and converted-wave)
Lifeng Wang (4C seismic and fractures)
Isabel Varela (Fracture modelling)
Zhongping Qian (4C seismic and fractures)
Adam Wilson (Frequency-dependent anisotropy)
Joao Marcos Ferreira (Micro seismic monitoring)
### APPENDIX B - EAP ACTIVITIES AND DATASETS

#### Converted-waves

<table>
<thead>
<tr>
<th>Marine 4C seismics</th>
<th>COMPLETED</th>
<th>ONGOING</th>
<th>PROMISED</th>
</tr>
</thead>
<tbody>
<tr>
<td>BP – Valhall(2D)</td>
<td></td>
<td>Agip – Emilio 3D 4C</td>
<td>BP-Vauhall Life of Field Seismic</td>
</tr>
<tr>
<td>Agip – Johnd Field 2D</td>
<td></td>
<td>BG – 4C</td>
<td></td>
</tr>
<tr>
<td>BP - Lomond 2D</td>
<td></td>
<td>Afflect 3D 4C</td>
<td></td>
</tr>
<tr>
<td>Mahagony 2D</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Chevron Alba 2D</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Shell – Guilemot 2D</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Chevron – Alba 3D</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Land 3C data</th>
<th></th>
<th>SinoPec 3D 3C</th>
<th>Petro-China 2D 3C 3C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Changqing 2D</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Offset VSPs/3D VSPs</th>
<th></th>
<th>PetroChina – Ordos VSPs</th>
<th></th>
</tr>
</thead>
</table>

#### Fractures

<table>
<thead>
<tr>
<th>Marine 4C seismics</th>
<th>COMPLETED</th>
<th>ONGOING</th>
<th>PROMISED</th>
</tr>
</thead>
<tbody>
<tr>
<td>Saga 2D (Geophone coupling)</td>
<td>Agip – Emilio 3D</td>
<td>Clair – 3D 4C</td>
<td>Norsk hydro Grange 3D</td>
</tr>
<tr>
<td>Shell – Guilemot 2D</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>2D/3D seismics</th>
<th>Shengli 3D wide azimuth</th>
<th>Physical modelling 3D wide</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fina – 2D +3D lines</td>
<td>azimuth data</td>
<td>DOE – Wyoming; wind river</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Walkaway VSPs /3D VSPs</th>
<th>Bluebell – VSPs</th>
<th>BP Clair VSP</th>
<th>BP Egypt VSP</th>
</tr>
</thead>
<tbody>
<tr>
<td>San Juan Basin VSPs</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>NW Colorado VSPs</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

#### TIME LAPSE SEISMIC

<table>
<thead>
<tr>
<th>Repeat VSPs/</th>
<th>Mobil – Camelot</th>
<th>Shell – Quarn Alam Weyburn VSPs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Saga –Snorre, 15 near-offset VSPs</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Micro-seismicity</th>
<th>USGS micro-seismicity data</th>
<th></th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>Marine 4C seismics</th>
<th>Teal South 3D</th>
<th>Vauhall LoFS data</th>
</tr>
</thead>
</table>

#### COMPLEX AREAS

<table>
<thead>
<tr>
<th>Surface seismic</th>
<th>Amera Hess – long offset two-boat shoot (Flare) Veritas DGC - 12km cable</th>
<th>Marathon 3D</th>
</tr>
</thead>
</table>

| Low frequency data           | Texaco-2D lines                                                          | Veritas – 2D lines              |