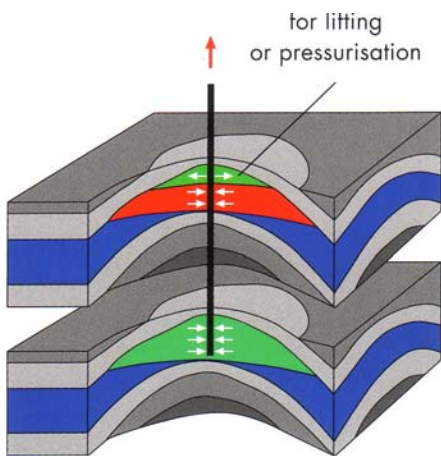
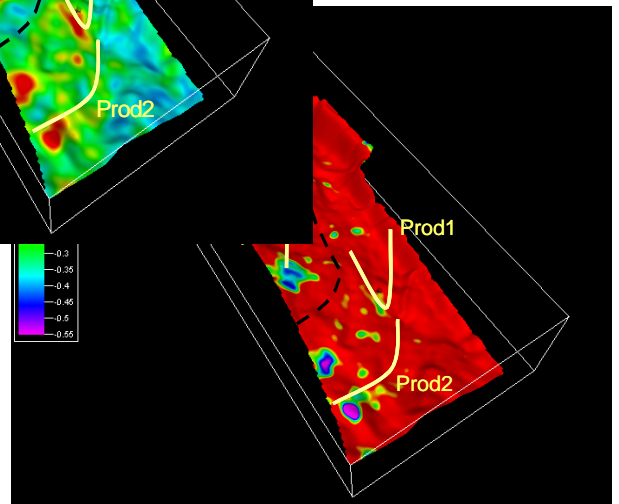
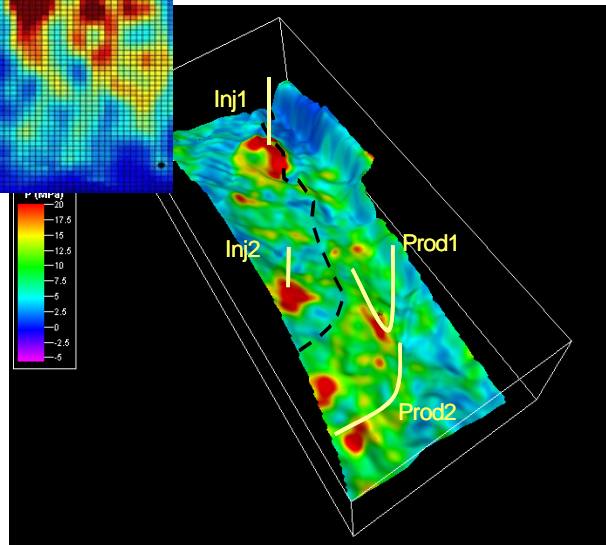
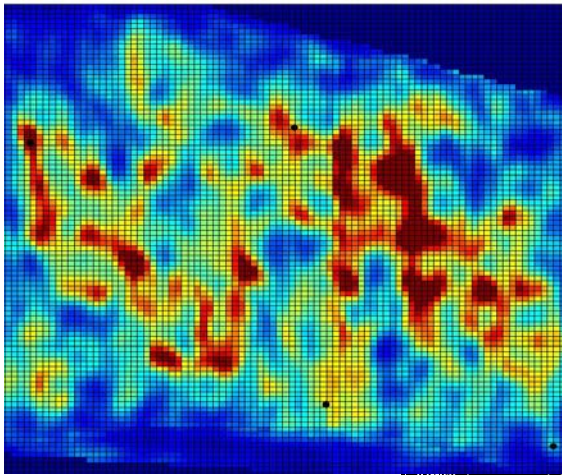
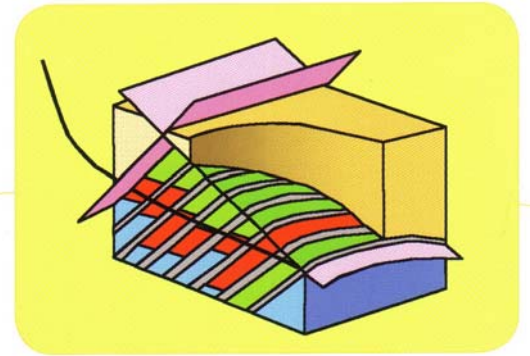


# Edinburgh Time-Lapse Project PHASE III



## EXECUTIVE SUMMARY

The Edinburgh Time-Lapse Project (ETLP) is a UK-based university research consortium specialising in the development and application of analysis tools for engineering-consistent quantitative interpretation of *4D* seismic data. The ETLP consortium is entering its third phase of research which will start on June 2006 and last until June 2009.

Our research programme has a strong emphasis on the integration of seismic and reservoir engineering. Our raison d'être is to deliver accurate estimates of those dynamic reservoir parameters that are of value in understanding the reservoir flow behaviour and connectivities, and can assist in improving field management. Thus, our research outputs are methods and results that can be used to better history match or update the simulation model and well plans. Each ETLP study is a unique blend of field data processing, modeling, empirical measurement and theoretical developments, and will be composed of the following basic ingredients: full-wave seismic modeling (pre- and post-stack), reservoir geological modeling, flow simulation, *4D*-specific processing, gemochanical modelling, and petro-elastic model development.

One of the principal drivers in ETLP research is the data donated from our sponsors. For example, our Phase II work portfolio covered clastic and carbonate fields from the North Sea, Southern Gas Basin, Norwegian Sea, West Coast Africa, Gulf of Mexico and Oman. The next three-year phase (Phase III) of the project will continue this distinctive ETLP theme, with our main attention turning to those datasets of high repeatability. This will allow us to comprehensively examine the limits, uncertainties and insights associated with our proposed integrated engineering methodologies, and to widen their application. We intend to actively pursue this research within four general subject areas:

- **Module 1 – Reservoir pressure and saturation (major)**
- **Module 2 – Dynamic reservoir parameters (major)**
- **Module 3 – Assessment of overburden-related 4D noise (major)**
- **Module 4 – Reservoirs with a low or complex 4D signature (minor)**

The exact emphasis and resources committed to each category was defined by our sponsorship group at our business meeting in June 2006.

ETLP is ideally placed to pursue the above research due to its unique location within the Institute of Petroleum Engineering at Heriot-Watt University, with a worldwide reputation IPE has been recognized over the past 10 years by its UK government RAE 5\* research rating. This setting provides the project with access to well-founded project staff in the necessary range of supportive disciplines.

## **SNAPSHOT OF PHASE II ACHIEVEMENTS - June 2003 to June 2006**

During Phase II of the ETLP the consortium was sponsored by twelve companies: BP, BG, ChevronTexaco, ConocoPhillips, ExxonMobil, Fairfield Inc., Shell, Statoil, Total, Landmark, Maersk, and Norsk-Hydro. CGG and PDO also sponsored studentships, but were not consortium members.

### **Publications**

The Heriot-Watt ETLP team wrote and submitted 14 papers for journals, presented 25 expanded and extended abstracts at EAGE, SEG, PESGB, SPE, and NPD conferences and workshops, and defended 7 PhD and 2 Masters theses.

Downloads of these publications are available from our website:

<http://www.pet.hw.ac.uk/research/etlp>

### **Additions to our ETLP toolbox**

Our 4D toolbox and software capability has been expanded over the past three years. In addition to revising and modifying our Phase I tools, we included the following extra components:

- An engineering-consistent pressure-saturation separation algorithm
- A pressure-saturation separation algorithm based on a simplified rock physics model
- A permeability and fault/barrier transmissibility estimation algorithm
- A coupled geomechanical and flow simulation capability
- Full-wave, pre-stack synthetic seismogram *sim2seis* software

### **Studies completed during Phase II**

Research projects initiated and completed in accordance with our Phase II proposal (i.e. those that were completed by June 2006) fall into the four proposed categories:

#### *Module 1 - Quantification of fluid saturation and contacts*

- Investigation of a possible practical seismic-scale saturation law
- Application to reservoirs undergoing gas out of solution (Foinaven)
- Use of spectral decomposition to detect gas saturation effects in stacked producing sands

#### *Module 2 – Monitoring of depleting reservoirs*

- A general assessment of monitoring in a reservoir undergoing pure pressure depletion

- Application of the results from above to clastic reservoirs (Sleipner Vest and Genesis).
- A laboratory based study of the pressure sensitivity of a shaley sand system (includes data from the West of Shetlands database)

#### *Module 3 - Assessment of challenging reservoirs*

- Investigation on how to separate the seismic signatures due to production and compaction using post-stack attributes (Ekofisk).
- Measurement of the overburden warp field (Valhall)
- An understanding of the petroelastic model for a deforming chalk reservoir
- Setting up of a resource for coupled geomechanical and flow simulation
- Analysis of the 4D signature for low-permeability fractured reservoirs, and the possible use of the 4D PP, PS and anisotropy signatures in a depleting gas reservoir in the southern gas basin.
- Analysis of a fractured carbonate reservoir in a poor seismic data area, and the role of microseismic activity (Qarn Alam, continuing).
- Appraisal of the petro-elastic model for a deepwater reservoir. Comparison with the results of the pressure-saturation estimation approach below to address gaps in our understanding (Genesis, continuing)

#### *Module 4 - Independent estimation of pressure and saturation*

- Development of a pressure-saturation technique constrained by engineering data. Use of Bayesian theory and PCA to analyse the uncertainties and choice of a suitable set of seismic attributes.
- Application of the engineering-consistent method to a North Sea dataset (Cormorant, Girassol)
- Development of another pressure-saturation technique based on a simplified rock and fluid physics trend that reorganises the reflectivity equations. Further development of this approach into an 'elastic impedance' framework.
- Application of the EI approach to a West of Shetlands dataset (Foinaven)
- Development of a method for calculating horizontal permeability and assessing fault transmissibility (not in the original proposal)
- Permeability estimation in a dataset from the North Sea (Schiehallion)

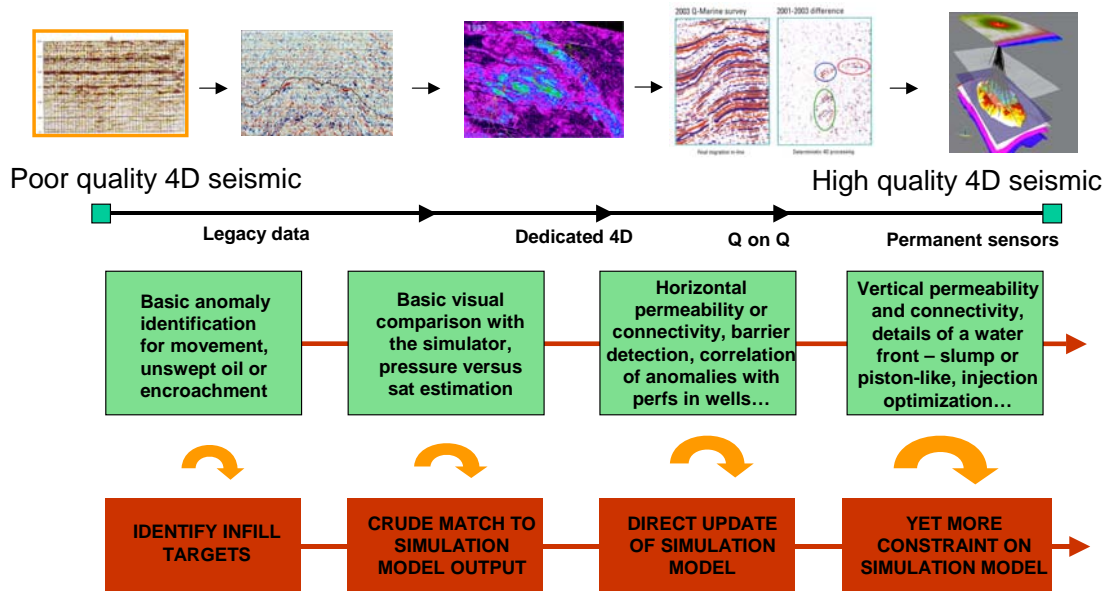
### **ETLP 4D datasets used during these Phase II studies**

Sleipner Vest (North Sea), Southern Gas Basin (North Sea), Valhall (Norwegian Sea), Girassol (West Africa), Genesis (Gulf of Mexico), Foinaven and Schiehallion (West of the Shetland Isles), Cormorant (North Sea), Ekofisk (Norwegian Sea), Qarn Alam (Oman).

### PHASE III PHILOSOPHY

Time-lapse seismic surveys help to track the lateral movement of injected gas and water-fronts or vertical fluid contacts, provide insight into pressure maintenance, or map reservoir compartmentalization and hence identify bypassed oil for in-fill drilling. They impact the monitoring of well performance and condition, refinement of forecasts of future reservoir performance, determination of accurate well depletion plans, drawing up of maps of drainage, and identification of candidates for workover or stimulation, and are therefore known to add value to field management and economics. Past case studies have demonstrated that this is achievable for a variety of reservoir types and IOR processes, even with quite rudimentary processing and interpretation of seismic times and amplitudes. Indeed, with more than a decade of 4D examples, the scientific rationale and business case for using this technique in dynamic reservoir management can be considered generally sound.

Time-lapse seismic surveying is now entering a new generation of activity in which the initial successes of the UK North and Norwegian Sea have been joined by many other successful case studies from fields elsewhere in the world. Industry projects have also become more ambitious, and there is a greater desire to harness value in challenging reservoirs such as compacting chalks or fractured carbonates. Furthermore this activity has stimulated a general improvement in equipment and acquisition capability in recent years, which has led to a overall rise in the level of data repeatability (Figure 1), and in some



**Figure 1.** Data are becoming increasingly more repeatable. With this increase in repeatability comes an ever increasing ability to extract important fine-scale details that can add value to the simulation model.

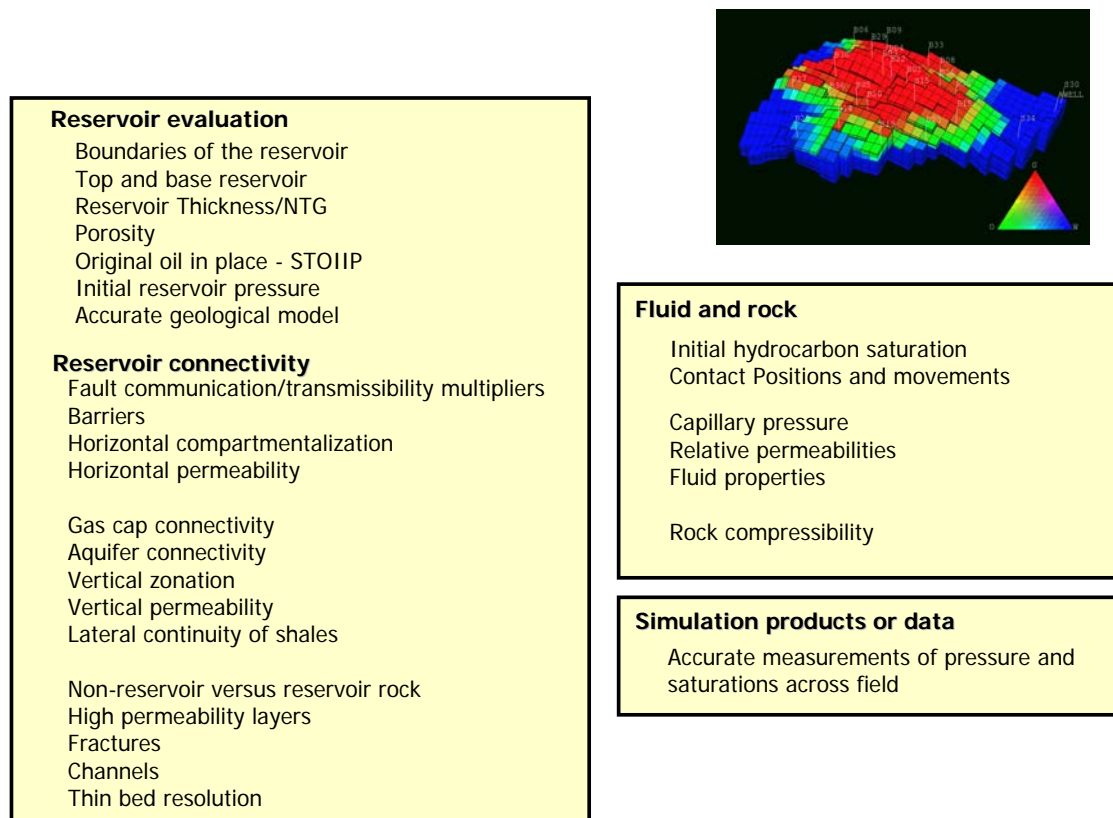
projects a reduction in the time period between surveys. There is also a general desire for a deeper quantitative understanding of the data. Given this backdrop, it is our feeling that quantitative *4D* seismic interpretation is now well positioned to ask, and answer, the question: *What does the Reservoir Engineer actually want and how can the Reservoir Geophysicists deliver it?* In addressing this, it is our belief that there is much more fine-scale information content still locked into *4D* signatures than we are currently accessing in conventional practice. It needs to be understood how to interpret these as engineering parameters, and the limits and uncertainties of their use clearly defined.

One example of the information mentioned above is found in the now well-established line of research that aims to independently estimate pressure and saturation from *4D* seismic. Another example is the estimation of dynamic reservoir parameters such the horizontal permeability, fault transmissibility and reservoir connectivity that ETLP II began addressing. The main advantage in obtaining estimates of reservoir properties in this way is that they can be used to directly update the simulation model, and can therefore be viewed as a means of jump-starting the optimization search in history matching. It is understood that visual adjustments based on the mapped *4D* signature still work well at, for example, locating dynamic barriers, varying fault transmissibilities, altering aquifer connectivity, and STOIIP adjustment, but they do suffer from an inevitable non-uniqueness and inaccuracy. In general therefore, we believe the challenge to industry and researchers is to make *4D* analysis deliver more precise and direct engineering information in those reservoirs where *4D* has already been shot and processed, together with associated uncertainties pressure, saturation or permeabilities. Thus, a time might come when, for example, we can detect a waterflood profile in 3D and absolute depth, determining the exact nature and location of the front and volumetric distribution of the constituents vertically and laterally. Addressing the above will also ultimately help us to close the gap in our understanding of the underlying petro-elastic model.

ETLP recognizes that the abovementioned advances in quantitative *4D* interpretation require reservoir seismic and engineering to be fully integrated at a basic and fundamental level, and perhaps even combined as a separate subject. A future, more idealistic, aim is to achieve a true *4D* interpretation in which time-lapse seismic signatures must be interpreted by simultaneously honouring rock physics, fluid physics, seismic wave propagation, geology, and engineering principles. ETLP research partly achieves this by blending an understanding of wave propagation effects with flow properties and preserving a particular focus on the engineering domain. It is our belief that our engineering-consistent interpretation methods might reveal some modifications or even a complete over-haul of cherished seismic theories that have in many cases been founded on naïve assumptions about the physical properties of the reservoir fluids and geology - this remains to be seen.

## TECHNICAL PROGRAMME - June 2006 to June 2009

The ultimate aim of our research is to build a suite of interpretative tools or scenarios to help companies best achieve a high-resolution dynamic reservoir characterization. This requires us to enhance the overall information content that can be extracted from *4D* seismic beyond current practice. We are guided in this by the needs of the Reservoir Engineers, and what they require to populate and constrain their range of simulation models. Figure 2 lists a range of possible variables that are of value to the Reservoir Engineer in understanding the reservoir and near well-bore flow dynamics. Our work researches how to extract accurate and stable estimates of these static and dynamic reservoir parameters and their distribution, by bringing together the seismic and engineering domains. We also seek to determine the limits and uncertainties of these predictions. This is our definition of the topic of 'quantitative *4D* seismic interpretation'.



**Figure 2.** Reservoir evaluation, management and description of an asset require an accurate and realistic simulation model. The above gives a list of parameters that are important to the Reservoir Engineer in building this model. However it is not possible to input all of these into the model – some can be determined from dynamic well data, but others must be guessed. A tighter constraint on this list of parameters would be an important step forward.

To address the research above, our Phase III technical programme builds on the results and software tools from our Phase II research by identifying several topics where substantial concentrated effort is required for further progress. As

ETLP now has a solid template of understanding in this area, there are a number of well-defined avenues of research that we have opened up and wish to pursue further as natural lines into the future. The programme continues these by broadly categorizing our activities into four thematic modules whose central concerns are: (1) Reservoir pressure and saturation, (2) Dynamic reservoir parameters, (3) Assessment of overburden-related 4D noise (4) Reservoirs with a low or complex 4D signature. Each of these modules addresses a number of specific questions upon which the success of 4D interpretation relies. Some of these questions were raised in the Phase II projects, and remain as yet unanswered, others have been raised as these projects progressed. Examples are:

- How uniquely and independently can we estimate the pressure and saturation fields in the hydrocarbon reservoir? What are the limits and uncertainties on these estimates? What sort of reservoir average does the seismic measure, and how does it relate to that required for engineering purposes? How does the overburden influence the determination of pressure and saturation in the reservoir?
- Can pressure and saturation effects be separately observed in difficult reservoirs such as the compacting chalks of the Norwegian Sea. Is it easier or harder than conventional reservoirs? Can pressure and saturation be measured reliably in fractured reservoirs?
- Can gas, oil, and water saturation be accurately estimated from seismic surveys? To what accuracy is it possible to estimate fluid saturation and hence volumes? What are the implications for injector-producer optimization? What are the limitations of the seismic method when trying to detect the exact vertical and lateral distributions of the reservoir fluids?
- Can individual flow units be defined? Here, the major challenge is to improve vertical resolution in inverting for dynamic reservoir properties.
- How can reservoir connectivity be assessed? How can such information from 4D seismic be used to effectively update the simulation model? Does this approach help the history matching process?

These, and many more related questions are addressed in the four modules that constitute the ETLP technical programme, laying down a series of targeted studies that explore critical links between the seismic and engineering domains. The work relies upon sponsor-donated data to provide a focus for extensive in-depth research. **New datasets will be taken on board as decided by ETLP sponsors at our setup business meeting on June 2006.**

## MODULE 1 – Reservoir pressure and saturation

A well-recognized topic of industry research is the development of methods that can estimate changes in the reservoir pressure and saturation directly from the *4D* signature. This is because such information provides one of the keys to understanding the reservoir dynamics. It is also important as in many cases production-logging tools are too expensive to run, provide sparse saturation information at different calendar times, or may in fact not be possible if the field is in deep water. Furthermore, although measurements can be determined using permanent gauges, such approaches are not in widespread use. The ability to output an areal distribution of the pressure and saturation from *4D* seismic also makes the job of updating the simulator easier. These are strong arguments in favour of pursuing this line of research further. The workplan suggested here builds on Phase II/Modules 1 and 4, and part of Module 2.

At the forefront of this module is the newly developed ETLP technique for pressure and saturation estimation based on an integrated combination of seismic and engineering data. For this, we added an engineering data constraint to the usual workflow, transferring the need for visual correlation into a mathematical calibration on 'hard' (but sparse) data from the engineering domain. The ETLP engineering-consistent pressure-saturation estimation technique will come under scrutiny during this phase. It is our intention to refine the approach, make it more robust, and develop a detailed uncertainty analysis. It will also be extended to deal with geomechanical phenomena, frequently acquired seismic, various degrees of sparse well data, and possibly pre-stack seismic data. The work will feed back our understanding of the petroelastic model (Figure 3) and its current limitations. Hopefully it will be possible to close the gaps in our knowledge of this by widening the application of our pressure and saturation estimation technique to a variety of different fields. Additionally, the varied applications will provide a way of selecting and classifying the best seismic attributes to use in the separation procedure.

Although both pressure and saturation will be simultaneously determined as a matter of course, the research should be tackled from two distinct perspectives:

**1a) Saturation focus** – accurate saturation measurements help to optimize production and injection to minimize encroachment on a well by detecting the evolution of injected water or gas fronts and locating critical fluid pathways. They are particularly vital for the application of drilling technology for multi-lateral horizontal wells and targeted applications aimed at attaining maximum reservoir contact. These measurements also help evaluate the effectiveness of the fluid displacement process and forecast its subsequent performance. Indeed, we wish to monitor the waterfloods without the over-riding pressure signal. Our estimation and evaluation of saturation (by excluding the pressure signal), aims

to determine the following information from a range of injection-production scenarios:

- The exact amount of saturation at a particular location, despite the overprint of the pressure signal
- The speed and direction of fluid movement
- The exact areas, volumes and saturation distribution for each saturant
- The precise spatial location vertically and hence the exact 3D profile – so that slump, piston-like, high permeability streaks, fingering fronts, or coning near wells, may be distinguished quantitatively. This will require an understanding of how best to probe the reservoir in depth, the averaging effect of flow versus seismic, and the choice of suitable seismic attributes.
- What happens when gas is present or there are three or more fluid phases?
- Should we treat the pressure gradient in the different fluid constituents?
- The resolution of individual producing intervals.

	Ranking	Comments
	<b>5</b>	<i>Quantified to some degree</i>
	<b>5</b>	<i>Not yet fully tested</i>
0 – low	<b>4</b>	<i>Theoretical prediction only, needs more understanding</i>
5 – high	<b>3</b>	<i>Untested, could create ambiguities</i>
	<b>3</b>	<i>Only for specific reservoirs</i>
	<b>3</b>	<i>Some theoretical predictions only</i>
	<b>2</b>	<i>Only for specific reservoirs</i>
	<b>2</b>	<i>Starting to be quantified</i>
	<b>1</b>	<i>... but completely uncertain</i>

**Figure 3.** A crude ranking of the importance of each physical phenomenon in assessing the overall predictive capability of the seismic petro-elastic model (SPM). Improving the physics in the model is something that ETLP naturally aims towards achieving through application of its methods.

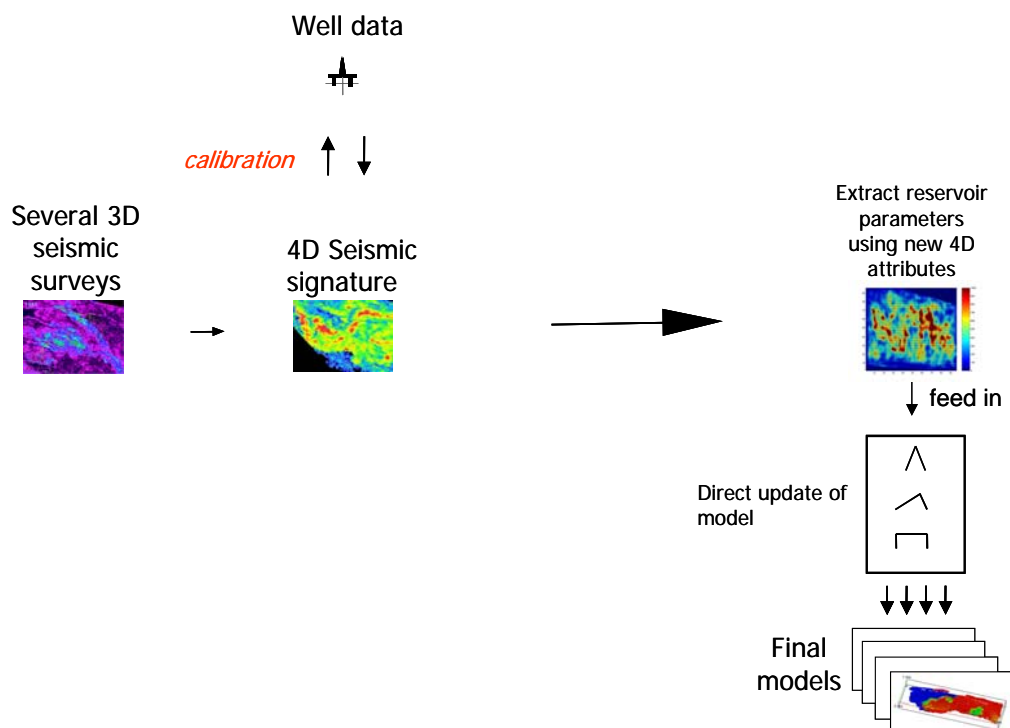
Achieving the above objectives will require a good understanding of the saturation equations (patchy versus uniform versus another?) linking the reservoir fluid and rock changes to the seismic response. A way of doing this for realistic saturation conditions is currently being developed in several Phase II projects, and it is planned to continue this research into Phase III. The studies

above will require a comprehensive database of well-based saturation data, and will investigate whether calibration of the method should be achieved via production from individual wells, sectors or across the field.

**1b) Pressure focus** - areally distributed pressure measurements from seismic can help to assess the strength of the aquifer pressure, and also allows a direct interpretation of compartmentalization and reservoir connectivity. The estimation of the exact distribution and amount of pressure/stress change will be tackled here using studies guided by coupled flow-geomechanical modeling, which is seen as a critical ingredient in this understanding. The role of the reservoir and overburden complexity will also be brought into this work, and data such as repeated VSP or wireline logs that might shed light on the pressure sensitivity laws. The near-borehole conditions will be considered in the use of dynamic well ties. If good well coverage and pressure measurements are available at the time of the seismic surveys, the techniques used here could provide insight into the nature of the seismic-scale pressure and stress sensitivity laws, which is still as yet one of the major uncertainties in *4D* seismic interpretation (Figure 3).

## MODULE 2 – Dynamic reservoir parameters

Another important group of parameters in Figure 2 are those that can be fed directly into the simulation model. Towards the end of ETLP Phase II we started to push the research envelope more vigorously, and made our first attempts at extracting the dynamic reservoir parameters of horizontal permeability and fault transmissibility. In this module we seek to continue with this theme, but broaden it out to include other parameters. We will follow a similar strategy to the pressure-saturation work, by providing constraints on the estimates using a combination of well data and fluid flow theory. However it is also our desire to cast the output in an algorithmic processing form, so that it can be used by Reservoir Geophysicists to manipulate seismic volumes. This module will therefore closely examine the validity of using a geophysical ‘processing’ approach to extract estimates. In this context, ways of making the results more robust and stable to noise will be developed. Phase II concluded that to achieve a permeability estimate we must separate the pressure and saturation fields, here however we investigate how we might obtain the estimates without this step (Figure 4)? Finally, export to the simulation model and the benefits of these property distributions to the history-matching of the production data are considered, along with associated uncertainties propagated from the 4D seismic.



**Figure 4.** It might even be possible for us to do away with the need to go through the intermediate route of pressure and saturation and step directly to a useful parameter such as permeability.

The main category of study is:

### **2a) Vertical connectivity**

This will be a major topic for the Phase III programme, building on our past understanding of horizontal permeability estimation. Critical to this work will be an understanding of the depth of investigation and what seismic attributes are of value in enhancing the overall vertical resolution and the precision to which they can be estimated. To this end, *4D*-specific impedance inversion constrained by well data will be investigated. Possible subjects to consider are:

- Vertical communication between compartments and an assessment of connectivity in large multi-zonal reservoir sections
- Determination of aquifer strength or gas cap connectivity
- Vertical permeability ( $K_z$ )
- The anisotropy term  $K_z/K_h$

This particular module will require application to particularly good datasets with low repeatability noise to extract meaningful results. Thus to be successful, research projects need access to high quality *4D*-dedicated surveys – for example, Q on Q marine and/or permanent installation data. Also required is access to a sector of the full field flow simulation model. The studies may also require researchers with an engineering skill-base.

Two further categories of study are:

### **2b) Lateral connectivity**

This is a continuation and further development of Phase II work in which horizontal permeability is considered. It will examine:

- General connectivity of the reservoir at a range of horizontal scales.
- Transmissibility multipliers for barriers and faults and an assessment of the degree of seal and compartmentalization.
- Horizontal permeability ( $K_h$ )

### **2c) Integrated simulation studies**

Here we wish to freely explore the merger of both the seismic processing and flow simulation equations into a joint analysis tool. A quasi-history matching approach will be implemented in a strategy in which the flow simulation is partly included in the *4D* seismic signature itself. Aerial simulation and segmentation/material balance algorithms will be considered as two ideas contributing to the development of this approach. Clearly implementation of these somewhat more speculative studies depends largely on the students, staff and data available for such projects.

### **MODULE 3 – Assessment of overburden-related 4D noise**

It is important to determine how far absolute pressure and saturation estimation, permeability estimation, or general interpretation of *4D* signatures can be pushed technically. This project looks carefully at the nature of the *4D* noise in this respect, and the impact of acquisition repeatability and geometry. It will fall in two parts, with the first being a modelling study and the second an application of the findings to a field dataset or datasets with different acquisition geometries.

General items for investigation will be:

- The influence of the geomechanical strain imprint in the overburden on the imaged reservoir events in the pre- and post-stack domain. What is the effect of cap-rock variation and faulting?
- What does the overburden do to the *4D* signal, and hence the spatial and temporal variability of the seismic wavelet?
- What is the impact of production and injection processes on the way the imaging is affected due to overburden strain?
- What is the effect of the migration velocity on the imaging of the reservoir? How can we improve the migration?
- Can we quantify the repeatability limits for different types of overburden?
- What is the interplay between the acquisition and processing domains, and can this knowledge help us understand the limits of the techniques?
- How can we adapt the ETLP techniques to obtain better pressure and saturation, or permeability estimates?

The seismic modelling aspect of the project will look at numerous geologically representative sections from a variety of geographical locations and include scatterers of various kinds. Repeated perturbation of acquisition geometries will attempt to establish an empirical indicator of how different overburden effects affect the acquisition versus NRMS relationship. A generic statement will be made which might translate into guidelines for the treatment of 4D noise in standard industry application and methodologies.

For the above research projects to be successful it will be particularly important to access good quality *4D* surveys, and an excellent database of well saturation and pressure data, and supporting information on permeability, with an associated simulation and (ideally) reservoir model. This will ensure that we extract maximum benefit from our studies. We may include clastic, chalk or middle eastern reservoirs in the range of possibilities for this work.

## MODULE 4 – Reservoirs with a low or complex 4D signature

This module continues the theme outlined in Phase II/Module 3. It considers the class of reservoirs defined as showing a ‘good chance’ for the application of 4D technologies, but which are nevertheless at the boundaries of our current understanding and require further specialized attention. For the purposes of this work we now define such reservoirs as those that have a low or complex 4D signature (i.e. not easily visible in the post-stack domain by conventional methodologies) and require further technological development to extract benefits, if any. In this category we include:

- *Carbonate reservoirs* (particularly, but not exclusively from the middle east) – opinion is divided on the value of 4D seismic for carbonate reservoirs. Part of the reason for this is that the signature is theoretically predicted to be weak. For seismic acquisition in some areas of the middle east the data quality is also poor due to imaging problems. However, conversely there are also some case study examples of carbonates observed to have a clear 4D signature. Thus there are still many outstanding issues to resolve in this area in connection with the petroelastic model, processing and acquisition.
- *Depleting gas or oil reservoirs* with low porosity and permeability have a 4D signature dominated by the stress sensitivity of the rock matrix. However this is thought to be rather weak in both clastic and carbonate reservoirs alike. We will consider detection of the geomechanical signature from the overburden as well as the possible role of the pre-stack signature in backing out the signal. This is a continuation of work from Phase II and also overlaps slightly with Module 1c.

In both cases the petro-elastic model is poorly understood for these reservoirs, and the role of fractures, faults, heterogeneities, facies (sand/shale) distribution and sedimentary architecture in enhancing the seismic-scale stress sensitivity is not known. Therefore some further work will be pursued to try to calculate the in situ stress sensitivity by indirect methods and relate it to the laboratory measurements. For the poor data areas, ETLP will also consider the concept of ‘data hardening’, where low frequency well-based engineering data are used to support the seismic signature. Following on from Phase II, we would also be interested in applying our methodologies to further analyses of PP and PS waves, and also to anisotropy. Phase I and II saw studies on the Rotliegend from the Southern Gas Basin using legacy data, and also on the high quality 2D repeat lines from Sliepner Vest. Both datasets were limited in different ways, and our learning from this is that the success of this module will depend very much on obtaining appropriate high quality dedicated 4D data from sponsors.

## **ETLP PERSONNEL**

The ETLP Phase III research team will consist of allied senior staff, two postdoctoral researchers, six or more PhD students, and will benefit from an annual influx of summer students on the Master's programme. ETLP has a close association with other active areas of research within the Reservoir Geophysics Group and the Institute of Petroleum Engineering's Reservoir Engineering and Reservoir Description groups.

## **DELIVERABLES TO SPONSORS**

- ETLP annual report in browsable *CD* form
- Bi-annual consortium meetings
- Analysis of sponsor-related data from key locations
- Advance viewing of submissions to geophysical and engineering journals
- Regular interim meetings for individual project updates
- Consultancy
- Software developed by ETLP personnel in research form

## **MEETINGS**

There are two meetings per year, scheduled to be in the winter and summer months. Past meetings have typically been held in early November and mid June.

## **SPONSORSHIP FEE**

The sponsorship fee is £26k per annum, held flat over the three years. Companies are free to join at any time during our three-year phase but after 1 June 2006 the fee will rise to £30k per year.

## **CONTACTS**

Further information can be found on the ETLP web site:  
<http://www.pet.hw.ac.uk/research/etlp>

or by contacting

Professor Colin MacBeth,  
Reservoir Geophysics Group,  
Institute of Petroleum Engineering,  
Heriot-Watt University,  
Edinburgh, UK.  
Tel: 0131-451-3607; Fax: 0131-451-3127  
Email: [colin.macbeth@pet.hw.ac.uk](mailto:colin.macbeth@pet.hw.ac.uk)

## APPENDIX – SNAPSHOTS OF PREVIOUS PHASES

### SNAPSHOT OF PHASE I ACHIEVEMENTS - June 2000 to June 2003

During Phase I of the ETLP project the consortium was sponsored by nine companies: BP, Shell, TFE, Statoil, Enterprise Oil, Schlumberger, Landmark, Concept Systems and Fairfield Inc.

#### Publications

The Heriot-Watt team wrote and submitted over 12 papers for international journals, presented a further 36 expanded abstracts at EAGE, SEG, PESGB, and NPD conferences and workshops, and successfully defended 3 PhD theses. Further details and downloads of these publications are available from our website:

<http://www.pet.hw.ac.uk/research/etlp>

#### The ETLP toolbox

Our 4D toolbox was assembled over 3 years. It contains:

- Cross-equalization and warping tools for post-stack processing
- 4D cross-equalization workflows
- SVD (singular value decomposition) differencing tools
- Seismic modelling codes
- Petrophysical calculator
- 3D visualization software for simulator to seismic computations
- Simulator-to-4D seismic link

#### Studies completed during Phase I

Research projects successfully completed in accordance with our Phase I proposal fall into four originally proposed categories:

##### *Acquisition and processing*

- Investigates the influence of water velocity variations on the interpretation of the 4D signature – with a particular emphasis on permanent OBC installations at the Teal South and Foinaven fields
- Post-stack cross-equalization of OBC and towed streamer data for analysis of compaction and production in the Valhall field
- Post-stack cross-equalization to determine whether it is possible to obtain a 4D signature from a depleting gas reservoir in the SGB
- Application of an SVD-based difference technique, selective spectral decomposition, and a cross-equalization flow to provide an enhanced

4D signature of water sweep in low net-to-gross areas on the Nelson field

*4D-specific attributes*

- Use of a spectral decomposition technique to determine 4D time-thickness variations due to production in a Gulf of Mexico reservoir
- Spectral decomposition investigated to interpret shadowing effects in producing turbidites
- Robust determination of P-wave AVOA for 4D OBC at the Teal South field, Gulf of Mexico

*New-wave Petrophysics*

- Development of new pressure sensitivity law for 4D feasibility studies, upscaling of laboratory tests and subsequent categorization of North Sea sandstones
- Quantification of gas saturation from seismic amplitudes in the Foinaven field
- Feasibility study to analyse the effect of fractures on the clarity of the 4D signature for a depleting gas sand reservoir

*Links and integration with the reservoir simulator*

- Geological model building, reservoir and seismic modelling of low net-to-gross regions on Nelson – implications for injection and production
- Combined fine-scale geological and 4D seismic interpretation to resolve well-well connectivity issues on Foinaven
- Use of P-P and P-S information to jointly constrain the reservoir model in the Teal South field
- A single seismic history match using seismic anisotropy from a turbidite sand
- A single history match using the P-P and P-S amplitude response enhanced by multi-component –related petrophysical developments

- Time-lapse borehole seismic analysis for Qarn Alam (VSP) and Steepbank (cross-well), involving the first use of spectral decomposition and SVD for cross-equalization. *4D* interpretation of steam flooding in a heavy oil reservoir, including petrophysical development.

### **ETLP 4D datasets used during Phase I studies**

Foinaven (NW Shetlands), Nelson (Northern North Sea), a Southern Gas Basin field, Valhall (Norwegian Sea), Teal South (Gulf of Mexico). Borehole seismic data include Qarn Alam (Oman) and Steepbank (Canada).