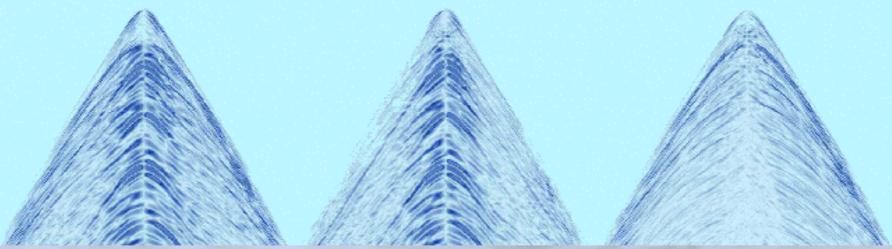
LITHOS III

PHASE 3 (2006-2010) - Draft Proposal



LITHOS III

IPG Paris-Cambridge Waveform inversion and long-offset imaging group

DRAFT PROPOSAL JULY 2005

Developing innovative integrated geophysical techniques to image subsurface lithology for hydrocarbon exploration in technically challenging areas

Phase 3: 2006-2010
Waveform inversion and imaging of long-offset P- and S-wave data for quantification of sub-surface lithology and fluids

LITHOS III Proposal

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Executive Summary

LITHOS Phase III is a joint initiative by the Institut de Physique du Globe de Paris (IPGP) and the Department of Earth Sciences at the University of Cambridge to develop new integrated waveform modelling and inversion techniques to quantify sub-surface lithology and fluids. We shall particularly focus on the full wavefield inversion of data from multi-component ocean bottom seismometers (OBC, OBS), that can record both high frequency controlled source data and passive low frequency signals on the seafloor. Such data provide quantitative information on P- and S-wave properties at different length-scales, which we believe are key to mapping and defining sub-surface lithology and fluids. LITHOS III is based on our solid foundations in combining seismic reflection with wide-aperture seismology during LITHOS Phase I for P-waves and waveform inversion of multi-component data in LITHOS Phase II, in which information from the entire wavefield is identified and exploited. The LITHOS group has unique expertise and capabilities in full wavefield elastic time-domain inversion. Application of wavefield inversion to multi-component OBC field data to address high resolution problems, reservoir characterisation and time-lapse (4D) will be the key area of research, whilst we also continue to develop our sound background in tomography and innovative processing ideas, many via the *tau-p* domain.

The Department of Earth Sciences at Cambridge and IPG Paris provide a stimulating international environment for the development of LITHOS III. We are able to attract the best students and research workers globally, who relish the opportunity to be based in these top institutions. We enjoy direct collaboration with our sponsors and appreciate close involvement in projects. Science is communicated formally at the Annual Science Meeting, and informally at any opportunities between. An important and unusual aspect of the LITHOS project is the delivery of our newly developed software to our sponsors for use in their own research projects. LITHOS software products are designed to be suitable for immediate application in a commercial research environment.

The project will be directed and coordinated by Professor Satish Singh and Dr Penny Barton: these two senior scientists have complementary expertise and experience in data acquisition, new modelling and inversion techniques, data processing and interpretation. A Steering Committee consisting of sponsor representatives and senior LITHOS staff will be responsible for approving the direction of research. LITHOS III will start in July 2006 and run for four years. The work will be carried out by senior researchers, research associates, and Ph.D. students at IPG Paris and the University of Cambridge, and funded by a Consortium of subscribing oil companies, each contributing £30k (approximately 45k EUR) (+VAT where applicable) per year. The participating companies will receive free access to all the research carried out under the project, royalty-free use of all software developed, and be entitled to representation on the Steering Committee.

Section 1: Research Plan

1.1 Introduction

The LITHOS project develops new methodology to image and quantify the physical properties of the subsurface using innovative integrated geophysical methods. LITHOS is a joint initiative by Professor Satish Singh at the Institut de Physique du Globe (IPG) Paris and Dr Penny Barton at the Department of Earth Sciences at the University of Cambridge. We have particular strengths in the combination of information from long offset with near normal incidence data using inversion methods (tomography and full elastic wavefield inversion) and novel data processing approaches via the tau-p domain (non-stretch stacking in tau-p and wavefield separation and receiver function analysis for exploration).

Satish Singh and Penny Barton have over the past two decades both played leading roles in the design, instrumentation, acquisition, processing, modelling and inversion of innovative geophysical surveys, including multi-component ocean bottom seismometer (OBS) technology, novel two-ship configurations and 3D tomography. Our particular unique expertise lies in the exploitation of wide-aperture data, the integration of information from the reflected and refracted wavefields, and the strong emphasis we place on the development of new theory hand-in-hand with its application to field data. We have wide experience in both modelling and inversion and also have particular interests in aspects of imaging that exploit the seismic information at longer offsets, such as critical and post-critical reflections, the refracted wavefield, and converted waves.

We have developed a series of techniques and strategies for analysing these unconventional data. Our approach has been focused on the modelling and inversion of integrated datasets, with the aim of solving real geophysical and geological problems. We are proud of our unique areas of expertise and specialisation. We are not simply a cloistered theoretical group, but believe strongly in the benefits of cross-fertilisation between new types of acquisition and new methods of exploiting the resulting data.

The LITHOS project is currently in its second four-year phase, with Phase II scheduled to end in June 2006. LITHOS is funded by a consortium of international oil and service companies. About twenty-five PhD students and fifteen post-doctoral research workers have been trained during the first two phases of LITHOS, many of them now in leading positions in industry and academia. The Department of Earth Sciences at Cambridge and IPG Paris, which have formal collaborative links, are both world leaders in Earth sciences, and provide a uniquely fertile environment for the continued development of the LITHOS project. Our prestigious institutions are ideally placed to attract the best students and research workers not only from two leading European countries, but from the whole world.

Since LITHOS was established in 1998 we have developed a set of unique algorithms for research applications in inversion, modelling and novel processing methods. Our approach is innovative and unconventional at the fundamental level, and the process of algorithm development generates many new ideas which we share with our sponsors. New algorithms are integrated for distribution to our sponsors under the LITHOS User Interface. Sponsors enjoy close interaction with the research group via science meetings and our comprehensive annual reports, and are encouraged to contribute data to the project for the evaluation of new techniques. Many LITHOS-trained students have been recruited into our sponsor companies, who appreciate their strongly numerate and analytical training.

Over the last seven years, LITHOS has evolved in to a fully developed project. In LITHOS I (1998-2001), we applied our experience of wide-angle imaging techniques to sub-basalt problems and developed a set of new tools to address this problem, whilst in LITHOS II (2002-2006) we have been focusing on the application of our long-offset full wavefield approach to ocean bottom data. During LITHOS I we mainly focused on travel time tomography, developing a battery of coded algorithms designed to take pre-stack data from the stage of picking, through travel-time inversion in order to obtain a well resolved background velocity model, to waveform inversion and imaging processes such as migration. During LITHOS II we built on these foundations, with special emphasis on the exploitation of converted data from multi-component OBC surveys by using novel techniques built on deconvolution in the tau-p domain and receiver function theory adapted for exploration geometry. We introduced new ideas from the compliance technique, which gives independent information about the S-wave velocity structure of the subsurface. We have also developed new methods for velocity imaging and stacking in the tau-p domain, with a focus on non-stretch methods to allow the incorporation of long-offset events into the stack. We now have a unique capability in time-domain elastic full waveform inversion, and we plan next to consolidate this for application to exploration and production datasets, including 4D time lapse.

During LITHOS I and II we have applied our techniques to several long and ultra-long offset datasets for sub-basalt imaging, trying several on the same data, to allow direct comparisons to be made. Datasets were contributed by Saga, Amerada Hess, Veritas, BGS Rockall Consortium, BP, ExxonMobil, Chevron, Norsk Hydro, TotalFinaElf, WesternGeco and Statoil. We have produced a blueprint for processing wide-angle data, using a combination of tomography and non-stretch stacking in the *tau-p* domain.

An exciting aspect of the LITHOS programme has been the integration of new technology. In Phase I, LITHOS pioneered the combination of the marine controlled-source electromagnetic method with seismic, which has achieved significant success in the last few years. In Phase II, we introduced further new technology from the academic arena by integrating new ideas from seafloor compliance measurements. In LITHOS Phase III, we plan to integrate the ideas from compliance with the emerging fields of noise and surface wave analysis.

Our sponsor Members include exploration teams and R&D divisions of major E&P oil and service companies, especially those involved in frontier exploration where conventional seismic methods have failed to provide adequate images of the subsurface, those with an interest in the full exploitation of multi-component and 4D time lapse data, and those interested in extracting the maximum information from both conventional and unconventional data. Members of LITHOS Phase III will contribute a subscription of £30K (~45K EU) per year for four years. We invite our sponsors to consider providing appropriate test-bed datasets (subject to individual confidentiality agreements as required) for proving new LITHOS concepts, and to take part in constructive interaction with the LITHOS teams in Cambridge and Paris.

1.2 LITHOS capabilities

Our areas of work can be summarized in four main categories, outlined below:

- Full wavefield inversion
- Travel-time tomography
- Imaging in *x-t* and *tau-p* domains
- Complementary data and techniques

We attach high priority to the importance of deriving the best possible velocity model, using a variety of techniques. Our general approach is to apply travel-time algorithms at the outset, followed by full waveform inversion and imaging.

The categories are naturally divided corresponding to individual analysis programs, most of which are integrated under the LITHOS User Interface, or available separately.

1.2.1 Full wavefield inversion

LITHOS has unique capabilities in 2D elastic time-domain full wavefield inversion. We have been developing this difficult technique for a number of years and have unmatched experience and expertise in this field. The inversion of the full wavefield allows resolution of the P- and S-wave velocity fields at a much finer scale than can be obtained using travel-times alone, but a stable solution can only be achieved with a good input background velocity field obtained from travel-time analysis.

Time domain versus frequency domain
Full waveform inversion provides detailed information on sub-surface P- and S-wave velocity. Waveform inversion may be carried out either in the time or the frequency domain. The objective of waveform inversion is to minimise the difference between observed and synthetic data point-by-point in the time domain or frequency-by-frequency in the frequency domain. If a least-squares criterion is used, then inversions in the two domains are equivalent.

In order to invert medium to long wavelength of velocity structure, a broadband source and wide angular coverage (offset) is necessary. Since waveform inversion is computationally intensive, redundancy in the data can be used to decrease the computation time and memory requirement. In the time-domain, decimated shot and receiver intervals may be used, whereas in the frequency domain, the frequency content of the data is usually decimated, although there is no theoretical basis for data decimation. Depending on the model, decimation may lead to aliasing effects in the time domain and ringing in the frequency domain.

Gerhard Pratt and co-workers use data decimation in the frequency domain and invert a single frequency at a time, using results from consecutive runs as starting models for successively higher frequencies. Since modelling in the frequency domain requires inverting a large matrix, the frequency domain requires a large amount of memory. This has been possible for 2D acoustic models, but has not been feasible for 2D eleastic media. The acoustic approximation is invalid for long offset data as the amplitude-versus-offset response for the PP reflection is incorrect and PS conversions are ignored. Since the long offset data are essential to prevent ringing in the frequency domain method, the present frequency algorithms are not appropriate for full waveform inversion of wide-angle seismic data. They are, however, applicable for inverting first arrival turning rays where the acoustic approximation is valid and a single frequency contains information on a broad range of wavelengths. Frequency domain methods may also be used for near-offset data where the acoustic approximation is valid providing a large number of frequencies are used.

Since we are interested in inverting wide-angle data, we have chosen to invert the data in the time domain. We have extensive experience with 1D inversion and have applied it to several geologically diverse datasets. Our 2D inversion schemes are based on finite difference modelling, back propagation of residuals and cross-correlation with source, and minimisation using a conjugate gradient algorithm. The first algorithm was developed by Richard Shipp (now at Shell) and was tested on the Flare data set. The algorithm was extended to invert S-wave from streamer data by Yann Freudenreich (now at CGG). In LITHOS II, we have extended this algorithm to invert multi-component OBC data (Tim Sears) and will be extending it to visco-elastic media from October 2005 (Gillian Royle). Mark Roberts has developed a new method to correct for 3D effects and will be applying waveform inversion to VSP data.

Waveform inversion and AVO

Four implicit processes contribute to full waveform inverion: (1) source deconvolution by including source wavelet in modelling; (2) non-linear AVO inversion for matching wavefom amplitude; (3) multiple removal (interbed as well as seabed); and (4) P-to-S conversion effects. All these effects lead to the estimation of P- and S-wave velocities. Therefore, waveform inversion includes the effect of non-linear AVO and much more.

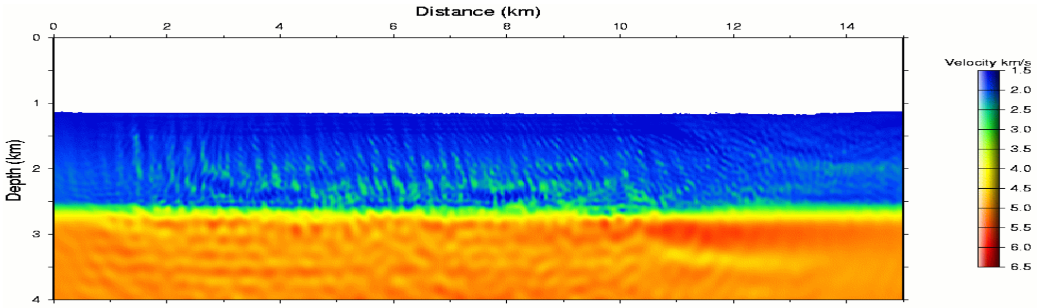
Our main wavefield inversion tools are summarised below.

i. 1D full wavefield elastic anisotropic inversion (*Wips*)

We have developed a series of one-dimensional full wavefield seismic inversion techniques to determine P-wave and S-wave velocities and anisotropy from a variety of acquisition geometries (surface seismic, vertical seismic profiling (VSP), offset VSP, ocean-bottom seismometer, ocean bottom cable). For modelling, we use a reflectivity method for transversely isotropic attenuating elastic media. For inversion, we use a hybrid approach, employing a non-linear method, such as Monte-Carlo, to obtain the solution in the vicinity of the global minimum, followed by a linear method, either conjugate gradient or Simplex, to obtain the final global solution. Our algorithms work in both the *tau-p* and the *t-x* domains. These methods have been applied to address many fundamental geological problems, and some of these results have been verified by drilling.

ii. 2D full wavefield elastic inversion (*Twist, Twist-PS and TwistPS-MC*)

In order to determine 2D velocity structure, we have developed a 2D full wavefield elastic inversion algorithm. Our algorithm uses the finite difference method in the time domain for modelling and an iterative scheme for inversion. It can handle both near and far offset data. In order to reduce the non-linearity, we use windowing and a multi-stage inversion scheme. Starting from the travel-time inversion results, we invert the far offset and low frequency data first. The results from each stage are used as the starting model for the next stage. We are able to invert alternately or simultaneously for P-wave and S-wave velocities, using a variety of strategies to suit the data. The algorithm has been successfully applied to several datasets. The program has recently been adapted to invert multi-component OBC data.



1.2.2 Travel-time tomography

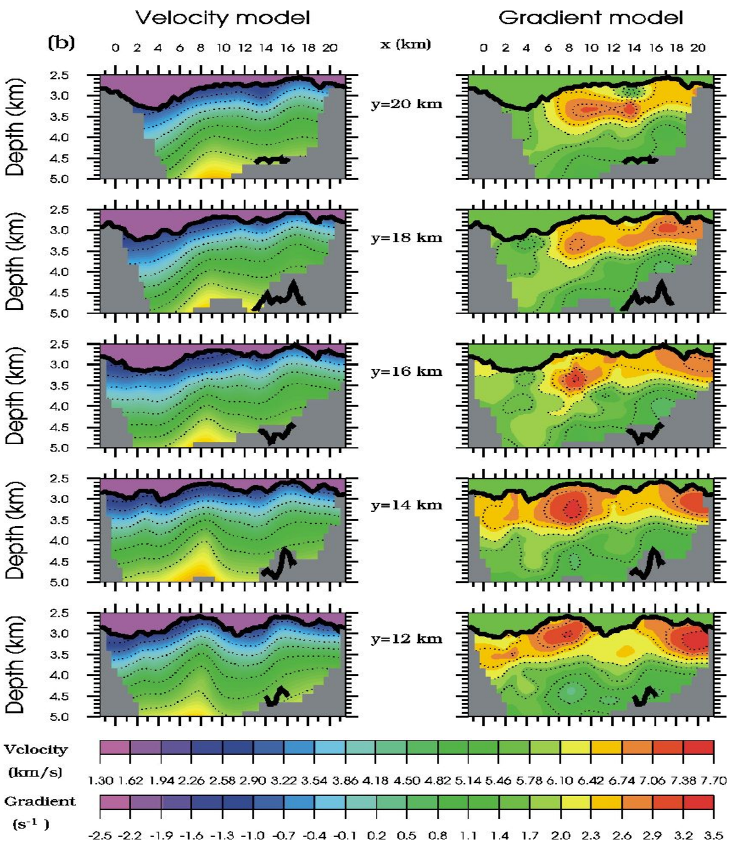
The first step in the inversion process is to use the travel-times of prominent reflections and refractions on pre-stack data to construct a well-resolved background velocity model, as the velocities obtained from conventional velocity analysis are inadequate for input to waveform inversion algorithms. We have extended travel-time inversion concepts to include polarisation and slowness inversions, and these techniques in themselves provide powerful insights into the structure and lithology of the subsurface, as well as independent depth and velocity information.

Our main travel-time inversion tools are summarized below.

i. Efficient semi-automatic travel time picking algorithm (*PickEd*)
The first step in travel-time inversion is to pick the arrival times for prominent events. We have developed an efficient new travel-time picking algorithm for long offset multichannel seismic data. The manual aspect is limited to the selection of a few starting points for the automatic process, which is carried out simultaneously on common offset and shot gathers. The process optimises not only the travel time, but every parameter characterising the single function, to give event slopes and curvatures (apparent slowness or velocity), local amplitudes and phases, and the signal-to-noise ratio. These parameters can themselves be used to characterise some aspects of the subsurface and also as input for travel-time inversions.

ii. Rapid automatic velocity imaging using wide-aperture travel time data (*Rave*)
We have developed a method that transforms the picked travel-time data into intercept and slowness domain and provides a spatial image of structure and velocity, which can be directly correlated with the stacked seismic section in depth and two-way-time. This method can be considered as a 'brute stack' of travel-time data. These results can then be used to build the starting velocity model for travel-time inversion and to allocate labels to seismic events in order to understand the composition and origin of the wavefield.

iii. 3D travel-time tomography (*Jive3D*)
We have a well-established tomographic inversion technique which utilises reflection as well as refraction data and provides a well constrained model containing both a continuous velocity field and interfaces. Our method is based on efficient ray tracing and an iterative non-linear inversion scheme. It also provides estimates of uncertainty and the resolution of model parameters. The algorithm has been extensively applied to both academic and industry 2D and 3D datasets. This code was developed by James Hobro (now at WesternGeco).



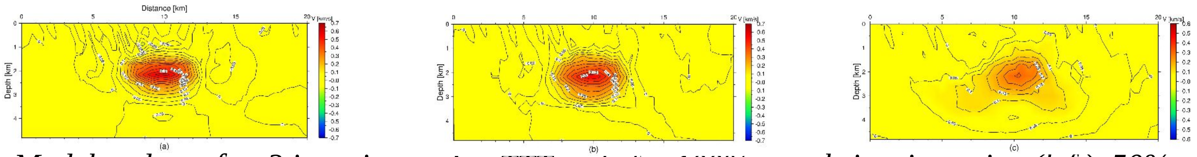
Slices through 3D velocity and velocity gradient models from JIVE3D inversion of OBS data from East Pacific Rise spreading centre (Chi Hang Tong)

iv. 3D travel-time and polarisation inversion in anisotropic media (*CRAYFISH*)

Anisotropy must be considered in the simultaneous tomographic inversion of near offset and wide-aperture data. However, travel-times alone cannot uniquely resolve anisotropy from heterogeneity. Polarisation data are mainly sensitive to anisotropy, and therefore provide independent constraints on anisotropy. We have developed an algorithm that inverts for 3D lateral heterogeneity as well as transverse anisotropic parameters. We have found that as well as determining both anisotropy and heterogeneity, the new algorithm converges to the final solution much faster than the algorithm using travel-time tomography alone. This code was developed by Adam Cherrett (now with TOTAL).

v. 2D high-resolution tomography for densely sampled wide-aperture data using both travel-times and slowness (TTT)

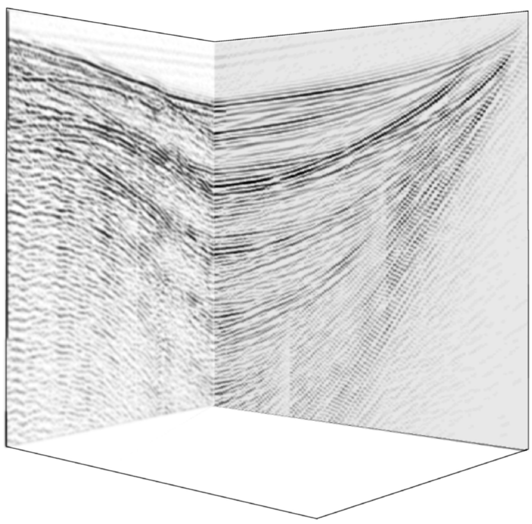
Up to this point we have used fine-scale regular parameterisation. As the resolution of the inversion depends on the ray density, which is non-uniform, we have developed a new efficient algorithm using adaptive parameterisation that is dependent on resolution. This program, written by Immo Trinks, also inverts for slowness, the spatial derivative of travel-time. This algorithm is particularly efficient for inverting very long-offset densely sampled seismic data, such as that from long streamers or two-ship surveys.



Model update after 3 iterations using TTT code for 100% travel-time inversion (left), 50% travel-time, 50% slowness (centre) and 100% slowness inversion (right) (Immo Trinks)

1.2.3 Imaging in *x-t* and *tau-p* domains

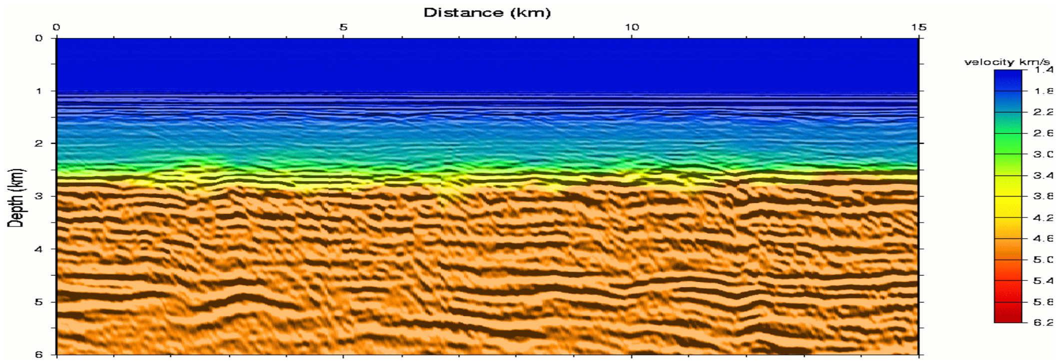
We have particular strengths in unusual imaging techniques in the *tau-p* domain. The longer offset reflected and refracted wavefield is normally discarded at the first step of conventional seismic processing, yet it contains extensive independent information about the P- and S-wave velocity fields, structures, and converting horizons. We have devised ways of preserving and incorporating the long offset data itself, and its rich velocity information, into the stack image.



Data cube in tau-p and zero-offset (Immo Trinks & Geraint Jones)

Our main imaging tools are outlined below.

i. 2D velocity imaging in the *tau-p* domain (*Down)*
We have developed a new method in which the long-offset seismic data are transformed into the *tau-p* domain and an image produced directly in this domain. Using a downward continuation algorithm, the background velocity is obtained from the refraction part of the data. In the downward-continued depth domain, the reflections will be flat if the velocity profile obtained from the refraction data is accurate, and thus the reflections may be stacked. In 2D, such a process results in a 2D seismic depth image with velocity superimposed. This work was carried out by Geraint Jones (now with OHM Surveys).



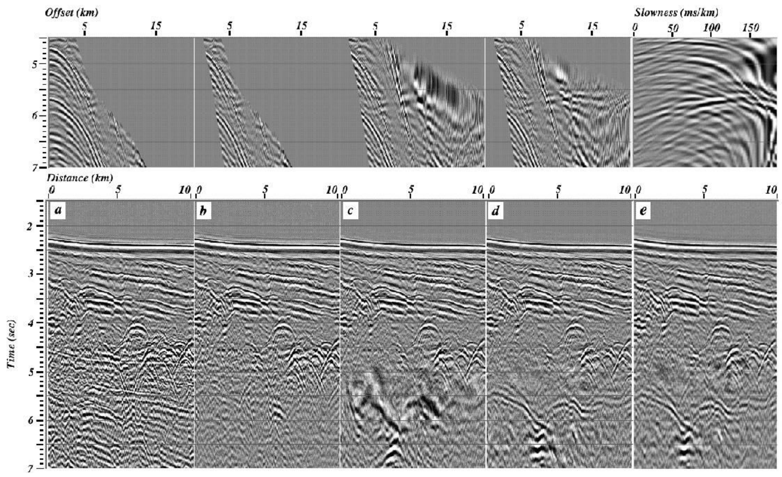
Stack of data from Faeroe-Shetland Basin after downward continuation to depth and stacking in the tau-p domain (Geraint Jones)

ii. Extraction of anisotropy in the *tau-p* domain

Our new method of *tau-p* imaging may also be used to extract anisotropic parameters. The turning rays used to obtain the background velocity provide information on the velocity at the turning point of horizontally travelling waves. In anisotropic media, this velocity corresponds to horizontal component of velocity. If we apply an elliptical moveout correction, then the reflection part of the data, sensitive to the vertical velocity, will not be flat due to anisotropy. Furthermore, a tau^2-p^2 plot will be straight line for elliptical and isotropic media and curved for non-elliptical anisotropic media. We use these properties to determine the anisotropic media using an iterative method. Benoit Gotab, Ph.D. student, is working on this project.

iii. Processing strategies for non-stretch stacking in *t-x* and *tau-p* domains

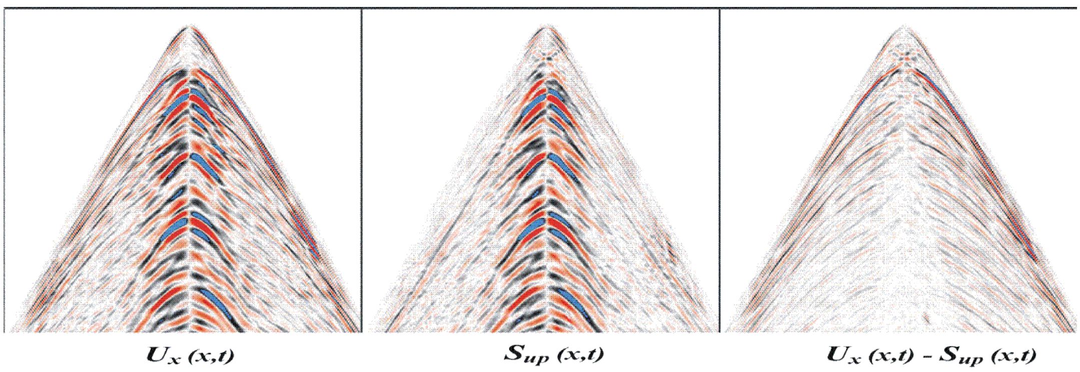
Long offset seismic data collected specifically to aid imaging in sub-salt or sub-basalt situations is often wasted when the crucial longer offset data is stretched and muted out after NMO. Hassan Masoomzadeh has been pursuing strategies for non-stretch stacking using a ‘zigzag’ velocity function based on iso-moveout curves in both the *t-x* and *tau-p* domains. The concepts developed may be applied via a standard processing package and represent a powerful technique for exploiting the unique information contained in the longer offset wavefield.



Long offset data from the NE Atlantic margin. a) conventional stack with stretch mute applied; b) as a) with inner mute to remove multiples; c) as b) without stretch mute; d) non-stretch stack in t-x; e) non-stretch stack in tau-p (Hassan Masoomzadeh)

iv. Decomposing the P- and S-wave fields from multi-component OBC data (*PSWSP*)
One of the main problems in analysing multi-component seismic data is the decomposition of the wavefield in to properly separated radial and transverse components. We have developed a new algorithm in which the data are first transformed in to the tau-p domain, and then rotated to maximise the first arrival P-wave along the radial component and minimise that along the transverse component according to slowness parameters.

v. Receiver function for exploration geometry
The receiver function method is commonly used in global seismology to extract locally converted S-waves and remove the effect of their long travel path. Inversion of receiver functions provides S-wave velocity, and migration gives an image of the conversion boundaries. We have extended this method to exploration seismology. In order to decompose P- and S-waves, we transform the data to the *tau-p* domain and use an iterative deconvolution to remove the effect of the travel path in the water column, to obtain up-going P- and S-waves, and receiver functions. These receiver functions are then used to obtain the pure P- and S-wave images. There is also potential for use in AVO analysis and waveform inversion. Pascal Edme, Ph.D. student, is working on this project.



Wave separation using receiver function approach. Left: vertical geophone data; centre: upgoing S wavefield; right: residual (Pascal Edme)

vi. 2D Wide-angle migration
Our wide-angle migration uses Maslov theory to compute the Green's function, and Kirchhoff theory for migration. It is a true-amplitude migration algorithm, and can take account of turning rays which are very dominant at wide angles. It has been successfully applied to two-ship SAP data and OBS data.

1.2.4 Complementary data and techniques

i. Compliance (*seafloor.com*)
Compliance is a measure of seafloor deformation under pressure forcing by ocean surface gravity (water) waves. The deformation is approximately inversely proportional to the shear modulus, making compliance measurements particularly sensitive to fluid reservoirs. The ocean waves span a range of wavelengths, with each wavelength sensitive to structure at a different depth in the subsurface. Compliance is measured using a broadband seismometer and a low-frequency pressure gauge deployed autonomously on the seafloor. Each measurement is independent, allowing compliance to be measured using only a few instruments.

ii. Inversion of geostatistical information (*JiveGeostat*)
An adaption of the original Jive3D allows the inversion to be constrained by *a priori* geostatistical information about expected velocities based on well-log or other local data.

iii. Controlled source electromagnetic methods
Controlled source electromagnetic sounding provides independent information about the electrical conductivity of the sub-surface. The CSEM methods developed during LITHOS I now form the basis of a large programme at Southampton University and OHM Surveys Ltd.

iv. Effective medium theory
The LITHOS project aims not just to determine seismic velocities, but also to seek to identify the lithology that might have produced the data. In order to relate our inversion results to lithology, we have developed a set of modelling algorithms that are based on effective medium theory, which is used to compute the physical properties (seismic velocities, anisotropy, electrical resistivity) of composite materials consisting of different components, which may be either fluid or solid.

1.2.5 LITHOS software

The LITHOS algorithms are developed by our students and post-doctoral workers as part of their research. LITHOS is committed to making these innovative programs available and usable both by our industry partners and by the academic community. To this end the necessary resources for finalising and documenting programs are made available within the LITHOS programme, organised and implemented by Clare Enright, Computer Associate. Delivered programs are written in generally available standard languages (C, C++, Fortran77 and Fortran 90, Tcl/Tk). We aim to provide programs portable across Unix platforms (including Linux). On-line graphics uses packages based on the X Protocol.

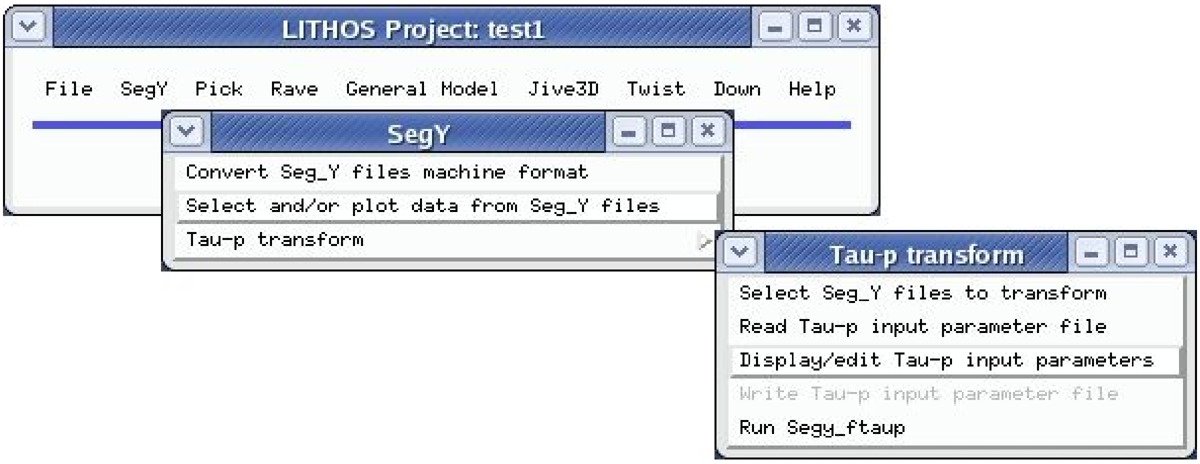
Programs are delivered as compilable code; industry partners therefore have the opportunity to carry out further development or to tailor programs to their own needs. In addition, the programs may be incorporated into a company's own preferred development environment. To gain maximum benefit from these advantages it is important that the individual programs retain their independence. However, to assist new users in becoming familiar with the LITHOS programs they are being integrated as much as possible under a single User Interface, which provides a user-friendly environment. The interface allows the user to set input parameters and call the required program from menus, and provides a variety of tools to assist the user in data preparation, model building, plotting of results etc.

The design of the User Interface maintains the independence of the component programs: e.g. communication between components is via disk file; common code is incorporated at link time rather than run time. A log of all file access and programs run is provided in order to assist the user in understanding the steps taken to run each program. New software and updates are released via the restricted-access website.

Software developed in LITHOS phases I & II

- LITHOS integrated User Interface
- 1D full wavefield elastic anisotropic inversion *(Wips)*
- 2D full wavefield elastic inversion for P- and S-waves and multi-component data *(Twist, TwistPS & TwistPS-MC)*
- Decomposition of the P- and S-wave fields from multi-component data *(PSWSP)*
- Receiver function (RF-PS)
- 1D inversion of seafloor compliance data (seafloor.com)
- 3D travel-time tomography *(Jive3D)*
- 2D travel-time tomography with geostatistical constraints *(Jive_Geostat)*
- 3D travel-time and polarisation inversion in anisotropic media *(CRAYFISH)*
- Efficient semi-automatic travel-time picking algorithm *(PickEd)*
- Rapid automatic velocity imaging using wide-aperture travel-time data *(Rave)*
- 2D velocity imaging and stacking in the *tau-p* domain *(Down)*
- 2D high-resolution tomography for densely sampled wide-aperture data using both travel-times and slownesses *(TTT)*
- Accurate tau-p transformations *(segy_ftaup)*

Pull-down menus from LITHOS User Interface (Clare Enright)



1.3 LITHOS III: Science proposal

A fundamental strength of the LITHOS group is our ability to apply theory to data. LITHOS phases I and II were a period of exciting rapid development of new algorithms and software, and there is now a battery of tools available for analysis, inversion and processing of long-offset seismic data. During development each module has been tested on datasets contributed by our members. Now it is time to evaluate the different approaches by applying them to larger and more varied datasets from technically challenging environments, at the same time making the LITHOS software more robust, generalised and user-friendly.

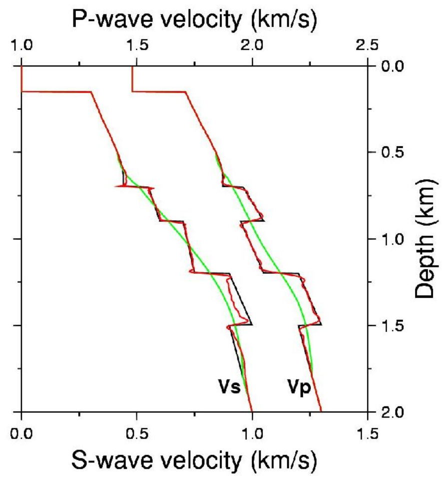
In LITHOS III, we will focus on applying and consolidating our new methodologies to determine accurate quantitative P- and S-wave images in challenging areas and 4D time-lapse situations. In the marine environment most of the S-wave arrivals are converted, and these can be efficiently recorded using multi-component ocean bottom cables. As the conversion takes place mainly at wide-angle, we shall use our expertise in wide-aperture seismology to analyse S-waves from multi-component data and to exploit our multi-domain approach to building images of the subsurface, by exploiting our unique capabilities in full elastic waveform inversion in the time domain, and in novel processing approaches in tau-p.

We already have multi-component OBC data sets from the Beryl and Alba fields given by our consortium members, but ideally we would like to focus on one site that has a variety of data, such as Valhall. The Valhall field in the Norwegian sector of the North Sea is licensed to BP Norge, Amerada Hess Norge, Norske Shell and Total E&P Norge. The field has been in production for several decades, and compaction of the chalk reservoir during extraction has caused problems with subsidence of the seafloor and diminishing returns. A recent water injection programme appears to have restored production rates to the peak values of 1999. Production is monitored closely using an array of about 10,000 4-component broadband receivers on the seabed, recording data continuously, and there have been several 4D surveys in the last few years. We shall initially investigate the feasibility of obtaining access to this data and its suitability. We also invite our industry partners to consider actively whether they could contribute other multi-component OBC datasets and challenging long offset multi-channel streamer datasets to evaluate the performance of our algorithms in different situations. A separate contract will be negotiated on the confidentiality of each dataset provided for development and testbed use by the LITHOS project.

Our objective is to quantify lithology using elastic properties (P- and S-wave velocities, Poisson’s ratio, λ, μ, P- and S-wave attenuation) to shed light on porosity, permeability and saturation in reservoirs. Our main tool will be full waveform inversion and data will be multi-component, recorded in both active and passive modes. The passive data (seafloor compliance and surface waves) will be used to determine long to medium scale S-wave velocity information whereas active data will provide fine scale information on both P- and S-waves. The application of the method to data in this focused way will pose some fundamental theoretical questions, which will be addressed during LITHOS III, and may also form the topic of LITHOS IV.

The LITHOS III focus will be on multicomponent waveform inversion and its application to 4D problems. At the same time we shall retain and develop our expertise in the development of tomographic techniques and imaging/processing in the *tau-p* domain, as these concepts give insight into the information available in the data, and form foundation stones for the difficult process of waveform inversion.

Inversion of synthetic multi-component data for P- and S-wave velocity structure. Black – true model; green – starting model; red – recovered model (Tim Sears)



Some key topics are outlined below.

1. Application of waveform inversion for 4D

The usual approach to time-lapse data consists of similar pre-processing of the seismic cubes and cross-equalization in order to subtract time sections and emphasize differences due to extraction and injection. To reach quantitative conclusions about fluid and gas saturation and flows, AVO analysis has been widely used. AVO practice is based on a linear approximation of the relation between reflectivity and elastic properties, which is not suitable for long offsets and wide apertures. Full waveform inversion overcomes these limitations and provides quantitative information on elastic properties, which can be used to determine the true depth topography of the reservoir, and to quantify the movement of fluids and gas. Since the presence of fluids leads to the distortion of deeper reflections, our quantitative approach may be used to determine the long wavelength of the subsurface velocity.

2. Waveform inversion - tuning effect and scattering

Fine layering produces tuning effects that either enhance or decrease the amplitude of events, and it is not possible to recover the physical properties of these layers using conventional methods. Similarly, small-scale objects produce scattering that cannot be recovered using conventional methods. Since waveform inversion requires fine sampling intervals – particularly for S-waves - and takes account of small-scale variations in the model, these features could potentially be recovered using this technique. We will first do sensitivity analyses and then apply these ideas to real data that show some of the features.

3. Inversion of correlated parameters for waveform inversion and well ties

Up to now we have been inverting for P and S-wave velocities, which can be used to obtain Poisson’s ratio, and Lame parameters. It is important to correlate these different physical parameters with information from wells and identify those that are most suitable for quantifying lithology, porosity, permeability, and saturation, and then to invert those parameters directly. We have access to well log data from the Alba field and will need to request the same for the Valhall field if that becomes the chosen dataset.

4. S-wave properties from inversion of seafloor noise

The Valhall field has about 10,000 4-C sensors that record continuously. They record signals generated by sea waves, infragravity waves etc, which is generally considered as noise. It has been shown that cross-correlating signals from two consecutive receivers along a propagation path can provide the Green's function between the two receivers, which can be used to invert sub-surface parameters. The depth of penetration depends on the distance between the receivers. We plan to develop a new inversion technique that provides 3D S-wave velocity structure below the receiver array. This information is vital for the inversion of multi-component OBC data. Such an approach may lead to the monitoring of reservoirs using natural sources.

5. Joint inversion of seafloor compliance and wide-angle seismic data

During LITHOS II, we found that seafloor compliance data provides information on large-scale S-wave velocity whilst wide-angle seismic data provides information on P-wave velocity. Wide-angle multi-component data record S-wave arrivals. We propose to use wide-angle multi-component seismic and compliance data to jointly invert for P and S-wave velocities.

6. S-wave static from seafloor compliance and surface wave data on the seafloor

S-wave statics pose serious problem in analysing multi-component OBC data. We propose to use a combination of full wavefield inversion, seafloor compliance from OBC data, surface waves, and sea noise (see point 4 above) to determine 3D S-wave static.

Achievement of any or all of the objectives listed above will depend on the funding level available to the LITHOS III programme, and hence on the number of subscribing companies. The LITHOS group will also be open to the investigation of other problems or projects suggested by our industry partners. Within this framework, the LITHOS Steering Committee will set priorities for the work to be undertaken year on year.

Section 2: Project Management Plan

2.1 Scientific management

2.1.1 Project Leaders

The project will be led by Professor Satish Singh and Dr Penny Barton. Singh will lead the work on theoretical and technical developments in seismic analysis and inverse theory, which forms the core of the LITHOS project. Barton together with Singh will oversee the application of seismic methods to real data. Singh and Barton will be responsible for day-to-day management of the project. The two Principal Investigators will be assisted by secretarial support at IPGP and Cambridge, depending upon requirements.

2.1.2 Steering Committee

The project will benefit from significant input from a Steering Committee consisting of senior LITHOS staff and one or more representatives from each subscribing industry member. The role of the Steering Committee will be to prioritise work within the LITHOS project, to determine the overall direction to be taken by the project, and to approve the project's annual financial plans. There will normally be two Steering Committee meetings per year: one will be combined with the annual LITHOS Science Meeting detailing work completed and in progress. The terms and conditions of the legal arrangement with our sponsors are laid out in the standard Contract (Section 4.3).

2.1.3 Research work and organization

Research students will continue to form the core of the programme, together with more senior Research Associates and Computer Associates as the budget allows. A steady flow of research students, each allocated a well-defined project, provides a stimulating balance between fresh ideas and accumulated knowledge. We are committed to providing opportunities for students to work on exciting and relevant geophysical problems with achievable solutions and minimal restrictions on the dissemination of results. Research Associates contribute experience, maturity and expertise to the project. Our Computer Associate provides the essential bridge between new codes written by students and researchers, and the recipients of these codes in the offices of our industrial sponsors.

Running a research group from two separate centres is both challenging and stimulating. The potential of electronically-based collaboration has increased dramatically since the beginning of the LITHOS project, and we will increasingly utilize these new technologies for working together. A contingent from Paris and Cambridge get together at least every six months, and Satish Singh travels to Cambridge for a week every 1-2 months in order to provide intensive supervision to joint students.

All researchers are expected to be able to give informal verbal presentations of their work, and this, in conjunction with more formal presentations at LITHOS Science Meetings and public conferences, together with the emphasis we place on regular report-writing to a professional standard, means that our students are trained to a high standard of oral and written communication which stands them in good stead for their future careers. Informal meetings provide students with an opportunity to learn to speak confidently to an audience, and to explain complex problems in an interactive discussion. We also like to learn from experts in our sponsor companies, and look for opportunites to invite individuals to give technical seminars or sometimes organise a workshop on a relevant topic, combining contributions from LITHOS researchers and sponsor members.

We encourage our students to spend time in work-experience placements with our consortium members, and this leads to recruitment opportunities welcomed by both sides. Industrial members of the consortium are encouraged to spend research periods in Cambridge or Paris, working with the LITHOS group on a specific problem, in order to strengthen links and co-operation within the group.

2.1.4 Training

Both Principal Investigators are reputed academic scientists and we have complementary research expertise. Our institutions are well placed globally to attract the best graduate students and post-doctoral research workers, and we are both experienced supervisors of Ph.D. projects. We regard the development and training of highly numerate geophysicists, with specialised and sought-after skills, as an extremely important role for the group in an era that has seen a decline in the supply of quantitative Earth sciences graduates. LITHOS students benefit from an attractive research programme and an environment that prepares them for rapid promotion within the industry after graduation. About twenty-five Ph.D. students and fifteen post-doctoral research workers have been trained during LITHOS Phases I and II, and most of them have taken up positions in industry and academia (see Appendix B).

2.1.5 Links between IPG Paris and Cambridge

We have operated LITHOS in a split-site configuration since September 1999 and have developed strategies that make us confident in the collaborative and management aspects of the challenge. A base at two world-class institutions gives us an advantage in terms of recruitment of students and research staff, and gives the group access to an enhanced pool of experts as well as super-computing and other facilities available in the two institutions. The University of Cambridge and IPG Paris have signed a Memorandum that encourages and formalizes collaborative projects between the two institutions, including joint appointments.

2.1.6 Links with other projects

LITHOS will receive direct and significant benefit from other projects funded from a variety of sources that are led by the Principal Investigators. These projects may include theoretical developments, data analysis and interpretation of proprietary data for a particular company or group of companies, or academic projects funded by public bodies, often including an element of novel data acquisition. The individual Principal Investigators will be responsible for these projects. Subject to restrictions imposed by sponsoring companies, public funding agencies or other partners, the output of such projects will be merged with the output of research directly funded by LITHOS to form a coherent scientific output all of which will appear under the LITHOS umbrella.

2.1.7 Publication and confidentiality

We are a research group and it is expected that all our results will be presented at conferences and published in international journals. Details of the arrangements are laid out in the standard Contract (Appendix E). Since a significant amount of the research will be carried out by Ph.D. students, these results will be included in their Ph.D. theses, except in specific cases where results are related to particular datasets which are the subject of a separate confidentiality agreement.

2.2 Project Structure and Financial Plan

2.2.1 Funding

The project will be funded by a consortium of oil companies, each company contributing £30k (approximately 45k EUR) (+ VAT where applicable) per year. The contribution will be in the form of a subscription, and will be the same arrangement as has worked successfully for LITHOS I & II. Assuming 8 subscribing companies (as for LITHOS II), the total funding available per year will be £240k.

2.2.2 Financial plan

Depending on the level of income, we plan to employ two or three Ph.D. students per year to carry out the programme of research. Some of these funds may be used instead for a post-doctoral Research Associate. To maintain all the software developed within the project and to incorporate an appropriate and consistent user interface into all software packages, we will continue to employ part-time Computer Associate Dr Clare Enright. We shall also allocate funds to part-time administration to provide project support, and to project management.

Indicative Annual Budget:	*UK £*
Two Ph.D. Students	*120 k**
One part-time Computer Associate	*40 k***
Administration	*10 k***
Sub-Total	*170 k***
Consumables	*10 k*
Travel	*15 k*
Computing	*15 k*
Deliverables	*10 k*
Project management	*20 k*
Total	***£240 k***

*This amount will fund each Ph.D. student for the full three years. It is a requirement of both the University of Cambridge and IPG Paris that a Ph.D. studentship must be funded at the outset for the entire period.
**Includes institutional overheads

The cost of employing students and researchers are different in France and the UK, depending on institutional overhead, taxes, university fees etc. The actual budget will depend on the income received from subscriptions, and the country in which people are employed. A financial plan for each year of the LITHOS programme will be presented for approval to the Steering Committee.

As in LITHOS I & II, we expect to attract funding from other national and international sources (e.g. research councils, EC) to support Ph.D. students and post-doctoral workers, which will enhance the LITHOS III research capabilities. Both IPG Paris and the University of Cambridge are committed to provide all possible support to make LITHOS successful and to ensure its long term continuity.

2.2.3 Start of LITHOS III

We shall hold the inaugural Steering Committee meeting in December 2005 in Cambridge, to prioritise initial research tasks and to set out milestones. The project will start from July 2006. During Spring 2006, we aim to recruit the first two Ph.D. students to work on the project from October 2006 for a duration of three years. It will be important to recruit new students as soon as possible to ensure continuity of LITHOS culture and know-how from Phase II, and to build on what has been learnt. Several Phase II students will be completing their studies at the end of 2006.

2.2.4 Duration of the project

Phase III of the LITHOS project will run for four years (2006-2010). At the end of each year the Steering Committee will decide on the number of students or post-doctoral researchers to recruit for the next year of the project. We shall review our overall progress and the requirements of our industrial partners at the end of the third year, to decide upon the future direction and form of the project beyond the year 2010.

2.3 Deliverables

Subscribing companies will be entitled to the following:

(a) Free and direct access to all research carried out under the LITHOS project. This will include the results of other research carried out by the PIs, but not funded directly by LITHOS - except where such access would conflict with confidentiality or other obligations of the PIs to other funding bodies/partners.

(b) Royalty-free use of all software developed by the LITHOS project. Software packages will be designed for applications in a commercial research environment.

(c) Annual reports and presentations. The LITHOS annual reports (see section 3.4) have been in the form of illustrated bound volumes 80-160 pages long. The Annual Science Meeting consists of a day or more of scientific presentations made by members of the group exclusively for sponsors.

(d) We encourage our students to spend time in work experience placements with our consortium members, and industrial members of the consortium are encouraged to spend research periods in Cambridge or Paris. In addition, all subscribing companies will have ready links to our associated projects in instrumentation, acquisition design advice, and data analysis.

2.4 Contact details and next steps

If you are interested in joining the LITHOS III Consortium, please respond as soon as possible to one of the PIs below. Companies intending to join LITHOS III will be invited to an inaugural meeting for further discussion of the project in late 2005. Standard contracts will be signed early in 2006 for a project start date in July 2006. Please send a letter of intent (for draft see Appendix D) to Penny Barton. If you need further information, please contact either Satish Singh or Penny Barton.

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