Mapping and Modelling Heterogeneous Stretching and Volcanism on the NW European Atlantic Margin

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Part 1: DESCRIPTION OF PROPOSED RESEARCH

Abstract:

We have assembled a powerful interdisciplinary team of academics, contractors and oil companies to tackle two of the biggest problems facing hydrocarbon explorationists on the NW European Atlantic margin and on all other volcanically dominated margins: these are the inability of conventional seismic reflection methods to image through basalt layers overlying sediments; and the failure of current models and software to model properly the stretching, subsidence and thermal history of rifted continental margins. Combination of our modelling and seismic acquisition skills will enable us to both image the extruded and lower-crustal intruded igneous component and to model the development of rifted margins where there is heterogeneous stretching and non-conservation of mass due to the addition of melt. This work is central to the scientific objectives of the Ocean Margins Link programme. We anticipate that both the modelling and the improved seismic imaging will be developed commercially for widespread use in the hydrocarbon industry.

The new rifted margin model will be developed from quantitative models of mantle flow, melt generation and transport previously applied to oceanic ridges and will incorporate continental rheology as an initial condition. It will have generic applicability to both non-volcanic and volcanic margins around the world. We shall apply this model to a study of heterogeneous stretching and anomalous subsidence along the entire NW European Atlantic margin, using a combination of data already available and new seismic data to be acquired by both university and industrial collaborators in this research programme. There will be a close synergy between the mapping of igneous material in the crust by the seismic projects on the Faroes-Shetland and Hatton-Rockall Basins and its incorporation as ground truth in the theoretical models.

We will address the seismic imaging problem by developing techniques using very long-offset streamers and wide-angle imaging with ocean bottom seismometers (OBS) to penetrate through the basalts. We will acquire data in two sites, the first a 350-km profile crossing the Faroes shelf and its transform continental margin into the oceanic crust of the Voring Basin, using both a state-of-the-art Q streamer system from Schlumberger Geco-Prakla and an array of 100 OBS with spacings of 500-5000m. The second survey will be of the heavily intruded continent-ocean transition of the Hatton-Rockall Basin where we shall deploy 100 OBS in an array across the margin. Both surveys will constrain basement thickness and the distribution of igneous rocks in the crust. This work will also examine possible lower crustal seismic anisotropy produced by multiple sill intrusions and oceanic crustal thickness variations after breakup in order to infer the magnitude of temperature changes caused by pulsing of the Iceland mantle plume.

Previous Work and Expertise

N.J. Kusznir has substantial experience in developing quantitative models of the rheological, thermal and isostatic response of continental lithosphere to deformation. In extension these models predict syn- and post-rift structural and stratigraphic basin development and have been applied to many basins. The models, applicable in both the forward and reverse sense, have been developed into commercial software packages in collaboration with Badley Technology Ltd. (eg Stretch and Flex-Decomp) and are in widespread use by the oil and gas industry. He has also developed and applied 1D and 3D models of temperature and hydrocarbon maturation in rift basins, including the effects of sill intrusion and magmatic underplating, in collaboration with the hydrocarbon industry. Models of thrust belt and foreland basin formation have also been developed. Early in his career he worked on thermal models of ocean ridge processes. Recent research focuses on the temporal and spatial partitioning of strain at rifted margins where he has demonstrated with colleagues that rifted margin stretching is depth dependent. He is also currently working on subduction dynamics. Substantial experience in numerical modelling of continuum processes applicable to geodynamic processes. He has successfully supervised 31 graduate students.

R.S. White has considerable expertise in organising and leading marine geophysical surveys, and particularly those involving seismic wide-angle seismic acquisition. His expertise extends from developing new acquisition techniques, including two-ship expanding spread and constant-offset profiles, and more recently working with Amerada Hess Ltd on the recording of very wide aperture seismic reflection data by multiple passes of two seismic vessels (FLARE technique, Faroes region), to applying of state-of-the-art processing and modelling computer programs. He has worked extensively on the volcanic rifted margins of the North Atlantic and on the nature and evolution of the Iceland mantle plume which so strongly influences these continental margins. He was responsible, with McKenzie, for formulating the theory for the formation of volcanic continental margins and flood basalts by the interaction of lithospheric rifting with thermal anomalies created by mantle plumes: this theory has been widely applied and underpins almost all work on volcanic margins. More recently, he has combined geochemical and geophysical measures of crustal generation to investigate melt generation processes in the mantle, in mantle plumes, at oceanic spreading centres and at rifted continental margins. He has also developed theoretical models of the generation of crust at oceanic rifts, and the modification of subsidence at rifted margins caused by thermal anomalies in the mantle and the addition of melt to the crust. He has successfully supervised 32 graduate students.

A.M. Roberts has worked as a consultant in the oil-and-gas industry since 1986, before which he worked for Britoil plc. His main interests lie in the application of techniques in structural geology and basin dynamics to the commercial environment of oil-and-gas exploration and production. With colleagues at Badleys he has brought to general use in the industry many of the research techniques and ideas initially developed by the Basin Dynamics and Fault Analysis groups at Liverpool University. He has written joint publications with members of both research groups, as well as with colleagues from Badleys. Over the past decade he has worked closely with Kusznir on the use of quantitative models for rift-basin formation, extrapolating these ideas to the tectonic setting of rifted continental margins. This project will continue the fruitful collaboration. He edited the best-selling Geological Society Special Publication entitled “The Geometry of Normal Faults”, and with Kusznir edited a thematic set of 21 papers on Passive Continental Margins for the Journal of the Geological Society. He is currently Publications Secretary of the Geological Society.

P.A.F. Christie's PhD on seismic refraction across the North Sea underpinned McKenzie’s crustal extension model, now widely used to model thermal maturation. During a career at Schlumberger, Christie has focused on reservoir geophysics, integrating borehole measurements with multi-component and time-lapse seismic. He has served as departmental director of engineering and research in Paris, Ridgefield (USA) and Cambridge, and established the Seismic Departments in Paris and Cambridge. On secondment to BP in 1996-7 he worked on sub-basalt imaging. Christie continues wide research interests as Scientific Advisor in Cambridge. He has served as External Examiner to MSc's, on NERC reviews, and contributed to professional meetings. Christie and White's PhD's overlapped in Cambridge and both have followed close and complementary technical paths. Their sub-basalt collaboration started when White’s post-doc, Fliedner, modelled Schlumberger's multi-component sea-bed cable data in the Faroes basalt area. Although a small amount of data, the promising results of this collaboration helped pave the way for this proposal.

Description of the Problem

When continents break apart above a mantle plume, huge volumes of melt are generated and emplaced in or over the rifting continental crust[1]. Together with the dynamic uplift from the underlying plume, which itself is strongly time-dependent[2,3], and spatially variable[4,5], this considerably modifies the uplift, subsidence and thermal history of the margin and its hinterland compared with that caused by extension in normal sedimentary basins such as the North Sea[6]. A further consequence of the emplacement of massive lava flows is that they create considerable problems in seismic imaging of underlying structure. To understand volcanic continental margins such as those on the NW European margin, it is important to develop both new modelling strategies which take account of the non-conservation of mass, and new seismic imaging techniques to map the amount of intruded and extruded igneous crust, and the extent to which it flows laterally from the regions where it is generated. This project combines improved seismic imaging of the whole crust and of its igneous component, with new theoretical modelling in order to understand better the development of continental margins.

Recent work suggests that there is heterogeneous stretching on many rifted continental margins[7-9], sometimes so extreme that it leads to the exhumation of mantle rocks. At volcanic margins the injection of basaltic melt into the lower crust and the higher geothermal gradients is expected to increase the degree of heterogeneous stretching and anomalous subsidence. The deep-waters of rifted continental margins are the new frontier exploration areas, and a sound understanding of the breakup process and the nature of the continent-ocean transition (COT) is of prime importance to the hydrocarbon industry. Improved quantitative models of rifted margin formation processes that take account of heterogeneous stretching, melt generation and dynamic uplift from mantle plumes are required by the oil and gas industry for the predicting subsidence, temperature and maturation history. New seismic techniques will also aid imaging and geological interpretation in frontier areas, particularly those with large volumes of basaltic rocks[10].

Extension estimates determined independently from faulting, crustal thickness and post-rift thermal subsidence show that upper-crustal extension is often significantly lower than whole-crustal or lithosphere extension thinning within 75-150 km of the COT (Fig. 1). At non-volcanic margins, seismic, geochemical and magnetic data show that continental mantle is exhumed[11-13] in a region up to ~100km wide (Fig. 2). Finite element modelling of non-volcanic rifted margins suggests that heterogeneous stretching occurs during early sea-floor spreading, generating a transitional COT exposing continental mantle at the surface. Heterogeneous stretching and anomalous subsidence is also observed at volcanic margins (Møre, Vøring).

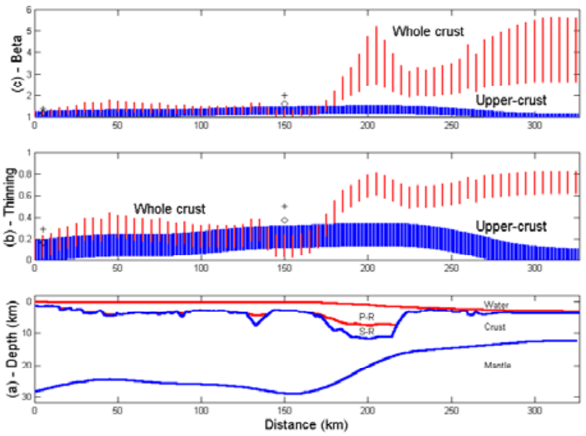

Figure 1 Depth dependent stretching observed on the S. China Sea Margin[9].

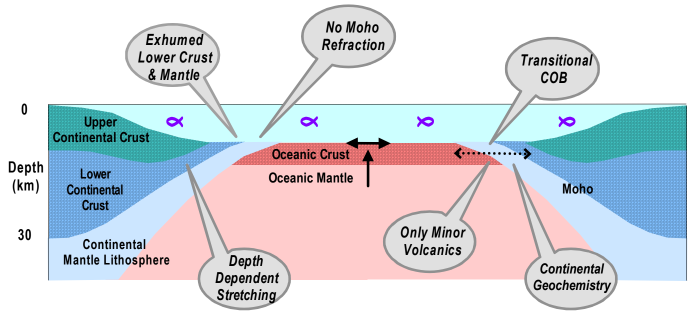

Figure 2 Summary of observations at rifted margins including mantle exhumation & heterogeneous stretching[9].

Justification for Government Funding

The formation of rifted margins is an important component of the large scale geodynamic processes that dynamically shape the surface of the Earth, and a sound conceptual understanding of the processes of rifted formation and the ability to image their structures and to develop quantitative models are fundamental science and are also of direct importance to the hydrocarbon industry. Yet because oil and gas companies are organised primarily into groups focused on particular small regions or assets, often with a short time horizon of a few months or years, it is difficult for them to support long-term generic research.

Historically, many of the concepts and techniques now in routine use in the hydrocarbon industry were developed in academia: e.g. the theory of sedimentary basin formation by lithospheric stretching; the relationship between rifting and volcanism; and, particularly relevant for this project, the use of wide-angle seismic methods at sea to investigate crustal structure. The combination of government and industry support for this project enables it to develop both generic modelling concepts that are beyond the immediate purview of most companies, while at the same time deploying NERC research vessels for OBS, and using the best technical seismic profiling methodology available through the commercial world.

The technological ability to seismically image sediments, basement and upper mantle in regions of intense volcanic extrusion and underplating at continental margins adjacent to mantle plumes is important not just to the hydrocarbon industry but also in order to advance our scientific understanding of volcanic and mantle plume processes. This component of the research is also applicable to volcanic hazard and risk assessment, and given the likely impact on the climate of massive volcanic eruptions such as occurred during continental breakup, is also of importance as an actual example of global environmental change that may help inform current deliberations on how best to address contemporary global climate concerns.

The UK will benefit directly from this work through an increased ability and effectiveness of the oil and gas industry to explore in rifted margin deep water environments both on the UK Atlantic margin and on other rifted margins world-wide where the UK hydrocarbon industry is active. The UK oil and gas industry has an excellent track record of operationally applying new scientific advances in short time scales.

The Research Programme

Scientific Objectives

The aims of this project are to develop a unique synergy between theoretical modelling and state-of-the art seismic imaging using long-offset and wide-angle techniques, to develop and to test new quantitative models of rifted margin formation**,** incorporating heterogeneous stretching, the effects of melt generation and emplacement and varying thermal anomalies in the mantle. These models and imaging techniques will be applicable to both volcanic and non-volcanic rifted continental margins world-wide.

The NW European Atlantic Margin provides an excellent natural laboratory in which to observe rifted margin properties and in which to test theoretical models. It is the best-known volcanic margin world-wide, with a wealth of regional surveys and oil company data available in which to embed our research. There is also crustal seismic and ODP drilling data available on the conjugate margins of East Greenland[5], and White has led a considerable amount of work on the still-active present day Iceland mantle plume[19-28] which provides control on the present-day spatial and temporal variations of the mantle plume which will inform our studies of its impact at the time the N Atlantic opened. The four PIs have immense experience in this area: Kusznir and Roberts have extensive knowledge of studying subsidence data along the entire North Atlantic margin, while White and Christie have been prominent in developing new seismic techniques and in mapping crustal structure and the effects of melt emplacement along the NW European margin.

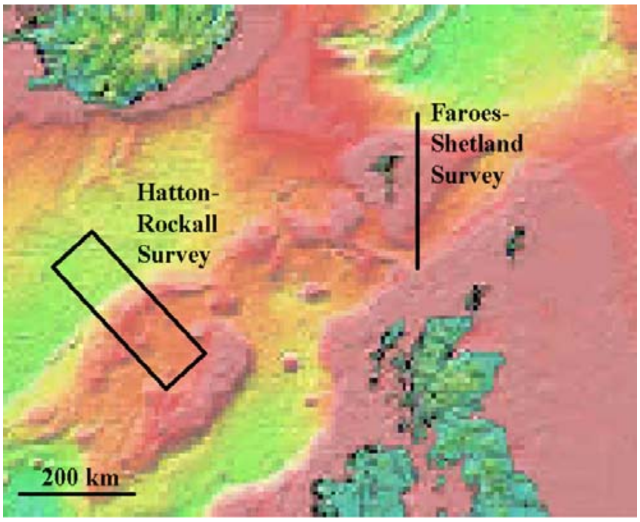

Figure 3 *Location map of Faroe-Shetland & Hatton-Rockall seismic surveys.*

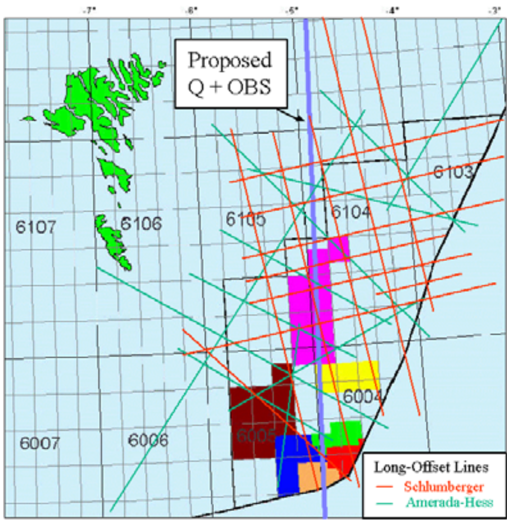

Figure 4 *Detailed location map of Q & OBS seismic surveys in Faroe-Shetland Basin and Margin.*

The research program will have four main components:

- Development of a new quantitative model of structural, volcanic, thermal and subsidence processes at rifted margins. Two-phase flow[14-16] models of mantle flow and melt transport, successfully applied to ocean ridges, will be used to model the initiation of sea-floor spreading and the formation of rifted margins. The model will be tested against existing observations of heterogeneous stretching and subsidence at non-volcanic margins, and against new observations from this study on NW European Atlantic volcanic margins. It will also be used to determine thermal and maturation histories along the NW Europe Atlantic margin.
- The mapping of heterogeneous stretching, subsidence and melt injection along the NW European Atlantic Margin. This will be carried out using a combination of new seismic data for the Faroe-Shetland and Hatton-Rockall Basins and adjacent margins, and existing data for the Edoras and Hatton Banks, Møre and Vøring margins. Maps of heterogeneous stretching, subsidence and melt injection for the NW European volcanic margin will be used to test the new theoretical model of rift margin formation, and the timing of depth-dependent stretching with respect to the initiation of sea-floor spreading will be determined.
- Field acquisition of a 330km-long wide-angle seismic profile extending north-south from the Faroes-Shetland Trough, crossing the Faroes shelf and across the northern transform margin into the Vøring Basin (Fig. 3). This will use the cutting-edge, 12km, Q-streamer system from Schlumberger Geco-Prakla, comprising high-density sampling of each individual sensor for optimal grouping, together with 100 closely-spaced ocean bottom seismometers (OBS), to provide a detailed crustal image from the sediments, through the basalt flows and into the possibly intruded or underplated lower crust. Results will be placed in the public domain, and we expect it to become a high-quality long-term test-bed profile against which other

new techniques can be tested, such as e/m sampling, bottom-cable tests, 3D long-offset profiling, and possibly even deep stratigraphic drilling, with the optimally-grouped Q data preserved by Schlumberger as a test dataset on which new processing algorithms can be developed.

- Field acquisition using a grid of 100 OBS and conventional seismic reflection profiles to map the transition from continental crust to fully oceanic crust across the Hatton-Rockall Basin and rifted continental margin (Fig. 3). The profile will extend well out onto the oceanic crust, which here is well dated by seafloor spreading magnetic anomalies, in order to map possible crustal thickness variations associated with gravity lineations thought, by analogy with the V-shaped ridges found south of Iceland, to represent pulsing of the mantle plume on a timescale of 3-5 Ma[2,19]. It lies in a region of rapid change in the impact of the Iceland mantle plume at the time of breakup, so will help to constrain spatial variations from that cause.

Deliverables to Industry

In addition to the scientific objectives above, this research programme will deliver the following to industry:

- Rifted margin modelling software incorporating structural, volcanic, thermal and stratigraphic processes.
- Crustal structure (incl. sediment and volcanic thickness) for Faroe-Shetland and Hatton-Rockall Basins.
- Development of new sub-basalt and lower crustal imaging strategies including incorporation of wide-angle 3-component data and possible converted S-wave imaging.
- Profiles for UK and adjacent Atlantic margins of stretching histories, bathymetry and subsidence evolution, and top basement heatflow with time.
- Temperature and maturation history at selected locations.
- Generic models for structural, stratigraphic and volcanic components of rifted margin formation.
- Reports prior to publication, access to established researchers, and access to bright young academic researchers in the form of PhD students and postdoctoral research assistants.

Research Methodology

Development of a new theoretical model of rift margin We believe that the formation of the outer parts of rifted margins, heterogeneous stretching and mantle exhumation owe more to sea-floor spreading initiation than to the processes of intra-continental rifting. We will adapt two-phase flow[14-16] models of mantle flow and melt transport, previously used at ocean ridges, and apply them to rifted margins. Steady state two-phase flow models (Fig. 5), incorporating the transport of both solid matrix and melt fluid, predict the divergent motion of the asthenosphere and lithosphere matrix and the focusing of basaltic melt into the narrow axial zone spreading centre at ocean ridges to form constant thickness oceanic crust. Two-phase flow models will be applied to the initiation of sea-floor spreading within continental lithosphere. Preliminary work (Fig. 6) shows that such models generate heterogeneous stretching and have the potential to exhume mantle when applied to the initiation of sea-floor spreading. Continental lithosphere rheology (quartz-feldspar crust, olivine mantle) will be incorporated into the initial conditions. The application of both passive (plate driven) and active (buoyancy driven) two-phase flow models to rift margin formation will be examined. The suppression of decompression melting by partial geotherm re-equilibration[6] during slow early sea-floor spreading will also be incorporated in the model. This work will be primarily carried out by the NERC funded PhD student supervised by Kusznir, White and Roberts.

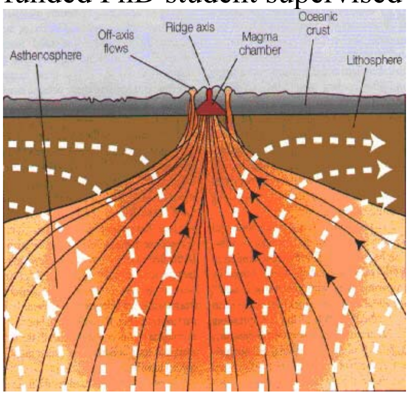

Figure 5 *Two-phase flow model of matrix and melt flow at an ocean ridge[16].*

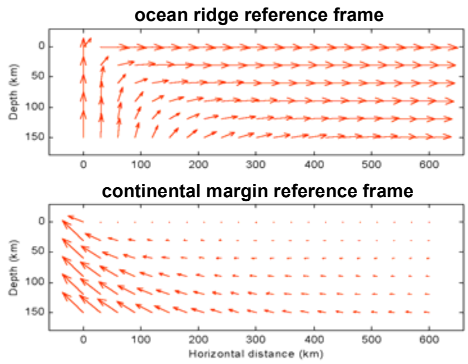

Figure 6 *Fluid flow model of divergent mantle flows at an ocean ridge shows depth-dependent stretching[9].*

Model predictions will be tested against observed heterogeneous (depth dependent) stretching on non-volcanic margins using existing published work[1,3], and on the NW European volcanic margins using new data from the seismic acquisition and stretching studies of allied projects in this research programme. The model will be used to predict not only the distribution of crustal stretching, thinning and volcanism, but also the margin subsidence, water depths and top basement heat-flow history. This will be developed into a commercial software package by Badley Technology Ltd with DTI support. The modelling part of this proposal is complementary to that of the scoping project "Thermal structure and magmatism at rifted margins" by R.S. White *et al.* which focuses on melt generation process, and we expect the two groups of researchers to interact on the melt generation and characterisation research to their mutual benefit.

Mapping of heterogeneous stretching and subsidence The UK and adjacent Atlantic margin shows depth dependent stretching for the Vøring, Møre and Goban Spur Margins[7,9]. Little is known of the stretching distribution and subsidence history of the UK Atlantic margin in the intervening area between these regions. Stretching will be determined from the upper crust using fault data, from the whole crust using seismically derived crustal thickness, and for the lithosphere from post-breakup thermal subsidence[7]. Using industry reflection data and existing and new wide-angle seismic data, we will map margin stretching and subsidence and assess the contribution of heterogeneous stretching to the formation of the NW European margins. Knowledge of the contributions of dynamic support and igneous additions to the crust are crucial to these interpretations, so they will be tied closely to the improved imaging of the igneous additions that our acquisition program will provide. This component will be undertaken by the industry funded PhD student supervised by Kusznir, Roberts and White.

Seismic data acquisition The main seismic data acquisition will be in the summer of year 1 (June 2002): the final decision on their component of the funding by NERC and the DTI in April 2001 will be too late to mobilise ships and such a large number of OBS for June 2001. The two main field areas have been chosen in consultation with our industrial collaborators tol enable us to address a wide range of issues, from the technicalities of improved seismic imaging through basalts and into the potentially intruded or underplated lower crust, to traverses of plume-influenced transform and rifted volcanic continental margin and integration with existing and planned subsidence data from boreholes.

The two field acquisition programs are described separately, although for logistical efficiency we plan to collect the OBS data in back-to-back cruises each of 21 days duration. The Q-data profile will shot separately by Schlumberger Geco-Prakla along the identical track to the Faroes OBS profile, since the 50m shotpoint intervals required for enhanced imaging would cause wrap-around multiples and subsequent degradation of the wide-angle data[29]. This also considerably eases the logistic problems that would arise if we tried to schedule the Q-profile acquisition and the OBS acquisition into the same narrow time window.

The Faroes seismic survey will cross from a region in the Faroes-Shetland Trough beyond the feather edge of the basalt flows, through the recently licensed areas in the SE Faroese waters, and northward across the transform continental margin into the Voring Basin oceanic crust (Fig. 4). Several holes will be drilled in the licensed areas in the next few years: although results from these will initially be confidential to the companies involved, they will be released into the public domain shortly after the end of this project and so will provide considerable added benefit to the usefulness of our profile. The extensive work that will be done by oil companies in these blocks, including planned 3D seismic surveys, will also in due course enhance the usefulness of our profile in tying together the regional structure. The major companies with Faroes licenses are all involved as collaborators, so our results will be of immediate benefit to them.

The main scientific objectives from this survey fall in two main categories. First, to investigate whether there is any lower-crustal intrusion or underplating under the Faroes shelf, and to map the crustal thickness and hence the degree of stretching so as to provide constraints for subsidence modelling. At present there is essentially no reliable crustal thickness information between the Faroes rifted margin and the bottom of the Faroes-Shetland Trough, and although underplated melt has been postulated to flow as far as the Shetlands, there is as yet no observational evidence that this is so. If we do not find evidence for underplating, it will mean that if there is underplating under the Shetlands and northern Scotland as seems to be required to explain their uplift, then it must have been emplaced from directly below those areas rather than have flowed laterally beneath the Faroes-Shetland Basin. Second, we will use the combination of Q-profile streamer with OBS to achieve continuous offsets from normal incidence to hundreds of kilometres, and use this data to develop enhanced sub-basalt and lower crustal imaging capabilities.

The profile is embedded in a grid of long-offset 2D profiles that have already been acquired by Geco-Prakla and Amerada Hess Ltd (Fig. 4): the aperture of existing profiles varies from 12 km using a single ship to 38 km FLARE data using multiple passes of two seismic ships[10]. Results from these existing long-offset profiles, on which White and Christie have worked, gives us confidence that we will be able to use the combination of the new 12-km offset Q-profile with very large aperture 3-component OBS data to improve sub-basalt imaging markedly. Sparse, wide-angle data from an offshore-onshore recording of a FLARE profile shows that the presence of low-velocity sediments beneath the basalt flows can be mapped across a wide area of the Faroes shelf[10,17,26,30] (Fig. 7). But the main advance in imaging comes from combining high-quality wide-aperture profile data with a good velocity model for the deep crust which allows pre-stack depth migration of selected parts of the wavefield to achieve sub-basalt and basement images[32] (Fig. 8).

We will record the wavefield at all offsets from normal incidence to hundreds of kilometres along the 350-km long line by shooting a 12-km Q-profile and by deploying separately 100 OBS at 5-km spacing along all the line, with a 20-km region of dense (500m separation) OBS along part of it. The dense portion will be chosen in a structurally simple area of flat-lying basalts, with good P to S wave conversion. We will experiment with deep imaging using OBS data directly, and also use the 3-component data to 'tag' arrivals that are from converted shear waves, then use the Q-streamer data to attempt to use these converted arrivals for direct imaging in the same way as with p-waves. The potential benefit of using converted s-waves is that the p-wave velocity in the sub-basalt sediments is likely to be similar to, though higher than the s-wave velocity in the overlying basalts, so it may be possible to record turning converted waves from the sediments that it is not possible to generate with pure p-waves, because the sediments form a low-velocity zone. The OBS will be deployed from a NERC ship and two passes of airgun shooting will be made along them: once with an airgun source tuned for low frequencies for enhanced lower crustal imaging; with a higher frequency source and closer shot spacing on the return traverse. A total of 21 days at sea will suffice to deploy, shoot into and recover the OBS, with Torshavn in the Faroes as a convenient close port.

Data processing will be primarily by a postdoctoral researcher and a tied CASE student (this proposal) with Schlumberger Cambridge Research, which will enable the student to use the powerful data processing facilities in the Schlumberger offices to work on the optimally-grouped data from the Q-profile.

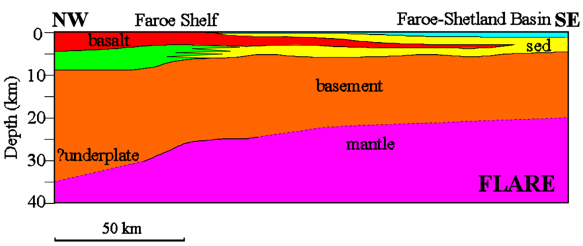

Figure 7 Crustal structure from wide-angle seismic in the Faroe-Shetland Basin[17].

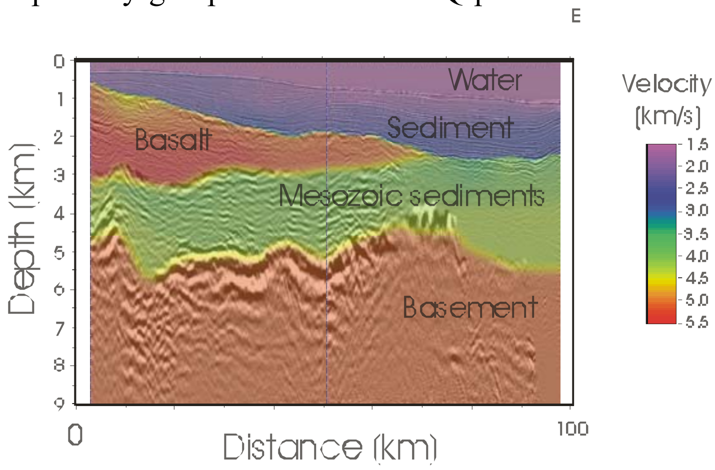

Figure 8 *Sub-basalt seismic imaging in the Faroe-Shetland Basin[32].*

The Hatton-Rockall Basin and Hatton Bank seismic survey will address the spatial distribution of melt products and the transition from continental to fully oceanic crust in the simplest portion of rifted margin of which we know in the North Atlantic, and in an area intermediate between surveys on the Faroes margin to the north and Edoras Banks to the south where White and co-workers have already found evidence for underplating[4,26,33,34]. There is also good seismic control along the conjugate East Greenland margin[5]. This area has been less fully explored by the hydrocarbon industry, though the Hatton-Rockall Basin may be prospective, so there is at present little well control. However, the advantage of this area is that it is a classic volcanic margin, with the continental Rockall-Hatton block that here split when the continents broke apart being separated from the European sediment supply by the sediment trap generated by Rockall Trough. The basement structure is therefore not obscured by a thick sediment or even salt layer, as it is on many other volcanic margins. This makes seismic imaging easier. Furthermore, we are able to take advantage of the simple relationship that exists between the mantle temperature beneath oceanic spreading centres and the thickness of crust that is generated when they rift to use the oceanic crustal section offshore the margin to investigate possible variations in the mantle plume temperature with time: such pulsing of 20-30 C° has been inferred from the present day Iceland plume, and gravity lineations suggest that it also occurred in the North Atlantic immediately following continental breakup[2]. If so, it will have a profound control on the sediment and subsidence pulses not only on the margin itself, but also in the hinterland around the UK.

We will deploy 100 OBS across the margin, with a series of short strike-lines along gravity highs and lows on the oceanic crust and a grid of OBS over the underplated region (Fig. 3). The sediments are relatively thin, and in order to make corrections for the sediment section in the wide-angle interpretation, we will record a 2.4 km normal incidence streamer profile in the course of shooting into the OBS. Though the shooting will be optimised for wide-angle OBS arrivals rather than the normal incidence profile, past experience shows that the reflection profile will be adequate for making corrections for the sediments. There are also dense grids of shallow reflection profiles in this region recorded by the BGS-industry Rockall Consortium, and we expect to be able to have access to these for making sediment statics corrections by agreement with the Rockall consortium (K Hitchen, pers. comm. to White, Sept 2000).

Acquisition will take 3 weeks on station, for OBS deployment and recovery, for airgun shooting, and some contingency time. Reflection data will be processed to stack commercially, with specialist post-stack processing at the Bullard Labs using Promax and SeisUnix. The OBS data will be processed at Cambridge using the suite of modelling and tomography software that is presently in use and is continually under development by a group of researchers working on a variety of wide-angle. In addition to mapping the crustal structure changes that occur across the Hatton margin we will use the 3-component data to investigate the presence of anisotropy in the lower crust caused by igneous intrusions. It is possible that the large quantities of melt added to the lower crust are injected as sills in the continental rocks rather than as solid underplate, and if so there should be a strong anisotropy in the velocities.

The research team, in addition to the four Principal Investigators, will include 4 PhD students (two based at Cambridge, two at Liverpool), an experienced postdoctoral researcher to handle the wide-angle data acquisition and processing, and a research assistant to be in charge of data archiving and distribution of raw and processed data and reports on the work. We expect the research assistant to also be involved in active research. We anticipate that the high-quality, novel datasets we record will be of considerable potential for future investigation of processing and modelling algorithms, and that we may take on other PhD students in the future to look into such developments. However, for the purposes of this funding we incorporate money for four PhDs (two from NERC, two from industry money), to undertake the obvious first steps.

Project Management

Kusznir will be overall project manager. We will integrate closely everyone involved in different aspects of the project to achieve maximum cross-fertilisation. Kusznir will lead the theoretical development and application of new quantitative models of rift margin development; White will take charge of the marine deep seismic data acquisition, data processing and interpretation of the surveys on the Faroes and Hatton-Rockall margins; Roberts will lead the construction of commercial software based on the numerical models of rift margin processes that we develop; and Christie will oversee the Q seismic system data acquisition, processing and interpretation.

Project team meetings of all the participants from Liverpool, Cambridge, Badleys and Schlumberger will take place quarterly, with the locations rotating around the offices of these 4 groups as appropriate. Minutes will be circulated to all project collaborators. Alternate quarterly project team meetings will be combined with a full syndicate meeting to which all collaborating oil companies will be invited, with presentations by project personnel summarising research progress. The research will also be presented at international symposia and published in the international literature in a timely manner in the normal way.

In order to facilitate interaction between academia and industry, to provide access to state-of-the-art computing facilities and to increase the value of their training all 4 PhD students will be expected to spend several months working in the offices of collaborating oil companies. Appropriate assignments are already starting to emerge. This project will generate a huge volume of data and, we anticipate, publications, so we include funding for a research assistant to be in charge of the data archiving and distribution and to assist in the production of reports; we expect them also to be research active in some appropriate area of the project.

Potential Benefits and Means of Dissemination

The deep water of rifted margin is the frontier exploration region for the oil and gas industry. Advances in our understanding of the formation of rifted margins (both volcanic and non-volcanic) will greatly assist this exploration effort. UK oil and gas companies are significant players in rifted margin exploration both on the UK Atlantic margin and globally and as a consequence will benefit from the results of this research project. At volcanic margins the inability to image through basalt extrusives using conventional seismic reflection techniques is a serious limitation to successful exploration. Prof. R.S. White has considerable expertise in sub-basalt imaging and this project, together with the collaboration with Schlumberger, will further advance sub-basalt reflection imaging technology. Existing quantitative models of continental lithosphere extension are applicable to intra-continental rifting and do not describe many of the first order observations seen at rifted continental margins. As a consequence the oil and gas industry has no effective quantitative model for predicting basement heat flow, subsidence and palaeo-bathymetry associated with heterogeneous stretching at rifted margins in either non-volcanic or volcanic environments. We will develop a new generation of predictive quantitative models of rifted margin formation process.

Badley Technology Ltd will develop, through this project, a new commercial software package of rift margin formation predicting stretching, volcanics, temperature, subsidence history and stratigraphy for use by the oil and gas industry. Badleys have previously sold and distributed earlier-generation basin-modelling software on a global basis and anticipate being able to do so again with the software product(s) derived from this research. In addition Badleys consultancy portfolio will be strengthened, enabling them to take new techniques to their clients. Exploration of rifted margins occurs world-wide and thus the benefits from this project will be global and not restricted to exploration in the UK or NW Europe alone.

Schlumberger Cambridge Research, through this project, expects to be able to identify improved methods of imaging sedimentary sequences beneath the basalt with sufficient resolution to enable exploration. If so, the successful combinations of acquisition and processing workflows and algorithms will then be made available to **Geco-Prakla** for further development and engineering into commercial-grade software and recommended best practice. SCR will seek to provide Geco-Prakla with a technical edge over its competitors in sub-basalt imaging. SCR will also benefit from access to an informed group of academic and industry researchers resulting in improved understanding of the processes that form magmatic margins.

In addition to the above, research results will be disseminated through:

- ***Syndicate meetings*** All industrial collaborators will be expected to attend 6 monthly meetings at which the research programme investigators will present research results and receive feedback from industry.
- ***Scientific publications*** The results of the research programme will be published in international journals and presented at major international conference. Collaborative authorship with industrial collaborators will be encouraged The principal investigators will also aim to organise at least one UK thematic discussion meeting within the UK on the theme of this research programme.
- ***PhD student industrial placements*** PhD students involved in the research programme will spend some of their time working in the offices of industrial collaborators, ideally for periods of several months. Appropriate links for this are already starting to emerge. Additional shorter visits by the PhD students, as well as by principal investigators, to industry collaborators will be encouraged.
- ***Project reports*** Yearly interim project reports will be produced by the research programme investigators for the benefit of industrial collaborators. This will also be available to NERC and the DTI. Reports will be completed and supplied to all contributors to the project.

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London, pp. 1243-1252; **11.** Pickup, S.L.B., *et al.* 1996, Insight into the nature of the ocean-continent transition off West Iberia from a deep multichannel seismic reflection profile: *Geology*, *24,* 1079-1082; **12.** Minshull, T. A., *et al.* 1998, Restricted melting at the onset of seafloor spreading: ocean-continent transition zones at non-volcanic rifted margins. *Trans., A.G.U.*, *79,* F906; **13.** Manatschal, G. & Bernoulli, D., 1999. Architecture and tectonic evolution of nonvolcanic margins: Present day Galicia and ancient Adria. *Tectonics 18,* 1099-1119. **14.** Spiegleman, M. & Reynolds, J.R., 1999. Combined dynamic and geochemical evidence for convergent melt flow beneath the East Pacific Rise, *Nature*, *402,* 282-285; **15.** Spiegleman, N. & McKenzie, D., 1987. Simple 2-D models for melt extraction for melt extraction at mid-ocean ridges and island arcs. *Earth Planet. Sci. Lett. 83,* 137-152; **16.** Perfit, M.R., 1999. 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Res., 103,* 5185-5201; **23.** Searle, R.C. *et al.* 1998, The Reykjanes Ridge: structure and tectonics of a hot-spot-influenced, slow-spreading ridge, from multibeam bathymetry, gravity and magnetic investigations. *Earth Planet. Sci. Letts, 160,* 463-478; **24.** Smallwood, J.R., White, R.S. & Staples, R.K. 1998, Deep crustal reflectors under Reydarfjördur, eastern Iceland: Crustal accretion above the Iceland mantle plume. *Geophys. J. Int., 134,* 277-290; **25.** Darbyshire, F.A., *et al.* 1998, Crustal structure above the Iceland mantle plume imaged by the ICEMELT refraction profile. *Geophys. J. Int., 135,* 1131-1149; **26.** Richardson, K.R., *et al.* 1998, Crustal structure beneath the Faroe Islands and the Faroe-Iceland Ridge. *Tectonophys., **300**,* 159-180; **27.** Darbyshire, F.A., White, R.S. & Priestley, K.P. 2000, Structure of the crust and uppermost mantle of Iceland from a combined seismic and gravity study. *Earth Planet. Sci. Letts, **181**,* 409-428; **28.** Darbyshire, F.A. *et al.* 2000, Crustal structure of central and northern Iceland from analysis of teleseismic receiver functions. *Geophys. J. Int, 143,* 163-184; **29.** McBride, J.H. *et al.* 1994,Seismic reflection profiling in deep water: avoiding spurious reflectivity at lower-crustal and upper-mantle traveltimes. *Tectonophys, **232**,* 425-435; **30.** Fruehn, J., White, R.S. *et al.* 1999, FLARE - A two-ship experiment designed for sub-basalt imaging. *World Oil,* January 1999, 109-113; **31.** Fruehn, J., Fliedner, M.M. & White, R.S. Integrated wide-angle and near-vertical incidence sub-basalt study on large aperture seismic data from the Faeroe-Shetland region. *Geophys,* in press, 2000; **32.** Fliedner, M.M. & White, R S. Sub-basalt imaging in the Faeroe-Shetland Basin with large-offset data. *First Break,* submitted September 2000; **33.** Spence, G D., *et al.* 1989,The Hatton Bank continental margin-I. 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Part 3: Exploitation Plan

Badleys Technology Ltd have a proven record of converting the results of academic research into commercial software for use in the oil-and-gas industry. Previously Badleys have received LINK funding (with the University of Liverpool) for exploiting the results of research work on fault analysis and fault visualisation. The resulting suite of programmes, collectively known as FAPS, is now into its fourth major release and is an industry standard. Currently Badleys and N.J. Kusznir are receiving EPSRC support for taking techniques of fault modelling and fault growth into 3 dimensions, with the results planned to be released as commercially-available software modules. In addition, without the aid of grant support, Badleys and Kusznir have worked to make the basin-modelling programmes STRETCH, FLEX DECOMP and HEAT available both commercially to industry and for research purposes to academic workers.

Badleys exploitation plan for the current project is three-fold:

- ***Software tools will be produced for commercial distribution within the oil-and-gas industry.*** The research-base of Liverpool/Cambridge will derive several new analytical techniques during the course of the planned project. Badleys will test these techniques for their relevance to commercial exploitation, and those that will be of benefit to the broader oil-and-gas industry will be developed into software tools. If the research is particularly successful this could ultimately lead to the development of a full forward-modelling programme for the development of rifted margins. The testing of the evolving modelling techniques will take place as the project proceeds. Further programming effort by Badleys on those techniques identified to be commercially-applicable will take place during year-3 of the project.

Badleys consultancy portfolio will be strengthened. Badleys perform consultancy for the oil-and-gas industry on a world-wide basis. To maintain their impetus as leading-edge consultants Badleys have continually added to the analytical techniques they offer their customers as part of their consultancy portfolio. Past work with Kusznir has shown that our current understanding of rifted margins is not complete and that Badleys cannot answer with full confidence all of the questions asked by clients. The current project should provide Badleys with a vastly-improved knowledge-base to take industry clients. Badleys' ability to exploit new concepts arising from the research should be immediate and ongoing during the project.

- ***Badleys will work with bona fide researchers to introduce them to the results of the planned research***. Current Badleys software (FAPS, STRETCH, FLEX DECOMP, HEAT) is provided on a not-for-profit basis research institutions both in the UK and overseas. Badleys provide technical support for the software, which extends to collaboration, advice and informal peer review of manuscripts. Badleys hope to be able to disseminate the results of the current work in a similar manner to academic institutions showing an interest in software developed from the project. In addition Badleys will collaborate with researchers at both Liverpool and Cambridge Universities in presenting and writing academic papers and technical seminars.

Schlumberger Cambridge Research (SCR) is a non-profit making SME providing a basic research function for Schlumberger as a whole. It has developed relationships with Cambridge University generally and Bullard Labs specifically in geophysics. There is a well-defined process for the research and engineering of new products within Schlumberger and hence a ready channel for the exploitation of results from this project, if successful. By sponsoring a CASE student to research methods of processing Q data for sub-basalt imaging, and integrating the Q data with OBS data, SCR expects to be able to identify improved methods of imaging sedimentary sequences beneath basalt with sufficient resolution to enable exploration. If so, the successful combinations of acquisition and processing workflows and algorithms will then be made available to Geco-Prakla for further development and engineering into commercial-grade software and recommended best practice. Since Geco-Prakla is operating in a highly competitive service sector, SCR will seek to provide Geco-Prakla with a technical edge over its competitors in sub-basalt imaging. SCR will also benefit from access to an informed group of academic and industry researchers resulting in improved understanding of the processes that form magmatic margins. This will help to identify the most interesting areas in which to carry out non-exclusive seismic surveys capable of being sold to multiple clients.

Geco-Prakla is a world-leading seismic contractor, headquartered in the UK, and offering acquisition, processing and interpretation services on both exclusive and non-exclusive surveys. It will benefit from the project through enhanced exposure to both oil companies and, indirectly, to industry regulators for its new technology Q systems. This technology is as yet untried in sub-basalt imaging, but has the potential to deliver improved resolution. If successful, exposure to the key players in the Faroese licensing round will have impact in the market place and allow Geco-Prakla to tailor seismic acquisition and processing to the needs of those players in the UK and Faroese sectors, and in similar deepwater margins world-wide.

Curriculum Vitae – Professor N.J. Kusznir

Present Position
- Professor of Geophysics, Liverpool, 1986 -

Date & Place of Birth
- 30th April 1951, Boston, U.K.

University Education
- Ph.D. Geophysics, Durham University, 1976
- B.Sc. Hons. Pure Physics, Durham University, 1972

University Appointments
- Head of Department of Earth Sciences, Liverpool University, 1997 - 2000
- Visiting Professor ETH-Zurich, Switzerland, 1996
- Professor of Geophysics, Earth Sciences Department, Liverpool University, 1986 -
- Lecturer in Geophysics, Geology Department, University of Keele, 1977-1985
- Senior Demonstrator, Geological Sciences Department, Durham University, 1974 -1976

Academic Distinctions & Awards
- Bigsby Medallist of the Geological Society of London, 1988
- Bullerwell Lecturer of the Royal Astronomical Society Geological Society of London, 1987

Recent relevant publications

- Kusznir, N.J., Stovba, S.I., Stephenson, R. & Poplavskii, K.N., 1996. "The formation of the N.W. Dniepre-Donetz Basin: 2D forward and reverse syn-rift and post-rift modelling". *Tectonophysics*, **268**, pp. 237-255.
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- Davis, M. & Kusznir N.J., 2000. Are buoyancy force important during the formation of rifted continental margins. *Geophysical Journal International*, Under Revision.
- Davis, M. & Kusznir N.J., 2000. Depth-dependent Lithosphere Stretching at Rifted Continental Margins, *Earth Plan. Sci. Let.*, In Review

Curriculum Vitae – Professor R.S. White

Date of Birth: 12th December 1952

1989	Professor of Geophysics, Cambridge University
1997	George P. Woollard Award of Geol. Soc. Amer. for "distinguished contributions to geology through the application of the principles and techniques of geophysics"
1993	Elected Fellow of the Royal Society
1991	Bigsby medal of the Geological Society of London
1985-89	Assistant Director of Research, Cambridge University
1981-85	Senior Assistant in Research, Cambridge University
1979-82	Emmanuel College, Cambridge, Research Fellow
1978-79	Postdoctoral Scholar, Woods Hole Oceanographic Institn.
1977	M.A., Ph.D., Cambridge University
1974	B.A., Cambridge University

Recent publications

- White, R. & McKenzie, D. (1989). Magmatism at rift zones: The generation of volcanic continental margins and flood basalts. *J. Geophys. Res.,* **94**, 7685-7729.
- Spence, G. D., White, R. S., Westbrook, G. K. & Fowler, S. R. (1989). The Hatton Bank continental margin-I. Shallow structure from two-ship expanding spread seismic profiles. *Geophysical Journal,* **96**, 273-294.
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- Fliedner, M. M. & White, R. S. Seismic structure of basalt flows from surface seismics, borehole measurements and synthetic seismogram modeling. *Geophysics,* in press, 2000.
- Fliedner, M. M. & White, R. S. Sub-basalt imaging in the Faeroe-Shetland Basin with large-offset data. *First Break,* submitted September 2000.

Curriculum Vitae – Dr A.M. Roberts

Present Position
- Consultant Structural Geologist, Badley Technology Ltd, 1986 -

Date & Place of Birth
3 December 1959, Glasgow

University Education
- B.Sc. Hons. Geology, University of London, 1977-80
- Ph.D., University of Liverpool, 1980-83

Employment History
- Badley Technology Ltd, Consultant Structural Geologist, 1986- present
- Britoil, Exploration and Production geologist, 1984-86
- University of Liverpool - Demonstrator for structural geology, 1980-83

Academic Distinctions, & Awards
- Recipient of William Smith Fund 1994
- Chartered Geologist 1991
- Honorary Secretary and Fellow with validation of the Geological Society, London

Contributions to UK Geology
- Honorary Secretary Geological Society, responsible for publications, 1998 - present
- Editor Journal of the Geological Society 1994-1998
- Convenor of the Geological Society Meeting "Geometry of Normal Faults" 1989
- Convenor of the Geological Society Meeting "Passive Continental Margins" 1996
- Active member of the Tectonic Studies Group and Petroleum Group (numerous papers presented)
- Member of the Glasgow Geological Society, Member of the PESGB

Recent publications
- Roberts, A.M. & Holdsworth, R.E. 1999. Linking onshore and offshore structures: Mesozoic extension in the Scottish Highlands. *Journal of the Geological Society,* **156**, 1061-1064.
- Berger, M. & Roberts, A.M. 1999. The Zeta Structure; a footwall degradation complex formed by gravity sliding on the western margin of the Tampen Spur; Northern North Sea. In*: 5th Conference on Petroleum Geology of NW Europe. The Geological Society*, 107-116.
- Roberts, A.M., Kusznir, N.J., Yielding, G. & Styles, P. 1998. 2D flexural backstripping of extensional basins; the need for a sideways glance. *Petroleum Geoscience,* **4,** 327-338
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- Kusznir, N.J., Roberts, A.M., Morley, C. 1995. Forward and reverse modelling of Rift Basin Formation. In: Hydrocarbon Habitat in Rift Basins. *Special Publication of the Geological Society,* **80**, 33-56.
- Roberts, A.M. & Yielding, G. 1994. Continental Extensional Tectonics. In: Hancock, P.L. (ed.) *Continental Deformation.* Pergamon Press, 223-250.
- Roberts, A.M., Yielding, G., Kusznir, N.J., Walker, I.M. & Dorn-Lopez, D. 1993. Mesozoic Extension in the North Sea : Constraints from Flexural Backstripping Forward Modelling and Fault Populations. In: *4th Conference on Petroleum Geology of NW Europe. The Geological Society,* 1123-1136.
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Curriculum Vitae – Dr P.A.F. Christie

Present Position

- Scientific Advisor, Schlumberger Cambridge Research – Advisor to Lab Director for seismic research, development of University and external research contacts. Liaison with Western-Geco. Geophysics Technical Community Leader

Education:

- B.A. Theoretical Physics, St. Peter's College, Oxford.
- M.A. Theoretical Physics, St. Peter's College, Oxford.
- Ph.D. in Explosion Seismology, Queens' College, Cambridge.

Experience:

- 1972 - 1975 Services Techniques Schlumberger, Angola, Nigeria, Gabon, Niger.
- 1975 - 1978 Ph.D. research in explosion seismology, Cambridge.
- 1979 - 1980 Post-doctoral research contract for National Coal Board, Cambridge.
- 1981 - 1985 Unit Geophysicist, Schlumberger Inland Services, London.
- 1985 – 1987 Seismic Department Head, Etudes et Production Schlumberger, Paris.
- 1987 - 1990 Geoacoustics Department Head, Schlumberger-Doll Research, Ct., USA.
- 1990 - 1996 Seismic Department Head, Schlumberger Cambridge Research, Cambridge.
- 1996 – 1997 Seismic Advisor on secondment to BP Exploration, Aberdeen.
- 1997 - 1998 Geosupport & Geophysical Craft Manager, Schlumberger Geco-Prakla, Gatwick.
- 1999 - 2000 Reservoir Geophysics Manager & Geophysics Community Leader, Geco-Prakla, Gatwick.
- 2000 - Scientific Advisor, Schlumberger Cambridge Research (from September 2000)

Professional Activities and Affiliations:

- Society of Exploration Geophysicists (Active member)
- 1988-1989 Associate Editor of Geophysics
- Session co-Chairman at 58th meeting of SEG, Anaheim, Ca (1988).
- Co-Organiser of 1999 SEG Development & Production Forum on Reservoir Monitoring, Kananaskis, Canada.
- European Association of Exploration Geophysicists (Active member)
- 1983 - 1984 Served on working group to create a recommended exchange format for borehole seismic data tapes.
- Session Chairman at EAEG meetings London (1984), The Hague (1988), Stavanger (1993), Glasgow (1995), Amsterdam (1996), Geneva (1997), Leipzig (1998) and Glasgow (2000).
- UK Natural Environmental Research Council Activities
- 1996 Member of NERC Geophysics M.Sc. Review Committee
- 1997 External Reviewer of Hydrocarbons, Offshore Surveys and Geophysical Monitoring for the British Geological Survey Programme Review Group.
- 1999 Member of Steering Committee for the Ocean Margins Programme bringing together industrial and academic research for a better understanding of tectonic, sedimentary and fluid flow processes at oceanic margins.
- University Affiliations
  - 1983 - 1987 External Examiner for Imperial College London Geophysics M.Sc. course; 1989 - 1991 External Examiner for Durham University Geophysics M.Sc. course; 1995 - 1998 External Examiner for Leeds University Geophysics M.Sc. course; Various Ph.D. external examinations at Imperial College, Oxford, Durham
- Refereed Submissions For :
  - Geophysical Journal of the Royal Astronomical Society; Geophysics; Geophysical Prospecting; Computing and Geoscience; First Break, NERC Grant Applications; National Science Foundation Grant Application; Expanded abstracts submitted to SEG and EAEG International Meetings

Publications

Morice, S., **Christie, P.,** Ozbek, A., Curtis, A., Martin, J., Combee, L., Svendsen, M., and Vermeer, P., 2000. 4D-ready marine seismic data: Annual Meeting Abstracts, Society Of Exploration Geophysicists, RC7.6.

1996-7: Five numbered internal reports for BP including one report on modelling seismic wave propagation in stacked basalt flows, and a second on the analysis of borehole seismic measurements in the Lopra well on the Faeroes.

Dangerfield, J.A., and **Christie, P.A.F.,** 1987, Borehole seismic profiles in the Ekofisk field: Geophysics **52**, 1328-1345.

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