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ACRONYM : OMNIBUS

TITLE: Development of the tools and interpretation techniques for ultrasonic surveys to monitor the rock barrier around radioactive waste packages in geological repositories.

PROJECT CO-ORDINATOR : University of Liverpool, UK

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EXECUTIVE SUMMARY

The overall objective of the OMNIBUS project was to develop operational hardware and software technology that can be used to monitor the rock barrier at potential geological radioactive waste disposal sites. The project has involved two main aims. The first aim includes the design and construction of a down-hole tool that can be deployed in a variety of field situations so as to collect ultrasonic data at both hard-rock (e.g. granite) and soft-rock (e.g. argillite) sites. The tool development has involved hardware and software components as well as a field test. The second aim of the project has involved developing new methodologies for processing and interpreting ultrasonic survey data collected by the tool. To maximise the potential for this technology it is important that the data can be interpreted in terms of useful engineering parameters that provide information on the stability of a given rock mass, such as the location, severity and extent of induced crack damage. The project has aimed to address these issues through a series of laboratory, in situ and numerical modelling experiments.

Two principal results have been produced by the OMNIBUS project:

- The project has resulted in the development and testing of an innovative and unique ultrasonic data-acquisition system for ultrasonic survey and acoustic emission (AE) monitoring for both soft-rock and hard-rock situations.
- The project has developed an advanced processing strategy that correlates full-waveform data from an ultrasonic survey recorded in an experiment with large numbers of numerical modelling simulations. By correlating the effects observed in many different models, with explicitly defined crack density, size, fluid-filling and geometry, with changes observed in the experimental survey data it has been possible to analyse changes in the modelled parameters experienced during the experiment. The tool is therefore able to quantitatively characterise the evolution of rock damage induced in a given rock mass through time.

The developed data-acquisition system includes an integrated hardware and software package. The hardware uses lower frequency ultrasonic sensors tuned to the highly attenuating transmission characteristics of argillaceous rocks and the down-hole equipment has been specifically designed for permanent installation in a rock mass. Switching electronics has been developed that allows each sensor in the array to act as both a transmitter and a receiver during ultrasonic surveys. The electronics is a vast improvement over available instrumentation, both in operational specification and in its ability to provide higher spatial resolution in the surveys. These components have been interfaced to a 16-channel high-frequency data acquisition unit operating at up to 10MHz with 16-bit resolution. A high-speed data link interfaces the unit to a PC. A trigger unit has been developed that allows the system to operate in ‘passive’ acquisition mode used for monitoring of AEs generated by fracture extension or movement in the rock volume. Calibration techniques for the ultrasonic system have been developed in order to interpret the resulting ultrasonic amplitude-frequency data in terms of absolute and changing rock mass properties.

Software functions have been written into ASC’s InSite Seismic Processor that completely integrates the hardware with data acquisition, management, processing and visualisation. The software provides configuration parameters to the data-acquisition hardware, controls the switching electronics for the ultrasonic surveys, and automatically captures full waveform information directly from the on-board memory. The data is then passed through real-time processing functions and stored into InSite’s data management framework.

The complete OMNIBUS Data-acquisition System has been successfully tested at Tressange Iron Mine in France where an argillite layer was targeted. The site was chosen as it offered excellent

opportunities for testing of the prototype equipment in a region of argillaceous material with broadly similar in situ properties as rock found in potential sites for the geological disposal of radioactive waste. The field experiment also provided the opportunity to collect an in situ data-set from an argillaceous rock type that could then be integrated with numerical modelling and advanced processing techniques developed as part of the project. A full-scale system was employed using 16 transducers fixed into four instrumentation boreholes. Three test boreholes were excavated through the rock volume within the instrumentation boreholes and then thermally and mechanically stressed (by injecting expansive resin). The OMNIBUS hardware and software package was shown to successfully record AEs (during thermal perturbations) and perform three-dimensional ultrasonic surveys. AEs were located close to the drilled boreholes and predominantly in tight clusters around the location of the heater positions. Signals during the ultrasonic surveys were able to transmit across the array, along ray paths of greater than 4m in length. Stereonets of absolute velocity show a slow velocity in a sub-horizontal orientation, which is perpendicular to the bedding planes. The majority of ray paths passing through the network of three test boreholes exhibit a reduction in velocity and amplitude after heating and injection of the central test borehole. Raypaths passing outside of the network show no change or slight increases.

Laboratory experiments have involved a series of controlled uniaxial and triaxial tests on argillaceous rock samples from ANDRA's *Bure en Meuse/Haute Marne* site in France. These are the only ones of their kind in Bure rock which combined acoustic emission (AE), mechanical measurements and ultrasonic velocity surveys. They were performed so as to establish recommendations on design and back analysis of ultrasonic properties for in-situ experiments, to determine basic empirical relationships between physical parameters of rocks with the wave propagation, and to provide ultrasonic and mechanical data for development of numerical models in the project. Results have demonstrated that the damaging of this rock can generate AEs. Ultrasonic velocities have been mapped in three dimensions and across a tomography plane. Anisotropy was observed to decrease during triaxial pre-peak stresses up to the onset of dilatency, whereupon the anisotropy variation becomes non-linear and decreases more and more quickly towards the peak stress and failure of the sample.

Wave propagation studies in finite difference models have been used to describe the effects of fracture density, sizes, geometry and fluid contents on ultrasonic signals. These were based around two laboratory and two in-situ experiments. In total, results for 667 models have been obtained totalling more than a year's computing time, with different models run in parallel on a super-computer cluster at Liverpool University. An advanced processing strategy for ultrasonic surveying has been developed using a frequency analysis in the amplitude and phase domains. The methodology is a sensitivity analysis for interpreting rock disturbance through the integrated study of full-waveform data from the numerical models with data from the ultrasonic surveys. The analysis is performed by correlating amplitude-ratio and phase-difference results for a selected ray path in an ultrasonic survey with waveforms produced by numerical simulations of the experiment.

Dedicated advanced-processing software has been written in order to facilitate the correlation. This has been written as an integrated module within the same InSite Seismic Processor software that performs the acquisition, management and processing of the survey data using the acquisition system developed as part of the project. The entire system is therefore an integrated tool. Case studies from the four modelled experiments have been used to develop the implementation of the strategy and to provide an interpretation of the rock disturbance in terms of changes in the modelled rock mass properties. For each experiment, a campaign of numerical simulations have been performed so as to model ultrasonic waves propagating through large numbers of cracks with varying crack density, size, fluid-filling, orientation and wave-type. The ranges and resolution obtained when analysing the modelled parameters are restricted by the number of models that can be performed on today's computing resources in a realistic processing time. In each of the four modelled experiments a range of values has been designed to cover the most likely cracking scenarios envisaged during the experiments. By then correlating the effects observed in the models with effects observed from the experimental survey data it has been possible to analyse what changes in these rock parameters the ultrasonic waves passing through the rock must have experienced. By analysing many different models it is also possible to obtain an interpretation of how sensitive the waves are to the rock parameters.

The principal objectives and deliverables laid out at the start of the project have been met. The success of the project can be measured by the fact that an OMNIBUS Data-acquisition System has now been commercially supplied to a nuclear waste stakeholder for use in an underground laboratory. It is anticipated that the technology developed here will be used by a wide variety of organisations charged with evaluating, selecting and operating deep geological repositories for nuclear waste, as well as having applications in other fields of civil engineering.

The full-waveform modelling and advanced processing methodologies for ultrasonic surveys represent important scientific research that is being further progressed by the partners beyond the OMNIBUS project and is being presented for publication in scientific journals. The results obtained here show the methodologies produce useful contributions to the interpretation of ultrasonic data and have considerable scope for use in future research. The limitation of this technique is that the resolution obtained in analysing the effects of the modelled parameters on wave propagation is restricted to the number of models in the pre-defined data sets. These in turn are restricted by the number of models that can be performed on today's computing resources in a realistic processing time. As large super-computer clusters become more highly developed, and computer power increases, then the effect of this limitation will reduce. One area for future development is likely to be the full integration of full-waveform numerical modelling routines with experimental data-acquisition and processing software so as to more efficiently utilise increasing computer power and provide a more efficient advanced-interpretation tool for engineers.

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1. INTRODUCTION AND OBJECTIVES

The overall objective of this project has been to develop tools and associated technologies for monitoring the rock barrier in both potential and operational deep underground repositories for nuclear waste disposal. The developed tools are based on ultrasonic monitoring technology which was proved to be well suited to this particular application in initial studies [*Young & Collins*, 2001; *Hoteit et al.*, 1999].

Currently, a number of large-scale research facilities are being developed to investigate the feasibility of final disposal of nuclear waste in deep repositories. Several international 'technology demonstration' experiments (both within Europe and worldwide) are already underway and a number of others are scheduled to commence over the next few years. These experiments are critical for developing practices for the design, engineering and operation of future repositories, some of which are already being implemented. Furthermore, they will be important for advancing the public's knowledge, understanding and, above all, confidence in the methods that will be employed at any future operational repository. In particular, the technology developed in this project is associated with monitoring to establish the integrity of the 'rock barrier' - a fundamental component of the deep geological disposal concept.

Ultrasonic survey technology involves the use of high frequency (> 30 kHz) elastic waves transmitted from a transducer, through a material, to a network of receivers. As these waves pass through a rock (or other material such as concrete), the characteristics of the waves are affected by the properties of that material. Factors which may influence the transmission of the waves include stress variations, rock fabric, fracture properties (density, size and orientation) and fluid content. The receivers used to record these ultrasonic pulses can also be used to record acoustic emissions (AEs) that occur within the material in response to changes in stress. The AEs indicate the creation of, or movement on, a crack within the material. Ultrasonic measurements have been undertaken on behalf of radioactive waste agencies [*Pettitt et al.,* 2001] and have shown that they can provide information about the internal behaviour of the rock that is otherwise hard to obtain, except by the use of invasive techniques.

Although previous experiments based on ultrasonic technology have shown great promise, considerable opportunities for enhancing and extending the applications of these methods exist. Processing methods employed software that required considerable expertise and experience to operate. The results obtained were often difficult to interpret as no comprehensive calibration studies had previously been undertaken. Even for data collected in more isotropic material such as granite, the interpretation is not unambiguous. Some initial experiments [*Forney,* 1999; *Homand et al.,* 1993] in argillaceous rocks indicate that the collection and interpretation of ultrasonic data are more complex than those in granitic rock.

This project has aimed to address these limitations through the development of state-of-the-art instrumentation and software. By undertaking a series of laboratory-based, field-based and numerical studies, this technology was tested and calibrated. The specific objectives of the project were thus:

1. To develop research equipment and processing methodologies that provide a robust and efficient tool for performing ultrasonic surveys in any rock type. The design of the hardware should ensure that the technology is suitable for deployment in soft, as well as hard rock environments.
2. To perform in-situ testing of the developed technologies in an experiment to examine induced fracturing and disturbance of microstructures in the rock barrier. In this project, a

soft-rock site (i.e. mudstone) was investigated as this, in theory, provides the bigger technological challenge.

3. To conduct controlled laboratory experiments to provide full-waveform ultrasonic data in order to examine the relationship between wave propagation and rock microstructure.
4. To study wave propagation using dynamic numerical models, where the rock microstructure can be explicitly defined. These studies have provided the understanding and framework to develop advanced processing and interpretation strategies for use with ultrasonic data.

At the end of the project the partners have access to a fully tested tool that can be deployed to collect ultrasonic data and assess the behaviour of rock and concrete in future repository experiments and operational sites. Furthermore, the system employs advanced processing methods which will allow rapid acquisition and on-line processing, thus maximising the ability of the system to provide information that can be used for engineering purposes. An improved understanding of how the results can be interpreted in terms of rock-mass properties is further enhancing the versatility of these technologies.

2. SCIENTIFIC AND TECHNICAL DESCRIPTION OF THE RESULTS

2.1. THE OMNIBUS ULTRASONIC DATA-ACQUISITION SYSTEM

2.1.1 An Overview

The OMNIBUS project has resulted in the development and testing of an innovative and unique ultrasonic data-acquisition system for ultrasonic survey and acoustic emission (AE) monitoring for both soft-rock and hard-rock situations. The system consists of a number of components that have either been developed specifically for the task or purchased 'off-the-shelf' where available technology exists [*Collins and Young*, 2004a]. This result has fulfilled one of the principal aims of the project; to develop and test an ultrasonic monitoring tool for investigating the rock barrier in both potential and operational underground nuclear waste repositories. The tool is easy to deploy and provides a high level of automation in terms of data collection and visualisation, both important attributes that were conceived at the beginning of the project. The success of this result has culminated in the first commercial supply of an OMNIBUS Ultrasonic Data-acquisition System to a nuclear waste management stakeholder for use in an underground laboratory in argillaceous clay.

A schematic of the developed system is shown in Figure 1. It is an integrated hardware and software package including the following principal components.

1) OMNIBUS 60kHz Transducers. These are particularly tuned to the highly-attenuating characteristics of argillaceous rocks.
2) OMNIBUS Pulser-amplifier Units. Switching electronics has been developed that allows each sensor in the array to act as both a transmitter and a receiver during ultrasonic surveys.
3) OMNIBUS Sensor Interface Unit (SIU). Specially developed electronics interfaces the pulser-amplifier switching units to software commands provided by the InSite software through a USB connection.
4) Gage Data-acquisition Unit and Computer. A 16-channel high-frequency data acquisition unit sourced from Gage Applied Inc., Canada, has been integrated into the system.
5) OMNIBUS Trigger Unit. A triggering unit, providing logic for triggering on AEs, has been specially developed for the project and integrated into the system.
6) InSite Software. Software routines have been developed to interface directly to the hardware for performing integrated data-acquisition, management, processing and visualisation.

Calibration techniques for the ultrasonic system have also been developed in order to interpret the resulting ultrasonic amplitude-frequency data in terms of absolute and changing rock mass properties [*Collins and Young*, 2004a]. The equipment package has been successfully tested during an in-situ experiment at Tressange Iron Mine in France where an argillite layer was targeted (Section 2.2). A full-scale system was employed using 16 transducers fixed into four instrumentation boreholes.

2.1.2 Borehole Sensor Packages

The sensor package consists of three separate items; an OMNIBUS 60kHz transducer, an OMNIBUS Pulser-amplifer Unit and a cable assembly connecting the pulser-amplifier into the surface electronics.

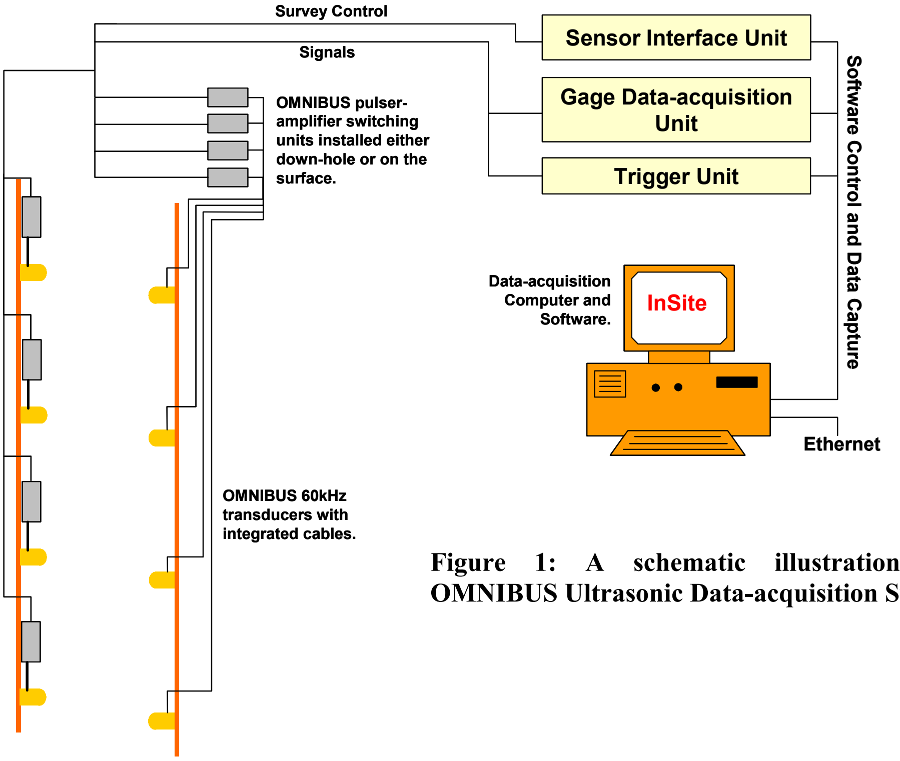

Figure 1: A schematic illustration of the OMNIBUS Ultrasonic Data-acquisition System.

The transducer (Figure 2b) has been custom designed and manufactured for the project. It has a brass casing with a hemispherical front face to fit the curvature of a 76mm instrumentation borehole. It contains a 60kHz 10mm-diameter PZT5a ceramic crystal damped using a unique Belville spring system in order to optimise the response. This provides a sensitivity in the range 25-100kHz; a lower frequency band than has been traditionally used in ultrasonic experiments (e.g. *Pettitt et al.*, 2004) and tuned particularly for the more highly attenuating argillaceous rock masses. The transducer is waterproof, calibrated to 45bar pressure and is connected to a pulser-amplifier unit using a coaxial cable. The cable length should always be minimised with a maximum recommended length of 10m so as to reduce the effects of signal loss and addition of noise before amplification.

The pulser-amplifier unit (Figure 2a) can either be situated down the borehole with the transducer, or positioned just outside the borehole collar (on the ‘surface’), depending on the depth of the transducers. In this project, surface pulser-amplifier units have been produced enclosed in water-resistant dicast boxes (as the boreholes used in the Tressange In-situ Test were sufficiently short). Section 2.5 describes a system that has been supplied with waterproof down-hole pulser-amplifier units using embedded circuity and integrated cable connections. The electronics in the pulser-amplifier has been developed in the project and provides: a) amplification of received signals (either 40 or 60dB); b) transmission of a high amplitude (up to 500V), short duration (rise time of 0.3µs) voltage spike. The latter results in an output elastic wave transmitted from the transducer to all the others in the array. This unique ability to switch between transmission and receiving modes means that: 1) there is a much higher spatial resolution in the surveys as every transducer is a receiver and a transmitter; 2) there is no need for additional costly transducers acting as transmitters.

The pulser-amplifier is connected to the surface electronics using a cable assembly consisting of separate control and signal cables. The control cable provides power and switching commands. The signal cable takes recorded signals to the data-acquisition unit and is separate from the control cable so as to reduce signal noise.

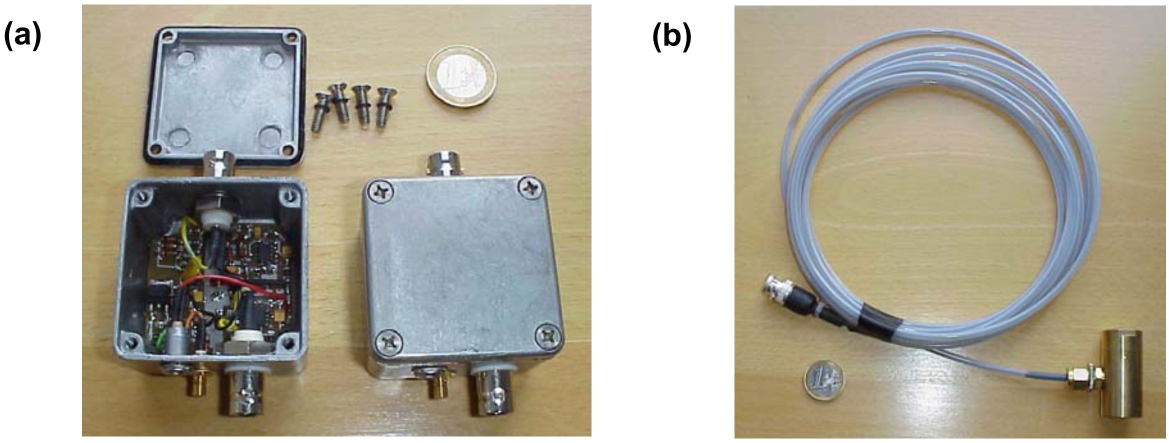

Figure 2: a) Photo of the prototype 3 Pulser-amplifier Unit. b) Photo of the prototype 2 sensor.

2.1.3 Borehole Installation Methodologies

The project has explored two methods of installing the borehole equipment.

1) A retrievable borehole clamping mechanism has been produced. This is optimal for studies in hard rock and short term studies in soft rock. In this case the clamping electronics, transducer and pulser-amplifier electronics are contained in an aluminium module [*Collins and Young*, 2003]. Modules can be connected together using inter-module supports of varying lengths containing cables and connectors. The motor unit and gearing clamps the transducer to the borehole wall, applying a 400N force that is sufficient to ensure good coupling of the sensor to the rock. Two prototype units were built, and successfully tested in a calibration block of Berea Sandstone of size 34x35x15cm containing two 76mm diameter boreholes. A clamping force test rig using a load cell has been designed as a calibration tool, to accurately monitor changes that may be occurring to the clamping force over time.

2) The preferred installation system for permanent deployments in soft rock, such as argillaceous clays, is an instrumentation frame on which the sensors and pulser-amplifier units are fixed. Frames have been developed with a spring-loading system behind each transducer position allowing them to slide into the borehole and ensuring good coupling to the borehole wall (Figure 3). These can either be left in an open or water-filled hole to be retrieved at a later date, or can be grouted into place using a slightly expansive grout. The expansive properties of the grout mitigate against de-lamination as it solidifies. In

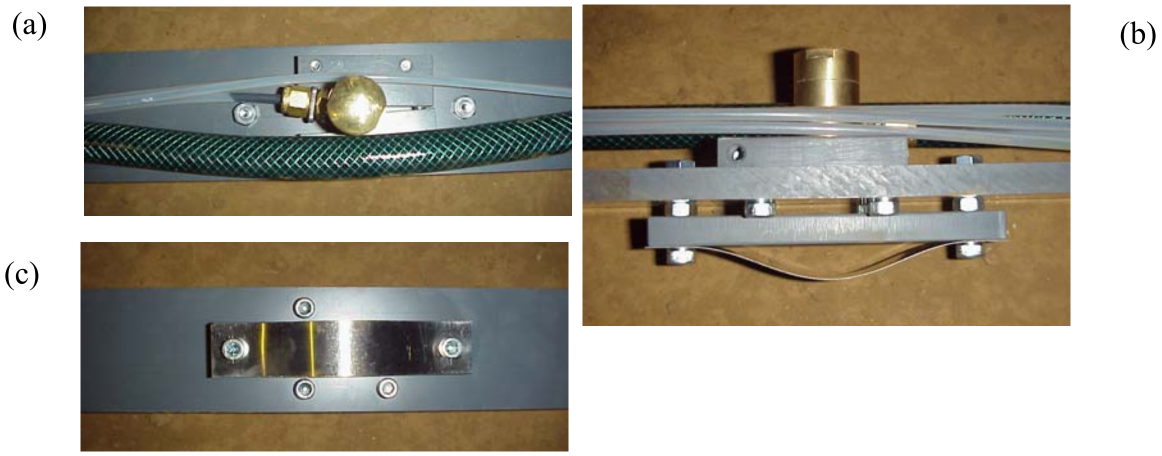

Figure 3: Photos of (a) top view, (b) side view, and (c) bottom view of the sensor, grip, and spring device. The sensor sits in a recess and is held in place by a two piece 'grip'. The spacing of the spring can be varied by 1mm intervals.

argillaceous rock masses the grout is believed to be essential so as to stabilise the borehole wall and stop stress or saturation inducing rock damage that can significantly reduce transducer coupling. A set of PVC installation frames have been built to hold 16 of the OMNIBUS 60kHz transducers. The design of the frame is such that: (1) the sensors are pressed firmly against the borehole wall, (2) grout can flow in all areas around the frame without leaving any air gaps, (3) they are sufficiently rigid that the position and orientation of the sensors are accurately known, (4) they are low cost and relatively easy to engineer, and (5) they consist of modular sections of approximately 2 meters long so that they can be shipped easily to an installation in kit form and then facilitate installation from within a tunnel.

Figure 4: Photo of borehole installation frames being installed at the Tressange In-situ Test.

The instrumentation frame method has been successfully used at the Tressange In-situ Test (Figure 4) and has also been successfully installed at two experiments at SKB's Aspo Hard Rock Laboratory.

2.1.4 Surface Data-acquisition Electronics

The 'surface' electronics is situated outside of the instrumentation boreholes in a suitable cabiner positioned reasonably close to the borehole collars (it can be situated up to 100m away in a 'safe' location away from underground operations). The electronics consists of four separate units (Figure 5).

- OMNIBUS Sensor Interface Unit (SIU)
- Gage Data-acquisition Unit (DAQ)
- OMNIBUS Trigger Unit
- Data-acquisition Computer (PC)

The SIU has been developed as part of the project and connects to the control cables of up to 16 borehole sensor packages. It provides power to the pulser-amplifier electronics and interprets software commands sent from the PC for switching individual sensors between transmitting or receiving mode, thus directing an ultrasonic survey. A 0-500V variable supply allows a user to vary the amplitude of the transmitted signal. The unit interfaces to the PC through a USB connection. A BNC trigger cable connects to the DAQ to give precise feedback on the transmission time (<0.1μs). A trigger input connects to the OMNIBUS Trigger Unit, which passes any trigger commands directly to the DAQ when an ultrasonic survey is not being performed.

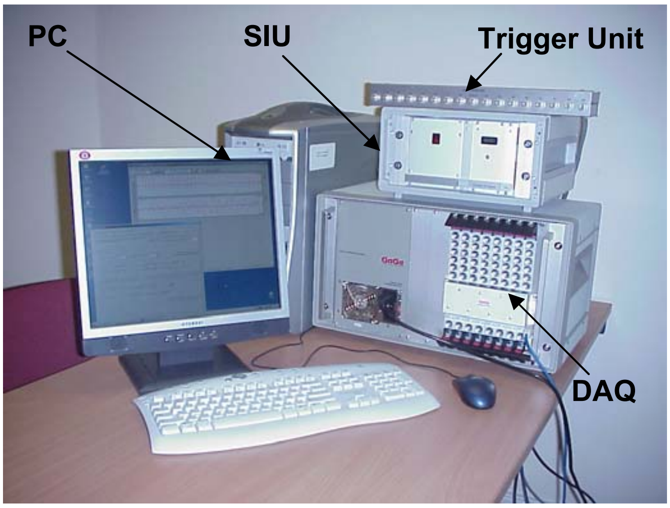

Figure 5: Photo of the surface electronics used in the OMNIBUS system.

The DAQ contains eight 2-channel Gage CompuScope 1610 compactPCI cards installed in a purpose built mainframe chassis. A high-speed National Instruments data link interfaces the unit to a PC. The cards operate in a master-slave configuration with a common time base. Data acquisition can be performed at up to 10MHz with 16-bit resolution up to 10V full scale. The DAQ connects to the data cables from up to 16 borehole sensor packages. An External Trigger input connects to the SIU and The configuration controls are entirely performed through software on the PC. Each card contains 1MByte of on-board memory, into which the waveform data is initially stored. This is then captured on the PC via the PCI interface providing the ability for very large data transfer rates (up to 100MBytes per second).

The OMNIBUS Trigger Unit has been developed for the project so as to allow the system to operate in ‘passive’ acquisition mode used for monitoring of acoustic emissions (AEs) generated by fracture extension or movement in the rock volume. This mode is utilised whenever the system is not performing an ultrasonic survey (‘active’ mode). In the passive case the DAQ must be sent a trigger command when an AE occurs. The Trigger Unit counts the number of ‘hits’ on each of the 16 input channels in a user-set time period. A hit is defined as a signal amplitude above a voltage threshold (0-1V) in time window (0.5-50ms). A trigger condition occurs when hits are recorded on a pre-defined number of channels within the desired time window. The configuration settings and hit count data are transferred to the unit from software running on the PC through a USB interface.

The PC is a standard desktop computer, which has been custom-built by Gage so as to effectively interface with the DAQ. The PC runs Microsoft Windows XP operating system and ASC’s InSite Seismic Processor.

2.1.5 InSite Data-acquisition Software

The OMNIBUS project has resulted in an integrated and comprehensive software package being developed for the hardware system. The software developments have been incorporated into ASC’s InSite Seismic Processor [*Pettitt et al.,* 2004] that provides a fully integrated data management, processing and visualisation platform. Advanced processing strategies for ultrasonic surveys, developed as part of the project and aimed at correlating acquired data with full-waveform numerical models, have been incorporated into a software module presented in Section 2.4.

A modular data-capture utility has been developed allowing new data recorded by acquisition

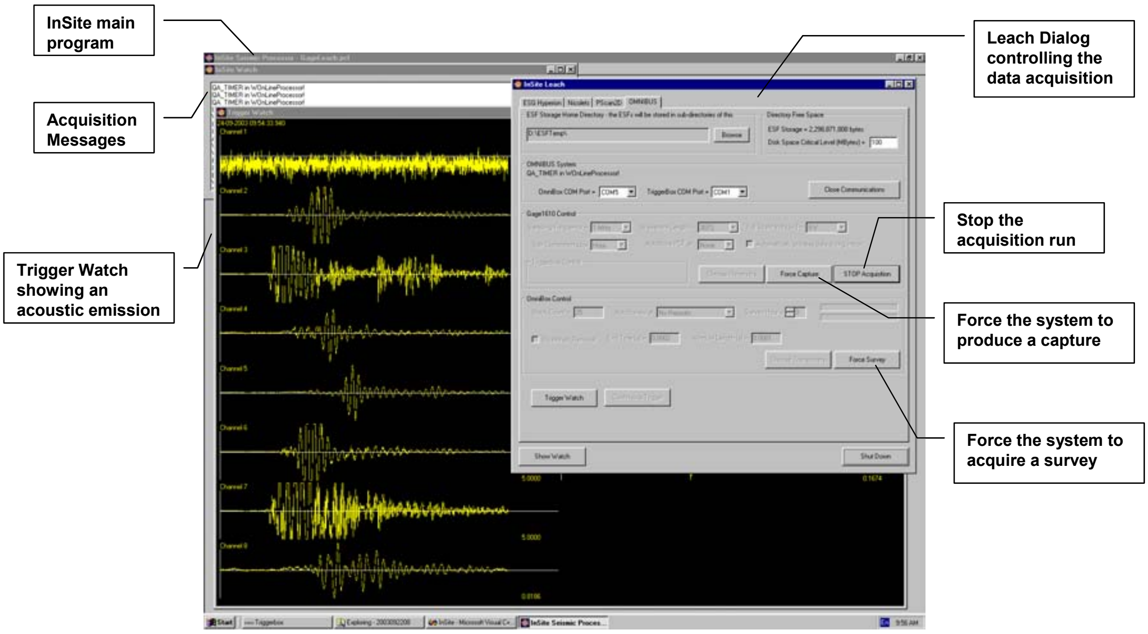

Figure 6: Screen capture of the InSite Software operating at the Tressange Iron Mine test. The Trigger Watch shows waveforms captured from an acoustic emission generated by a heat source.

hardware to be automatically imported into InSite's data-management framework and then processed in real time. The utility, named the InSite Leach, contains a flexible code framework so that the software can be easily updated to be compatible with any seismic acquisition hardware. This is important as it means that the software can be updated for alternative hardware solutions, providing analogue-to-digital (A/D) conversion in the OMNIBUS hardware package. Thus the software can provide consistent and continuous data processing and visualisation functionality. A module was initially written in the Leach to capture waveform data directly from an ESG Hyperion Acquisition System that was initially used in the project for testing of the developing OMNIBUS hardware. This version of the InSite Leach is now installed, and successfully operational, at two underground laboratories investigating the feasibility of high-level radioactive waste disposal (SKB's Hard Rock Laboratory, Sweden and AECL's Underground Research Laboratory, Canada). Research applications of the Leach have resulted in the interfacing to two further laboratory data-acquisition systems.

A software module has been added to the Leach framework, in order to directly control each of the OMNIBUS hardware components presented in the previous section (Figure 6). The software provides configuration parameters to the data acquisition hardware, controls the switching electronics for the ultrasonic surveys via the SIU, and automatically captures full-waveform information directly from the DAQ on-board memory. The data is then passed through real-time processing functions and stored into InSite's data management framework. The software therefore provides an integrated hardware control, data acquisition and real-time processing environment for a user, providing instant results that can potentially be used as a feedback to engineers on the stability of a critical structure being monitored. The hardware and software package has been used during the Tressange Test (Section 2.2).

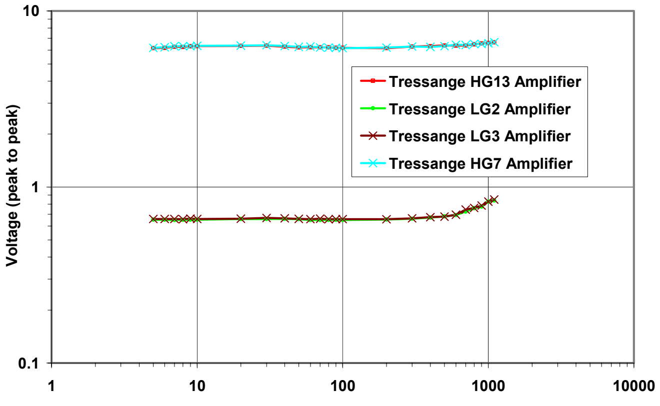

Figure 7: The amplitude frequency response for four of the final developed OMNIBUS amplifiers used in the Tressange field experiment

2.1.6 *Equipment Calibration Methodologies*

A suite of calibration procedures have been developed for the OMNIBUS Data-acquisition System [*Collins and Young*, 2004a]. These aim to calibrate the amplitude-frequency response of the individual components and thus determine the response of the entire recording system – this cannot be determined in the laboratory using a single test as the amplification produces signals too large for data acquisition. The ideal system response is a reasonably flat trend of amplitude versus frequency in the range of interest. For ultrasonic surveys this guarantees that a fairly equal amount of all frequencies are being input into the rock, and therefore losses can be interpreted as due to transmission losses through the rock mass. Figure 7 gives the amplitude-frequency response obtained for amplifier circuitry used in the Tressange Test.

An aluminium calibration block has been designed and built as a tool to help measure the transducer response under realistic in-situ fixing conditions. The cylindrical block has a central 76mm-diameter borehole, in which a transducer mounted on an installation frame (acting as a receiver) can be positioned. A second transducer (acting as a transmitter) can be fixed in a groove (simulating another borehole wall) on the outside of the cylinder. Since aluminium is relatively non-attenuating, the only loss of amplitude is due to geometrical spreading, and therefore the transducer frequency response can be documented. The shape of the block minimizes the effects of artefacts such as reflections from side interfaces. Furthermore, by moving the transmitter around the outside radius of the block the azimuthal response of the receiver can be obtained.

2.2. AN IN-SITU TEST OF THE OMNIBUS SYSTEM

2.2.1 Objectives

The objectives of the Tressange field study were two-fold.

1) To test the hardware and software developed in the OMNIBUS project (see previous section) in an underground environment similar to a future repository, and, in particular, target an argillaceous rock mass. Modifications to the design and construction of the equipment could then be made based on the results.
2) The field experiment also provided the opportunity to collect an in situ data-set from an argillaceous rock type that could then be integrated with numerical modelling and advanced processing techniques developed as part of the OMNIBUS project (Section 2.4).

OMNIBUS[2003] provides a review of the experiment. The site that was chosen is an old Iron Mine offering excellent opportunities for testing of the prototype equipment in a region of argillaceous material with broadly similar in situ properties as argillaceous rock found in potential sites for geological disposal of radioactive waste. Section 2.2.5 summarises results and interpretations from the standard processing of data collected during the in situ test reported by *Haycox and Pettitt*[2004a].

2.2.2 Experiment Site Selection

During the writing of the OMNIBUS proposal it was hoped that the experiment could take place at a site that would have a direct impact on the Nuclear Waste programme in France, i.e. the *Bure Meuse/Haute Marne* site, operated by ANDRA. However a series of delays and operational problems at that site meant that access would not be possible within the time-period required by the experiment. Although it was hoped that an in situ experiment would be possible at *Bure* as part of a shaft extension phase, the results from that experiment would not be ready in time for this final reporting on OMNIBUS. Section 2.5 presents an OMNIBUS system that is now being utilised at this site. Furthermore, one of the main objectives of the field deployment was to test the equipment. Therefore, this was best done at a site, and in an environment, where maximum control over the design and scope of the experiment was retained.

After extensive discussion, the project partners agreed that the *Tressange* site in France offered the best solution. This was considered an optimal site for several reasons:

- The site geology/stratigraphy (a layered iron-stone formation) includes a layer of argillaceous material with broadly the same in situ properties as the argillaceous rock typically found in potential sites for geological disposal of radioactive waste .
- INERIS, one of the main partners involved in the field experiments has extensive experience of working at that site and thus has access to contacts and logistical support that would greatly facilitate the experiment.
- The site offered full flexibility for designing the experiment to meet our own requirements, including the number and positioning of the boreholes

From discussions between the ASC and INERIS partners, and a workshop meeting held with all the partners as part of the mid-term meeting, an outline plan for the field experiment was devised

Baker and Balland[2003]. The actual field experiment was conducted in September 2003 and closely followed the outline plan [*OMNIBUS,* 2003].

2.2.3 Design of the Field Test

The experiment consisted of four 76mm-diameter instrumentation boreholes containing an array of 16 transducers. These were spring-loaded on sensor-installation frames and then cemented in using a slightly-expansive grout. Three 40mm-diameter test boreholes were excavated through the rock volume within the instrumentation boreholes and then thermally and mechanically stressed. During the stress perturbations ultrasonic surveys were performed in which each sensor in turn acts as a transmitter while the other sensors record a response. When not carrying out the surveys the sensors were used to monitor for passive AE events.

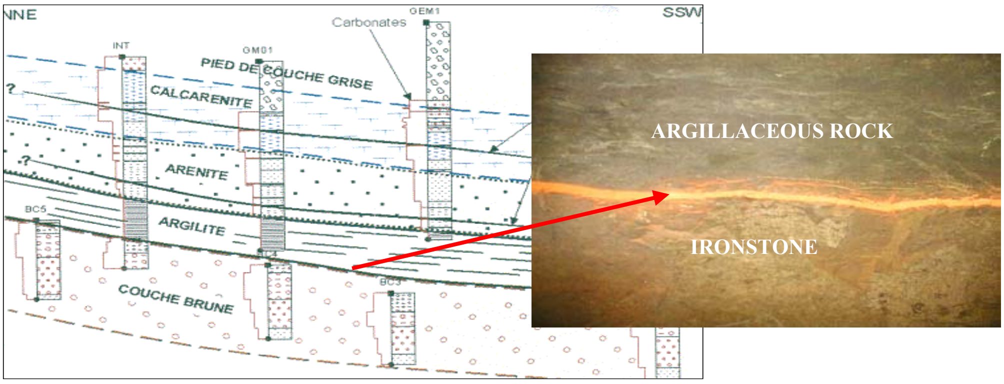

Figure 8 : Geologic log observed on the main cross-cut wall.

The target of the experiment was constituted by two geological facies located at 240m depth in the Tressange Iron Mine, France (Figure 8).

- the iron stone layer is a ferriarenite (particle with high iron and silica content) with a cement which becomes more calcic and argillaceous to the top;
- the argillaceous rock is characterized by a high clay content and a fine grain, the interface with the ironstone is clear but the transition with the upper facies is very progressive.

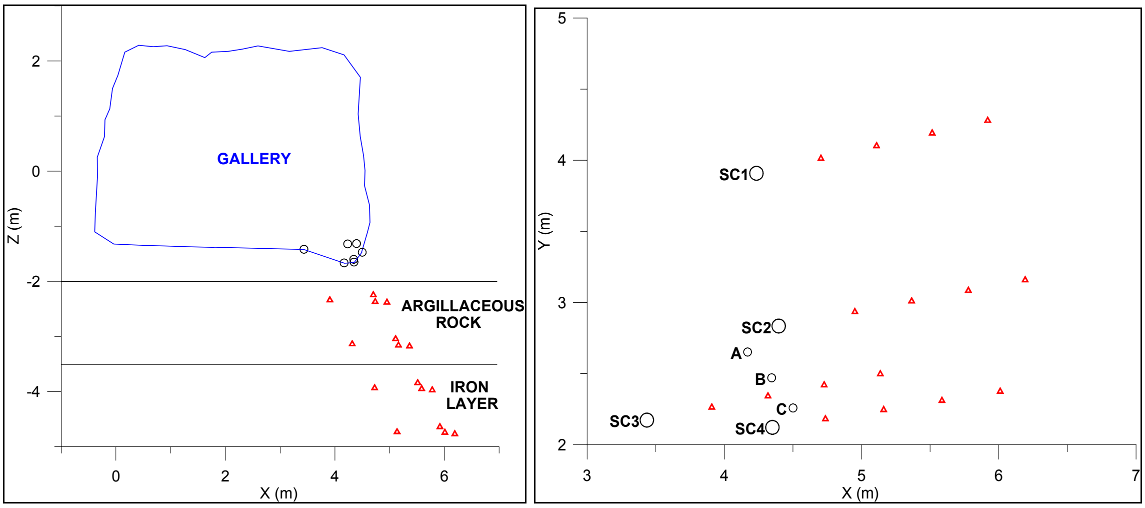

Figure 9 : Schematic plan of borehole and sensor configuration.

The instrumentation (SC1-4) and test (A,B,C) boreholes were drilled at 60° from a mine gallery (Figure 9). A heater element was employed to induce fracturing around one of the test boreholes.

Expansive resin was inserted into the test boreholes to induce a disturbed zone, and alter the stress regime in the region through which raypaths during ultrasonic surveys passed. The induced stresses were designed to simulate those experienced around much larger diameter boreholes used for canister deposition in a future repository.

The acquisition system monitored the experiment during 4 phases:

- during grouting of the sensors in boreholes to observe the effect of grout on the surveys performed every hour,
- during the period of the first expansive resin stress perturbation,
- during the thermal perturbation in acoustic emission monitoring mode,
- during the second expansive resin perturbation with surveys performed every half hour.

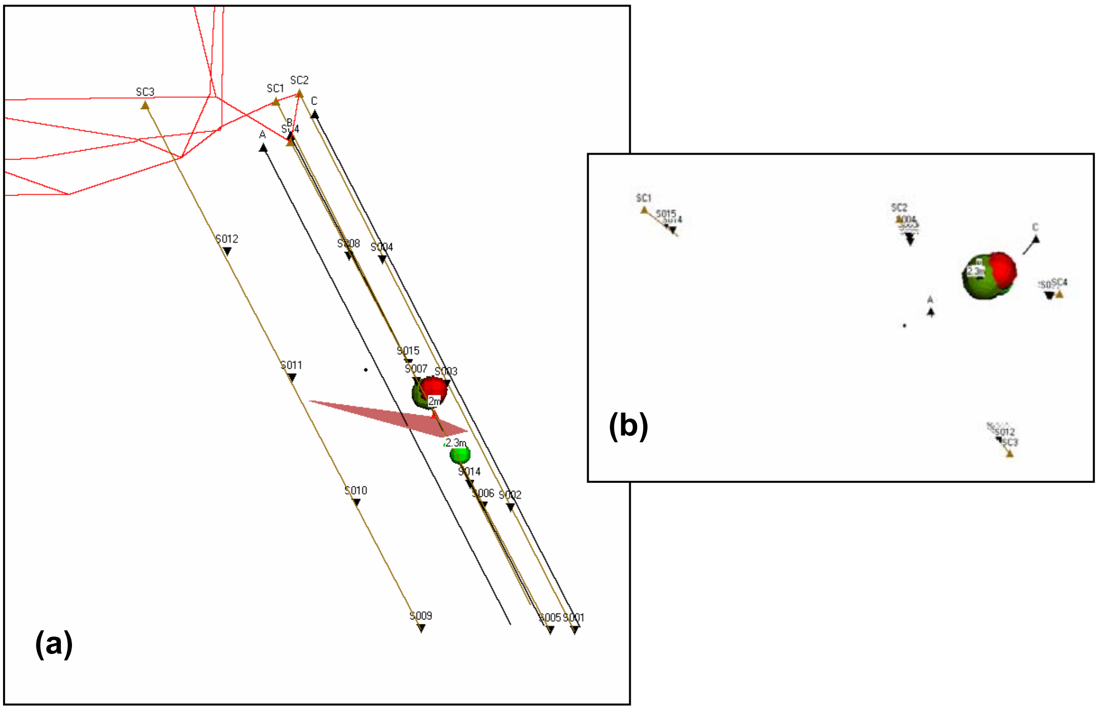

Figure 10: Spatial distribution of acoustic emissions recorded in an argillite, associated with a thermal experiment. Location uncertainty ellipsoids are shown colour scaled to location magnitude. The red lines show the tunnel, the black lines show boreholes, triangles are transducer locations, and the plane represents the interface between argillaceous rock (top) and ironstone (bottom).

2.2.4 Conclusions of the Field Test

Conclusions from the in situ monitoring include the following.

- The OMNIBUS hardware and software package successfully records AEs and performs three-dimensional ultrasonic surveys in an in situ environment. Signals during the ultrasonic surveys were able to transmit across the array, along ray paths of greater than 4m in length.
- The method of sensor coupling used during the experiment facilitated a good signal quality. The coupling method involved a hemispherical shaped sensor that was first spring loaded against the borehole wall and then grouted in.
- Solidification of the borehole grout had no obvious detrimental effect on the signal quality, indicating that the slightly-expansive grout that was used successfully reduced any de-lamination effects.

- The sensor frequency response that was used provided good transmission through the more highly attenuating argillite rock mass. The sensors have a lower ultrasonic frequency range (60kHz) than that generally used in hard rock applications. The sensors were also sufficiently robust when used under water and in grout.
- The dual-mode capability of the OMNIBUS electronics provided the desired result of a higher ray path coverage through the monitored volume by allowing all the sensors to be utilised as both transmitters and receivers.
- Two types of pre-amplifier were utilised, a 60dB and a 40dB version, in order to test differences between the two. It was found that the 60dB version provided a much higher signal quality.
- Signals containing the frequency range used in the experiment could be successfully transmitted across the argillite rock mass. This indicates that the tuning of the hardware to the rock type had been successfully applied and has given confidence that the OMNIBUS hardware can be useful for ultrasonic surveys in soft-rock applications.
- The argillite rock mass can generate recordable AEs, but probably only under intense fracturing conditions. The OMNIBUS hardware was successful in triggering and acquiring this data during thermal perturbations.

2.2.5 Ultrasonic Results

Acoustic emissions were recorded during the two thermal experiments. Events caused by the first experiment occur in the argillaceous rock at 2 m depth (Figure 10). Events due to the second experiment occur at 2.3 m depth in the ironstone. All of the events are located close to the drilled boreholes and predominantly in tight clusters around the location of the heater positions. During the second experiment the events locate in an elliptical shape when viewed down the boreholes. The long axis of the ellipse is in the direction of the other boreholes, which may suggest that microcracks are propagating between them.

Stereonets of absolute velocity show a slow velocity in a sub-horizontal orientation, which is perpendicular to the bedding planes (Figure 11). Amplitude measurements agree with this observation. Amplitude increases are observed on many ray paths after injection of the expansive resin in test boreholes A and C. The theoretical effect of the grout is to increase the compressive stresses around the test boreholes by approximately 40MPa. The stress increase causes a closure of the rock microstructure leading to a decrease in anelastic attenuation and thus an increase in signal amplitude. Increases in measured velocities are also observed in this period, but the changes are often small indicating that elastic moduli are not as sensitive to this effect for this type of rock.

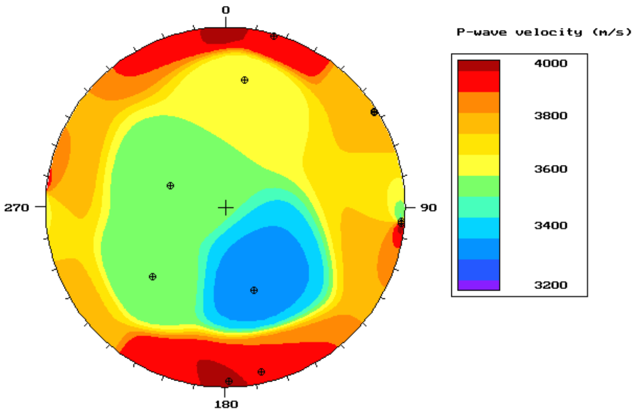

Figure 11: Stereonet of P-wave velocity through the argillite layer.

The majority of ray paths passing through the network of three test boreholes exhibit a reduction in velocity and amplitude after heating and injection of the central test borehole. Raypaths passing outside of the network show no change or slight increases. Figure 12 displays example velocity and amplitude change graphs for all raypaths on the horizontal plane comprising of sensors 2, 6, 10, and 14.

The pattern of observed velocity and amplitude change could be explained by considering the effects of the stress applied by the expansive resin and heating in the near and far fields. In the near field the stress causes additional cracking or extension of existing microcracks in the rock causing a velocity and amplitude decrease for ray paths passing between the test boreholes. In the far field, the stress would have a more elastic response, causing voids and microcracks in the rock to close resulting in velocity and amplitude increase, as observed for the majority of ray paths after injection of resin in the first two test holes.

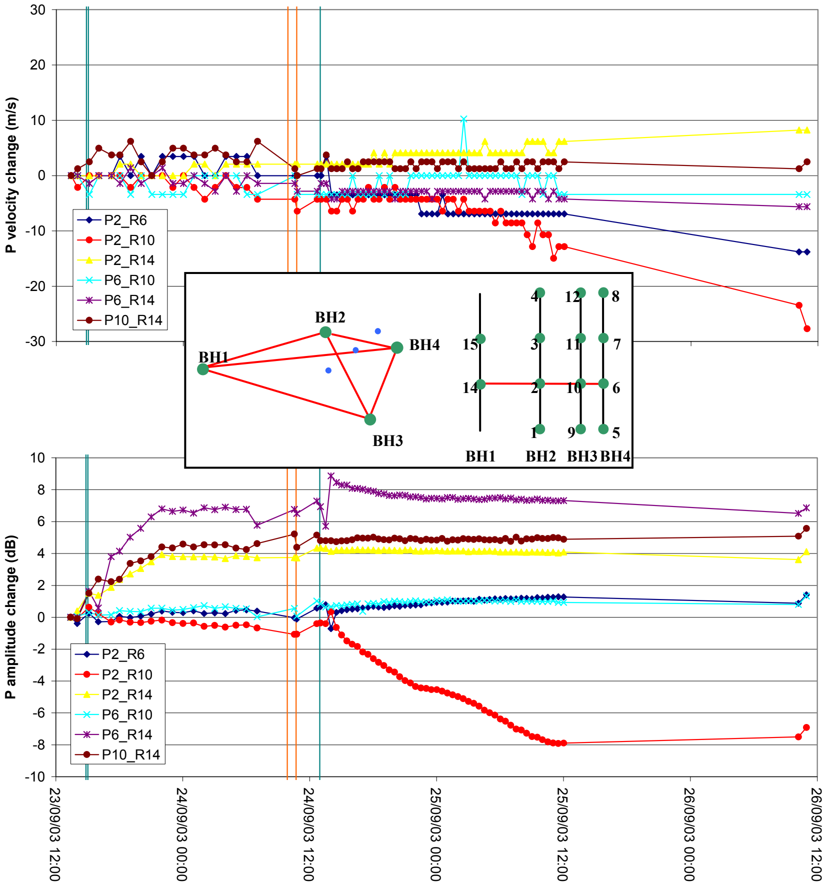

Figure 12: P-wave velocity change (upper) and amplitude change (lower) for raypaths on the same horizontal plane. The raypaths shown on the graph include transducers 2, 6, 10 and 14.

2.3. LABORATORY EXPERIMENTS INVESTIGATING FRACTURING IN ARGILLACEOUS ROCK

2.3.1 Introduction

A series of controlled laboratory experiments have been conducted on argillaceous rock samples from the *Bure en Meuse/Haute Marne* site. The rock samples were provided for the OMNIBUS project by ANDRA. The laboratory tests were the first ones of their kind in Bure rock which combined acoustic emission (AE), mechanical measurements and velocity surveys. The tests included two uniaxial and one triaxial experiment described by *Balland*[2003] and *Balland and Damaj*[2004]. They were performed with the following objectives.

- to establish some recommendations on design and back analysis of ultrasonic properties for in-situ experiments to be performed in the future,

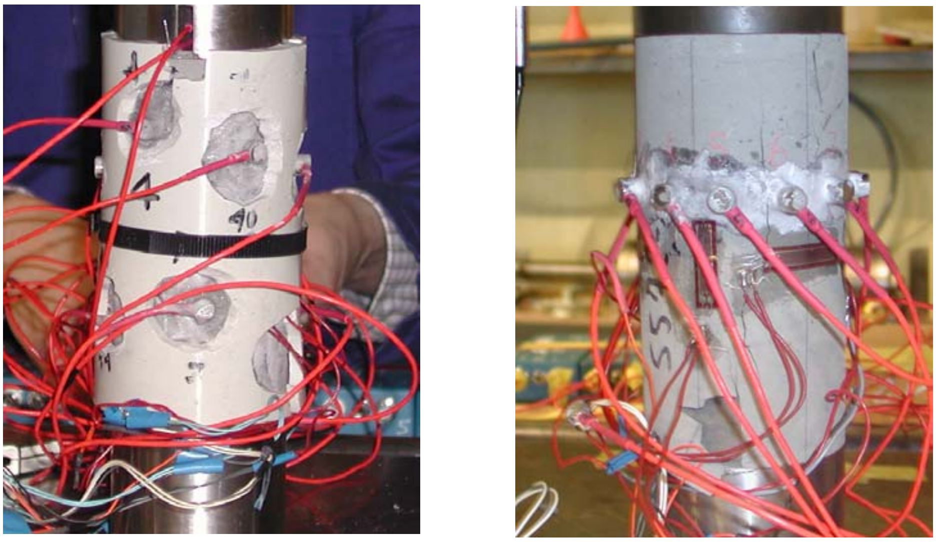

Figure 13: Photographs of the two transducer arrangements used in the uniaxial tests.

- to determine basic empirical relationships between physical parameters of rocks with the wave propagation,
- to provide ultrasonic and mechanical data for development of numerical models with Wave^{3D} (Section 2.4).

The cores were taken from a deep borehole at a depth ranging between –460 m and -472 m. INERIS and LAEGO also developed specific laboratory apparatus to combine uniaxial and triaxial mechanical tests and ultrasonic surveys. The aim of the development was to design and build an adapted triaxial cell and a small box device to protect each of the piezoelectric transducers during the triaxial tests, where the hydrostatic pressure is induced by hydraulic oil injected into the cell. This work was conducted as part of a PhD and was achieved in September 2003. Specific developments were also achieved for data processing, particularly in signal processing and tomography inversion.

2.3.2 Results from the Uniaxial Tests

The uniaxial experiments [*Balland*, 2003] used two different array configurations of 8 receivers and 4 transmitters.

- <u>in configuration 1</u>, the transducers were arranged in order to cover the whole sample allowing to monitor the spatial and temporal variations in AE activity and P-wave velocity field during the experiment. The surveys included 31 rays with length ranging between 20 mm and 140 mm.
- <u>in configuration 2</u>, the transducers were arranged in order to form tomographic plane so as to better describe the variation of the P-wave velocity field in the median plane of the sample. The best angular covering was found in the case of equally spaced transducers, which leads to 96 rays (48 original rays).

Prior to any experiment, several physical parameters as well as the average composition were determined on the first core. The porosity was determined from the mercury

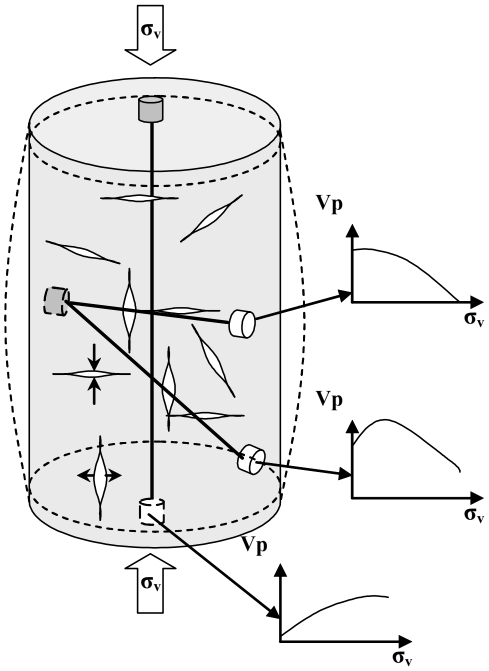

Figure 14: Schematic illustration of the fracturing process of the sample and the correlation between velocity and stress

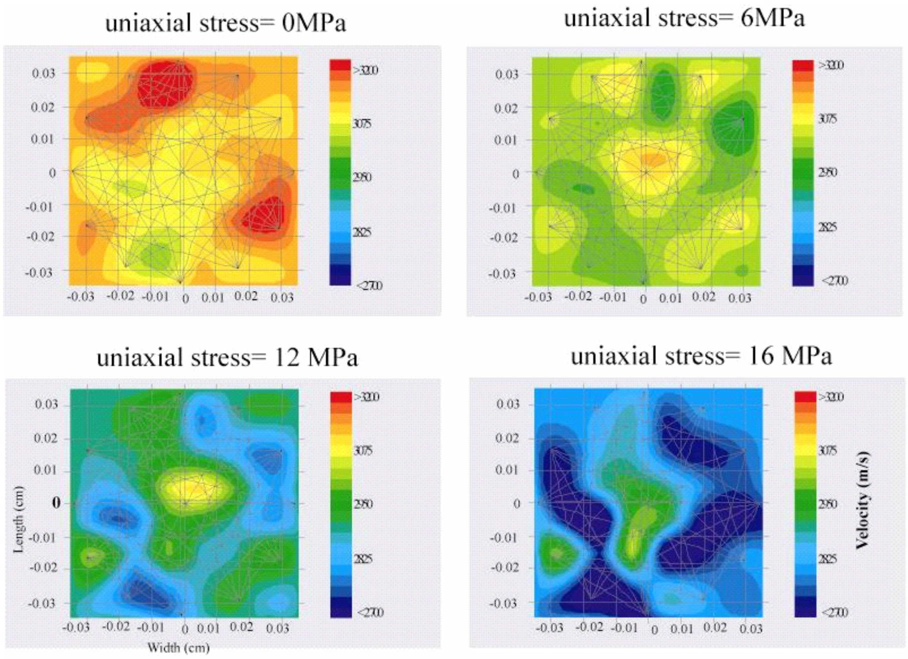

Figure 15: Ultrasonic velocity images across the tomography plane.

porosimetry method; the dry density is the weight of the dried rock per unit volume; the natural density is the weight of the rock per unit volume; the water content is given by the ratio of the water weight and the dry weight of the sample; the content of $CaCO_3$ was determined according to the AFNOR standard.

The ultrasonic measurements highlighted some characteristics related to damage:

- The P-wave velocity decreases from the beginning of the mechanical test in the radial direction and increases in the axial direction. These variations are caused by a closure of the cracks oriented perpendicular to the axial stress direction and by an opening of the cracks on the planes crossing axial stress. The final trend is the addition of both effects (Figure 14).
- Without stress, the attenuation along the cylindrical axis is 5 to 10 times bigger than the one along the perpendicular plane. The perpendicular attenuation increases dramatically when the stress reaches about 6 MPa, beyond which it becomes similar to the one along the cylindrical axis. In the same way, the transversal isotropy, which is significant (14%) in the beginning of

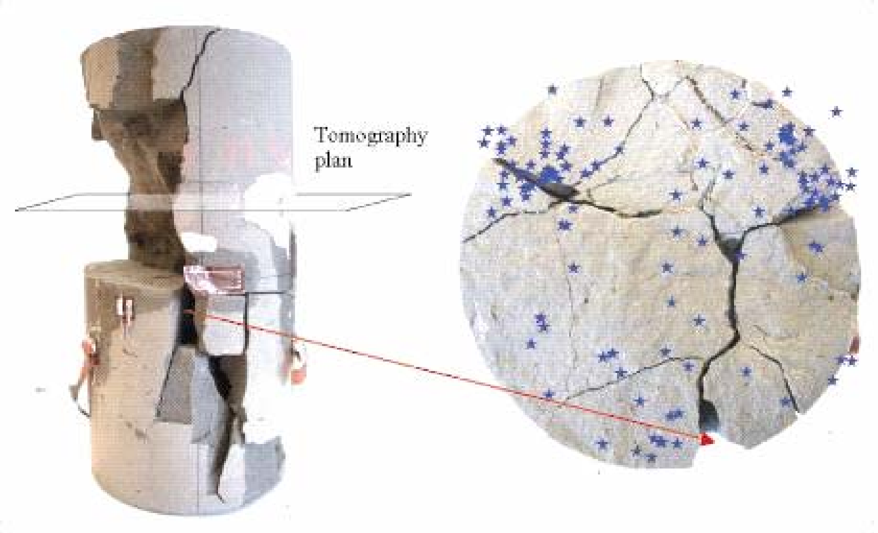

Figure 16: Correlation of AE activity and observed fracturing during a uniaxial test on Bure mudstone.

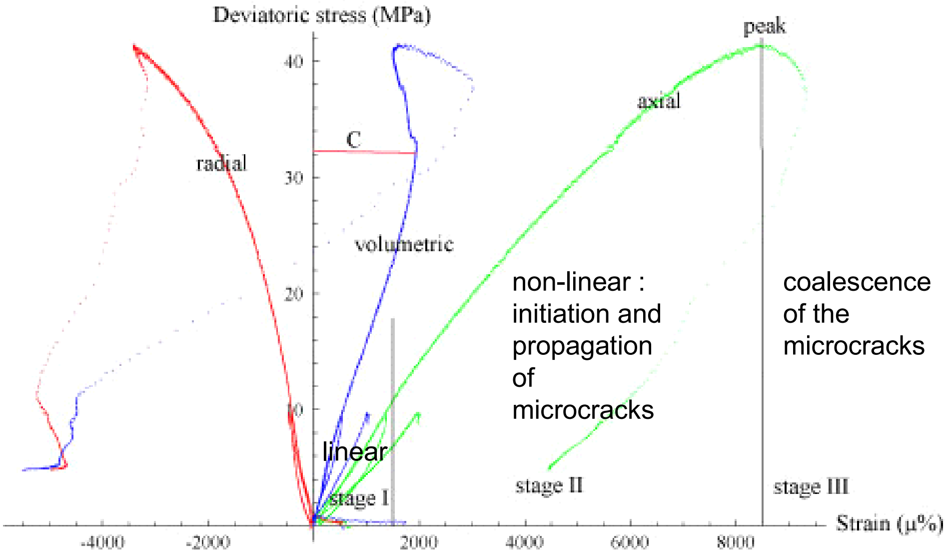

Figure 17: Deviatoric stress vs. axial strain (green), radial strain (red), and volumetric strain (blue) for a triaxial test (at 10MPa confining pressure) on Bure mudstone.

the mechanical test, tends to 0% at the end.

- The discrepancy of the velocity in the tomography plane increases strongly after 4 MPa in axial stress (standard deviation 80 to 110 m/s) and increases strongly again around 13 MPa in axial stress (standard deviation 140 to 170 m/s). This scattering can be interpreted as anisotropy effect in the median plane, that can be of the order of few percent at unloading (without stress) and up to 10 % at the peak stress. Figure 15 shows some example tomographic images highlighting the decreasing velocity field as the test progresses.
- During uniaxial compression, the dynamic characteristics depreciate very soon in the planes oriented perpendicular to the axial stress and decrease dramatically after around 2/3 of U_c. At the beginning it may correspond to the initiation of damage and later it may be related to the coalescence of the microscopic damage to macroscopic fractures that finally cause the failure of the samples. The tests have demonstrated that the damaging of this rock can generate AEs (Figure 16). The localisation of the acoustic emission seems to show that the coalescence of major fractures begins on the edge of the sample.

2.3.3 Results from the Triaxial Tests

Potential nuclear repositories are usually located at relative great depth, in particular for the argillaceous rock Research Laboratory of Meuse/Haute-Marne, which is situated at depths ranging between -422 to -522m. The local state of stress is significant and may cause damage during the excavation of the gallery. In order to approach the local state of stress, it is necessary to take into account the confining pressure while undertaking lab tests. For this reason, a triaxial test was conducted to compare with the uniaxial results.

The experiment was conducted using conventional triaxial apparatus consisting of a stiff loading machine and a confining cell. Eleven ultrasonic sensors were isolated from confining oil within a jacket around the sample. The test was composed of 6 phases:

1. hydrostatic loading up to 4MPa during which the piston is not in contact with the sample;
2. deviatoric (σ_1-σ_3) loading up to 10MPa that starts once the piston is in contact with the sample, while the confining pressure is kept at 10MPa;
3. a relaxation period by keeping the sample height constant to stabilise the deviatoric stress;
4. a deviatoric unloading down to 0MPa;

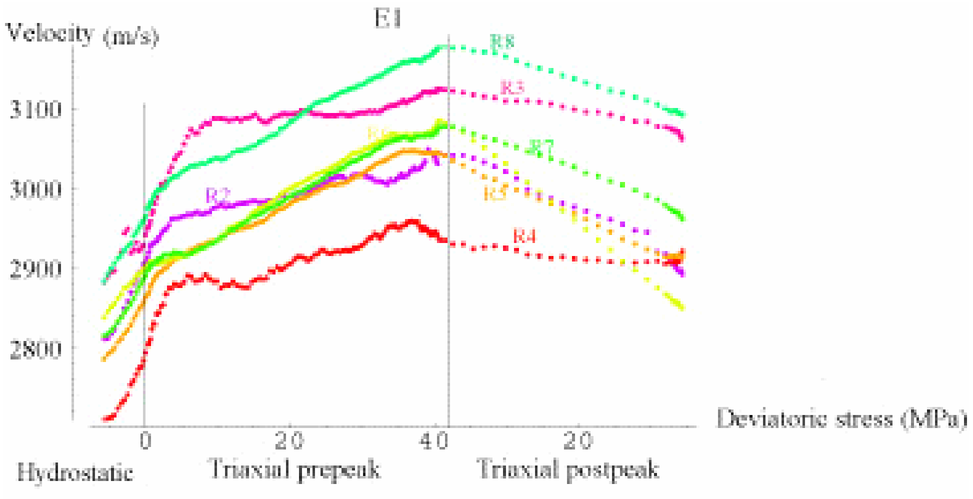

Figure 18: Measured velocities during triaxial loading of Bure mudstone.

5. deviatoric re-loading up to peak stress and post-peak by applying a constant strain rate loading;
6. triaxial and hydrostatic unloading.

Observations of the rock response included the following:

- The critical states of stress (the onset of dilatency and the peak stress) increase with confining pressure; the axial stress at peak stress increases from ~18MPa for the uniaxial tests to 51.6MPa for the triaxial test performed at 10MPa confining pressure. Figure 17 gives the stress-strain behaviour of the sample, where C is the onset of dilatency – peak volumetric strain.

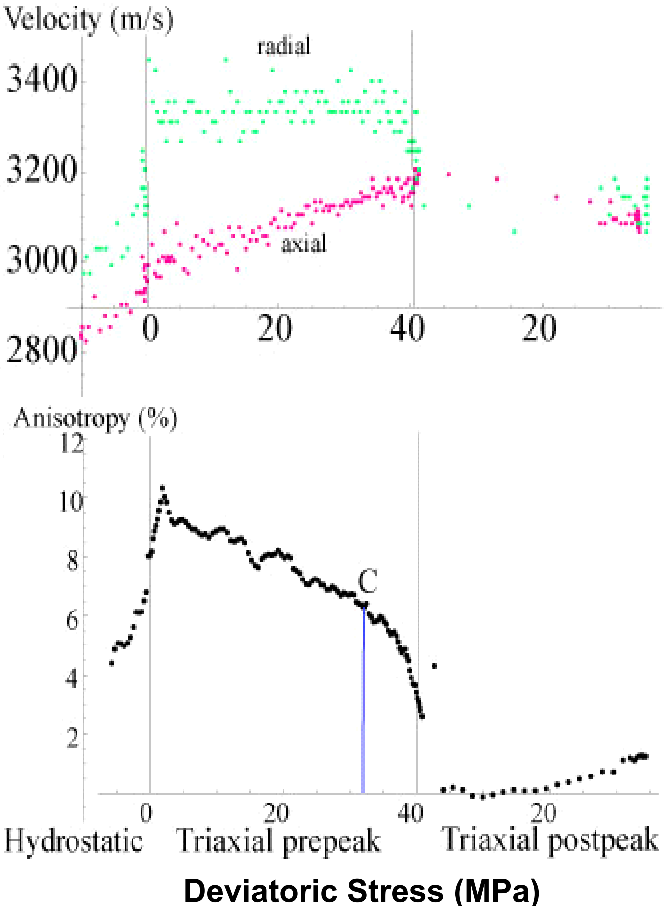

Figure 19: Upper plot is a comparison of axial and radial velocities. Lower plot is calculated anisotropy.

- The P-wave velocity increases with confining pressure; the rise is about 300m/s from 0 to 10MPa confining pressure. This increase is almost of the same magnitude in both radial directions.
- Measured axial velocities started to decrease after the peak stress was attained, rather than at the onset of dilatency (C) – as is often observed in brittle rocks (Figure 18).
- Anisotropy was observed to increase during the hydrostatic loading, followed by a linear decrease during triaxial pre-peak stresses up to the onset of dilatency (Figure 19), where the anisotropy variation becomes non-linear and decreases more and more quickly towards the peak stress.
- Most of the AE events took place during the hydrostatic loading which can be linked to closure of joints. Almost no AE activity was detected during the triaxial loading, except near the peak stress. The surge in AE activity that is observed just after the peak stress is

due to the rupture of the sample that fails due to the development of macroscopic fractures

2.4. INTERPRETING ROCK DISTURBANCE USING FULL-WAVEFORM NUMERICAL MODELS

2.4.1 Introduction and Methodology

The overall objective of the OMNIBUS project is to develop technology that can be used to monitor the rock barrier at potential geological radioactive-waste disposal sites. The project has focussed on two main areas of development. Section 2.4 has provided an overview of the first principal result of the project, that is an ultrasonic data-acquisition system that can be deployed in a variety of field situations as an ultrasonic-survey tool, and which includes an integrated hardware and software package.

The second principal result of the project has been the development of new methodologies for processing and interpreting ultrasonic data collected by the tool. To maximise the potential for this technology it is important that the data can be interpreted in terms of useful engineering parameters that provide information on the stability of a given rock mass, such as fracture densities and sizes. The methodology this project has focussed on is a sensitivity analysis for interpreting rock disturbance through the integrated study of full-waveform data from numerical models with data from the ultrasonic surveys. The overall processing strategy for ultrasonic surveys is presented in Figure 20.

Waveforms from ultrasonic surveys are first processed for standard velocity and amplitude parameters using real-time processing algorithms (Section 2.1). The real-time processing will allow on-site engineers to quickly assess whether changes in environmental conditions during the monitoring period has induced observable changes in rock properties. The waveforms can then be used to produce ‘amplitude ratio’ and ‘phase difference’ frequency spectra [*Hildyard*, 2004] in an advanced processing procedure aimed at interpreting the waveforms into changes in rock properties. The spectra are produced in the frequency domain from two recorded waveforms on the same ray path; the first is a reference waveform from the start of the monitoring period and the second is from the survey being analysed. The two spectra contain all effects produced on the recorded frequency band from the changes in rock properties. Since the data-acquisition system remains constant through the monitoring period then the frequency effect of the system is removed from the analysis.

In order to interpret changes in the spectra in terms of rock properties, a campaign of numerical simulations have been performed to model ultrasonic waves propagating through large numbers of cracks with varying crack density, crack size, fluid-filling, orientation and wave-type (Section 2.4.2). These were based around two laboratory and two in-situ experiments. By correlating the effects observed in the models with effects observed from the experimental survey data it is possible to perform an analysis of what changes in rock parameters the ultrasonic waves passing through the rock must have experienced. By analysing many different models it is possible to obtain an interpretation of how sensitive the waves are to the rock parameters. In total, results for 667 models have been obtained totalling more than a year’s computing time, with different models run in parallel on a super-computer cluster at Liverpool University.

Dedicated advanced-processing software has been written in order to facilitate the correlation analysis (Section 2.4.5). This has been written as an integrated module within the same InSite Seismic Processor software that performs the acquisition, management and processing of the survey data using the acquisition system developed as part of the project (Section 2.1). The entire system is therefore an integrated tool.

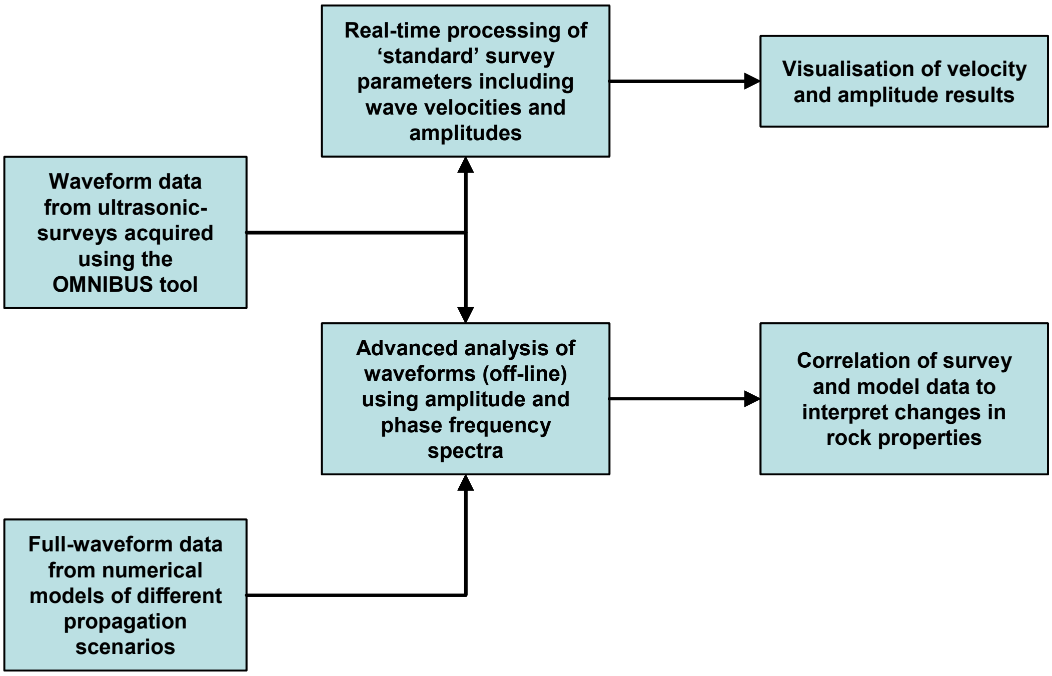

Figure 20: Overview of the processing strategy developed for ultrasonic surveys in the OMNIBUS project.

2.4.2 Analysing Wave-propagation Effects in Finite-difference Models

A series of numerical simulations were produced to model ultrasonic waves propagating through large numbers of cracks with varying crack density, crack size, fluid-filling, orientation and wave-type [*Hildyard*, 2004]. These were based around two laboratory and two in-situ experiments. The objective was to provide the OMNIBUS project with a large theoretical data-set from models with a known microstructure, and to provide a methodology for analysing the waveforms. The data-set and methodology has then been integrated into analysis software to aid the interpretation of cracking from ultrasonic surveys.

The methodology used is to analyse changes in wavespeed and amplitude in the frequency domain. This was extended from previous work [*Hildyard*, 2001] which requires waveforms recorded from two positions along the wave path. Since this is impractical in ultrasonic surveys, a relative method was developed where waveforms are compared against a reference waveform from the same position. The spectral phase difference then relates to the change in wavespeed whilst the spectral amplitude ratio relates to change in attenuation.

The first set of models is based on an experiment which recorded ultrasonic waveforms through sandstone cubes under true triaxial loading with induced cracking along a single direction. This data-set has the most detailed variations and investigates the effects of variations in crack density, crack size, and fluid-filling, on P-waves and two polarisations of S-waves, for wave-paths either parallel or transverse to the cracks. The second set of models was for a uniaxial laboratory experiment in mudstone (Section 2.3) and investigates wave propagation through two orthogonal crack sets at different path angles. The last two sets of models are based on in situ geometries in mudstone and diorite and have the complication that the fracture zone is only a fraction of the volume and a fraction of the path-length. They investigate how the size and shape of the fracture zone influence the waveforms for in-situ measurements and whether such differences are sufficiently detectable. Analysis of the modelling results has then provided an important insight into how crack geometries and properties effect wave propagation.

- The effects of crack density and crack size are coupled. A number of the theoretical waveforms indicate the difficulty of estimating crack density using arrival times alone. Results indicate that these effects are more readily decoupled in the frequency domain.
- In general, the Fourier amplitude should be useful for estimating crack size, while the low frequency phase-difference has a direct relationship to crack density.
- Models with a simple approximation of fluid-filled cracks showed that the only significant effect of different levels of fluid-fill was on P-wave propagation transverse to the cracks. The fluid-fill reduces the frequency at which attenuation occurs, increases amplification effects, and decreases the phase-difference.
- Models also show that the frequency behaviour includes effects due to both cracks and the geometry. This makes measurements geometry dependent. Future ultrasonic-survey analysis software could feasibly include integrated modelling to provide theoretical results which match the specific geometry and requirements of each measurement application.

2.4.3 Modelling Experimental Scenarios

The aim of this work was to use the Wave^{3D} code [*Cundall*, 1992; *Hildyard et al.,* 1995] to produce theoretical results for wave propagation through idealised distributions of cracks. Wave^{3D} is a finite difference wave propagation code capable of simulating cracks in a 3D elastic continuum. These crack distributions are defined to have a certain crack density and size distribution. The crack density value assumes the cracks are open but the cracks can have a normal or shear contact stiffness (or other coupling conditions).

Previous work [*Hildyard*, 2001] developed a modelling method which was able to establish the effect of the cracks alone, independent of geometrical and source effects. This method produced attenuation and phase velocity as a function of frequency for different crack distributions. In this project, however, the models are required to include geometric effects so they can be directly compared with measurements in a specific geometry. In addition, the measurements do not include a measurement near the source. Hence a relative method is used, where attenuation and phase-difference are calculated relative to some reference waveform.

In the relative method, waveform 1 is the chosen reference waveform, and waveform 2 is the recorded waveform (e.g. at a latter point in time). In this case, the difference in wave-speed is related to the phase-difference by the following [*Hildyard*, 2004]:

$$c_1(\omega) - c_2(\omega) \approx \frac{c_2(\omega)c_1(\omega)}{\omega(x_2 - x_1)}(\phi_2 - \phi_1)$$

Equation 1

where ω is frequency, $c_1(\omega)$ and $c_2(\omega)$ are the wave-speeds and $\phi_1(\omega)$ and $\phi_2(\omega)$ the phase functions of the two waveforms, and x_2-x_1 is the path-length. The above formula shows that it is non-trivial to calculate the actual change in wave-speed. Nevertheless, it shows that the phase-difference is directly related to this change in wave-speed. The phase-difference can therefore be used as an indicator of change in wave-speed. Similarly, the ratio of the Fourier amplitude spectra gives a measure of relative attenuation. The relative method therefore entails extracting graphs of phase-difference and amplitude ratio relative to some reference received waveform. The spectral phase difference then relates to the change in wave-speed whilst the spectral amplitude ratio relates to change in attenuation.

Table 1: Modelled Data sets.

Model	Number of Models
Laboratory Bure Mudstone	55
Laboratory Sandstone	534
In-Situ Tressange Mudstone	39
In-Situ SKB Diorite	39

Models were constructed to approximate the geometry in four types of experiments. Table 1 presents the 4 experiments that have been modelled. Significantly more models were performed for the Laboratory Sandstone experiment due to the controlled and oriented fracturing that was created, and the fact that P S_1 and S_2 pulsers and receivers were used. The 'Laboratory Sandstone' and 'In-Situ SKB Diorite' experiments are reported as part of the SAFETI project also funded by the EC under the 5th Framework EURATOM program [*Baker and Pettitt*, 2004]. They are summarised by *Pettitt and Haycox*[2004]. The 'Laboratory Bure Mudstone' and 'In-Situ Tressange Mudstone' experiments are summarised in Sections 2.3 and 2.2 respectively.

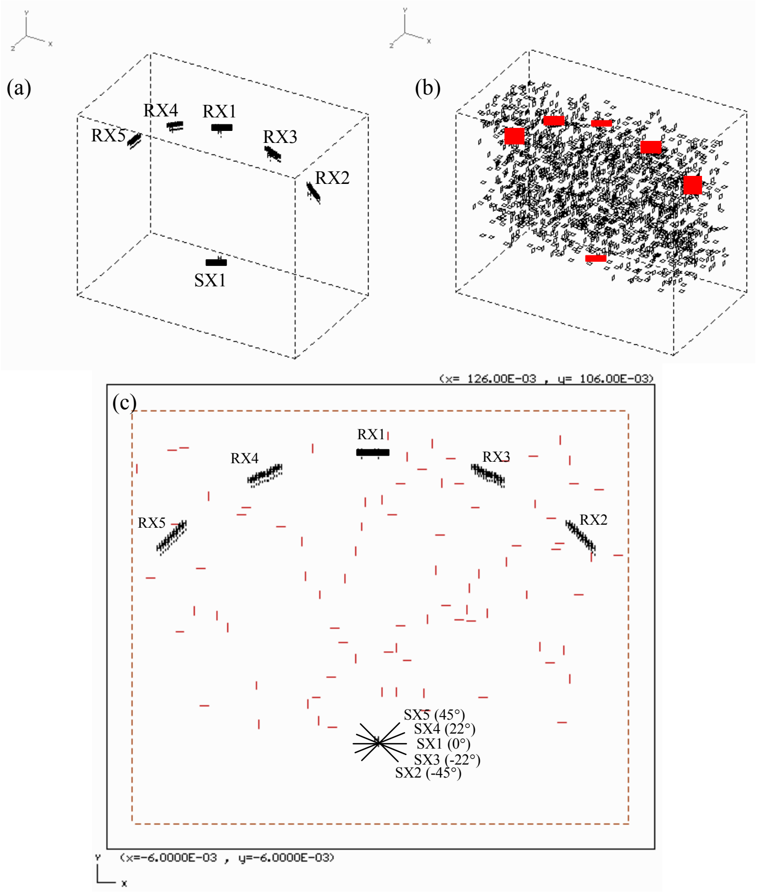

Figure 21: Geometry for mudstone models. (a) Source-Receiver positions (b) 2cm cracks with a crack density of 0.05 (c) 2D Cross-section through centre of 'b' showing source-receiver pairs.

2.4.3.1 Laboratory Bure Mudstone

The Wave^{3D} model consisted of sets of orthogonal cracks approximating the axial cracking, with 5 normal source-receiver pairs with 70mm paths at different angles through the cracked sample, corresponding to the aligned source-receiver pairs in the experiment. The geometry is shown in Figure 21.

Different source orientations were required for these models, ranging from –45° to 45°. SX1-RX1, SX2-RX2, etc., correspond to aligned source-receiver pairs in the experiment. The angled paths (e.g. SX1-SX2, etc.) were also recorded, but their path-lengths are longer than similar paths in the experiment. The crack variations considered were 5 source angles relative to the crack orientation, 4 crack sizes (2mm, 4mm, 6mm and 10mm), and 4 crack densities (0, 0.05, 0.10 and 0.20). This corresponds to 55 distinct models, with 225 sets of normal and tangential receiver waveforms, including the non-normal paths. Models used approximately 7 million finite difference zones with an element size of 0.5 mm. The sample was modelled as an isotropic, linear elastic material with P- and S- wave-speeds of 3100 m/s and 1550 m/s respectively and a density of 2240 kg/m^3. The source and receiver sizes were 8mm x 8mm, and the source shape was a pulse chosen to give a broad frequency range up to 1 MHz. The number of cracks in the model varied considerably according to the crack size and crack density, from 30820 cracks for a crack density of 0.05 with ~2 mm cracks down to 572 cracks for a crack density of 0.20 with ~10 mm cracks.

Mudstone is a transversely isotropic material having a fast and slow direction for wave propagation. This is often represented by a linear, transversely isotropic, elastic material model. The wave-speeds in such a material however, are not frequency-dependent, so that this representation is valid only for wavelengths much larger than the (lateral) openings in the layers causing this anisotropy. As expected, applying the above frequency analysis to models of a transversely isotropic, elastic material did not exhibit frequency-dependent attenuation or frequency-dependent wave-speed. Another valid question is whether waves through a cracked, transversely isotropic elastic material will be affected differently from those through a cracked isotropic elastic material. The crack behaviour in Wave^{3D} is valid only for surrounding isotropic material. It was hypothesised that a transversely isotropic elastic material with cracks each surrounded by a very thin isotropic layer, would behave similarly with respect to wave propagation, as a transversely isotropic elastic material with cracks. Some preliminary models were investigated which suggest that cracks can be combined with a transversely isotropic material in this manner. No detailed modelling has been done to quantify the differences between the base material being transversely isotropic or isotropic.

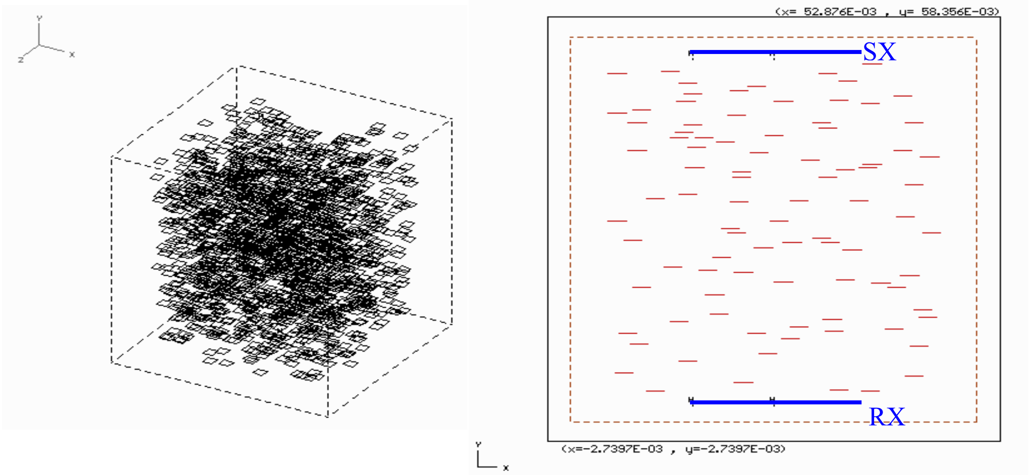

Figure 22 Geometry for sandstone models. (a) 3447, 2mm cracks with a crack density of 0.05 (b) 2D Cross-section through centre of 'a' showing source and receiver.

2.4.3.2 Laboratory Sandstone

A Wave^{3D} model was created for the geometry of a polyaxial test on a sandstone cube [*Baker and Pettit*, 2003]. This was used to study the effects of crack density, crack size, and fluid filling on the different wave-types in the horizontal and vertical directions. Fluid filling was modelled by allowing the cracks to have a normal stiffness but no shear stiffness. Figure 22 shows the geometry of the model. Models consisted of a 50mm x 50mm x 50mm cube and used approximately 8 million finite difference zones. The cube was modelled as an isotropic, linear elastic material with P and S wave-speeds of 4800 m/s and 3300 m/s respectively and a density of 2431 kg/m^3. The source and receiver sizes were 20mm x 20mm, and the source shape was a pulse chosen to give a broad frequency range up to 2 MHz. Element sizes were chosen to avoid numerical dispersion in this frequency range. The number of cracks in the model varied considerably according to the crack size and crack density, from 33045 cracks for a crack density of 0.05 with 1mm cracks down to 22 cracks for a crack density of 0.20 with 16mm cracks.

2.4.3.3 Field Experiments

Models were constructed so as to be applicable to in-situ experiments. The model consisted of a normal source-receiver path for three different angles through a volume with a fractured region of aligned cracks (Figure 23). An additional aspect of these models compared to the models based on laboratory experiments, is that the fracture zone is only a fraction of the volume and a fraction of the path-length. The same cases were modelled for mudstone and for diorite so as to be applicable to two in-situ experiments. The models had the following variations:

- 5 variations of fracture zone size and shape: (zero fracturing case) 0x0cm, and (a) 16x16cm (b) 32x16cm (c) 16x32cm and (d) 32x32cm. (The first is the horizontal size, the second the vertical size).
- The fracture zone had horizontally aligned cracks with three variations in the crack size and crack density, (a) 3cm cracks, cd=0.05 (b) 6cm cracks, cd=0.05 (c) 6cm cracks, cd=0.20.
- Three path orientations (vertical, 45 degrees and horizontal) with normally aligned source-receiver pairs, and a path-length of 1.6 m.

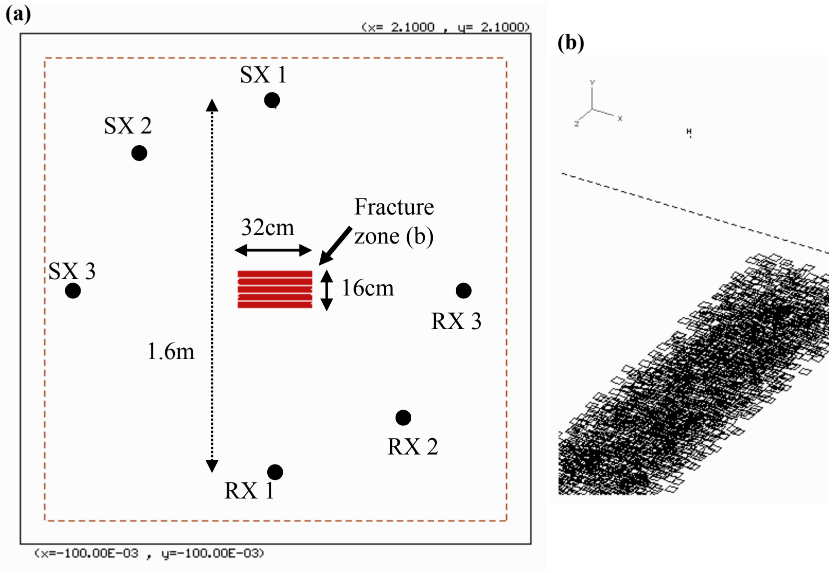

Figure 23: Geometry for in-situ models. (a) Vertical cross-section showing dimensions for fracture zone 'b' and source-receiver positions. The fracture zone extends 1.2m in the third dimension. (b) Zoomed up 3D region showing fracture zone (3cm cracks).

Models for both experiments used 12 million finite difference zones with an element size of 6.67 mm. The volume was modelled as an isotropic, linear elastic material. The source and receiver sizes were 6.7 mm x 6.7 mm, and the source shape was a pulse chosen to give a broad frequency range up to 100 kHz. For the Tressange experiment (Section 2.2), the mudstone model used P- and S- wave-speeds of 3100 m/s and 1550 m/s respectively and a density of 2240 kg/m^3. The diorite models, applicable to SKB experiments [*Pettitt and Haycox*, 2004], used P- and S- wave-speeds of 5988 m/s and 3392 m/s respectively and a density of 2630 kg/m^3.

2.4.4 Example Wave-propagation Results

Selected results from these models are shown in Figure 24 to Figure 31. Figure 24 shows wave patterns from three of the Wave^{3D} simulations in sandstone with different crack densities and crack sizes. There is a clear delay in the wavefronts, and a reduction in amplitudes, due to the open cracks.

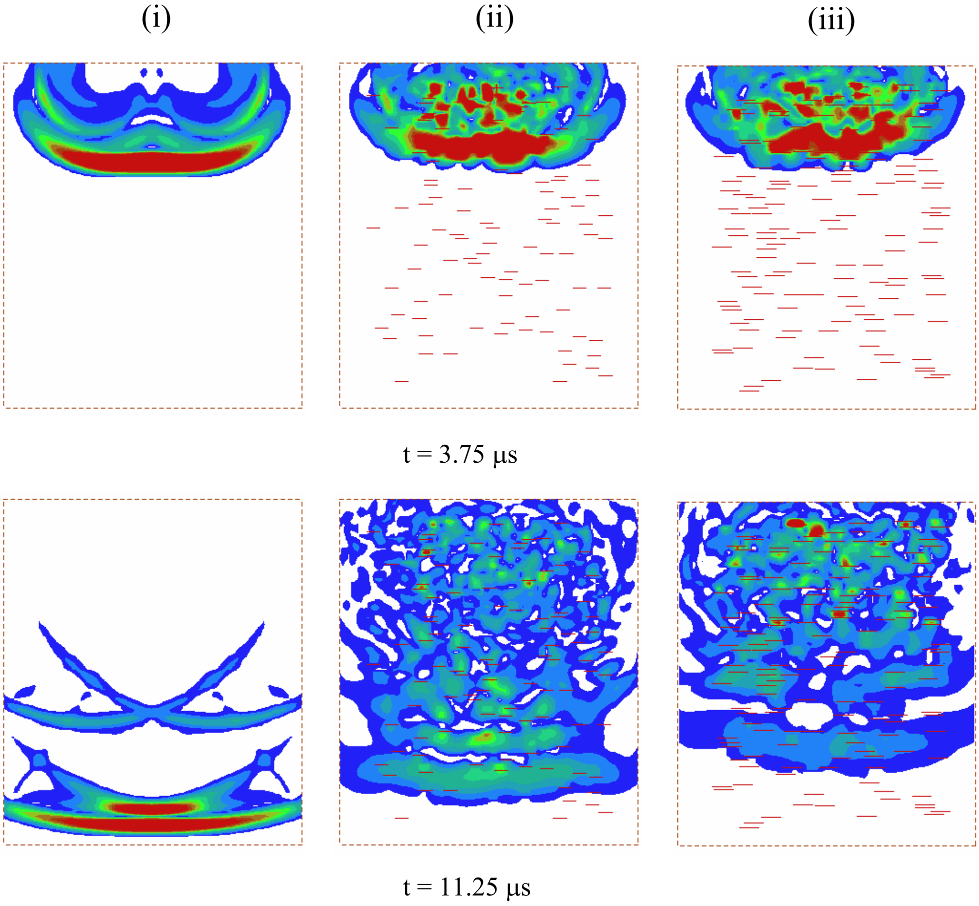

Figure 24: Models of the sandstone laboratory experiments showing wave patterns (snapshots of particle velocity) at an earlier and later time for three different crack models. (i) Elastic (ii) Crack density 0.05, crack size 2 mm (iii) Crack density 0.10, crack size 3 mm.

Figure 25 shows how modelled waveforms are affected by cracks for increasing crack-size and constant crack density. The time-domain arrivals are delayed but are less delayed for increasing crack-size. Similarly, the waveforms become more attenuated with increasing crack-size. A change in wave-speed, calculated using time-domain arrivals, will therefore not give a unique or consistent value for crack density, unless crack sizes are also understood. Figure 26 shows how the amplitudes from waveforms can be analysed in the Fourier domain and that the frequency at which attenuation occurs provides information on the size of cracks. Conversely, Figure 27 shows that changes in phase difference can provide information on the crack density. Importantly, the models demonstrated that these effects were not necessarily evident in the time-domain waveforms.

Figure 28 shows how the modelled wavefronts are effected in the laboratory mudstone for one of the source orientation. It was found that the orthogonal crack set appears to have a similar influence on the wave patterns for all source orientations. Comparing the positions of the first P-wave front in Figure 28, it is clear that the wave propagation is slowed for the model with smaller cracks. The model with larger cracks does not slow the wave propagation to the same degree, but is highly attenuated. This is a significant result as both models have the same crack density.

Figure 29 illustrates the wave propagation in models of the *in situ* experiment showing the wave interaction with the fracture zone. Indications from these models were that changes to either the crack density, the size of the fracture zone, or the size and orientation of fractures, could be observed with sufficiently accurate recordings. The effects on waveforms are visible even for the smallest fracture zone (10% of path length). Figure 30 shows the changes in the time-domain waveforms for mudstone models. The smaller (3 cm) cracks have a greater effect on arrival time while the larger cracks (6 cm) have a greater effect on amplitude. The frequency-domain (Figure 31) shows amplification of low frequencies and attenuation of higher frequencies, and a phase-difference which increases with the size of the zone. These changes are consistent with a change in crack density, such that the larger fractured zone could also be viewed as an increase in the average crack density.

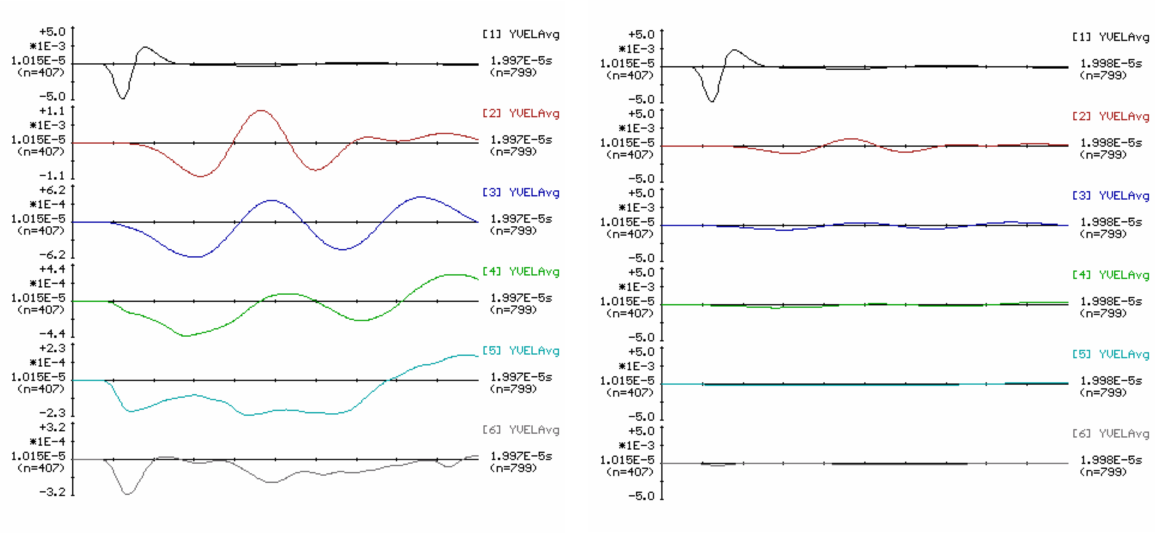

Figure 25: Effect of crack size (on P-waves normal to cracks). Time-domain waveforms ranging downwards from no cracks (elastic) to 2mm, 3mm, 4mm, 8mm and 16mm cracks with a crack density of 0.10. (a) individual vertical scales (b) linked to vertical scale of elastic waveform.

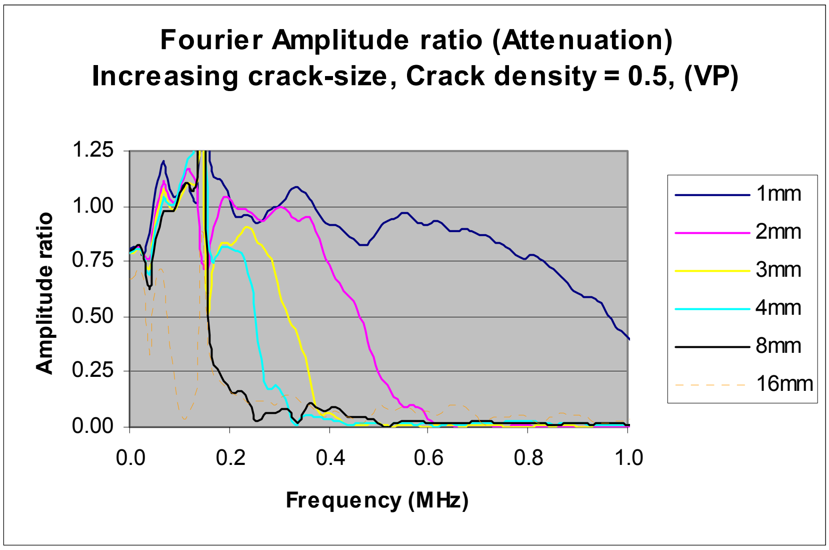

Figure 26: Fourier amplitude ratio relative to an uncracked model for P-wave propagation transverse to cracks of increasing size, maintaining a crack density of 0.05.

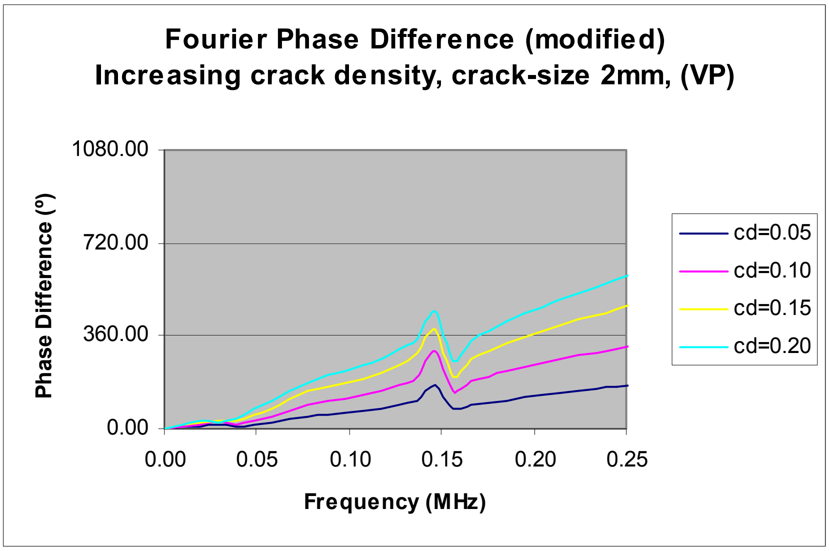

Figure 27: Fourier phase-difference relative to an uncracked model for P-wave propagation transverse to cracks with increasing crack density and a constant crack size of 2 mm.

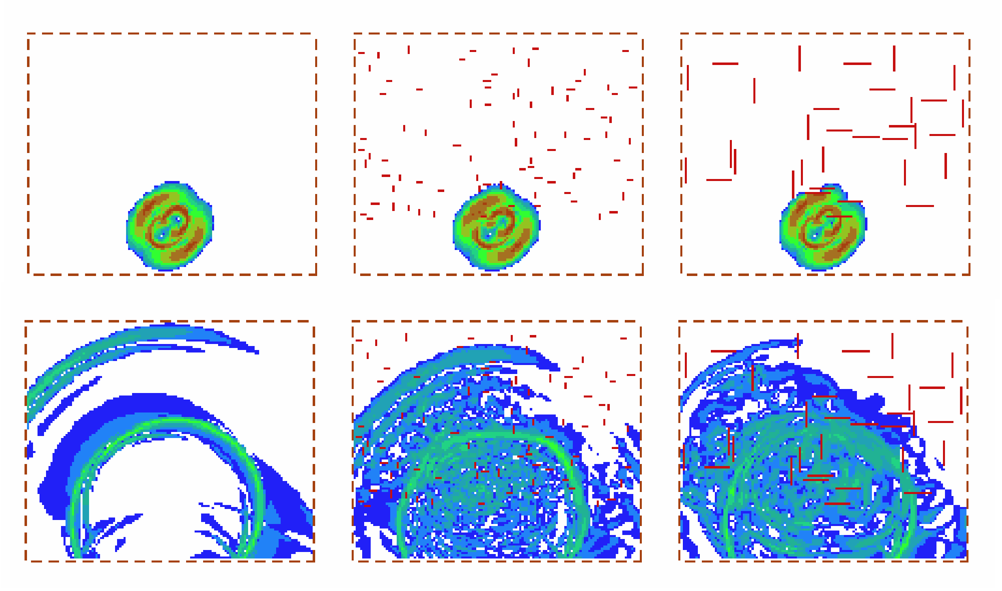

Figure 28: Cross-sectional snapshots of particle velocity at two time-steps, for a source angle of 45º, and three different crack models. The model on the left has no fracturing, the model in the centre has a crack density of 0.05 with 2mm cracks, and the model on the right has a crack density of 0.05 with 6mm cracks.

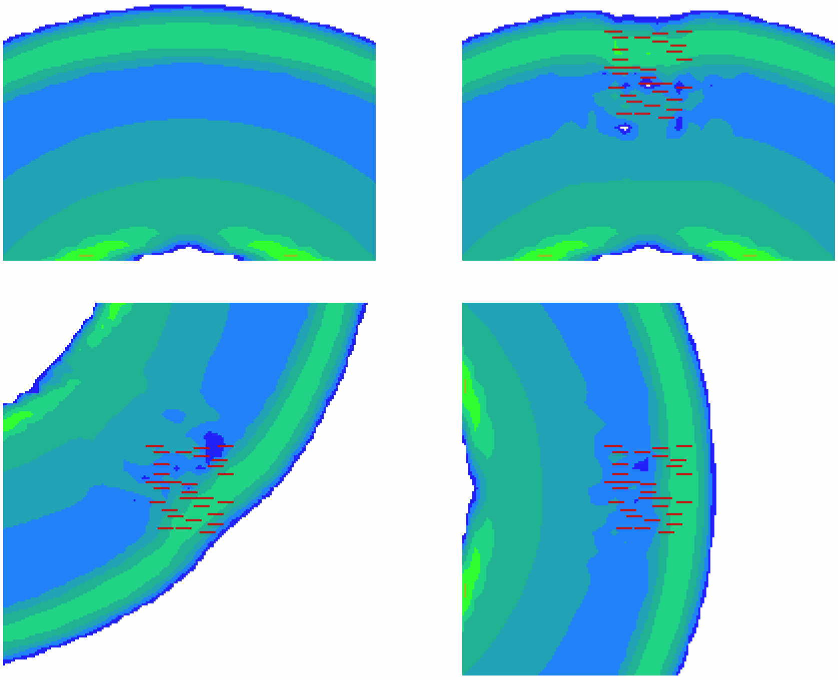

Figure 29: Wave propagation in models of the in-situ experiment in diorite showing interaction with the fracture zone, contrasted for the elastic model and three source orientations for cracked models with 6 cm cracks and crack density of 0.05.

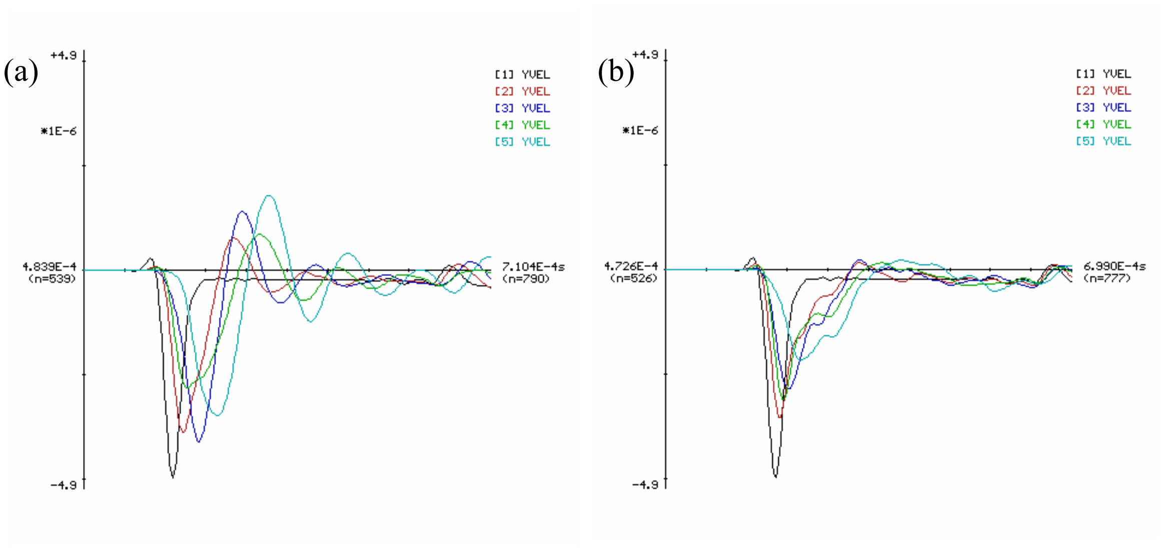

Figure 30: Waveforms for in-situ mudstone models with five different fracture-zone sizes of 0x0cm, 16x16cm, 32x16cm, 16x32cm and 32x32cm. (a) Crack size 3 cm, crack density 0.05, (b) Crack size 6 cm, crack density 0.05.

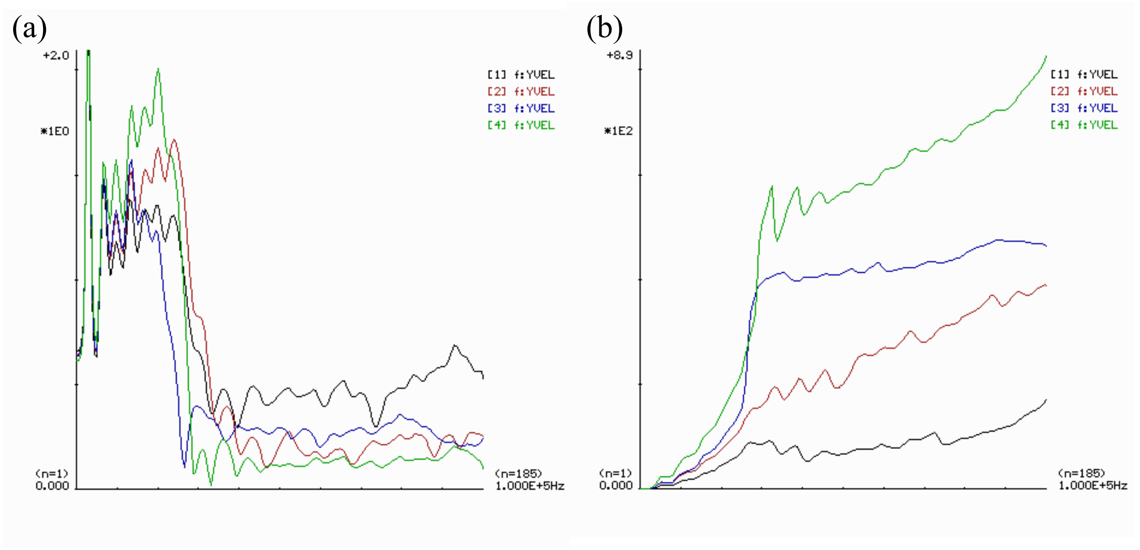

Figure 31: (a) Fourier amplitude ratio and (b) Fourier phase difference, compared to the unfractured model, for in situ mudstone models with 4 different sized fracture zones (16x16cm, 32x16cm, 16x32cm and 32x32cm). All cases are for 3cm cracks with a crack density of 0.05. (*cf.* Figure 30a for time-domain waveforms).

2.4.5 An Advanced Processing Software for Ultrasonic Surveys

The advanced processing strategy for ultrasonic surveys uses a sensitivity analysis to back calculate rock properties from recorded signals and full-waveform models. The procedure for performing the analysis has been implemented into the InSite software as a new module (called the Velocity Visualiser). This is the same software that performs the acquisition, management and processing of the survey data using the acquisition system developed as part of the project (Section 2.1). The entire system is therefore an integrated tool. The procedure operates by correlating results from an experiment with a set of modelled simulations for that experiment considering different crack parameters such as densities, sizes, geometries and fluid content. The 667 models from the four experiments described above have been used as case studies for implementing the strategy. Example results are given in the following section and in two supplementary reports [*Collins and Young*, 2004b; *Haycox and Pettitt*, 2004b]. The reports also include a presentation of the full processing procedure.

The analysis is performed in the frequency domain by correlating amplitude-ratio and phase-difference results for a selected ray path in an ultrasonic survey with waveforms produced by numerical simulations of the experiment. The correlation can either be performed qualitatively by correlating the output graphs visually, or by using a best-fit approach. The procedure adopted here uses the best-fit approach to grade the given modelled simulations in order of which best (and worst) matches the experiment data. The best-fit model is then visually compared with the experiment data in the frequency domain to check the fit results. The output 'RMS Difference' value also provides a check of how well the best-fit model correlates with the experimental data.

The developed software has three main functions:

1) The software provides a unified management of both the experimental and modelling data, so that individual waveforms can be easily selected and the frequency domain parameters plotted in an identical fashion for both. The experimental data is managed within the existing framework of the InSite software. A scheme for managing the large modelling data set has been developed, which allows individual model results to be selected and plotted. The scheme uses a 'look-up table' of all the results that can be easily edited to add further model results in the future.

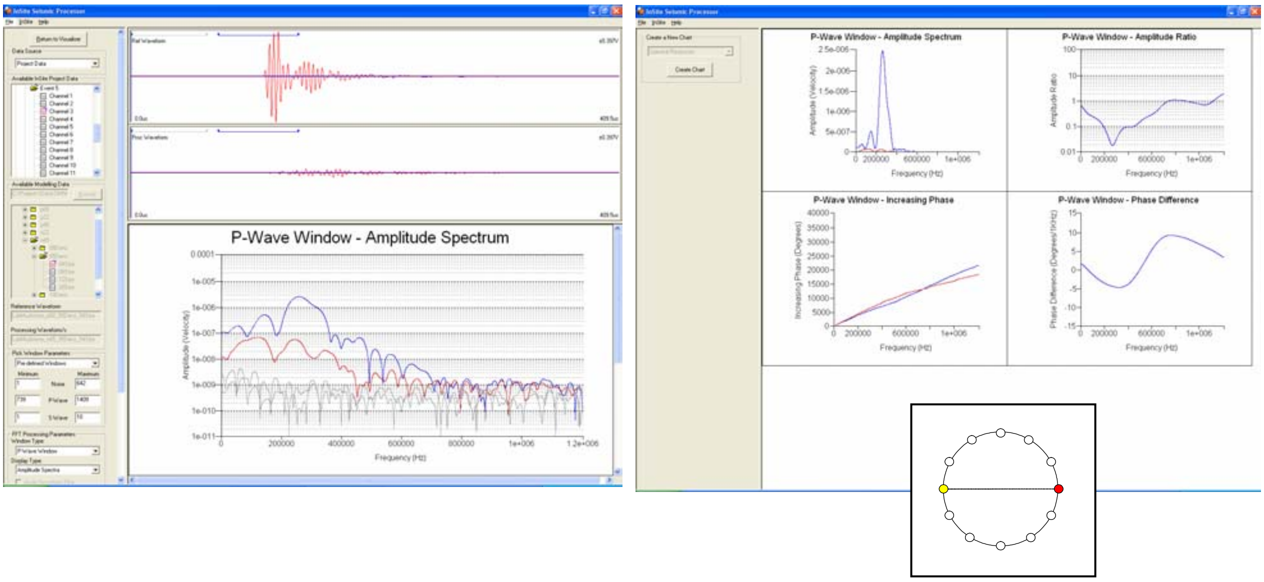

Figure 32: Screen captures of the InSite Velocity Visualiser. The data shown is for the survey at 16:05:36 in a uniaxial test on Bure mudstone (Section 2.4.6.2).

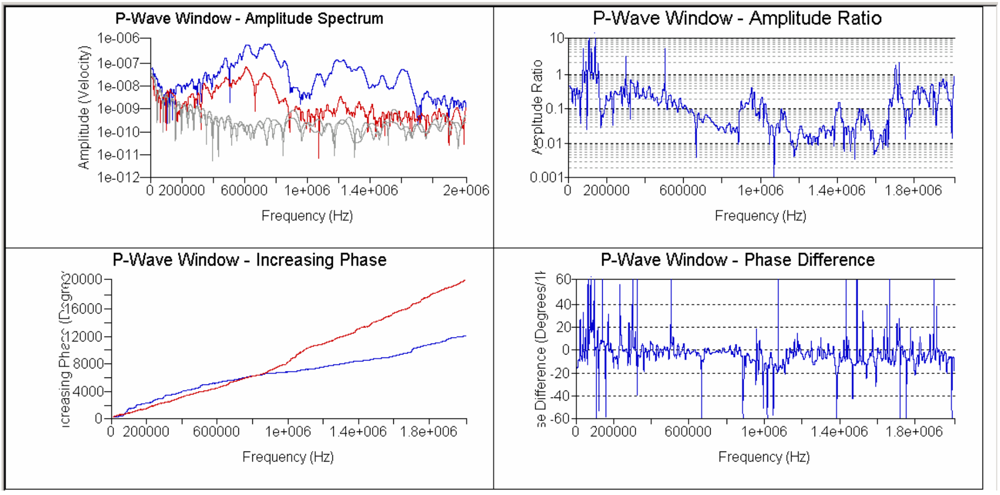

Figure 33: A comparison of the reference velocity survey data compared to the processed velocity survey data for the P-wave measurement in a direction parallel to σ_3 (crossing a set of aligned cracks) The amplitude spectrum and increasing phase plots show the reference data in blue and the process data in red.

2) The software plots the required graphs in such a way that they are easily manipulated. The plot options include: i) amplitude spectra of the processed waveform data, the reference waveform data and noise windows on each; ii) equivalent phase spectra; iii) amplitude ratio; iv) phase difference. The plots produced are displayed on one canvas so that they can be easily qualitatively compared. Figure 32 presents some example screen captures of the software.

3) The software performs a best-fit analysis to find the modelled simulation that best matches the experiment data. The analysis cycles through a selected group of modelled simulations and produces an ‘RMS Difference’ between the amplitude ratio (or phase difference) obtained on the experimental data and that obtained on each of the models. The RMS Difference is a measure of how similar the two results are. The modelled simulations are then ordered with respect to this parameter and the information provided to the user.

2.4.6 Case Studies of an Integrated Interpretation for Changes in Rock Properties

Case studies from the four modelled experiments have been used to develop the implementation of the advanced processing strategy in the software described above. The studies have allowed an integrated interpretation of experimental and modelled data in each of the experiments and thus an interpretation of the changes in rock properties during the monitoring period. Two supplementary reports give results for selected ray paths. *Collins and Young* [2004b] presents an analysis of data recorded in a sandstone cube during a true-triaxial laboratory test. *Haycox and Pettitt* [2004b] presents an analysis of data recorded during a uniaxial experiment in Bure mudstone and in situ experiments in argillite at Tressange and diorite at SKB’s Hard Rock Laboratory.

2.4.6.1 True-triaxial Test on Sandstone

In this study measured P- and S-wave velocity survey data from a polyaxial experiment on Crosland Hill sandstone is analyzed. The rock was taken through a deviatoric damage cycle, similar to *King* [2002] in order to induce a set of aligned cracks. Initial analysis of the P- and S-wave velocity data showed the main change to be a significant decrease in velocity following the loading cycle, parallel to the σ_3 direction, suggesting that an aligned microcrack fabric has been induced. The data before and after the damage cycle has been analyzed using the advanced processing strategy developed in this project and full-waveform outputs from the modelling work presented in Section 2.4.3.2.

The reference ultrasonic survey chosen in the experiment has been selected as one representing an isotropic-elastic medium with no cracks. The survey occurs before the deviatoric loading phase, in which damage is induced. It also occurs at the highest hydrostatic stress of 100 MPa, and therefore any pre-existing microcracks should be firmly closed and any voids or porespace should be minimized in the rock sample. Additionally, measured P- and S-wave velocity values are highest at this survey, again suggesting this survey to be the one where the rock is most competent. The process survey occurs directly after the completion of the deviatoric loading phase, in which damage is believed to have occurred to the sample. The survey occurs at a low 5 MPa hydrostatic stress. The reference and process surveys are analyzed in the frequency domain using the amplitude and phase spectra of the 9 measured P- and orthogonally polarised S-waves.

Figure 33 shows example results for the P-wave measurement crossing the set of aligned, parallel, cracks. The amplitude spectra show the measured data, as well as the background noise level (in grey) which is important for assessing the frequency range of the coherent signal. The amplitude ratio and phase difference plots show a number of ‘spikes’, which are an artefact of the calculation. The figure shows a clear effect on the amplitude and phase results from the induced fracture set. A series of processing steps were performed to determine a ‘best fit’ between the measured and modelled data, described in *Collins and Young* [2004b]. This includes a ‘smoothing’ method which was incorporated so that the main trends in the amplitude ratio and phase difference plots could be obtained by removing the spike artefacts. Figure 34 gives example amplitude-ratio and phase-difference plots for the measured P-wave data, and for the model that is found to best fit the P-wave data. Both P- and S-wave amplitude ratio plots show a general trend of increasing amplitude loss with frequency. The amplitude loss varies between approximately unity to 1/100th. The P- and S-wave phase difference plots show significant variations between approximately 0 and -10. The values show a clear dependency on frequency. Best fit models were obtained for the 6 measurements of amplitude ratio and phase difference on the P and two orthogonal S-waves. The model that was found to best represent all the data was a set of aligned cracks with crack length = 4mm, normal stiffness = 1e13 Pa/m, and crack density = 0.2. Future thin section analysis of the sandstone sample is planned as part of another project in order to measure and calculate crack length and crack density. This may provide physical evidence for this result.

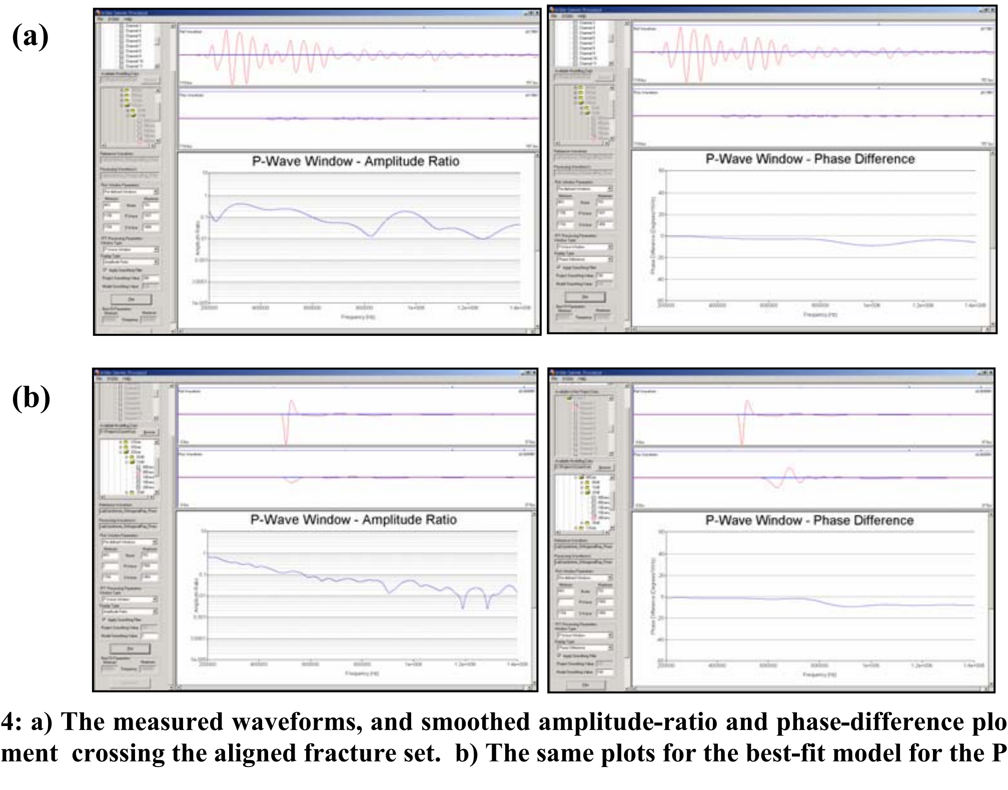

Figure 34: a) The measured waveforms, and smoothed amplitude-ratio and phase-difference plots for the P-wave measurement crossing the aligned fracture set. b) The same plots for the best-fit model for the P-wave.

2.4.6.2 Uniaxial Test on Bure Mudstone

Haycox and Pettitt[2004b] describe an analysis of results from Bure mudstone obtained during a uniaxial test conducted for this project (Section 2.3). A ray path passing through the sample, parallel to σ_3 has been studied at four different times through the test, corresponding to different points in the loading path. Figure 32 shows the waveforms and amplitude spectra from the ray path on a survey close to the peak stress. There is a clear reduction in all amplitudes indicating the presence of induced damage in the sample. The best fit analysis has been used for each survey enabling the change in nature of fractures in the sample to be quantified through the loading history (modelled simulations are described in Section 2.4.3.1). The fracture size and density for the modelled data is shown to increase with time, which is consistent with the increase in stress and number of acoustic emissions recorded during the experiment. Figure 35 compares recorded and modelled results at two positions in the stress history. At approximately mid-way through the test (8MPa load) there is little change in the amplitude ratio resulting in a best-fit model with 0 cracks (Figure 35a). Close to the peak stress there is a reduction of almost $1/100^{th}$ in the amplitude spectra at some frequencies resulting in a best-fit model with large cracks through the sample. The models best describing the final survey have the highest crack densities and largest crack sizes, which is what would be expected after observing the sample when the experiment was completed (Figure 16).

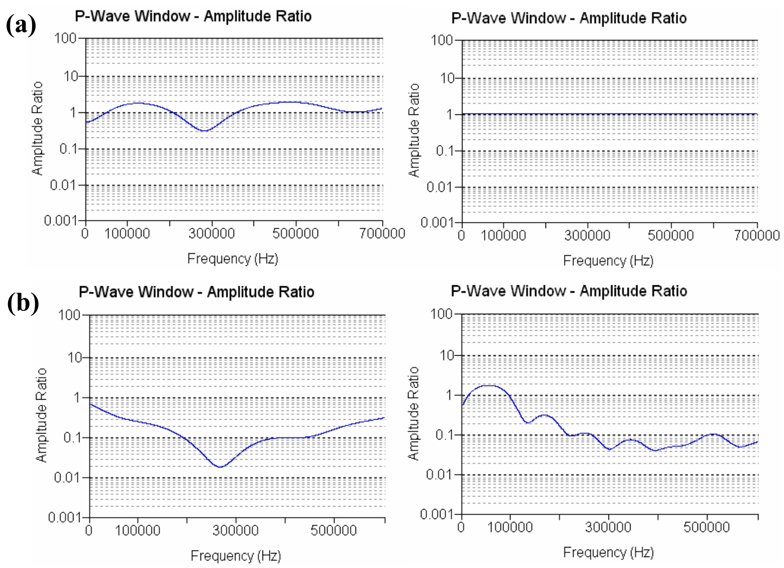

Figure 35: Comparison of recorded (left) and modelled (right) amplitude ratios for a uniaxial test on Bure mudstone. a) For a survey with no apparent cracks midway through the loading history. b) For a survey close to the peak stress of the sample.

2.4.6.3 Tressange In-situ Test

Ultrasonic surveys from the Tressange in-situ experiment have been analysed using the advanced processing strategy. *Haycox and Pettitt*[2004b] show results from a survey recorded at the end of the experiment, after heating and expansive-resin injection, when compared with one before the stress perturbations were introduced. Observation of the velocity and amplitude results showed that the greatest changes occur along the raypaths which travel through the region containing the three test boreholes. Results from this analysis show the amplitude ratio decreases below zero for frequencies in the range 30 to 70 kHz where the highest amplitude signal is obtained (Figure 36).

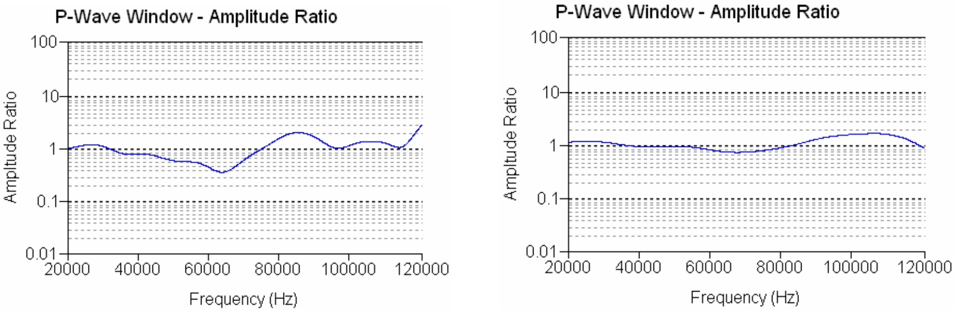

Figure 36: Comparison of measured amplitude ratio through the test volume (left) and the best-fit model (right).

The changes are small, as expected for long ray paths where changes in rock properties are occurring along only a fraction of the ray path length. Using the best-fit analysis, and model simulations presented in Section 2.4.3.3, the most appropriate model has a 16x16 cm damage zone (ray path lengths are approximately 2m). The angle at which the waves intersect the cracks appears to be important and shows the cracks to be perpendicular to the ray path. This agrees with the three-dimensional ultrasonic-velocities suggesting that the injection of expansive resin causes fractures to develop between the three test boreholes.

2.4.6.4 SKB In-situ Diorite

Ultrasonic surveys from an in-situ experiment conducted at SKB's Hard Rock Laboratory, during full-scale deposition-hole excavation, have been examined using the advanced processing strategy [*Haycox and Pettitt*, 2004b]. Raypaths were chosen which pass through specific regions around the void. Six ray paths were studied which lie on a plane. Three of these are skimming raypaths which pass within centimetres of the deposition hole's edge and exhibit the greatest changes in velocity [*Pettitt and Haycox*, 2004]. The other three ray paths pass at varying distances away from the deposition hole wall. Figure 37 shows the amplitude and phase spectra from one of the skimming ray paths, that passes through a tensile (or low-compressive-stress) zone. This shows a decrease in amplitude, over a wide range of frequencies.

Results from the best-fit analysis fit in well with interpretations based on the ultrasonic data and acoustic emissions alone. The ray paths that are situated further from the void were best suited to models with no cracks. The extent of the damage induced by the evcavation is such that these raypaths do not pass through regions in which fracturing has been induced. Conversely, the raypaths which skim the deposition hole wall do pass through volumes where fractures are generated. The ray path that passes through the tensile zone (which experienced acoustic emissions and large velocity drops over the excavation period) has the largest crack sizes and density (a damage zone of 16x32cm is resolved).

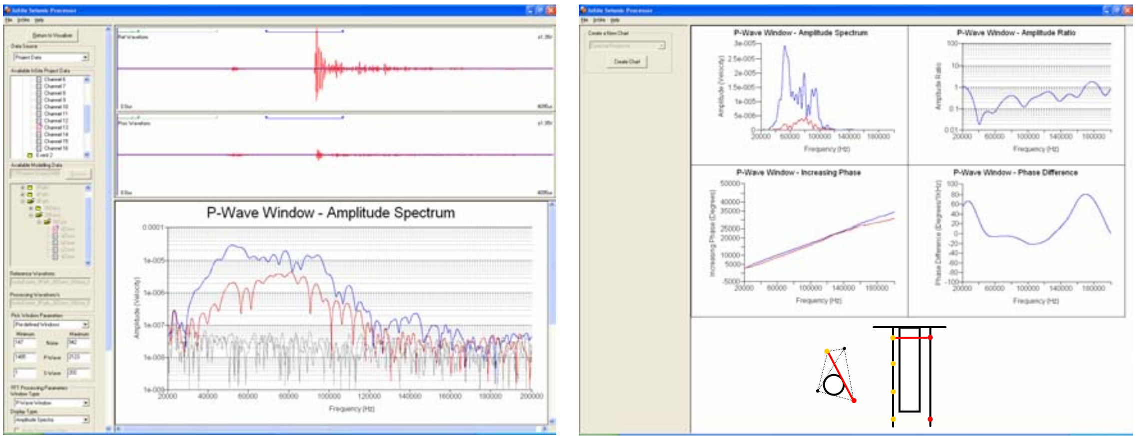

Figure 37: Waveform and spectral results from a ray path that passes within a few centimeters of a full-scale deposition hole at SKB's Hard Rock Laboratory. Red line on the amplitude spectrum is after excavation; blue line is before excavation.

2.5. AN OMNIBUS SYSTEM FOR ANDRA'S BURE SITE

An 'OMNIBUS' ultrasonic system has been purchased by INERIS, working on behalf of ANDRA, the French agency responsible for management and disposal of nuclear waste. The system has been integrated by Applied Seismology Consultants Ltd. (ASC) and manufactured using suppliers from the OMNIBUS project including Liverpool University. The aim of the system is to perform an ultrasonic monitoring experiment during the shaft-extension phase of ANDRA's Meuse/Haute-Marne Underground Research Laboratory (the REP-Ultrasonic Experiment). Once installed the equipment is expected to operate for many weeks (up to 4 months) without any direct maintenance as there will be limited access to the galleries during the excavation. After this period it is envisaged that the equipment will remain installed at the laboratory for between 1 to 3 years.

The aim of the REP-Ultrasonic Experiment is to characterise the extent and nature of the generated Excavation Disturbed Zone (EDZ) around a section of the shaft and to monitor its evolution through the excavation and operational phases. The ultrasonic velocity field within a sensor array installed down three instrumentation boreholes will be mapped in three dimensions using ultrasonic surveys. The array will initially be installed around a volume of rock that is in an intact and undisturbed state. The shaft will then be extended past the array causing the volume to undergo stress-disturbance, damage and hydraulic changes in the EDZ around the shaft.

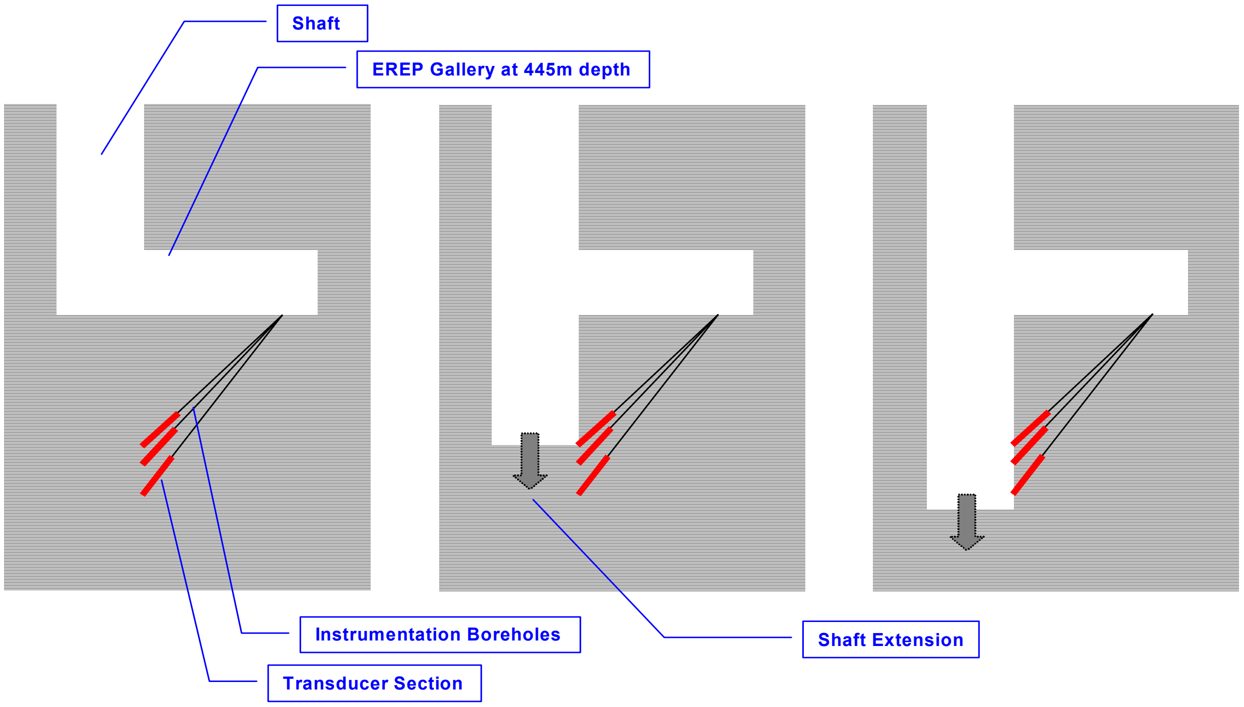

Figure 38: Illustration of the shaft-extension phase and layout for the REP-Ultrasonic Experiment.

A DTM (Dossier Technique Materiel) and PAQ (Plan Assurance Qualite) have been provided to INERIS by ASC. The PAQ [*Pettitt and Young*, 2004a] includes a description of the system, the principal components contained within it, the installation procedure and the quality assurance methods that are used to certify the system's operating performance before and after installation at the laboratory. In the DTM [*Pettitt and Young,* 2004b], a detailed description of the connections and operation of the OMNIBUS system have been provided along with a series of quality assurance results certifying the operating performance of the system. A set of proposed acquisition settings has also been provided for use in situ. The quality assurance results calibrate the frequency response of every acquisition channel, transducer, and pulser-amplifier electronics.

The system provided consists of 21 OMNIBUS sensor packages fixed to borehole installation frames. Each sensor package consists of a transducer, a pre-amplifier and pulsing electronics sealed into pressure-rated enclosures, and integrated cable assemblies. The down-hole electronics allows each transducer to act as both a transmitter and receiver. The down-hole sensor packages will be connected to data-acquisition equipment positioned underground in the REP gallery and consisting of an OMNIBUS Sensor Interface Unit, a Gage data-acquisition unit, and a data-acquisition PC running ASC's InSite Seismic Processor. The software provides total control over the hardware operations and data management, as well as an ability to review the waveform data. An Ethernet connection will provide the ability for a remote user to log onto the data-acquisition PC to examine the data or to download it to their local computer.

3. ASSESSMENT OF RESULTS AND CONCLUSIONS

The overall aim of this project has been to develop technology and associated techniques that can be used to assess and monitor the condition of a rock mass and its temporal response for use in radioactive waste repository environments. The technology is based on the use of active and passive ultrasonic measurements to remotely monitor the rock barrier around excavations (e.g. access tunnels and deposition holes). The principal objectives and deliverables laid out at the start of the project have been met. The OMNIBUS project can therefore be considered as a success.

The principal outcomes of the project have been the development of the OMNIBUS Data-acquisition System for ultrasonic surveying and acoustic emission monitoring and an improved understanding of how data from ultrasonic surveys can be interpreted in terms of rock mass properties. The latter has resulted from the development of an advanced processing strategy that correlates full-waveform data from an ultrasonic survey recorded in an experiment with large numbers of numerical modelling simulations. By correlating the effects observed in many different models, with explicitly defined crack density, size, fluid-filling and geometry, with changes observed in the experimental survey data it has been possible to analyse the changes in these parameters the rock must have experienced during the experiment. The tool is therefore able to quantitatively characterise the evolution of rock damage induced in a given rock mass through time.

Full-waveform modelling and advanced processing methodologies for ultrasonic surveys represent important scientific research that is being further progressed by the partners beyond the OMNIBUS project and is being presented for publication in scientific journals. The results obtained here show the methodologies produce useful contributions to the interpretation of ultrasonic data and have considerable scope for use in future research. The limitation of this technique is that the resolution obtained in analysing the effects of the modelled parameters on wave propagation is restricted to the number of models in the pre-defined data sets. These in turn are restricted by the number of models that can be performed on today’s computing resources in a realistic processing time. As large super-computer clusters become more highly developed, and computer power increases, then the effect of this limitation will reduce. One area for future development is likely to be the full integration of full-waveform numerical modelling routines with experimental data-acquisition and processing software so as to more efficiently utilise increasing computer power and provide a more efficient advanced-interpretation tool for engineers.

The work in the OMNIBUS project can be considered in 4 phases:

i) Development of research equipment and processing methodologies that provide a robust and efficient tool for performing ultrasonic surveys in any rock type.

ii) Perform in-situ testing of the ultrasonic technologies developed by conducting experiments to examine induced fracturing and disturbances in rock at an underground test site.

iii) Undertake controlled laboratory experiments to provide ultrasonic waveform data to investigate the relationship between wave propagation and rock microstructure.

iv) Use a dynamic numerical model to provide advanced interpretation of wave propagation and so develop interpretation routines and strategies for ultrasonic surveys.

The specific scientific and technological objectives of the project, as specified in the original proposal document, are as follows:

- □ Advance the current state of the art in ultrasonic survey technology by developing an integrated ultrasonic tool for data acquisition and on-line processing for use in any repository environment with particular emphasis on the application in argillaceous materials.
- □ Develop current processing procedures into efficient on-line software so that recorded full-waveforms are processed into wave velocities and signal amplitudes in near real time.
- □ Research and develop advanced processing techniques to extract amplitude-frequency attenuation parameters from recorded full waveforms, for comparison with numerical modelling results. Integration of strategies for interpretation of ultrasonic survey measurements into reliable measures of rock properties such as crack density and saturation.
- □ Test ultrasonic acquisition technologies during in situ investigations of the response of an argillaceous material. Provide robust ultrasonic and mechanical data for testing of advanced processing and interpretation strategies using numerical models.
- □ Perform controlled laboratory experiments in isotropic and transversely-isotropic media to provide robust ultrasonic and mechanical data for development of numerical models in order to investigate fracture development and the effect on ultrasonic wave propagation.
- □ Use wave propagation studies in finite difference models (WAVE^{3D}) to describe the effects of fracture density, fracture sizes and fluid contents on ultrasonic signals. Apply this to isotropic and transversely-isotropic media for validation by ultrasonic data obtained during controlled laboratory experiments.

Leading from these specific objectives, the project has involved the following areas of research and development:

- The first element has included the design and construction of a data-acquisition system for ultrasonic survey and acoustic emission (AE) monitoring. This tool is able to collect ultrasonic data at both hard-rock (e.g. granite) and soft-rock (e.g. argillite) sites. The tool development has involved hardware and software components as well as a field test. The tool is easy to deploy and provides a high level of automation in terms of data collection, processing and visualisation thus minimising the time between data acquisition and results visualisation. Through this approach, it is expected that the technology can become an integral part of real-time monitoring systems at future repository sites.
- The complete OMNIBUS Data-acquisition System has been successfully tested at Tressange Iron Mine in France where an argillite layer was targeted. The site was chosen as it offered excellent opportunities for testing of the prototype equipment in a region of argillaceous material with broadly similar in situ properties as rock found in potential sites for the geological disposal of radioactive waste. The field experiment also provided the opportunity to collect an in situ data-set from an argillaceous rock type that could then be integrated with numerical modelling and advanced processing techniques developed as part of the project. A full-scale system was employed using 16 transducers fixed into four instrumentation boreholes. Three test boreholes were excavated through the rock volume within the instrumentation boreholes and then thermally and mechanically stressed (by injecting expansive resin). The OMNIBUS hardware and software package was shown to successfully record AEs (during thermal perturbations) and perform three-dimensional ultrasonic surveys. AEs were located close to the drilled boreholes and predominantly in tight clusters around the location of the heater positions. Signals during the ultrasonic surveys were able to transmit across the array, along ray paths of greater than 4m in length. Stereonets of absolute velocity show a slow velocity in a sub-horizontal orientation, which is perpendicular to the bedding planes. The majority of ray paths passing through the network of three test boreholes exhibit a reduction in velocity and amplitude after heating and injection of the central test borehole. Raypaths passing outside of the network show no change or slight increases.

- Laboratory experiments have involved a series of controlled uniaxial and triaxial tests on argillaceous rock samples from ANDRA's *Bure en Meuse/Haute Marne* site. These are the only ones of their kind in Bure rock which combined acoustic emission (AE), mechanical measurements and ultrasonic velocity surveys. They were performed so as to establish some recommendations on design and back analysis of ultrasonic properties for in-situ experiments, to determine basic empirical relationships between physical parameters of rocks with the wave propagation, and to provide ultrasonic and mechanical data for development of numerical models in the project. Ultrasonic velocities have been mapped in three dimensions and across a tomography plane. Anisotropy was observed to decrease during triaxial pre-peak stresses up to the onset of dilatency, whereupon the anisotropy variation becomes non-linear and decreases more and more quickly towards the peak stress and failure of the sample.

- New methodologies for processing and interpreting ultrasonic data collected by the tool have been developed. An advanced processing strategy for ultrasonic surveying has been developed using a frequency analysis in the amplitude and phase domains. The methodology is a sensitivity analysis for interpreting rock disturbance through the integrated study of the full-waveform data from numerical models with data from the ultrasonic surveys. The analysis is performed in the frequency domain by correlating amplitude-ratio and phase-difference results for a selected ray path in an ultrasonic survey with waveforms produced by numerical simulations of the experiment. Wave propagation studies in finite difference models have been used to describe the effects of fracture density, sizes, fluid contents and geometry on ultrasonic signals. These were based around two laboratory and two in-situ experiments. In total, results for 667 models have been obtained totalling more than a year's computing time, with different models run in parallel on a super-computer cluster at Liverpool University.

- Using the models, an investigation was performed into how the size and shape of the fracture zone influence the waveforms for in-situ measurements and whether such differences are sufficiently detectable. Analysis of the modelling results has then provided an important insight into how crack geometries and properties effect wave propagation. The effects of crack density and crack size are shown to be coupled. A number of the theoretical waveforms indicate the difficulty of estimating crack density using arrival times alone. Results indicate that these effects are more readily decoupled in the frequency domain. In general, the Fourier amplitude should be useful for estimating crack size, while the low frequency phase-difference has a direct relationship to crack density. Models with a simple approximation of fluid-filled cracks showed that the only significant effect of different levels of fluid-fill was on P-wave propagation transverse to the cracks. The fluid-fill reduces the frequency at which attenuation occurs, increases amplification effects, and decreases the phase-difference. Models also show that the frequency behaviour includes effects due to both cracks and the geometry. This makes measurements geometry dependent. Future ultrasonic-survey analysis software could feasibly include integrated modelling to provide theoretical results which match the specific geometry and requirements of each measurement application.

- Dedicated advanced-processing software has been written in order to facilitate the correlation analysis of modelled and experimental data. This has been written as an integrated module within the same InSite Seismic Processor software that performs the acquisition, management and processing of the survey data using the acquisition system developed as part of the project. The entire system is therefore an integrated tool. Case studies from the four modelled experiments have been used to develop the implementation of the strategy and to provide an interpretation of the rock disturbance in terms of changes in the modelled rock mass properties. For each experiment, a campaign of numerical simulations has been performed so as to model ultrasonic waves propagating through large numbers of cracks with varying crack density, size, fluid-filling, orientation and wave-type. The ranges and resolution obtained when analysing the modelled parameters are restricted by the number of models that can be performed on today's computing resources in a realistic processing time. In each of the four modelled experiments a range of values has been designed to cover the most likely cracking scenarios envisaged during the experiments. By then correlating the effects observed in the models with effects observed from the experimental survey data it has been possible to analyse what changes in these rock parameters the ultrasonic waves passing through the rock must have experienced. By analysing many different models it is also possible to obtain an interpretation of how sensitive the waves are to the rock parameters.

The research and developments have resulted in the following specific outcomes from the project:

- An integrated instrumentation system has been developed for the collection of ultrasonic data during long-term field deployments. The system consists of a number of components that have either been developed specifically for the task or purchased 'off-the-shelf' where available technology exists.
- Integrated computer software has been developed that interfaces to the above hardware providing data acquisition, management, real-time processing and visualisation. The software can be also be used with other acquisition systems.
- The integrated hardware and software system has been shown during an in situ test to be a robust tool that can be deployed during the excavation or operational phase of an underground laboratory or repository.
- A processed data set has been collected during the testing of the prototype hardware including results from ultrasonic survey processing and AE analysis.
- A processed data set has been obtained relating rock properties, ultrasonic velocity measurements and AE response for a series of uniaxial and triaxial laboratory tests undertaken on argillaceous rock.
- A set of full-waveform numerical modelling simulations have been performed, resulting in an extensive data set investigating the effects of material parameters such as cracks and fluid contents on the properties of ultrasonic waves.
- An advanced processing strategy has been developed for interpreting changes in rock properties, including crack density, size, fluid content and geometry, measured using ultrasonic surveys. Advanced processing and visualisation software for implementing the processing strategy has been developed into the same software package that performs the data acquisition.

These achievements constitute a successful completion of the projects principal objectives and deliverables as set out in the original proposal. A measure of the success of the project can be obtained from the fact that an OMNIBUS Data-acquisition System has been commercially supplied to a nuclear waste stakeholder for use in an underground laboratory.

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GLOSSARY

acoustic emission (AE)	Small magnitude (around M = -5), high frequency seismic event radiating elastic waves that can be detected by sensors operating between 30 kHz and 1 MHz.
argillaceous rock	A rock largely composed of clay minerals; e.g. mud, clay, mudstone, shale and marl.
attenuation	The tendency of elastic waves to lose energy as they travel through a dispersive medium.
BNC	An electrical connector, larger and more common than SMB and SMC connectors
ESG	Engineering Seismology Group, a Canadian based manufacturer of seismic monitoring equipment
EDZ	Excavation Disturbed/damaged zone – term given to region of rock around an excavation that has been disturbed or damaged due to the excavation process or stress change
HRL	Hard Rock Laboratory at SKB's Aspo site in Sweden
Hyperion System	An ultrasonic system manufactured by ESG, Canada
INSITE	Seismic processing software package produced by ASC Ltd.
Phase velocity	Generally equivalent to wave-speed, but often a frequency-dependence is implied
PVC	A cost effective material, popular amongst designers and builders, excellent for machineability, and good for impact strength and chemical resistance
PZT	Lead zirconate titanate, a ceramic used in the manufacture of piezoelectric transducers.
triaxial test	A standard laboratory testing procedure where the sample is loaded and/or confined along all three principle stress axes.
transversely isotropic	A material that shows the same elastic properties in one plane and a different response in a direction perpendicular to this plane. Many layered sedimentary rocks can be considered to behave in this way. Described by 5 independent elastic constants
ultrasonic frequencies	Frequencies in the range 30-500KHz (or higher)
uniaxial test	A standard laboratory testing procedure where a rock is loaded along one axis only.
Wave^{3D}	A finite difference code capable of modelling wave interaction with cracks in three dimensions

APPENDIX I – DELIVERABLES, EXPLOITATION AND DISSEMINATION

An itemised list of deliverables resulting from the project is presented in Table 2.

Table 2: ***Itemised list of deliverables for the OMNIBUS project.***

Deliverable	Report or Deliverable Title	Author or Organisation	Type
1	Prototype equipment for ultrasonic surveys in both soft and hard rock environments	Collins, Young (Liverpool)	Equipment for experimentation
2	Calibration data for ultrasonic equipment	Collins, Young (Liverpool)	Report
3	Report acting as a user guide for the equipment and summarising the techniques used	Collins, Young (Liverpool)	Report
4	Software for on-line and advanced processing.	Pettitt (ASC)	Software
5	Report acting as a user guide for the software and summarising the techniques used	Pettitt (ASC)	Report
6	Report on the in situ experiment design, results and interpretation of data.	Haycox, Pettitt (ASC)	Report
7	Digital data set from the in situ experiment.	Haycox, Pettitt (ASC)	Data set
8	Report on laboratory tests and results, with interpretation of data	Balland (INERIS)	Report
9	Digital data-set of ultrasonic and mechanical measurements from laboratory tests	Balland (INERIS)	Data set
10	Report on the modelling programme and the relationship of ultrasonic wave propagation with fracture/fluid content.	Hildyard, Collins, Young (Liverpool)	Report

Table 3 lists the main results from the OMNIBUS project. It is not yet certain whether any of the items developed during this project will be considered for patent protection. The hardware sub-components or software routines developed may be protected should this be appropriate. The intellectual property rights (IPR) and ownership of the results rest with the partners that developed each result. The developed hardware is owned by the University of Liverpool, while the software will be exploited by ASC. Data sets and 'know-how' acquired as part of the other work-package will be available for the other partners to publish jointly as part of the dissemination process.

The main target audience for results from the OMNIBUS project are scientists and engineers working within the fields of radioactive waste disposal (especially geological repositories), civil engineering, mining and petroleum extraction. Some of the results associated with the numerical modelling of the wave propagation will be of more general interest to the earth science/seismology community.

In the first instance dissemination is expected to take the form of journal publications, presentations at international conferences and conference proceedings. This will serve to raise the awareness of the project and its most significant results and applications. Hardware, software and consulting services that have the potential for commercial exploitation will be marketed by the various partners. It is expected that the hardware will be available for purchase by third part organisations and would also be used as a consulting tool by the partners through agreement with Liverpool. Sub-components of the hardware (e.g. low frequency sensors and dual-mode components) would be exploited through sale to third party organisations for use in their own borehole and laboratory sensor systems.

Table 3: Main results from the OMNIBUS project

Main Result	Description
1. Acquisition hardware system and associated technology	An integrated instrumentation system for the collection of ultrasonic data during long-term field deployments. This consists of several components which individually contain exploitable technology.
2. Acquisition & Processing software	An integrated computer program interfacing to the above hardware, but which can be used with other acquisition systems, providing data acquisition and real-time processing.
3. Data-set from in situ field experiments	A processed data set collected during the testing of the prototype hardware including results from ultrasonic survey processing and, if applicable, AE analysis.
4. Data-set of ultrasonic laboratory data	A processed data set relating rock properties, ultrasonic velocity measurements and AE response for a series of uniaxial and triaxial laboratory tests undertaken on argillaceous rock.
5. Data-set from numerical modelling experiments	A set of results from full-waveform numerical modelling studies, investigating the effects of material parameters such as cracks and fluid contents on the properties of ultrasonic waves.
6. Procedure for the interpretation of ultrasonic data	An advanced processing strategy for interpreting changes in rock properties measured using ultrasonic surveys. Advanced processing and visualisation software for implementing the processing strategy.

The developed software routines have been incorporated into ASC's InSite software. This is being marketed by ASC to organisations that would routinely collect acoustic and seismic data as part of long-term monitoring campaigns. Interested parties include the radioactive waste, petroleum and mining sectors. As the capabilities of the software are enhanced with the addition of 'advanced' processing routines it is anticipated that this software would be used by academic and research institutions also.

Table 4: List of primary organisations within EC responsible for Radioactive Waste Management.

Country	*Organisation*
Belgium	ONDRAF/NIRAS
Finland	POSIVA
France	ANDRA
Germany	BfS
Italy	NUCLECO
Netherlands	COVRA
Spain	ENRESA
Sweden	SKB
United Kingdom	NIREX, BNFL, UKAEA

As the project was conceived to develop technologies aimed at the radioactive waste disposal sector, the initial target audience will come from this sector. Table 4 shows a list of organisations from within the EC that are engaged in the management of research into geological disposal of nuclear waste. Similar organisations from outside the EC will also be targeted.

The following papers have been presented or submitted as part of OMNIBUS.

“Acoustic emission and velocity measurements using a modular borehole prototype tool to provide real-time rock mass characterisation”, Collins, D.S, W.S. Pettitt and R.P. Young. ESG-AGU-EUG Conference, Nice, France April 2003. [Session GI2.02 *Downhole Instrumentation and Analysis*].

“Geophysical measurement of the excavation damaged zone for radioactive waste repositories – OMNIBUS” Baker, C., C. Balland, P. Bigarre, D.S. Collins, W.S. Pettitt and R.P. Young, accepted for presentation at CLUSTER Conference on *Impact of the EDZ on the performance of radioactive waste geological repositories*, Luxembourg 3-5 November 2003.

“An Ultrasonic Tool for Examining the Excavation Damaged Zone around Radioactive Waste Repositories - OMNIBUS”, Pettitt, W.S., D.S. Collins , C. Balland, P. Bigarre, and R.P. Young. *Euradwaste04 Conference*, Luxembourg, March 2004.

“Seismic Wave Propagation to Diagnose the State of Fracturing”, Hildyard, M.W., R.P. Young, D.S. Collins, and W.S. Pettitt, Submitted to Journal of the South African Institute of Mining and Metallurgy, 2004

It is further envisaged that papers will be submitted for journal publication on the following aspects of the work.

- « An integrated tool for ultrasonic monitoring of rock masses and concrete structures in radioactive waste repositories ».
- « Ultrasonic analysis of an indurated clay in laboratory compression tests.»
- « Using numerical models to provide a sensitivity analysis of ultrasonic measurements through fractured rock masses »

In addition, results from the work will be included in brochures and promotional material from ASC, INERIS and the University of Liverpool. This will take the form of booklets, CDs and web-site content. The material will be used to attract future clients, students, researchers and as support for funding for new research projects.

A webpage for the OMNIBUS project has been posted at:
http://www.liv.ac.uk/seismic/research/current/omnibus.html.
This will be used to inform a broader audience about the main aims and objectives of the project as well as the key results.

APPENDIX II – PROJECT PARTNERS

The primary participants in the OMNIBUS project are shown in Table 5.

Table 5: The primary participants in the OMNIBUS project, and the associated contact details. Prof. R.P. Young is Formerly Chair of Earth Sciences, University of Liverpool, and now Hon. Research Professor, University of Liverpool, and Chair of Civil Engineering, University of Toronto.

University of Liverpool	*Applied Seismology Consultants*	*INERIS*	*ANDRA*
Prof. R.P. Young (administrative coordinator) Dr. D. Collins Dr. M. Hildyard	Dr. W Pettitt (scientific coordinator) Mr. Jon Haycox Mr. David Maffioli	M. C. Balland Dr. P. Bigarre Dr. E. Klein	M. P. Lebon
Prof. R. P. Young, University of Toronto, 35 St. George St., Toronto, M5S 1A4, Canada, Tel: +1 416 978 5252, paul.young@utoronto.ca www.lassondeinstitute.utoronto.ca/young	Dr. W.S. Pettitt, ASC Ltd., 5 Swan Hill Court, Shrewsbury SY1 1NP UK Tel: +44 1743 271440 will@seismology.org www.seismology.org	M. C. Balland INERIS-LAEGO, École Des Mines, Parc de Saurupt, 54042 Nancy, France Tel: +33 3 83 58 42 89 cyrille.balland@ineris.fr	M. P. Lebon ANDRA Parc de la Croix Blanche, 1/7 rue Jean Monney, 92298 Chatenay-Malabry, France Tel: +33 1 46 11 80 00 patrick.lebon@andra.fr