Faculty of Science and Engineering
Department of Exploration Geophysics

Land Seismic Repeatability Prediction from Near-Surface Investigations at Naylor Field, Otway

Yousuf Y. Al Jabri

This thesis is presented for the Degree of
Doctor of Philosophy
of
Curtin University of Technology

March 2011

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I have read the university regulations on cheating and plagiarism, and I state that this piece of work is my own, and this dissertation contains no material previously published by any other person except where due acknowledgment has been indicated in the text.

Signature:

Date: 25 March 2011

DEDICATION

I would like to dedicate my thesis to my beloved wife (Asmahan Al-Habsi), my parents (Yaqoub Al-Jabri and Hamida Al-Minji) and my children (Jinan, Bayan and Alwarith)

ABSTRACT

Time-lapse seismic is a powerful methodology for remotely monitoring changes in oil and gas reservoirs. Its high sensitivity and resolving power make it the methodology of choice for monitoring CO_2 sequestration in deep saline aquifers or depleted oil and gas fields. This method is now routinely applied offshore but rarely onshore because of inherently poor repeatability of land seismic data. Considering that CO_2 sequestration on land is becoming a necessity, there is a great need to evaluate the feasibility of this method for land based CO_2 sequestration projects. A feasibility study, onshore Otway Basin, Australia, aims at evaluating the viability of monitoring methodologies for the case of CO_2 storage into a depleted gas field. Since injection of CO_2 into a depleted gas field at a depth of around 2 km causes very subtle changes in elastic properties of the reservoir rock, it is critical to achieve high repeatability of time-lapse seismic surveys if they are to be implemented into a monitoring program. The goal of this thesis is to analyse the main factors affecting seismic repeatability at the Otway site. I aim to achieve this goal through the deployment of pre-base line measurements and combining the results with detailed numerical modelling studies. Such measurements have to be rapid, effective and quantitative so that a seismic monitoring team can decide whether to use time-lapse methodology when processing their data.

To find the most likely repeatability at the Otway site I used so-called micro-arrays (surface and borehole) in a time-lapse manner to determine the seasonal variation of elastic properties of the near surface. The measurements were aimed at determining directional P-wave velocity and attenuation (Q-factor). The top soil (0.5m thick agricultural layer or elasto-plastic zone) had a low velocity and low Q-factor and hence significantly attenuated seismic energy.

The elastic parameters obtained were then used to numerically simulate real time-lapse surveys. The results obtained were compared and verified against conventional time-lapse studies conducted at the Otway site over a three year period, at different times of the year and with different sources. The agreement between numerical and field data, expressed through a normalised root mean square (NRMS) difference confirms that the effect of the near surface variation in the time-lapse land seismic can be predicted with minimum cost and through the deployment of small, inexpensive experiments.

ACKNOWLEDGMENTS

In The Name of Allah, The Most Gracious, The Most Merciful

First of all, I would like to convey my sincere gratitude to my supervisor Associate Prof. Milovan Urosevic. I am grateful for his continual advice, motivation and knowledge which have provided the impetus for me to push through the hard times during my PhD research. I am also very thankful to the other members of my thesis panel Prof. Boris Gurevich (Chair), Prof Brian Evans (Associate supervisor), Dr. Christian Dupuis (Associate supervisor), Associate Prof. Anton Kepic (Associate supervisor) and Dr Valeriya Shulakova (Associate supervisor) for their guidance, ideas, comments and support that contributed much on improving the content and the structure of this project.

I would like to pass my special thanks to Prof. Brian Evans, Associate Prof. Bruce Hartley and Dr. Brett Harris, for their support and help in the editing process which has greatly benefited my work. I also appreciate the participation and feedback of my advisors throughout the process of completing this research. In addition, I would like to thank the other research staff in the Exploration Geophysics Department who have offered their friendship, advice, and support, especially Associate Prof. Roman Pevzner, Mr. Aleksander Dzunic, Mr. Dominic Howman, Dr. Donald Sherlock and Dr. Brett Harris for their direct or indirect help and support. I always remember the brilliant science and life discussions with my colleagues and office-mates (Previous and current PhDs students): Nasser Keshavarz, Dariush Nadri, Abdullah Al Ramadan, Putri Wisman, Marcos Grochau, Mrs Dina Makarynska, Mr Andrew Greenwood, Mr Elmar Strobach, Miss Eva Caspari, Majed Al-Malki, Miss Sofia Correla Lopes, Mehdi Asgharzadeh and Faisal Al-Onaizi who have offered their friendship, advices, and support.

ACKNOWLEDGMENTS

This work was undertaken with the Cooperative Research Centre for Greenhouse Gas Technologies (CO2CRC), Otway Basin Pilot Project for CO_2 Sequestration and therefore I would like extend my gratitude to CO2CRC for their cooperation and assistance throughout the development of this work and for allowing the publication of these results.

I would like to pass my warm thanks and gratitude to Mr. Robert Verstandig for software support and proof reading my thesis. I would also like to thank the secretarial staff, Deirdre Hollingsworth and Tanya Wallace at the Department of Exploration Geophysics for their continuous help and support during my study at Curtin University.

Research cannot be conducted in today's environment without financial support and I would like to recognise the sponsors of my research project. The primary sponsor of my research was Petroleum Development Oman (PDO). Additional support was provided by CO2CRC and Curtin University.

I wish to acknowledge Landmark, Hampson Russell, TessralCS-2D and Reflexw for the use of their software in this work.

Eventually, I am thankful to Allah for all opportunities that I have had. Also my sincere thanks and gratitude go to my family especially my father and my mother for their encouragement and prayers that helped me a lot throughout the work in this project. I also thank my brothers and sisters for their encouragement throughout this long process. My final acknowledgement must be given to my wife, Asmahan Al-Habsi for her support encouragement and long suffering patience while I was working in this project, without her help and forbearance, this project would not have been done.

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Chapter 1 : Introduction

1.1 Overview of land seismic repeatability

The production of oil and gas causes pressure and saturation within a reservoir to change over time. The goal of 4D seismic monitoring is to identify where in a reservoir the changes are taking place. Time-lapse or 4D seismic data are increasingly used to study and image the changes in the seismic response induced by the production of hydrocarbons or the injection of CO_2, water or steam into a reservoir. Time-lapse seismic monitoring is straightforward; seismic data sets acquired at different times are calibrated, compared, and the intersurvey differences analysed and interpreted in terms of fluid changes or movement. Several papers have been published in a variety of journals and extended abstracts in a variety of conferences demonstrating time-lapse results in cases of water flooding, steam flooding, gas injection, aquifer drive, production drive, etc. They present a very positive and almost exciting image of what seismic monitoring has done, and what the technology's potential can be. However, many of these results are the products of well planned and executed research projects. Time-lapse technology has had limited commercial ("real world") exposure and, as we perform more "real" work, we will become more aware of the limitations of time-lapse seismology (Ross et al., 1997). The challenge of producing 4D seismic repeatability can be achieved only by accurately repeating surveys so subtle changes in the reservoir's seismic response are revealed. The time-lapse seismic signal is generally a combination of non-repeatability effects due to differences in acquisition and overburden as well as production or injection effects at the reservoir level. Practice so far has shown that the signal inherent to non-repeatability is often larger in magnitude than the production imprint in the 4D data. However, to obtain an accurate estimate of the actual changes in a producing reservoir, it is important to distinguish between the non-repeatability and production effects, as well as to reduce the turnaround time of time-lapse seismic processing.

The main goal of 4D seismic processing and acquisition is to maximise the repeatability between two or more seismic sets while preserving and resolving differences in the reservoir associated with production. While time-lapse reservoir monitoring is a proven technology, industry is still developing and improving best practice strategies regarding 4D seismic data acquisition and processing.

One of the main issues encountered during 4D seismic experiments is the degree of repeatability between successive surveys. The repeatability helps determine the level of confidence in the interpretation of the time-lapse signature and methods such normalised root mean square (NRMS), which measures the difference between two surveys, and predictability, which measures the correlation between two traces (Bertrand et al., 2004), can be used to measure this.

The major problem with time-lapse seismic is how to deal with the non-repeatability factors in both data acquisition and processing. For time-lapse seismic data acquisition, the main non-repeatability factors are related to the differences between geometries, sources, observation directions, geophone types, offsets of shot and receiver points, seismic crews and equipment as well as near-surface conditions. For data processing, the non-repeatability factors are associated with the differences between processing workflow, parameters, algorithms, precisions, and contractors (Ross, 1996; Rickett, 1999). One way to enhance the repeatability is to correct time shift, reflection energy, bandwidth and phase using cross-equalisation or workflow. This includes rebinning, space- and time-varying amplitude balancing, matching filters for pre-stack and poststack, statics and post-stack migration, etc. Several questions arise nowadays, such as, what degree of precision (level of repeatability) is required for the specific field, and whether this threshold varies from one field to another, what are the critical parameters causing this variation and how the overburden complexities might cause variations in 4D repeatability encountered at the reservoir level.

1.2 Motivation for Studying Land Seismic Repeatability

High seismic repeatability is critical to the monitoring of fluid movement in the subsurface. At the CO_2 sequestration pilot project at Otway, the initial 2D seismic tests suggested that it would be difficult to achieve a good seismic repeatability at this site. After a sequence of repeated 2D seismic tests along the Soda's Road at different seasons with different seismic sources, it was found that the variation of water content at the near surface can affect the seismic repeatability. However, most of the previous time-lapse studies were conducted offshore. In addition, most of the previous studies only focussed on the monitoring changes at the reservoir level.

From the literature reviews, it is rare to find studies on the effect of the near surface on land seismic repeatability. It was decided that understanding the most important factors affecting land seismic repeatability was important as a preliminary to finding where the seismic conditions were changing.

On land, time-lapse seismic changes are produced by variations in the near-surface conditions, source signature variation, acquisition geometry (positioning and spacing), acquisition equipment, recording fidelity, differences between the surveys, processing methods and ambient noise. The confidence level in interpreting any seismic changes depends on how good the seismic repeatability is. The residual differences in the repeated time-lapse data that do not represent changes in the subsurface geology may compromise the effectiveness of the time-lapse seismic methodology.

It is widely accepted that time-lapse repeatability of land seismic is low. It is, however, less understood which factors are critically important for time-lapse land surveys. In the case of the Naylor CO_2 injection test site area, the presence of sinkholes and karst topography in the near-surface zone makes seismic non-repeatability investigations challenging but also interesting (Figure 1.1).

In such geological terrain, the degree of signal scattering caused by the rugose top limestone surface and caverns is greatly dependent on the depth to the water table. This is because if the water drops to a level below the rugose limestone surface, then the degree of signal scattering caused by the rugose limestone surface is increased.

Figure 1.1: Corrugated top limestone in the near surface of the western Otway Basin.

Consequently, repeated 2D seismic test lines have been acquired at the Naylor location prior to the 3D baseline seismic acquisition and certainly before CO_2 injection commenced at this field. These seismic lines were recorded with Mini-Vibroseis and weight-drop sources during both wet and dry conditions. The early 2D seismic data (Figure 1.2) show that the depth of penetration of seismic energy and frequency characteristics of the seismic wavelet will be different in dry and wet periods of the year (Urosevic et al., 2007). Furthermore, these tests showed clearly that seasonal variations have a first order effect on the seismic signature, while the source type and positioning accuracy of the recording instruments have secondary and tertiary effects on time-lapse studies respectively. Clearly, to improve the repeatability for the detection of time-lapse changes due to CO_2 injection, the effect of the near surface on seismic repeatability needs to be evaluated. Only then can attempts to compensate for the variability in the signal character by specialised field measurements be carried out.

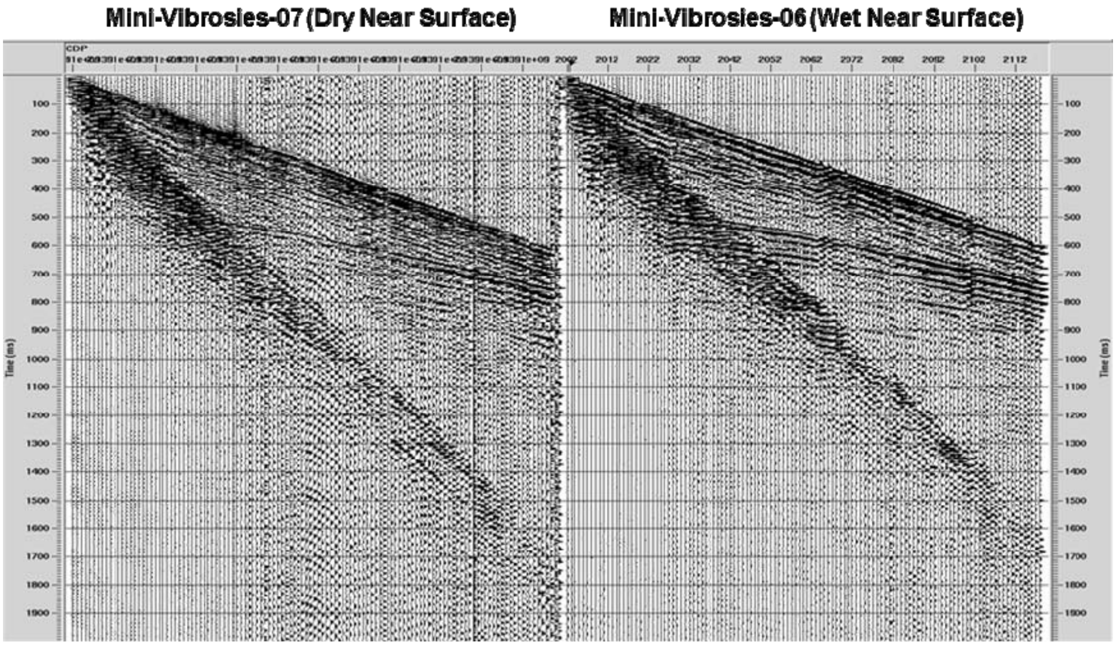


Figure 1.2: The first shot gather at the beginning of the 2D seismic test along Soda's Road for the dry (left) and wet (right) seasons. Data collected during wet seasons show a higher frequency content, higher signal-to-noise ratio, and better penetration.

A time-lapse seismic survey is one of the best methods for monitoring changes in the reservoir relating to oil/gas reservoir depletion or CO_2 sequestration. Understanding the factors influencing repeatability and possible limitations of the method is crucially important to the success of this kind of survey. Because the seismic experiments were performed in a real world situation, identical data could not be obtained from two seismic experiments even though the acquisition parameters were the same. A logical question to be asked is, what level of repeatability do we need? A partial answer to this question may be obtained by modelling the 4D signal. Therefore the next questions that we should ask are, can we model the 4D seismic response and can we then predict the level of seismic repeatability that could be achieved at a future site.

In the case of the CO_2 sequestration pilot project at Naylor Field, conducting land time-lapse surveys is a challenging task because of typical variability of ground conditions, source-receiver coupling and ambient noise, all of which contribute to the poor repeatability of land seismic surveys. Changes in near-surface conditions will produce kinematic differences but also different surface wave (ground-roll) patterns. This will generally require slightly different parameters for processing two successive surveys if they are acquired from vastly different soil conditions. After conducting extensive numerical and field tests it was shown that the signal-to-noise ratio (S/N) variability as function of the source strength and relative to the background noise level, is crucial (Pevzner et al., 2009). The near-surface agricultural layer combined with the rugged limestone surface (which constitutes a near-surface part of the section in the Otway Basin) is likely to create scattering that will change with soil saturation at the underground water level. Top soil hardness will also be more important for impact sources such as weight drop. To get an idea of the magnitude of these effects on non-repeatability, we conducted a series of numerical tests (Al-Jabri et al., 2008) which we compared with stacked sections from different models of near-surface properties obtained by finite-difference modelling.

This research will provide insights into the factors that influence land seismic repeatability and its possible limitations, and will help develop a better understanding of how to improve the seismic repeatability measurements. The results of this research will provide new knowledge to the scientific community in Australia and elsewhere. Therefore, the potential impact of this research is significant.

In order to understand the limitations of land time-lapse seismic repeatability, I shall investigate the influence of the main factors through a combination of the S/N and NRMS difference. The S/N and NRMS measurements in the pre-stack seismic data are easily controlled by the source strength and the near surface conditions while in the post-stack seismic data, they are influenced mainly by the source strength, the near surface conditions and the data fold. For very high fold data, the source strength, source type and near surface were less critical.

1.3 Aims and Objectives of this Research

The repeatability implies that the same acquisition and processing parameters used in two surveys taken at the same location but at different times should generate equivalent seismic data provided the subsurface conditions do not change during these times. The purpose of this study was to examine the seismic repeatability at Naylor Field. The repeatability of 3D surveys is much higher than the repeatability of 2D surveys acquired with the same parameters (Pevzner et al., 2009).

This is the case in the Otway Basin and it is shown in this thesis that 3D seismic repeatability, measured at about 20%, is much better than corresponding 2D repeatability which is estimated at 50% in the same area. This is because of the advantages in processing the 3D data using illumination and visualisation of the target (Pevzner et al., 2009). This is particularly important in the case of the Otway Project, as the target is exceptionally small, while time-lapse (TL) effects are rather subtle. We were unable to achieve an acceptable repeatability level for 2D lines for monitoring purposes. However, the repeatability of 3D surveys turned out to be excellent for the Otway data, with an average NRMS value of ~20% at the target horizons located at a 2 km depth. The main aim of this research is to assess the land seismic repeatability using specified methodology to investigate the causes of low land seismic repeatability and verify our findings at Otway Basin Pilot Project (OBPP). This involves an analysis of the effect of the near surface conditions and ambient noise on the variability of the seismic signature. Understanding these effects could help design optimum time-lapse surveys with improved levels of repeatability.

This research aims to develop methodology to predict the level of the land seismic repeatability at Naylor field for the CO_2 sequestration monitoring and verifications program of the OBPP. A crucial first step in any time-lapse project is a feasibility study. Such a study reduces the uncertainty in the outcome of the time-lapse project and determines the optimal seismic acquisition time during the field's life.

1.4 Methodology

It is reasonable to assume that the principal cause of non-repeatability issues in land seismic data is related to temporal variations of the near surface conditions. A set of repeated 2D seismic lines were acquired in Naylor Field at different seasons and using different seismic sources for feasibility studies of the land seismic repeatability at this site. In this study, I investigated the non-repeatability of seismic data by computing and analysing the amplitude spectra and NRMS value of the pre-and post-stack seismic data. In addition, the repeated pre-stack VSP data were also used to study the applicability of the Vibroseis sources compared to the weight-drop sources on the land seismic repeatability in cases where near surface conditions changed with water variation at the near surface. These VSP data were also used to investigate land seismic repeatability due to the change in the near surface condition. One of the methods I used to investigate and test the seismic repeatability at Naylor site, was to perform a “zero-time repeatability test” by recording multiple seismic shot gathers at the same location using the same seismic source within a very short time interval and before any changes could occur in the reservoir. To understand the effect of ground conditions and improve land seismic repeatability, I conducted so-called “micro-array” investigations of the near-surface layers at this site during the wet and dry seasons to determine their properties. After that, the field measurements of the near surface property layers from the micro-array surveys were used in the numerical modelling to predict the effect of the near surface changes in the seismic repeatability at the reservoir level before any injection activities. This was to evaluate the concept of the application of micro-array survey results for assessing the seismic repeatability at Otway. Finally, numerical tests were performed with calibrated soil parameters using the measured properties from the near surface surveys during the wet and dry conditions of the near surface to evaluate the effect that these seasonal variations had on seismic non-repeatability.

1.5 Thesis Outline

The structure of this research is designed to follow the chronological development of the project. The thesis will consist of 7 chapters: Chapter 1 presents an introduction to land seismic repeatability, which is part of the research background, and is followed by the motivation, objectives, methodology and configuration of the thesis. Chapter 2 introduces the reader to CO_2 sequestration projects around the world, the concept of land seismic repeatability from the literature reviews and finally, the objectives of the OBPP. The chapter begins by providing a general introduction in CO_2 sequestration followed by the concept of land seismic repeatability from the literature reviews, It also provides the reader with past and current investigations of seismic repeatability, both off and on shore. Then, historical perspectives and the geological setting of the Otway Basin are given followed by the aims of the Australian Cooperative Research Centre for Greenhouse Gas Technologies (CO2CRC) Otway Project. Chapter 3 then presents the analysis and results of the short-time (zero-time) seismic repeatability using repeated pre-stack seismic data acquired at the same time using surface seismic and VSP data test lines. Chapter 4 presents the methods, analysis and resultant workflow applied to the micro-seismic investigations for seismic repeatability of the near surface. Chapter 5 presents the prediction of the seismic repeatability through numerical modelling of the Otway data by using the elastic parameters that were measured from the micro-array surveys. Chapter 6 presents investigation results and the methodology developed for the evaluation of land seismic repeatability using the test lines recorded along Soda's Road versus a micro-array based prediction. This approach is aimed at producing a new understanding in land seismic repeatability and paves the way for rapid and inexpensive site characterisation for time-lapse seismic studies. The conclusions and recommendations of my research are outlined in Chapter 7.

Chapter 2 : CO_2 Sequestration and Land 4D Seismic Repeatability Concepts

After giving an introduction to this research, chapter 2 introduces the reader to CO_2 sequestration projects around the world, the concept of land seismic repeatability from the literature reviews and finally the objectives of OBPP.

2.1 CO_2 Sequestration

Arguably the most viable way at present of decreasing greenhouse gas in the atmosphere is to sequester it below the ground. That is, CO_2 is captured and injected into deep permeable formations. Sequestration is considered to be of high importance for reducing CO_2 emissions from coal fire power stations (U.S. Department of Energy, 2004). In the petroleum industry CO_2 is commonly injected into hydrocarbon reservoirs to enhance oil and gas recovery. The enhanced oil recovery (EOR) industry has been using CO_2 as an injection gas to increase the pressure of reservoirs and reduce the viscosity of oil for many years (Oxy Permian Ltd., 2003). Besides oil and gas fields, saline aquifers, deep ocean water and deep unmineable coal seams can all be used as sequestration reservoirs. Sequestration of CO_2 in coal seams is also considered a viable method to reduce CO_2 released into the atmosphere. Sequestration may have benefits for methane gas recovery, thereby making the process potentially economical regardless of the technical difficulties (Salehi and Gowlli, 2006; Saghafi et al., 2007). Capturing and sequestering CO_2 has an almost immediate benefit in reducing CO_2 in the atmosphere, that is, deep cuts in greenhouse gas emissions can be made while the benefits using fossil fuels are retained. Geosequestration involves the capture and storage of carbon dioxide i.e. Carbon Capture Storage (CCS). CCS enables the combustion of fossil fuels (coal, gas or oil) without significant emissions of carbon to the atmosphere. It utilises technology that has been widely practiced in the oil and gas industry for many years. There has been considerable research in geosequestration. This research indicates that the largest quantities of CO_2 could be stored in saline aquifers. However, the major CO_2 emitting power plants are rarely located near large saline aquifers. Another option is to store CO_2 into depleted gas and oil fields. Depleted gas and oil fields are widespread and some, or all, of the infrastructure may already be in place. Figure 2.1 shows an overview of geological storage options which are commonly used. The world's first industrial application of CO_2 storage in saline aquifers commenced at the Sleipner Field in 1996 (Arts et al., 2004; McKenna, 2004). Other examples include the Weyburne Project in Alberta, Canada (Brown, 2002; Davis and Benson, 2004; Davis et al., 2003; Herawati and Davis, 2003; Herawati and Davis, 2002), the In Salah Project in Algeria (Riddiford et al., 2005) and the Gorgon Project in Western Australia. All other projects are of a strictly scientific nature such as the Frio Project in Texas (Hovorka et al., 2006) and the Ketzin Project in Germany (Forster et al., 2006). The global sequestration projects around the world are shown in Figure 2.2.

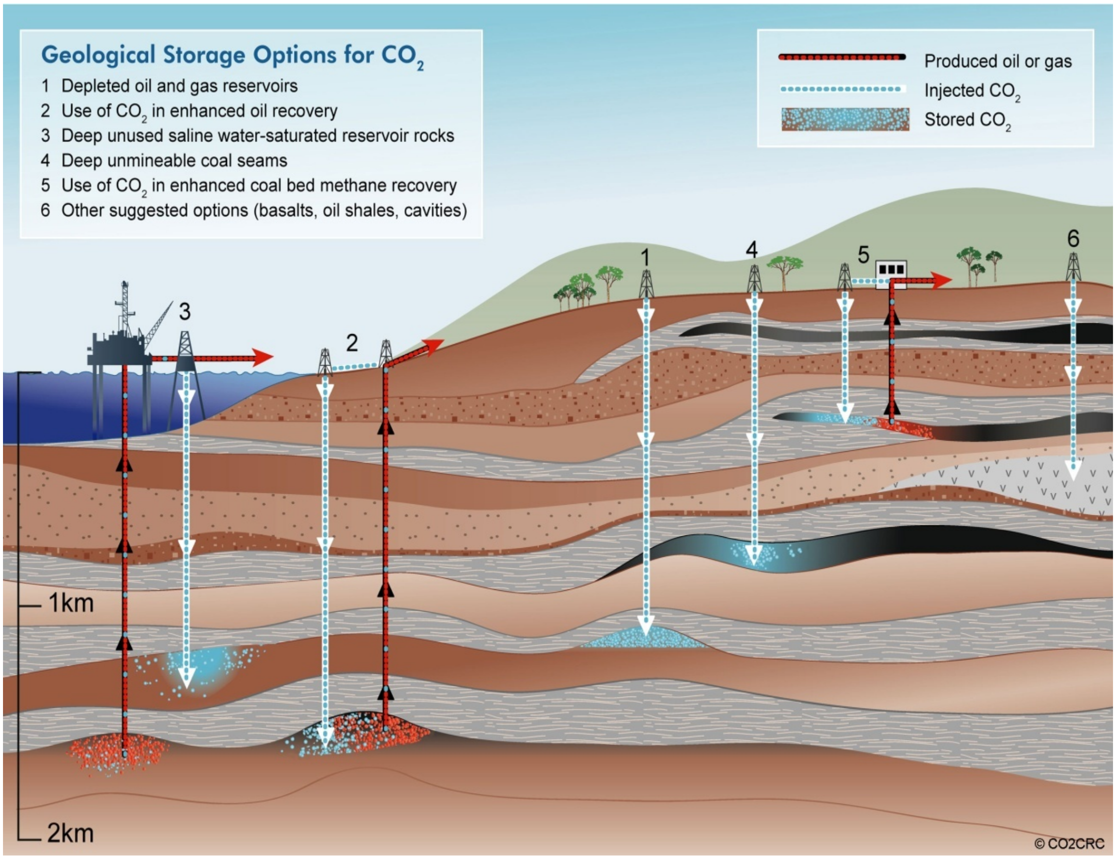


Figure 2.1: Overview of geological storage options (CO2CRC, 2010)

Australia's first demonstration of deep geological storage is ongoing. The CO2CRC Otway Project aims to demonstrate that geosequestration is a viable option for CO_2 mitigation under Australian conditions (Cook, 2006). The project differs significantly in terms of geological character and storage processes when compared to the existing Sleipner, Weyburn, Frio and Ketzin sequestration projects. Besides allowing international collaboration in research, this project offers an opportunity to gain important additional information on the permanent and safe geologic storage of CO_2.

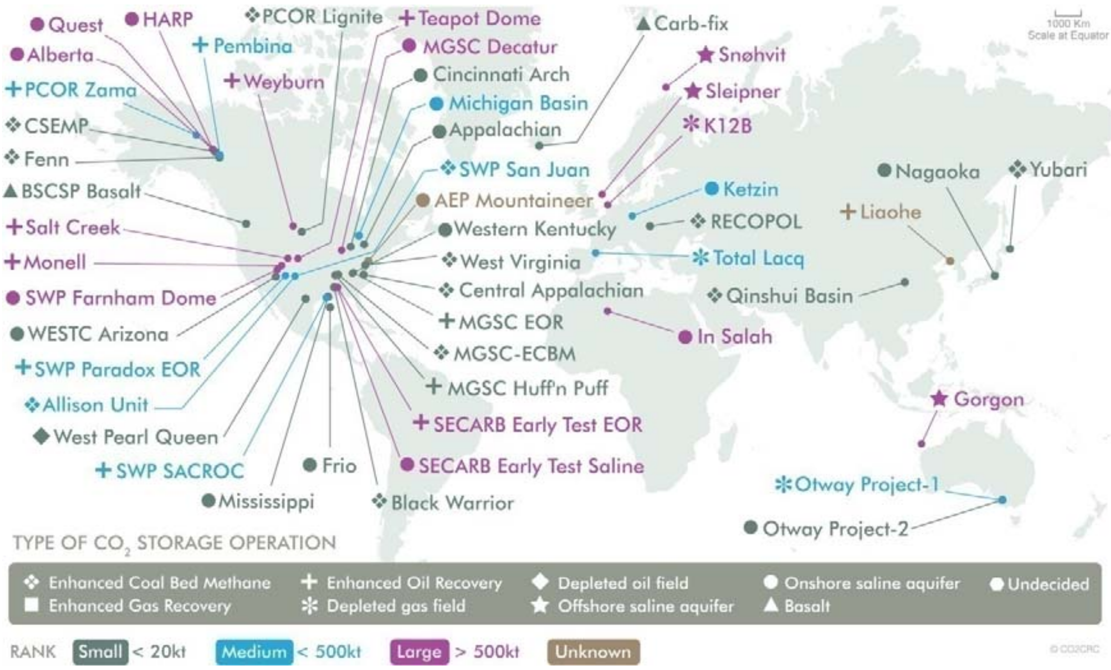


Figure 2.2: CO2 storage demonstration projects around the world (retrieved on the 11th of August 2010 from http://www.co2crc.com.au).

2.2 4D Seismic Monitoring

Time-lapse, often labelled 4D, seismic methods provide information about elastic changes in oil and gas producing reservoirs, in space and time. These changes can be used to interpret fluid distribution in the reservoir as a function of time. This knowledge is enormously important for both efficient secondary hydrocarbon recovery and CO_2 sequestration objectives. Worldwide, the remaining oil reserves are now almost similar to those already consumed (Calvert, 2005). That is a vast amount of oil but it is being consumed rapidly, and additional conventional reserves are becoming increasingly harder to find. It is imperative for the industry and for the consumer that we are more effective in the extraction of remaining oil from existing oil fields. Time-lapse seismic has a key role in enhanced hydrocarbon recovery from the existing fields (Calvert, 2005).

Time-lapse or 4D seismic has gained increased interest in the area of EOR (Jack, 1998). The purpose of this relatively new methodology is to monitor hydrocarbon saturation changes in reservoirs during production. Time-lapse seismic is in general capable of detecting bypassed hydrocarbon compartments and allows the mapping of hydrocarbon migration path ways. These methods also enable the mapping of the oil-water contact with time, and consequently facilitate better control over the impact of injector wells. All of this information can be used to assist in well field planning and optimisation. However, to get reliable results from time-lapse seismic methods, the repeatability of the seismic data acquisition and processing of the data is highly important (Jack, 1998).

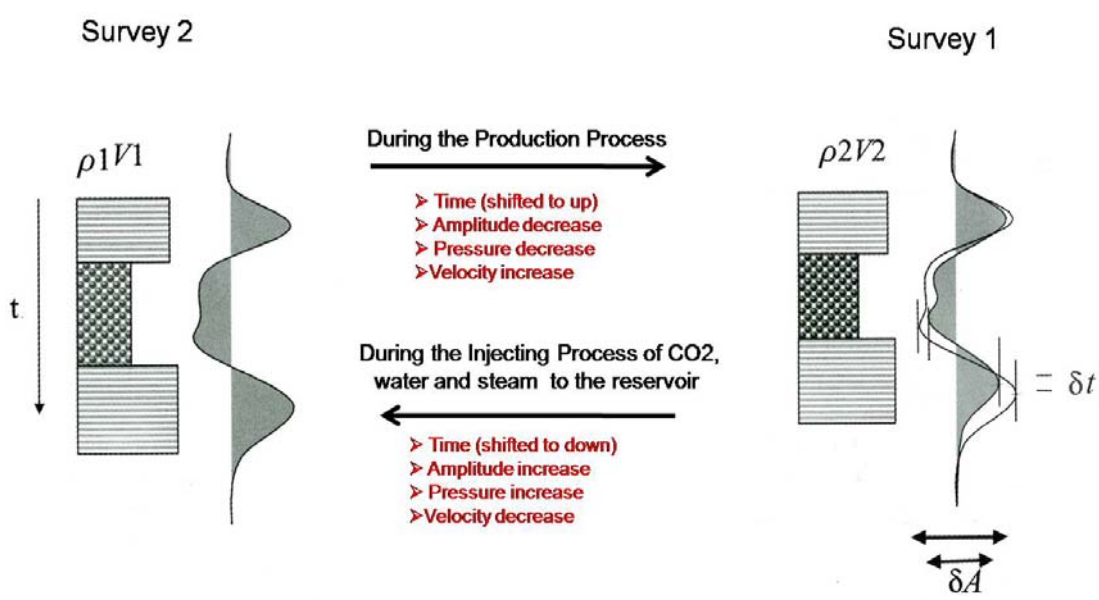


Figure 2.3: The geophysics of 4D monitoring. V_p, V_s, and the density of a reservoir change as a result of production or injection of CO_2, thereby giving response changes that appear on seismic lines as amplitude and timing changes (modified after Calvert 2005).

Optimisation includes recognition of safety and environmental concerns, recovery factors, production time lines and, dollar cost and profit. Time-lapse seismic data can be a major contributor to the knowledge of what is happening and where it is happing in our reservoirs. If we survey producing oil or gas fields before and during the production process, we can estimate the change to the reservoir. As hydrocarbons are replaced by water/CO_2/steam and as pressure changes, seismic velocity and density of the reservoir fluids change (Figure 2.3). From 4D surveys, we can measure the effect of these changes and identify where the changes are occurring in the reservoir. 4D seismic monitoring is the ideal tool for gathering information on where the fluids are moving, where to place relief wells, how to optimise reservoir stimulation. This situation occurs when we inject fluid under pressure into the subsurface, whether for CO_2 sequestration purposes or for EOR.

An example of CO_2 sequestration and associated time-lapse seismic effects was presented by Arts, Elsayed, Van Der Meer, et al., (2002) for the Sleipner case. Figure 2.4 clearly shows the amplitude brightening as CO_2 moves up through the formation. The increased delays caused by the associated velocity reduction are also visible.

The time-lapse or 4D seismic methods generally involve the acquisition, processing, and interpretation of repeated seismic surveys over a producing hydrocarbon field. The objective is to determine the changes occurring in the reservoir as a result of hydrocarbon production or injection of water or gas into the reservoir by comparing the repeated datasets. A typical final processing product is a time-lapse difference dataset (i.e., the seismic data from Survey 1 ‘Base Survey” is subtracted from the data from Survey 2 “Monitoring Survey”). The difference should be nearly zero, except where reservoir changes have occurred. The time-lapse seismic methodology requires high data repeatability therefore all data must be recorded and processed under identical conditions. While this may be readily achieved in offshore surveying, land surveying presents quite different problems. Despite that, some studies have had relatively good success in measuring differences using 2D seismic recordings with different instruments and methods in the seismic acquisition stage (Calvert, 2005).

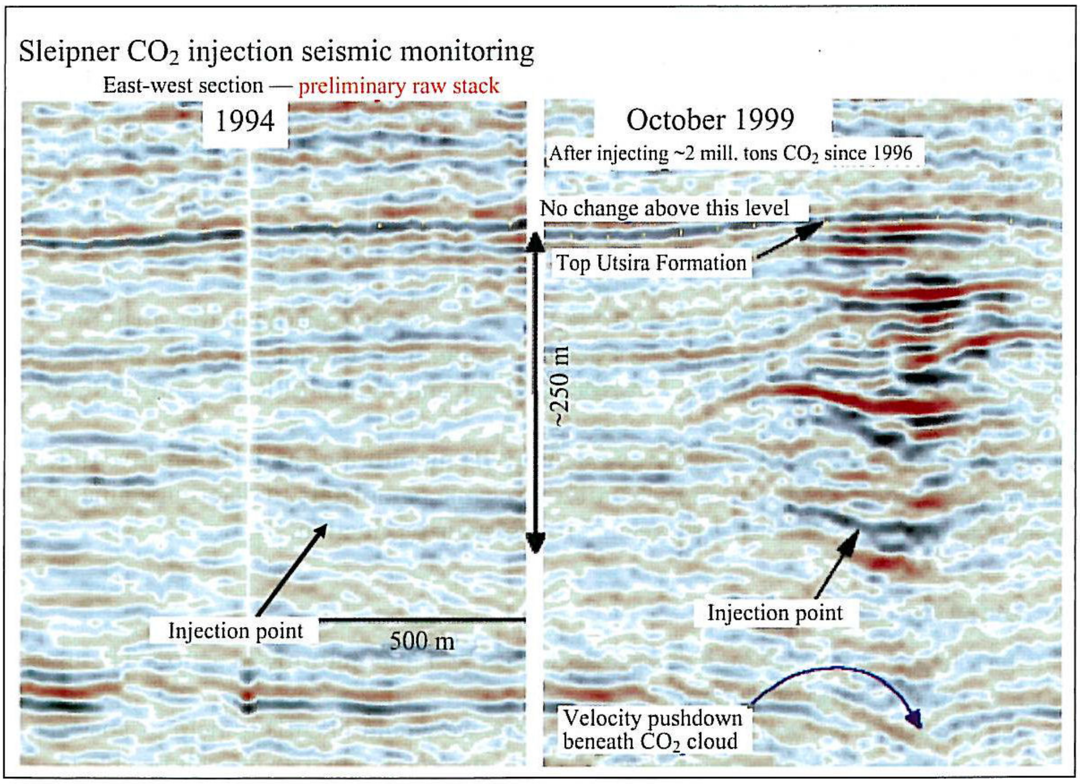


Figure 2.4: A 4D survey allows us to monitor fluids moving in the subsurface. Here, we see the effect of CO_2 injection near the Sleipner Field. This is an analogue of what we would see with an internal gas blowout. A 4D survey should be considered immediately for monitoring any dangerous loss of reservoir sealing (Arts et al., 2002; Arts et al., 2000).

4D seismic data analysis has been shown to be an important tool for mapping and monitoring fluid movements and pressure changes in petroleum reservoirs during production, thus contributing to improved recovery rates and better management of the fields (Arts et al., 2002). Consequently, the use of time-lapse seismic methodology has increased dramatically over recent years and the success stories accumulate. Figure 2.4 shows how 4D seismic data can be used to map CO2 accumulation underneath a seal. Such examples are extremely rare and the question of seismic repeatability remains. Several major challenges remain with regards to both data quality, repeatability, data assessment and the confidence level for seismic data analysis. Some of these challenges will be addressed in this research.

2.3 Factors affecting the seismic repeatability in marine and land seismic acquisition

The factors that need to be taken in consideration during the acquisition design in marine seismic are as follows:

- Different Positioning (Receivers and Sources)
- Different Streamer Feather
- Undershooting Platforms / Vessels
- Different Cross-Line Geometry
- Different Streamer / Source Depths
- Tides / Currents (different multiples)
- Water Temperature
- Different Processing Flows

Whereas land seismic survey considerations are as follows:

- Different Positioning (Receivers and Sources)
- Changing Water Table level (near surface)
- Different Shot/Receiver Coupling
- Environmental Noise (e.g.: Tractors, Airplane, Trains, Electric Power, Wind)
- Different Processing Flows

2.4 Causes of non-repeatability in land time-lapse seismic

Uniform seismic processing flows between multiple data sets is crucial for successful time-lapse 3-D interpretation, but uniform processing of multiple data sets can be problematic if there are differences in the acquisition type or in ambient recording conditions (Landrø, 1999). Increased repeatability is recognised as one major issue for improving time-lapse seismic technology as a reservoir management tool. For time-lapse seismic data acquisition, repeatability between two or more surveys is a key issue. Several studies have been done for conventional marine surface seismic data on the topic of repeatability. However, for repeated 3-D marine surveys, typical NRMS differences between repeated stacked sections are as high as 60% (Landrø, 1999). Several techniques are available for equalising two seismic data sets prior to the differencing process. Most seismic-processing software packages contain an option for the design of matched filters aimed at minimising the difference between two traces or gathers of traces. Ross, Cunningham, Weber, et al., (1996) presented a cross-equalisation method and an example of an application, demonstrating the impact of the cross-equalisation procedure on seismic data.

The quality of land seismic data suffers from irregularities within the near surface, which is composed of layers that have experienced varying degrees of weathering. Examples of these irregularities include: lateral variation in thickness, lateral and vertical velocity variations, rugged topography, karst structures, and effects of near-surface water. The effects of these irregularities on seismic data include: statics, scattering, multiples, ground roll, weak penetration of signal into deeper layers, and severe amplitude losses. These effects on seismic data are more severe in arid areas due to the extensive weathering that these areas have experienced during their geological history. Therefore, it comes as no surprise that petroleum companies working with seismic data in Middle Eastern countries suffer greatly from near-surface effects. This can be evidenced by the increasing number of forums devoted to issues of the near-surface during the last few years. These events were organised by regional and international petroleum companies and societies.

2.4.1 Soil Conditions

Tests of seismic repeatability at Naylor Field site were performed in which 2D seismic data were acquired along the adjacent Soda's Road during different seasons. These tests highlight the effectiveness of time-lapse seismic methodology. On land, the so-called non-repeatability component of seismic signature can be split into: (1) a complex effect of the agricultural soil (elasto-plastic zone), and (2) the relatively simple scattering effect of a corrugated near surface clay/limestone interface (purely elastic zone).

In case of the Otway test site, it was noticed that the absorption of energy by the near-surface zone had a significant effect. Unfortunately, time-lapse seismic changes are not induced just by the production of hydrocarbons or the injection of CO_2, water or steam into a reservoir but also by the variations in the near-surface conditions such as water saturation of the near surface zone. The previous repeated 2D seismic test lines at Naylor Field showed that changes in the near surface conditions were primarily responsible for large seismic response differences observed between different surveys. Therefore the land seismic repeatability is poor compared with the marine seismic repeatability if we take into account the same source signature, acquisition geometry (positioning and spacing), acquisition equipment, recording fidelity, processing methods and environmental noise. The variation of water saturation at the near surface could change seismic velocities and quality factor (Q) of absorption or attenuation from season to season and therefore will affect the seismic signal. Differences in the repeated time-lapse data that do not represent changes in the subsurface geology impact on the effectiveness of the method. Baker et al. (1997) and Jefferson et al. (1998) observed over periods of days to weeks that short-term moisture variations in the near surface could have a significant impact on the quality and character of shallow seismic reflection data. Typically, these variations are attributed to differences in the source and receiver coupling. This impact therefore has an effect on the deeper seismic reflection data of the subsurface. However, analysing the changes in attenuation (absorption and scattering) and the propagation velocity of seismic energy in the upper four metres of the near surface at the Naylor Field site is an important additional factor to be taken into account when collecting seismic data for 4D analyses. The near surface conditions of Naylor Field consist of shallow karst and weathered in-fill which, during times of rainfall, provide a good seismic transmission medium, but during times of drought provide very poor seismic transmission as the water table lowers and the karst dries (AlJabri et al., 2008). This can be a first order effect requiring major manipulation of the input data in order to recover similar seismic transmissions as that of previous or subsequent surveys. This would be the same whether the survey is a 2D or 3D surface seismic or VSP survey.

2.4.2 Source generated noise

In general, the level of ambient noise and intensity of the ground roll are important for time lapse surveys. Weak sources, such as weight drop, produce data that are more affected by the ambient noise level than high power sources such as big vibrators or explosive sources which tend to readily overpower the background noise. The distribution of elastic energy with frequency changes with the source type, so that a weight-drop source tends to produce more surface waves than a vibrating source and hence has a spectrum shifted towards lower frequencies with respect to the much flatter Vibroseis spectra. A weight drop tends to produce plastic deformation, hence care needs to be taken in real-time vertical stacking (Yordkayhun et al., 2009).

2.4.3 Ambient noise

In order to quantify the impact of random noise on repeatability, it is important to take into account the ambient noise that was included during the recording process. The movement of vehicles, weather condition changes (rain and winds) and power lines around the recording area can produce different ambient noise which can affect seismic repeatability.

2.4.4 Survey geometry, recording equipment and parameters

In the presence of near surface variation, sometimes one meter positioning accuracy is needed to keep 4D noise within acceptable limits. I have also observed that changes in the arrays themselves (receiver or source or both) could significantly increase the 4D noise. It became natural to think of possible ways not only to evaluate but also to compensate for positioning differences. In time-lapse seismic acquisition, monitor traces should ideally be recorded at exactly the same physical position as the corresponding reference trace. However, in practice this is rarely possible, particularly for marine seismic but also for land seismic. 4D positioning errors are common for the repeated surveys. These errors contain a known and an unknown component: the differential GPS system can give a monitor location that deviates significantly from the reference.

Although stacking and binning might eliminate parts of this problem, the errors will still affect pre-stack processing such as NMO, DMO and pre-stack depth migration.

A commonly used method for cross-equalising a 4D difference between two seismic surveys is to derive and apply matching filters between the two surveys. This may be done on a trace by trace basis or using a single filter for the entire survey. Whilst it is true that it is necessary to match the wavelets of the two surveys, simple matching filters will be ineffective if event positioning errors remain in the data. For example a misaligned dipping event for a given trace position will produce an apparent time difference. The magnitude of that difference will depend on the magnitude of the dip. So, if the matching filter is derived above the reservoir and if the reservoir has a different dip to the design gate, a false 4-D signal could be created and hence detected at the reservoir level.

2.4.5 Scattering of Seismic Energy

Our observations from the collected data at Naylor field show strong scattered noise in complex near-surface areas. The scattering is dominated by the rugged topography of the near surface layers. These strong near-surface scatterings can seriously decrease the energy of valid signals and significantly increase noise levels that mask the interesting reflections. The simulated wave scattering by a low-velocity topographic structure in our modelling of the Naylor Field case shows that the topographic effect is the most important factor for degrading the quality of seismic data in these areas. Rough topography and complex near-surface velocities pose significant challenges for seismic acquisition and processing. The first problem involving static time shifts in seismic traces has been extensively addressed (e.g., Widess, 1946; Selem, 1955). The widely used static correction technique to compensate for time shifts assumes that waves propagate vertically in the near surface. When raypath emergence angles are large, the static shift produces unsatisfactory results. In some regions where the topography is rugged, we will always have extremely poor signal-to-noise data. In such situation, both the conventional static correction techniques and the wave equation-based methods are not applicable (Wang et al., 1998; Mazzotti et al., 2000) or are likely to generate strong artifacts (Bevc, 1997). It is an established fact that the strong wavefield scattering generated by rugged topography and strong near surface velocity variations is the cause of the extremely poor quality of the field data acquired from rugged topography. The investigation of the Naylor field data confirms that the scattering within the cavernous limestone of the near surface was the prime reason for the poor quality of the data. The diffused scattering attenuates and distorts the seismic wavefield so that it shows little coherent energy on shot records. To remove the near-surface effects on surface seismic data, a thorough understanding of wave propagation in the shallow subsurface region is needed.

2.4.6 Absorption of Seismic Energy

The quality factor (*Q*) is a measure of how dissipative a material is (Mavko et al., 1998). A lower *Q* indicates larger attenuation of a seismic wave as it propagates through a medium. Seismic attenuation is caused by scattering and absorption. The spectral ratio method is a popular way to estimate *Q* within seismic data. Because 1/*Q* is a measure of the fractional loss of energy per cycle of oscillation, there is a tendency for shorter wavelengths to be attenuated more than longer wavelengths after a fixed distance of propagation (provided *Q* is independent of frequency). Particle motion for a seismic wave travelling in a viscoelastic solid can be expressed in terms of displacement by:

$$\mu(x,t) = \mu_0^{-\alpha(\omega)x + i(\omega t - kx)}, \tag{1}$$

where α is the spatial attenuation factor (Mavko et al., 1998). If the amplitude of the propagating wave is given by:

$$\mu(x,t) = \mu_0^{-\alpha(\omega)x} = \mu_0^{-\frac{\pi f}{VQ}x}, \tag{2}$$

it is possible to compare the spectral amplitudes at two different distances and estimate Q from the logarithmic decrement:

$$\ln\left[\frac{S(f,x_2)}{S(f,x_1)}\right] = -\frac{\pi f}{VQ}\left(x_2 - x_1\right), \tag{3}$$

as shown in Figure 2.5 (Mavko et al., 1998).

Typically, signal data are converted from the time domain to the frequency domain using the Fast Fourier Transform (FFT). The z-transform can be used to represent a seismic trace as an n^{th} order polynomial in the variable z. A general approach for specifying the z-transform of a seismic trace $w(t)$ is to express it as a system function (Poularikas and Seeley, 1985):

$$W(z) = -\frac{\left(\sum_{i=0}^{M} b_i z^i\right)}{\left(1 + \sum_{i=0}^{L} a_i z^i\right)}. \quad (4)$$

The polynomials defined in the numerator and denominator of this expression can be solved with traditional polynomial algebra. Solutions to the numerator are called zeros, as they specify points at which the power spectrum ($W(z)$) is zero. Solutions to the denominator are called poles, and they specify peaks in the power spectrum ($W(z)$).

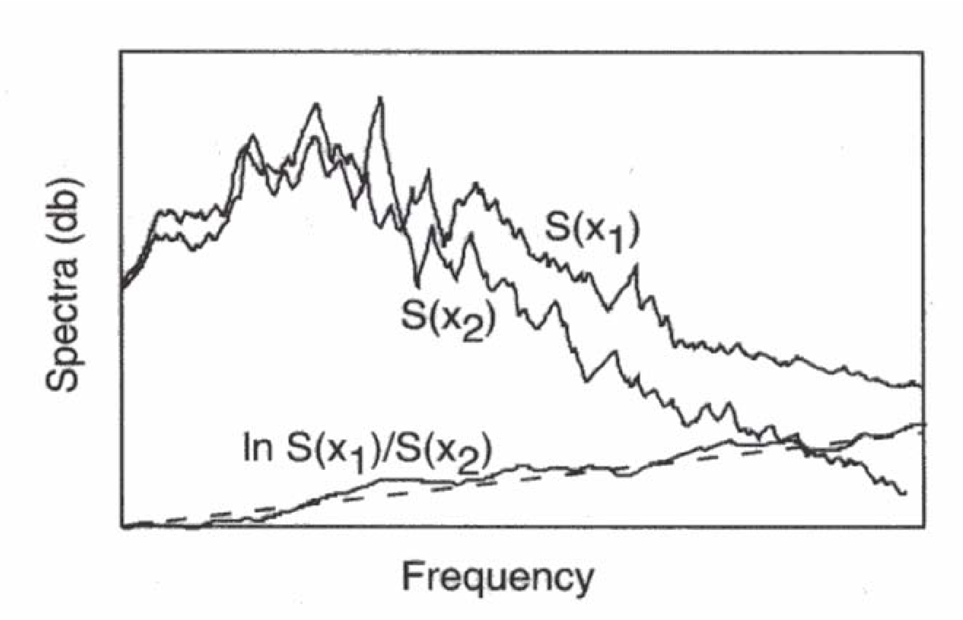


Figure 2.5: Schematic diagram illustrating increased attenuation of frequency with increased travel distance ($x_2 > x_1$). The difference in spectral decay between points x_1 and x_2 can provide an estimate of the quality factor (Q) of a medium (after Mavko et al., 1998).

If a power spectrum is estimated with only values in the numerator, it is known as an all-zero model. If a power spectrum is estimated with only values in the denominator, it is known as an all-pole or maximum entropy model (Burg, 1967). One method of calculating the single most dominant frequency within a seismic trace is to use the maximum entropy method.

A multi-coefficient polynomial is used to model the power spectrum and identify its most significant peak (or pole). This methodology gives reliable estimates of the peak frequency using a limited number of samples, unlike FFT-based methods. An estimate of power decay can be achieved by calculating a linear fit through the modelled power spectrum values between the dominant peak frequency and a nominal high frequency limit.

2.5 Establishing Probability of Time-Lapse Seismic Success

As discussed previously, the main non-repeatability factors are related to the differences in acquisition geometries, source types, observation directions, instrumentation, and near-surface conditions. For data processing, the non-repeatability factors are associated with the differences from processing workflow, parameters, algorithms, precisions, and contractors (Rickett et al., 1999; Ross et al., 1996). One way to enhance the repeatability is to correct time shift, reflection energy, bandwidth and phase using cross-equalisation or workflow. This includes re-binning, space and time-varying amplitude balancing, matching filters for pre-stack and post-stack, statics and post-stack migration, etc.

2.5.1 The Feasibility Study for Time-Lapse Seismic Monitoring Program

A crucial first step in any time-lapse project is a feasibility study. The study mainly covers the evaluation of rock properties, fluid properties, fluid substitution and pressure response, seismic property variation with fluid, pressure and the effect of the weathering zone on near surface for land seismic. Seismic-oriented evaluation parameters include vertical resolution, lateral resolution, S/N, repeatability of shooting and receiving, and fluid boundary imaging (Lumley et al., 1997). Factors that lead to a successful time-lapse seismic project are high porosity, large variation of fluid saturation, large impedance change, small structural dip, high vertical and lateral resolutions, high S/N, good repeatability of source and receiver positions, and high-precision imaging. Such a study reduces the uncertainty in the outcome of the time-lapse project and determines the optimal acquisition time in the field's life. An initial check can be performed in a matter of hours using a few facts about the reservoir and the base seismic survey (Lumley et al., 1997). Similarly, economic feasibility can be demonstrated with a value-of-information study that highlights the risk-weighted costs and benefits. A positive outcome of these initial studies will justify further investigation. Key elements in this follow-up feasibility study are:

- A change in the near surface for land seismic
- A rock- and fluid-property study
- A reservoir flow simulation to calculate expected saturation and pressure changes
- An estimate of the noise level in the base seismic

The feasibility study results and the reservoir properties to be delivered will ultimately determine the survey acquisition, processing, and inversion parameterisation. The influence of seismic processing parameterisation is considered during acquisition design. The extraction of the 4D signal requires the subtraction of two seismic volumes (baseline and monitor) over the same spatial reference, acquired at different times. The repeatability of the seismic method (both acquisition and processing) is an important factor in determining the true 4D signal, over and above acquisition and/or processing artefacts.

2.5.2 Time-Lapse Seismic Acquisition Evaluation and Design

Acquisition is best conducted with identical parameters used with identical systems. It is, therefore, important to consider only those acquisition systems/methods that are not approaching obsolescence. Critical in the design of a 4D monitor survey will be the extent to which the baseline or legacy survey geometry should be followed, bearing in mind that the legacy survey may often be poorly sampled relative to the currently accepted best practices in the industry for sampling, offset distribution, and fold of coverage. More fundamental to the issue of repeatability is the orientation of the survey. Operational constraints often require surveys to be acquired in non-optimal orientations in terms of purely geophysical criteria. Obstructions, weather patterns, cost constraints, and land and maritime traffic can all influence the survey orientation. Repeat surveys must follow the orientation of the baseline survey to ensure maximum repeatability. Not only must we consider these issues at the time of the baseline survey, but also project forward to the proposed date(s) of subsequent repeat survey(s). It is particularly important to understand long-term plans for additional infrastructure likely to be added to a producing field during the interval between baseline and subsequent surveys. Having considered the above sources of error in repeatability, we must also look at the acquisition system itself to determine the inherent perturbations present due to positioning accuracy, receiver sensitivity/calibration and source calibration.

The effect of reservoir changes on seismic response must be larger than background noise in the seismic data. It is important to repeat every aspect of acquisition as closely as possible to the baseline data. For studying the true 4D seismic effect, we should consider the following parameters for the marine seismic: source and receiver positioning, source signature and coupling, acquisition hardware (geophones, recording equipment), time of the year (water temperature, currents) and data processing flow. However, for land seismic we should consider the following parameters: source and receiver positioning, source signature and coupling, acquisition hardware (geophones, recording equipment), time of the year (near surface ground conditions) and data processing flow. Previous studies and experience have convinced us that repeating the acquisition imprint is of great importance for time-lapse seismic. As a final point it has to be kept in mind that seismic surveys should be designed and documented to ensure that the acquisition can be reproduced at a different time.

2.5.3 Time-Lapse Seismic Processing Techniques

Specific time-lapse processing techniques are appropriate where two or more surveys have been acquired and a measurable time-lapse response is expected. The key to the technical success of 4D seismic applications lies in the repeatability and resolution of the seismic data. If the processed seismic datasets are not identical then the 4D signal can become masked by, or confused with, 4D noise. Historically, differences in the acquisition characteristics of baseline and monitored 3D surveys have been a significant source of this 4D noise. It is not always possible to exactly repeat two seismic datasets, and often the surveys to be compared have been recorded with significantly different parameters. The equalisation method obtains a “best match” filter from the non-reservoir reflector window which, after convolution with the reservoir, eliminates the differences of amplitude, frequency, and phase (Pevzner et al., 2009). Any remaining differences in the reservoir are interpreted as the changes caused by variations of oil, water and gas in the reservoir.

The primary objective of time-lapse seismic processing is, therefore, to maximise the repeatability of the datasets, while attaining sufficient temporal and spatial resolution for the detection of the expected subsurface variations. The subsurface variations are normally changes in acoustic impedance, but may also be an AVO effect, a time shift, or any other aspect of the seismic data. Combinations of responses can also occur. The expected time-lapse response must be considered when developing the processing flow and areas where production effects are likely to have occurred must be monitored to ensure that any genuine changes in the seismic response are preserved.

Two decisions can significantly increase repeatability and thereby increase the possibility of detecting small time-lapse changes: (1) base and monitor data should be processed in parallel by the same contractor and (2) if there are doubts concerning the quality of the navigation data of the base survey, then this navigation data has to be reprocessed as well. Deterministic processing methods are preferred over data-adaptive processes.

Different processing schemes and/or parameters are likely to be applied when processing the acquired data volumes. This may seem likely to introduce an unnecessary mismatch to the 4D data since it should always be possible to apply exactly the same processing steps to the data sets. But, we have to recall that changes in the source/receiver geometry often necessitate altered processing parameters in order to get comparable results.

Consequently, in order to be able to compare the seismic signals from different vintages of the same area, a matching scheme, or more generally, several complementary matching schemes should be applied. Such schemes should ideally reduce all variations that are due to acquisition artefacts and at the same time have no effect on the seismic signal differences due to drainage of hydrocarbon compartments in the reservoir zone. In reality, one of course has to accept a trade-off between these requirements. Several matching methods exist to achieve the stated objective (Beasley et al., 1997). We can apply frequency spectrum shaping through digital filtering in order to compensate for differences in the seismic source signatures or differences in the receiver responses of the hydro/geophones, interpolation and binning to compensate for variations in the acquisition geometry, and amplitude scaling to calibrate the reflection strength. When matching seismic data sets, we have to consider whether we should apply the matching scheme(s) pre-stack, post-stack or post migration. While it seems intuitive to put most effort in pre-stack processing since mismatch errors propagate in a complex manner through stacking and migration, this may nevertheless prove difficult because the signal to noise ratio is lower in the pre-stack domain. Consequently, a matching scheme solving residual mismatch errors after migration is desirable.

2.5.4 The Uncertainties of Time-Lapse Seismic Surveys

4D seismic is becoming a standard technique for reservoir monitoring. It corresponds to recording 3D surveys over the same field, at different periods of production life. Ideally, the observed amplitude variations between two surveys are connected with physical changes in the reservoir zone induced by fluid flows. 4D seismic interpretation is often based on multi-attribute analysis techniques. In this frame, statistical pattern recognition is widely used (Nivlet et al., 2001). It is a probabilistic approach designed to translate a set of features, such as amplitudes, in terms of reservoir classes, such as low against high porosity facies. In the 4D seismic context, it helps in reliably detecting and interpreting changes within the reservoir zone (Lucet and Fournier, 2001). Particularly, supervised pattern recognition is popular since it allows training the interpretation on *a priori* classes representative of the fluid variations within the reservoir. A supervised approach is based on the various methods for discriminant analysis.

To make 4D data interpretable, seismic acquisition must be repeatable: amplitudes in areas not impacted by fluid and pressure changes within the reservoir should be identical between the base survey and the repeated ones. This is difficult to achieve, especially when the different data sets have not been acquired or processed in the same way. To minimise these undesirable variations, a careful pre-processing is necessary (Ross, 1996). Yet, the homogenisation of the different surveys is never perfect. This means that a fraction of amplitude changes within the reservoir are not connected to their physical changes, but merely express a lack of repeatability. This kind of uncertainty on the attributes being interpreted should be accounted for. Despite a careful pre-processing based on cross-equalisation of the different surveys, repeatability is always imperfect. This aspect is a good basis to estimate the uncertainties on the whole seismic data sets. However, the differences outside the reservoir are zero mean, which signifies that 4D data quality is sufficient to go on in interpretation: there is no bias in the data (Nivlet et al., 2001).

2.6 Business and Technology Challenges for 4D Seismic Monitoring

There are many business and technology challenges to be overcome before 4D seismic can become as routinely applied as a mainstream technology in the petroleum industry as 3D seismic is today. On the business side, these include a shift towards a long term finite-resource management strategy, more financial incentives for new technology research and development, and a renewed emphasis on value rather than cost. On the technology side, these include the development of new acquisition technologies to enhance 4D repeatability and signal-to-noise (including permanent array deployment and borehole seismic), and interactive modelling/analysis/inversion technologies to help improve interpretation, reservoir property estimation, and quantitative analysis of producing reservoirs and their 4D seismic responses (Lumley, 2004).

Time-lapse seismic may be used to optimise the number and location of infill wells to access untapped reserves or to accelerate production or storage of CO_2, as in the OBPP. Ideally, this will minimise infill costs and maximise recovery. It may also indicate the need to shut off “thief zones” to avoid premature water or gas breakthrough. It will possibly lead to adjustments in the production and injection rates for maximum recovery. Not all reservoirs are ideal candidates for 4D seismic monitoring technology. The best reservoirs have very compressible rocks (e.g., unconsolidated sands or heavily fractured rock), high-contrast fluid compressibilities (e.g., high GOR oil versus salty brine), and excellent seismic data quality (e.g., structure, faults, stratigraphy and fluid contacts are well-imaged seismically). This includes most of the world’s young sedimentary basins and turbidite deposits. However, older and more compacted rocks, such as Jurassic North Sea rocks, or hard reservoir rocks such as cemented sandstone and carbonates, are much more challenging for the 4D seismic technique. These challenging reservoirs will require breakthroughs in high-repeatability, permanent seismic array systems (such as the current BP Valhall pilot test project), borehole seismic arrays, and seismic data processing in order to increase the signal-to-noise ratio of the 4D seismic data so that very subtle changes in such hard rock reservoirs can be imaged. 4D seismic acquisitions, in general, face ongoing challenges in terms of optimising time-lapse repeatability and dealing with an ever-increasing number of acquisition obstacles during the life of a field (platforms, pipelines, changing in near-surface, etc.).

Significant 4D fidelity can be achieved by being very careful and precise in all data processing stages, and by processing 4D data sets simultaneously; that is deriving “common operators” like surface consistent amplitude compensation and deconvolution, to ensure that the subtle time-lapse anomalies we are looking for are not being suppressed, or falsely created, by imprecise and non-repeatable processing work flows and algorithms. Synthetic seismic modelling should be utilised for the analysis and interpretation of 4D signals. This includes zero-dimensional modelling (one piece of rock) of the time-lapse seismic response to variations in fluid saturation, pressure, stress and temperature, based on core data, 1D time-lapse AVO modelling of seismic data based on core and well logs, and time-lapse 2D and 3D modelling of seismic data from flow simulations and digital rock property volumes.

2.7 CO2CRC Otway Pilot Project

2.7.1 Geological Outline of the Naylor Field

2.7.1.1 Geological Setting

The Naylor Gas field is situated in the Port Campbell Embayment (Figure 2.6), which in turn is situated on the onshore part of the Otway Basin. The Otway Basin consists of a series of superimposed sedimentary successions, each deposited during different phases of the separation of Australia and Antarctica. The first sedimentation is represented by the Otway Group which was deposited within an intracratonic basin. In the Late Cretaceous the Sherbrook Group was deposited in a marginal marine basin setting. In the Lower Tertiary a deltaic sequence called the Wangerrip Group was deposited and in the Upper Tertiary marine sandstones and carbonates (Nirranda and Heytesbury Groups) (Laing et al., 1989). The formation of interest, the Waarre Formation, was deposited as part of the Sherbrook Group at or near the end of the Cenomanian that continued into the Turonian. In the onshore Port Campbell Embayment, the Waarre formation rests directly on the Otway Unconformity and its thickness varies significantly. It is particularly thin in our area of interest, which is the Naylor Gas field (about 30 to 40 m), and it thins out to an erosional zero edge to the north. The Waarre formation continues offshore and is part of the Shipwreck Trough (Spencer and LaPedalina, 2006). The Otway Basin is one of several extensional and transitional sedimentary basins along the margin of the Australian continent. It was developed during the Late Jurassic and extended west-northwestward for over 500 kilometres along the southern margin of the eastern

Australian mainland coast. It is located both onshore and offshore from southwestern Victoria and southeastern South Australia (Lang et al., 1989).

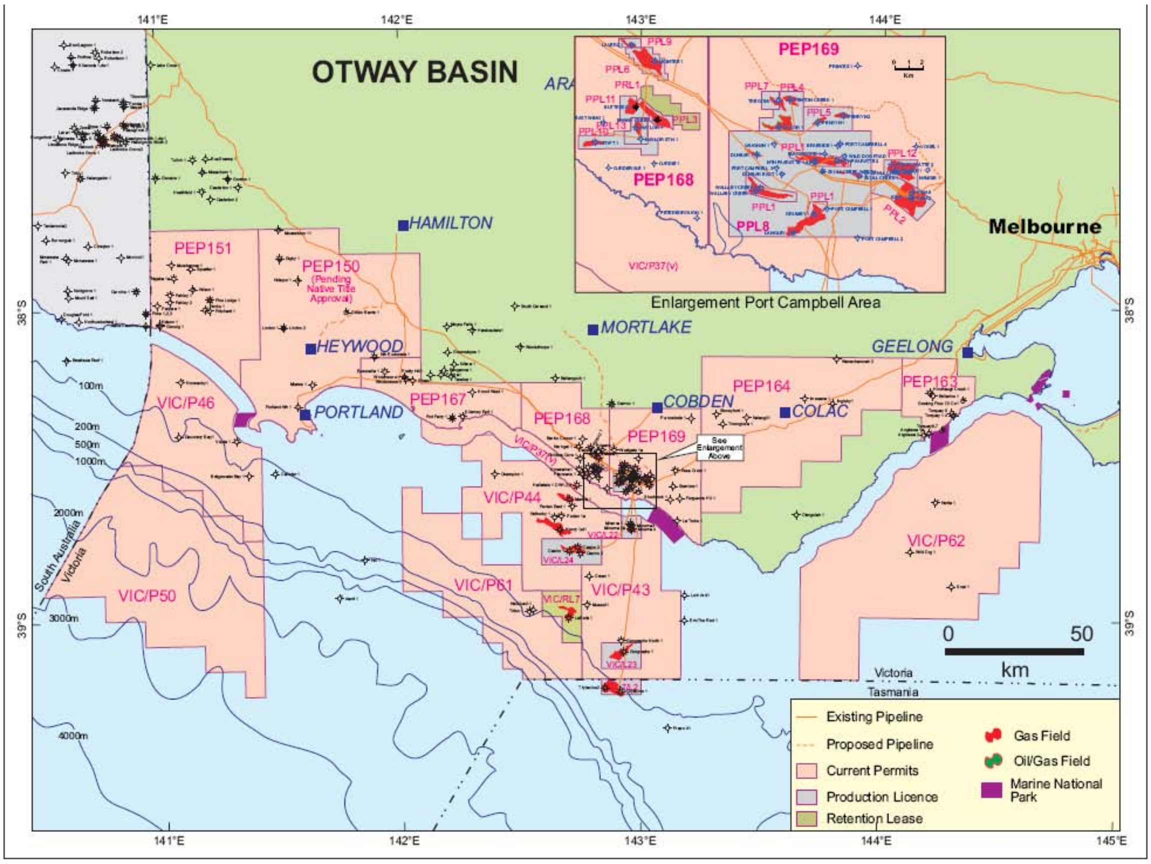


Figure 2.6: Map of Port Campbell area (CO2CRC, 2010).

The Otway Group (intracratonic basin) was the first sequence deposited during Late Jurassic to Early Cretaceous rifting. Then overlain by The Sherbrook Group (marginal marine basin) during Late Cretaceous, followed by The Wangerrip (deltaic sequence), Nirranda (marine standstone) and Heytesbury (marine carbonates) Groups during Lower and Upper Tertiary (Lang et al., 1989). The Waarre Formation is the lower part of the Sherbrook Group (Figure 2.7) within the Otway Basin. The Waarre Formation traditionally represents the primary reservoir of the Otway Basin, with hydrocarbon and CO_2 occurring in both onshore and offshore locations.

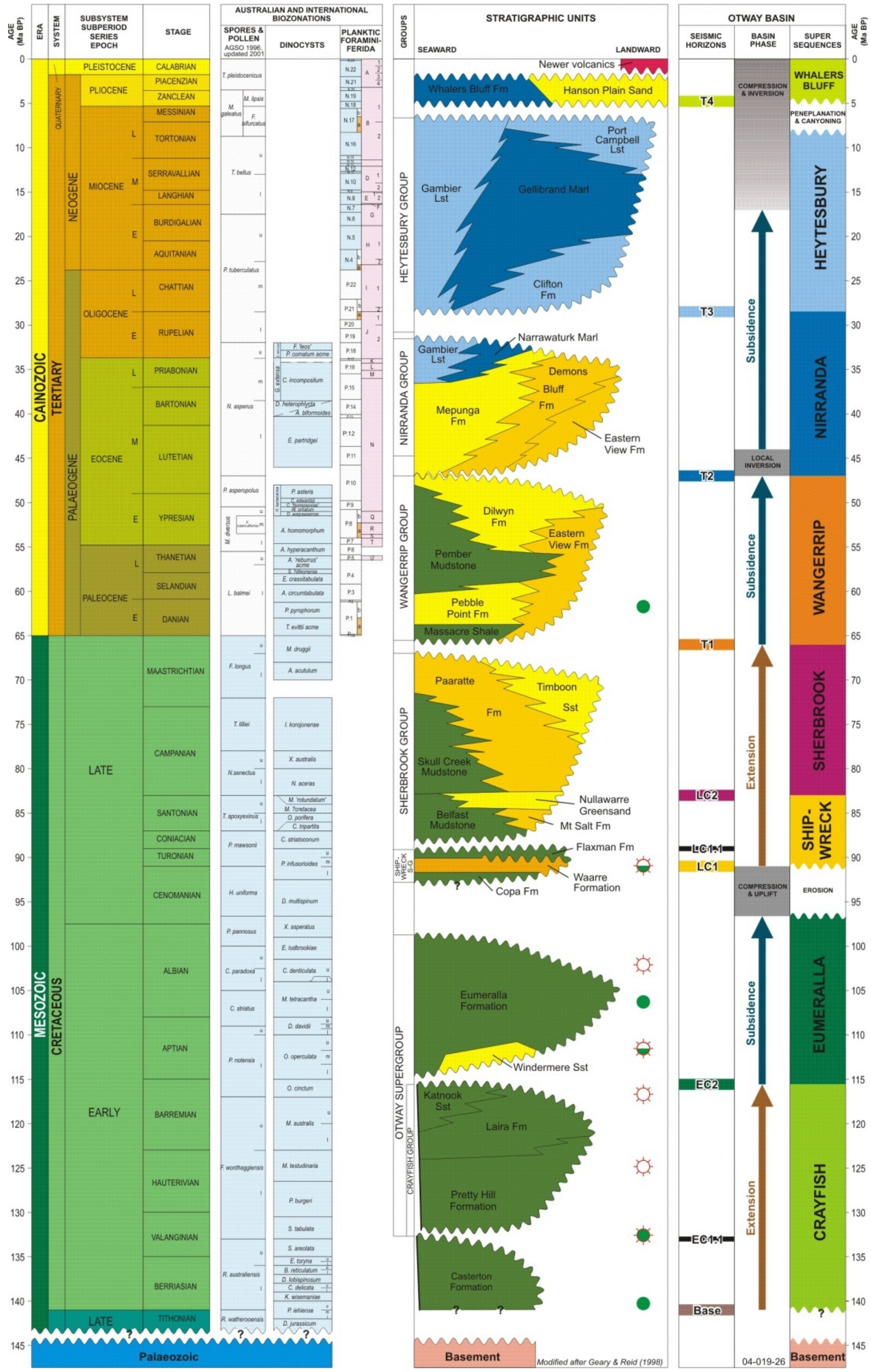


Figure 2.7 Regional Chronostratigraphic Chart – Otway Basin (CO2CRC, 2010).

2.7.1.2 Structure

The Otway Basin is structurally complex as a result of the superposition of a number of tectonic events which occurred both during and after the development of the basin (Lang et al., 1989). The major faults in the Otway Basin are interpreted as normal, trending northeast-southwest in the western part of the basin and more north-west toward the eastern end of the basin. Often, the faults extend to the surface and given this fact, they provide the only obvious migration pathway from the Waarre Formation into any younger formation. There are three major faults bounding the Naylor structure at each side of the Naylor-1 well and the southern part of the Naylor South-1 well. Figure 2.8 illustrates the complex fault zones around the Naylor field (Spencer and Pedalina, 2006). There are no significant faults evident in the Naylor-1 well at the Waarre C level. However, faulting is important away from the wells and all fields in the area have some fault control of either structural closure and/or spill-point. Figure 2.9 illustrating the location of the following wells on seismic section: Buttress-1, Boggy Creek-1, Naylor-1, CRC-1, Naylor South-1, Croft-1 and Curdie-1.

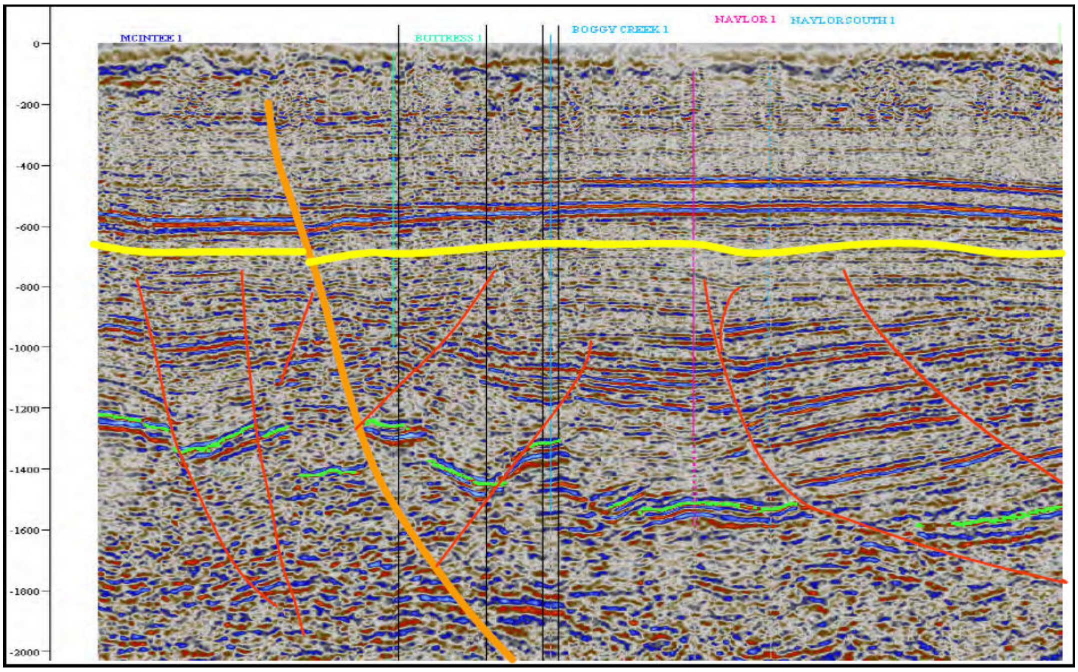


Figure 2.8: Seismic cross-section from North to South of Naylor field. Green marker represents top of Waarre C. Flaxmans Formation and Belfast Mudstone overlain above it. Red faults mostly stop at the top of the Sherbrook Group (the yellow marker). Orange fault is accompanied by a few faults that have been reactivated by Miocene to Recent compression regime (modified from Spencer and Pedalina, 2006).

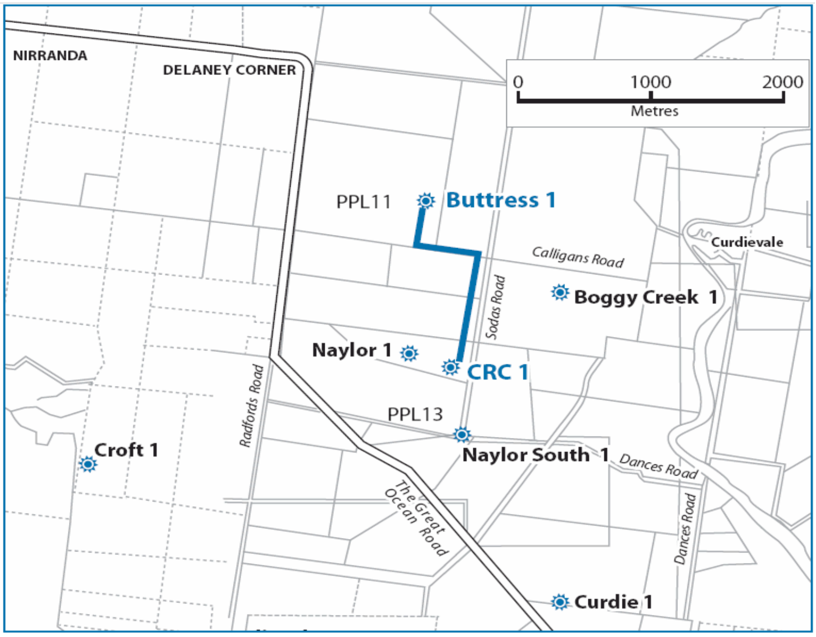


Figure 2.9: The well locations of Buttress-1, Boggy Creek-1, Naylor-1, CRC-1, Naylor South-1, Croft-1 and Curdie-1 at this site (CO2CRC, 2010).

2.7.1.3 Depositional environment

The accepted depositional model currently used by the CO2CRC is that of a regressive low sinuosity braided fluvial environment (Faulkner, 2000). Recent unpublished work done by CO2CRC based on core samples from CRC-1 confirms that model. In particular it was interpreted that the Waarre C Formation consists of two distinct depositional environments. The overlaying Flaxman Formation is interpreted as consisting mainly of offshore shelf muds with some reworked sand, probably of fluvial origin. At the top of Waarre C at 2053 m there is a distinct sequence boundary where there appears to be a marine transgression and the depositional environment changes to a gravel dominated and stacked amalgamated, low sinuosity, fluvial environment. At 2065 m there is another sequence boundary which is interpreted to be a regression to a tidal/wave reworked fluvial environment.

2.7.1.4 Stratigraphy

The Waarre formation is recognised as the principal reservoir unit throughout the Port Campbell Embayment where the small gas fields were discovered in the late 1970s and the early and mid-1980s (Buffin, 1989).

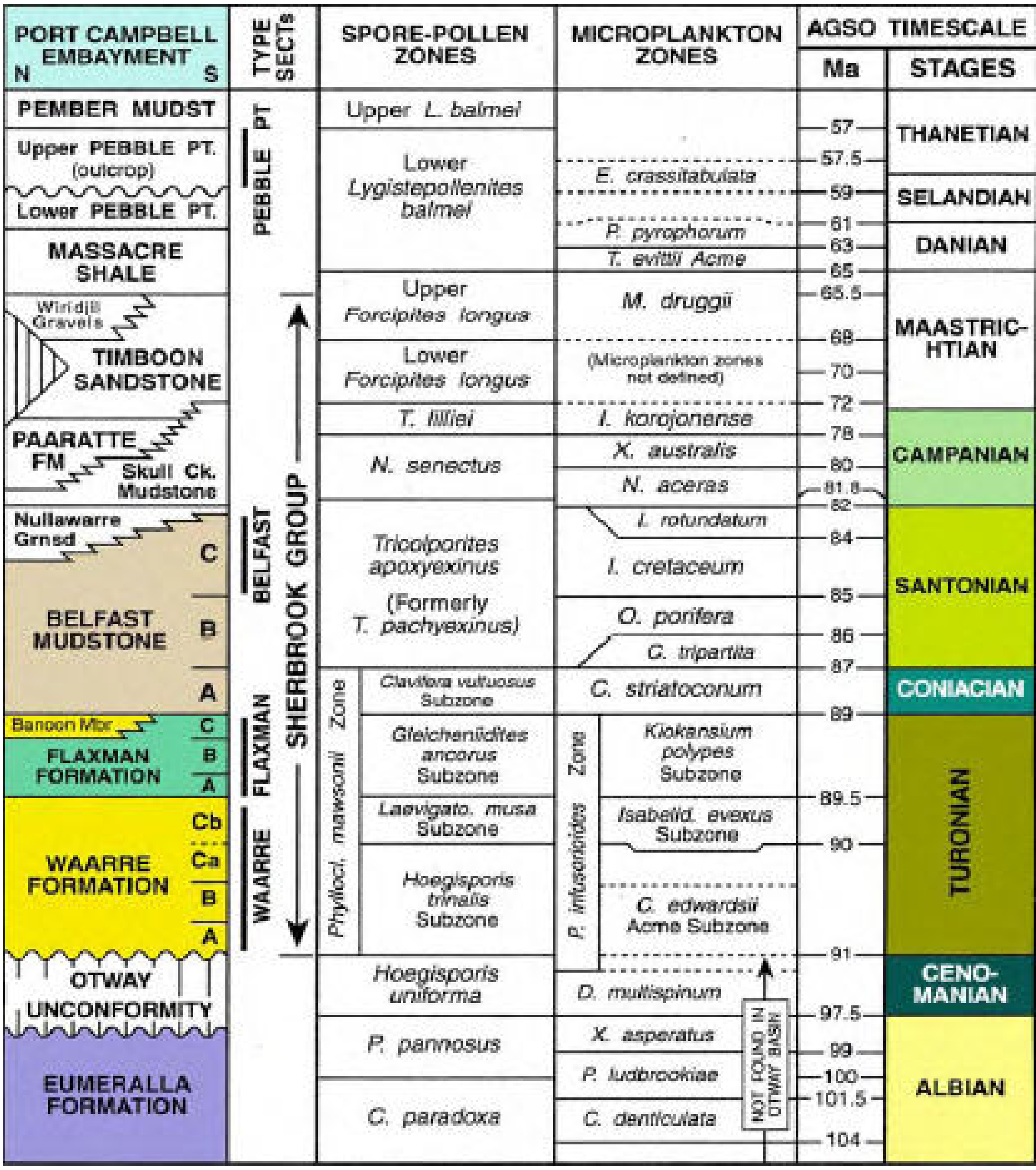


Figure 2.10: Detailed stratigraphic chart of Sherbrook Group (modified from Partridge, 2001).

The Waarre Formations are defined as four sub-units lying between the Mid Cretaceous unconformity and a major Upper Cretaceous transgression (Buffin, 1989). They are A, B, C and D units although it is only the C unit that is of immediate interest (primary gas reservoir), with Unit D in this system known as Flaxmans Formation. Partidge (2001) mapped and incorporated it into a new stratigraphic scheme (Figure 2.10), while Faulkner (2000) established a framework for the sequence stratigraphy of the Sherbrook Group in the Shipwreck Trough and Port Campbell Embayment using a sequence stratigraphic nomenclature with the same biostratigraphic zones (Figure 2.11). The Waarre formation is overlain and sealed by the Flaxmans Formation and the Belfast Mudstone. The Belfast mudstone has proven to be a good seal during the production from Waarre C.

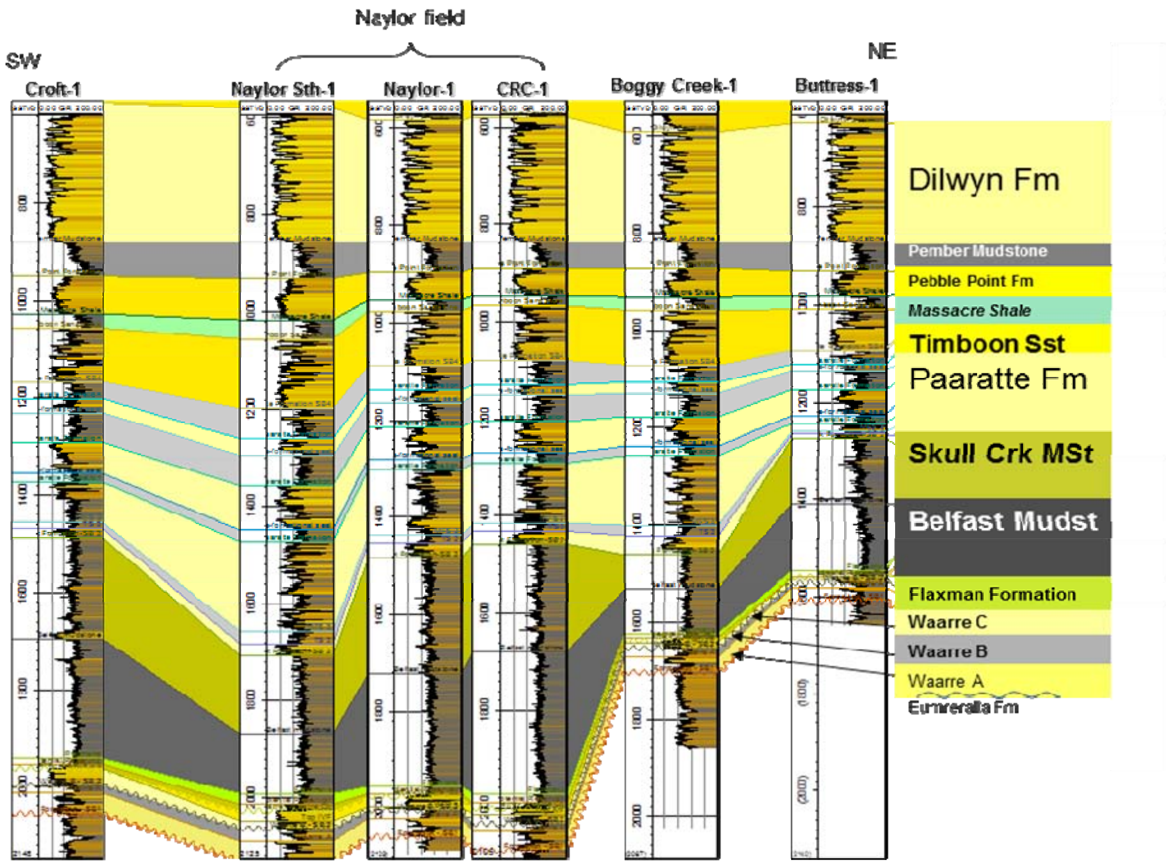


Figure 2.11: Regional stratigraphic cross-section of Waarre Formation at the north of the main ESE trending fault showing a fairly uniform Waarre C thickness (10-20 m) as the key wells (Faulkner, 2000).

Comprehensive and detailed stratigraphy of Naylor field can be found in Faulkner (2000), Partridge (2001) and a recent report by Dance (2008). Dance (2008) recompiled and reinterpreted a detailed stratigraphy framework around Naylor field as shown in Figure 2.12.

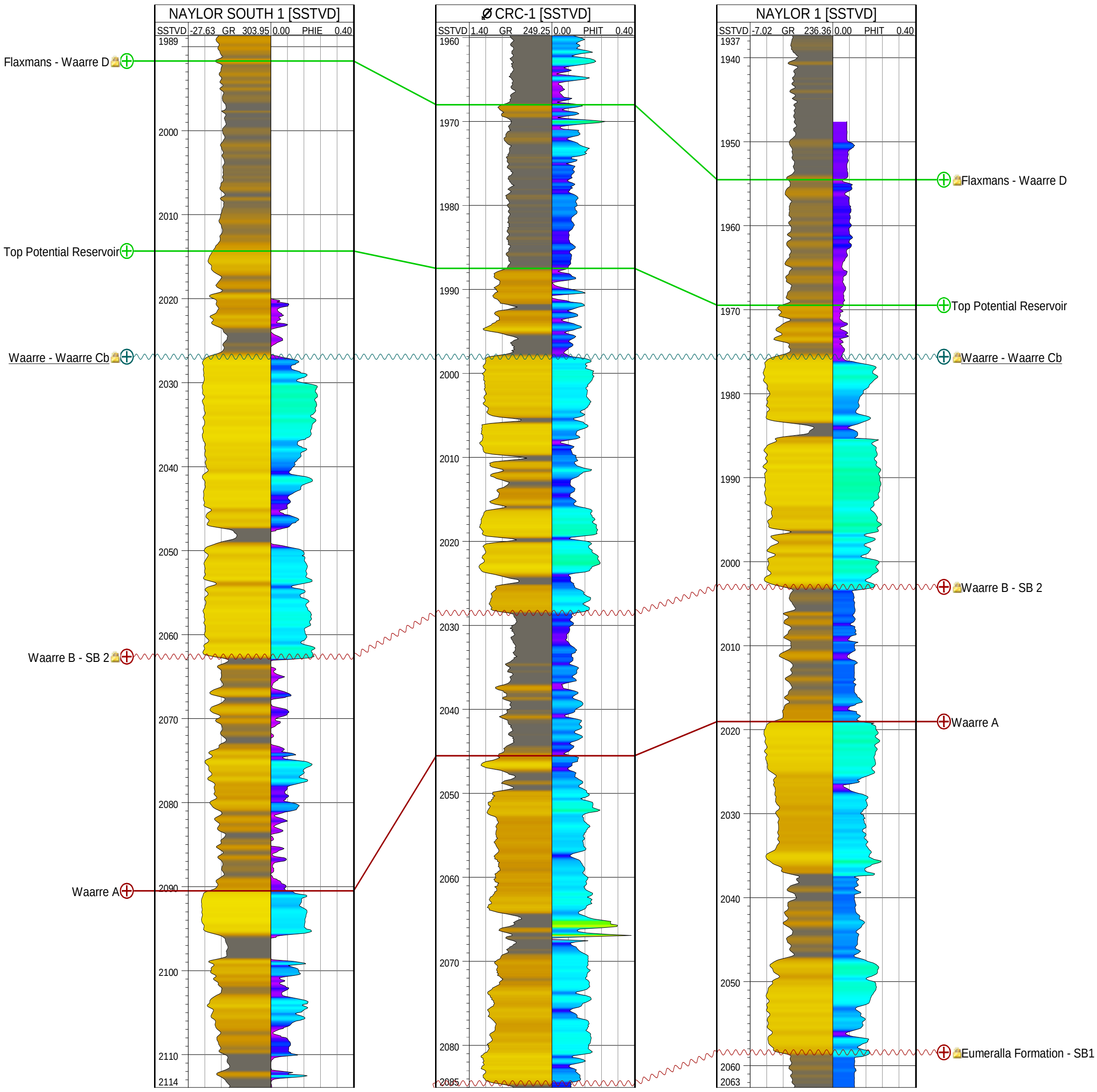


Figure 2.12: The well-cross section from South to Southwest shows the thickening of Waarre C (Wisman et al., 2008).

2.7.2 Naylor Gas Field

In the past few years, awareness of global warming and the effects of anthropogenic CO_2 emissions have increased dramatically. The CO2CRC Otway Project is presently Australia's first project in this area, and the most comprehensive geosequestration project in the world. It is capturing, compressing, transporting, injecting and storing CO_2 in the geological subsurface. The objective is to demonstrate that CO_2 capture and storage is a viable, safe and secure option for greenhouse gas abatement in Australia. This will be achieved through a carefully designed monitoring program which will incorporate a variety of scientific methodologies to verify the capture and storage process. The CO2CRC is currently undertaking the OBPP for the injection and storage of carbon dioxide within the subsurface. The aim of this project is to inject approximately 100,000 tonnes of CO_2 into the Waarre C Formation (a deep depleted gas reservoir) as stage I and inject about 10,000 tonnes of CO_2 into the Paaratte Formation (shallow saline aquifers) as stage II. The CO_2 gas can be safely extracted from a nearby natural accumulation, transported via pipeline and injected into reservoir sandstone over a two year period (Figure 2.13). The Otway Project is the first of its kind where CO_2 will be injected into a depleted gas reservoir. The use of depleted fields for CO_2 storage is likely to become globally adopted and therefore the project will provide important experience for monitoring under these conditions. Time-lapse seismic monitoring is a crucial component of the project as it will provide assurances that the injected CO_2 stream remains confined to the target formation. There are substantial challenges for monitoring the migration (Figure 2.14) of the CO_2 plume within the reservoir due to the presence of residual gas which is expected to cause very subtle changes in the seismic response. Critical to the success of geosequestration processes will be to ensure optimum seismic resolution and repeatability. This project will demonstrate deep geological storage of carbon dioxide (CO_2, the most common greenhouse gas) for stage I and shallow for stage II. The project provides technical information on geosequestration processes, technologies, monitoring and verification regimes that will help inform public policy and industry decision-makers while also providing assurance to the community (http://www.co2crc.com.au/otway/).

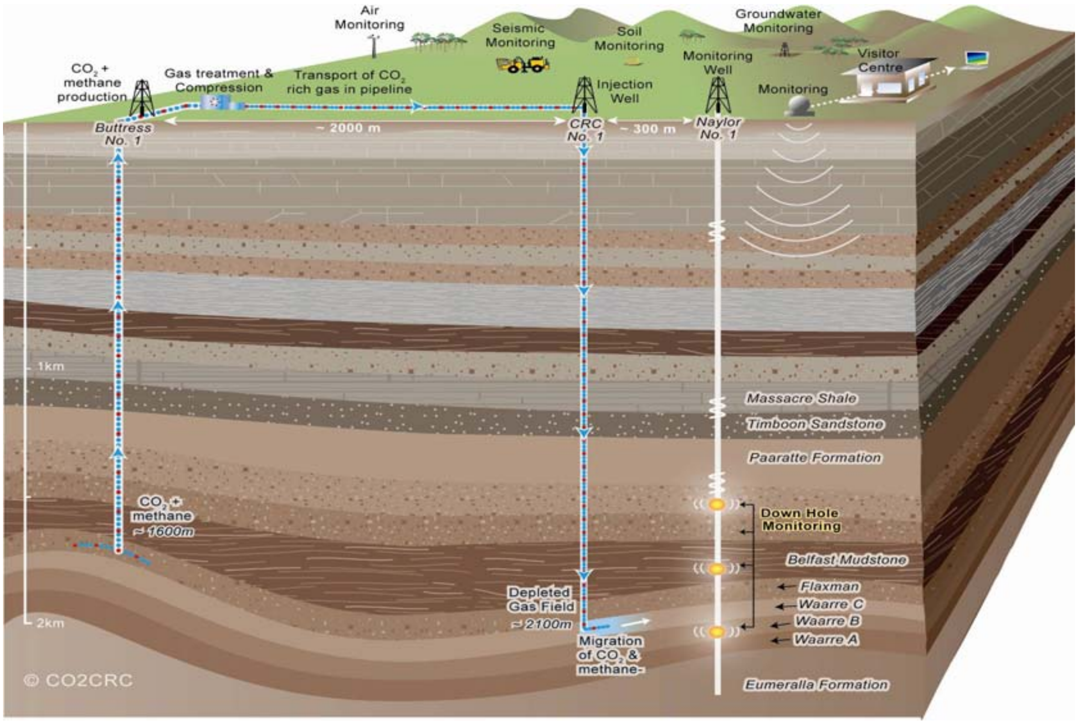


Figure 2.13: Schematic diagram of CO_2 transport, injection and monitoring scenario for the Otway project (CO2CRC, 2010).

The monitoring and verification program (M&V) has as its main objectives: (1) assurance verification and safety of the site (Naylor Gas field) for CO_2 storage and (2) to understand the behaviour of the injected CO_2 within the Waarre C depleted gas reservoir for stage I and Paaratte Formation (Water Aquifer). One technique deployed to support these objectives is the time-lapse 3D surface seismic reflection method. Since repeated surface 3D seismic surveys have to be performed under identical recording and processing conditions, it is very important to assess the seismic repeatability for this site.

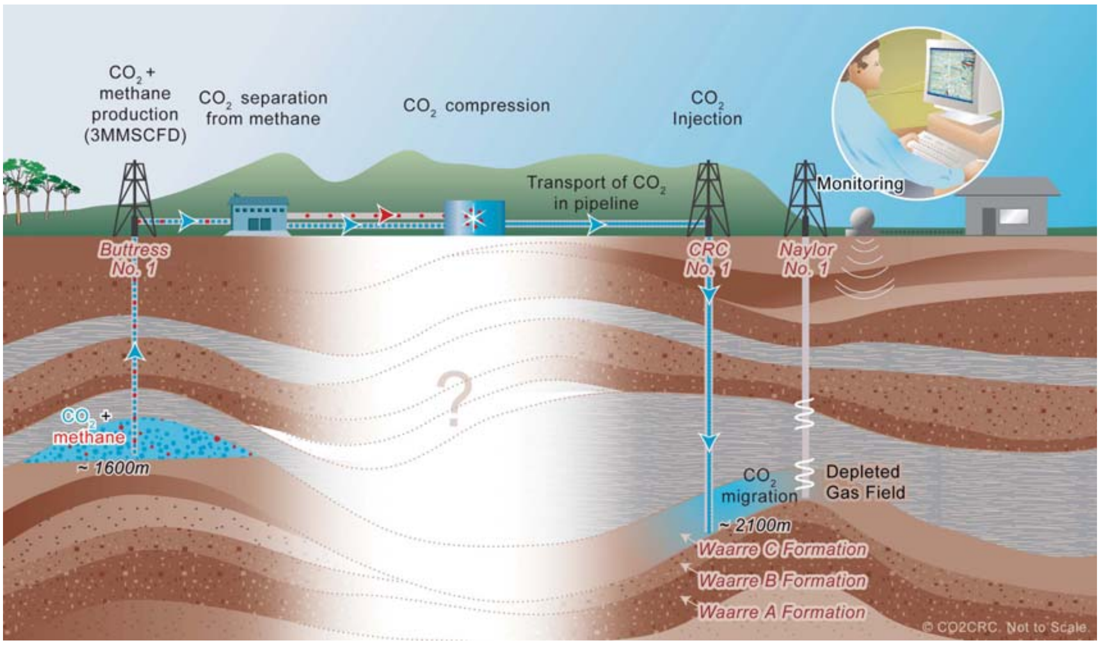


Figure 2.14: Schematic diagram of CO_2 transport, injection and monitoring scenario for the Otway project (CO2CRC, 2010).

The Otway Basin is nearly 500km long and covers an area of approximately 150,000 square kilometres. It contains over 10,000 m of Jurassic to Tertiary sediments (Laing et al., 1989). Geographically, the Otway Basin is located in south-eastern South Australia and south-western Victoria (Figure 2.15) both offshore and onshore. The Naylor Gas Field is a small field (1square km) with a single depleted gas well, Naylor-1. The field is located off the Great Ocean Road, around 40 km from the town of Warrnambool in south-western Victoria, Australia and in the onshore area of Otway Basin situated in the Port Campbell Embayment (Figure 2.15). The Naylor-1 well was discovered and drilled by Santos in 2002 on the basis of a strong gas effect at the Waarre Formation unit C. The Naylor-1 well was producing 3.965 BCF of natural gas until October 2003, when it was suspended due to the high water cut. The Naylor Gas Field was then proposed to be used as a CO_2 geological storage site. The Naylor-1 production well was then selected to be the monitoring well for CO_2 movement in the reservoir. In 2007, the CRC-1 injection well was drilled at about 300 m down-dip from Naylor-1(Figure 2.16).

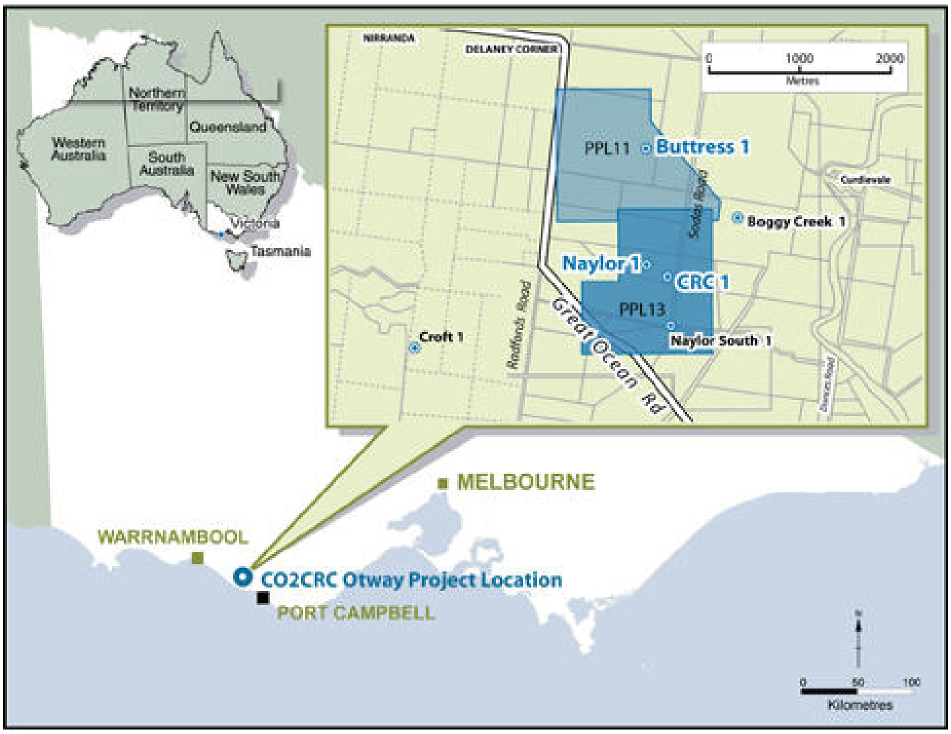


Figure 2.15: The location of Naylor Field in the south-east of Australia at Otway Basin (CO2CRC, 2010).

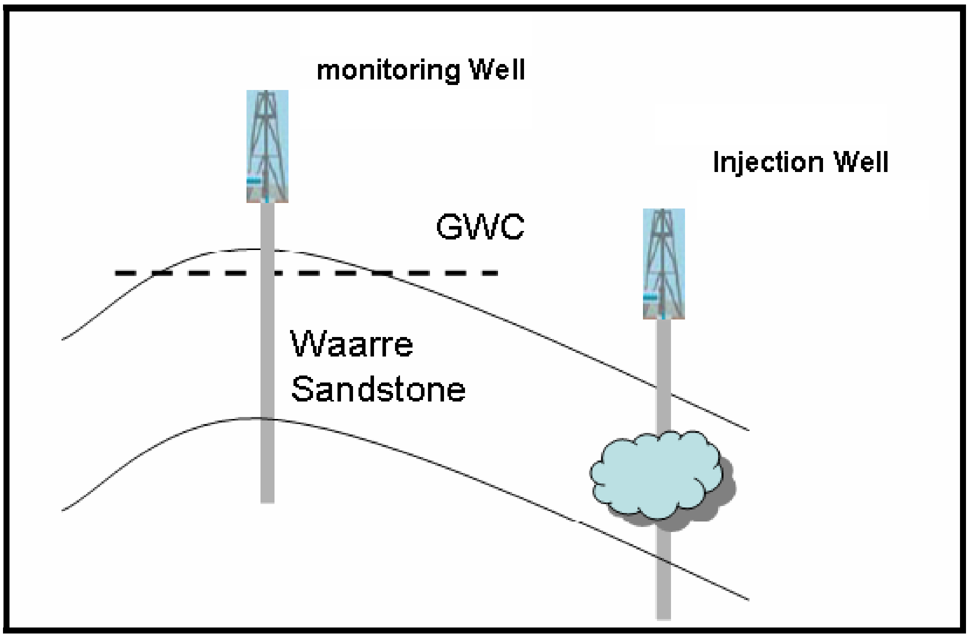


Figure 2.16: The injection of CO_2 at Naylor field (after Li et al., 2006).

2.7.3 Gas Production and CO_2 Injection

Naylor-1 was drilled by SANTOS as a bright spot or being a direct hydrocarbon indicator (DHI) to the first degree of approximation. Indeed a gas saturated column was discovered at the level of the Waarre C sand. Because the field was expected to be small prior to drilling, economic considerations required exceptional cost minimisation. The operator completed the well as a mono-bore (with a 3½ inch casing) and did no additional sampling or testing. That is, there is no conventional core, no Side Well Core (SWC), only a basic wire-line log suite and no Vertical Seismic Profiling (VSP). Also, the exact original Gas Water Contact (GWC) for the Waarre C was uncertain, as the well encountered gas down to the base of the Waarre C reservoir, and the water pressure gradient in nearby wells was variable. This meant that the geotechnical evaluation required an extrapolation of information from adjacent wells, which added to the complexity and uncertainty of the assessment (Spencer et al., 2006).

In 2000, a commercial land 3D seismic survey was performed over the field, resulting in the drilling of a methane accumulation, to become known as the Naylor Gas Field. Naylor-1 well was perforated over the upper 4m of the Waarre C and remained in production until the well started making water. As the cost of water handling equipment is economically prohibitive, the Waarre C was abandoned. A steel patch was placed over the upper perforations and following a brief production attempt from the lower Waarre A reservoir, the well was shut-in. After some years of gas production from Naylor-1, the field was abandoned. The well was acquired for CO_2 sequestration as a demonstration project and to be used for monitoring the migration of CO_2 as it travels up-dip due to buoyancy (Figure 2.16). CO_2 would be injected via a new well (CRC-1) into the Waarre sandstone reservoir about 300 m down-dip from the monitoring well Naylor-1, within the water leg.

The plan was that injected CO_2 would replace the original reservoir fluid (brine) in the periphery around Naylor-1 well. It was expected that the CO_2 plume would diffuse towards the monitoring well (Naylor-1), where it should create a thin layer underneath the remaining methane cap. The thickness of the Waarre Sandstone at Naylor-1 is about 28 m, and the temperature in the reservoir is about *92 ºC* (Li et al., 2006). The nearest well, Naylor South-1 (about 860m to the south east), was drilled because the post Naylor-1 assessment suggested a possible field extension across to the Naylor South structure; although it is worth noting that there is no direct hydrocarbon indicator over this feature. The well did not intersect hydrocarbons and was subsequently abandoned. Similarly to Naylor-1 it has a minimal test program; no cores, no SWCs and only a basic log suite. Although there is good quality 3D seismic, seismic inversion, useful for facies mapping, was found to be at the limit of its resolution due to the thin Waarre C (about 30 to 40m). Also, there were strong gas amplitude effects over the Naylor and Croft Fields and throughout the general area. Consequently, the use of the current 3D seismic, for all but the structural interpretation, would be limited.

2.7.4 Geological consideration of CO_2 sequestration at Naylor Field

The advantage of injecting CO_2 into a depleted gas field is having access to established infrastructure, pre-existing geological and geophysical exploration data, production history and well log data. On the downside, the Naylor gas field is relatively deep (2km), small (~0.5 square km) and surrounded by complex faulting that presents significant challenges for detailed reservoir characterisation. The field is located in a tilted fault block structure and the Belfast Mudstone provides the top and lateral seal for the Waarre Sandstone reservoir. Injection would take place just below the original pre-production gas-water contact but the CO_2 plume would rise through buoyancy into the pore space originally occupied by methane, where it would be approximately 30% in residual gas (CH_4) saturation remaining post production (Figure 2.17).

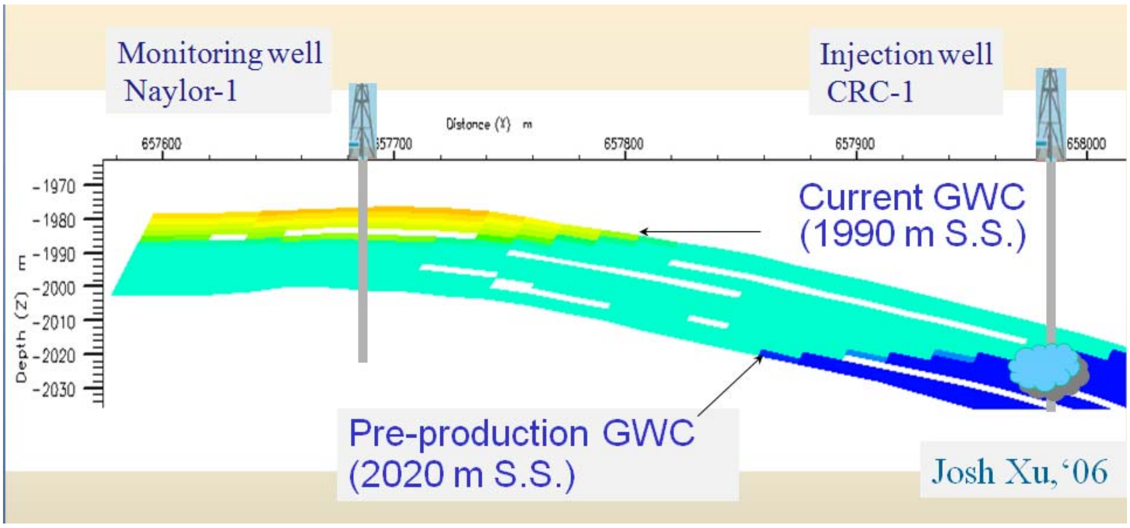


Figure 2.17: Schematic cross-section of Waarre-C reservoir. Present day gas (CH_4) saturation conditions in the Waarre-C sandstone, based on history matching simulations from production data and post-production logging in Naylor-1 (after Xu et al., 2006).

Reservoir simulation predicts that the supercritical CO_2 will migrate up-dip through the region of residual methane until it reaches the free gas cap that remains at the crest of the reservoir, at which point it would accumulate under the gas cap as a thin layer. During migration the injected CO_2 would become enriched with CH_4 but remain as a supercritical fluid. There are several things that needed to be considered in the scope of planning a monitoring program of CO_2 sequestration. During CO_2 sequestration, the success of seismic monitoring will be directly determined by the magnitude of the change in the elastic properties of the reservoir. These changes are due to displacement of in-situ pore fluid by free CO_2. The magnitude of these changes depends on several factors such as rock type and its composition, temperature and pressure in the reservoir. They are also related to CO_2 phase, CO_2 injection rate, porosity and permeability (Li et al., 2006; McKenna et al., 2003).

Chapter 3 : Zero-time seismic repeatability from the analysis of repeated shots from the same seismic survey

3.1 Introduction

The key to successful seismic monitoring is repeatability. Major concerns are source and receiver positioning accuracy between surveys, inter- and intra-survey seismic pulse consistency and data processing in the presence of noise. One way to determine system repeatability is a "zero-time repeatability test." Such a test consists of recording multiple data sets within a very short time interval so that injection/production effects will not be observable and then subtracting the base survey from the repeated surveys. If the difference section or volume (when plotted at the same gain as the base or monitor volume), yields "zero" then the system repeatability is adequate for interpretation. If the inter-survey signal or noise varies significantly, the difference will include structural and stratigraphic information, and it becomes difficult to separate real from error induced effects. Without zero-time repeatability tests, the accuracy of interpretation of seismic monitoring data is questionable because the threshold of detection for the time-lapse seismic system is unknown (Ross et al., 1997).

3.2 Assessing the zero time-lapse seismic repeatability using Pre-Stack 2D Seismic data

The study of time-lapse seismic surveys is not equally cited comparing land versus marine data. More time-lapse seismic case histories are reported using offshore (marine) data such as fields with primary or water-flood production in the North Sea and the Gulf of Mexico. Land time-lapse seismic case histories are mainly concerned with shallow reservoirs with thermal heavy oil production such as those in Canada and Indonesia. Excluding the extreme cases, the major problem for land time-lapse seismic is how to deal with the non-repeatability factors in both acquisition and processing data. For data processing, the non-repeatability factors are associated with the differences in processing workflow, parameters, algorithms, precisions, and contractors (Ross et al., 1996; Rickett et al., 1999). The main non-repeatability factors with regards to field data tests are related to differences in geometries, sources, observation directions, geophone types, offsets of shot and receiver points, seismic crews and near surface conditions as well as equipment. These factors will be discussed in this chapter. Repeatability is the measure of consistency in acquisition and processed data. Ideal repeatability results from identical data acquisition, such that the difference between the two measurements is zero. However, seismic data processing is required to enhance repeatability when acquisition is less than ideal. This also raises a cost issue. An extensive data acquisition effort may be too costly and may not even be necessary. If we can estimate the magnitude of the changes we expect to see by carefully evaluating the field conditions, we can design an efficient monitoring and verification program.

One way to test system repeatability is to perform a “zero-time repeatability test” by recording multiple datasets within a very short time interval before any changes occur in the reservoir. Another way is to examine differences between datasets on a horizon basis where conditions are known to be static. If the differences between the surveys are less than the expected differences in the reservoir, the system repeatability is favourable for interpretation. If the measured differences are larger, then the data processing flow needs to be redesigned or the acquisition parameters adjusted. Without zero-time repeatability tests, the accuracy of the observed differences can be questionable. To elaborate on this idea, I analysed zero time-lapse changes using repeated 2D pre-stack seismic data. The data was recorded using a Mini-Vibroseis seismic source with a liner sweep of 20-120Hz. The pilot trace was recorded at every shot position from an accelerometer fixed to the base plate. This trace was correlated with the recorded data. I analysed the NRMS difference and the amplitude spectra between the multiple repeated shots at the same location for seismic sources and receivers to gain an idea of the zero-time repeatability. This was carried out for the repeated pilot traces, repeated uncorrelated data and repeated correlated data. Furthermore each shot was correlated with its original pilot signal and compared to the case when all repeated shots were correlated with one representative pilot signal. To substantiate this approach, I also analysed pre-stack VSP data recorded with two different sources (Mini-Vibroseis and weight drop)

3.2.1 Repeatability of the pilot signals

Vibroseis seismic source energy (ground vibration controlled by shaking the mass of the ground plate) is distributed over a time of several seconds. This distribution of energy over time is in sharp contrast to explosive methods of generating seismic energy in which the source is generated in a small fraction of a second. The vibroseis signal is generated over several seconds (4-12s commonly). It typically starts with low frequency that increases towards the total sweep time. Vibroseis signal and its "decoding" or cross-correlation which yields a simple short impulse like signal is illustrated in Figure 3.1.

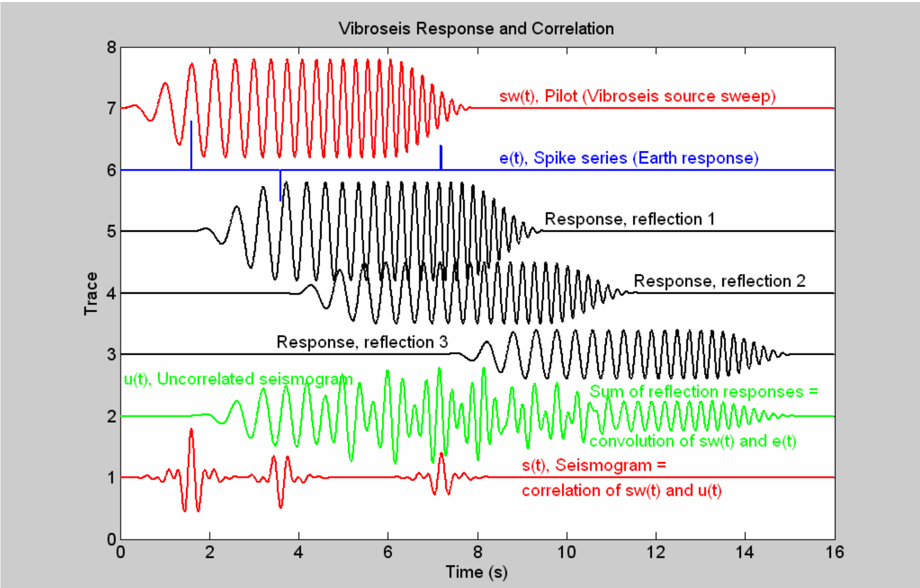


Figure 3.1: A synthetic vibroseis recording and processing example (calculated using Matlab). The 1 to 5 Hz, tapered, vibroseis sweep ("pilot") generates three reflections from the three reflection coefficients of the spike series. The sum of the three reflection responses produces the uncorrelated (recorded) seismogram, equivalent to the convolution of the spike series and the pilot. After cross-correlation of the uncorrelated seismogram with the pilot, the correlated seismogram (lower trace) is produced. Note that the cross-correlation process collapses the sweep into a relatively compact and symmetric wavelet that is centred at the arrival time of the reflection.

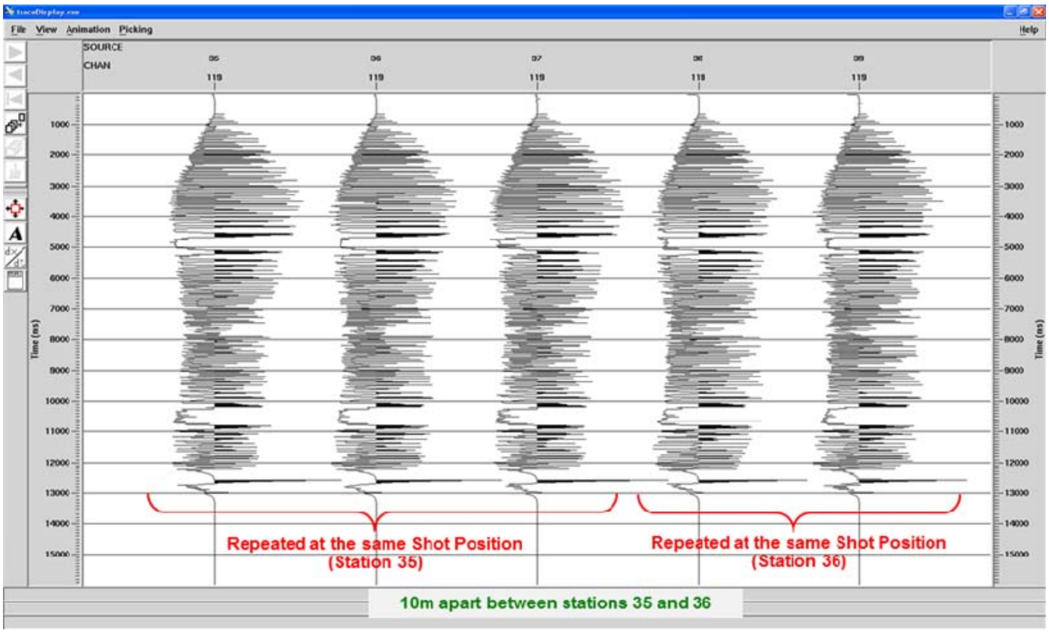


Figure 3.2: The vibroseis sweep signals 35, 36, 37, 38 and 39 respectively that have been recorded on the vibrator plate during the 2D seismic test line in May 2006 along Soda's Road. The pilot traces 35, 36 and 37 have been acquired at the same position (shot position 35) and the pilot traces 38 and 39 have been acquired at the same position (shot position 36, which is 10m from shot position 35). The source sweep is sixteen seconds long and consists of a signal that begins with a 20 Hz sinusoid that progressively becomes a 120 Hz sinusoid at 16 seconds.

A real field data example of vibroseis signal or "sweep" is shown in Figure 3.2. I used this data for repeatability analysis. Shots 35, 36 and 37 were acquired at the same shot location (shot position 35) while shots 38 and 39 were acquired at the shot position 36 which was 10m from shot position 35. This data was acquired as part of the 2D seismic test line in May 2006. I used repeated shot positions to analyse repeatability of the pilot signal recorded at the base plate by the accelerometer.

This analysis shows that the NRMS difference between the repeated pilots at the same position is approximately 15-30% (Figure 3.3 and Figure 3.4). I interpreted these changes to be due to the change of the ground compaction and radio transmission noise. By comparison I found that pilots at shot position 35 produced more repeatable correlated traces than when using individual pilots for each shot.

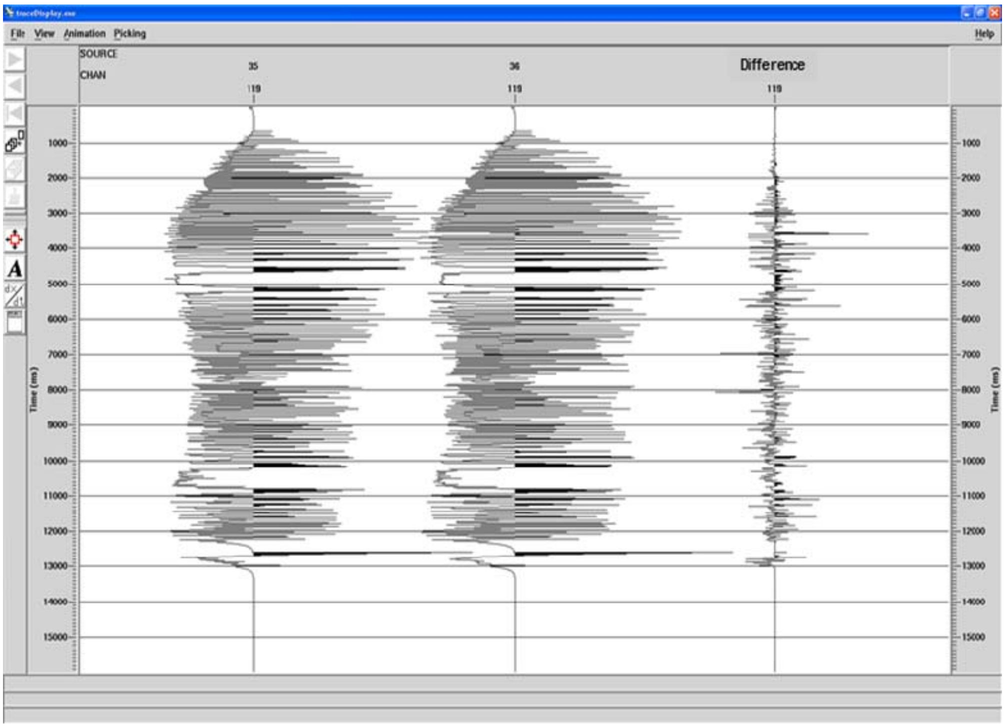


Figure 3.3: Traces of the vibroseis sweep signals that have been recorded on the vibrator plate for the repeated shots 35, 36 and their difference respectively from the left to right, during the 2D seismic test line in May 2006 along Soda's Road.

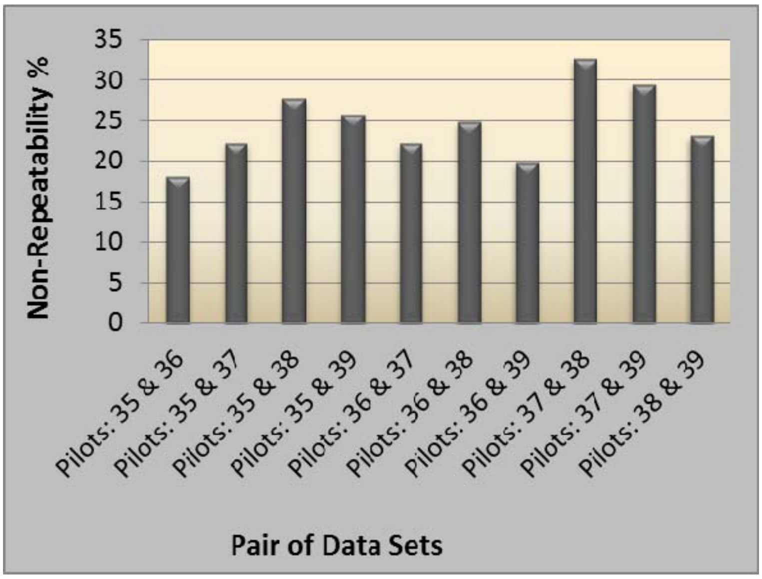


Figure 3.4: The results of the NRMS difference between the multiple recorded vibroseis sweep signals. Approximately 15-30% of non-repeatability measured for seismic window 0-16000ms.

Pilot number 35 was selected for correlation. In addition to the NRMS difference, the amplitude spectra have also been measured for every pilot trace. Changes in the amplitude spectra between the repeated vibroseis sweep signals 35, 36 and 37 are small (Figure 3.5) compared with the other two repeated shots, 38 and 39.

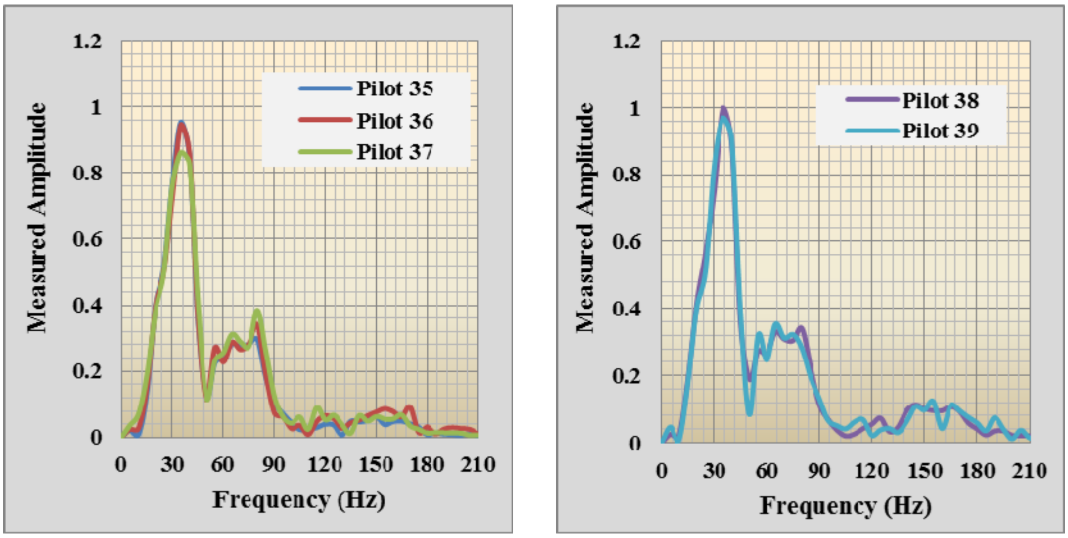


Figure 3.5: Amplitude spectra of the pilot traces 35, 36 and 37 (Left) that have been acquired at the same position (shot position 35) and amplitude spectra of the pilot traces 38 and 39 (right) that have been acquired at the same position (shot position 36, which is 10m from shot position 35) measured for seismic window 0-4000ms.

3.2.2 Repeatability of the uncorrelated vibroseis data

Uncorrelated shot gathers recorded at stations 35 and 36, respectively are shown in Figure 3.6. The NRMS difference obtained is 5-15% (Figure 3.7). These small changes are likely related to the ground compression and variations in background noise. As before, amplitude spectra are similar and only very small changes are observed.

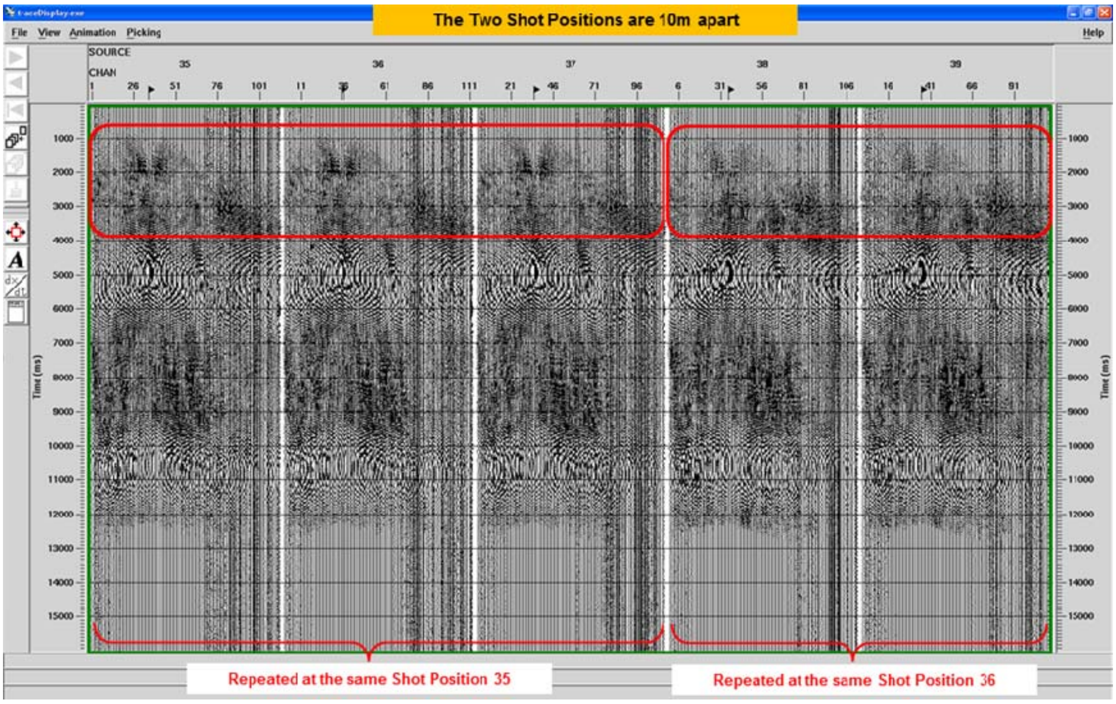


Figure 3.6: Uncorrelated vibroseis shot records 35, 36 and 37 (station 35) and shot records 38 and 39 (station 36). The record is sixteen seconds long (12s sweep + 4s listen time). The sweep starts at 20 Hz and tapers off at 120 Hz.

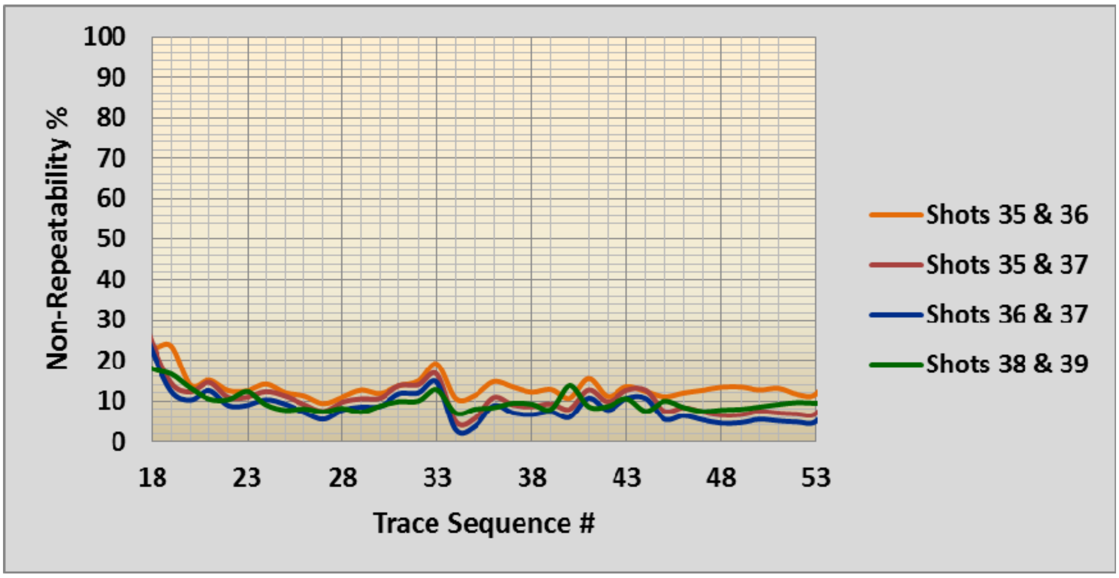


Figure 3.7: NRMS difference for uncorrelated repeated shot records. On average 5-15% of non-repeatability is measured for a seismic window 0-16000ms.

3.2.3 Repeatability of the correlated and vibroseis data

NRMS differences and amplitude spectra have been measured for both cases when shots were correlated with a single pilot and also when each shot was correlated with its own pilot. These differences, when shots are correlated with their own pilot and with one selected pilot, are shown in Figure 3.8 and 3.9, respectively.

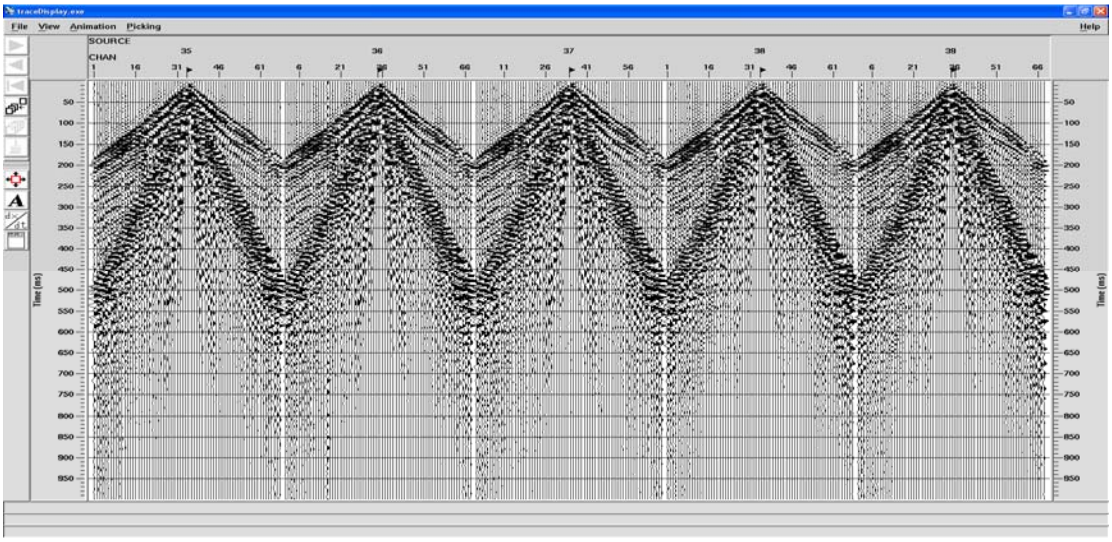


Figure 3.8: Correlated vibroseis records of shots 35,-39. Every shot in this figure has been correlated with its own recorded pilot.

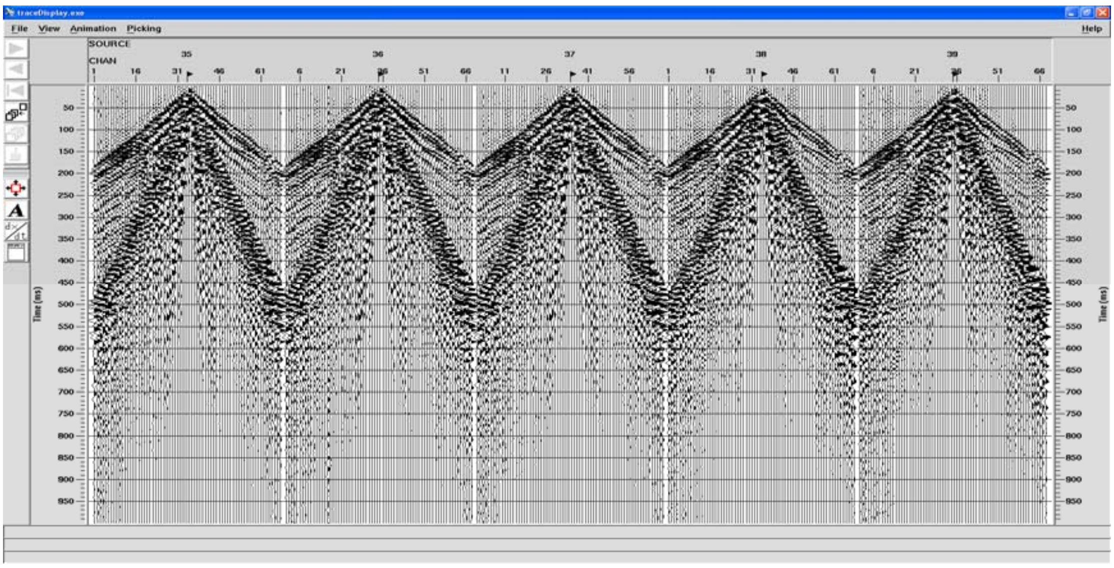


Figure 3.9: Correlated vibroseis records as in previous figure but this time using a single selected pilot (pilot 35).

Respective differences are shown in Figures 3.10 and 3.11. This confirms low pilot trace repeatability. Also note that the seismic repeatability between shots 38 and 39 is better than the seismic repeatability between shots 35, 36 and 37.

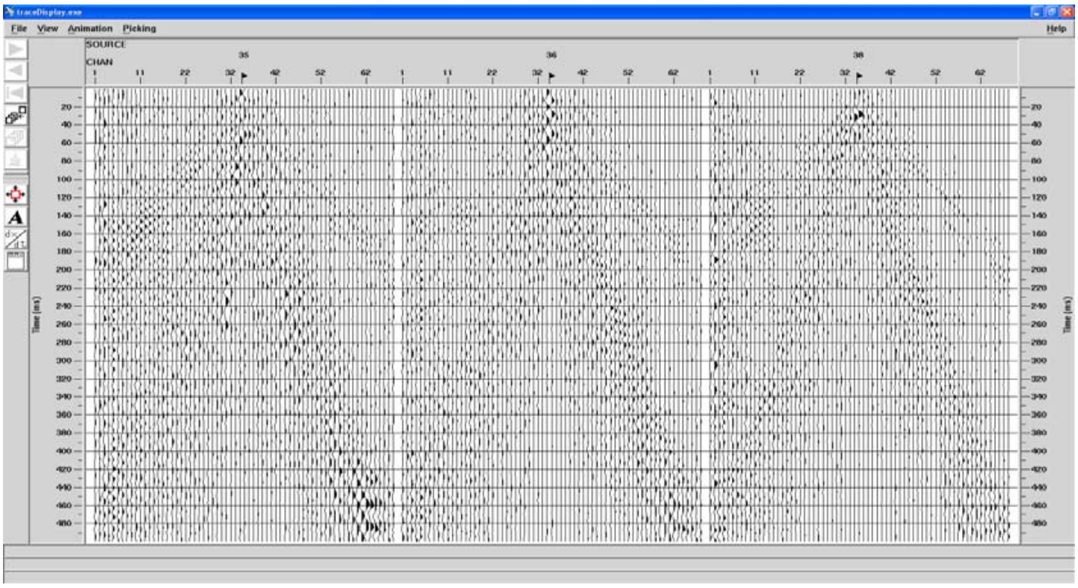


Figure 3.10: The difference between shots 35&36, 35&37 and 38&39. Every shot was correlated with its own pilot.

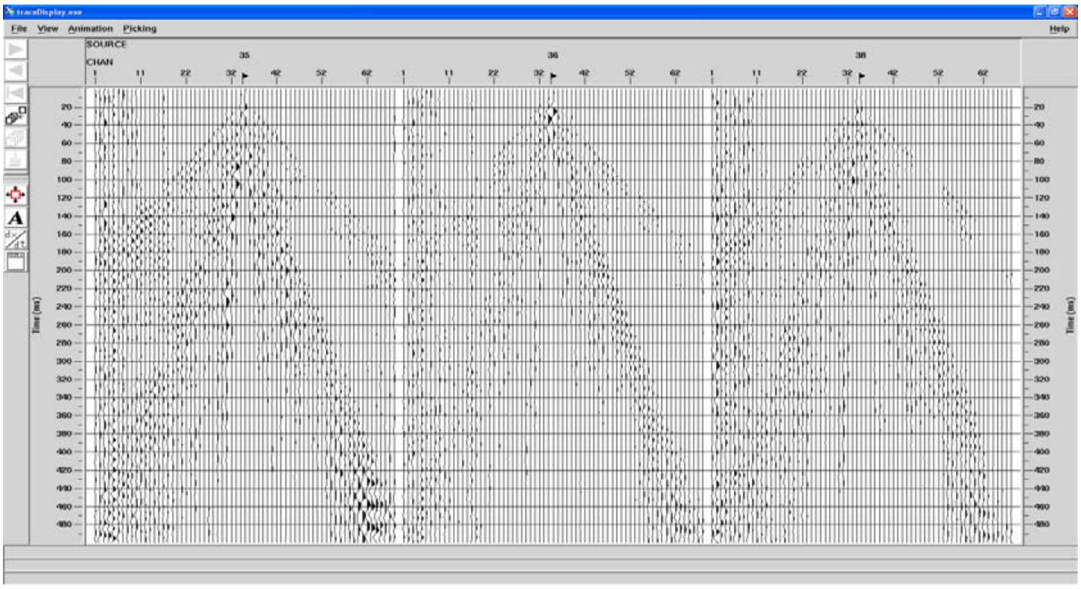


Figure 3.11: The difference between shots 35&36, 35&37 and 38&39. Every shot was correlated with the same pilot.

This can be attributed to variation in the near surface and background noise levels. Improved repeatability was observed when the pilot signal was kept constant during the correlation compared to the use of different pilots (Figures 3.10 and 3.11). This can be clearly seen in Figures 3.11.

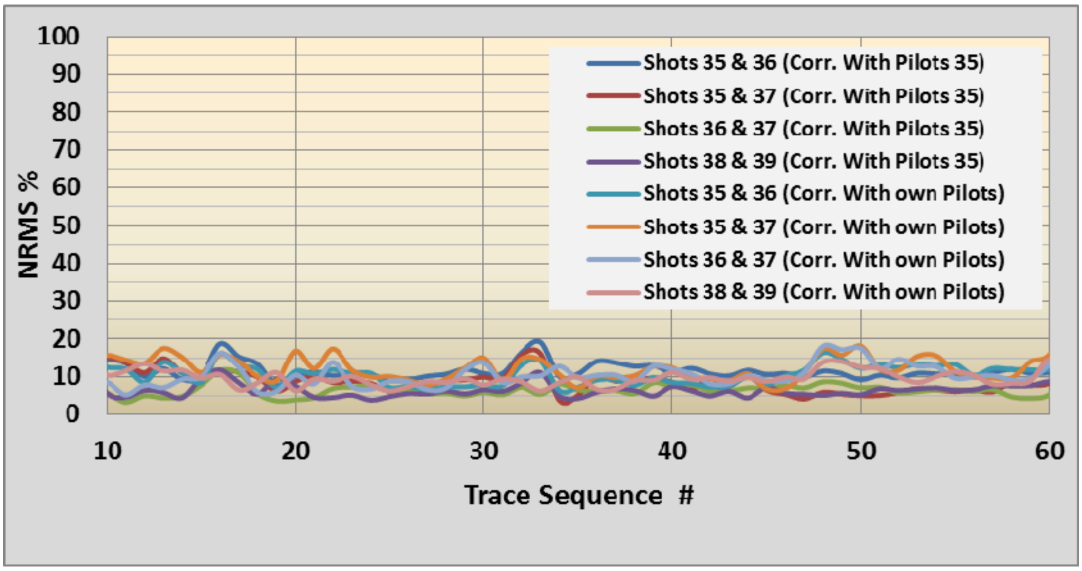


Figure 3.12: The NRMS difference for shots 35-37 using a time window 0-2000ms. The repeatability was enhanced when all shots were correlated with one pilot trace.

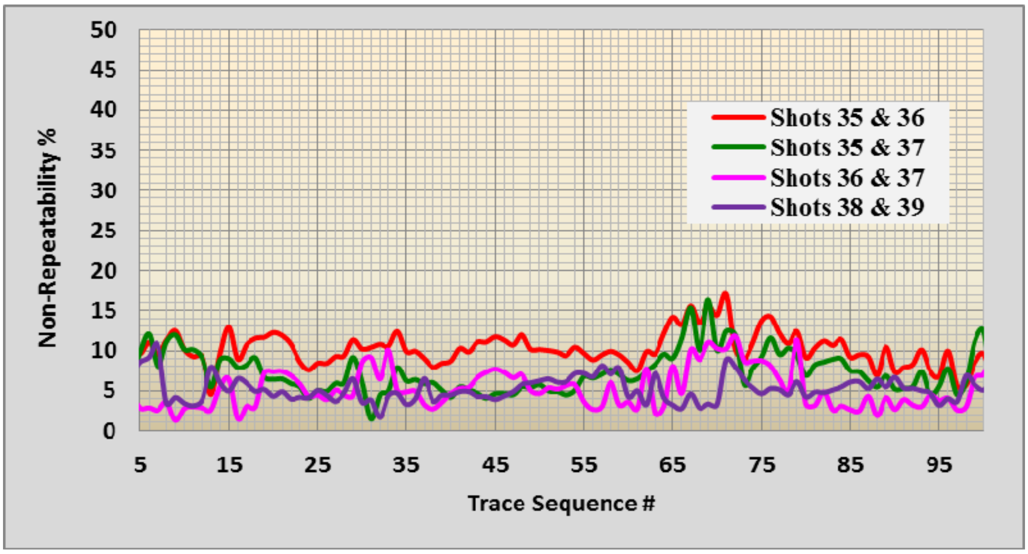


Figure 3.13: NRMS difference computed for refraction events shows values below 10% in all cases.

It turned out that refraction events are more repeatable than the reflection events. The main reason is that the N/S ratio for the refraction is superior compared to reflection. This can be seen in Figure 3.13 where the NRMS for refraction events is below 10% in all cases.

3.3 Zero time seismic repeatability analysis from VSP data

VSP data typically provide better seismic repeatability because receivers are placed in the borehole where they have identical coupling and are very well protected from the ambient noise (especially wind, rain, traffic, cattle).

To compare repeatability of raw seismic data acquired with different seismic sources, namely Mini-vibroseis and weight drop, we compared the differences between different shots acquired with the same source. Weight drop is not the best source for time-lapse experiments as its performance is heavily dependent on the ground conditions; more plastic effects are experienced in soft soils. I used five repeated shots acquired by two different sources, vibroseis and weight drop.

The difference between the performance of Mini-vibroseis and weight drop can be clearly observed from Figures 3.14 and 3.15. The Mini-vibroseis data had a very high repeatability (NRMS difference ~ 1-4%) and from our observations from the field data, I believe that three repeated shots per shot station using vibroseis is sufficient to be stacked as one shot (Figure 3.16). The VSP weight-drop data shows less repeatability, as expected (NRMS difference ~ 20%, Figure 3.17)

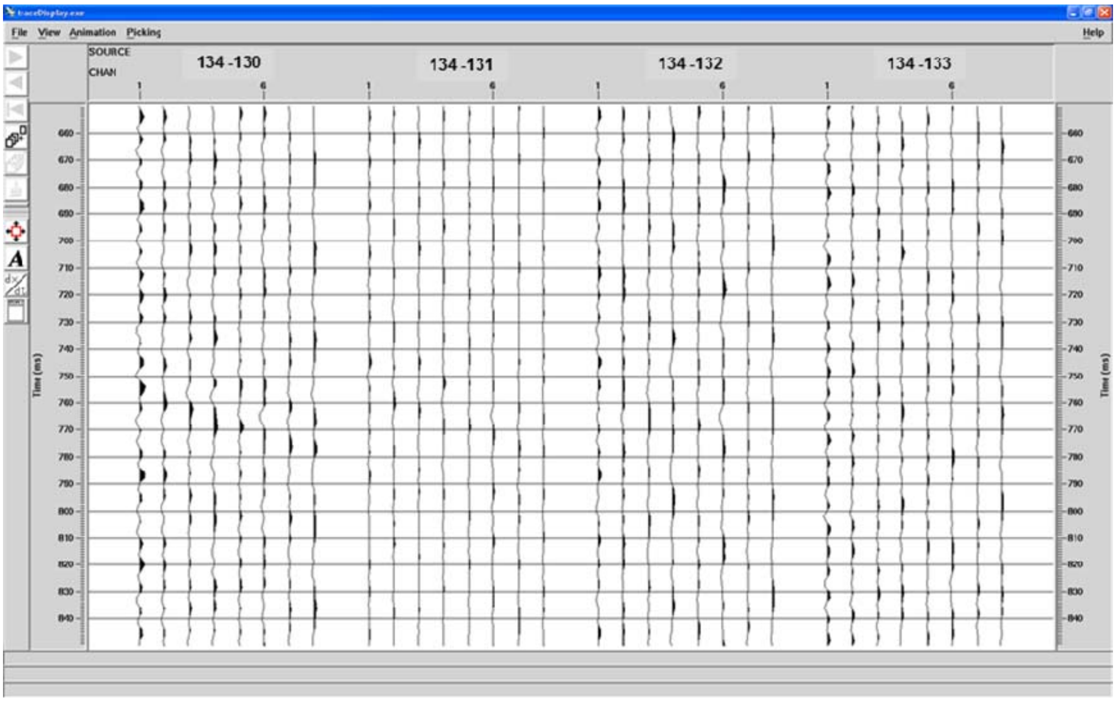


Figure 3.14: Difference between the pairs of shot gathers 130 and 134, 131 and 134, 132 and 134, and 133 and 134 respectively using the vibroseis seismic source.

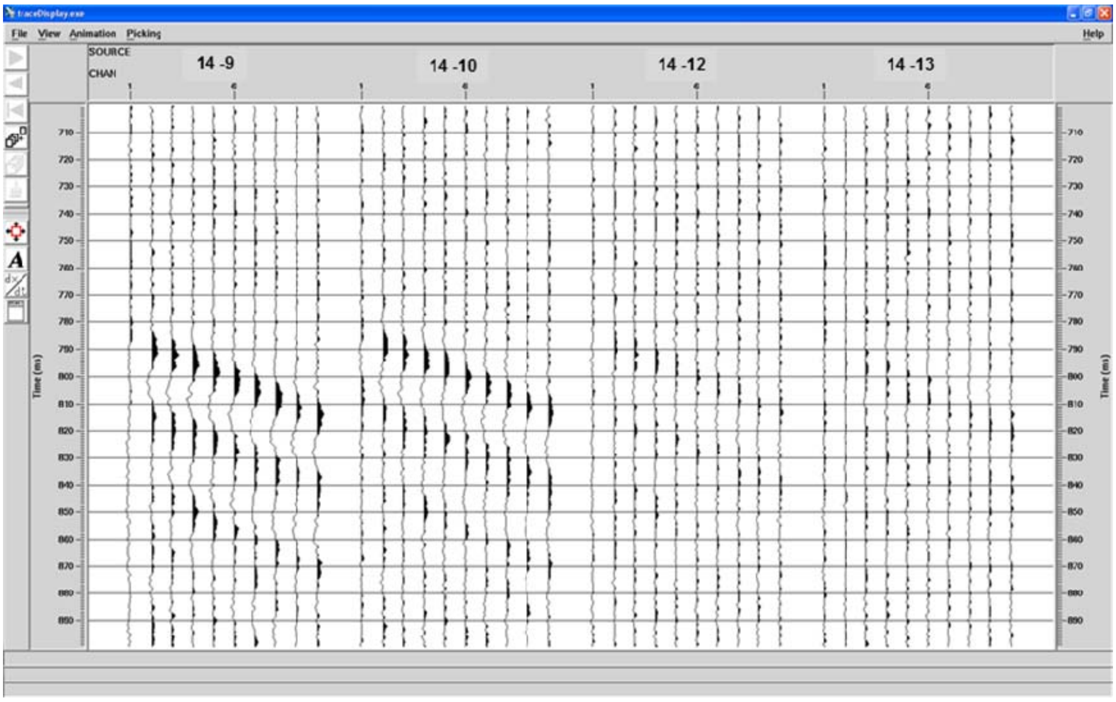


Figure 3.15: Differences between the pairs of shot gathers 9 and 14, 10 and 14, 12 and 14, and 13 and 14 respectively using the weight-drop seismic source.

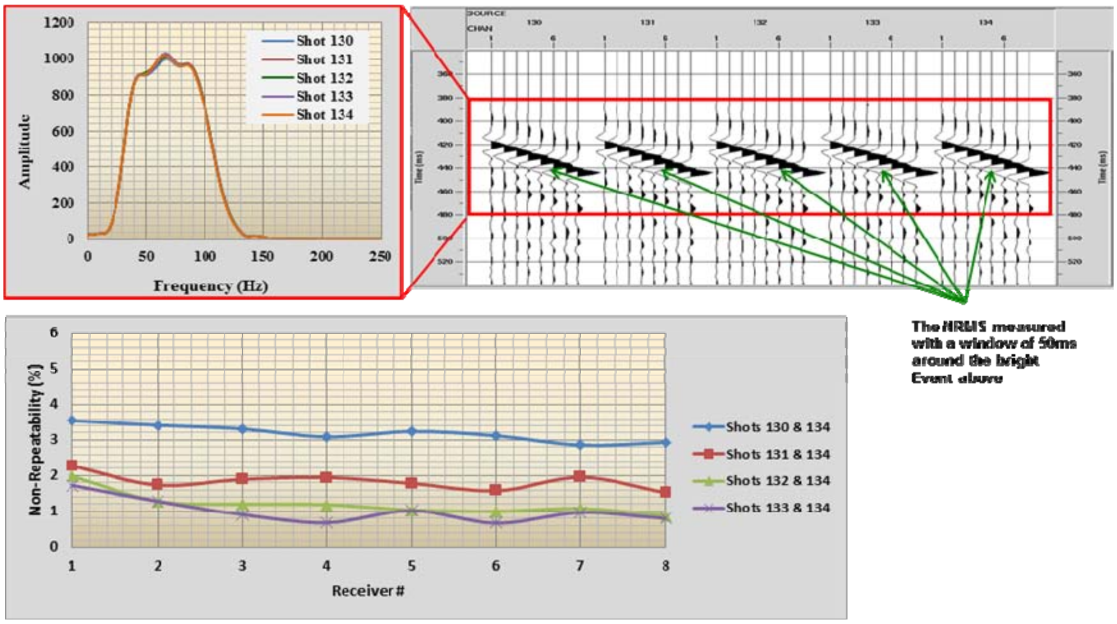


Figure 3.16: The pre-stack statistical amplitude spectra (top left) of five repeated shots using Mini-Vibroseis. All shots have identical amplitude spectra. The NRMS difference between theses shots decreased as the number of shots increased.

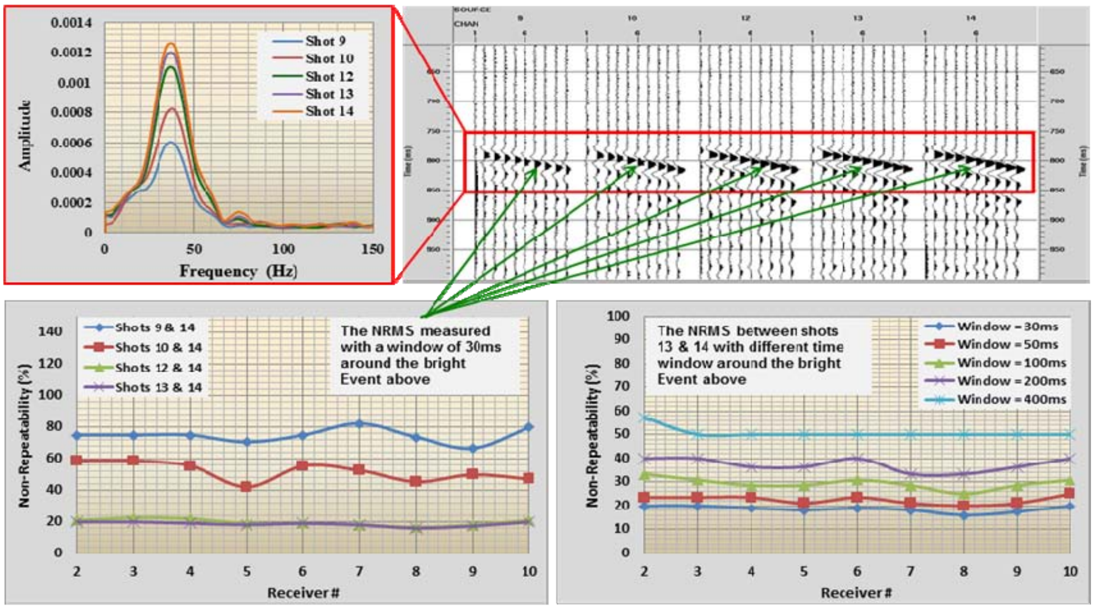


Figure 3.17: The pre-stack statistical amplitude spectra (top left) of five repeated shots using weight drop at SP1075. The amplitude spectra increase as the number of shots increase due to the ground compaction. All shots were compared with the last shot when the near surface became more compacted; the NRMS difference between these shots decreased as the number of shots increased.

3.4 Chapter Summary

Zero-time repeatability testing is an important tool when evaluating the effectiveness of seismic monitoring. Correlating the vibroseis data with a single pilot signal enhanced the seismic repeatability. Near surface effects (soil conditions) have a high impact on seismic repeatability. Mini-Vibroseis is a more repeatable source than a weight drop for the Naylor Field case. Five repeated shots per shot station using a weight drop were the minimum number of repeated shots that needed to be stacked whereas three repeated shots by a Mini-Vibroseis source were more than sufficient. Clearly VSP data provides a better seismic repeatability than surface seismic data. Weight drop seismic source performance is heavily dependent on the soil properties.

Chapter 4 : Micro-Array Seismic Investigations for Seismic Repeatability

In the previous chapter I completed the first analysis of short-time (zero-time) seismic repeatability which showed the effect of the near surface in seismic repeatability. In this chapter I analyse the change of near surface properties due to water variations in the near surface layers.

4.1 Introduction

In the case of the Naylor CO_2 injection test site area, the presence of sinkholes and karst topography in the near surface zone makes seismic non-repeatability investigations necessary and interesting (Figure 1.1). In such a geological terrane, the degree of signal scattering caused by a rugose limestone surface and caverns may depend on the depth of the water table. Consequently, to test such a possibility, repeated 2D seismic test lines have been acquired at the Naylor location prior to the 3D baseline seismic surveys. These seismic lines were recorded with Mini-Vibroseis and weight-drop sources in both wet and dry conditions. The aim of this work was to assess non-repeatability due to the source type change and variations in soil saturation conditions (Urosevic et al., 2008). To help understand field observations, we conducted near surface measurements to determine the variation in elastic properties of the near-surface layer at different seasons. Baker et al. (1997) and Jefferson et al. (1998) observed over periods of days to weeks that short-term saturation variations in the near surface could have a significant impact on the quality and character of shallow seismic reflection data. Analysing the changes in attenuation (absorption and scattering) and the propagation velocity in the upper 4 m of the near surface at the Naylor Field site could give us additional clues which may be important for 4D analyses. The aim of this work was to analyse the effect of the variation in water saturation on the seismic signals in the first few metres of the near surface and to understand the effects of variable near surface conditions on time-lapse seismic surveys. In particular, we investigate the variation of elastic properties of both top soil and the deeper rugose clay-limestone interface as function of soil saturation.

Such measurements effectively evaluate in-situ repeatability, that is, 4D seismic effects produced by seasonal variations with changes of elastic properties due to variations in the water table depth. High seismic repeatability is critical to the monitoring program of the Naylor Field because of the small time-lapse effect related to CO_2 injection into a depleted gas reservoir. To understand the effect of ground conditions and improve repeatability, I conducted a so-called “micro-array” investigation of the near-surface layers at this site (Figure 4.1).

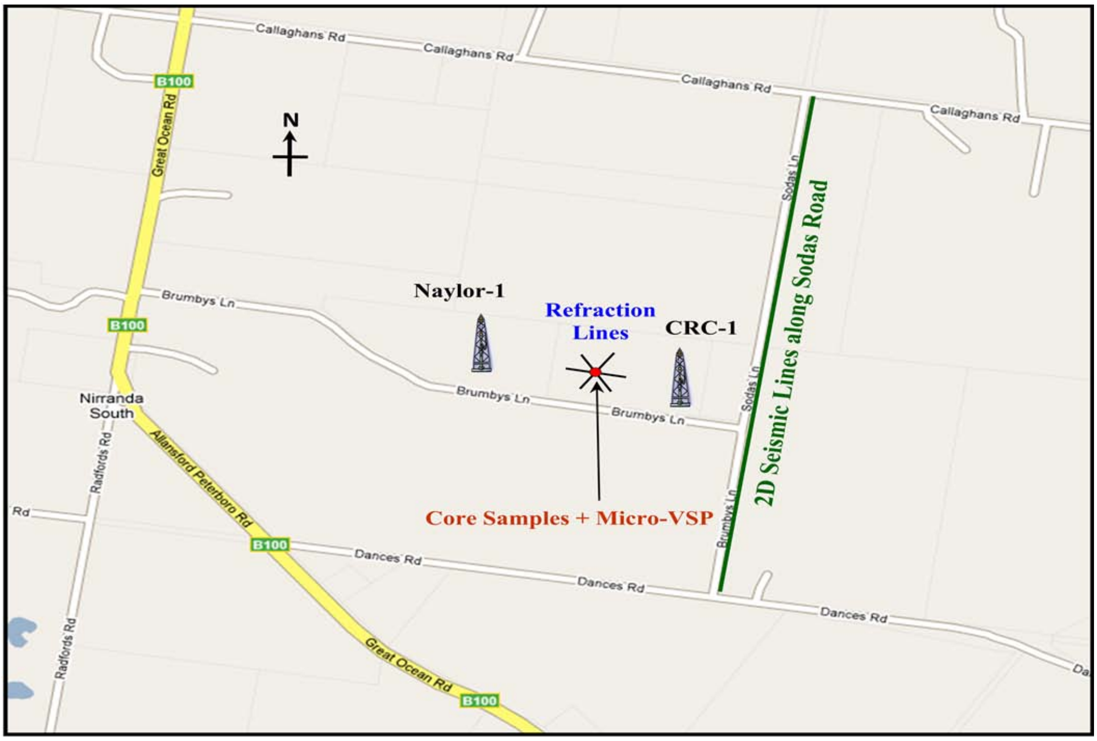


Figure 4.1: Location of the near-surface survey which has been acquired at the Naylor Field during both wet and dry conditions. The refraction surveys and micro-VSP data have been acquired in-between the Naylor-1 and CRC-1 wells, the distance between the Naylor-1 and CRC-1 wells is about 300m. The green line shows the location of the repeated 2D seismic test along Soda’s Road.

A feature of the injection test site area is the near-surface karst topography. In such geological terrain, any change in the water table level can influence the seismic response and cause changes in the seismic wave scattering pattern. Hence the aim of micro-array measurements was to determine the properties of the near surface layers during the wet and dry seasons. This could help us understand and ultimately predict the seismic response and hence survey repeatability to improve the reliability of time-lapse analysis.

The main idea of this approach is to utilise elastic properties of the near surface measured by micro-arrays to forward model 4D seismic responses. Measurements of the variation of elastic properties of both top soil and the deeper rugose clay-limestone interface as a function of soil saturation and scattering related to water table level will provide us with the magnitude of near-surface related non-repeatability. To estimate these near-surface related effects more precisely, I used both micro-borehole (micro VSP) and micro-refraction arrays to analyse directional (depth and azimuth) properties of the near surface. These measurements were subsequently calibrated by core sample tests. Finally, numerical tests were performed with the calibrated soil parameters.

4.2 Near surface seismic acquisition survey

It is anticipated that for a given source, the non-repeatability issues are, to the first order of approximation, related to variations in the properties of the top soil and underlying layers. This can be quite drastic at Naylor Field (Figure 4.2 and Figure 4.3). To investigate the presence of near surface directivity I performed a refraction survey along three different directions and reversed VSP and ultrasonic measurements (Figure 4.1 and Figure 4.4). Due to the very small dimensions of these surveys, I named them "micro-array" measurements. Together with these measurements, I acquired core samples and measured P-wave velocities, amplitudes and absorption (Q and its proxy seismic attributes such as the peak frequency) during the wet and dry conditions of the near surface. The three refraction/reflection lines were 23m long each. The orientation of the three seismic lines was at an azimuth of 30° for line A, 90° for line B and 150° for line C, the last coinciding with the maximum horizontal stress direction in this area.

A total of 24 shot stations were deployed along every refraction seismic line which utilised 24 geophones at 1m spacing. The seismic sources used were a 4.5 kg sledge hammer for the refraction seismic surveys and explosive charges (seismic detonator) for the reverse VSP. There were 7 shot positions for each of the refraction lines (Figure 4.5).

Figure 4.2: A "wet case" of the near-surface and the weather at Naylor Field during the first near-surface survey: 24th–26th August 2009.

Figure 4.3: A "dry case" of the near-surface and the weather at Naylor Field during the second near-surface survey: 18th–19th January 2010.

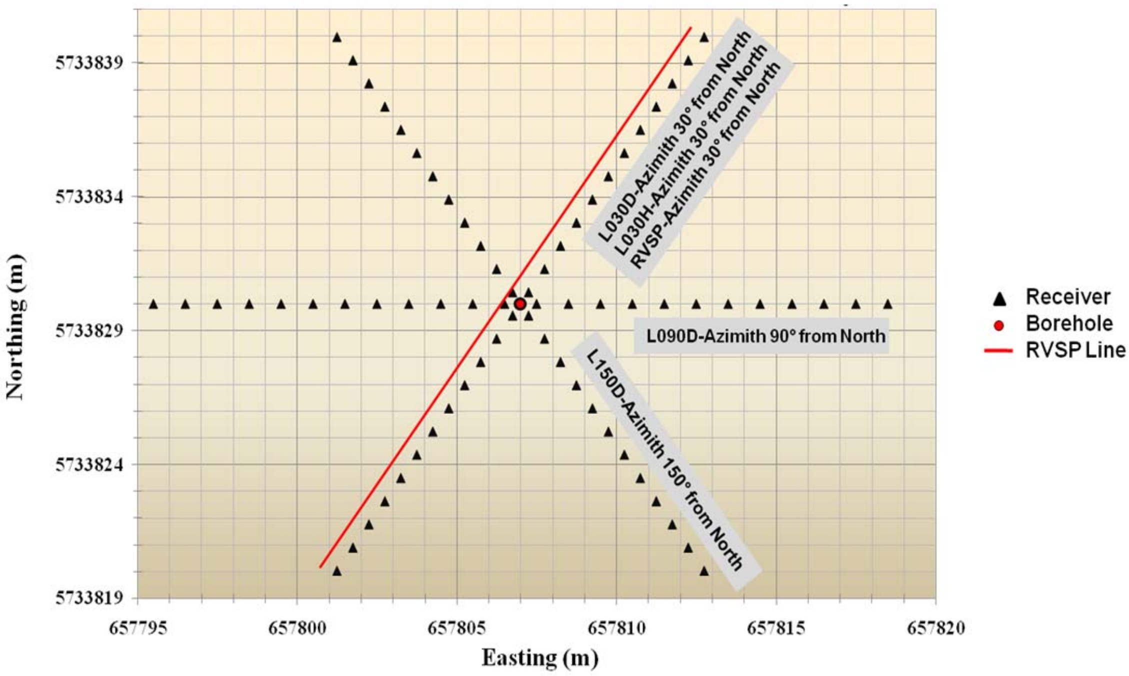


Figure 4.4: The layout of three refraction lines A, B and C along azimuths 30º, 90º and 150º respectively. Each line consists of 24 stations and they intersect each other at the middle. The borehole for micro-VSP is located at the line intersections.

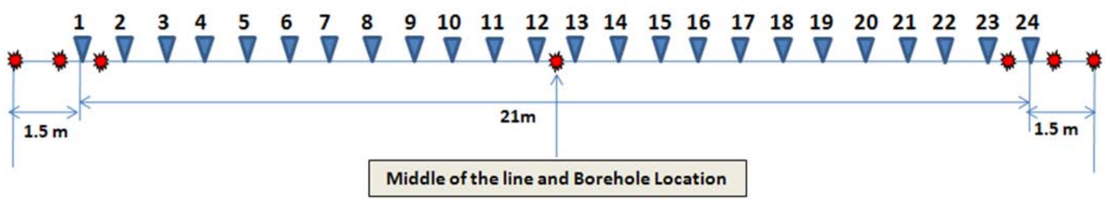


Figure 4.5: The layout of each line of the seismic refraction lines. Each line consists of 24 receivers and the spacing between the receivers was 1m. Each refraction line was recorded using 7 shots.

After the refraction survey was performed, a borehole was drilled at the intersection of the three refraction lines to extract the core samples and to use this borehole for the micro- array reverse VSP (Figure 4.6).

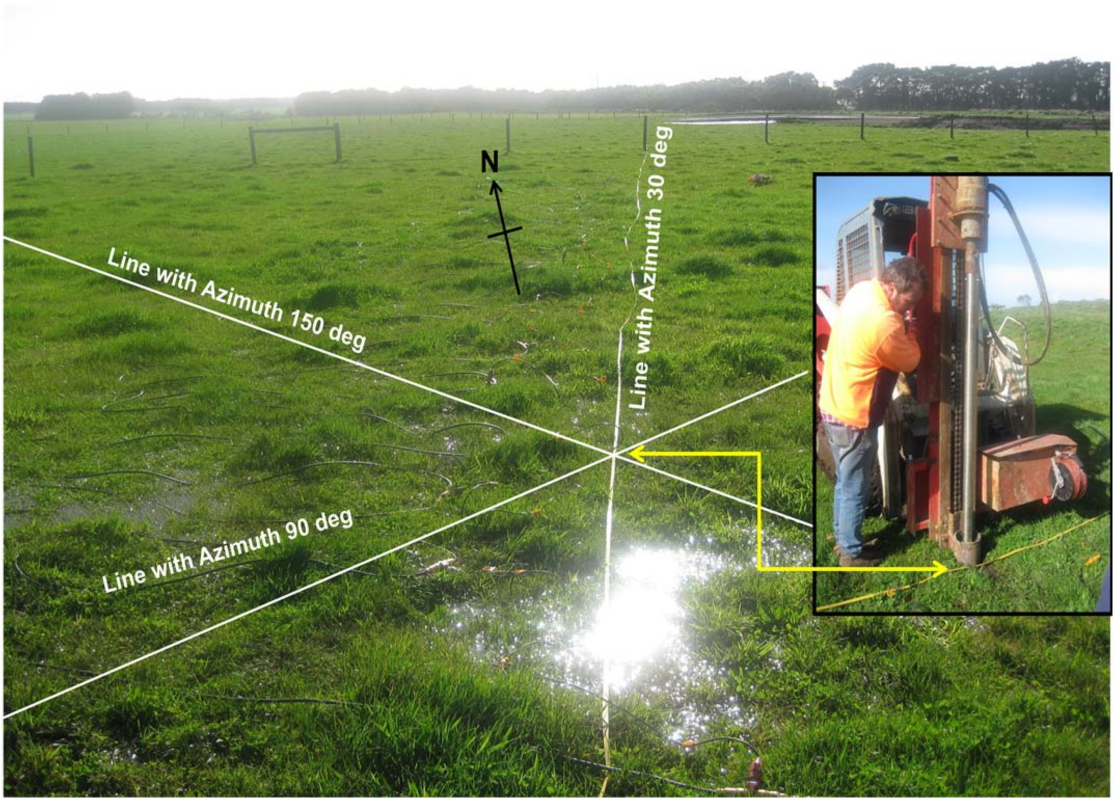


Figure 4.6: This photo was taken from the Naylor Field Site during the micro-array survey, showing the layout of the three seismic lines A, B and C with azimuths 30º, 90º and 150º, respectively. The coring was done at the intersection of the three seismic lines.

The RVSP survey involved shots fired inside the borehole from depth of 1.9 m up to 0.2m with 10 cm interval (Figure 4.7). 24 surface geophones were utilised at the surface to record borehole shots, as a walk-away RVSP system. Preserved core samples were measured with their in-situ saturation and also dry. These results were compared to RVSP and refection measurements. I subsequently used these measured elastic properties for detailed numerical tests (chapter 5).

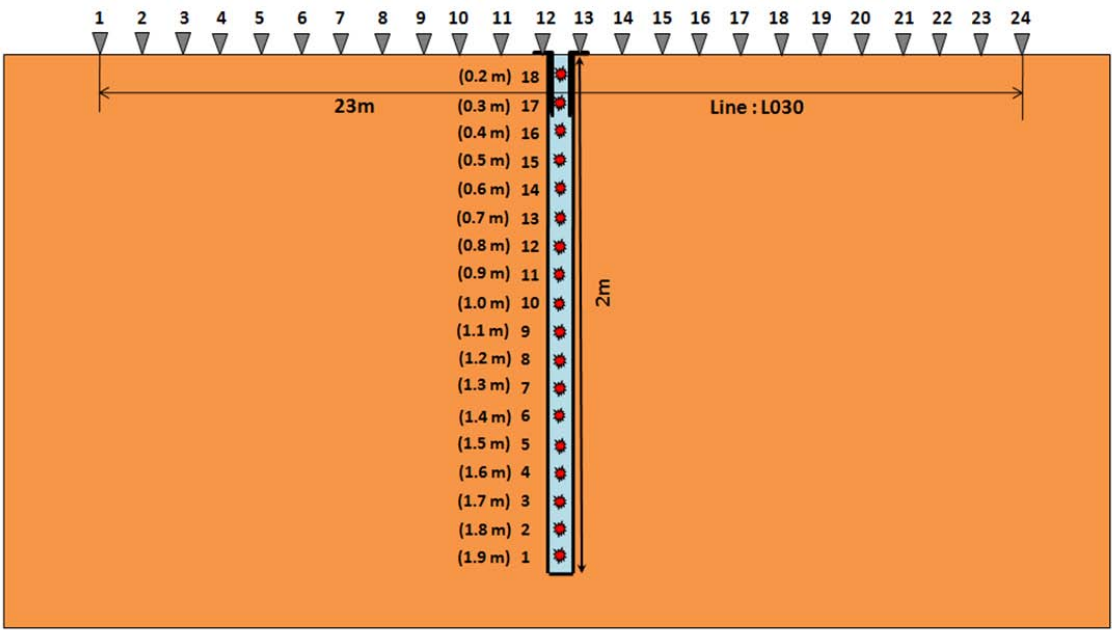


Figure 4.7: Geometry of the micro-VSP survey. 24 surface receivers of line A were utilised to record borehole shots. Using the 2m borehole, 18 shots were acquired in the borehole starting from shot 1 at depth 1.9m to shot 18 at depth 0.2m with depth intervals of 0.1m.

4.3 Measurements of the elastic seismic properties from refraction seismic surveys

Using refraction analysis, the directional variations of the velocities and attenuation were calculated from refraction lines A, B and C. P-wave velocities were calculated from the inverse of gradient lines of each layer from the travel-time graphs. To calculate the depths to the limestone, the critical angle was first calculated from the following equation:

$$\theta_{12} = \frac{v_1}{v_2} \quad ; \quad \theta_{23} = \frac{v_2}{v_3} \quad ; \quad \theta_{34} = \frac{v_3}{v_4} \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (5)$$

Then, the thickness of each layer can be calculated from the following equations:

$$z_1 = \frac{t_1 v_1}{2\cos\theta_{12}} \quad ; \quad z_2 = \frac{t_2 v_2}{2\cos\theta_{23}} \quad ; \quad z_3 = \frac{t_3 v_3}{2\cos\theta_{34}} \quad , \ldots\ldots\ldots\ldots\ldots\ldots\ldots (6)$$

where z is the thickness; v is the velocity; θ is the critical angle; t_1, t_2, and t_3, can be calculated from travel-time graphs as shown Figure 4.8.

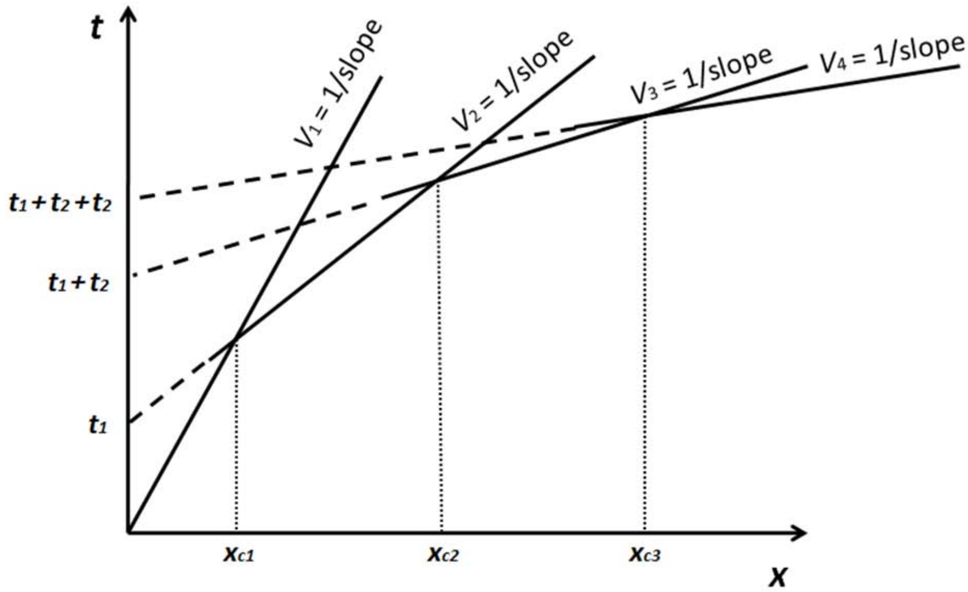


Figure 4.8: Travel-time graph provides useful information of the intercepts times, velocities, critical angles and critical distance for the refraction of each layer.

Refraction data analysis has been carried out to calculate the p-wave velocities of the top 4m of the near-surface with three different azimuths in the example for line A during the dry season (Figure 4.9). Three different velocities can be identified from the travel-time graph which represents three different layers at near surface. First branch is direct wave, other two slopes are refracted. This analysis has been carried out for every refraction line at both ends and the middle of each line during both wet and dry season.

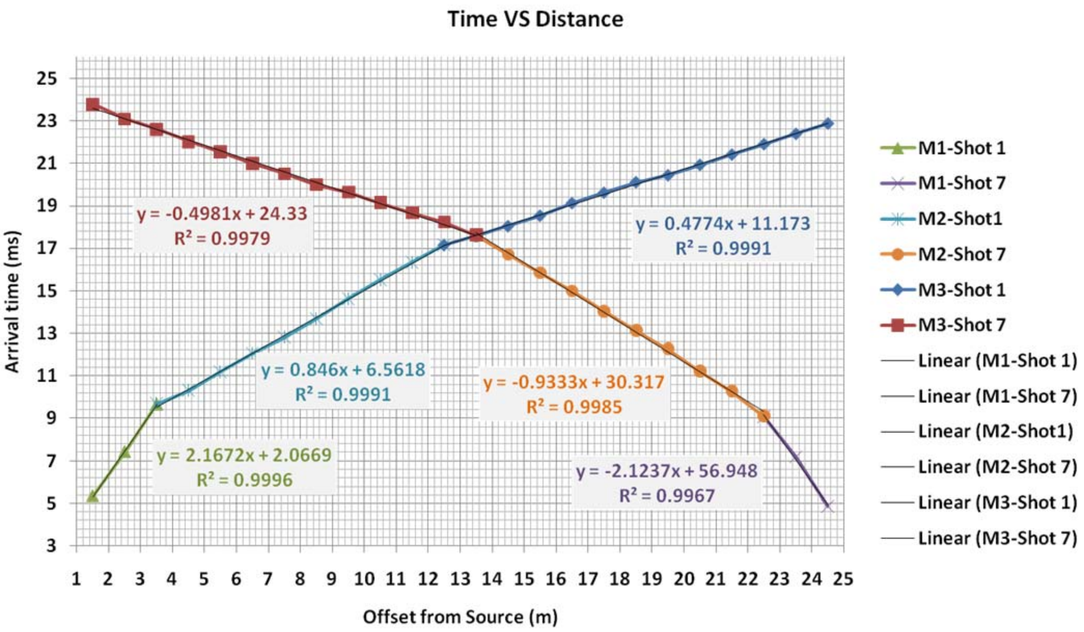


Figure 4.9: Travel-time graph recorded during the dry session along line A with azimuth of 30° from shots 1 and 7 with offset 1.5 from each end of the line representing symmetrically. Three different layers can be identified with three different velocities.

Then, the determined velocities from the refraction lines during wet and dry season were interpolated from three different points along each line for studying the change in the seismic velocity with different directions (Figure 4.10). The results of these calculated velocities show that there is a consistent increase in velocity with depth and therefore the average directional variations of the velocities are small (Figure 4.10). The RMS amplitude of the first arrival has been measured for the central receiver from six different shots at three different azimuthal directions around the borehole during the wet and dry conditions of the near surface. Figure 4.11 shows the change in amplitudes due to a change in the water saturation, for wet and dry seasons.

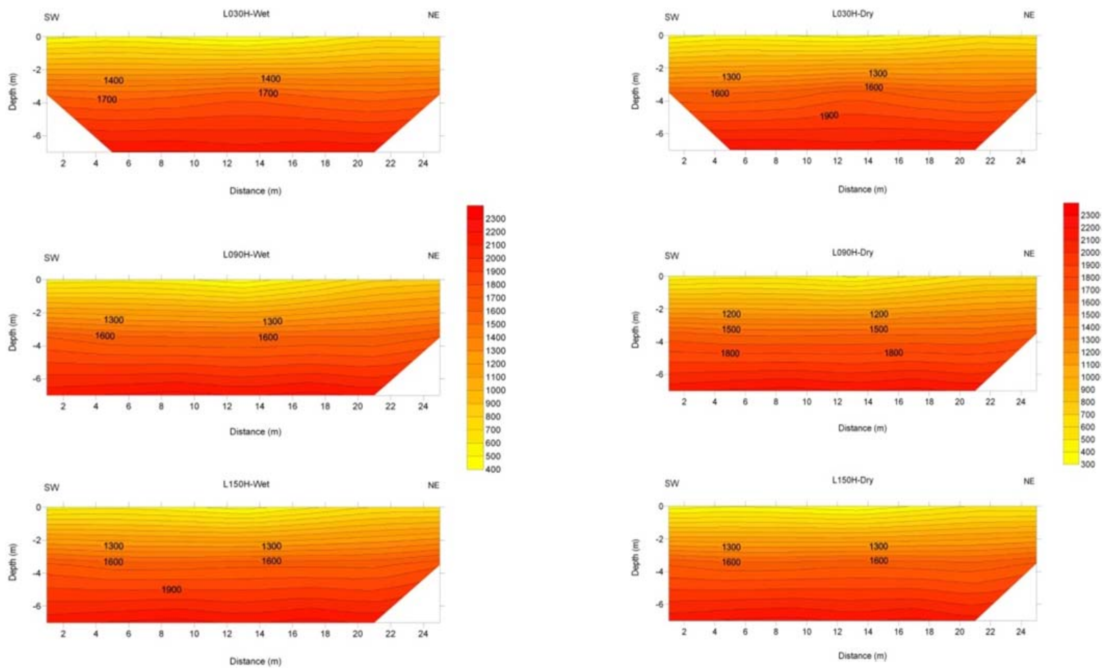


Figure 4.10: The nearsurface velocity of the wet (left column) and dry (right column) measured along each of the refraction lines, along azimuths 30, 90 and 150 degree.

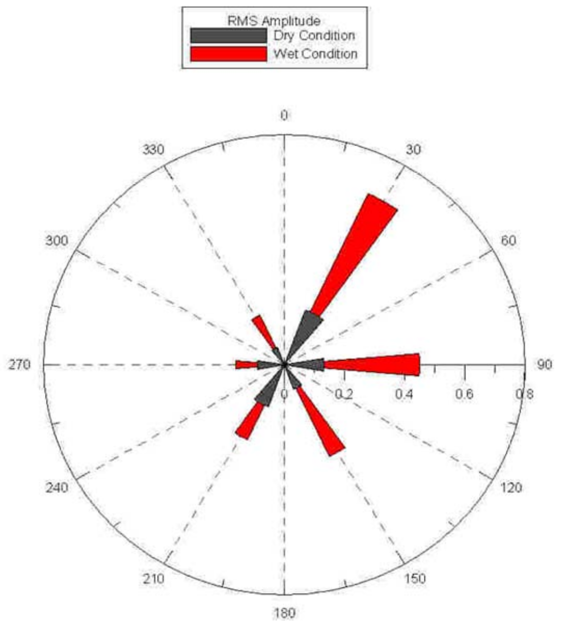


Figure 4.11: Measured RMS amplitude variations for the central receiver from three different azimuthal directions for wet (in red) and dry (in grey) soil conditions. Some directivity can be observed in the wet season.

4.3.1 Q-factor measurements

The Q-factor was calculated using the pulse rise time-domain method (Kjartanson, 1979). The general equation relating the measured rise time τ to the Q of the rock is given by:

$$\tau = \tau_o + \frac{CT}{Q} \qquad \text{……………………………………………………………………… (7)}$$

; where τ_0 is the rise time at the source, T is the pulse travel time, and C is a constant.

In this work, we set C to a constant equal to 0.3. This calculation has been carried out after the refraction analysis to make grouping of the rise times easier (Figure 4.12).

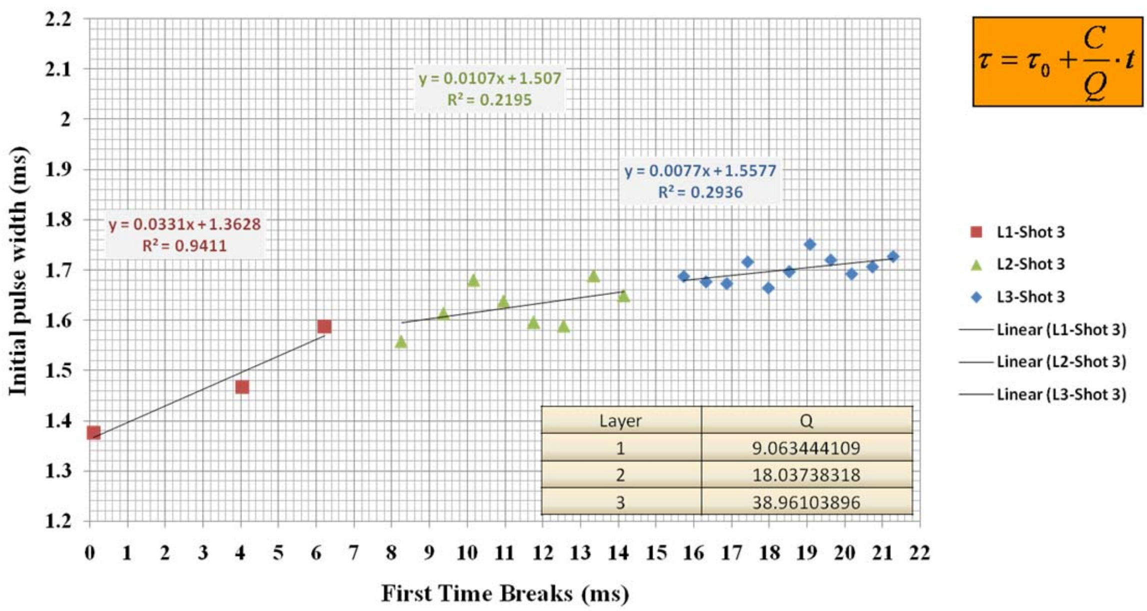


Figure 4.12: Q-factor is calculated from the slope of the line using equation 7. Three different layers can be potentially identified with three different slopes, the second and third being very similar.

This analysis has been carried out for every refraction line at both ends and the middle of each line during both wet and dry seasons. Then, the Q factors determined from measurements on the refraction lines during wet and dry seasons were interpolated from three different points along each line for studying the change in the Q in different directions (Figure 4.13). There is a consistent increase in Q-factor with depth, while the average directional variations are small (Figure 4.13)

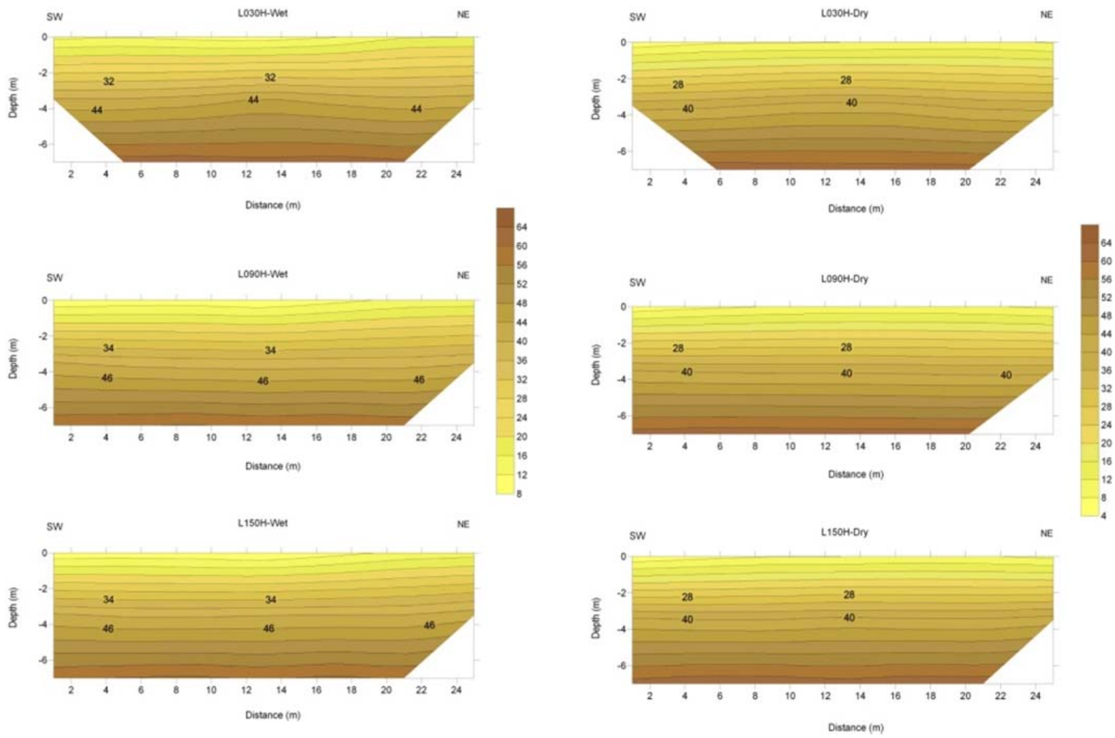


Figure 4.13: The Q-factor model of the wet (left column) and dry (right column) near surface measured from the three different positions along each refraction lines, Line A with azimuth 30 degrees from the north (top), Line B with azimuth 90 degrees from the north (middle) and Line C with azimuth 150 degrees from the north (bottom).

4.3.2 Summary

The micro-array investigation of the near-surface layers at the Naylor site indicated that the velocities and Q-factor exhibit negligible directional variations at this site. The top soil (0.5m thick agricultural layer or elasto-plastic zone) has a low velocity and low Q-factor, which affects reflection amplitudes, phase and arrival times. This zone significantly attenuates seismic energy.

Average Properties Measurements at Near Surface of Naylor Field using Refraction Data					
		Wet Season		Dry Season	
Layer	Depth (m)	Velocity (m/s)	Qp	Velocity (m/s)	Qp
1	0	405	14	298	7.7
2	0.5	814.6	19.4	614	13.4
3	1.56	1022.8	36.62	977	33.7
4	4.19	1790.9	50	1790	50

Table 1: The average velocities and Q-factors of the near surface between the Naylor-1 and CRC-1 wells. Top soil showed very small Q values (non-linear range, where the reliability of pulse-rise method is low)

4.4 Micro-array VSP data

The micro-array reverse VSP was recorded by shooting in the borehole starting from the bottom of the borehole with shot No. 1 of depth 1.9m and continuing shooting with 0.1m spacing between shots up to shot No. 18 at depth 0.2m. 24 geophones on refraction line A were used to record borehole shots. A small delay of the arrivals recorded in dry season with respect to the wet one was observable even in the raw data. The source generated noise also looked different (Figure 4.14 and Figure 4.15). In addition, the data recorded in the dry season were attenuated more, compared to the data recorded in the wet season. The seismic record of the shallow shots shows greater amplitude losses compared to the deep shots (Figure 4.16). This confirms the high attenuation in the first 0.5m of the near surface. The average velocities were also measured from each shot of the micro-array RVSP at every receiver location. The average velocity generally increases with depth, being higher in the wet season when compared to the dry season. Micro-RVSP measurements show a consistent increase in velocity with depth and no seismic anisotropy (Figure 4.17), Figure 4.18 and Figure 4.19 show the change in the velocities against receiver offset from the borehole for different shot depths from reversed VSP data along line A with azimuth 30°**.** These results show: a) velocities in the wet season are higher than in the dry season, and b) no anisotropy (polar) was observed as the velocity depth gradient is constant for all incidence angles (offsets).

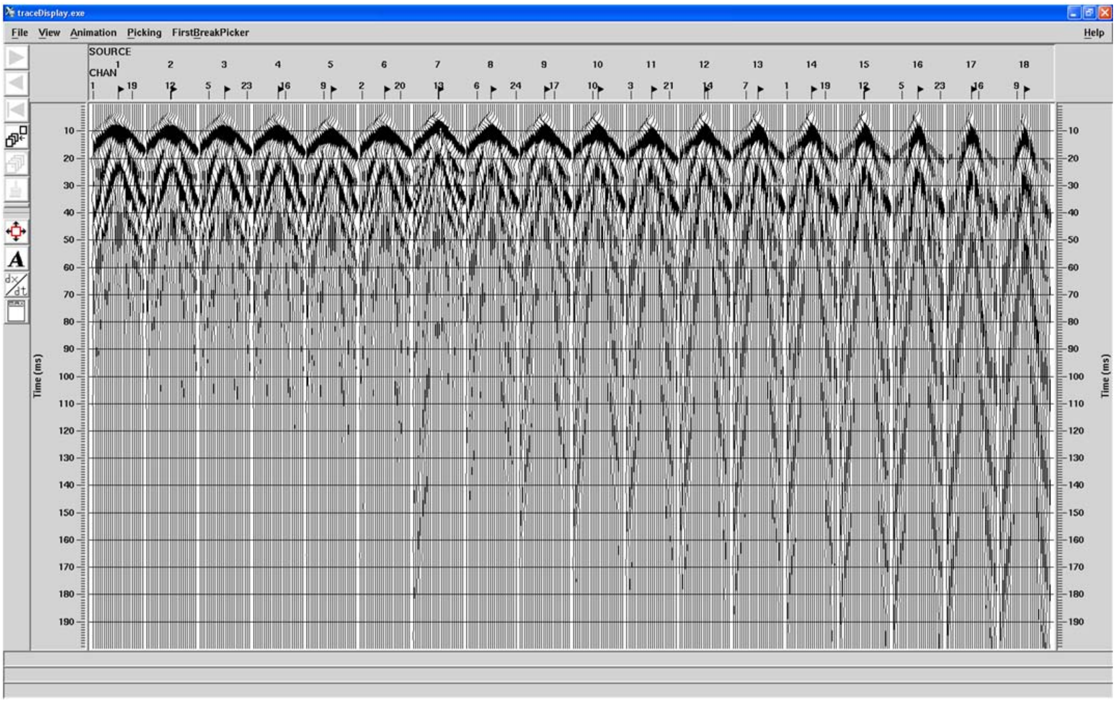


Figure 4.14: RVSP shot gathers obtained with seismic detonators as a seismic source for shots 1-18 (respectively from left to right) during the wet season.

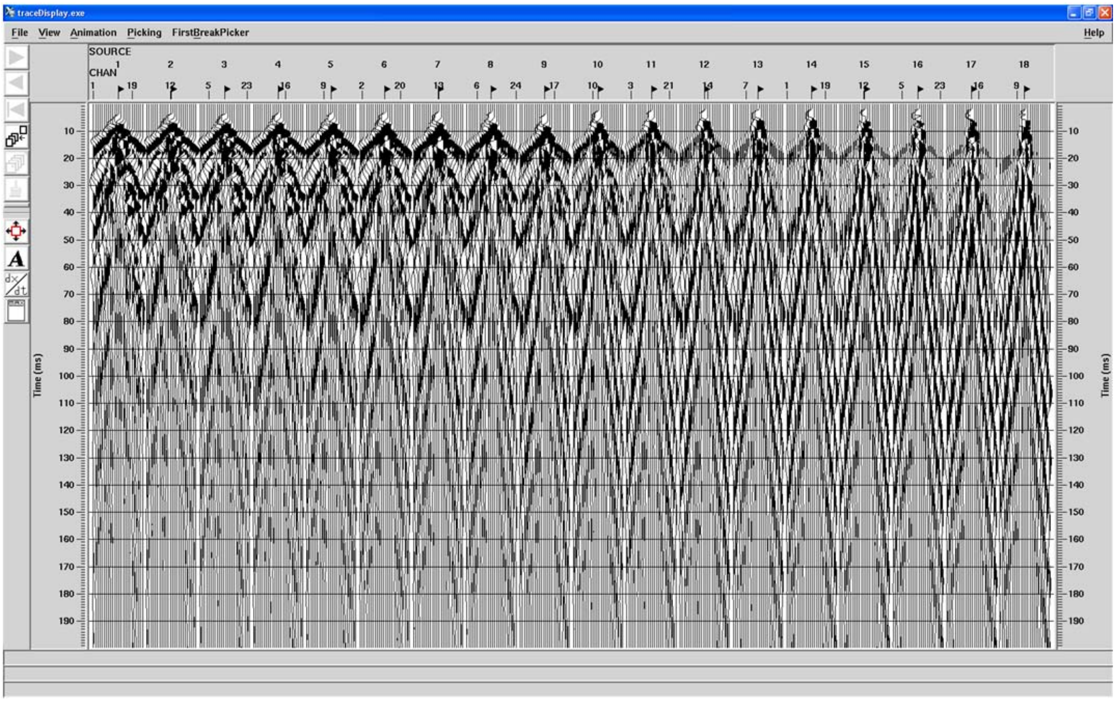


Figure 4.15: RVSP shot gathers obtained with seismic detonators as a seismic source for shots 1-18 (respectively from left to right) during the dry season.

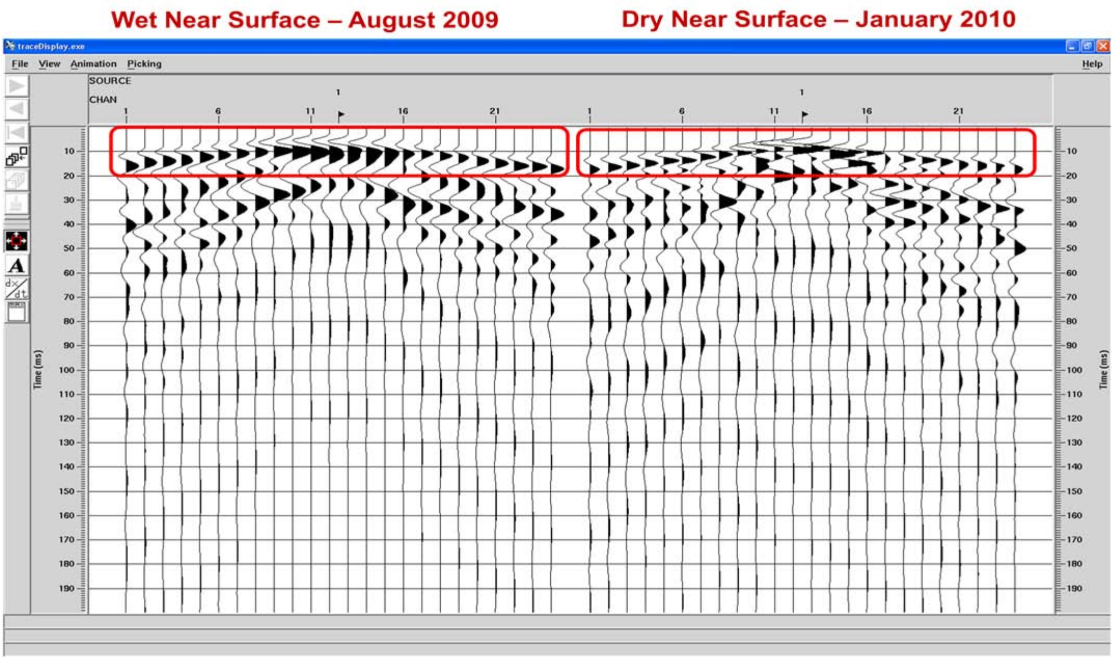


Figure 4.16: Shots for 1.9 m depth. Dry data showed higher attenuation compared to the wet near-surface data.

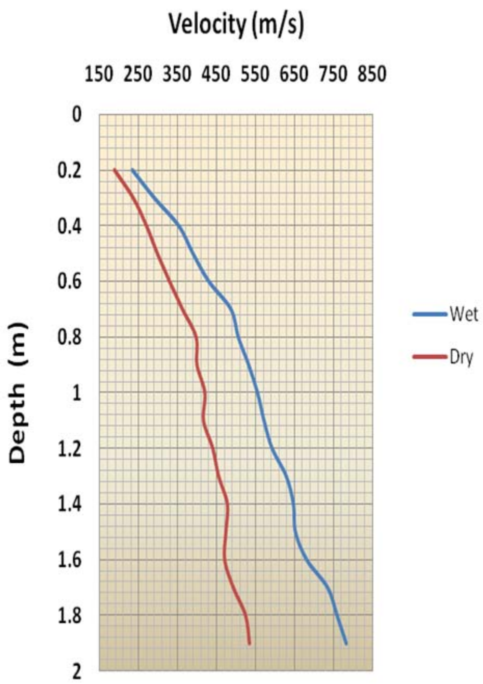


Figure 4.17: Average velocity profiles during dry and wet seasons as measured from reversed walk-away VSP.

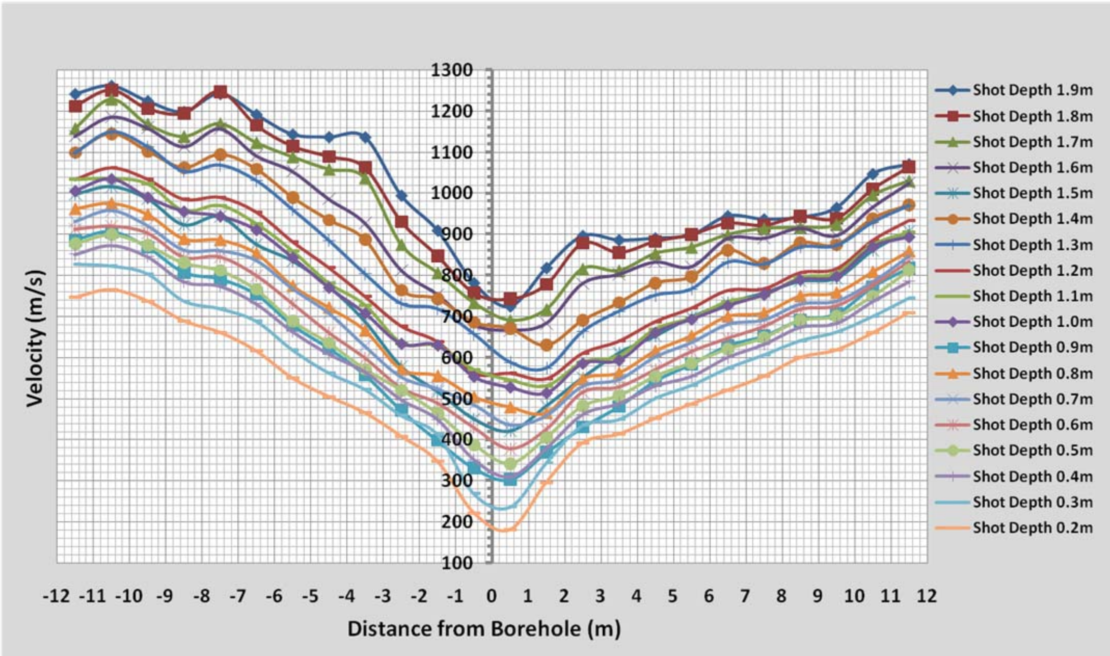


Figure 4.18: The average velocities against the receiver offset from the borehole for shots fired in the wet season. These results show a consistent velocity increase with depth for all incidence angles (no anisotropy).

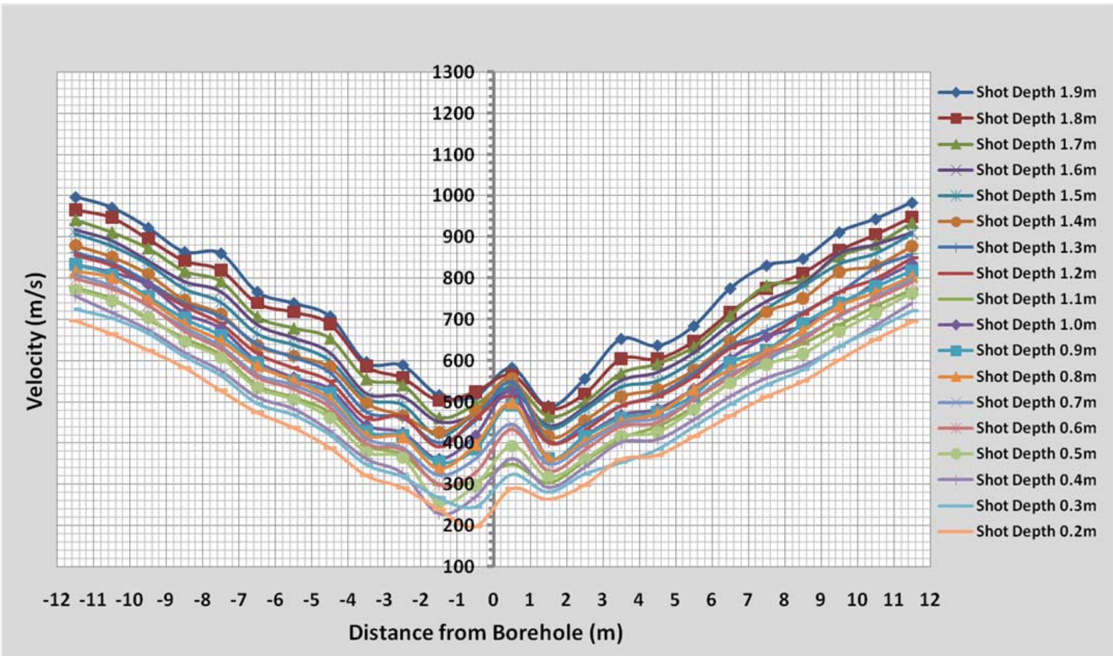


Figure 4.19: The average velocities against the receiver offset from the borehole for shots fired in the dry season. These results show a consistent velocity increase with depth for all incidence angles (no anisotropy).

The first arrival amplitudes (maximum trough amplitude where transmitted pulse is less affected by the interference), Figure 4.20 and Figure 4.21, show amplitudes of direct waves for offset -12m to -4m and 12m to 4m from the borehole. These results show a consistent offset decay in both directions regardless of the season.

Around the first break of the shallowest (shot 18) and deepest shot (shot 1) from the micro-array VSP survey of the wet and dry near surface data, the analysis of the amplitude spectra for the seismic window of 15ms also shows more attenuation in the dry season compared to the wet season (Figure 4.22). In the wet case, the amplitude spectrum clearly shows a broader frequency range when compared to the dry case (Figure 4.22). Overall, the wet near surface can provide better seismic energy transmission and a broader signal compared to the dry case.

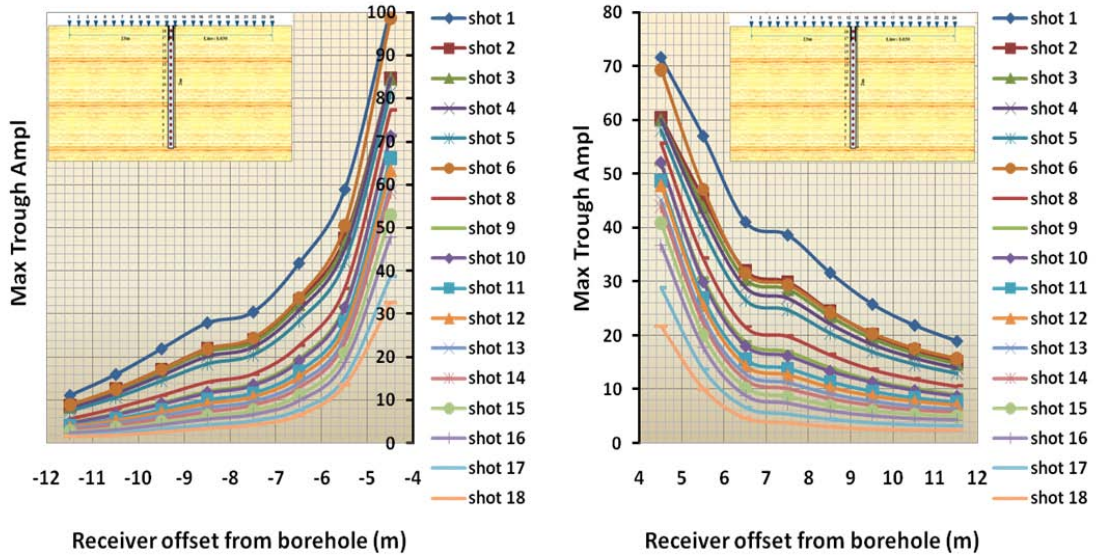


Figure 4.20: Measured maximum amplitude from the transmitted wavefield (wet season). Offset range of -12m to -4m and 12m to 4m from the borehole were used.

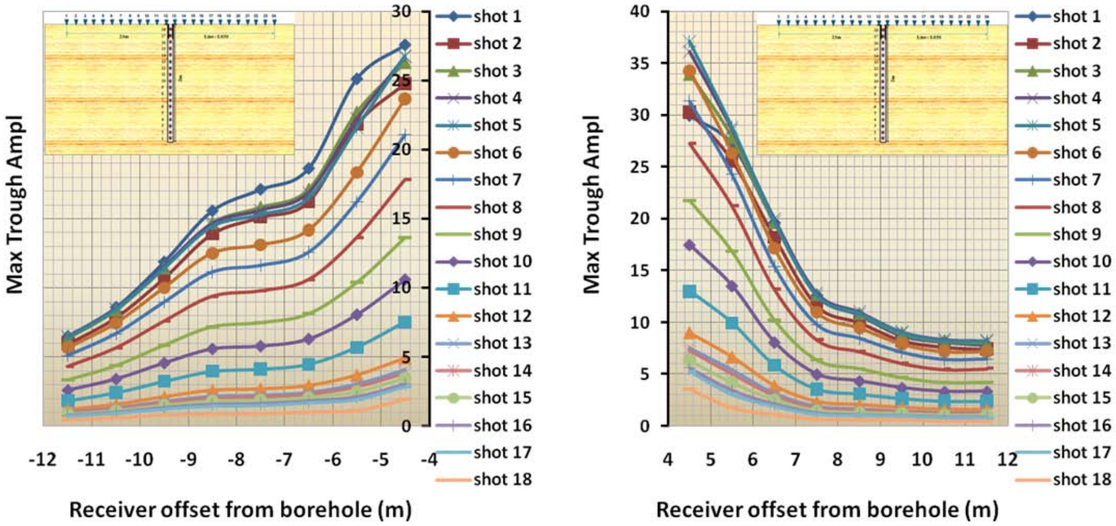


Figure 4.21: Measured maximum amplitude from the transmitted wavefield (dry season). Offset range of -12m to -4m and 12m to 4m from the borehole were used.

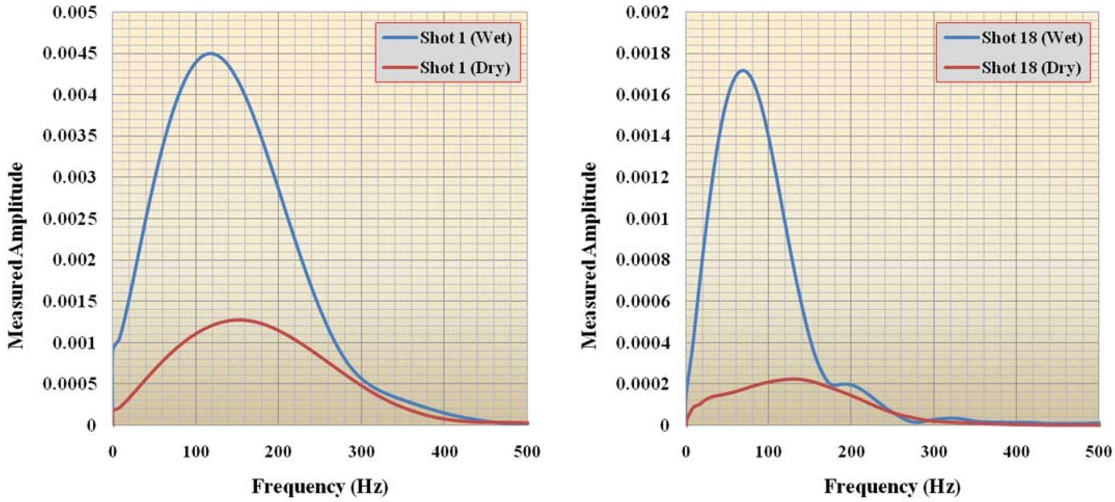
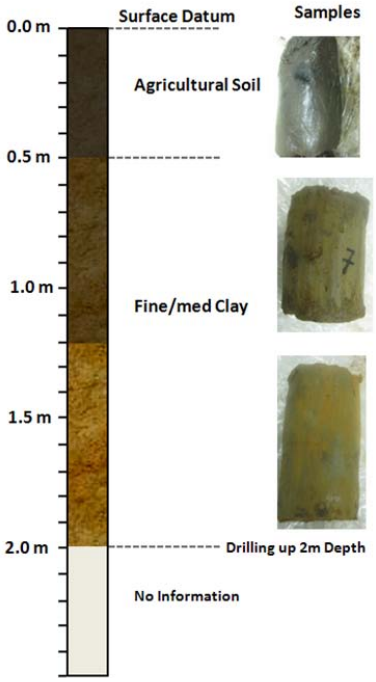


Figure 4.22: Amplitude Spectra for the deepest (left) and shallowest (right) shots gathers of the micro-array VSP data for wet (blue) and dry (red) seasons. Dry data typically show a narrow spectra.

4.5 Ultrasonic measurements of seismic properties from core samples

The near surface layers at this site between Naylor-1 and CRC-1 are mostly clay and the first half meter is mostly agricultural soil overlaying a corrugated limestone which starts from a 1- 4m depth, depending on the location. The compaction of the clay increases with depth and the colour changes from dark to light. I have extracted core samples for a depth 2m from the borehole at the intercept point of the three refraction lines. The samples were quickly wrapped with special plastic to preserve their moisture content then kept in the refrigerator until they were sent to the CSIRO Laboratory for ultrasonic measurements (Figure 4.23). The velocities, attenuation and densities were measured for each sample before and after drying them (Figure 4.24).

Figure 4.23: Ultrasonic measurements of the extracted core samples at the Ian Wark Laboratory, Petroleum Resources Department, CSIRO, Melbourne.



For Wet Samples

Layer	Depth Range (m)	Average Velocity (m/s)	Average Q	Average Density (Kg/m^3)
1	0.0-0.5	766	?	1787
2	0.5-1.0	915	9.89	1981
3	1.2-2.0	1232	26.97	2169.5

For Dry Samples

Layer	Depth Range (m)	Average Velocity (m/s)	Average Q	Average Density (Kg/m^3)
1	0.0-0.5	502	?	1351
2	0.5-1.0	717.2	5.81	1609
3	1.2-2.0	964.7	12.83	1704.3

Figure 4.24: Average calculated velocities, Q-factor and densities for the wet and dry samples.

4.6 Chapter Summary

The micro-array investigation of the near-surface layers at the Naylor site indicated that the velocities and Q-factor show a consistent pattern at this site. The top soil (0.5m thick agricultural layer or elastic-plastic zone) has a low velocity and low Q-factor hence affects both reflection amplitudes and arrival times. This zone significantly attenuates seismic energy. Micro-RVSP measurements show a consistent increase in velocity with depth and no seismic anisotropy. The change in water saturation of the near surface can thus cause changes in velocity and attenuation. This has to be taken into account when designing monitoring programs.

Chapter 5 : Prediction of Seismic Repeatability through Synthetic Modelling

After measuring the seismic properties of the near surface layers in last chapter, I have used these measurements in this chapter in synthetic modelling experiments to predict the seismic repeatability at Naylor Field.

5.1 Introduction

In time-lapse seismic, the difference between seismic data sets acquired at different times during the production process is used to infer changes in the distribution of fluids and pressure due to production or injection. A decision to use time-lapse seismic methodology for tracking fluid movement in the reservoir over time is commonly based on the outcome of simulation of the physical processes (reservoir simulation) and corresponding seismic signature changes.

Time-lapse seismic reservoir monitoring requires a very accurate forward modelling technique that will at least predict the changes in body wave velocities and amplitudes. In-depth modelling may be required in some cases to analyse attenuation and dispersion as changes in frequency and phase could arise due to changes in anelastic attenuation (Jack, 1998).

Forward modelling could be carried out in several stages. For example, it is often necessary to run a 3D ray tracing model, particularly if a 3D time-lapse VSP survey is planned, to investigate and interrogate acquisition geometry that will result in an optimum illumination of the target. Ray methods have been used extensively in seismology and seismic exploration to study the propagation of seismic waves in layered media with varying elastic parameters. In early applications, the focus was mostly on calculating ray paths and travel times, referred to as kinematic ray tracing, but throughout the 1970s and 1980s numerical techniques were developed for dynamic ray tracing (Červený and Hron, 1980), which yields wave front curvature and geometric-spreading attributes. In the case of applying a point source in the starting point of the ray, we refer to the various attributes calculated by ray tracing (travel time, amplitude, geometric spreading, etc.) as Green's function attributes. The attributes calculated by ray tracing are generally stable if the interface normal and gradients of the elastic parameters (e.g., P- and S-wave velocities for an isotropic medium) vary smoothly within a region surrounding the ray. This region depends on the dominant seismic frequency and is referred to as the Fresnel volume (Červený and Soares, 1992).

More accurate modelling requires a numerical solution derived from full elastic wave equations (Virieux, 1986). The changes in the reservoir due to injection-production processes can be masked by the "noise" encountered during a time-lapse survey. This "time-lapse noise" is related to non-repeatability of successive surveys. If the two repeated surveys are not similar (repeatability is low) then their difference is likely to exceed the time-lapse seismic signal arising from fluid changes in the reservoir. Excluding the end member such as Sleipner, the NRMS difference is typically in the range 10-20%. Hence, our non-repeatability should be in the same range. Unfortunately, for land surveys, non-repeatability of 30-40% is common.

Considering that, it is relatively easy to repeat acquisition geometry on land and deploy controlled sources such as vibroseis. It is logical to assume that such low repeatability must be related to changes in the near surface, so it seems worth putting effort into examining the effect of the near surface on the time-lapse seismic signal.

Elastic properties of near-surface materials and their effects on seismic wave propagation are of fundamental interest in groundwater, engineering, and environmental studies. It is also necessary to examine how the seismic repeatability can be affected by changes in the near surface, that is, changes of elastic properties of the near surface sediments due to saturation changes, agricultural activities, excessive temperature changes, etc. Such effects could be first studied in a 2D time-lapse numerical experiment assuming an expected range of changes in the reservoir and then introducing changes in the near surface in a staged manner. The end result is defined by the analysis of the difference sections.

5.2 Prediction of seismic repeatability at Naylor Field

As geoscientists become more involved in the characterisation of reservoirs, the use of seismic attributes and amplitudes to measure reservoir properties such as porosity, pressure, saturation, and, ultimately, perhaps permeability are becoming commonplace. However, as discussed already, the changes in these seismic attributes and amplitudes in 4D studies can be caused by the variation of the near surface and not only because of the changes in the reservoir itself. In order to create the link between reservoir properties and the details of the seismic wavefield, I generated many realistic synthetic models, and for that purpose, I used 4th order, stress-velocity formulation on a staggered grid.

As shown (mainly qualitatively) with early 2D field tests (Figure 5.1), the depth of penetration of seismic energy and frequency characteristics of the seismic wavelet will be different in dry and wet periods of the year (Urosevic et al., 2007). Furthermore, these tests clearly showed that seasonal variations have a first order effect on the seismic signature, while the source type and positioning accuracy of the recording instruments have secondary and tertiary effects on time-lapse studies, respectively. Consequently, we analyse the effect of the near surface zone on the seismic signature by splitting it into two components: (1) top soil (agricultural part approximately 0.5 m thick) and (2) shallow (2-6 m thick) clay zone overlying irregular karst topography. We expect a relatively simple scattering effect from the clay/limestone interface due to similar elastic properties; the limestone velocity is only 400-500 m/s higher than the clay velocity. The corrugation of the interface is harder to model as it is not known precisely how it varies across the area of investigation. It is logical to suppose that top soil saturation changes may have an effect on repeatability. This can be understood from Figure 5.1 where the difference in the source footprint for the wet and dry cases is clearly visible. Similarly the difference in the signal strength and, hence, the signal-to-noise ratio between wet and dry 2D stacks is also clearly visible from this figure.

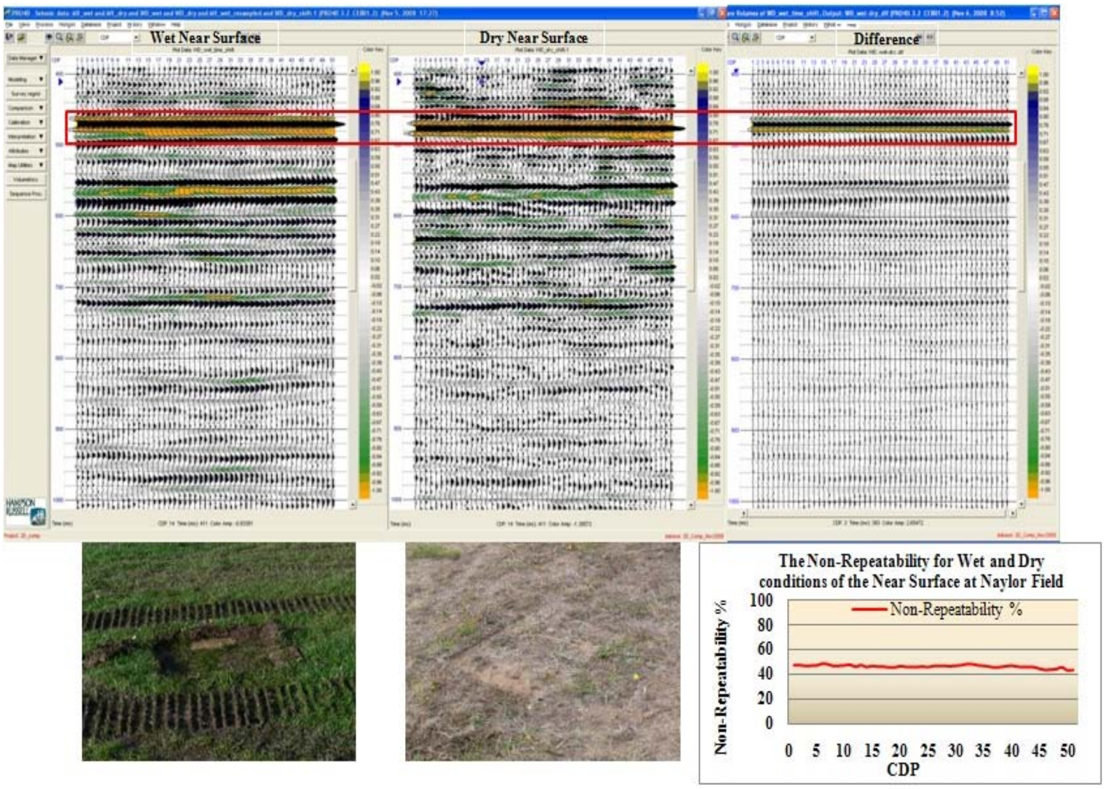


Figure 5.1: 2D seismic data recorded at the Naylor site with weight drop when the near surface is wet (left), dry (middle), and their difference (right). Weight-drop footprint for wet and dry topsoil is shown below. The lower right corner graph shows non-repeatability between wet & dry surveys computed for the Clifton Formation within the red time window.

Clearly, to improve our chances for remote detection of time-lapse CO_2 related effects, the effect of the near surface on seismic repeatability needs to be evaluated. Only then can we attempt to compensate for the variability in the signal character with specific field measurements.

It can also be noticed in Figure 5.1 that the impact source footprint changes drastically with soil saturation. This means that the plastic-elastic deformations due to source impact will be quite different in wet and dry periods. It is, however, less clear what the magnitude of elastic changes in relation to such effects is, and therefore can only be approximately modelled.

5.3 Numerical modelling results

5.3.1 Introduction

Finite-difference (FD) methods allow for the full response to be synthesised as the wavefield interacts with a seismic model. This includes wave propagation in heterogeneous anisotropic and anelastic media, scattering, mode conversions, etc. Although accurate, FD calculations can be highly computationally expensive. We demonstrate our approach through a comparison with a case study at Naylor Field in Australia, where a comprehensive time-lapse study was carried out by the Curtin University Geophysics group. For numerical modelling, I used information from logs and cores for the deep formations. However the properties of the top clay layers were unknown and for the modelling experiments first run, were the “best estimates”.

5.3.2 Methodology

It was anticipated that the non-repeatability issues would be to the first order of approximation related to variations of the properties of top soil and underlain clay/limestone contact. The modelling experiments were meant to evaluate the contribution of each of these two factors to non-repeatability. Therefore we modelled the near surface changes at Naylor by assuming three different scenarios:

1. Top soil with corrugated shale/lime interface
2. No corrugations
3. Thin (zero thickness) top soil layer

Dry and wet situations are assumed to cause changes in the elastic properties as shown in Table 2.

Formation	Thickness (m)	Top Subsurface (m)	Wet Near Surface Model			Dry Near Surface Model		
			Density (kg/mc)	Velocity (m/s)	Absorption (Q)	Density (kg/mc)	Velocity (m/s)	Absorption (Q)
Soil	0.5	0	1300	500	50	1100	250	25
Clay Dry	3.5	0.5	1800	1600	80	1400	1250	40
Limestone	118	4.0	2430	1900	100	2430	1900	100
Gellibrand Marl	335	122.0	2500	2100	120	2500	2100	120
Clifton Formation	17	457.0	2700	2600	140	2700	2600	140
Clay	-	474.0	2346	2985	160	2346	2985	160

Table 2: The thicknesses, top sub-surfaces, densities, velocities and (Q) absorptions for each formation of Otway Basin models at Naylor-1.

Source dominant frequency	80 Hz
Signal	Ricker Wavelet
Spread	Continuous (100 channels)
Shooting Pattern	Shoot Through
Number of Sources	100
Number of Receivers	100
Receivers Spacing	10m
Sources Spacing	10m
Offset range, m	5-995
Trace length	1000 ms
Sample rate	1 ms

Table 3: Acquisition parameters for three different scenarios of the synthetic seismic data.

Model 1: Representing the case of the near surface at Naylor field consisting of top agricultural soil (0.5m thick) and corrugated top surface of the limestone (Figure 5.2). This enables us to assess the total effect of the near surface on seismic non-repeatability.

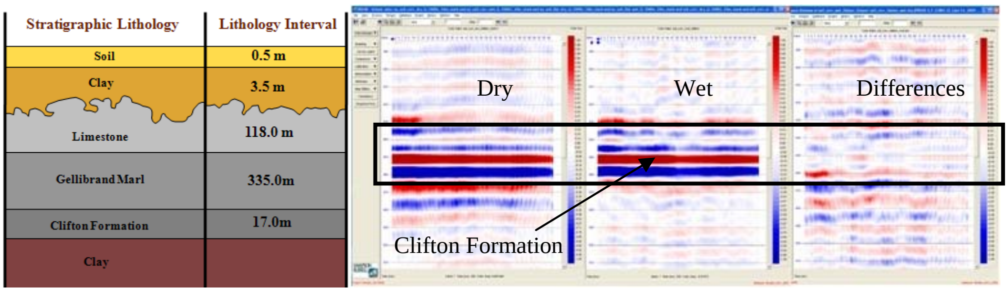


Figure 5.2: Model 1 represents wet and dry cases for top soil plus corrugated limestone top surface. Shown from left to right are: depth model, synthetic data for dry and wet cases and their difference. The lateral extent of this model is 1000m and the cell size of FD modelling 5x5. The window for computation of non-repeatability is also shown.

Model 2: Representing a more favourable case for the application of time-lapse seismic when only a simple (flat) limestone topography is present (Figure 5.3). This enables us to assess sole contribution of the topsoil to seismic non-repeatability.

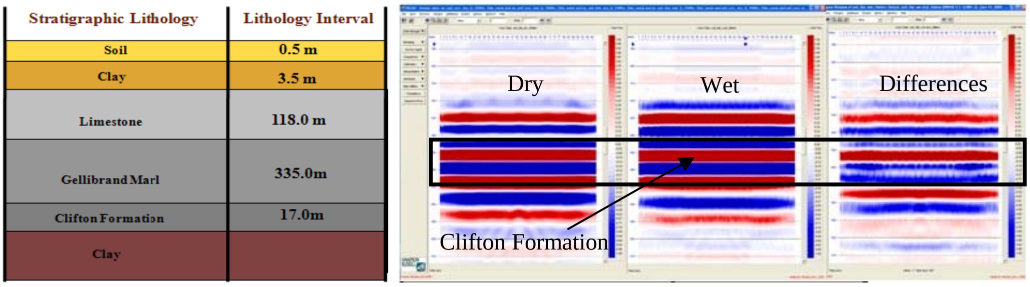


Figure 5.3: Model 2 represents the wet and dry cases for both topsoil and a flat limestone top surface. Shown from left to right are: depth model, synthetic data for dry and wet cases and their difference. The lateral extent of this model is 1000m and the cell size of FD modelling 5x5. The window for computation of non-repeatability is also shown.

Model 3: Representing the best case scenario of the top soil being absent, enabling us to analyse contribution of lime corrugations solely on seismic signature (Figure 5.4).

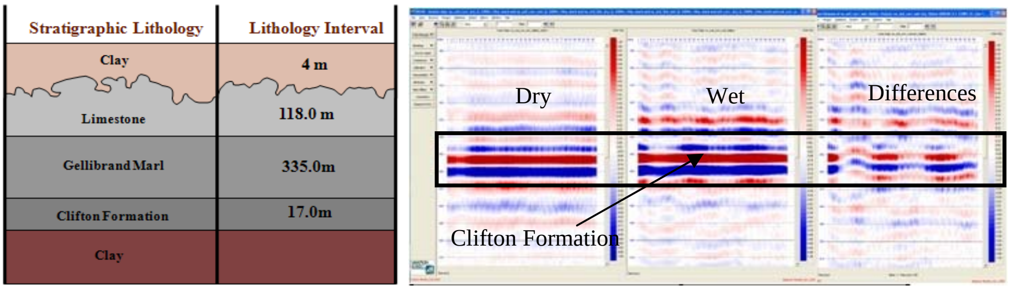


Figure 5.4: Model 3 represents the wet and dry case for no topsoil but a corrugated limestone top surface present. Shown from left to right are: depth model, synthetic data for dry and wet cases and their difference. The lateral extent of this model is 1000m and the cell size of FD modelling 5x5. The window for computation of non-repeatability is also shown.

These models have been simulated with stress-velocity finite difference formulation (Vireaux, 1986) which is implemented in TesseralCS-2D Full Wave Modelling software. Information from logs, cores and surface seismic measurements were used as input for the simulations (Table 1). The three cases have been designed to evaluate the contribution of each of the selected factors (top soil and corrugations) plus their total effect on the seismic signature. Generated shot records for the three different models were processed and analysed for non-repeatability.

5.3.3 Results of the initial modelling tests

One of the conventional measures of time-lapse seismic effectiveness is through a computation of the NRMS difference between repeated datasets. The non-repeatability of seismic amplitudes in two traces, a_t and b_t, can be measured by the NRMS difference, defined in time gate t by the RMS of the difference between a_t and b_t normalised by the mean RMS of the two traces and expressed as a percentage.

I measured the NRMS for the Clifton Formation because the seismic event has the highest S/N ratio (the best case scenario for the Naylor Field) and assumed that seismic strength was similar for the deeper reservoir target. The window of 40 ms was selected for computation via the equation provided by Kragh and Christie (2002) and Calvert (2005):

$$NRMS = \frac{2 \times \mathrm{RMS}\ (\mathrm{monitor} - \mathrm{base})}{[\mathrm{RMS}\ (\mathrm{monitor}) + \mathrm{RMS}\ (\mathrm{base})]} \times 100 \qquad (8)$$

From the above equation we get NRMS for two random surveys to be 140%; for two surveys with opposite polarity 200%. We want this number to be as small as possible for the successful application of time lapse methodology.

A non-repeatability modelled case for the wave scattering by a corrugated limestone interface is illustrated in Figure 5.5. The NRMS difference between flat and corrugated interfaces accounts for ~15%. Total non-repeatability for all three models together with the measured field data is shown in Figure 5.6. The non-repeatability between wet and dry for Model 1 is ~46%; non-repeatability between wet and dry for Model 3 is ~38% and non-repeatability between wet and dry for Model 2 is ~30%. The real data (average ~ 52% variations) fits closely to Model 1.

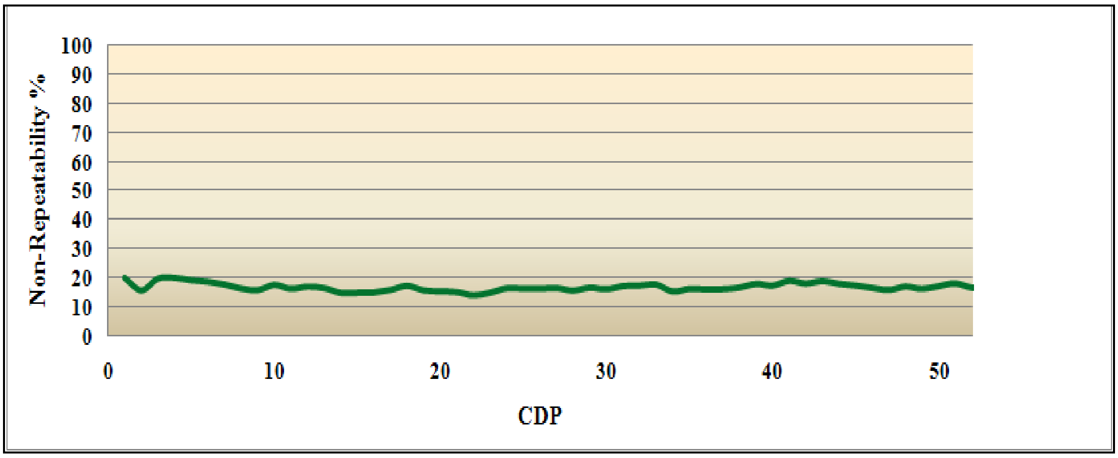


Figure 5.5: The non-repeatability as measured for Model 2, assuming a wet condition of the near surface. The normalised root mean square computed expresses the difference between flat and corrugated top limestone surface.

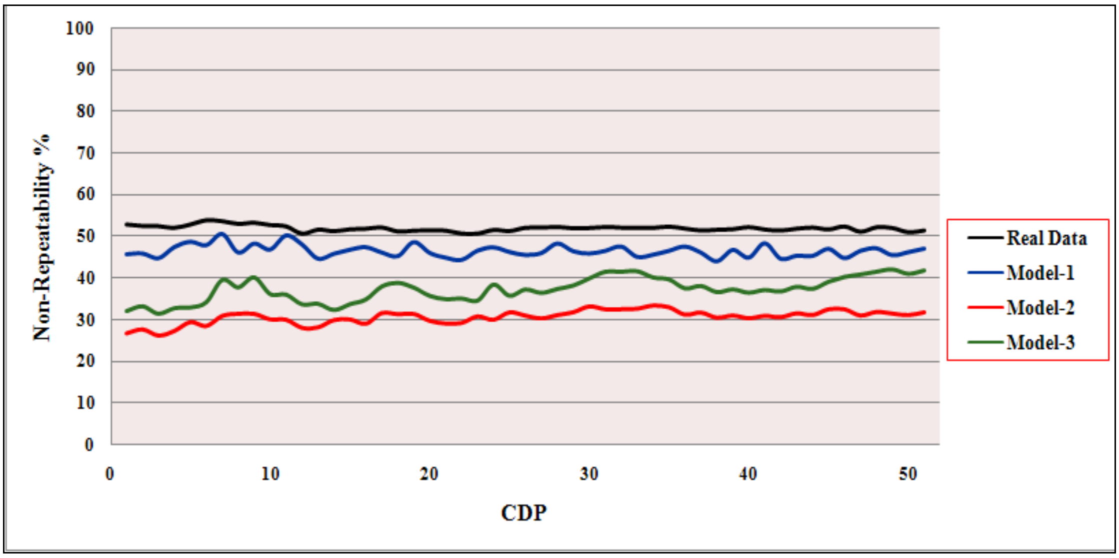


Figure 5.6: The non-repeatability curve computed for the wet and dry case for field data from a weight-drop source for a window of 40 ms around the Clifton Formation against the non-repeatability curves computed for three models across a range of traces and within the same window: The black line represents the non-repeatability for the wet and dry case using field data from a weight-drop source, blue line represents the non-repeatability for the wet and dry case for Model 1, green line represents the non-repeatability for wet and dry cases for Model 3 and the red line shows non-repeatability for Model 2.

Numerical tests suggest that the time-lapse seismic surveys should be conducted under the same near-surface conditions to maximise repeatability (this applies for both surface seismic and VSP). Changes in the water table can influence the seismic response through increased scattering by the corrugated interface at the top of the limestone. It appears that the effect of the weathered zone on the seismic signature can be split into two components:(1) a complex effect of the agricultural soil (elasto-plastic zone); and (2) the relatively simple scattering effect of the corrugated near-surface clay/limestone interface (purely elastic zone). The first is more difficult to simulate, hence the need for further field experiments. From our models we can conclude that: (1) 30% of non-repeatability comes from the change of the near-surface saturation; and (2) 15% of non-repeatability results from the scattering related to the corrugated surface of the limestone. An agreement between numerically predicted and measured NRMS values encourages further numerical tests and also field studies.

5.4 Micro-array based modelling

5.4.1 Introduction

To further improve simulation studies I needed to actually measure changes in the elastic properties of the near surface that were related to saturation. This was necessary because at Otway we expected a very subtle change in seismic response due to injected CO_2 at the Waarre C formation (Stage I). Therefore, before acquiring the base line seismic data and later interpreting the difference sections, it was important to understand the factors affecting seismic repeatability and its most likely magnitude.

5.4.2 Methodology

To analyse the 4D seismic effect due to the variation of elastic properties in the near surface layers during the wet and dry season at Naylor Field, I have designed my geological model scenarios of the Naylor Field and generated our synthetic seismic modelling with the advantages of the elastic finite-difference (FD) modelling. The acquisition geometry used in these modelling experiments was identical to the one deployed for the 2D seismic test surveys. 112 shots 10m apart were fired across 112 receivers. The size of the model was extended from each end of the model in Tesseral in order to avoid contamination due to imperfect absorbing boundaries. A Ricker wavelet was used in this modelling with dominant frequency of 100Hz. The recorded trace length in these experimental models was 3000ms with sample rate of 1ms (Table 3).

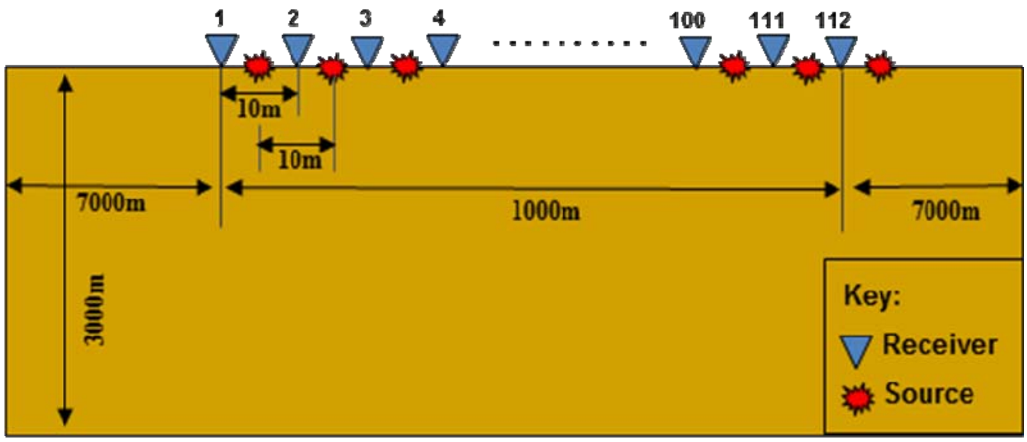


Figure 5.7: The acquisition geometry of the micro-array based prediction modelling.

Source dominant frequency	100 Hz
Signal	Ricker Wavelet
Spread	Continuous (112 channels)
Shooting Pattern	Shoot Through
Number of Sources	112
Number of Receivers	112
Receivers Spacing	10 m
Sources Spacing	10 m
Offset range, m	5-1115 m
Trace length	3000 ms
Sample rate	1 ms

Table 4: Parameters used for numerical modelling.

Wet Condition							
Top Name	**Top start at Depth (m)**	**Reflectivity**	**Thickness (m)**	**Density (kg/mc)**	**Interval Velocity[m/s]**	**Q**	**Qs**
Soil	**0**		**0.50**	**1787**	**405**	**21**	**15**
Clay-1	**0.5**	**0.3904**	**1.06**	**1981**	**814**	**26.4**	**22**
Clay-2	**1.5**	**0.2548**	**2.63**	**2169**	**1022**	**43.6**	**29**
Limestone	**4.2**	**0.4465**	**117.81**	**2430**	**1790.9**	**60.7**	**35**
Gellibrand Marl	**122**	**0.1360**	**335.00**	**2500**	**2289**	**80**	**48**
Clifton Formation	**457**	**0.1295**	**17.00**	**2700**	**2750**	**100**	**60**
Narrawartuk Marl	**474**	**-0.0938**	**76.50**	**2590**	**2375**	**120**	**75**
Mepunga Formation	**550.5**	**0.0174**	**118.50**	**2200**	**2895**	**130**	**85**
Dilwyn Formation	**669**	**-0.1248**	**209.00**	**2100**	**2360**	**140**	**95**
Pember Mudstone	**878**	**0.1720**	**60.50**	**2300**	**3050**	**150**	**105**
Pebble Point Formation	**938.5**	**0.0062**	**58.50**	**2230**	**3185**	**160**	**115**
Massacre Shale	**997**	**0.0577**	**27.00**	**2380**	**3350**	**170**	**125**
Timboon Sandstone	**1024**	**-0.0594**	**105.50**	**2280**	**3105**	**180**	**135**
Paaratte Formation	**1129.5**	**-0.0216**	**398.00**	**2350**	**2885**	**200**	**155**
Skull Creek Formation	**1527.5**	**0.0612**	**205.50**	**2410**	**3180**	**210**	**160**
Belfast Mudstone	**1733**	**0.0435**	**289.50**	**2470**	**3385**	**220**	**165**
Flaxmans Formation	**2022.5**	**0.0752**	**30.00**	**2500**	**3888**	**230**	**170**
Waarre C Formation	**2052.5**	**-0.0514**	**30.50**	**2340**	**3748**	**240**	**175**
Waarre B Formation	**2083**	**0.0589**	**17.00**	**2550**	**3870**	**250**	**180**
Waarre A Formation	**2100**	**-0.0796**	**39.00**	**2370**	**3550**	**260**	**185**
Eumeralla Formation	**2139**	**0.0980**		**2480**	**4130**	**270**	**190**

Table 5: Shows the thicknesses, top sub-surfaces, densities, velocities and absorptions (Q) for each formation of Otway Basin models at Naylor-1 during the wet condition of the near-surface.

I supposed that velocity (*v*), and attenuation (Q) can vary at the near surface during different seasons. While some reasonable assumptions can be made for changes in velocity due to saturation it is much harder to assume even initial Q values. This is where micro-array measurements can help.

Thus properties of the near surface from the micro-array survey that I acquired during different seasons (Chapter 4) were now used for further modelling. Detailed layer properties are given in Tables 5 and 6. Both velocities and attenuation are now changed to investigate the effects of the dry and wet season.

Dry Condition							
Top Name	**Top start at Depth (m)**	**Reflectivity**	**Thickness (m)**	**Density (kg/mc)**	**Interval Velocity[m/s]**	**Q**	**Qs**
Soil	**0**		**0.50**	**1351**	**320.8**	**14.7**	**12**
Clay-1	**0.5**	**0.3904**	**1.06**	**1609**	**614**	**20.4**	**15**
Clay-2	**1.5**	**0.2548**	**2.63**	**1704**	**977**	**40.7**	**25**
Limestone	**4.2**	**0.4465**	**117.81**	**2430**	**1790.9**	**60.7**	**35**
Gellibrand Marl	**122**	**0.1360**	**335.00**	**2500**	**2289**	**80**	**48**
Clifton Formation	**457**	**0.1295**	**17.00**	**2700**	**2750**	**100**	**60**
Narrawartuk Marl	**474**	**-0.0938**	**76.50**	**2590**	**2375**	**120**	**75**
Mepunga Formation	**550.5**	**0.0174**	**118.50**	**2200**	**2895**	**130**	**85**
Dilwyn Formation	**669**	**-0.1248**	**209.00**	**2100**	**2360**	**140**	**95**
Pember Mudstone	**878**	**0.1720**	**60.50**	**2300**	**3050**	**150**	**105**
Pebble Point Formation	**938.5**	**0.0062**	**58.50**	**2230**	**3185**	**160**	**115**
Massacre Shale	**997**	**0.0577**	**27.00**	**2380**	**3350**	**170**	**125**
Timboon Sandstone	**1024**	**-0.0594**	**105.50**	**2280**	**3105**	**180**	**135**
Paaratte Formation	**1129.5**	**-0.0216**	**398.00**	**2350**	**2885**	**200**	**155**
Skull Creek Formation	**1527.5**	**0.0612**	**205.50**	**2410**	**3180**	**210**	**160**
Belfast Mudstone	**1733**	**0.0435**	**289.50**	**2470**	**3385**	**220**	**165**
Flaxmans Formation	**2022.5**	**0.0752**	**30.00**	**2500**	**3888**	**230**	**170**
Waarre C Formation	**2052.5**	**-0.0514**	**30.50**	**2340**	**3748**	**240**	**175**
Waarre B Formation	**2083**	**0.0589**	**17.00**	**2550**	**3870**	**250**	**180**
Waarre A Formation	**2100**	**-0.0796**	**39.00**	**2370**	**3550**	**260**	**185**
Eumeralla Formation	**2139**	**0.0980**		**2480**	**4130**	**270**	**190**

Table 6: Shows the thicknesses, top sub-surfaces, densities, velocities and absorptions (Q) for each formation of Otway Basin models at Naylor-1 during the dry condition of the near-surface.

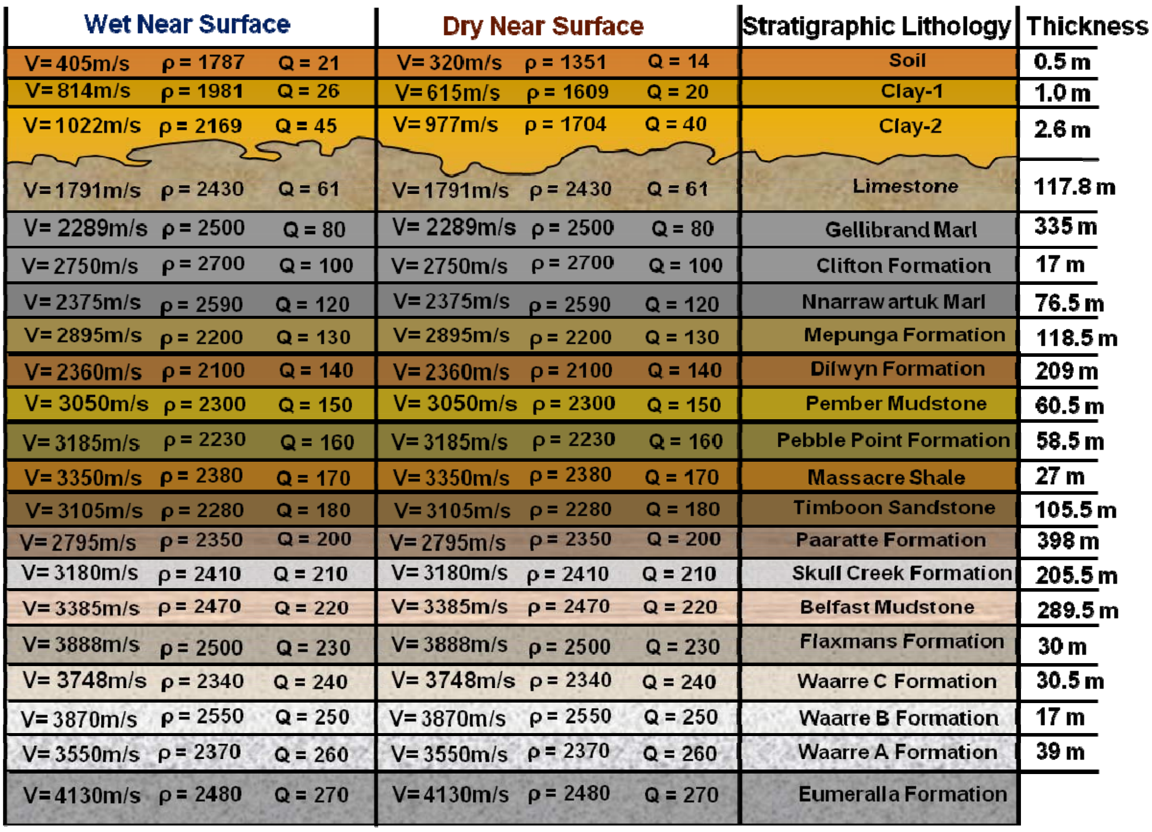


Figure 5.8: Schematic geological profile for the Naylor site. Elastic parameter changes are introduced for the first three near-surface layers. The lateral distance used for this model is 5000m.

5.4.3 Analysis and results of the micro-array based modelling

I generated pre-stack synthetic seismic data representative of wet and dry seasons. Figure 5.9 shows the pre-stack synthetic seismic data for shot gather number 1 from the seismic line using properties given in Tables 5 and 6. From the shot gather for the wet period both the refraction and reflection data are of higher amplitudes compared to the dry near-surface model. Also note that ground-roll for the wet near-surface model arrived earlier compared to the dry near-surface model. Therefore, processing these two land seismic data sets may not be straightforward as for example noise artefacts after multi-channel filtering can be different for the two sets. Finally, I observe that the S/N ratio for the wet near-surface model is higher than for the dry.

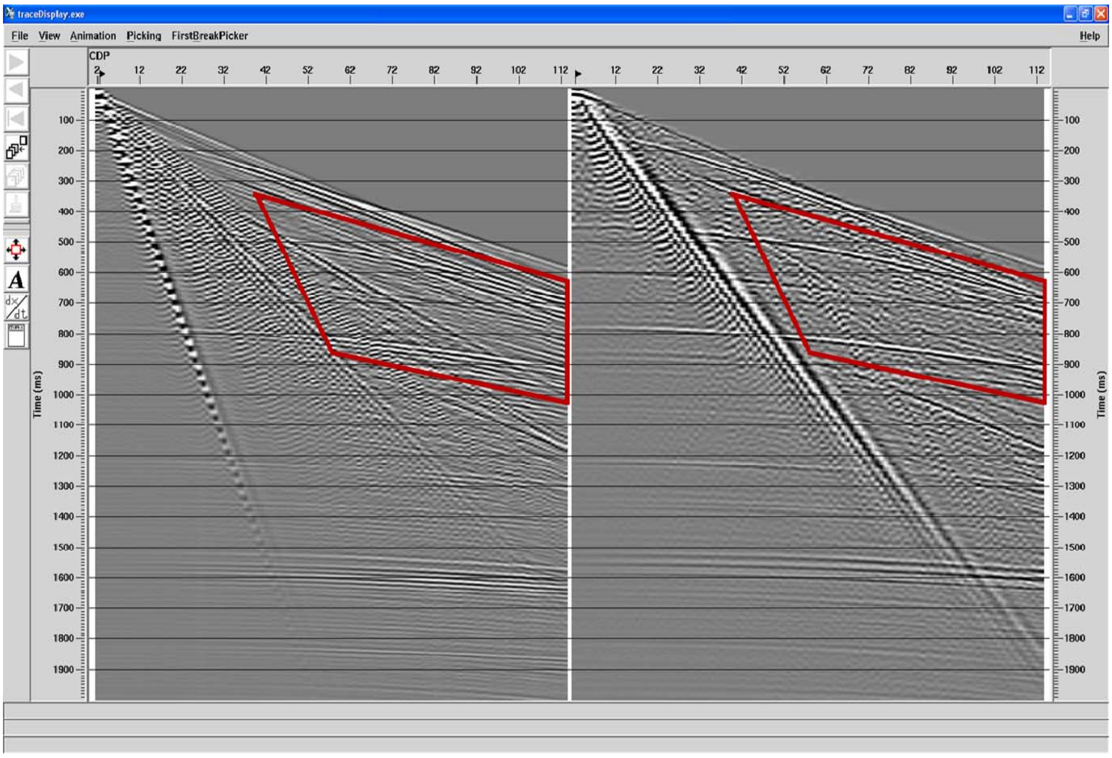


Figure 5.9: Synthetic seismic shot gathers for dry (left), wet (right) near-surface conditions. Dry near-surface data shows higher attenuation and lower S/N ratio.

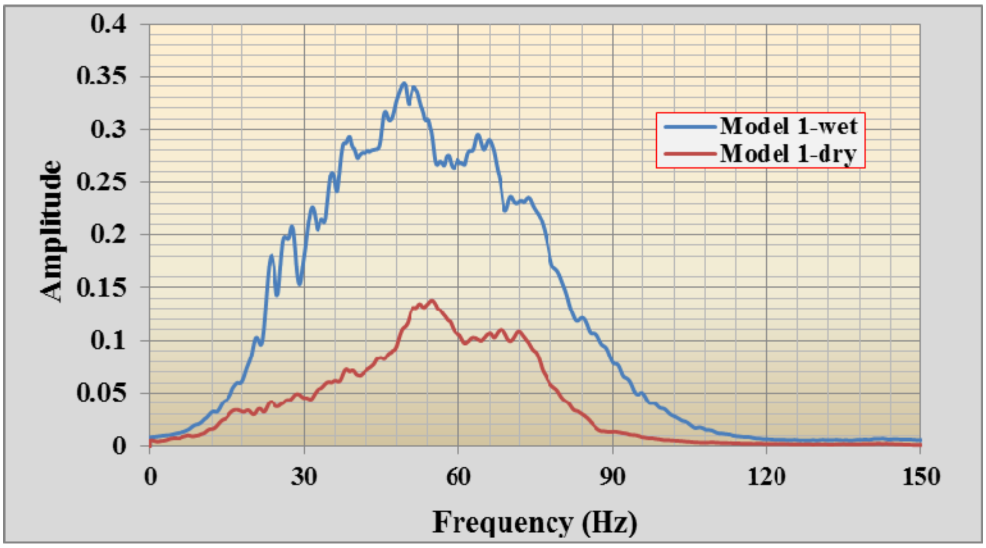


Figure 5.10: Amplitude spectra of reflection data for the selected red window of the seismic data in Figure 5.9 for data from both wet and dry models.

Comparing the amplitude spectra for wet and dry near-surface modelling data for the selected red seismic window in Figure 5.9 confirm higher S/N ratio and higher energy in general (Figure 5.10 and Figure 5.11).

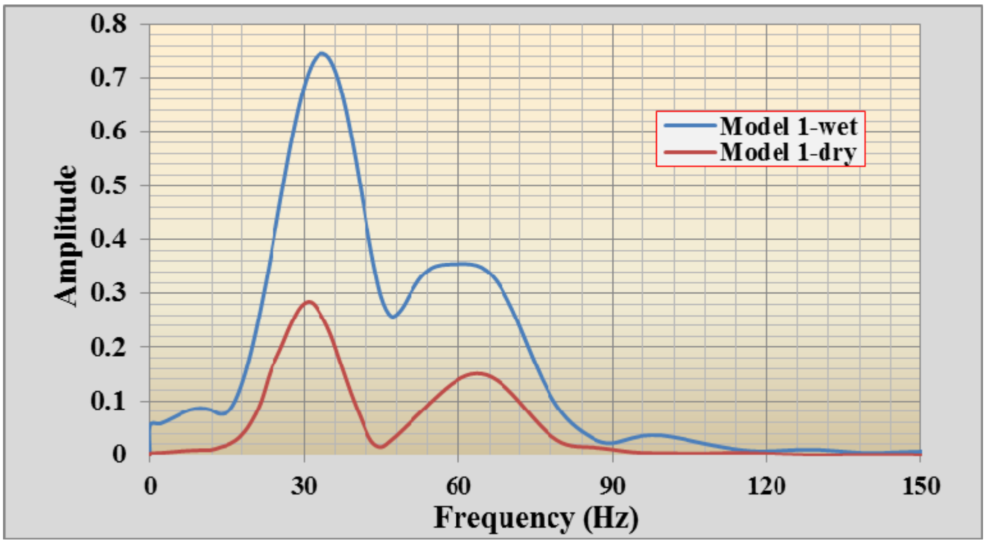


Figure 5.11: Amplitude spectra around the Waarre C Formation for the seismic window 1500-1700ms in Figure 5.9 for data from both wet and dry models.

The simulated pre-stack seismic data sets were processed using the same processing flow and parameters to eliminate any differences of the 4D effect caused by the processing and to measure the effect that could only be caused by the change of the near-surface properties during different seasons. The amplitude spectra of the three different selected horizons at three different depths for the above seismic stack in Figure 5.12 were measured as part of the 4D study to compare the two models during wet and dry near-surface conditions. The amplitude spectrum of the Dilwyn Formation was measured for a seismic window of 200ms (500-700ms) around the Dilwyn Formation horizon for the wet and dry near-surface conditions (Figure 5.13). The amplitude spectrum of Skull Creek and the Waarre C Formations were measured for a seismic window of 50ms (1200-1250ms for Skull Creek Formation and 1500-1550 for the Waarre C Formation) around both horizons for the wet and dry near-surface conditions (Figure 5.14 and Figure 5.15).

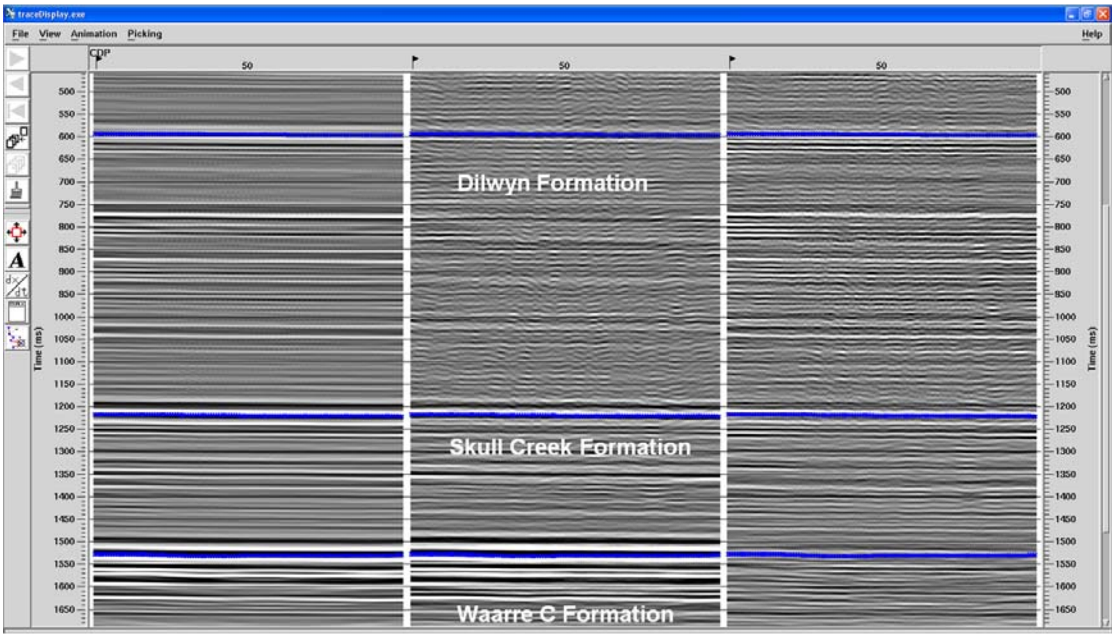


Figure 5.12: Synthetic seismic stack data for wet (left), dry (middle) near-surface conditions and their differences (right). Three different formations were marked for 4D studies.

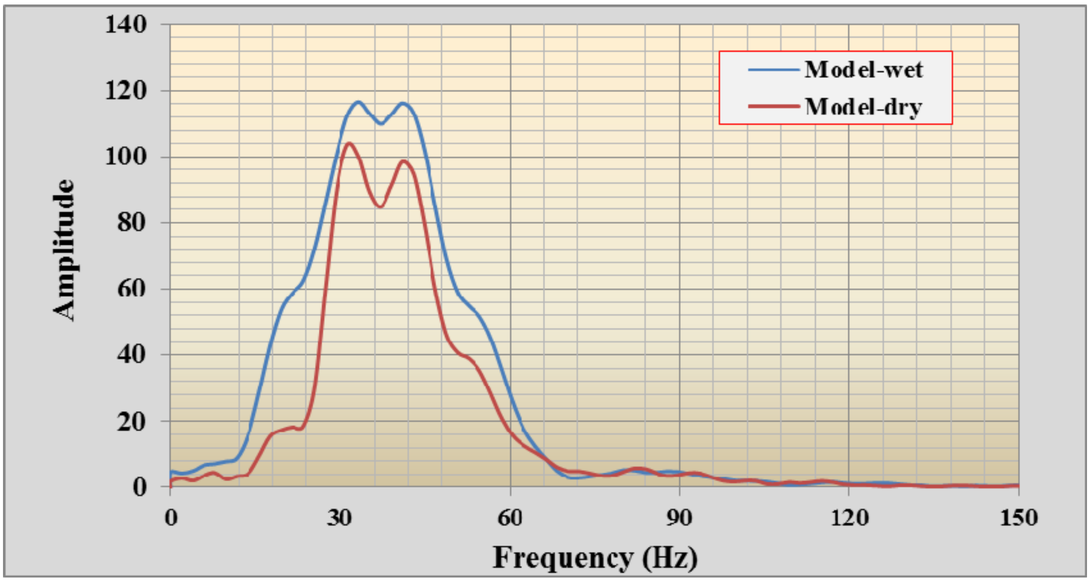


Figure 5.13: Amplitude spectra around the Dilwyn Formation for the seismic window of 200ms (500-700ms) in Figure 5.12 for data from both wet and dry models.

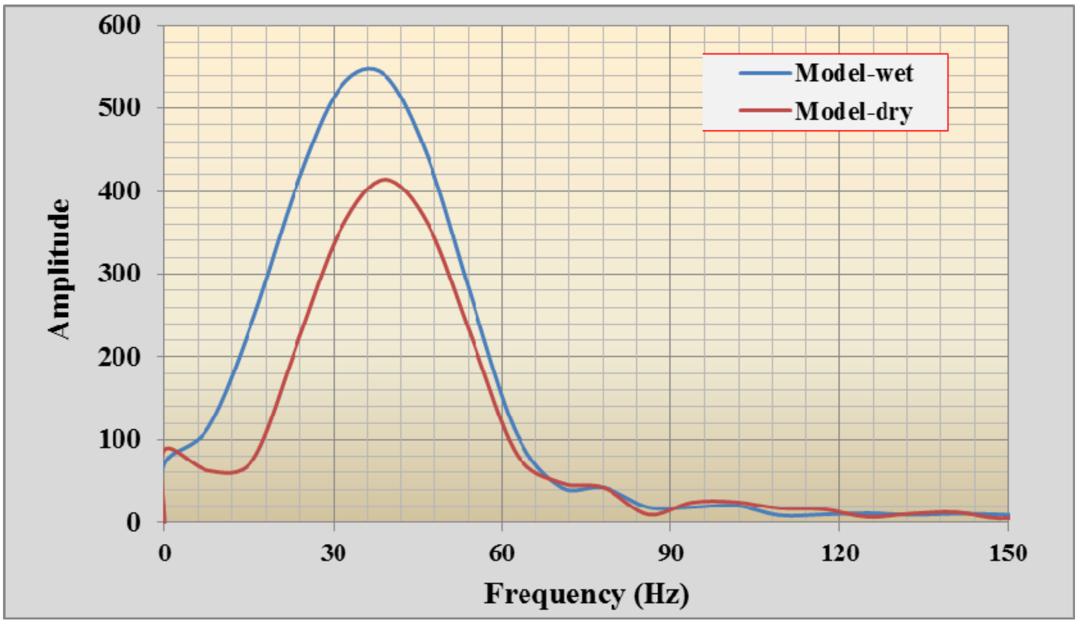


Figure 5.14: Amplitude spectra around the Skull Creek Formation for the seismic window of 50ms (1200-1250ms) in Figure 5.12 for data from both wet and dry models.

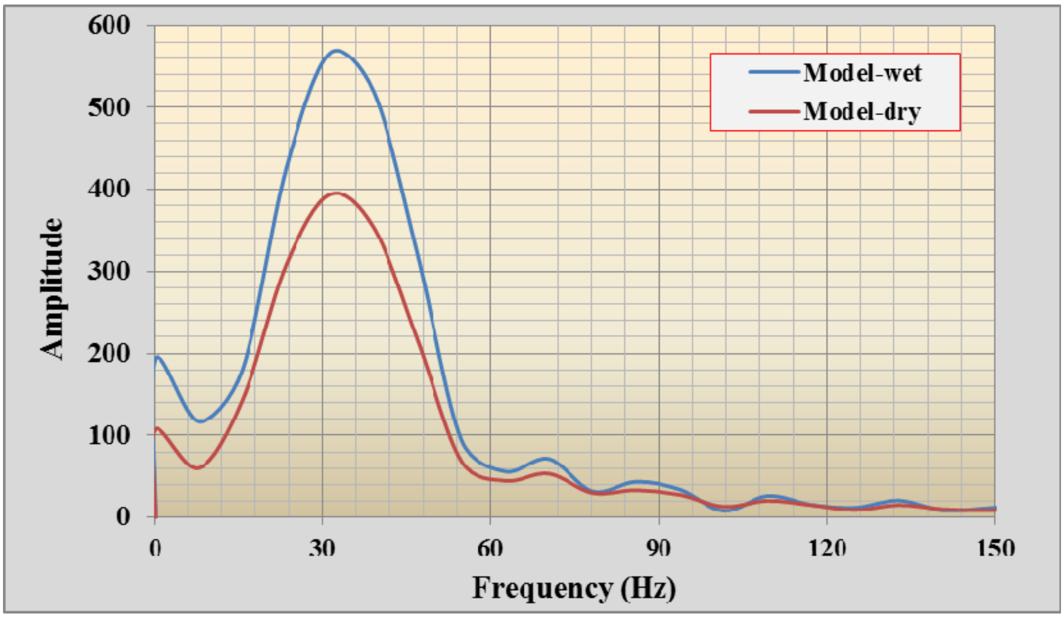


Figure 5.15: Amplitude spectra around the Waarre C Formation for the seismic window of 50ms (1500-1550ms) in Figure 5.12 for data from both wet and dry models.

The NRMS difference was also measured for a seismic window of 40ms around each horizon for data from both wet and dry models using Skull Creek (Figure 5.12) horizons. The NRMS results from these three different horizons show that there is 30-35% of non-repeatability due to variations in the near surface properties during different seasons (Figure 5.16).

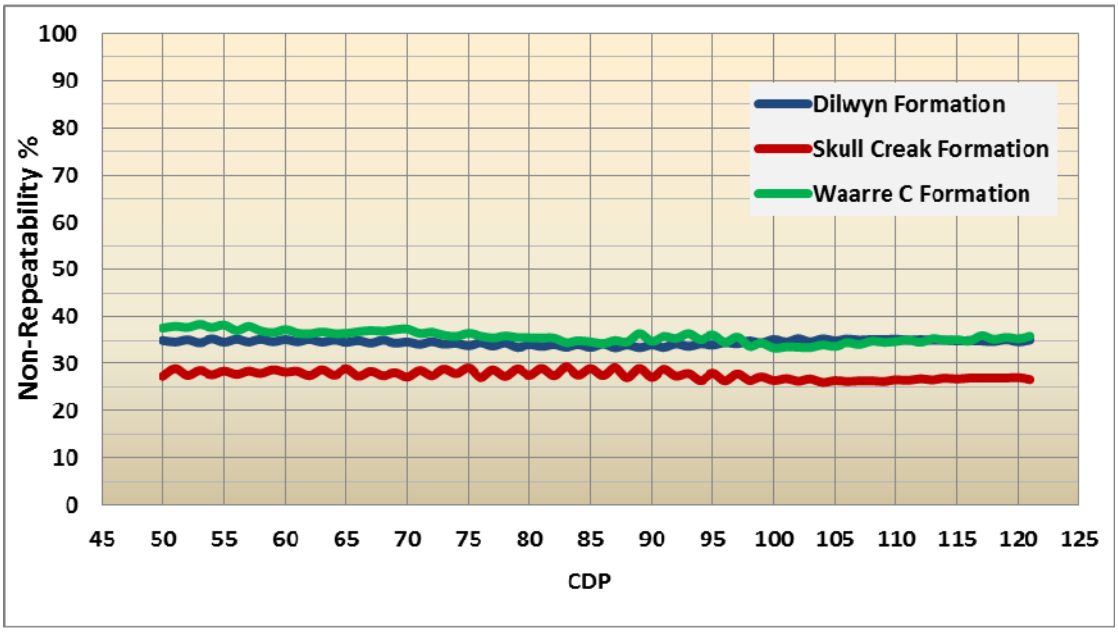


Figure 5.16: The NRMS difference between wet and dry near surface conditions in the Naylor Field models, measured at three different horizons for a seismic window of 40ms around each horizon in Figure 5.12 for both wet and dry models data using Skull Creek horizon from wet season data as a reference for cross equalisation between these different data sets.

These changes are purely caused by the seasonal changes in soil saturation and water table level. The NRMS difference was measured for a seismic window of 40ms around the horizon which represent the top of Clifton Formation. It is obvious that the S/N ratio and hence repeatability increases with reflectivity. The Top Clifton Formation is the brighter horizon and thus has a high S/N ratio. Measuring the amplitude spectra of the seismic horizon with high S/N ratio such at the top of the Clifton Formation provides an end member (best case) for 4D signal prediction. The amplitude spectra were also measured around this horizon at two different seismic windows 100ms and 30ms (Figure 5.17).

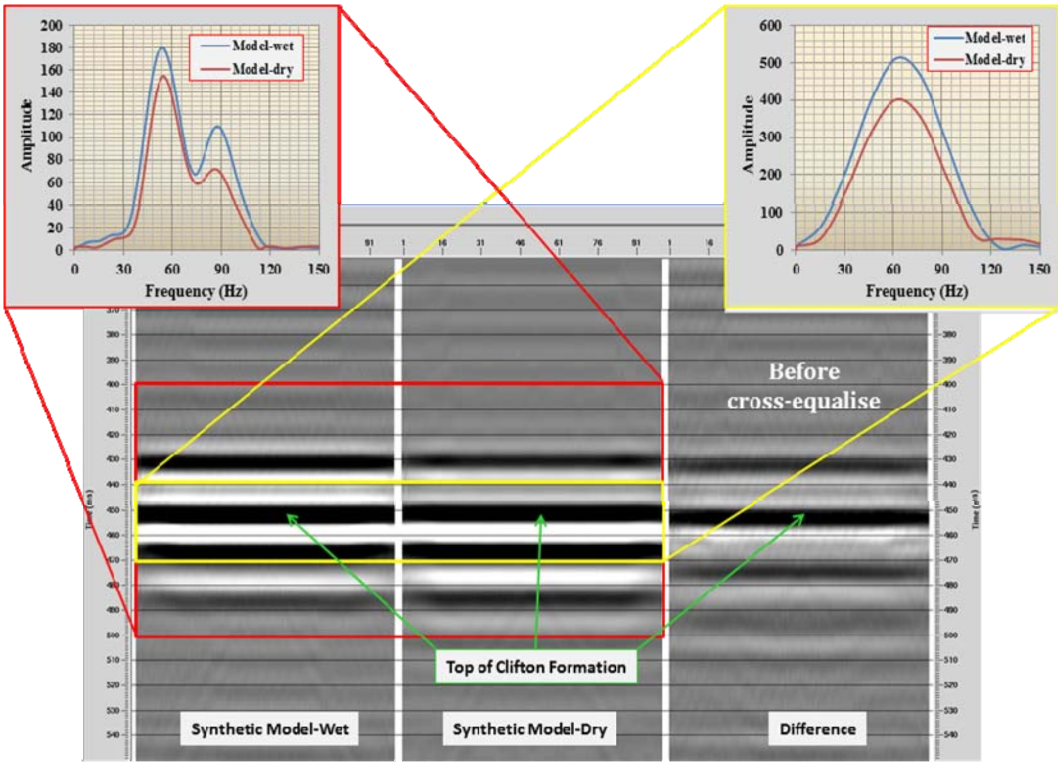


Figure 5.17: Synthetic seismograms for dry (left), wet (middle) near-surface conditions and their differences (right). A non-repeatability curve computed for wet and dry cases using a window of 40 ms around the Clifton Formation is shown on this figure.

I have also measured the NRMS difference for the top of the Clifton Formation for wet and dry near surface which shows that the RMS amplitude difference is about 30% (Figure 5.18).

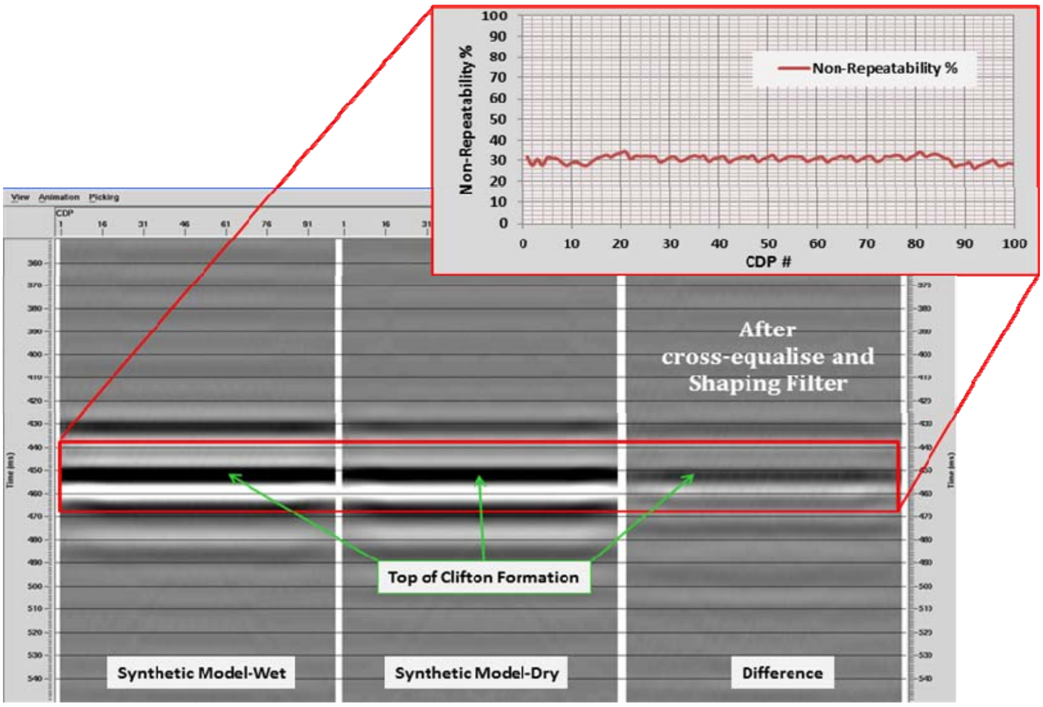


Figure 5.18: Synthetic seismograms for dry (left), wet (middle) near-surface conditions and their differences (right). A non-repeatability curve computed for wet and dry cases using a window of 40 ms around the Clifton Formation is shown on the top of this figure.

5.5 Chapter Summary

This study utilised repeated numerical tests to understand and forecast the effects of variable near surface conditions on time-lapse seismic surveys. The numerical tests were aimed at reproducing the scattering related to changes in the near surface. The first initial seismic modelling data show that the relatively simple scattering effect of the corrugated near surface clay/limestone interface can have profound effect on time-lapse surveys. Modelling the variation in elastic properties of near surface layers during different seasons and having the same elastic properties for the reservoir at Naylor Field can yield insight into the significance and reliability of 4D attributes.

Incorporating field measurements of near surface properties into the numerical modelling enable further refinement of the results and, I believe, a more realistic estimate of repeatability level at the Naylor site. These significant differences in the 4D signal are likely to be dominated by soil saturation changes. This modelling study proves that the elastic properties of the near surface layers are important and cannot be automatically excluded from 4D studies. I expect that soil saturation changes can be much larger in other locations where we could have very competent rock overlain by a slow weathered zone. Then the time-lapse effect caused by the changes in the elastic properties of the near surface layers could be larger than the seismic time-lapse effect in the reservoir. For Naylor Field, the data acquired in different seasons is likely to differ and moreover the difference will exceed the tiny signal coming from CO2 injection into the Waarre C reservoir. It is, hence, recommended that the repeatability at any monitoring site be predicted before injection, that is, at the baseline level. Around 30% of RMS amplitude difference was measured at the reservoir level that originates from changes in the near surface conditions. Therefore, the residual differences in the repeated time-lapse data that do not represent changes in the subsurface geology impact on the effectiveness of the time-lapse seismic methodology. I also observe that numerical modelling results closely match field data results. Therefore, numerical modelling experiments that incorporate near surface investigations could be used as a tool for prediction of repeatability at any site and help to better design time-lapse surveys.

Chapter 6 : Land seismic repeatability tests versus micro-array based prediction

In this chapter I have analysed seismic repeatability with different seismic sources and at different near surface conditions then compared the data with micro-array based predictions.

6.1 Introduction

A feasibility study, onshore Otway Basin, Australia, aims at evaluating the viability of CO_2 storage into a depleted gas field. Of particular interest for this study is the assessment of monitoring methodologies: injection of CO_2 is expected to cause very subtle changes in the elastic properties of the reservoir rock. Such conditions present a serious challenge for the application of time-lapse seismic monitoring technologies. However, poor repeatability caused by significant changes in weathering properties (ground saturation level, variations in the composition of the near surface) and ambient noise (wind, machinery at work) could easily overcome predicted 4D seismic response changes (~5%) caused by CO_2 injection (Li et al., 2005). The gas that was injected into Naylor Field for the CO_2 sequestration project is a mixture of 80% CO_2 and 20% CH_4. This project currently consists of two stages with the first stage largely completed by January 2010. During phase I of the program, around 70,000 tonnes of a CO_2-CH_4 (80%-20%) gas mix was injected into a depleted gas reservoir at a depth of 2025 meters Waarre C Sandstone Formation). Gas has been injected at a rate of around 4000 tonnes per month since March, 2008. During phase II, the gas-mixture was injected into a saline aquifer at a depth of around 1400-1600 m, above phase I. Phase II could have several stages at various depths in the shallower aquifer reservoir (Paaratte Formation). Consequently we expect that the injection of a gas mixture will produce very subtle changes of the elastic properties of the reservoir rock for the stage one and hence hardly measurable 4D seismic effects. High seismic repeatability is therefore of critical importance to the monitoring at this field. Repeated 2D seismic test lines have been acquired at the Naylor location prior to the 3D baseline seismic from 2006-2008. These seismic lines were recorded with Mini-Vibroseis and weight-drop sources in both wet and dry conditions. The aim of this work was to assess non-repeatability due to the source type change and variations in soil conditions (Urosevic et al., 2007 and 2008).

6.2 Seismic sources

Selecting appropriate seismic sources to achieve our objectives is crucial and important for the S/N ratio, resolution, penetration and repeatability. In reality the choice is however often dependent on the local conditions: permission, inability to clear, footprint, etc. Explosives for examples are high-energy and high-bandwidth seismic sources but permission and expensive drilling operations make these sources unsuitable in some cases. For example, explosive charges were used in the Otway Basin Pilot Project for regular recording of the High Travel Time Resolution (HTTR) surveys (CO2CRC, 2010).

Several studies have dealt with various aspects of sources, for example, site dependence and environmental conditions, energy and frequency content, signal-to-noise ratio, source wavelet, repeatability, portability, efficiency and finally the economics. The energy and frequency content required from a seismic source depends on many factors, such as the depth of the target and its thickness (Knapp and Steeples, 1986). Selecting seismic sources that are capable of generating adequate broad bandwidth is important since the seismic resolution depends on the dominant frequency of the signal. The energy of a seismic wave can be quantified by the energy density (energy per unit volume), which is proportional to the square of the amplitude within the same medium (Sheriff, 1975; Telford et al., 1990). The main issue is that seismic attenuation increases exponentially with the increasing frequency of the seismic signal and decreasing quality factor (Q) of the probed medium (Buhnemann and Holliger, 1998).

Even if there are no substantial differences in frequency content, the source can significantly influence the signal-to-noise ratio (Feroci et al., 2000). Air blasts and source generated noise, especially noise due to the coupling effect of impact sources, can be so large in amplitude that they contaminate all the reflections on near offset traces. In areas where random noise dominates, vertical stacking improves the signal-to-noise ratio if the source is repeatable. However, if the noise is due to source coupling, then vertical stacking will not yield any improvements.

Four seismic sources were tested in the pilot study at Naylor Field for the CO2 Sequestration Project; an accelerated weight drop, a Mini-Vibroseis, a VIBSIST source and Mini-Buggy (Figure 6.1). The Mini-Vibroseis (Figure 6.1A) and Mini-Buggy (Figure 6.1C) use a swept frequency signal (sweep) that changes frequency at constant amplitude from a low limit f_1 to a high limit f_2 over a period of seconds. A linear sweep of 10–150 Hz was used for the data presented here. The coupling of the vibrator to the ground introduces limitations at the high end of the sweep frequency. After acquisition, the field records were cross-correlated with a reference signal (the measured pilot sweep). The correlation process using the sweep yields, in theory, a zero phase wavelet. However, in practice the correlated signal is mixed phase due to sweep specifications, vibrator imperfections and ground coupling.

VIBSIST sources have been developed over the past decade and are based on the Swept Impact Seismic Technique (Park et al., 1996) which is a combination of the Vibroseis swept frequency and the Mini-Vibroseis (Barbier et al., 1976) multi-impact methods (Figure 6.1B). A few to several hundred seismic pulses are generated according to a pre-set monotonic impact sequence in which the impact rate either increases linearly with time (upsweep) or decreases with time (downsweep).

A concrete breaker was used here to replace the weight drop (Figure 6.1D). The momentum at impact, size (mass) of the base plate and near surface conditions influence the amplitude and frequency content of the signal. Since the energy of this source is relatively low and uncontrollable, it may not be a favourable “time-lapse seismic source”. However, in favourable ground conditions, vertical stacking can increase energy without lengthening the wavelet. To improve repeatability, the ground below the base plate should be compacted before production recording begins to reduce the amount of plastic deformation which is often very high for the first impact. The source is controlled by a trigger sensor mounted on the base plate that transmits the trigger pulse to the recording system by radio link.

Figure 6.1: The seismic sources used in the 2D seismic test line of the Otway Pilot Project at Naylor Field. A) IVI Mini-Vibroseis source, B) VIBSIST source, C) IVI Mini-Buggy source, D) Weight-drop source.

A unique set of repeated 2D trial surveys was collected over three years (2006-2008) within the CO2CRC Otway Basin Pilot Project scientific program. This comprised of six repeated 2D seismic lines collected with the same geometry and acquisition system. Data were acquired during different times of the year (water table and soil saturation varied) and with different sources (several different weight-drop energies and vibrators). This comprises an interesting data set for examination of repeatability. I have studied the following seismic data:

Source	Time	Recorded during
Mini-Vibroseis	June 2006	Wet Season
Mini-Vibroseis	March 2007	Dry season
Weight drop (free-fall 5kJ)	July 2007	Wet Season
Weight drop (free-fall 5kJ)	November 2008	Dry season
VIBSIST (rock breaker)	July 2007	Wet Season
Mini-Buggy	November 2008	Dry season

Table 7: 2D seismic test lines acquired along Soda's Road at different times and their near surface condition using different seismic sources at the Otway Basin Pilot Project study

6.3 Data Acquisition

Receiver and source points were located at the same position (source points between receiver points) along the same line for all surveys. The record length of weight drops was 3 seconds while for VIBSIST (Rock Breaker) was 2.5 s (3 s after shift and stack procedure)., Mini-Vibroseis and Mini-Buggy (MB) surveys were recorded with a 10-120 Hz liner 12 s sweep and a 3 s listen time. The average fold of this 2D data in the central part of the line is greater than 80. The shooting pattern in these surveys was "shoots-through steady receiver line". The receiver and source spacing were 10m for all lines acquired (Figure 6.2). Single receiver L-40A Mark Products 10 Hz geophones with 10 cm spikes were used for these tests. I have processed all the lines using only the first 112 channels and sources to cover the reservoir zone and make survey geometries identical.

The first data set was collected in June 2006 using Mini-Vibroseis (6000 lb) during the rainy season (damp ground). The same survey was repeated in March 2007 using Mini-Vibroseis and weight drop as seismic sources when the near surface condition was dry. The survey was repeated again in July 2007 and involved weight drop and VIBSIST as seismic sources. The ground was fully saturated. Finally the last 2D survey took place during November 2008 when the near surface was dry. Weight-drop and Mini-Buggy sources were this time concurrently recorded and then compared. Ground hardness differed from survey to survey mainly as function of soil saturation as did the foot print (Figure 6.3).

	Test 1	Test 2	Test 3	Test 4	Test 5	Test 6
Source Type	Mini-Vibrator (6000 lb)	Mini-Vibrator (6000 lb)	Weight-Drop (1650 lb)	Vibsist (1650 lb)	Weight-Drop (1650 lb)	Mini-Buggy
Acquisition Date	June 2006	March 2007	July 2007	July 2007	November 2008	November 2008
Ground Conditions	Wet	Dry	Wet	Wet	Dry	Dry
Spread	Continuous (120 channels)	Continuous (156 channels)	Continuous (162 channels)	Continuous (162 channels)	Continuous (156 channels)	Continuous (156 channels)
Shooting Pattern	Shoot Through	Shoot Through	Shoot Through	Shoot Through	Shoot Through	Shoot Through
Total Number of Sources	120	156	158	158	156	156
Total Number of Receivers	120	156	162	162	156	156
Sources and Receivers Positioning	10m/10m	10m/10m	10m/10m	10m/10m	10m/10m	10m/10m
Offset range, m	5-1105	5-1555	5-1605	5-1605	5-1555	5-1555
Weather Conditions	Patchy Rain, Windy	Windy (moderate)	Patchy Rain, Windy	Patchy Rain, Windy	Windy (dry)	Windy (dry)
Reference Character	MV-06-Wet	MV-07-Dry	WD-07-Wet	VS-07-Wet	WD-08-Dry	MB-08-Dry

Table 8: Acquisition parameters of all different 2D seismic test lines at the Otway Basin Pilot Project.

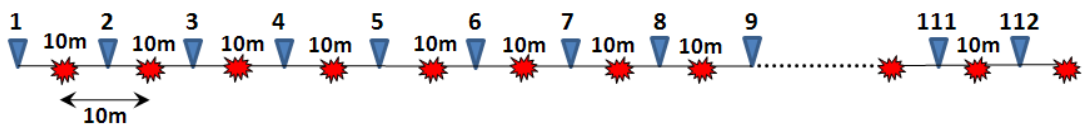


Figure 6.2: The 2D seismic test line geometry.

A summary of all tests in terms of sources used and the resulting quality of field records is shown in Figure 6.4. At glance, it is clear that the sources compared differ in the total energy generated and also in the distribution of surface waves, that is, the ratio of primary versus coherent noise. The same ratio varies with soil saturation for the same source type.

Figure 6.3: Source footprint for the March 2007 and July 2007 surveys.

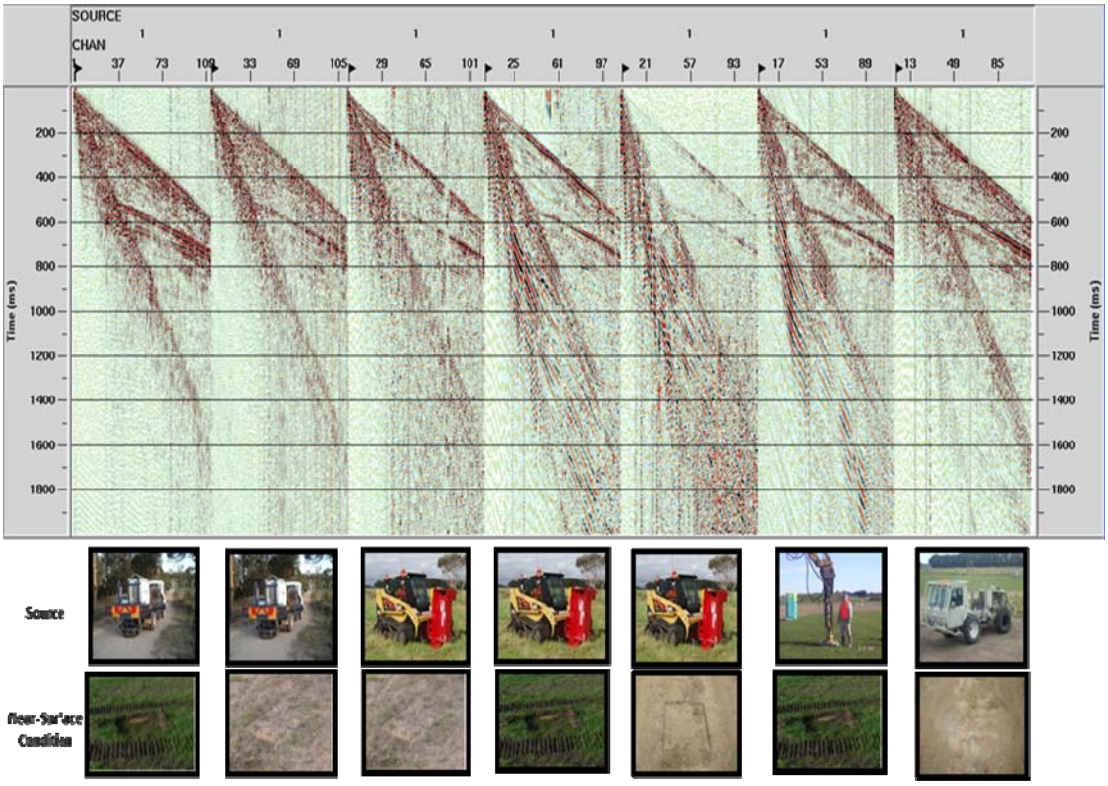


Figure 6.4: The first shot gather of the seven repeated 2D seismic test lines which were acquired at the same place using different seismic sources and during different near-surface conditions.

The overall variation in the signal-to-noise ratio across the surveys can be seen even more clearly in Figure 6.5. The differences in the source-generated noise pattern are particularly significant. Most of the difference can be related to the source type, and to some extent, the ground conditions (dry and wet periods). In general, the level of ambient noise and intensity of the ground roll is much higher for data acquired with the weight-drop source. This can be attributed to a varying plastic-to-elastic energy ratio generated by a weight-drop source. This ratio varies significantly with soil saturation (Figures 6.3, 6.4 and 6.5). For vibroseis, the component of plastic deformation of the ground at the plate contact is much smaller compared to weight drop. Of course the penetration and frequency content can be controlled to a large extent with vibroseis by changing the sweep length and the percentage of the peak force.

Analysis of the data indicated that factors other than the degree of source and receiver coupling varied between surveys and also along the line for the same survey. I have analysed the following data sets:

1. IVI Mini-Vibroseis (MV) source data collected during June 2006 when the near-surface condition is wet
2. IVI Mini-Vibroseis (MV) source data collected during March 2007 when the near-surface condition is dry
3. Weight-drop (WD) source data collected during July 2007 when the near-surface condition is wet
4. Weight-drop (WD) source data collected during November 2008 when the near-surface condition is dry
5. VibSIST (VS) source data collected during July 2007 when the near-surface condition is wet
6. IVI Mini-Buggy (MB) source data collected during November 2008 when the near-surface condition is dry

Mini-Vibroseis data acquired in June 2006 provided better signal/noise ratio than the Mini-Vibroseis data acquired in March 2007 (Figure 6.6). This can only be explained by a difference in the saturation level of the near surface and respective source/receiver coupling. Similar arguments can be used for repeated weight-drop surveys in wet and dry periods (Figure 6.6). In addition, weight-drop data left a bigger footprint (plastic deformation higher in wet season).

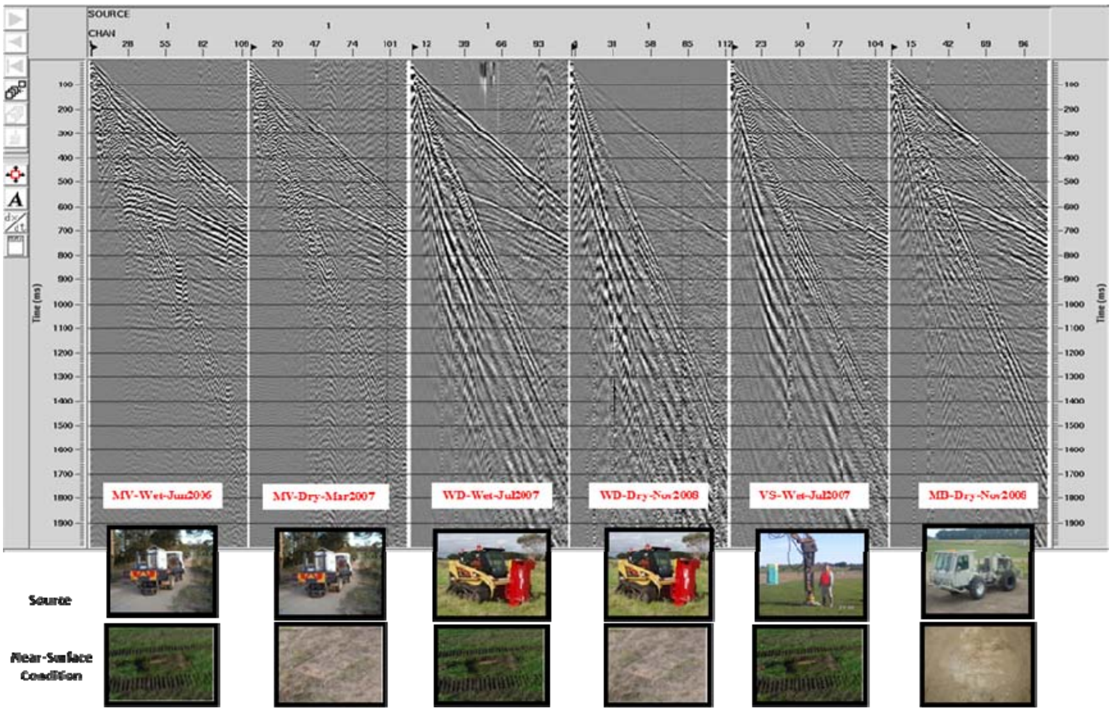


Figure 6.5: The first shot gather of the six selected repeated 2D seismic test lines acquired at the same place using different seismic sources and during different near-surface conditions.

Comparing two (Mini-Buggy) vibroseis surveys in 2008 with a Mini-Vibroseis survey acquired in 2007 it is clear that Mini-Buggy (MB) as a stronger source provided superior S/N ratio. However, Mini-Vibroseis performed better than weight drop in both wet and dry near-surface conditions.

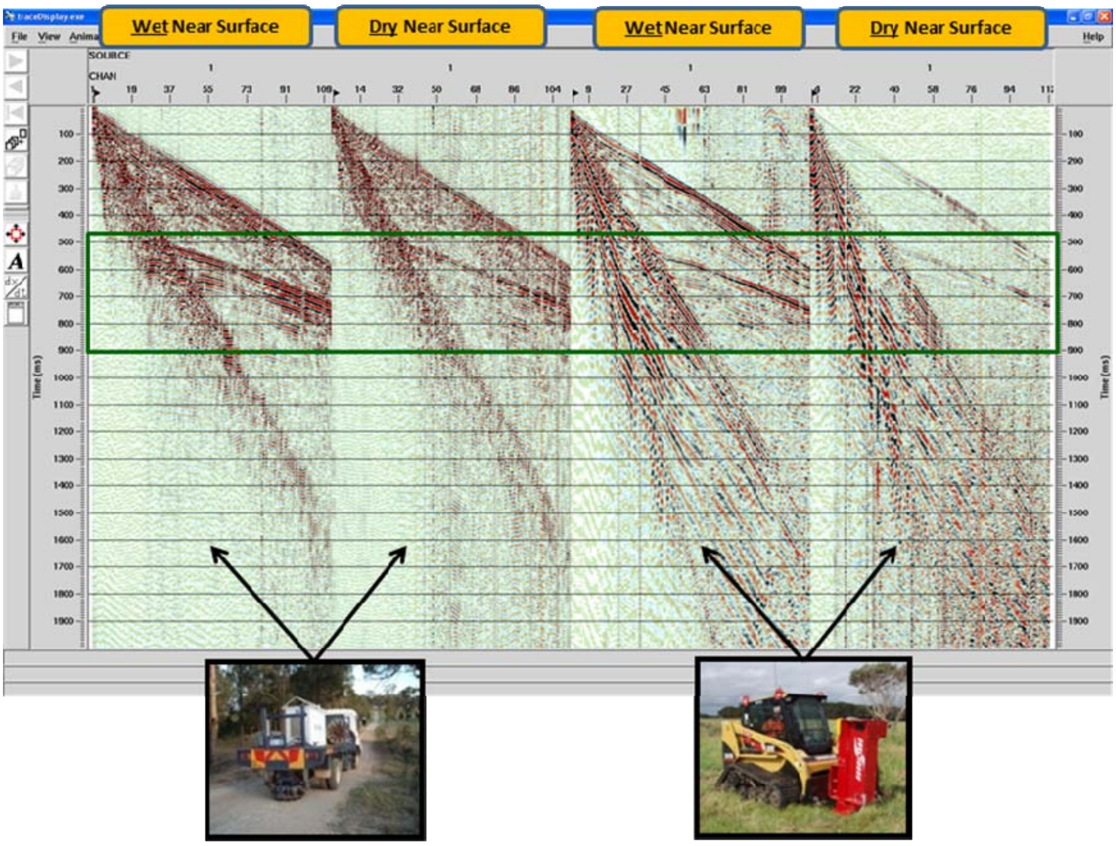


Figure 6.6: Comparison between the first shot gathers of the Mini-Vibroseis and weight drop during both wet and dry condition of the near surface.

Resolution naturally decreases with depth due to attenuation preferentially removing the higher frequencies in the propagating seismic waves (Praeg, 2003). The low frequency end of the spectrum is attenuated primarily by the frequency response of the geophone and field record filtering, while the decrease at the high end of the spectrum is mainly due to propagation through the earth. Therefore, a comparison of relative amplitude decay curves from the three sources in different frequency bands may give an indication of which frequency band gives the best penetration for a given source. It should be also said that ambient noise at Otway site can be significant due to a strong and variable wind factor, farmer’s activities, electric fences, etc.

6.4 Data Processing

All the data sets were reduced to common acquisition geometry and recording parameters by choosing the same number of active channels and sampling rate (Table 8). Processing of the data was performed with ProMax^{TM}. I tried to use similar amplitude-preserving processing flows for all three datasets, however it was found to be impossible to use exactly the same flows. There are two main reasons for this. First, variation in near surface conditions required slightly different stacking velocities (seasonal variation). Second, changes in near surface conditions and/or properties of the source affected properties of the coherent noise, such as ground roll. Variations in the near surface ground saturation produced coherent noise patterns of variable intensity. Relative amplitudes between surveys were preserved through the application of a single time-varying gain function.

For the time-lapse seismic analysis, I have used Pro4D tools from the Hampson-Russell software package to cross-equalise the data. At first post-stack static shifts were computed by cross-correlation between corresponding pairs of traces. Computed time shifts demonstrate a much higher consistency in the surveys acquired during 2008 than in surveys acquired across two years. Note that unmigrated data are analysed to avoid migration artefacts due to short line length (~1200 m). After that, a single matching filter (Wiener) was designed for each pair of surveys by averaging across the filters computed for each pair of corresponding traces from the two surveys. The filter length was 100 samples with 0.1% of white noise being added. Data sets having wider spectral bandwidth were “degraded” to fit the bandwidth of the poorer quality set. The lowest data quality and narrowest bandwidth are observed for the weight-drop data acquired in 2008 (dry season). The final energy normalisation was accomplished by deriving a single scalar computed over 400-1100 ms window.

6.5 Assessing the repeatability of Post-Stack 2D Seismic data

The data from the repeated test lines were processed using the same processing flow and then as cross equalised with Mini-Buggy data since this has the highest S/N ratio among these repeated 2D test lines.

The Mini-Buggy and Mini-Vibroseis data show the highest peak amplitude in the first arrival time window; whereas the amplitudes of the VIBSIST and weight-drop data are lower, suggesting that the Mini-Buggy and Mini-Vibroseis are putting the largest amount of energy into the ground. In case of VIBSIST however it is more likely that the shift and stack procedure used in the field was not appropriate. Given potential issues with VIBSIST, the Mini-Buggy source has the greatest penetration and frequency compared to other sources.

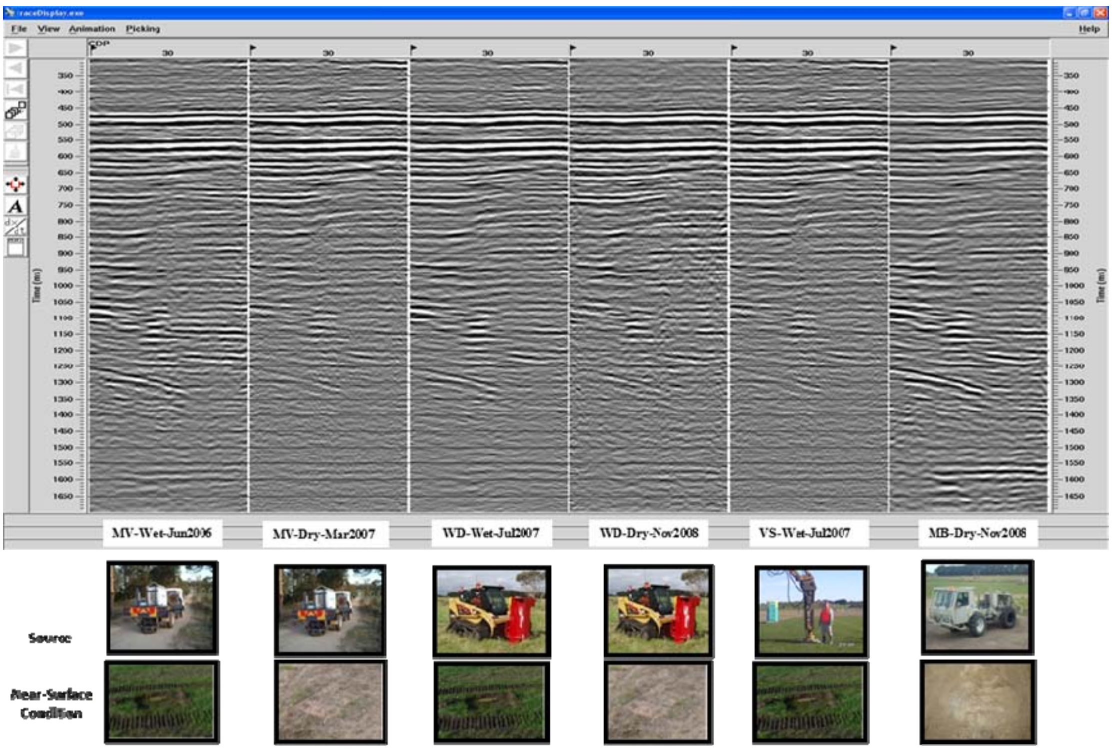


Figure 6.7: Comparison of the stack data of the 2D seismic test lines.

The amplitude spectra for each source in the same time window are shown in Figure 6.8 and 6.9.

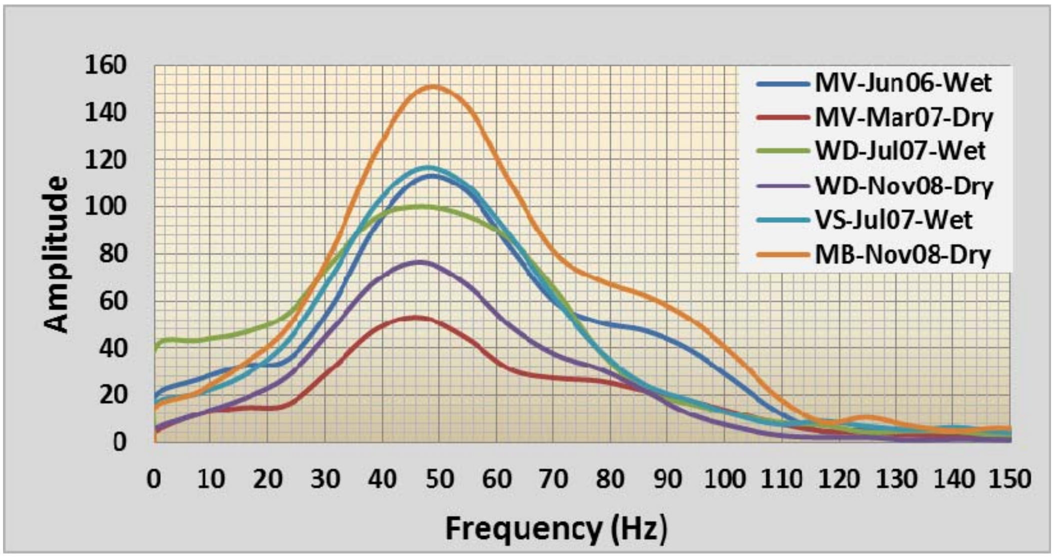


Figure 6.8: Amplitude spectra of above stacked data for a seismic window of 450-500ms.

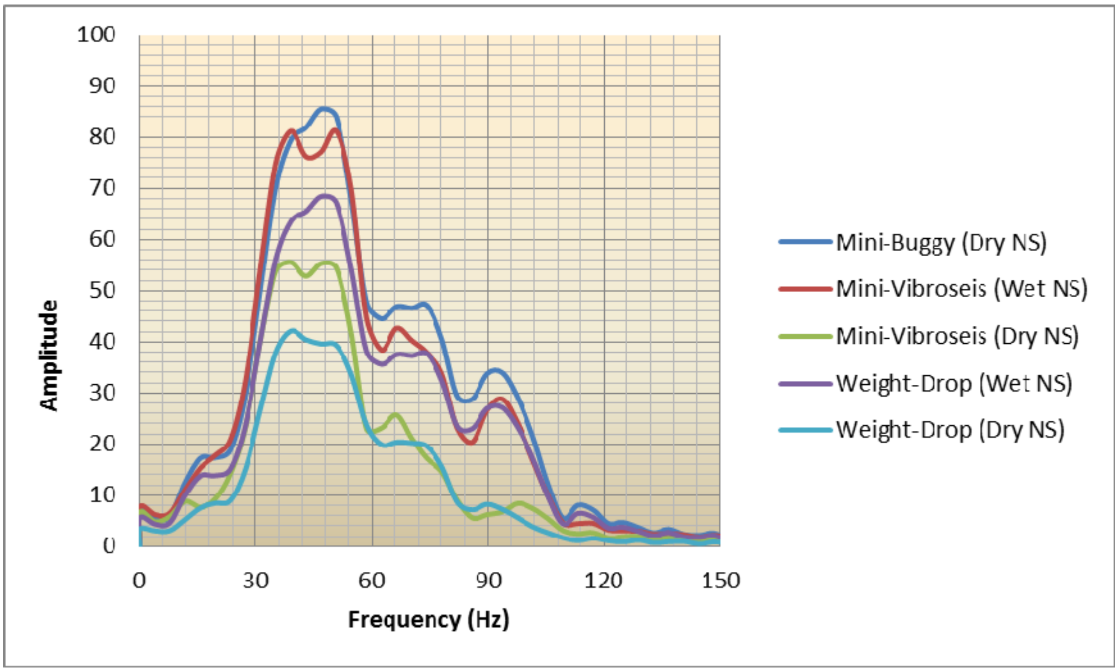


Figure 6.9: Amplitude spectra of the repeated 2D seismic test lines of above stacked data for a seismic window of 450-550ms.

The seismic attenuation is very high during the dry season recordings of Mini-Vibroseis compared to the wet season (Figure 6.10) However, using the Mini-Buggy source with about double the energy of Mini-Vibroseis during the dry season enabled us to better image the reservoir. Mini-Vibroseis source data during the wet near surface shows a better signal-to-noise ratio (Figure 6.10) and higher amplitude spectra compared to the Mini-Vibroseis source data during the dry near surface (Figure 6.11 and Figure 6.12). However, Mini-Buggy (stronger source) data during the dry near surface shows better a signal-to-noise ratio (Figure 6.10) and higher amplitude spectra compared to the Mini-Vibroseis source data acquired during the wet and dry near surface (Figure 6.11 and Figure 6.12).

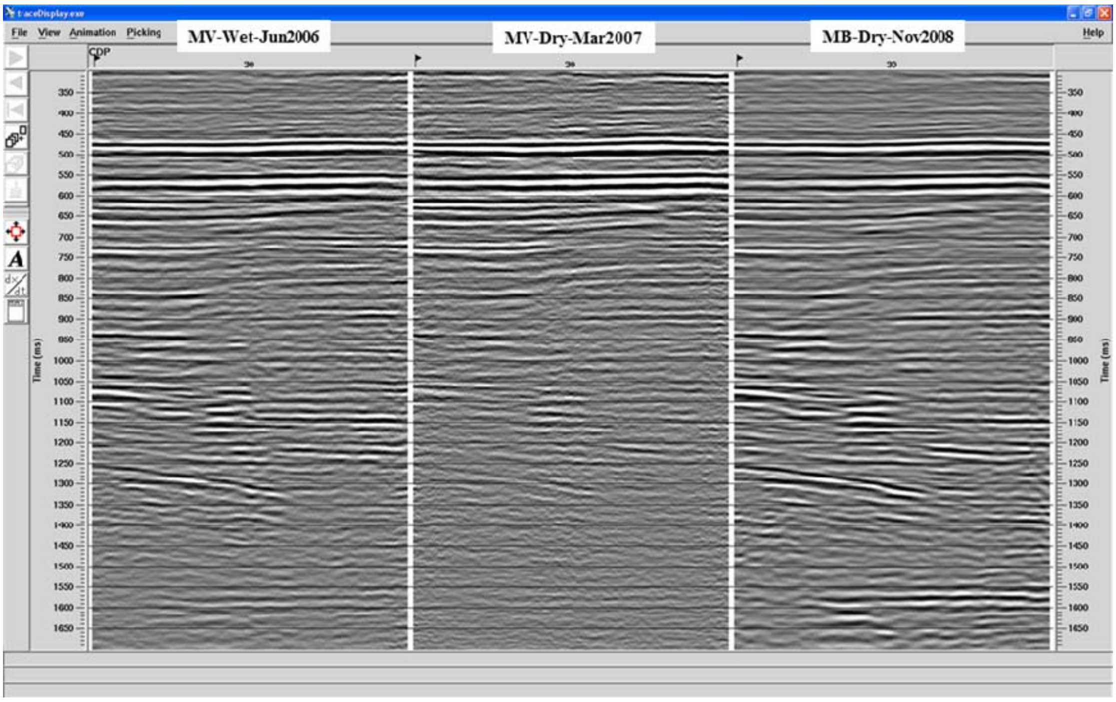


Figure 6.10: Comparison between the stacked data of the 2D seismic test lines: Mini-Vibroseis (wet near-surface), Mini-Vibroseis (dry near-surface), and Mini-Buggy (dry near-surface), from left to right.

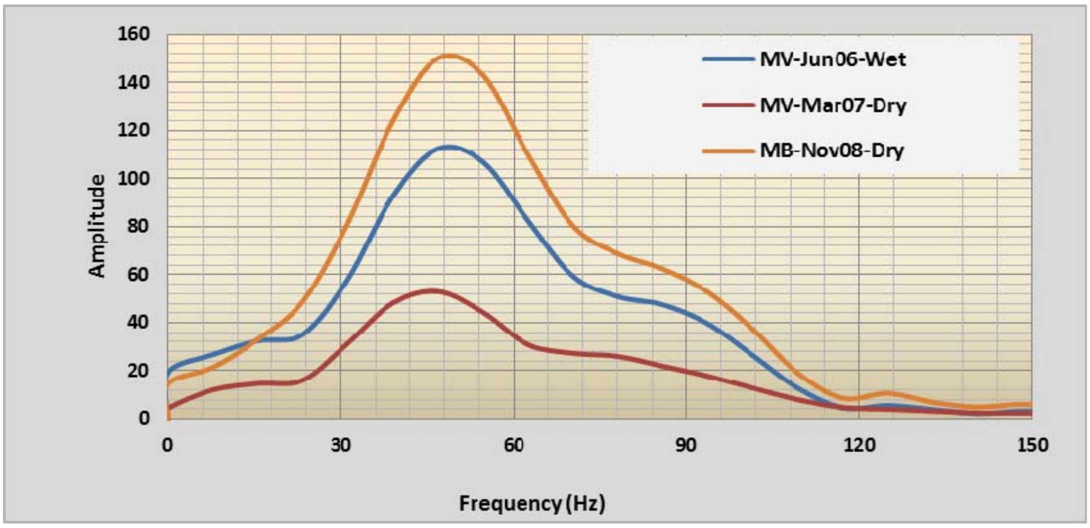


Figure 6.11: Amplitude spectra of Mini-Vibroseis sources for dry and wet periods. Reference MB spectra are also shown for a seismic window of 450-550ms.

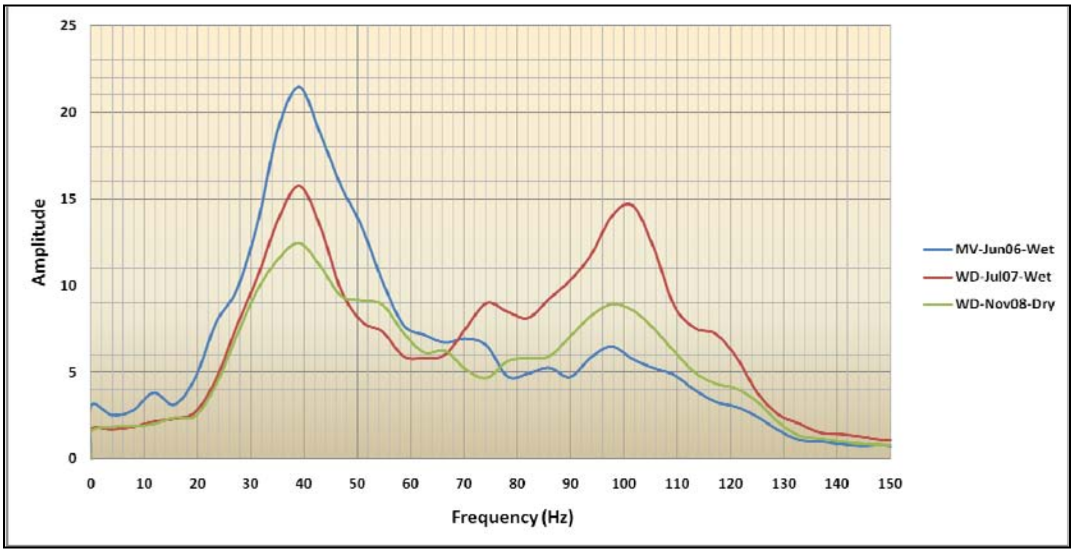


Figure 6.12: Comparison between the amplitude spectra of vibroseis sources for the stacked seismic data within a seismic window of 1500-1600ms.

The weight-drop source data collected during the wet near surface shows a better signal to noise ratio (Figure 6.13) and higher amplitude spectra compared to the weight-drop source data collected during the wet near surface (Figure 6.14 and Figure 6.15).

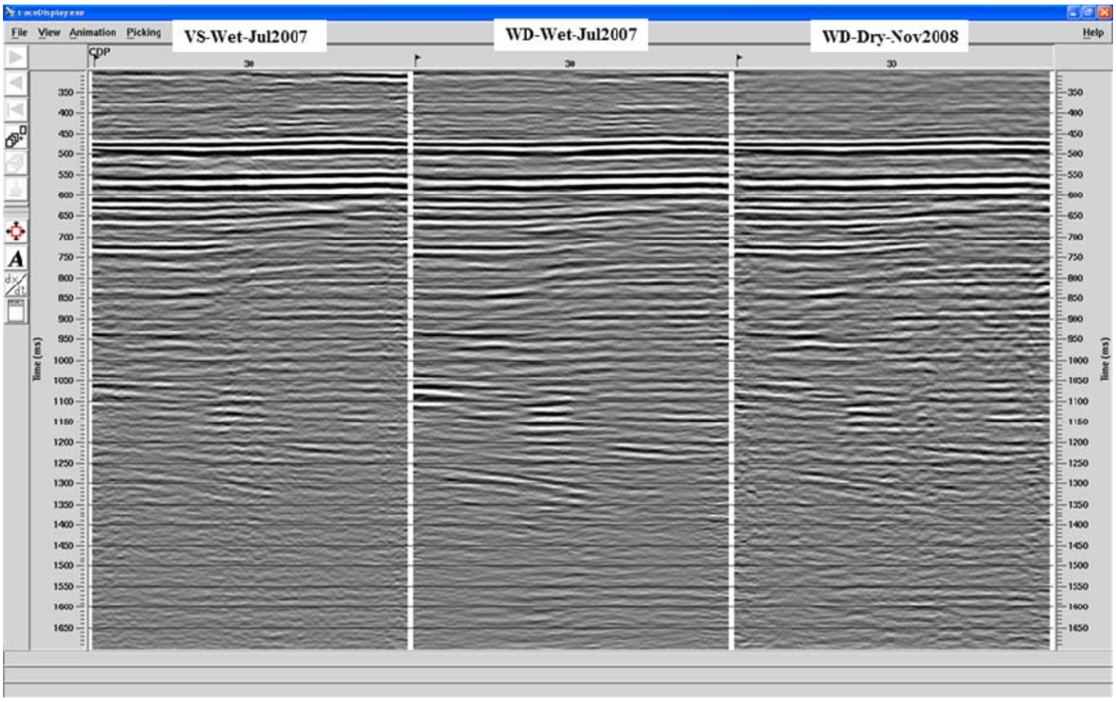


Figure 6.13: Comparison of the stack data of the 2D seismic test lines: VIBSIST (wet near-surface), weight drop (wet near-surface) and weight drop (dry near-surface) from left to right.

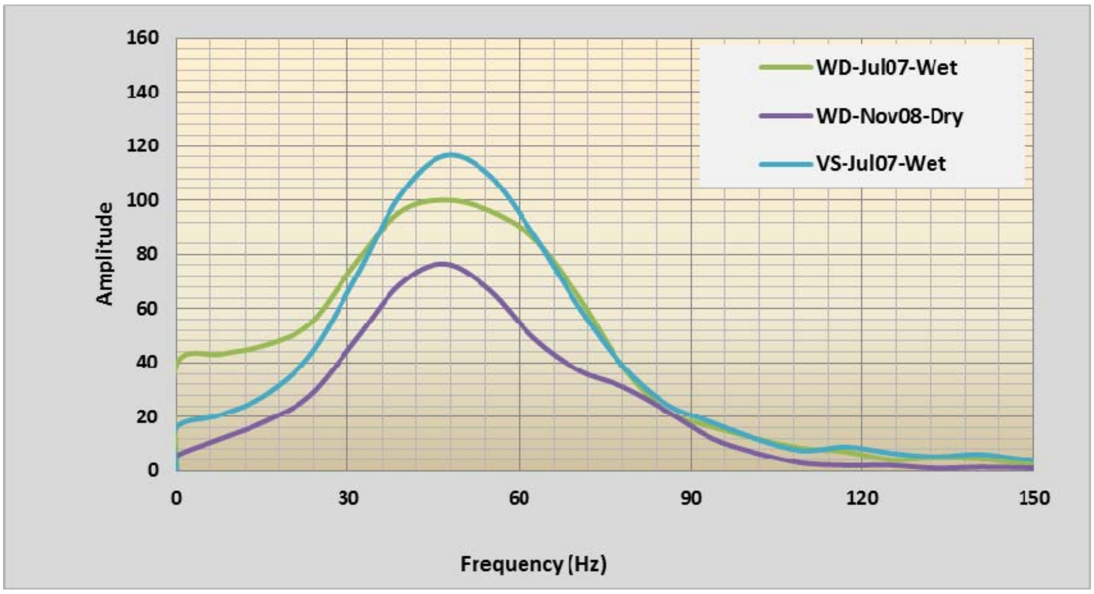


Figure 6.14: Comparison between the amplitude spectra of impact seismic sources for stacked seismic data for a seismic window 450-550ms.

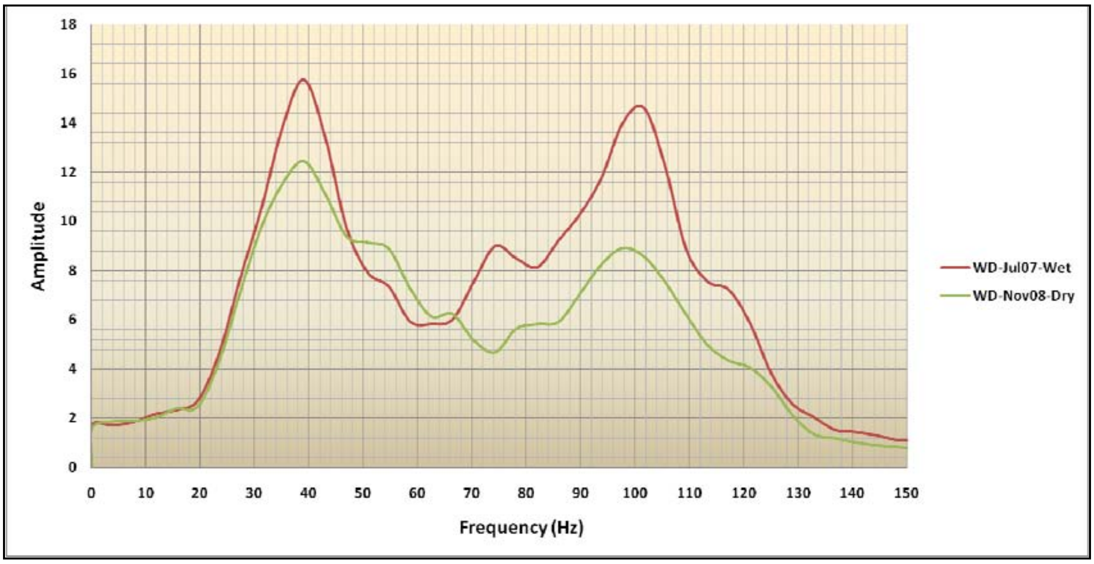


Figure 6.15: Shows the difference in amplitude spectra for the staked seismic window 1500-1600 around the Waarre C Formation (reservoir) using weight drop as a seismic source during wet and dry condition of the near surface.

6.5.1 Influence of ambient noise

The IVI Mini-Buggy is a more powerful source than the 1320 kg weight drop as it shows much greater S/N values for the same ground conditions (Figure 6.16). As mentioned before, the amplitude spectra around the Waarre C Formation (Reservoir) at frequency 30-40Hz (dominant frequency) is very high for Mini-Buggy compared to the weight drop (Figure 6.16 and Figure 6.17). As a result, the S/N ratio of Mini-Buggy data at the reservoir level is much higher compared to weight drop. That means that the Mini-Buggy has been more effective in attenuating ambient noise. To achieve the same effect, a weight-drop source would need high fold and large number of vertically stacked impacts. The latter is hard to implement due to environmental restrictions.

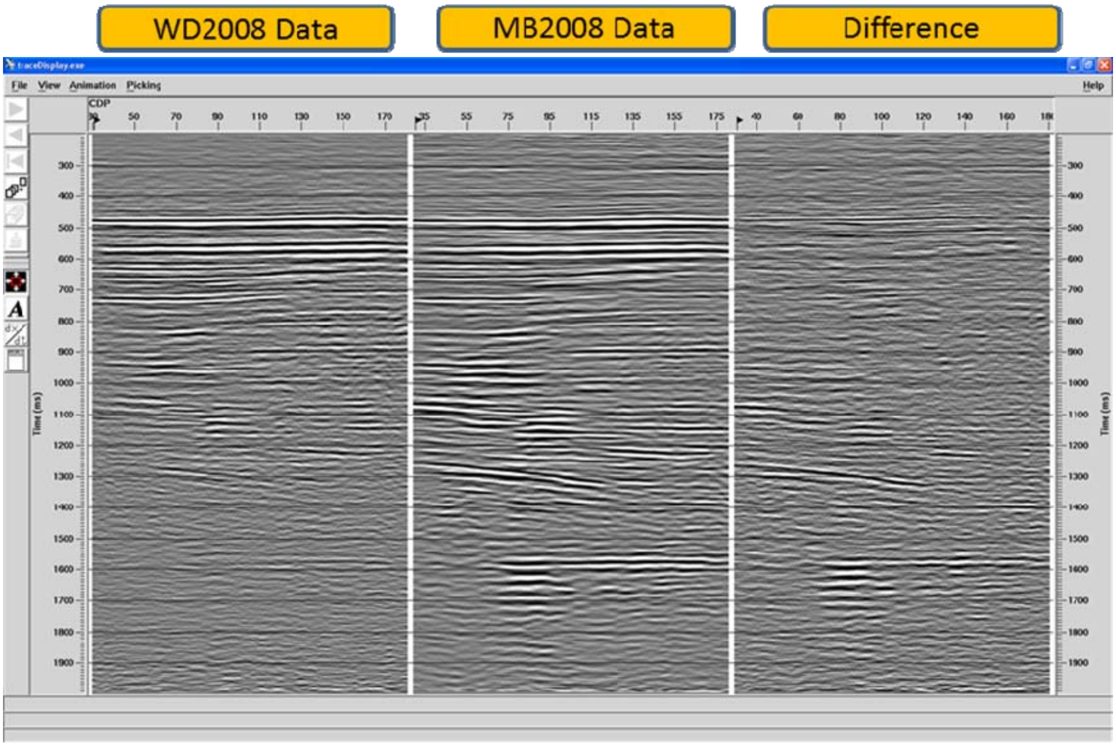


Figure 6.16: Comparison between weight drop (*left*), Mini-Buggy data (*middle*) and their difference (*right*) during November 2008 when near surface conditions were dry.

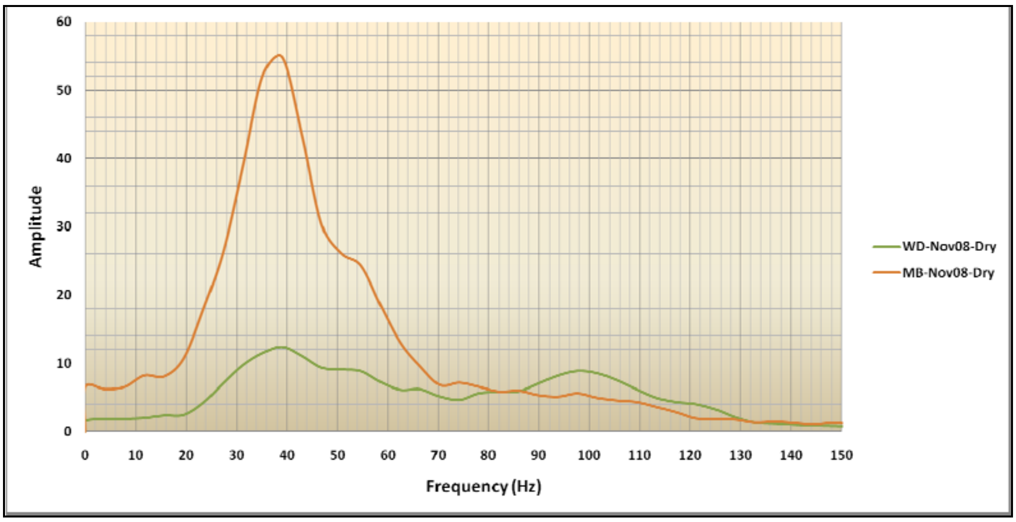


Figure 6.17: Shows the difference in amplitude spectra for the seismic window of 1500-1600 around the Waarre C Formation (reservoir) using Mini-Buggy (green) and weight drop (orange) as seismic sources during the dry condition.

6.5.2 Influence of near surface variation

The examination of either Mini-Vibroseis (Figure 6.18 and Figure 6.19) or weight drop (Figure 6.20 and Figure 6.21) clearly shows the first order effect of the near surface variation on the land seismic repeatability at Naylor Field.

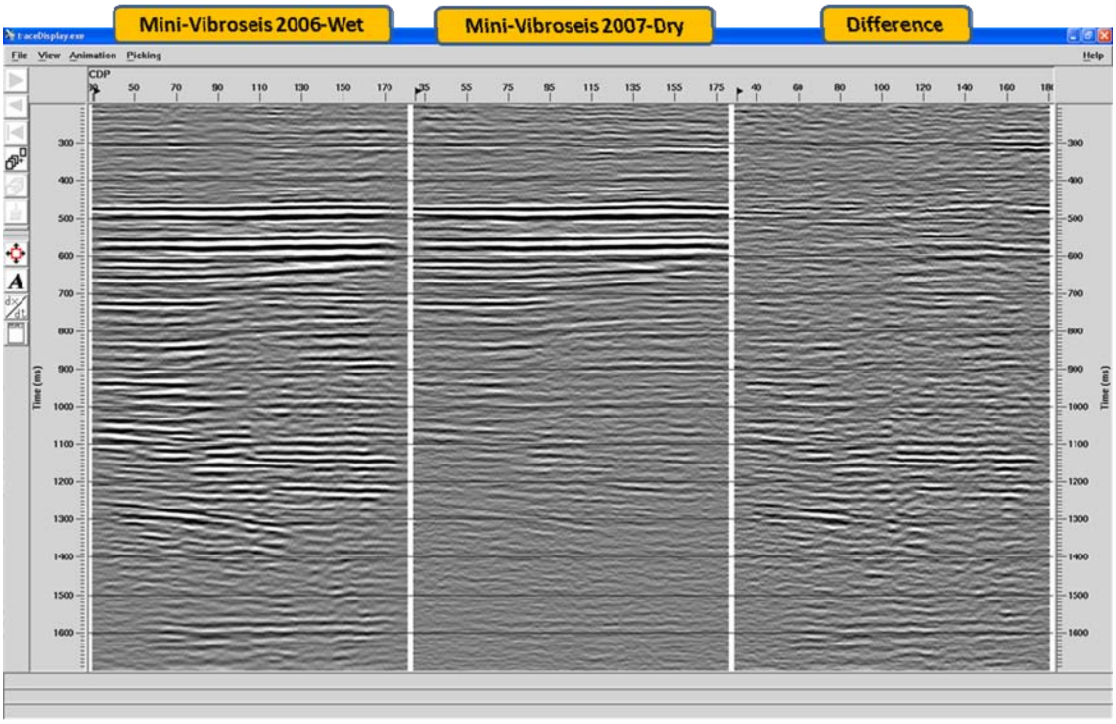


Figure 6.18: Comparison between wet (*left*), dry (*middle*) data and their difference (*right*) using Mini-Vibroseis as a seismic source.

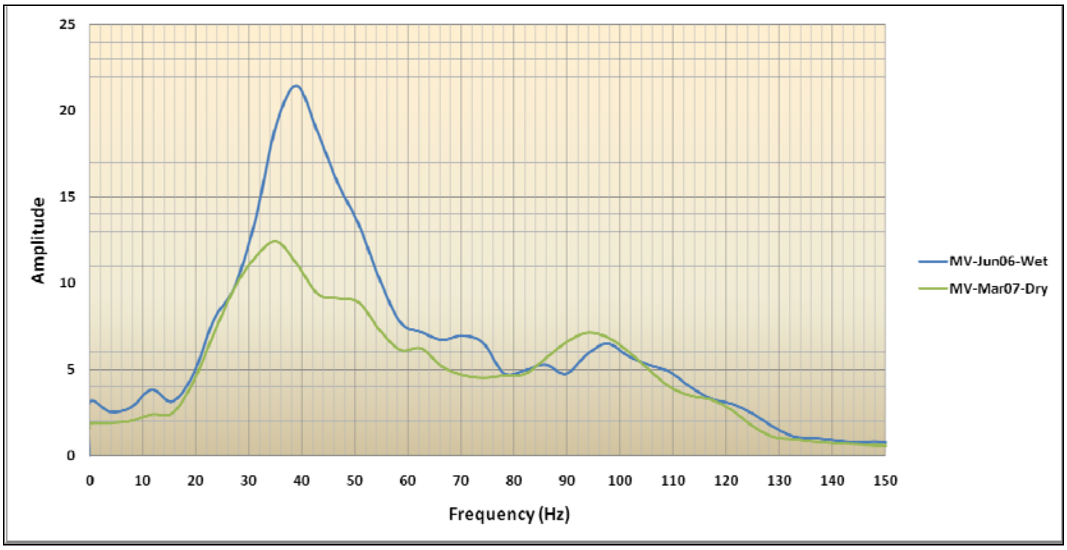


Figure 6.19: The difference in amplitude spectra for the seismic window of 1500-1600 around the Waarre C Formation (reservoir) using Mini-Vibroseis as a seismic source during wet and dry conditions.

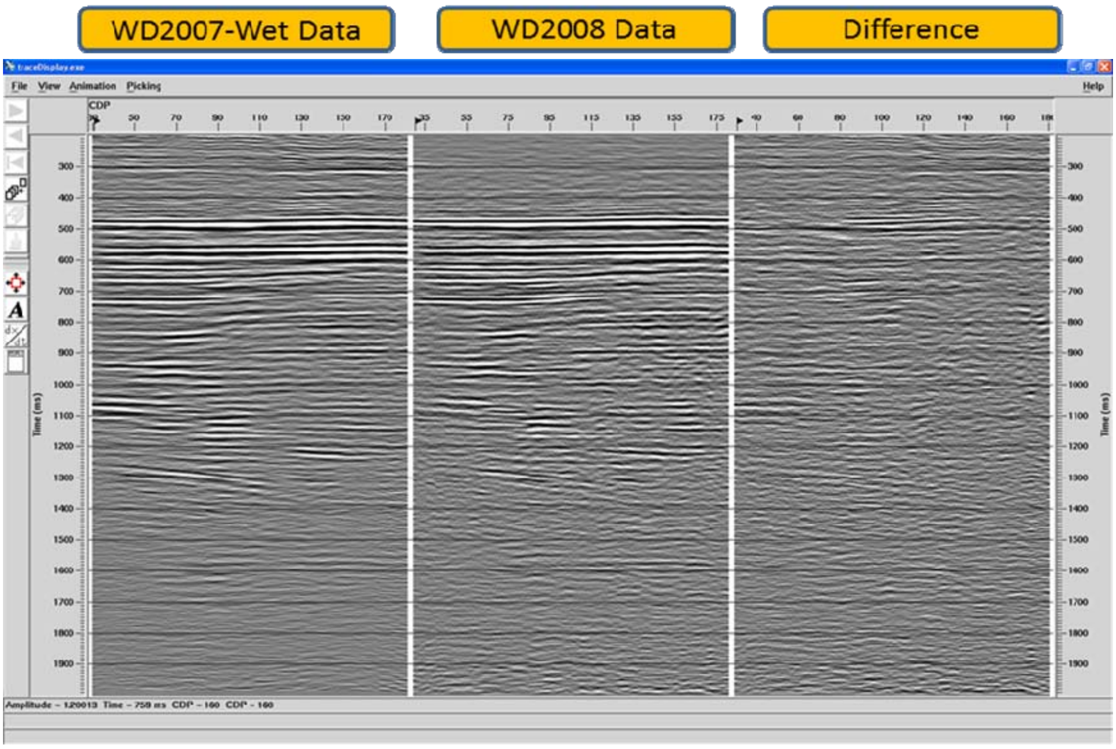


Figure 6.20: Comparison between wet (*left*), dry (*middle*) data and their difference (*right*) using weight drop as a seismic source.

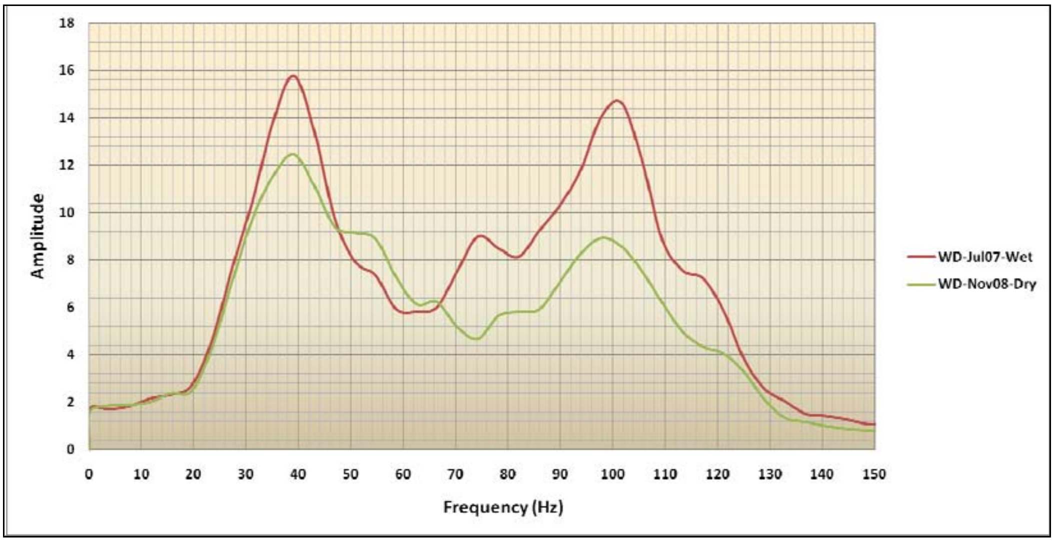


Figure 6.21: Shows the difference in amplitude spectra for the seismic window of 1500-1600 around the Waarre C Formation (reservoir) using weight drop as a seismic source during wet and dry conditions.

The IVI Mini-Buggy is about as twice as powerful as the Mini-Vibroseis. Figure 6.22 shows much greater S/N values for the IVI Mini-Buggy compared to the Mini-Vibroseis, even though Mini-Buggy data was acquired during the summer when the near surface was dry whereas the Mini-Vibroseis was acquired when at wet near surface conditions (Figure 6.22). The amplitude spectra around the Waarre C Formation (reservoir) at the frequency of 30-40 Hz is very high for the Mini-Buggy compared to the Mini-Vibroseis although these data have been acquired with the same near surface conditions (Figure 6.23). As a result, the S/N ratio of Mini-Buggy data at the reservoir level is very high compared to the Mini-Vibroseis data. I believe that the source strength can enhance the data quality.

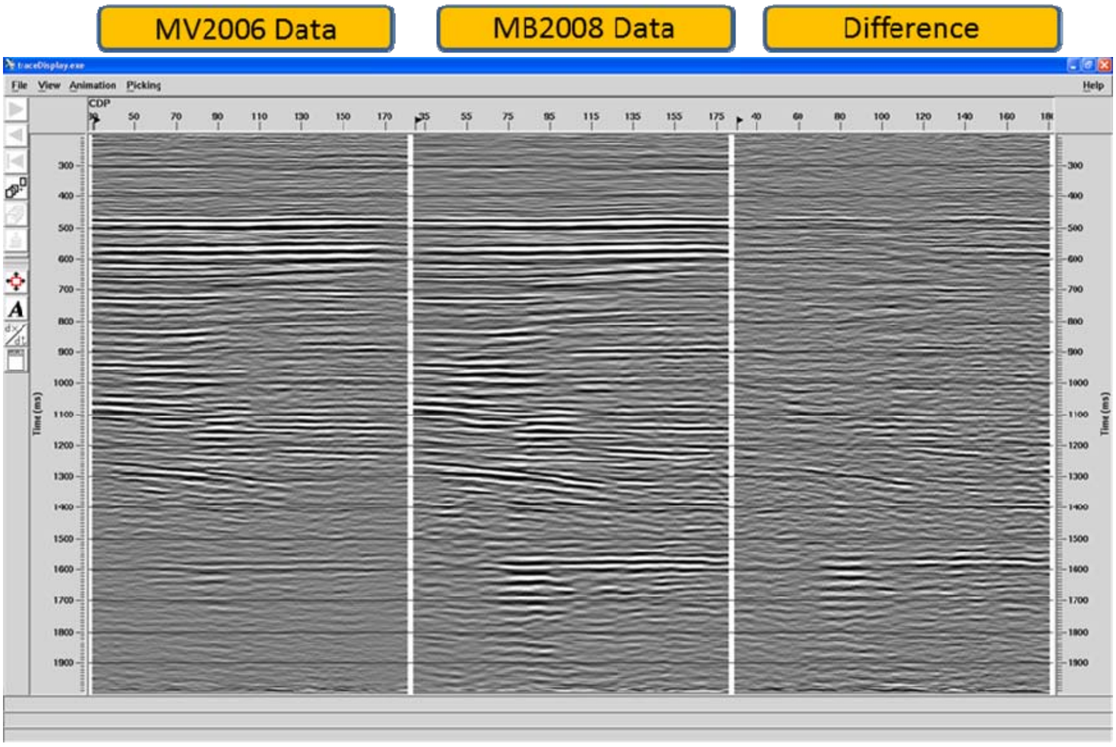


Figure 6.22: Comparison between Mini-Vibroseis data (*left*) when the near surface is wet, Mini-Buggy data (*middle*) when the near surface is dry and their difference (*right*).

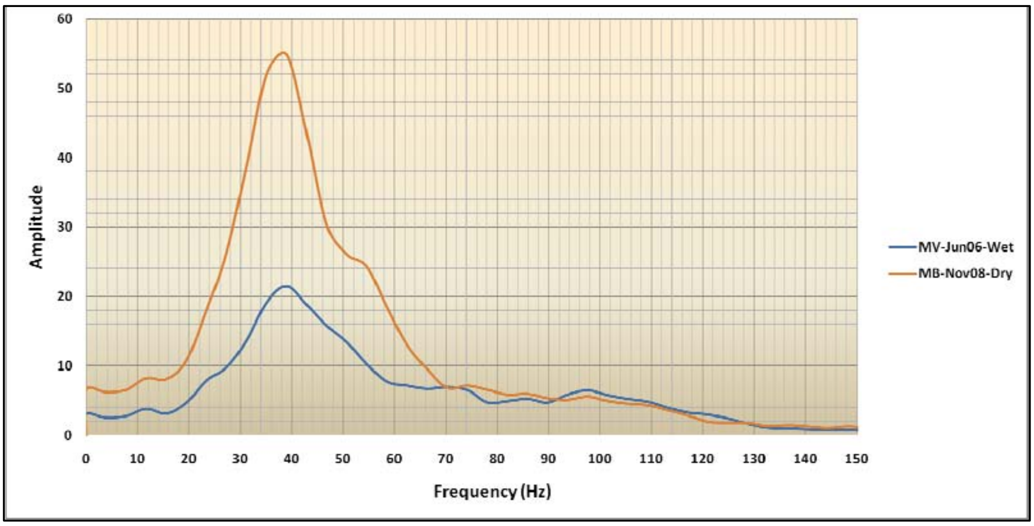


Figure 6.23: The difference in amplitude spectra for the seismic window of 1500-1600 around the Waarre C Formation (reservoir) using Mini-Buggy (orange) and Mini-Vibroseis (blue) as seismic sources during dry and wet conditions of the near surface, respectively.

6.5.3 Different seismic sources - comparison

The comparison between the Mini-Vibroseis and weight drop sources for the data acquired at the same time of the year (near surface condition) is shown in Figure 6.24. Clearly vibroseis has better penetration and an overall higher S/N ratio. Spectral comparison (Figure 6.25) demonstrates a higher penetration rate of high frequencies for Mini-Vibroseis in comparison to weight drop.

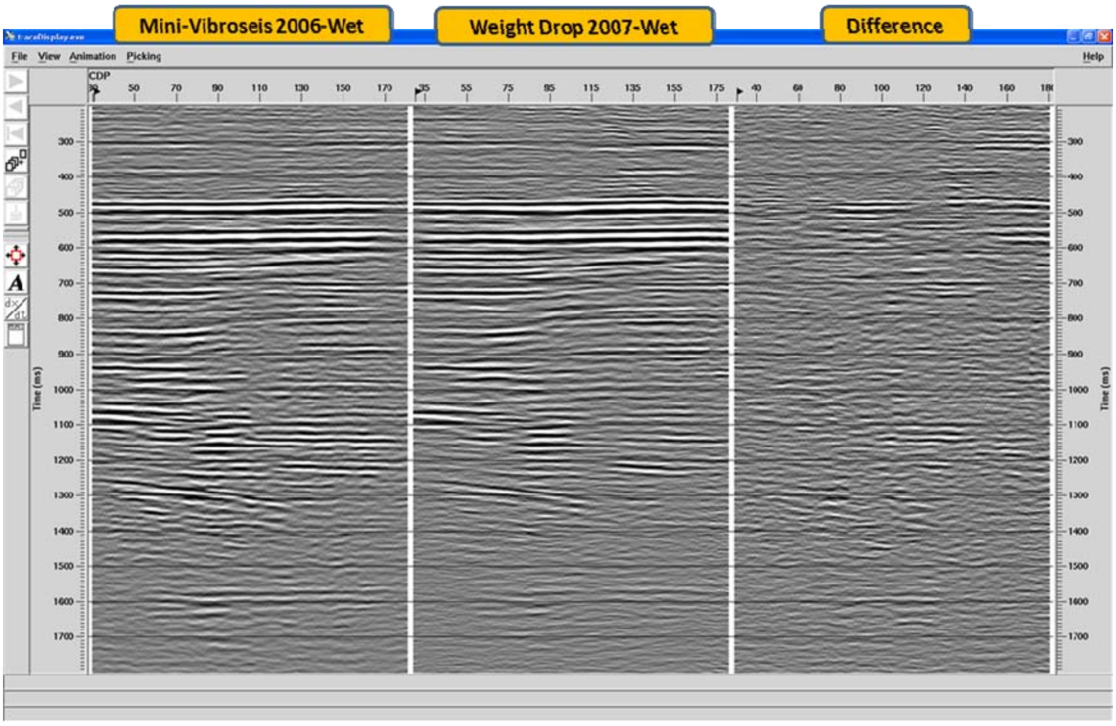


Figure 6.24: Comparison between Mini-Vibroseis (*left*) and weight drop (*middle*) data when the near surface is wet and their difference (*right*).

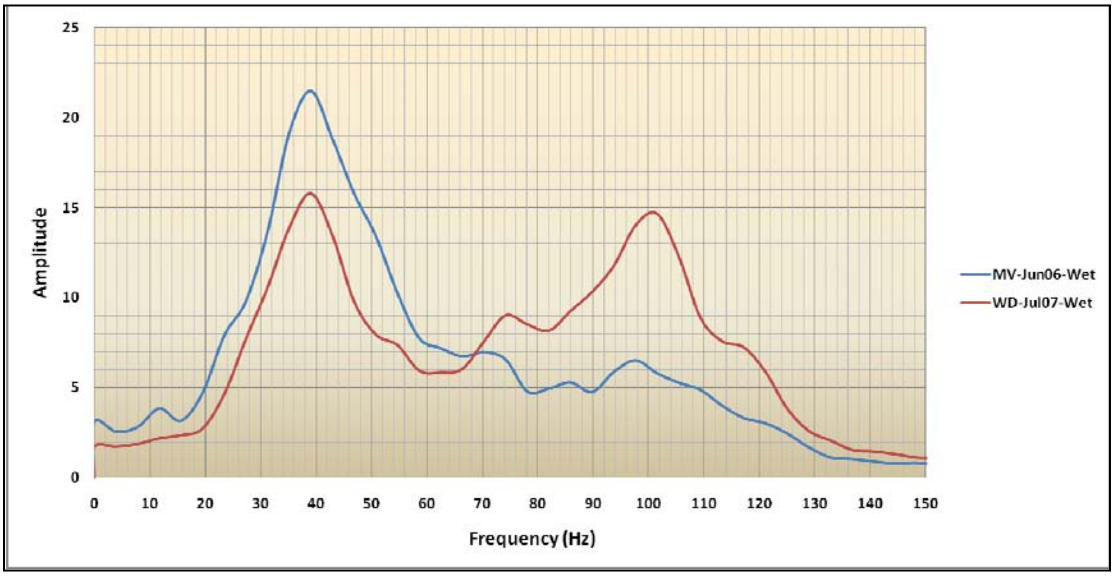


Figure 6.25: Amplitude spectra for the seismic window of 1500-1600 around the Waarre C Formation (reservoir) using Mini-Vibroseis (red) and weight drop (blue) as seismic sources during the wet condition of the near surface.

6.6 Results

I computed the NRMS graphs in the time window of 450-600 ms to evaluate repeatability of different pairs of lines when changing the source type at same near surface conditions and using the same seismic source for different near surface conditions using Eq. (8) from Chapter 5.

The 4D analyses along Soda's Road showed that both soil condition and source type are important for time-lapse seismic surveys. This is summarised in Figure 6.26 where NRMS difference between wet and dry seasons for two sources is shown along the entire line length. In general we see again that the Mini-Vibroseis source provides a better S/N ratio, better frequency content and therefore better repeatability compared to the weight drop source regardless of the season. Similarly, for the same source type, near surface conditions in the wet period allowed for better penetration, frequency content and apparently repeatability. However the last one should be taken with caution as the test took place along relatively firm ground (dirt road). In agricultural areas the wet soil will cause a larger foot print.

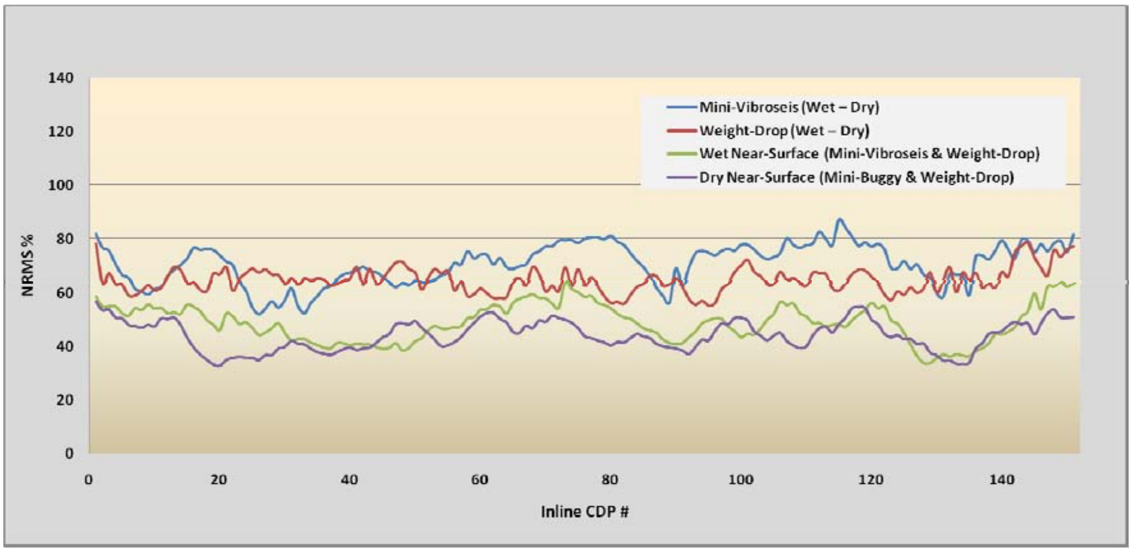


Figure 6.26: The NRMS difference for the seismic window 450-600 around the Clifton Formation.

The results of this study show a very strong agreement between modelled results using micro-array information and combining it with log data. Note that the generated seismic non-repeatability also includes ambient noise effects.

The repeatability of 3D surveys computed in a 60ms sliding window (Figure 6.27) shows much better repeatability than 2D surveys acquired with the same parameters. The main reasons for this is in the power of the 3D processing algorithms (FXY decon compared to FX decon, 3D migration compared to 2D migration, etc) (Pevzner et al., 2009). This is particularly important in the case of the Otway project, as the target is exceptionally small, while time-lapse effects are rather subtle. For monitoring purposes, I was unable to achieve repeatability similar to 3D levels for 2D lines. Hence 3D time lapse remains preferred methodology for monitoring particularly when subtle time-lapse signals are expected.

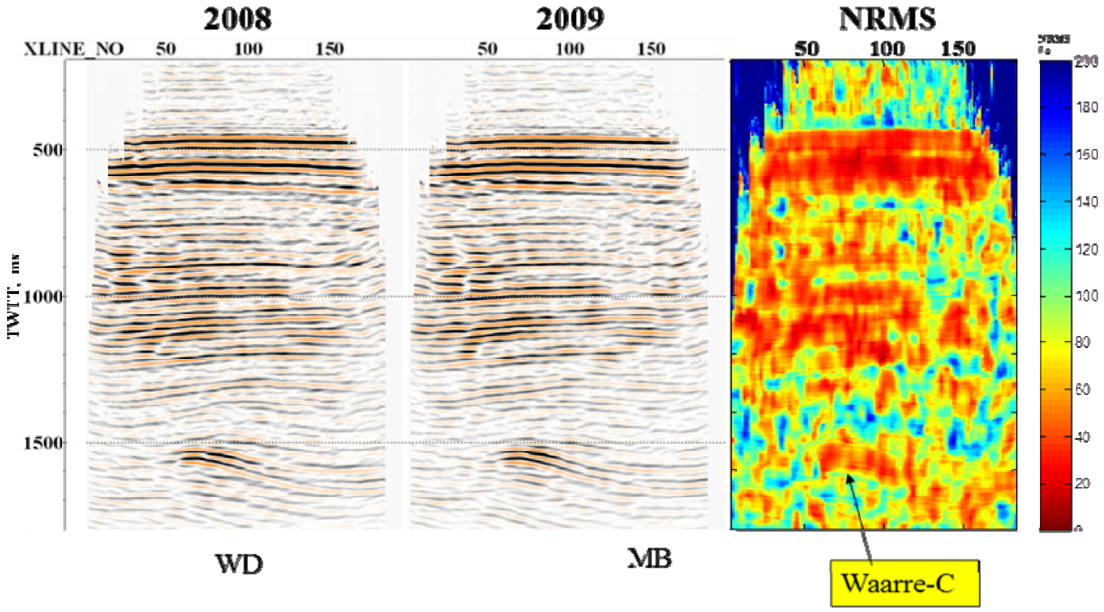


Figure 6.27: 3D base line survey 2008, acquired by weight drop (*left*) and the first monitor survey 2009 (Mini-Buggy) after cross-equalisation and their NRMS difference (*right*). (Pevzner et al., 2009)

However, the repeatability of 3D surveys turned out to be excellent for the Otway data, with an average NRMS value of ~20% (Figure 6.27) at target horizons located at a 2 km depth.

6.7 Chapter Summary

Several 2D seismic tests conducted in the Otway Basin, over a period of nearly two years, were used to investigate the effects of near surface conditions and source type on repeatability. It was shown that soil conditions top the list, followed by the source type. The two are not fully independent as dry conditions may be favourable for very strong sources while wet conditions may be favourable for weaker sources. Again, the actual implementation is dependent on the site and land access.

Important for this research is that field repeatability matches closely to the alternative methodology proposed in my study which combines micro-arrays with numerical modelling to predict site repeatability. If so, then the very effective and inexpensive micro-array approach can be used to predict site repeatability and hence predict the minimum magnitude of the time-lapse signal that can be detected. An extension to this approach can be made via micro-3D arrays or, it may be reasonable to assume that 3D repeatability is on average 50% better than 2D.

The results of this work may have impact on other areas not associated with CO_2 sequestration, such as imaging oil production over areas where producing fields suffer from a karst topography such as the Middle East or Australia.

Finally the S/N variability is a function of the soil conditions and source strength relative to the background noise level. In the post stack domain, this translates into a ratio of the signal strength to background noise. Consequently, the data fold is crucial for intrinsically low S/N conditions that are generated by weak sources. Source type is important but even impact sources can be used for certain soil types with high rates of vertical stacking and high fold.

Chapter 7 : Conclusions and Recommendations

Time-lapse seismic technology has been increasingly used in monitoring and characterising changes in a reservoir. On that basis and past experience, time-lapse seismic methodology has been also used in CO_2 sequestration studies. For land-based CO_2 projects, the dependency of this methodology on local ground conditions is not well understood. An understanding of the factors influencing repeatability of land seismic and evaluating limitations of the time-lapse seismic method is crucially important for its application in CO_2 sequestration projects. In particular, to date there has been no methodology that would provide a priori or a rapid answer about the potential of time-lapse seismic methodology at a particular CO_2 sequestration site. Thus, the main aim of this work was to find such methodology that enables us to predict non-repeatability at a site by utilising a set of pre-base line measurements which are then used to provide input parameters for time-lapse numerical modelling. The crux of this methodology is the analysis of near surface through deployment of micro-array measurements.

7.1 Conclusions

High seismic repeatability is critical to the monitoring program of the Naylor Field because of the small time-lapse effect related to CO_2 injection into a depleted gas reservoir (Naylor). In the case of the Naylor CO_2 injection test site area, the presence of sinkholes and karst topography in the near surface zone make seismic non-repeatability investigations challenging. In such geological terrain, the degree of signal scattering caused by a rugose limestone surface and caverns depends on the depth of the water table. For that purpose Curtin's seismic monitoring team has conducted several repeated 2D tests along Soda's road. There are seven sets of repeated 2D seismic test lines and 3D baseline seismic acquisition before CO_2 injection commenced at this field. These 2D seismic test lines were acquired at the same position but during different seasons and using different sources. Of particular interest was the analysis of Mini-Vibroseis and weight-drop sources in both wet and dry conditions. The aim of this work was to assess non-repeatability for each source type and variations in soil conditions (Urosevic et al., 2008). From the 2D seismic test lines data, I have observed that there is higher seismic data attenuation during the dry season compared to the wet season.

To study the effect of the near surface variation on the seismic repeatability, I first had to evaluate other factors affecting it such as instrumentation, source type and survey geometry. To do so I utilised a “zero-time” seismic approach to determine the “system repeatability” prior to further analysis aimed at determining near-surface variations.

Subsequent analysis was aimed at determining geological factors that affect repeatability. For that purpose I conducted so-called micro-array surveys. The main objective of the time-lapse micro-array surveys was to determine the change of elastic properties related to water table variations and changes in the top soil layer (agricultural activities).

Initially I intended to use these results to explain 2D time-lapse reflection experiments and the NRMS measured in these surveys. Subsequently I realised that the micro arrays, combined with full elastic modelling could be used to predict the most likely range of repeatability at a given site. Indeed, results obtained by such an approach compare well to real field observations (repeated reflection tests along Soda’s road).

Time-lapse micro-array measurements can help simulate 4D seismic effects produced by seasonal variations and evaluate the contribution of these variations to seismic measurements in terms of non-repeatability. The micro-array investigation results indicated that the velocities and Q-factor show directionally independent patterns at this site. The top soil (0.5m thick agricultural layer or elastic-plastic zone) has a low velocity and low Q-factor and hence affects reflection amplitudes, frequency content and arrival times. Micro-RVSP measurements show a consistent increase in velocity with depth and no seismic anisotropy. These measurements proved that the change in water saturation at the near surface can cause changes in velocity and attenuation.

Time-lapse numerical modelling tests were implemented to understand and model the effects of variable near surface conditions. The numerical tests were aimed at reproducing the significant scattering observed in field experiments conducted at the Naylor site in the Otway Basin for the purpose of CO_2 sequestration. I used full elastic pre-stack modelling experiments to quantify these effects and evaluate their individual contribution. Initial seismic modelling results show that relatively simple scattering effects, due to a corrugated near-surface clay/limestone interface, can have a profound effect on time-lapse surveys. From my modelling study I conclude that the changes in the elastic properties of the near surface layers cannot automatically be neglected when studying time-lapse seismic effects in producing reservoirs or when injecting fluid into a reservoir. This is especially true at the Naylor Field where we have very subtle time lapse seismic signal variations. In a more general sense, it can only be advantageous that the repeatability at any monitoring site is predicted before a time-lapse monitoring program is designed and executed. In the case of CO_2 sequestration projects, numerical simulation of the changes in the reservoir, aimed at estimating time-lapse seismic reflection signals, should be followed by an investigation of repeatability. In the case of Otway, the aim of 3D time-lapse studies is to verify CO_2 containment in the reservoir by observing zero time-lapse signals in and above the reservoir.

However, by comparing two different sources at the same near surface condition such as WD 2008 vs MB 2008, the NRMS difference between data acquired with same surface conditions WD 2008 vs MB 2008 is less than between WD surveys themselves acquired over two different seasons. So the near-surface condition is most likely the factor of primary importance. However, a WD source showed greater variability in the frequency content and phase of the signal generated. This was largely eliminated after stacking thanks to high data fold and dense spatial sampling. In general it can be stated that the use of a weight-drop source degrades repeatability of land seismic data in comparison to controlled seismic sources such as vibroseis. However, the non-repeatability of the WD source in the same surface conditions is less than the non-repeatability resulting from variations in soil saturation and agricultural activities. For that reason the season of the year chosen to acquire seismic data (i.e., near-surface conditions) should be taken into account during planning of the land time-lapse seismic surveys. Ideally, land time-lapse surveys should be conducted at the same time of the year to mitigate the effects of soil saturation changes and agricultural activities.

In the Otway study the initial 2D time-lapse field tests suggested that it would be hard to achieve good repeatability at this site due to near surface variations. This problem was exacerbated by the fact that the monitoring program was limited to low-impact (low-power) sources. Estimated 2D seismic non-repeatability by reflection 2D time-lapse surveys agrees well to the one I modelled from micro-array investigations. In both cases the value of 30-50% of non-repeatability is determined both from 2D field tests and numerical simulations. However, it turned out that the repeatability of 3D surveys is better and NRMS is in the range 20-30% at the reservoir level. The main reasons for this difference relates to the power of 3D processing algorithms. Thus, the results of any 2D investigations aimed at repeatability estimate, whether micro-array or conventional, have to be adjusted for the case of 3D surface seismic.

Hence, I can now propose an effective methodology which can be utilised at future sites that aim to utilise time-lapse seismic for either CO2 sequestration purposes or for monitoring of saturation or pressure changes in the producing oil and gas reservoirs.

7.2 Recommendations

This research has demonstrated the effect of variations in the near surface on the seismic repeatability and its impact on the effectiveness of the time-lapse seismic methodology.

From my results and observations of testing the seismic repeatability due to the change of the water content at near surface, I found that land seismic repeatability is affected by seasonal variations so that successive surveys should be undertaken at the same time of the year.

Before committing to an expensive 3D time-lapse seismic program, seismic repeatability can be estimated through the application of rapid inexpensive surveys such as the micro-array surveys proposed in this study. The alternative is to conduct a set of 2D conventional pre-base line measurements. This is however much more costly than the micro-array method. Further advances in this field could perhaps be achieved through the implementation of 3D micro-array surveys which could be very effective in the case of deep and variable weathering.

Of particular importance could be the application of this technique in the Middle East fields where the weathering depth is extreme and the propagation of waves is significantly affected by the change in the water table at different seasons.

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Yours sincerely

Yousuf Al-Jabri | ***PhD Student in Exploration Geophysics***
Department of Exploration Geophysics | Western Australian School of Mines
Curtin University | Technology Park West
[**Postal Address**: GPO Box U1987, Perth, Western Australia, 6845] [Bld 613, Rm 4H21]
[**Street Address**: ARRC/CSIRO Building, H Block, Level 4, 26 Dick Perry Avenue, Kensington, WA]
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Fax | +61 8 9266 3407
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Phone: (918) 497-5506; Fax: (918) 497-5557
E-mail: tbakamjian@seg.org; Web: http://www.seg.org/

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Yours sincerely

Yousuf Al-Jabri **|** ***PhD Student in Exploration Geophysics***
Department of Exploration Geophysics | Western Australian School of Mines
Curtin University | Technology Park West
[**Postal Address**: GPO Box U1987, Perth, Western Australia, 6845] [Bld 613, Rm 4H21]
[**Street Address**: ARRC/CSIRO Building, H Block, Level 4, 26 Dick Perry Avenue, Kensington, WA]
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Fax | +61 8 9266 3407
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