UPTEC W08 029
Examensarbete 30 hp
September 2008

Processing of VSP data at Ketzin CO_2 storage site

Databehandling av VSP data från Ketzins lagringsplats för CO_2

Nils Henoch

ABSTRACT

Processing of VSP data at the Ketzin CO_2 storage site
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The Ketzin CO_2SINK project, located in Germany, was launched in April 2004. The aim of the project is to use in situ methods, on a fully fledged onshore demo construction, to fill the gap between engineering and scientific studies on geological CO_2 storage. One of the main elements is comprehensive monitoring and development of verification methods to track the long term spread of injected CO_2. The Ketzin site is situated in the Northeast German Basin (NEGB). NEGB is part of a Permian basin system that extends from the southern North Sea to Poland. More specifically, the site is located in the eastern part of a double anticline called the Roskow-Ketzin Anticline. The objective of the CO_2SINK project is to inject CO_2 into the Stuttgart Formation at a depth of 500-700 meters.

Seismic methods have proven useful in earlier Carbon Capture and Storage (CCS) projects, like the Sleipner project in the North Sea. Uppsala University is one of the main participants in the seismic part of the CO_2SINK project. Seismic monitoring methods that have been applied at the CO_2SINK project include 2D and 3D surface surveys, Crosswell Survey, Moving Source Profiling (MSP) and Vertical Seismic Profiling (VSP). The borehole-based seismic measurements are used to get a higher resolution around the boreholes than obtained with regular surface surveys.

The VSP survey was performed during November and December in 2007. The recording depth started at 325 meters and ended at 720 meters. The survey recorded 14 shots with varying offsets. The nearest shot was located at the wellhead while shot offset between 300 meters and 1200 meters were used for offset VSP. One essential aspect of VSP surveys is that both upgoing and downgoing rays are recorded. However, the raw field data can only be interpreted after data processing. The data processing was done using the seismic software GLOBE Claritas™ on a LINUX computer. The main processing steps were kept simple with the purpose to minimize the risk of introducing artefacts into processed volumes.

The data quality of the VSP survey is not as good as expected and the resolution deteriorates with increased offset. Nevertheless some results were interpretative after the data processing. The most important step in the processing sequence was the multichannel velocity filtering. Because of the bad quality of the data, the velocity models, used for the depth conversion and the synthetic seismogram were kept simple. The K2 reflection from the Heldburg-Gips at a depth of 552 meters was the clearest and, thus, the easiest one to localize. One strong reflection at 960 ms was identified as double-path multiple of the K2 reflector. In general, the results from the VSP survey agree with the 3D surface seismic survey and borehole data.

Keywords: Vertical Seismic Profiling; VSP; Borehole Seismic; Seismic data processing; CO2SINK Project; Ketzin; Saline Aquifers; Geological Storage; Carbon Capture and Storage; CCS;

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ISSN 1401-5765

REFERAT

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Ketzins CO_2SINK projekt, beläget i Tyskland startades i april 2004. Syftet är att använda in-situ metoder på en fullskalig demostrationsanläggning för att fylla kunskapsluckorna mellan de kommersiella och akademiska kunskaperna om geologisk CO_2 lagring. Några av de viktigaste komponenterna är omfattande övervakning och utveckling av verifieringsmetoder för att spåra den långsiktiga spridningen av injicerad CO_2. Ketzins berggrund tillhör den nordöstra tyska sedimentära bassängen (NEGB). NEGB utgör en del av det permianska bassängsystemet som sträcker sig från södra Nordsjön till Polen. Mer specifikt är platsen belägen på den östra delen av dubbelantiklinen Roskow-Ketzin Antiklin. Syftet med CO_2SINK projektet är att injicera CO_2 i Stuttgart Formationen på ett djup av 500-700 meter.

Seismiska metoder har visat sig användbara i tidigare ”Carbon Capture and Storage” (CCS) projekt, bland annat Sleipner-projektet i Nordsjön. Uppsala universitet är en av huvuddeltagarna i de seismiska undersökningarna under CO_2SINK projektet. Seismiska undersökningar som har tillämpats vid CO_2SINK projektet inkluderar 2D och 3D ytseismik, Crosswell, Moving Source Profiling (MSP) och Vertical Seismic Profiling (VSP). De seismiska mätningarna som använder borrhål är till för att få en klarare och skarpare bild av bergrunden än vad vanlig ytseismik kan inhämta.

VSP undersökningen genomfördes under november och december 2007. Geofoner var placerade från 325 meter till 720 meters djup. Undersökningen utgjordes av 14 skottpunkter. Den närmaste skottpunkten låg vid borrhålet medan övriga skottpunkter låg mellan 300 och 1200 meter från borrhålet. En väsentlig aspekt av VSP undersökningar är att både uppåtgående och nedåtgående vågor kan registreras. Emellertid måste fältdata databehandlas innan interpretation. Databehandlingen gjordes med hjälp av den seismiska programvaran GLOBE Claritas™ på en LINUX-dator. Databehandlingen utfördes så enkelt som möjligt för att inte få in fabricerade signaler i det slutliga resultatet.

Kvaliteten på datat från VSP undersökningen är inte så bra som förväntat. Upplösningen avtar med ökat skottavstånd. Likväl erhölls vissa resultat efter databehandlingen. Det viktigaste steget i databehandlingen var flerkanalig hastighetsfiltrering. På grund av den dåliga kvaliteten på datat användes relativt enkla hastighetsmodeller för djupomvandling och syntetiska seismogram. K2 reflektionen från lagret kallat Heldburg-Gips på 552 meters djup var den lättaste att lokalisera. En stark reflektion vid 960 ms. identifierades som en långväga multipel av K2 reflektorn. I stort stämmer resultatet från VSP undersökningen överens med tolkningen av den tidigare 3D ytseismikundersökningen.

Nyckelord: Vertical Seismic Profiling; VSP; Borrhålsseismik; Seismisk dataprocessering; CO2SINK projektet; Ketzin; Salina akviferer; Geologisk lagring; CCS

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PREFACE

Geophysical explorations in general and seismic methods especially have during the 20th century mostly been associated with hydrocarbon exploration. This is not because there are no other fields of application for seismic methods, but due to the fact that using seismic methods in other areas has not been economically feasible. Thanks to the rapid development of the computer science, seismic exploration methods have become less expensive and during recent decades, the interest for it has grown. One of the new fields in which seismic methods are applied is paradoxically the so called CCS (Carbon Capture and Storage), a technique developed to limit the global warming caused by hydrocarbon exploration and burning of fossil fuel. Often it is the same type of geological formation that has been of interest for the oil and gas exploration that is now suitable for CCS. For that reason, methods and knowledge developed by the oil industry are also applicable for CCS.

As a student of environmental engineering geophysics with seismic as one major concentration is a natural field to study. Its usefulness stretches all the way from groundwater supervision to the identification of polluted grounds. This thesis concludes my Master of Science program with a major in Environmental and Aquatic Engineering at Uppsala University. It covers 30 ECTS credits.

I would like to thank my supervisor Professor Christopher Juhlin at the Department of Earth Sciences, Uppsala University and the reflection and refraction seismic group at the Department of Earth Science, Uppsala University. GLOBE Claritas™ under licence from the Institute of Geological and Nuclear Sciences Limited, Lower Hutt, New Zealand, which was used to process the seismic data is gratefully acknowledged as well as the European Commission is for funding the CO_2 Storage by injection into Natural Storage site (CO_2SINK), Project no. 502599.

Uppsala September 2008

Nils Henoch

Printed at the Department of Earth Sciences, Geotryckeriet, Uppsala University, Uppsala 2008

POPULÄRVETENSKAPLIG SAMMANFATTNING

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Den globala uppvärmningen är det största överhängande hotet för vår och kommande generationer. IPCC (Intergovernmental Panel on Climate Change) har fastslagit att antropogena utsläpp av växthusgaser såsom koldioxid (CO_2) bidrar till den globala uppvärmningen. Utsläpp av koldioxid orsakas framför allt av förbränning av fossila bränslen. Exempel på fossila bränslen är olja, naturgas och kol. Idag är världen beroende av energi från fossila bränslen. På lång sikt är det möjligt att ersätta fossila bränslen med förnyelsebar energi från förslagsvis sol, vind och vatten. En sådan omställning kommer emellertid att ta tid och kräva hårdare krav på energieffektivisering. Dessförinnan kommer världen fortsätta att vara beroende av fossila bränslen och fortsätta släppa ut växthusgaser såsom koldioxid.

Det är först när koldioxiden når atmosfärer som den bidrar till växthuseffekten och den globala uppvärmningen. Därmed går det att minska den globala uppvärmningen genom att avskilja den koldioxid som bildas vid förbränning. Då det är stora mängder koldioxid som måste hindras från att nå atmosfären är det viktigt att utveckla passande förvaring för koldioxiden. Avskiljning och lagring av koldioxid (CCS) är en ny teknik som ska minska utsläppen av koldioxid till atmosfären. CCS genomförs i tre steg, avskiljning av koldioxid, transport av koldioxid till lagringsplats och slutligen måste koldioxiden injiceras till lagret. Vidare måste den injicerade koldioxiden övervakas för att utesluta läckage. Lagringsplatser som är lämpliga för lagring av koldioxid är bland annat stora havsdjup och olika bergrunder. En förutsättning för att lagra koldioxid i berggrund är att bergrunden innehåller hålrum. Bergrunder som har hög porositet och därmed mycket hålrum består oftast av sedimentära bergarter som till exempel sandsten. En salin akvifer utgörs av en kringskuren sedimentär bergart mättad med saltvatten och är speciellt lämplig för lagring av koldioxid. Den yttre gränsen för den salina akviferen ska utgöras av en tät bergart som gör det svårt för koldioxiden att avvika när den väl har injicerats. Vid välplanerade CCS projekt kan koldioxiden förbli i lager under flera miljoner år.

Ketzin CO_2SINK är ett CCS projekt i Tyskland som ska lagra koldioxid i en salin akvifer. Projektet är finansierat av EU och ska tjänstgöra som ett empiriskt forskningscenter för olika discipliner relaterade till CCS teknik. För att bestämma egenskaper hos berggrunden och övervaka den injicerade koldioxiden används geofysiska mätmetoder. En av dessa mätmetoder använder seismiska vågor för att kartera bergrunden. Seismiska vågor är vågor som breder ut sig i marken till följd av en jordbävning eller en explosion. Geofysiska mätmetoder använder oftast seismiska vågor genererade av explosioner eller stora släggor. De seismiska vågorna reflekteras mot berggrundens olika lager och genom at registrera de reflekterade vågorna kan man avgöra hur berggrunden ser ut och vilka egenskaper den har.

De seismiska undersökningarna har varit flera under CO_2SINK projektet. 2005 genomfördes en omfattande tredimensionell undersökning där man registrerade de reflekterade vågorna vid markytan. Resultatet från undersökningen var mycket användbart, men vissa osäkerheter fanns gällande tolkningen. Bland annat var det svårt att avgöra hur djupt det var till berggrundens olika lager och vilka reflektioner som hörde ihop med vilka lager. För att utesluta feltolkningar av undersökningen 2005 har resultatet jämförts med information från borrhåll i Ketzin och en kompletterande seismisk undersökning från 2007. Den kompletterande undersökningen betecknas VSP och mäter både de direkta seismiska vågorna och reflektionerna. Detta är möjligt då VSP registrerar de seismiska vågorna i borrhål istället för vid markytan. Med VSP undersökningar är det lättare att identifiera vilka reflektioner som hör ihop med vilka lager. Eftersom både den direkta seismiska vågen och reflektionerna registreras på olika djup blir det lättare att urskilja från vilket djup en viss reflektion har sitt ursprung. För att förstå informationen från en VSP undersökning måste insamlat fältdata filtreras på olika sätt. Bland annat är det viktigt att separera de direkta vågorna från reflektionerna. Filtreringen görs fördelaktigt digitalt på en dator.

I stort bekräftar den VSP undersökningen 2007 det tidigare resultatet från den mer omfattande undersökningen 2005. Emellertid kunde ursprunget från två av de registrerade reflektionerna i 2005 års undersökning ifrågasättas med hjälp av information från VSP undersökningen 2007. Vidare gav VSP undersökningen en mer detaljerad djupprofil av berggrunden samt mer information om hur fort de seismiska vågorna rör sig i Ketzins bergrund.

TABLE OF CONTENT

1. INTRODUCTION

The global warming is the prime environmental threat for our and forthcoming generations (IEA, 2004). Global warming is caused by anthropogenic emission of greenhouse gases like carbon dioxide (CO_2). Carbon Capture and Storage (CCS) is an attractive technique to reduce the emission of CO_2 and thereby prevent an accelerating global warming. To verify that the carbon dioxide remains in storage different types of measuring techniques have to be used. Seismic methods including vertical seismic profiling (VSP) have proven to be useful to choose suitable areas for CCS and to monitor the injected CO_2 (Chadwick et al., 2004).

In seismic surveying, geological structures are monitored using seismic waves. The aim is to map geological structures and, if possible, to determine their material properties. Between two layers of different physical properties an incident seismic pulse is partitioned into transmitted and reflected pulses. By recording travel-times and the amplitudes of the scattered pulse different characteristics such as depth, velocity and density can be determined for the subsurface (Figure 1) (Kearey and Brooks, 1991).

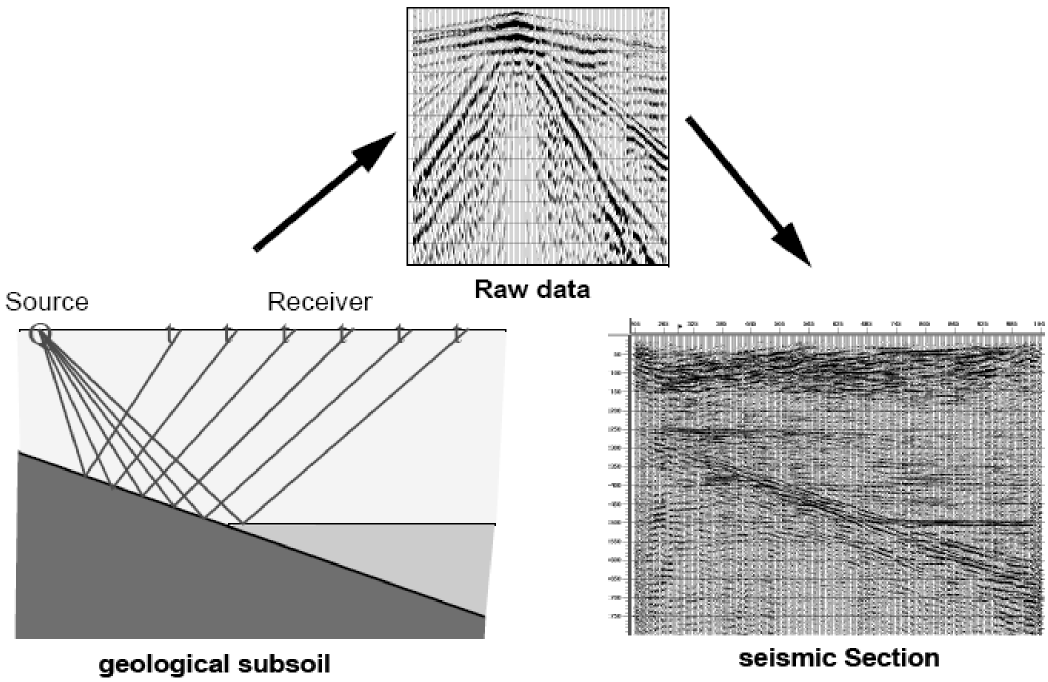


Figure 1 Schematic picture over the seismic methodology (Kruk, 2005).

For a standard seismic measurement both the source and receivers are placed on the surface. A disadvantage with this configuration is that only upgoing events can be recorded. To avoid this problem some seismic surveys place the source, the receivers or both in a borehole. One of these methods is called Vertical Seismic Profiling (VSP). In VSP shots are normally fired at the surface, at the wellhead or at some offset further away, and recorded at different depth within the borehole (Figure 2).

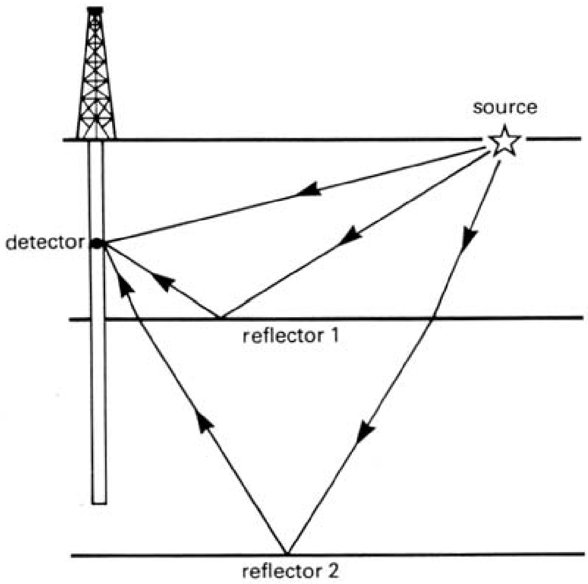


Figure 2 Typical offset VSP measurement (Kruk, 2005).

The EU project CO_2SINK aims to develop the basis for CCS by injecting CO_2 into a saline aquifer near the town of Ketzin in Germany (http://www.co2sink.org, 2008). Different types of seismic surveying have been carried out to determine the geological structure of the subsurface. Additional surveys will be carried out in the near future to monitor the injected CO_2. One of the methods used is VSP.

1.1. GOALS OF THE PROJECT

The main goal of the CO_2SINK project is to develop the basis for CCS technique by injecting CO_2 into a saline aquifer. One of the bases is the monitoring, using seismic methods, of the injected CO_2 in the aquifer.

Uppsala University is one of the main participants in the seismic part of the CO_2SINK project. During the fall of 2005 a 3D reflection seismic survey was completed. The interpretation of the survey was published September 2007 in GEOPHYSICS. Two months later borehole baseline seismic data were acquired, both Vertical Seismic Profiling (VSP) and Moving Source Profiling (MSP).

The objective of the VSP and MSP measurements was to obtain a higher resolution image of the subsurface in the vicinity of the injection site. This thesis focus on processing the VSP data acquired in late autumn of 2007. The result will be integrated with the 3D surface seismic data and data from the borehole. Main goals are to identify the location of the main reflectors in the borehole, to identify multiple reflections in the VSP and surface seismic data, and to obtain higher resolution images of the subsurface.

2. CARBON CAPTURE AND STORAGE (CCS)

CCS is carried out in three steps, separation of CO_2, transport of separated CO_2 to storage site and finally CO_2 injection. Moreover, the injected CO_2 must be monitored to exclude leakage. The biggest difference is between storage in seawater and storage in subsurface geological formations (only the latter is discussed in this thesis). The subsurface geological formation can be located under the sea or on land (IEA, 2004).

In 2007 more than 4 million tons carbon dioxide was injected into subsurface geological formations in three major storage projects: Sleipner in Norway, Weyburn in Canada and Salah in Algeria. Besides, summing up all Enhanced Oil Recovery projects (EOR), 40 million tons CO_2 were injected in formations containing oil to increase the oil extraction. Only 10 of the 40 million tons came from anthropogenic sources while the remaining came from natural subsurface CO_2 sources (Energimyndigheten, 2008). The global potential of long-term geological storage of CO_2 is estimated from 1000 to over 10 000 $GtCO_2$. As a comparison the global emission of CO_2 from fuel combustion amounted to about 24 $GtCO_2$ in 2001 (IEA, 2004).

Underground accumulation of CO_2 in reservoirs is a natural phenomenon. Existing EOR projects have proven that it is feasible to store CO_2 in subsurface geological formations. Depleted oil and gas reservoirs, unminable coal seams and saline aquifers can be used for storage of CO_2 (Figure 3). At depths over 800 meters, supercritical CO_2 has a liquid-like density. Thereby the storage space in the pores of sedimentary rocks is efficiently utilized (IEA, 2004). Storage of CO_2 in deep saline aquifers is believed to have the largest capacity for Europe (Juhlin et al., 2007). Saline aquifers are defined as deep sedimentary rocks saturated with salt water or brines.

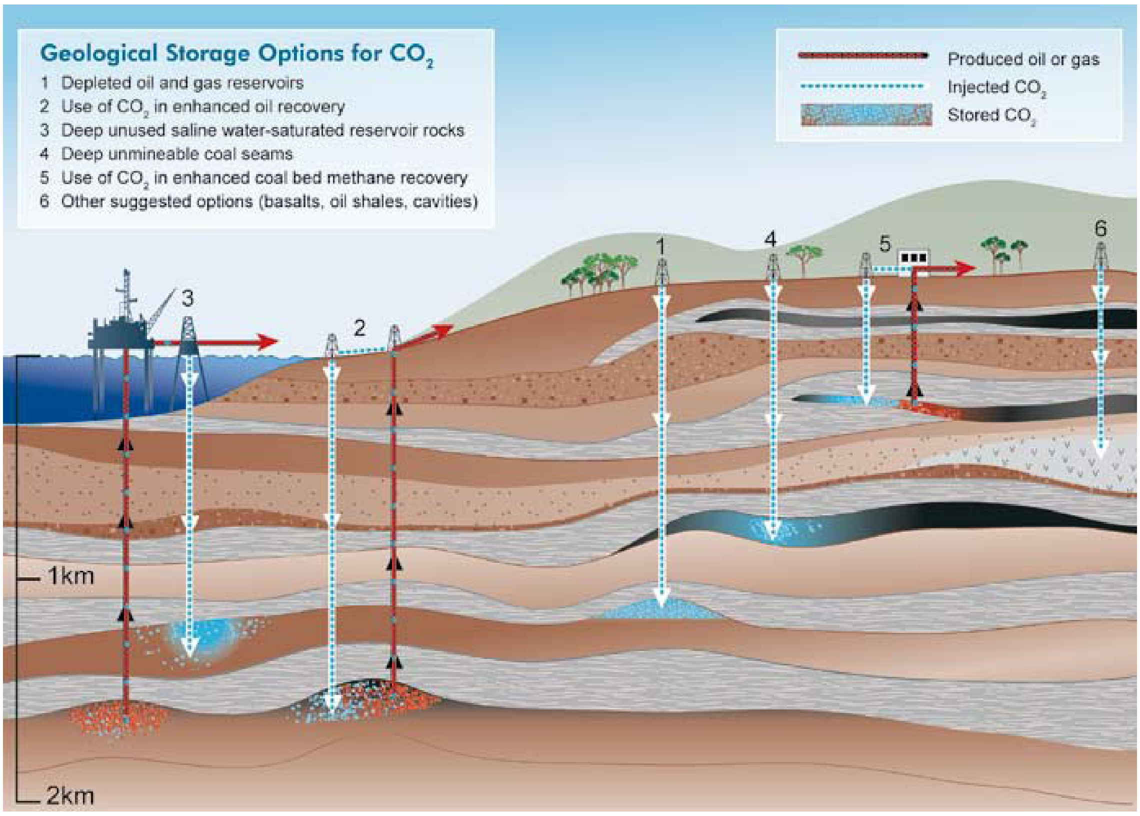


Figure 3 Options for storing CO_2 in deep underground geological formations (IEA, 2004)

CO_2 can remain trapped underground by different mechanisms, for instance: trapping below an impermeable confining layer (caprock); retention as an immobile phase trapped in the pore spaces of the storage formation; dissolution in current fluids; and/or adsorption onto organic matter in coal and shale. Additionally it may be trapped by reacting with the minerals in the storage formation and caprock to produce carbonate minerals. Finally, CO_2 becomes less mobile over time as a result of multiple trapping mechanisms (IPCC, 2005). By avoiding deteriorated wells, open fractures and faults injected CO_2 can be retained for millions of years (Energimyndigheten, 2008).

2.1. THE SLEIPNER PROJECT

The Sleipner Project in the North Sea is a good example of CO_2 storage in saline aquifer. It has been operated by Statoil since 1996 and is the first industrial scale CCS. The CO_2 is injected into the Utsira formation, 800 meters below sea bottom (Tore and Gale, 2004). The Utsira Sand consists of a basinally restricted deposit of Mio-Pliocene age. Its lateral spread is about 400 km from north to south and between 50 and 100 km from east to west (Figure 4) (Chadwick et al., 2004).

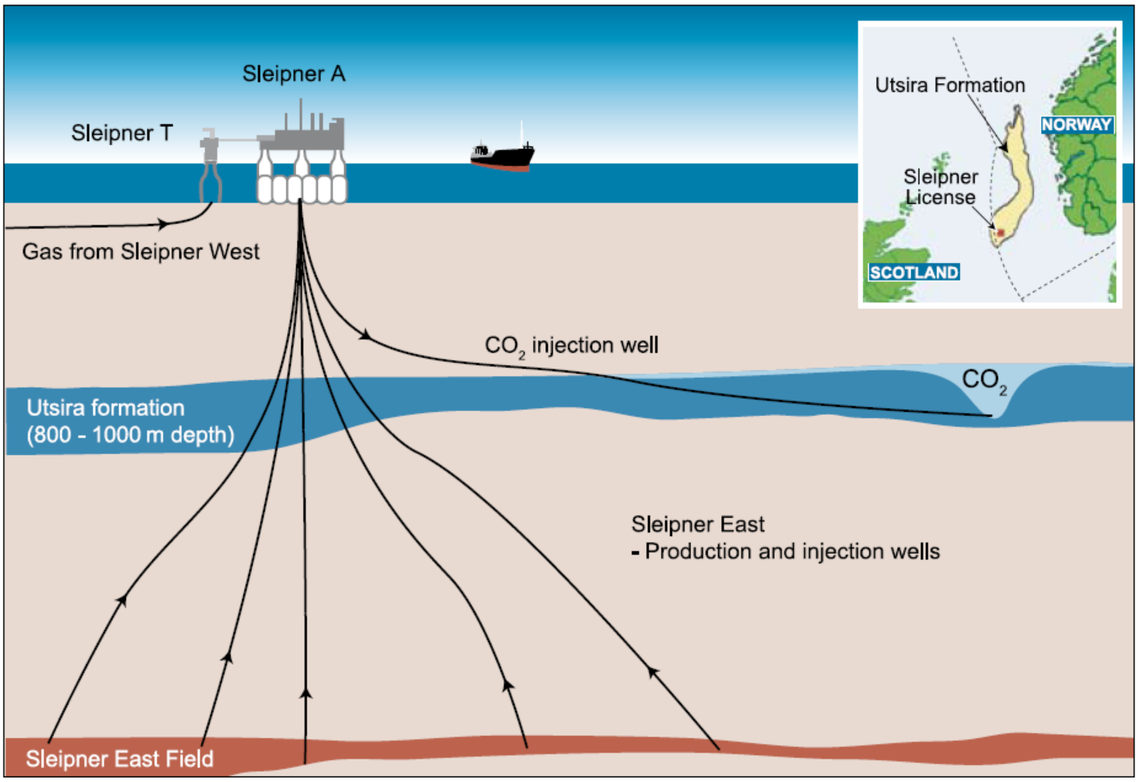


Figure 4 Simplified diagram of the Sleipner CO_2 Storage Project. Inset: location and extent of the Utsira formation (IPCC, 2005).

The caprock overlying the Utsira reservoir can be divided into three main units: lower seal, middle seal and upper seal. The lower seal known as the Shale Drape extends by a wide margin the area currently occupied by the CO_2 injected at Sleipner and forms the primary sealing unit. A regional map of the reservoir was constructed from about 16,000 line km of 2D seismic data, and logs from 132 wells. In addition 770 km^2 of 3D seismic data were completed and interpreted around Sleipner (Chadwick et al., 2004). Figure 5 below shows one of the seismic lines from the regional 2D survey.

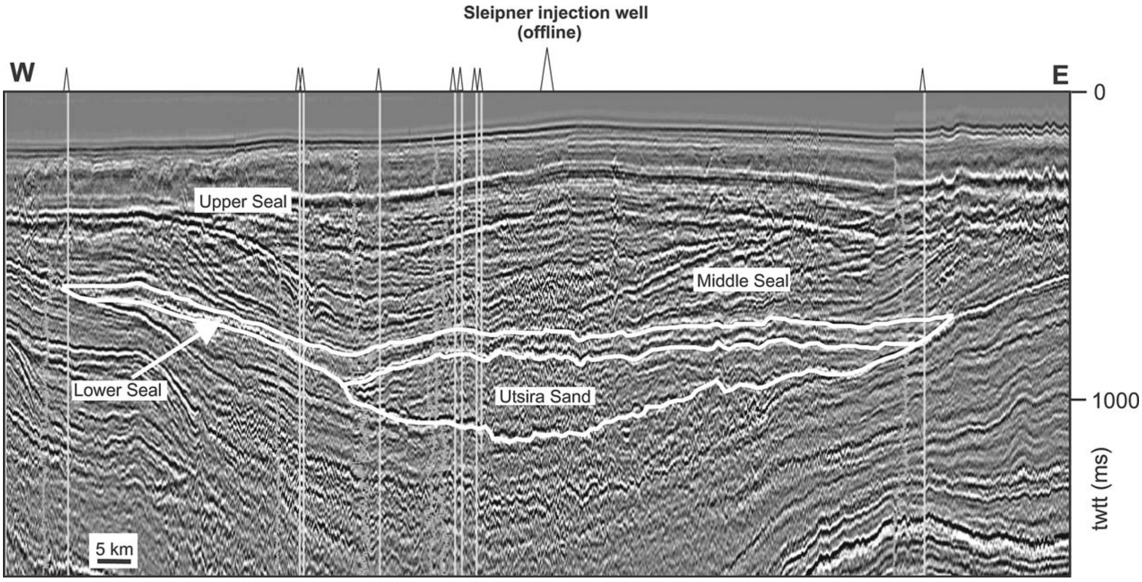


Figure 5 Regional seismic line through southern part of the Utsira formation (Chadwick et al., 2004).

The seismic project at Sleipner has been the foundation for the planning of the seismic project at Ketzin. Some of the major learnings from Sleipner are: an initial 2D seismic survey complemented with well log data provides an adequate basis for regional structural and physical property mapping which is suitable for strategic planning purpose; 3D seismic survey is necessary around the injection site; in spite of very detailed data, fine scale reservoir heterogeneities can be difficult to discover. These might seriously affect the CO_2 migration, in the case of Sleipner and possible also elsewhere. Because of these time-lapse seismic imaging of the CO_2 plume is needed to monitor the injected CO_2. To get an idea of the possible pathways of migration additional studies such as the development of reservoir depositional models may be helpful; a full caprock sealing evaluation, rendering core material, from both reservoir and caprock is also a desirable pre requisite (Chadwick et al., 2004).

2.2. IMPORTANT PROBLEMS (ENVIRONMENTAL ASPECTS)

CO_2 geological storage sites require adequate capacity and injectivity, satisfactory sealing caprock or confining unit and a sufficiently stable geological environment to avoid compromising the integrity of the storage site. When deciding storage site tectonic activity, sediment type, geothermal and hydrodynamic systems are used as characteristics regarding suitability. Whether a sedimentary basin is appropriate for CO_2 storage depends on its location on the continental plate. Mid-continental locations or locations near the edge of stable continental plates are often suitable because of their stability and structure. The same is true for basins found behind mountains formed by plate collision. The European basins immediately north of the Alps have such a location. Basins must however be assessed on an individual basis to minimize the risk of leakage (IPCC, 2005).

The environmental concerns regarding leakage are related to both local and global effects. The local health, safety and environmental hazards are due to three different factors:

1. Direct effects of toxic gas-phase concentration CO_2 in the shallow subsurface and near-surface environment.
2. Dissolved CO_2 in groundwater chemistry affecting local water supplies.
3. Effects that arise from the displacement of fluids by the injected CO_2.

The global concerns arise from the uncertainty whether the injected CO_2 will remain in storage where it does not contribute to the global warming (IPCC, 2005). There are many possible pathways from saline formations where carbon dioxide may escape. According to figure 6 below seven major types of leakage are possible (IPCC, 2005):

A. CO_2 pressure exceeds capillary pressure and passes trough siltstone.
B. Free CO_2 leaks into upper aquifer up fault.
C. CO_2 escapes trough gap in caprock into higher aquifer.
D. Injected CO_2 migrates up dip, increases reservoir pressure and permeability of fault.
E. CO_2 escape via poorly plugged old abandoned well.
F. Natural flow dissolves CO_2 at CO_2-water interfaces and transports it out of closure.
G. Dissolved CO_2 escapes to atmosphere or ocean.

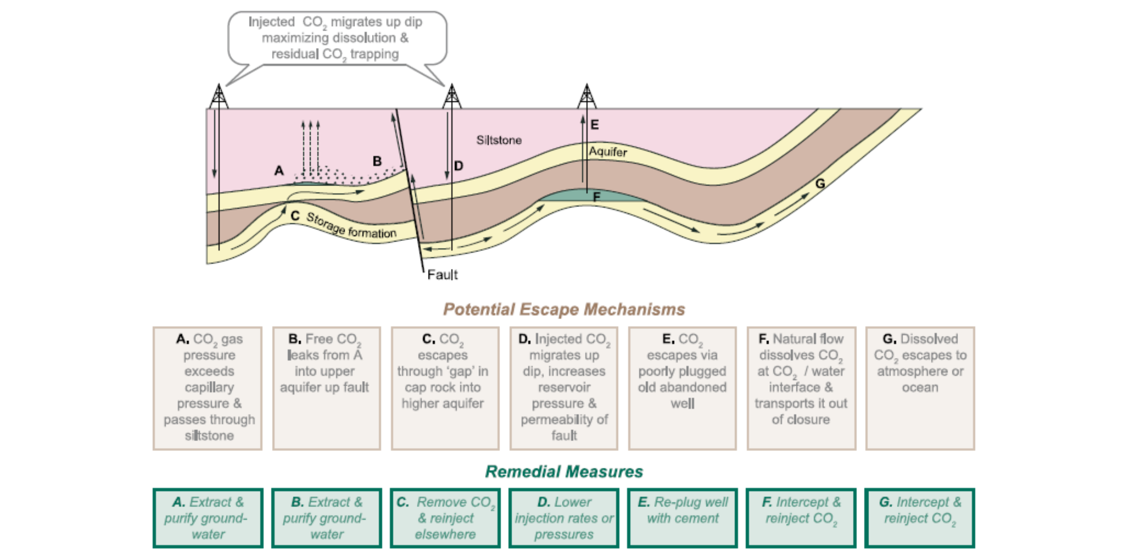


Figure 6 Some potential escape routes for CO_2 injected into saline formations (IPCC, 2005).

3. THE CO_2SINK PROJECT

The CO_2SINK started in April 2004. The European Commission initiated the project which it is also funding along with German funding agencies. By building a fully fledged onshore storage demo the project will use in situ methods to fill the gap between engineering and scientific studies on geological storage. The Ketzin site was selected for the CO_2SINK project because of the following reasons:

- Its geological structure is believed to be favourable for geological CO_2 storage.
- Already existing surface infrastructure from earlier gas storage.
- A strong support of the project from the local community and authorities.
- The short distance to Berlin makes it a good showcase for CCS technique.

During the project detailed analysis of samples of rocks, fluids and micro-organisms from the underground will be carried out. Furthermore the project involves intensive monitoring of the injected CO_2 using different geophysical and geochemical techniques as well as numerical models. The geophysical methods will focus on structural geometry for flow pathways within the reservoir and to evaluate their evolution as the reservoir is injected with CO_2 (http://www.co2sink.org, 2008).

3.1. THE SEISMIC PROJECT AT KETZIN

Seismic monitoring methods that have been applied include 2D and 3D surface survey, Crosswell, Moving Source Profiling (MSP) and Vertical Seismic Profiling (VSP) (Juhlin et al., 2007).

The first seismic investigation was a 2D survey carried out in 2004 as a pilot study. A more detailed 3D baseline seismic survey was performed in autumn 2005. The investigation covered an area of 14 km^2 to a depth of one kilometre. The fold of the survey was about 25 with a bin size of $12 \cdot 12\ m^2$. The main purposes of the 3D survey were to determine the structural geometry for flow pathways within the reservoir, to provide a baseline for comparison of before and after injection and finally to provide detailed subsurface images near the injection borehole for the drilling operations. In the future the 3D survey will be repeated in order to obtain a time-lapse data set (Juhlin et al., 2007).

In addition borehole seismic measurements like VSP, MSP and Crosshole have been, and will be used. MSP measurements use seismic receivers in a borehole while the seismic source moves to different locations on the ground surface. Crosshole tomography uses two boreholes. The seismic source is placed at different levels in the first borehole and the seismic response is recorded at different levels in the second borehole. All the borehole-based seismic measurements are used to get a higher resolution around the boreholes than ordinary surface surveys can resolve, both for the velocity models and the 3D image (http://www.co2sink.org, 2008).

3.2. GEOLOGICAL SETTINGS

The Ketzin site is situated in the Northeast German Basin (NEGB). NEGB is part of a Permian basin system that extends from the southern North Sea to Poland.

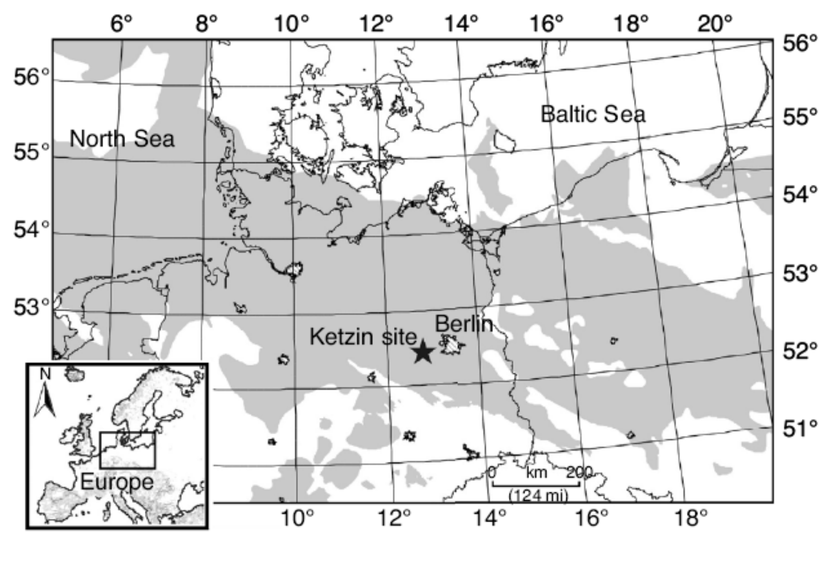


Figure 7 Location of the Ketzin site in the mid-European Permian Basin (gray shaded) (Juhlin et al., 2007).

The first origin of the basin was rifting in the early Permian. The following subsidence gave rise to the deposition of Permian clastic rocks and the Upper Permian Zechstein salt. The subsidence was rapid under the Permian but slowed down during the middle Triassic and early Jurassic (Juhlin et al., 2007). Throughout the Triassic, Jurassic and early Cretaceous major rift- and wrench-tectonics took place. It entailed the formation of local NNE-SSW directed depocenters in the NEGB. Through the late Cretaceous and Paleocene, which formed the Alps, the NEGB remained quite stable (Juhlin et al., 2007).

In NEGB a system of anticlines and synclines has formed. The foundation is a continuous salt flow since the Triassic which have formed pillows, walls and diapers (Juhlin et al., 2007). The Ketzin site is located in the eastern part of a double anticline called the Roskow-Ketzin Anticline. The anticline is formed above an elongated salt pillow situated at a depth of 1500-2000 meters and the axis strikes NNE-SSW like the overall depocenters. The flanks of the anticline are quite flat with a dip of about 15 degrees. Above the salt pillow the immediate overburden is geological formations of the Triassic and Lower Jurassic (http://www.co2sink.org, 2008).

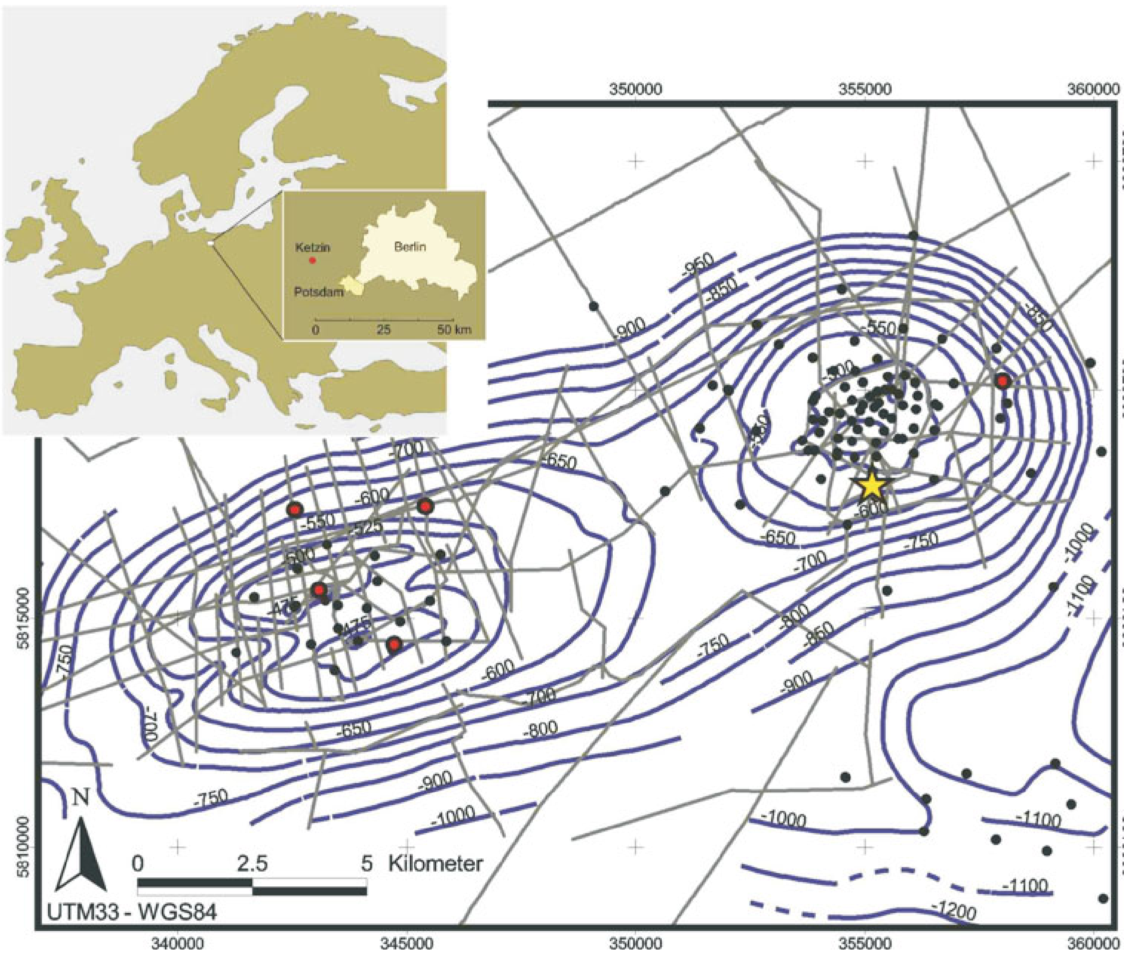


Figure 8 Index map of the Roskow-Ketzin anticline. Boreholes are shown as dots. Gray lines denote seismic lines of former exploration at Ketzin. The CO_2SINK injection borehole location is marked with a yellow star. Contour interval of the Heldburg-Gips isolines is 50 m (http://www.co2sink.org, 2008).

Ketzin anticline first began its uplift in the early Triassic. Later, about 140 Ma years ago, a major uplift took place which lead to total erosion of the Lower, Middle and

Upper Jurassic formations. All together over 500 m of rock has been eroded (Juhlin et al., 2007).

The first geologic formation unaffected by the anticlinal uplift is a sediment of the Oligocene. Because of the younger sediments the topography of the Ketzin area is relatively flat. However it does enclose some isolated highs consisting mainly of Quaternary sands (Juhlin et al., 2007).

The purpose of the CO_2SINK project is to inject the CO_2 into the 80 meters thick and lithologically heterogeneous Stuttgart Formation of the Middle Keuper (Upper Triassic) age at a depth of 500-700 metres (http://www.co2sink.org, 2008). The Stuttgart Formation consists of sandstone alternated with mudstone. It is the sandstone with its high porosity that makes the formation suitable as a CO_2 reservoir. The intervals of sandstone reach a thickness of tens of meters. The intervals are also attached to one another by subchannels with widths up to several hundreds of meters (Juhlin et al., 2007).

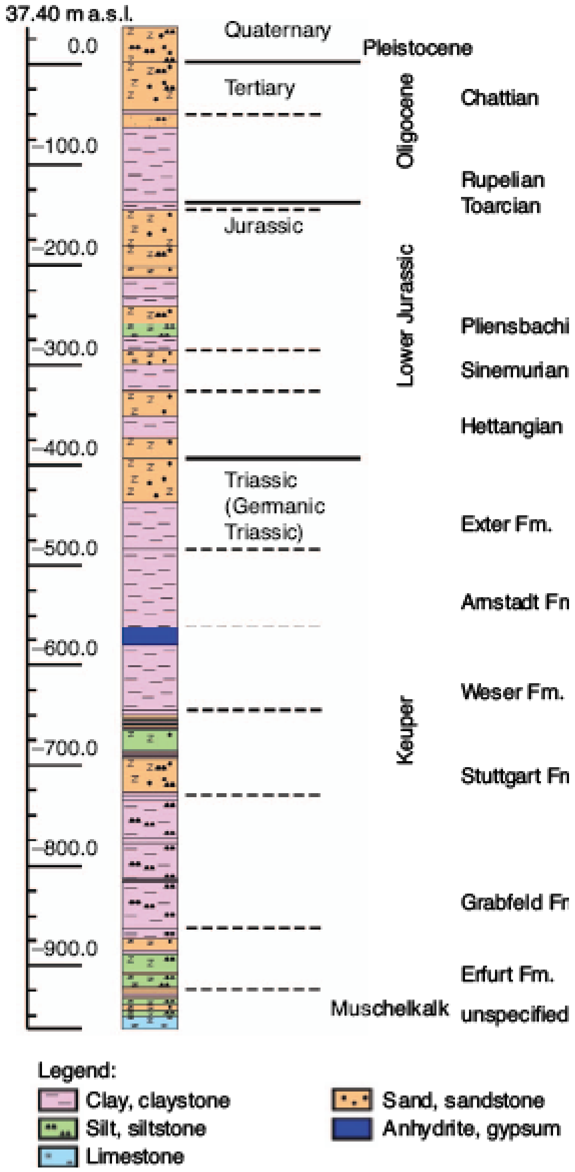


Figure 9 Stratigraphy of the Ketzin area based on drilling of the Ktzi 169/63 borehole (Juhlin et al., 2007).

Above the Stuttgart Formation lies a layer of thick playa-type rocks (of Weser and Arnstadt formation), forming a first caprock. The layer is stratal with claystone, silty claystone, and anhydrite. In Figure 9 a blue layer is marked between the Weser and Arnstadt formation. It is 10-20 m thick anhydrite layer known as the Heldburg-Gips. The layer gives a strong reflection and is accordingly called K2 (Keuper) reflector (http://www.co2sink.org, 2008).

Until 2000, natural gas was stored in Jurassic sandstone on a depth between 250 and 400 m. The sandstone is interlayered with mudstone, siltstone and anhydrite which form a multiaquifer system. Above the aquifer lies a 80-90 m thick layer of Tertiary clay (the Rupelton) that works as a major aquitard, separating the saline waters (brines) in the deeper aquifer from the nonsaline groundwater in the shallow Quaternary aquifer. Notably is that the Rupelton aquitard has been exposed for local erosion, causing dilution between fresh water and ascended salt water (Juhlin et al., 2007).

4. REVIEW OF THE VSP METHOD

Vertical seismic profiling (VSP) is seismic reflection surveying using boreholes. Normally the geophones are within the borehole and the source at the surface. If the source is located at the wellhead it is called zero-offset VSP. If there is an offset between shot and the wellhead the method is known as offset VSP (Reynolds, 1997). VSP is originally an expanded routine check shot velocity survey. The development started in the Soviet Union in the 1960s. Using boreholes in seismic surveying has many advantages such as investigate a target formation more closely with acoustic measurements. With a borehole subsurface attenuation phenomena are also minimized. Furthermore accurate depth measurements overcome the great limitation of all surface geophysical surveys, the lack of correct depth control (Kennett et al., 1980).

One essential aspect of VSP surveys is that both upgoing and downgoing rays are recorded. Figure 10 illustrates a very simple situation of two primary reflectors in the subsurface and the event pattern that would be generated in a VSP survey. The ray paths to two geophones positions are shown in the left figure. For simplicity the top geophone is drawn with only upwards travelling events and the lower geophone is drawn with only downwards events even if both the upper and the lower geophone receive both upgoing and downgoing events. The diagram on the right of the figure shows the expected pattern of events.

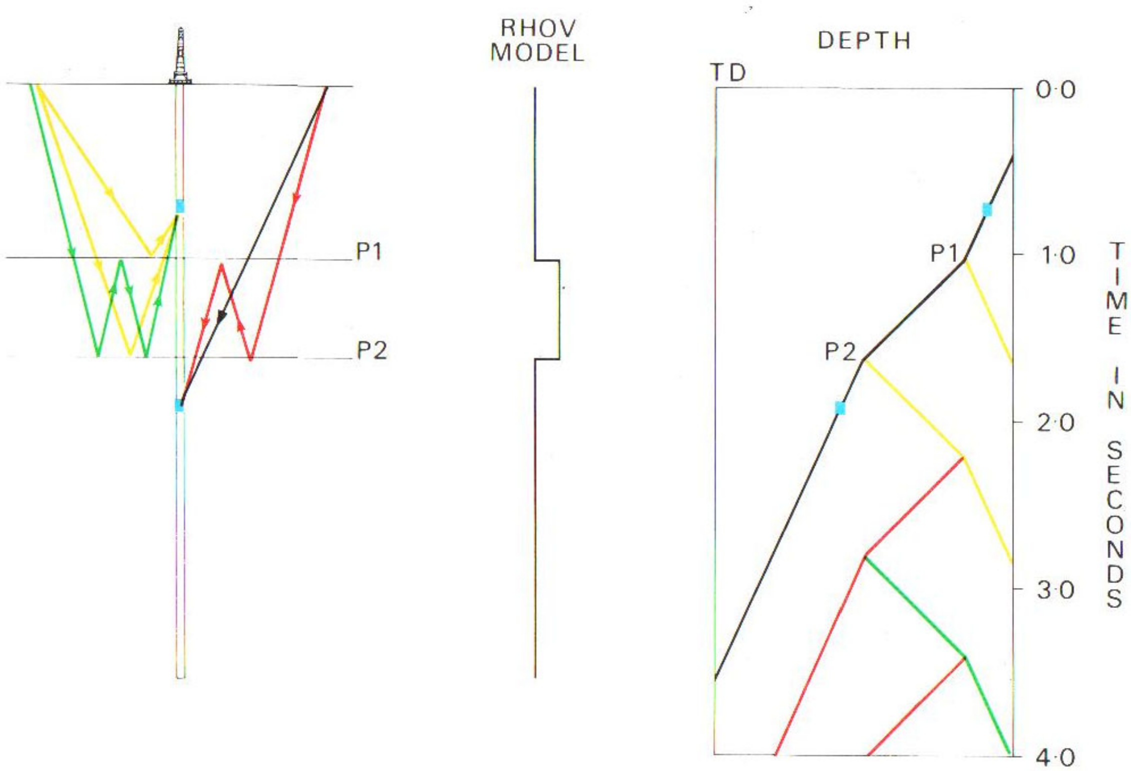


Figure 10 Schematic of ray paths and event pattern for 3-layer model (Kennett et al., 1980).

In Figure 10 yellow raypaths represent single reflection primary events, green raypaths are upgoing multiple bounce events. Both the yellow and the green events, when they emerge at the surface, constitute the seismic surface survey. The black events are direct arrival and the red events are multiple bounces arriving downwards. Neither the black nor the red events are observed on the surface seismic data (Kennett et al., 1980).

4.1. VSP DATA PROCESSING

VSP can, only be interpreted after extensive computer processing of the raw field data. Standard processing techniques used in surface seismic profiles usually must be modified to the conditions associated with VSP (Lee and Balch, 1983). Below the processing sequence presented by Lee and Balch in 1983 is accounted for. Details of the processing steps vary depending on the specific data set.

Edit

Each record is individually plotted for a first quality check. Noisy and other visibly unsuitable recordings are deleted from the data set at this stage.

Stacking

The record of one shot is often too weak and contaminated with noise to give a good signal. Several shots are often required for each detector level. Usually it is not until after stacking sufficient signal-to-noise ratio (S/N) is obtained. On account of uncorrelated ("white") background noise the S/N ratio improves approximately by $N^{1/2}$, where N is the stack fold.

Shot static correction

If many shots are stacked to improve the S/N ratio the source depth may change substantially during the time of the survey. This can cause change in recorded arrival time due to changed source-receiver geometry. The direct arrival time from shot *i* to the well phone is:

$$T_i = \frac{\sqrt{l^2 + (H - d_i)^2}}{V} \qquad (1)$$

Where T_i is direct arrival time at the first geophone from shot location *i*. *l* is shot offset distance from the centre of the well, d_i is shot depth of the shot location *i*. *H* is the depth of the first geophone. *V* is the average velocity in the region between the source and the receiver. The correction time for shot 2 ($d_2 = d_1 + \Delta d$) will be:

$$\Delta T = T_2 - T_1 = T_1\left[\sqrt{1 + \frac{\Delta d(\Delta d - 2H + 2d_1)}{l^2 + (H - d_1)^2}} - 1\right] \qquad (2)$$

Equation (2) is the exact equation used for the shot static correction. If $H >> l$ and $H >> d$ or $l = 0$ an approximated equation for the shot static correction can be used:

$$\Delta T \cong \frac{-\Delta d}{V} \qquad (3)$$

The latter equation is often used for geophones deep down while equation (2) is used for shallow geophones.

Frequency analysis and band-pass filtering

Even when initial editing has been performed noise often remains. Further improved S/N ratio can often be obtained by band-pass filtering. Moreover coherent tube noise can be suppressed in this manner. Foremost spectral analysis is required to determine signal, coherent noise and random noise frequency bands. The best thing to do is to design a filter to pass only the signal frequency band. Sometimes noise partly lies within the same frequency as the signal, but even in these cases the S/N ratio is often improved by band-pass filtering.

Amplitude analysis

Geometrical spreading, loss in downward-travelling energy due to upward reflection, intrabed multiple effects and inelastic attenuation all contribute to amplitude decay with increasing depth. Difference in amplitude can be as much as 10^6 to 1. Geometrical spreading is neither dependent of frequency nor related to the subsurface rock properties. Consequently it is desirable to remove its effects before making geological interpretation. Furthermore it is common to make some additional compensation besides geometrical spreading. The amplitude of the first arrival is fitted by least square to the following function:

$$\frac{ce^{-\alpha R}}{R} \qquad (4)$$

Where *R* is the distance from the source or is the arrival time, *c*, *n* and α are constants. The quantity *R* helps to account for geometrical spreading, *n* and α help compensate for transmission losses and attenuation, *c* is an arbitrary constant or scale factor.

Transmission losses and attenuation is frequency-dependent why *n* and α may vary with the frequency range of data.

When using VSP data it is extra important to be careful when making gain compensation function. This is because of the existence of tube noise. Since the amplitude does not fall off with time at the same rate as other events enormous tube noise amplitude in the gain-compensated data may be generated.

Multichannel velocity filtering

In regular seismic surface surveys all recorded events are upgoing waves. In VSP recorded events consist of both downgoing and upgoing events. To identify the different events it is often needed to separate the upgoing and downgoing waves.

In multichannel velocity filtering apparent velocity of coherent events on a set of adjacent traces is used to distinguish the upgoing events from the downgoing. Velocity filtering is the most important step in processing VSP data. By picking out the upgoing events it is possible to identify a reflected event and its point of origin.

Downgoing wave train deconvolution

The ideal seismic record would come from a spike, or short impulse. Unfortunately reverberation of seismic energy from the surface and other layers makes shots to a scrambled mixture of wave trains, not a series of discrete pulses from each layer. This fact makes it hard to do geological interpretation of raw data. Deconvolution computes a set of data that is an estimate of the recordings that would have been if the downward wave had been a spike or short impulse at every depth. This is done by autocorrelation of the recordings at each level. After this it is possible to calculate a downgoing wave-spiking filter, a deconvolution operator for a shallow recording, and apply this operator to all deeper depth.

Vertical stacking

To improve the S/N ratio further, vertical stacking is often used. This is done by time shifting the data from two or more adjacent levels to align coherent events. Subsequently the shifted events are added in an appropriate way, to enhance coherent events. There are many types of stacking processes. Local vertical stacking, when *N* is odd, is defined by the following formula:

$$\bar{S}_J(t) = \frac{1}{N}\sum_{i=1}^{N} S_{i+k}(t)\, f_i(t) \qquad (5)$$

N is the number of traces to be stacked, $S_i(t)$ is the input at depth level *i*, $S_J(t)$ is the output at depth level *J*, *k* is equal to $J-½(N+1)$ and $f_i(t)$ is the filter function. The best choice of $f_i(t)$ and *N* depend on the local variation of the S/N ratio, frequency content, degree of coherency and the spatial resolution desired.

Transfer function

A recorded seismogram could be interpreted as an output of the convolution of a shot wavelet and some function corresponding to the reflectivity of the subsurface. In mathematical terms this explanation can be described by:

$$S(t) = W(t) \bullet f[R(t)] + N(t) \qquad (6)$$

Where S(t) is the recorded signal, W(t) is the shot wavelet, N(t) is noise assumed to have an uncorrelated random distribution. R(t) is the reflectivity of the subsurface and • means convolution.

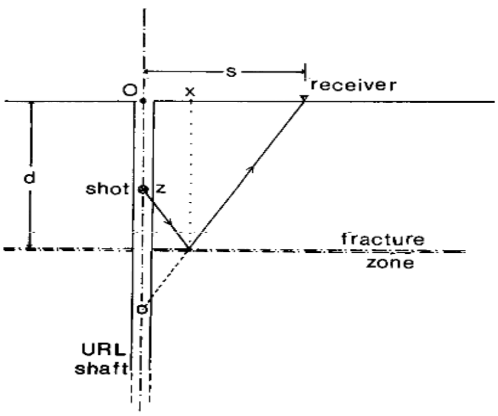
The concept of transfer function is very significant for seismic data interpretation while intricate detailed analysis of the interaction between the wave field and the rock, within some given section of earth, can be avoided. Instead the attention can be focused on the way a section of earth, taken as a gross unit, changes the seismic input into seismic output. Through this approach, all the acoustic properties of the rock unit are described by the transfer function.

Impedance log estimation

Impedance calculation using VSP data is easier to make and more accurate than using surface reflection data. This is because the seismic source is more accurately known and the reflected wave field can be measured near the reflecting sequence of interest. The first thing to do when estimating the impedance is to calculate the transfer function. Assume that each peak or trough in the transfer function corresponds to a change in impedance. The first impedance log is made by a good guess. Later on the change in impedance from the amplitude of each prominent event is calculated. Final each change is added to the previous impedance value to generate a new value.

4.2. ADDITIONAL PROCESSING STEPS

Besides the processing sequence given by Lee and Balch several other papers have been written concerning offset VSP. The VSP-CDP transformation for offset VSP described by Carswell and Moon (1989) was used here to process the offset VSP. The transform assumes a single-offset VSP trace in a medium consisting of one layer over a half-space which gives the following travel time for a primary reflection:



$$T = \frac{\left[s^2 + (2d - z)^2\right]^{1/2}}{V} \qquad (7)$$

$$x = \frac{s(z - d)}{(z - 2d)} \qquad (8)$$

Figure11 Schematic diagram showing a simple raypath configuration (Carswell and Moon, 1989).

Where *V* is the velocity of the upper layer, *s* is the horizontal source offset from the borehole, *d* is the depth of the layer, *x* is the offset to the CDP location, *z* is the depth. In conventional seismic surface surveys, the CDP lies at the midpoint of shot-receiver spread regardless of the depth of the reflector. In the VSP configuration, the CDP migrates horizontally through the subsurface as a function of reflector depth. As the depth of the reflector increases, the CDPs from both methods converge. Equation (7) is similar to the normal moveout equation (9), used for surface seismic:

$$t^2 = t_0^2 + \frac{x^2}{V^2} \qquad (9)$$

Where t_0 is the arrival time for zero offset, x is the offset, V is the velocity and t is the arrival time for offset shot. If $d >> z$ equation (9) can be used instead of equation (7). It is however only an approximation and since a constant velocity most be used for all primary reflections the error becomes even bigger.

Hampson and Meworth presented a paper in 1983 were they used VSP to investigate a multiple problem in western Canada. They showed that, by compositing VSP traces to produce the primaries-only and the primaries-plus-multiples responses, residual multiple effects could be unambiguously identified in surface seismic data. After a data processing similar to the one described by Lee and Balch, the authors tried some different vertical stacking to indentify multiple reflections. The figures below show the two different types of vertical stacking and the difference in correlation with surface seismic data.

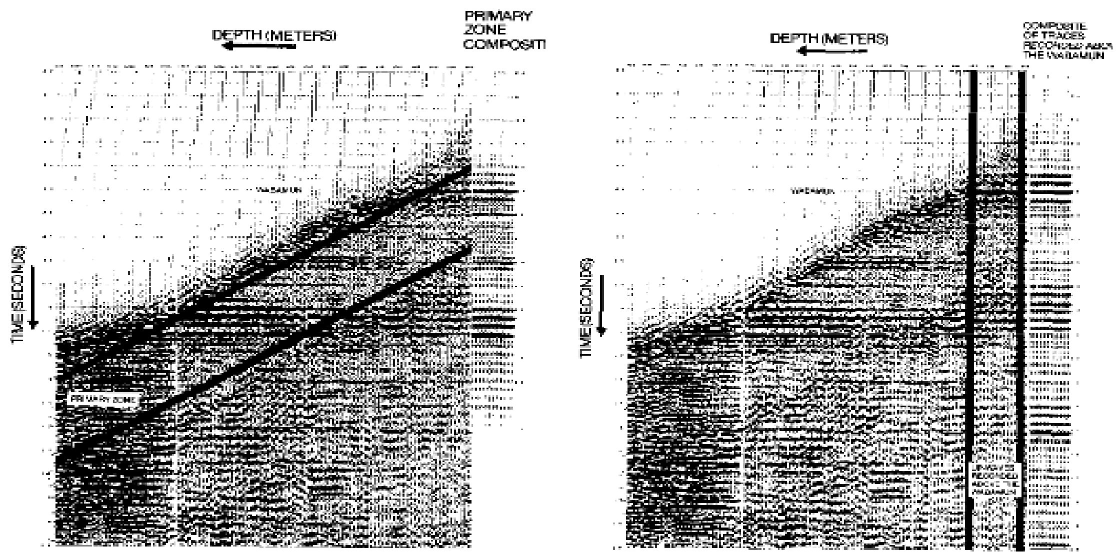


Figure 12 Two different vertical stacking of Up-wave dephased VSP, filtred to match seismic data (Hamson and Mewhort 1983).

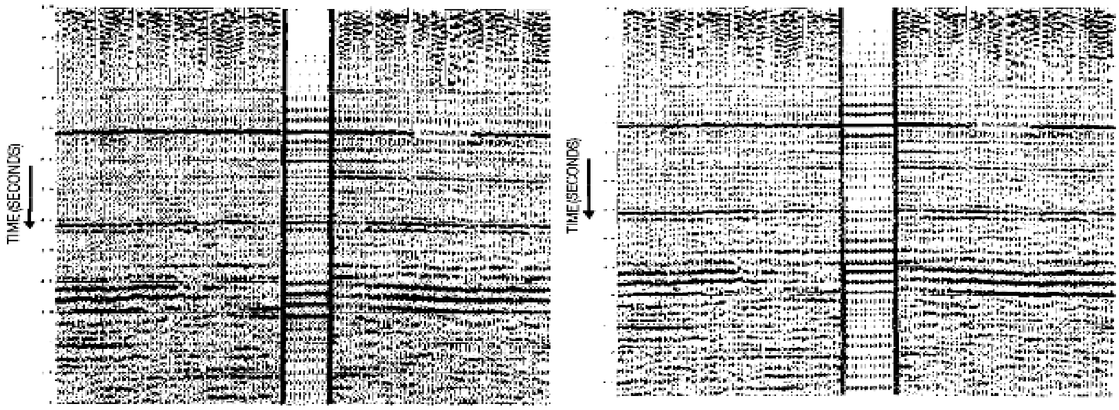


Figure 13 Seismic data correlated with (left) primary zone VSP composite and (right) VSP composite, recorded above the major multiple generating layer (Hamson and Mewhort 1983).

By stacking according to the primaries-only the need for deconvolution decreases. As previously mentioned, deconvolution is used to reduce multiple energy, but through stacking the primaries-only little multiple energy remains in the stacked section.

5. DATA ACQUISITION

The VSP survey was performed during November and December 2007. The measurements were carried out with a swept impact seismic source called VIBSIST 1000, the same used in 2005 for the 3D survey. The VIBSIST 1000 can produce both shear and compressional waves. Its impact energy reaches 2500 joule and it is working with a frequency between 340-680 blows/min. The geophones used were 3 component R8XYZ-cg geophone chains. Finally a 100 channel DMT Summit II 24 bit distributed acquisition system was used for the recordings (Figure 14) (Surface Geophysics (WP 6.3): VSP/MSP Baseline, 2008).


Figure 14 VIBSIST 1000, channel DMT Summit II 24 bit distributed acquisition system and a 3 component R8XYZ-cg geophone chain from left to right (Surface Geophysics (WP 6.3): VSP/MSP Baseline, 2008).

The geophones were placed in borehole 202/2007. The recording started at 325 meters and ended at 720 meters. The spacing between the geophones was 5 meters, implying the use of totally 80 geophones. The VSP survey covered a smaller region than the 3D around the injection site. The source was placed at 14 different locations along the 7 lines used for the 2D time-lapse survey. Figure 15 shows the configuration of the survey.

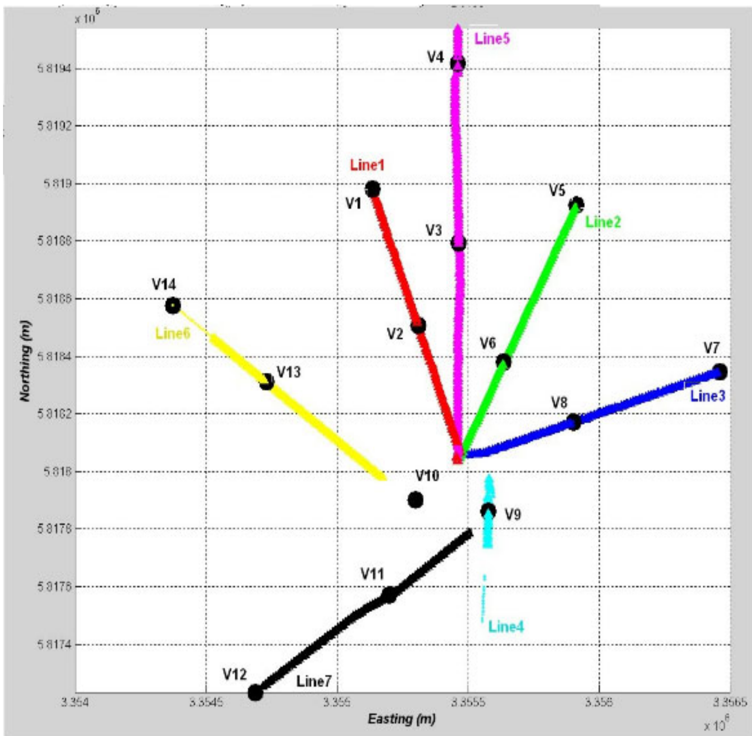


Figure 15 Configuration of the VSP survey in 2007. (Surface Geophysics (WP 6.3): VSP/MSP Baseline, 2008)

The coordinates and elevation for the shot points are shown in Table 1 below:

Table 1 The coordinates and elevation for the shot points

Shot	UTM northing (m)	UTM easting (m)	elevation (m.a.sl.)	offset (m)
1042	5818508.00	3355309.00	32.3	606.1
1084	5818980.50	3355136.25	33.5	1090.6
2033	5818380.00	3355636.00	34.7	585.4
2084	5818926.00	3355912.75	37.9	1194.4
3039	5818170.50	3355900.75	35.9	659.8
3088	5818346.00	3356460.75	34.4	1244.6
4010	5817862.00	3355576.50	34.4	281.4
5064	5818794.00	3355464.00	33.2	907.3
5116	5819418.00	3355460.00	33.7	1524.6
6047	5818311.50	3354730.00	37.6	700.2
6084	5818577.00	3354374.00	36.4	1144.3
7033	5817570.50	3355198.25	34.2	346.2
7084	5817233.50	3354688.00	33.5	905.0
zero-offset	5817902.00	3355298.00	34.0	0

6. DATA PROCESSING

The data processing was done in GLOBE Claritas^{TM} on a LINUX computer. The main processing steps (Table 2) were kept simple to minimize the risk for introducing artifacts into processed volumes. Some additional processing steps were acquired for the offset VSP compared to zero-offset VSP. Furthermore, different vertical stacking was used as well as different conversions to integrate the data with 3D surface seismic data, borehole data and to identify multiple reflections. Appendix A shows screen dumps of the continuous workflow done in GLOBE Claritas^{TM}.

The data was gathered through “common shot”, though it is also possible to process VSP data gathered through “common receiver” (Kearey and Brooks, 1991). The initial quality check showed that the resolution of the data was not as good as expected. Besides, the quality of the data deteriorated with increasing offset. The biggest problem with the far offset data was the bad resolution of the first arrivals, a shortage that made further processing very difficult. Figure 16 shows an example of raw data from shot 4010 (offset=281,4 meters) and figure 17 shows an example of raw data from shot 6084 (offset=1144,3 meters). The comparison shows that far offset shot contain less first arrival energy than near offset shot. The zero-offset shot had, compared with offset VSP, good quality except for strong coherent noise in the upper geophones. This was managed by removing all traces recorded above 460 metres depth.

Table 2 Main processing steps applied to the VSP data set.

Step	Parameters
1	Read raw data
2	Vertical shift and stack
3	Extract and apply geometry in addition to calculate the offset
4	Sorting to common shot gather
5	Initial quality check
6	Rotatation of the azimuth angle
7	Initial velocity analysis of first arrivals and primary reflections
8	Bulk static shift to compensate for source delay: 25 ms
9	Elevation static: datum 30 m, replacement velocity 1800 m/s, v_0 1000 m/s
10	Trace edit
11	Synthetic trace interpolation of deleted traces
12	Spherical divergence correction: v^2t
13	NMO for offset VSP using constant velocity: 2310 m/s
14	Pick first arrivals
15	Add pick of first arrival to header
16	Align coherent downgoing energy horizontal, using first arrival
17	Subtracting downgoing events by a horizontal velocity filter
18	Align coherent upgoing energy horizontal, using first arrival
19	Enhance upgoing events by horizontal velocity filter
20	Mute before stacking, either to obtain primary zone VSP composite or VSP composite, recorded above the major multiple generating layer
21	Automatic gain control
22	Vertical stacking
23	Gather 9 copies of stacked section for correlation
24	Band-pass filter: 7-14-60-80 Hz
25	Correlation between depth converted zero-offset VSP and Stratigraphy of the Ketzin area based borehole 202/2007
26	Correlation between zero-offset VSP and borehole data, using synthetic generated seismogram
27	Integrate stacked VSP section in 3D surface seismic data

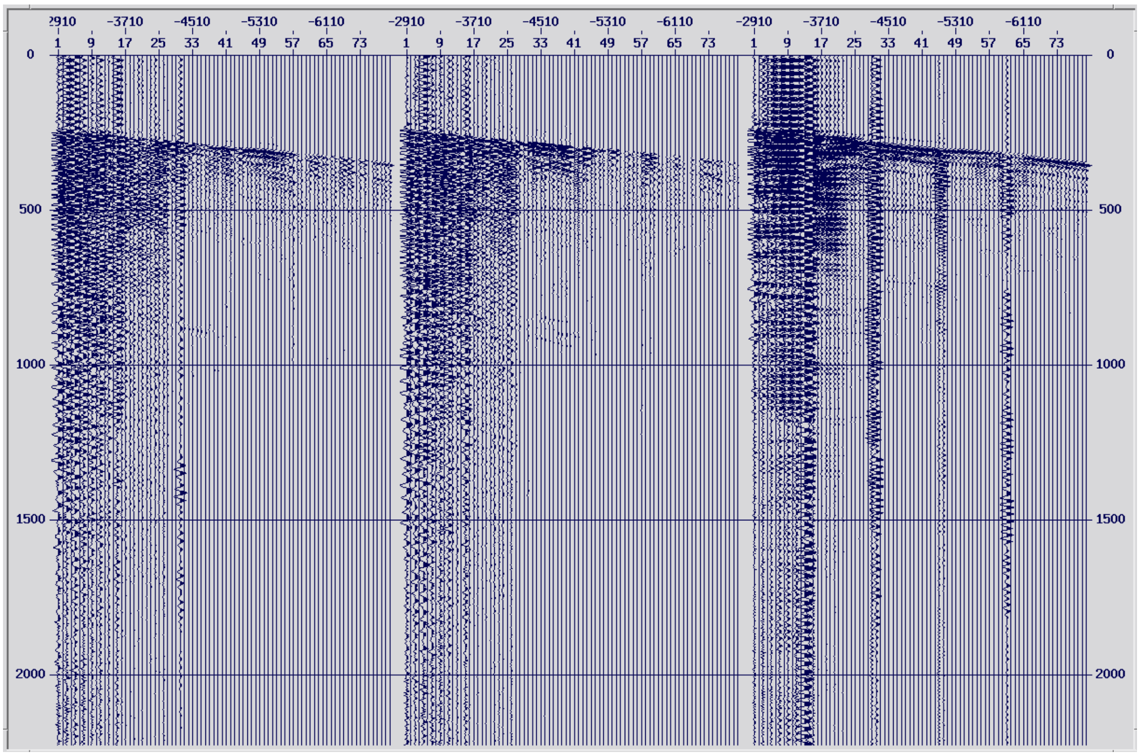


Figure 16 Raw data from shot 4010 (offset=281,4 meters). H1, H2 and V component from left to right.

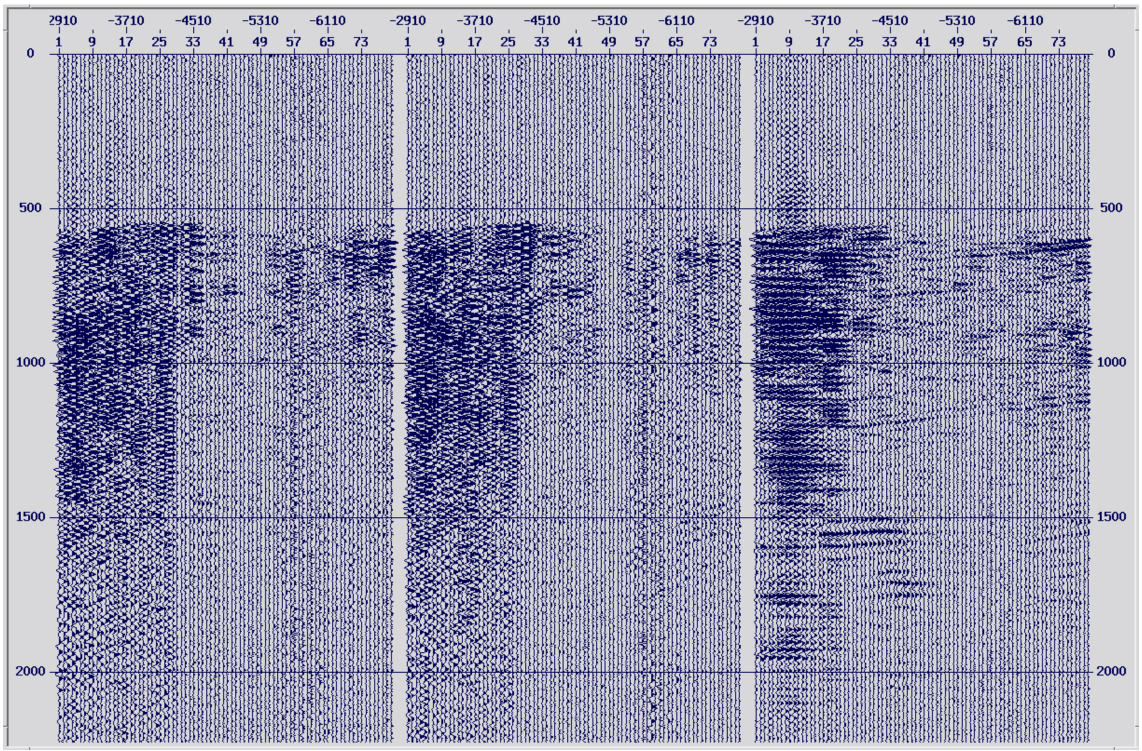


Figure 17 Raw data from shot 6084 (offset=1144,3 meters). H1, H2 and V component from left to right.

The motive for rotating the azimuth angle was to obtain two seismogram with outstanding P-wave energy from each shot. Since upgoing and downgoing events have different directions, rotating should gather upgoing and downgoing events on the H2 and V component. The rotation was however unsuccessful while the V component was the only component suitable for P-wave analysis.

The initial velocity analysis showed that the average velocity of the upper layers was relatively low. The average velocity down to 460 metres depth was 2210 m/s while the average velocity between 460 metres and 700 metres was 3050 m/s. This first estimate of the velocity profile was also confirmed by an earlier report regarding the velocity profile (Yordkayhun et al., 2007). The initial velocity analysis also identified the primary reflection of the Heldburg-Gips (K2) which could only be seen on geophones above 550 meters depth. This agrees with the Stratigraphy of the Ketzin area based on borehole 202/2007.

Bulk static shift was performed to compensate for source delay. A datum level of 30 meters was added since the 3D survey used the same datum level. Traces with severe noise were removed. Because of the bad quality of the data up 10 traces were removed from individual shots. In order to simplify the processing the removed traces were linearly interpolated using the fourier transform domain, frequency and primary key (SHOTID).

NMO correction was applied on offset VSP using constant velocity and offset. The offset was set to the distance separating the wellhead and the shot. The velocity was set to 2310 m/s since the initial velocity analysis showed that the average velocity down the K2 reflector was 2310 m/s. The K2 reflector was chosen as reference because it had the strongest primary reflection. Because of NMO correction used a constant velocity events above K2 shifted little downdip and events below K2 shifted little updip. However if a NMO correction with varying velocity would be used many of the events would have been damaged.

The first arrivals were picked automatically with settled velocity and time to define initial picking. The picks were also checked manually for errors and replaced if necessary. The pick of the first arrival was used to line up the downgoing and upgoing events horizontally. This was done by subtracting or adding the first arrival to the traveltime and thereby align coherent energy horizontally. As stated by Lee and Balch (1983) velocity filter is the most important step in processing VSP data. By selecting the upgoing events it is possible to identify a reflected event and its point of origin. Figure 18 shows the workflow of the velocity filtering of the zero-offset shot. Some trace balance is added to the data for an easier overview.

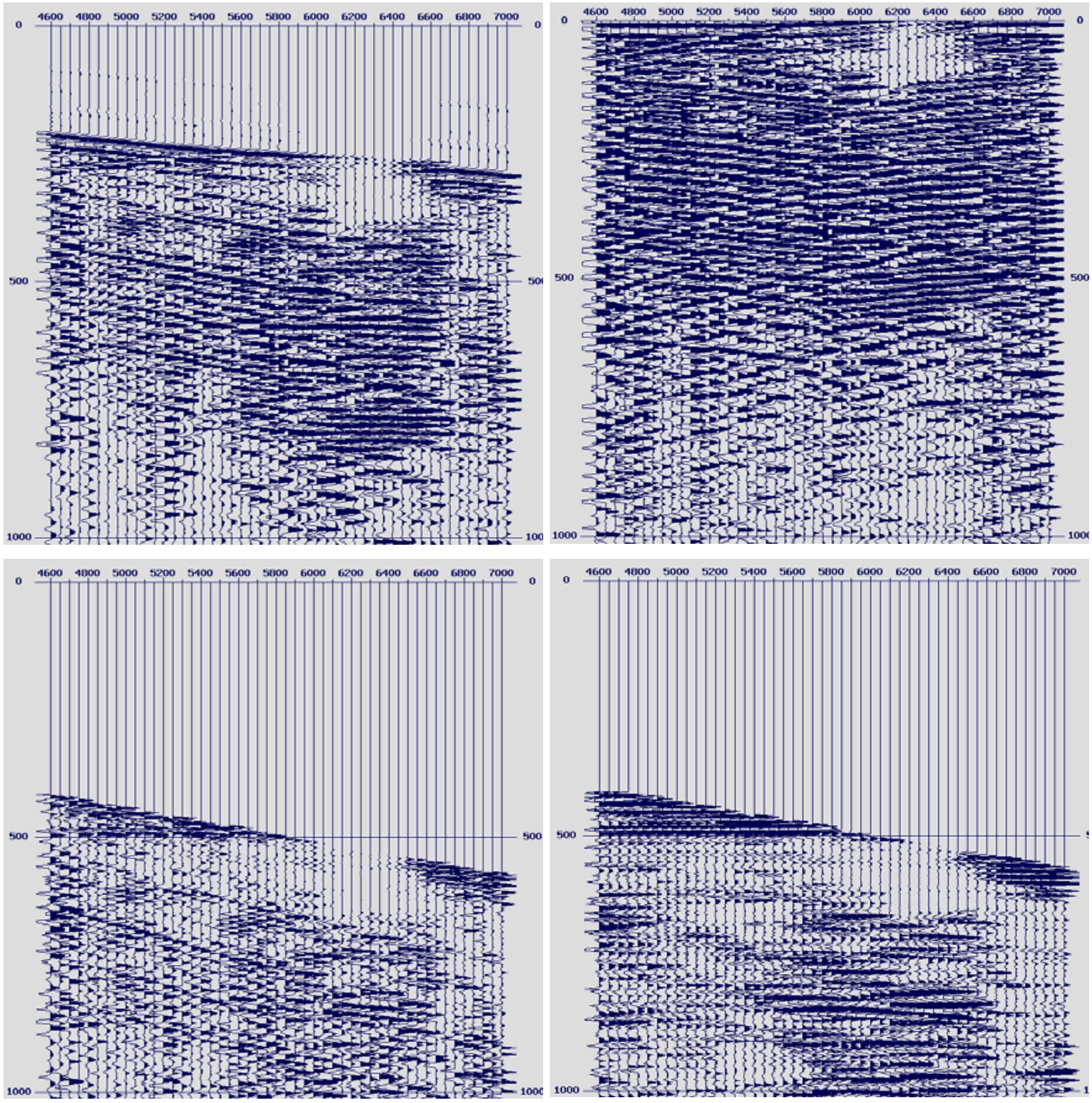


Figure 18 Seismogram of zero-offset shot. Top left: Before shift of first arrival. Top right: After align coherent downgoing energy horizontal, using shift of first arrival. Bottom left: After horizontal velocity filter of downgoing events plus opposite shift of first arrival. Bottom right: Upgoing events after positive velocity filtering of horizontal events.

Further processing steps differed a lot depending on which data the VSP was integrated with. Some of them included different types of muting to stack different events according to Hampson and Mewhort (1983). In order to correlate the VSP composite with the surface seismic data, it was necessary to filter the broadband VSP to match the relatively narrower band surface seismic. For the most part a bandpass filter (7-14-60-80 Hz) was used for this. The zero-offset VSP was in addition depth converted for correlation with the stratigraphy of the Ketzin area based on borehole 202/2007.

7. CORRELATION OF VSP DATA WITH BOREHOLE DATA

Only the zero-offset shot was used for correlation with borehole data. This is due to the fact that only zero-offset VSP has its reflection points at the borehole. Offset VSP has its reflection points between the shot and the borehole and is therefore better correlated with surface seismic. To correlate the VSP with borehole data two different approaches were used.

7.1. CORRELATION OF DEPTH CONVERTED VSP WITH STRATIGRAPHY

The first approach used a time to depth conversion module in GLOBE Claritas called TDCONV1. The process required a velocity model, which was calculated from the initial velocity analysis. Various complex velocity models were used to obtain the best correlation. The depth converted stacked VSP section was compared with the stratigraphy based on borehole 202/2007. Figure 19 shows the correlation of the best velocity model where the velocity was set constant to 2310 m/s.

Since all traces above the depth of 460 meters were removed, in the initial state of the data processing, no reflections above this level could be seen in the zero-offset VSP. There was good agreement between the strongest reflection (K2) and the Heldburg-Gips. Furthermore, it was possible to distinguish some reflections belonging to the upper Arnstadt Formation and upper Stuttgart Formation. However the reflection belonging to upper Arnstadt was shifted downdip while the reflection belonging to upper Stuttgart was shifted updip. This was due to the fact that the velocity model uses constant velocity. The velocity was too high for depth conversion above the K2 reflector and to low below the K2 reflector. Nevertheless, the best agreements between the stratigraphy and the depth converted VSP were obtained using a constant velocity model. Models with more velocities tended to stretch the data in an undesirable way.

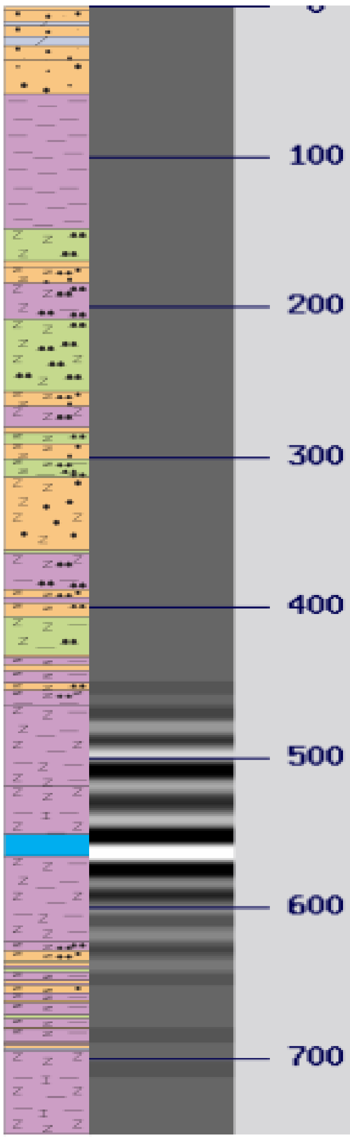


Figure 19 Correlation between borehole stratigraphy and depth converted zero-offset VSP (see Figure 9 for more detailed explanation).

7.2. CORRELATION BETWEEN VSP DATA AND SYNTHETIC SHOT

In addition, to the correlation between depth converted VSP and stratigraphy from borehole 202/2007, the stacked zero-offset VSP was correlated with 1D synthetic generated seismogram based on the velocity log from the same borehole. As in the earlier correlations, various complex velocity models were used. The synthetic seismogram was generated using the reflectivity method. To generate the synthetic waveform, thickness (T) velocities (V), densities (ρ) and attenuation (Q) were required as input parameters for the different layers. To simplify the models, density and attenuation were set to constant. Same elevation statics (datum 30 m, replacement velocity 1800 m/s, v_0=1000 m/s) were used on the synthetic data. Figures 20-23 shows the correlation between real VSP and synthetic traces for two of the velocity models. For interpretation, the synthetic traces were generated both with and without multiples included.

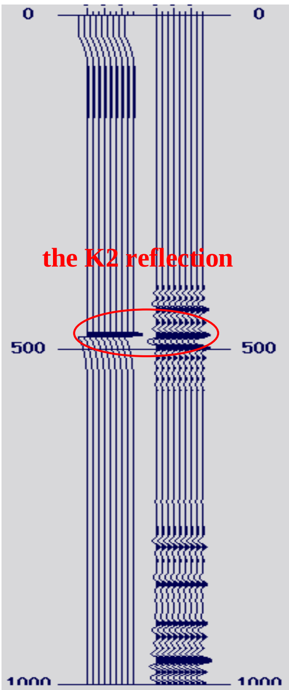


Figure 20 Correlation between VSP and synthetic trace (without multiples), using velocity model 3.

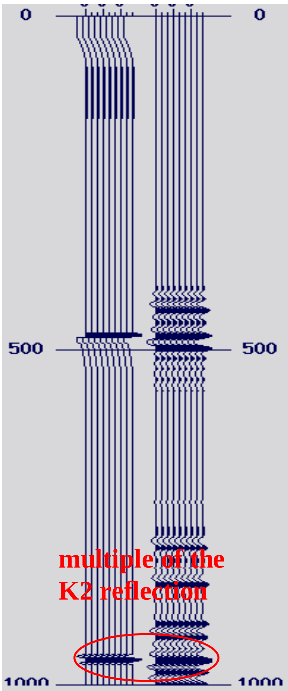


Figure 21 Correlation between VSP and synthetic trace (with multiples), using velocity model 3.

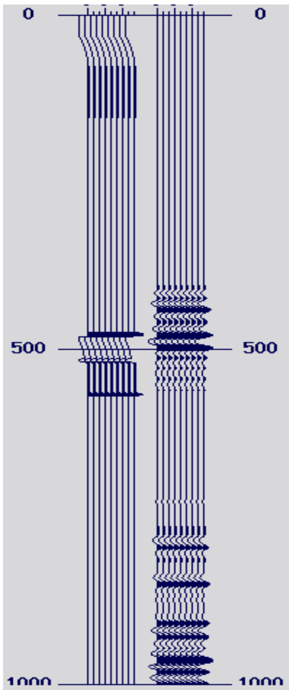


Figure 22 Correlation between VSP and synthetic trace (without multiples), using velocity model 5.

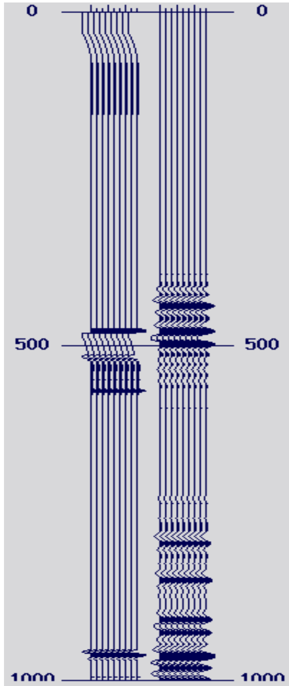


Figure 23 Correlation between VSP and synthetic trace (with multiples), using velocity model 5.

Velocity models with up to 10 layers were used for synthetic modelling. However the interpretation and correlation became difficult with models containing more than 3 layers. Nevertheless the K2 reflection was identified as well as a multiple of the K2 reflection in the zero-offset VSP data. This was done by using a 3 layered model with the highest difference in acoustic impedance for the Heldburg-Gips. The multiple was revealed by synthesizing the model both with and without multiples. Table 3 gives information about the velocity models used.

Table 3 Used velocity models for generating synthetic seismograms, using the reflectivity method.

Velocity model 3				**Velocity model 5**			
T (m)	*V (m/s)*	*Q*	*ρ (ton/m3)*	*T (m)*	*V (m/s)*	*Q*	*ρ (ton/m3)*
552	2310	100	2.5	552	2310	100	2.5
12.5	5100	100	2.5	12.5	5100	100	2.5
100	3100	100	2.5	57.5	3400	100	2.5
				73	2900	100	2.5
				55	3100	100	2.5

8. CORRELATION OF VSP DATA WITH SURFACE SEISMIC

As already discussed, the quality of the VSP data deteriorates with increased offset. For that reason only zero-offset and near-offset VSP were stacked according to the primaries-only described by Hampson and Mewhort (1983). Since the first arrivals used for stacking primaries-only were in a small time window some additional information was extracted from the last traces. Figure A15 in Appendix gives a good representation of the approach when stacking primaries-only. Because of the additional information from the last traces it is risk for multiple energy below 700 ms in the primaries-only sections as well.

For far-offset VSP the second stacking method with primaries-plus-multiples response was used. The largest disadvantage with this approach is that the identification of multiple reflections becomes less obvious. Nevertheless, it becomes easier to correlate the VSP with the surface seismic while the CDP for the VSP converge to the CDP for the surface seismic. Furthermore it was the only way to get any information at all from far offset VSP.

Figure 24 shows the primaries-only stacked section of zero-offset VSP data integrated between crossline 1107 and inline 1172 (the CDP corresponding to borehole 202/2007). Figure 25 illustrates the same correlation, but with the primaries-plus-multiples method used for stacking the zero-offset VSP.

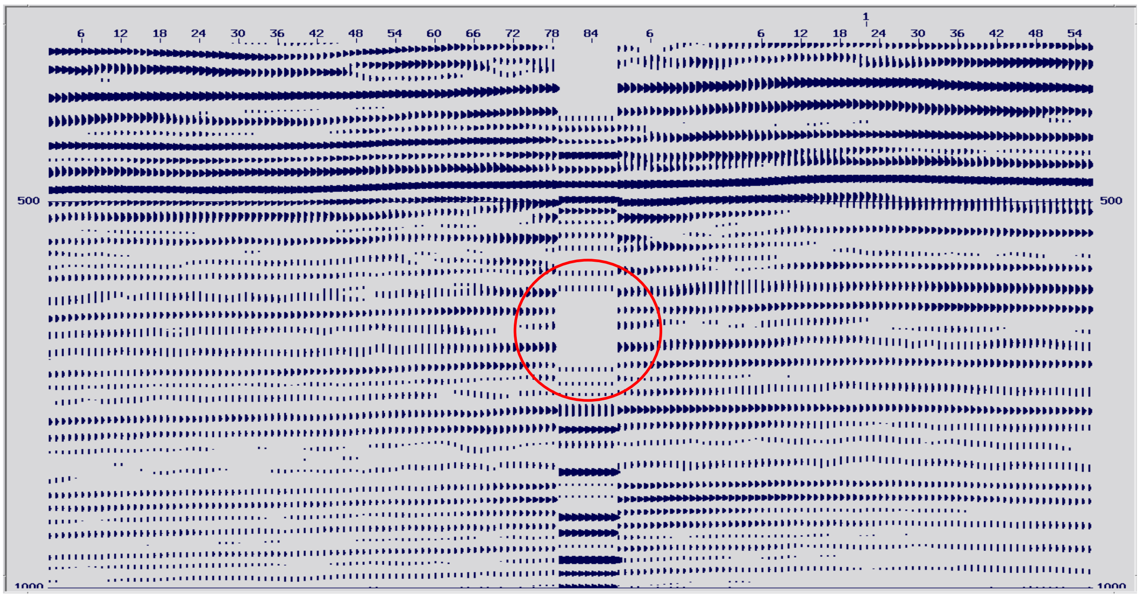


Figure 24 Primaries-only stacked section of zero-offset VSP integrated between crossline 1107 and inline 1172 (the CDP corresponding to borehole 202/2007).

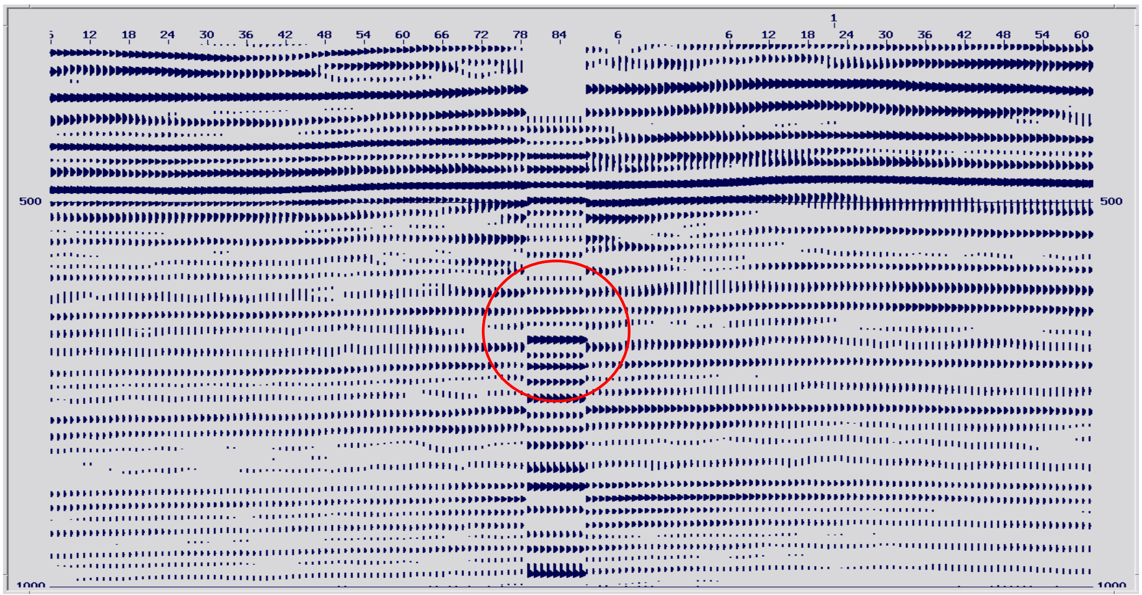


Figure 25 Primaries-plus-multiples stacked section of zero-offset VSP integrated between crossline 1107 and inline 1172 (the CDP corresponding to borehole 202/2007).

The correlation of VSP data with borehole data gave the best agreement for the K2 reflection. The same result is also valid for the correlation of zero-offset VSP data with surface seismic. In the correlation with the surface seismic some additional reflections above 500 ms are fairly well correlated. Other events are harder to correlate, yet the best correlation is given by the primaries-only stacked section. The comparison between figure 24 and 25 suggests that there are a lot of multiple energy between 600 and 700 ms in the VSP.

Two shots had an offset of about 300 meters, shots 4010 and 7033. This is a rather close offset and the processed data were stacked using both the primaries-only and the primaries-plus-multiples methods. In figure 26-29 the stacked VSP data is compared with handpicked CDPs between the wellhead and the shot point. Even if the reflection points for the VSP does not correspond to the CDP in the middle of the wellhead and the shot point, the VSP section was integrated at that CDP as an approximation. When making comparison, it is nevertheless important to take into account that many of the reflections of the VSP correspond to CDPs closer to the wellhead. It is also important to keep in mind that the NMO correction used constant velocity of 2310 m/s and the K2 reflector as a reference. Because of this events above K2 are shifted little downdip while events below K2 are shifted little updip.

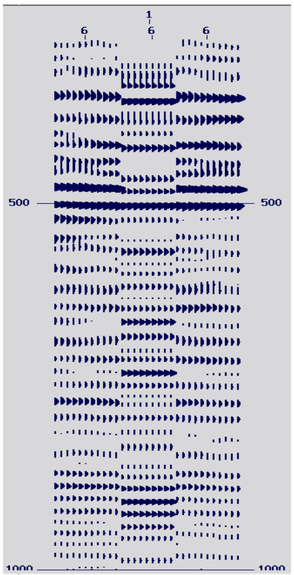


Figure 26 Primaries-only stacked section of 4010 integrated with CDPs between wellhead and shot point.

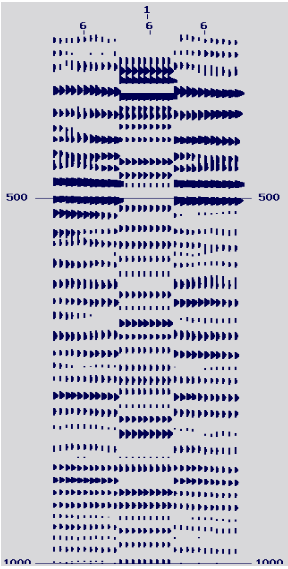


Figure 27 Primaries-plus-multiples stacked section of 4010 integrated with CDPs between wellhead and shot point.

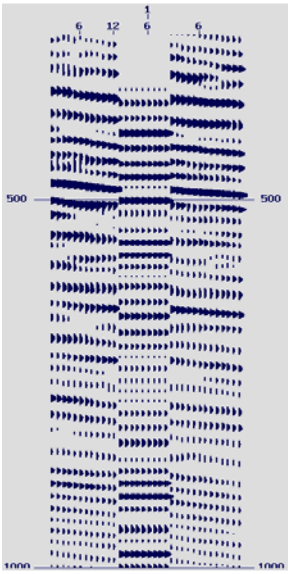


Figure 28 Primaries-only stacked section of 7033 integrated with CDPs between wellhead and shot point.

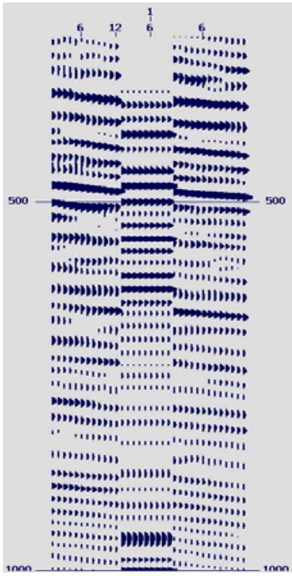


Figure 29 Primaries-plus-multiples stacked section of 7033 integrated with CDPs between wellhead and shot point.

Even at an offset of about 300 meters the VSP data became quite jumbled and, thus, made processing more difficult. The K2 reflector was however identified in shot 4010 and shot 7033. The best agreement with the surface seismic was obtained using the primaries-only stacked section. Other reflections were hard to correlate with the surface seismic although some agreements were possible to distinguish. In the zero-offset VSP multiple energy was identified in the region between 600 and 700 ms in the VSP section. This was done by comparing the two different stacking methods. The same correlation for shot 4010 and 7033 does not give any valuable information about multiple energy.

For far-offset VSP only the second stacking method with primaries-plus-multiples response was used. For shots between 300 meters and 700 meters the K2 reflection was, only just, identified while other reflections were lost during the processing sequence. For shots above 700 meters even the K2 reflection was undetected. Figure 30 shows shot 1042, integrated at the CDP corresponding to the midpoint between the shot and the borehole, as an example. No further explanations or results regarding the far-offset VSP will be presented in this thesis. The reason for this is that no reassuring data processing and correlation has been obtained for shots with an offset above 300 meters. Figure 30 is just accounted to illustrate that it is possible to withdraw further information from the far-offset VSP data.

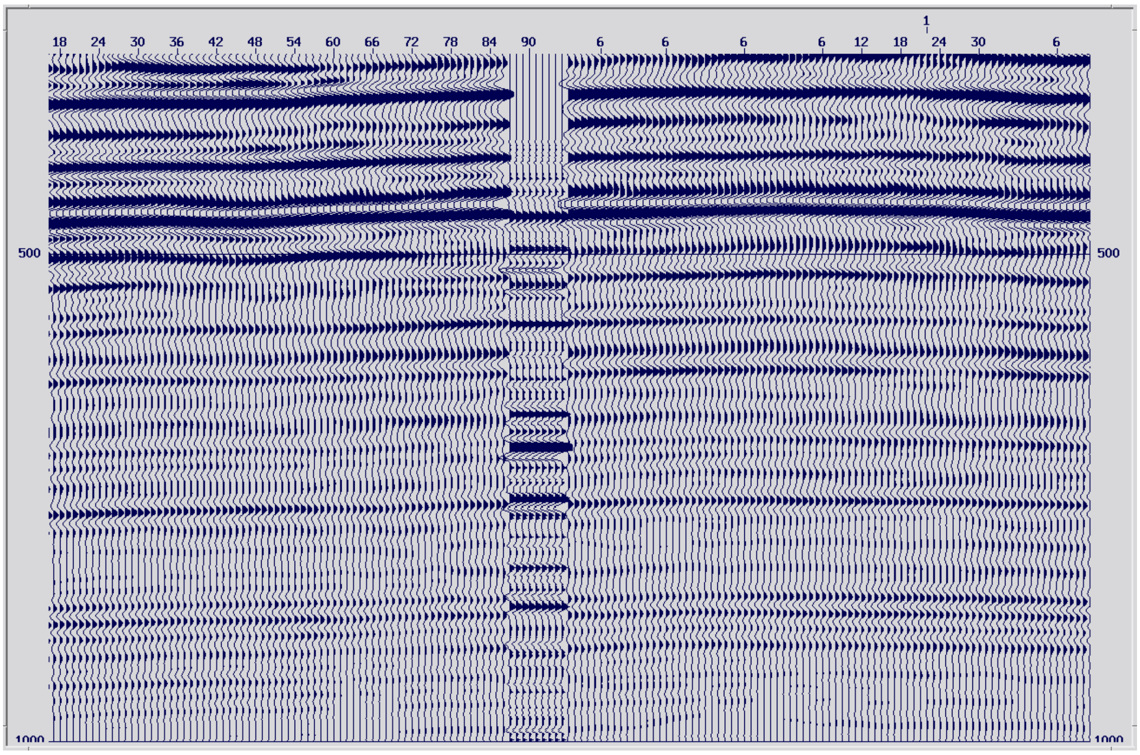


Figure 30 Primaries-only stacked section of 1042 integrated between crossline 1115 and inline 1196 (the CDP corresponding to midpoint between shot offset and borehole).

9. DISCUSSION OF RESULTS

A VSP survey was acquired in the late autumn of 2007. The survey was acquired with 80 geophones, 14 shots and a small field crew. This was a rather small VSP survey compared with those carried out for petroleum exploration purposes. The aim of the Ketzin VSP survey was to obtain a higher resolution around the boreholes, both for the velocity models and the 3D image. The data quality was not as good as expected and deteriorates with increased shot offset. This was probably due to the poor cementing of the casing above 460 meters. Nevertheless, it was possible to gather some information after careful selection of traces. The most important step in the processing sequence was the multichannel velocity filtering. This step made it possible to separate the downgoing and upgoing events. The upgoing events were correlated with surface seismic and borehole data while the downgoing events were used for velocity analysis.

Due to the bad data quality the velocity models used for depth conversion and synthetic seismogram were kept rather simple. Using velocity models with more than three layers did not add any further understanding of the events in the VSP. Only the zero-offset VSP was used for the correlation with borehole data and after the data processing the K2 reflection, from the (Heldburg-Gips) at a depth of 552 meters, as well as a multiple of the K2 reflection were identified.

The correlation between zero-offset VSP and surface seismic, also, gives the best agreement for the K2 reflection. Other matches between surface seismic and zero-offset VSP are distinguishable and do probably belong together. The surface seismic does has a reflection around 960 ms. Since a similar reflection in the VSP turned out to be a multiple it is most likely that the reflection at 960 ms in the surface seismic also is a multiple. Furthermore the VSP indicate that there are a lot of multiple energy between

600 and 700 ms. Some reflections in this region have earlier been interpreted as reflections from the Weser Formation. This interpretation is still likely, but less certain.

For offset VSP only the K2 reflection could be definitely established while other reflections were more questionable. One reason for this is that the NMO correction used constant velocity. This led to that events above K2 were shifted downdip while events below K2 were shifted updip. It was also difficult to distinguish multiple energy in the offset VSP. The comparison between different stacked sections, which was applied on zero-offset VSP, was not applicable for the offset VSP. The strong event around 960 ms though point to that the double-path multiple of the K2 reflector is present in offset VSP.

While the VSP data was integrated with both the 3D surface seismic data and data from borehole, the VSP survey works as verification of the 3D image. In general the results from the VSP survey agree with 3D surface seismic survey and with that the earlier interpretation of the seismic project at Ketzin is established.

10. CONCLUSIONS

This work has processed the VSP data from Ketzin, with the ambition to (1) integrate the VSP data with the 3D surface seismic data, (2) integrate the VSP data with data from the borehole, (3) identify the location of the main reflectors in the borehole, (4) identify multiple reflections in the VSP and surface seismic data and finally to obtain a higher resolution images of the subsurface.

In general the integration of the zero-offset VSP data with the data from the borehole was manageable. The correlation of the depth converted VSP and the stratigraphy from borehole 202/2007 clearly showed that the strong reflection at 480 ms belongs to the anhydrite layer (Heldburg-Gips) at a depth of 552 meters. Others reflections were harder to correlate with specific layers, but it was possible to distinguish some reflections belonging to the upper Arnstadt Formation and upper Stuttgart Formation. The correlation of the zero-offset VSP and the synthetic seismogram endorsed that the reflection at 480 ms belongs to the anhydrite layer. The synthetic seismogram also confirmed that the strong upgoing event at 960 ms is not a primary reflection, but a double-path multiple of the K2 reflector.

The integration and correlation with the 3D surface seismic data was clearest for the zero-offset VSP. For offset VSP only the K2 reflection could be definitely established while other reflections were more questionable. Comparisons between different stacked sections of the VSP indicate that there is a risk for multiple energy in the 600-700 ms. window.

In addition to showed results, the VSP data has given additional information about the subsurface velocity. This information can be used in later investigations. Furthermore, it is possible to extract more information from the VSP data acquired in 2007 than showed in this thesis. Later on it is presumably that a more detailed paper, concerning VSP measurements at Ketzin, will be published by Ph.D. Student Can Yang as main author. In the mean time this thesis works as an overview of the VSP data at the Ketzin CO_2 storage site for those concerned and interested.

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A. SCREEN DUMPS OF PROCESSING STEPS

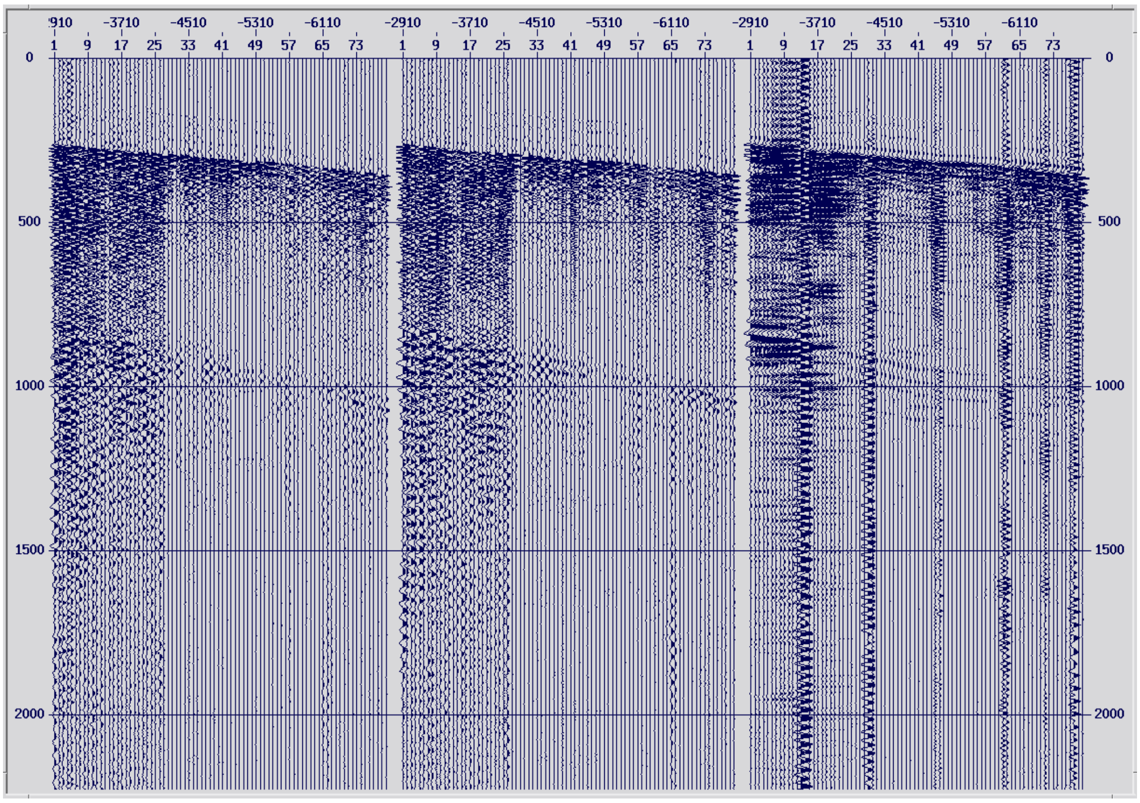


Figure A1 Initial quality check of raw field data. The figure shows common shot gather of shot 7033. H1, H2 and V component from left to right.

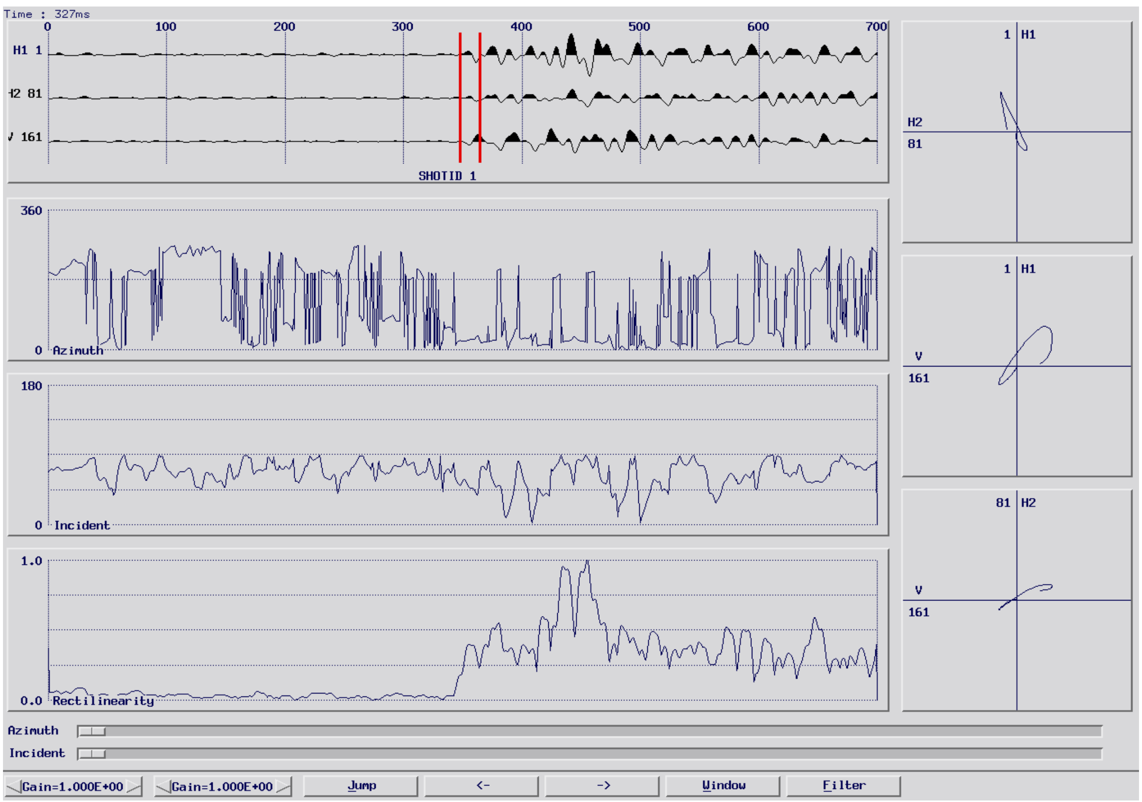


Figure A2 The rotation tool in Claritas used for rotating the azimuth angle.

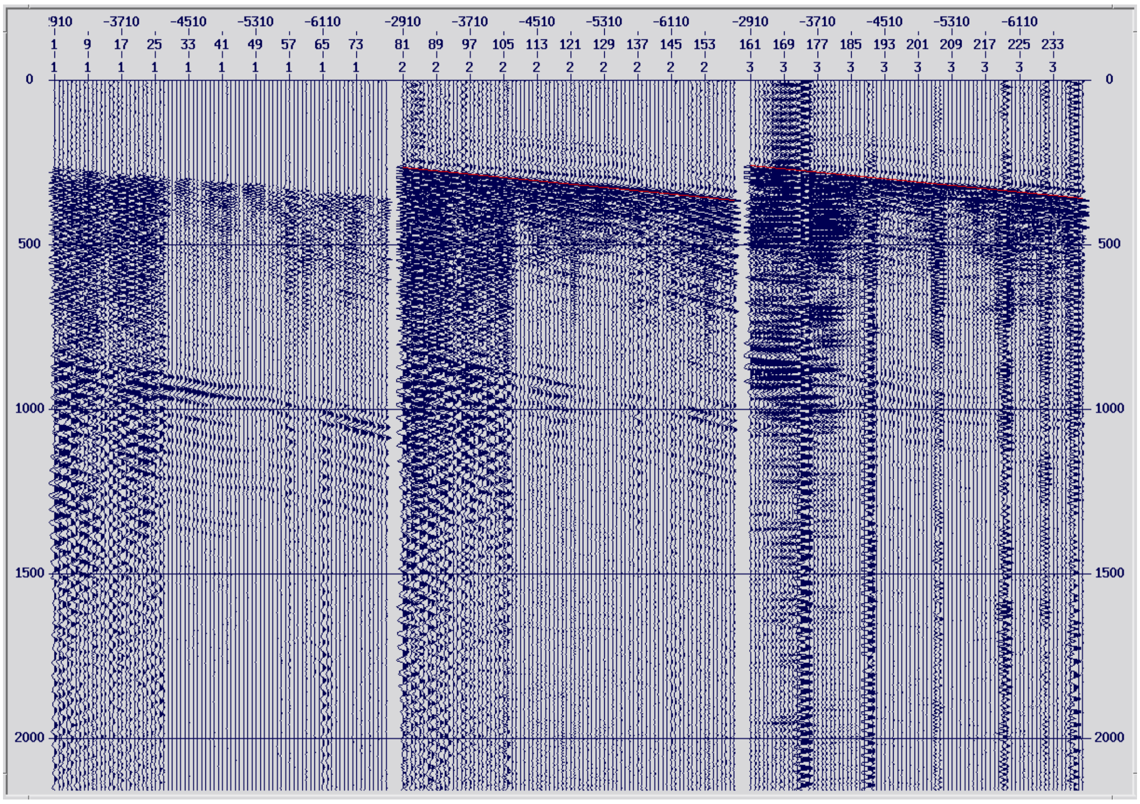


Figure A3 Shot 7033 after rotation. H1, H2 and V component from left to right.

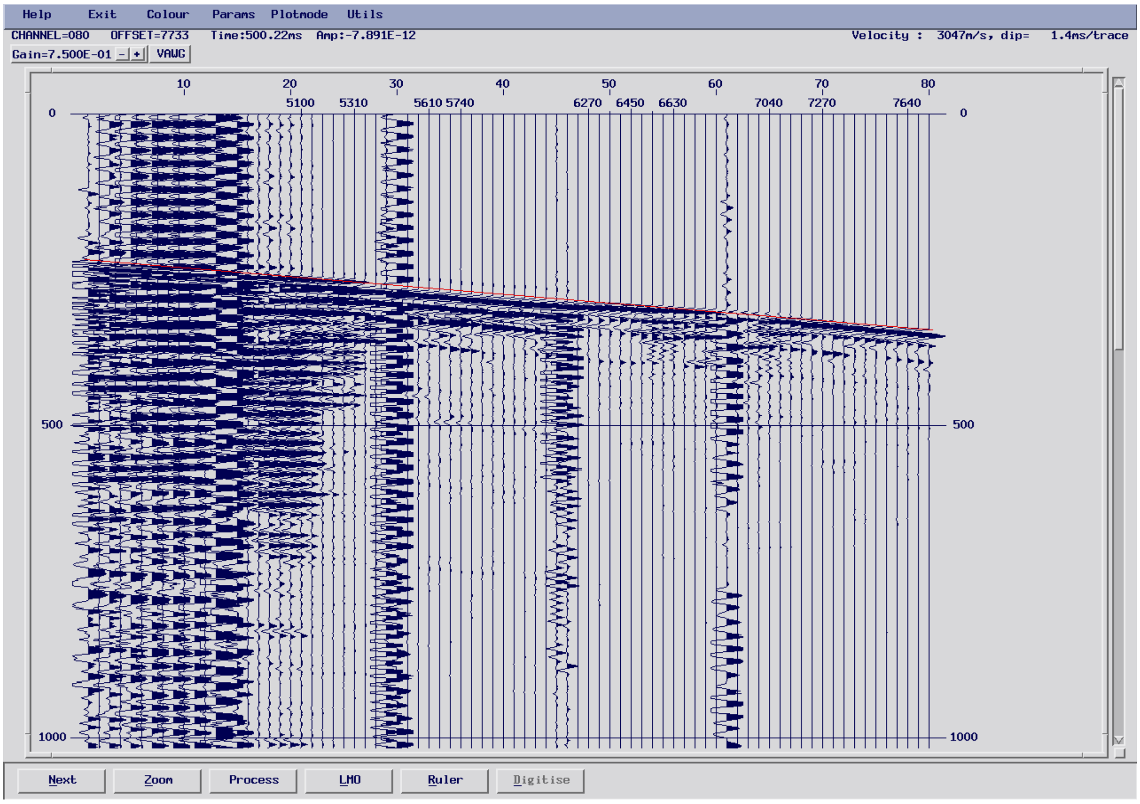


Figure A4 Initial velocity analysis of shot 4010 V component.

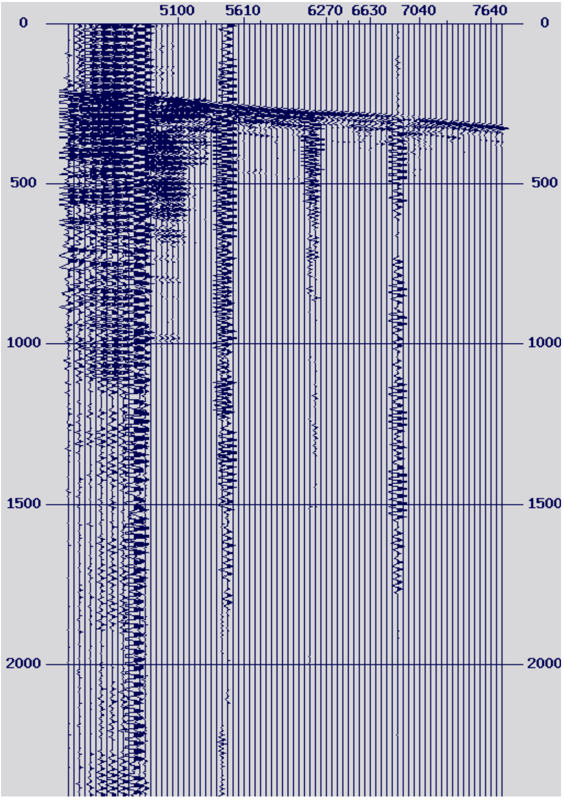
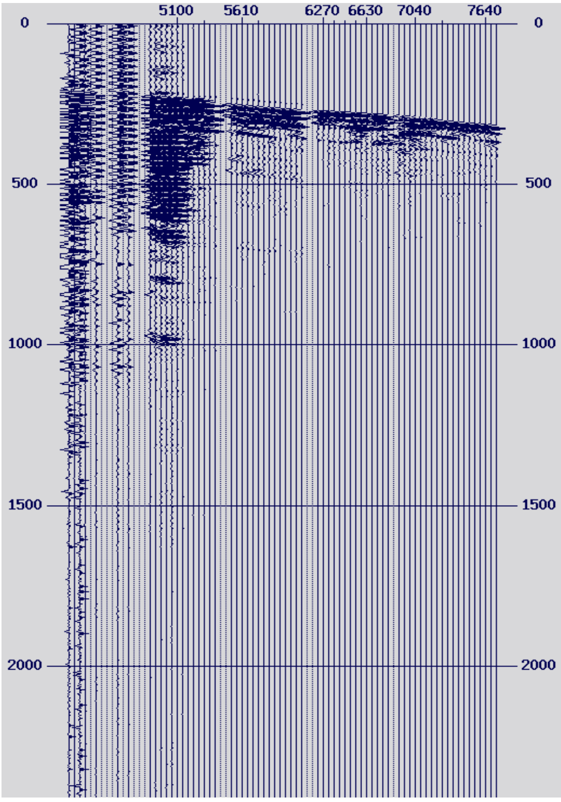


Figure A5 V component of shot 4010 after bulk static shift and refraction static.



FigureA6 V component of shot 4010 after trace edit and polarity reversal.

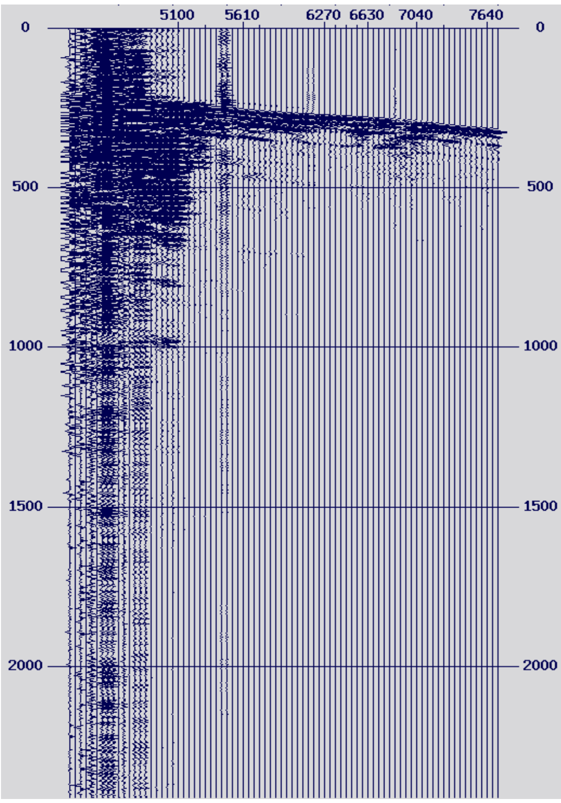


Figure A7 V component of shot 4010 after synthetic trace interpolation of deleted traces.

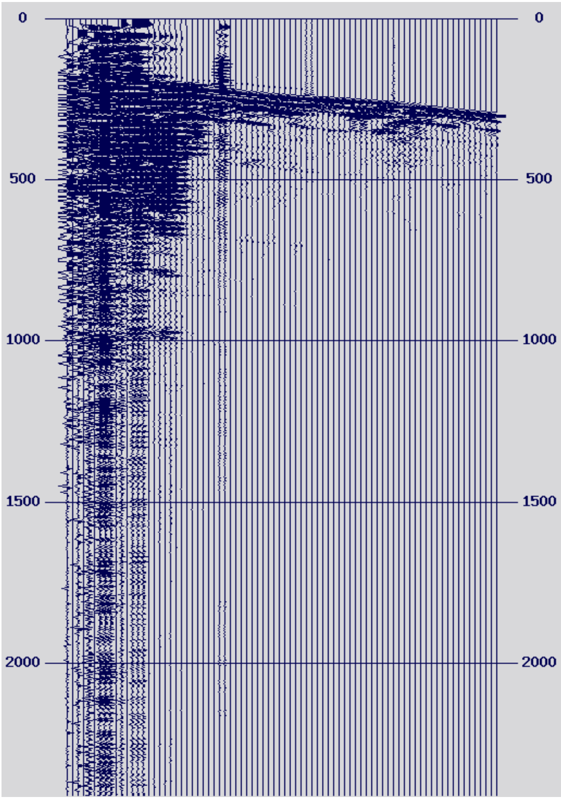


Figure A8 V component of shot 4010 after NMO using constant velocity: 2310 m/s.

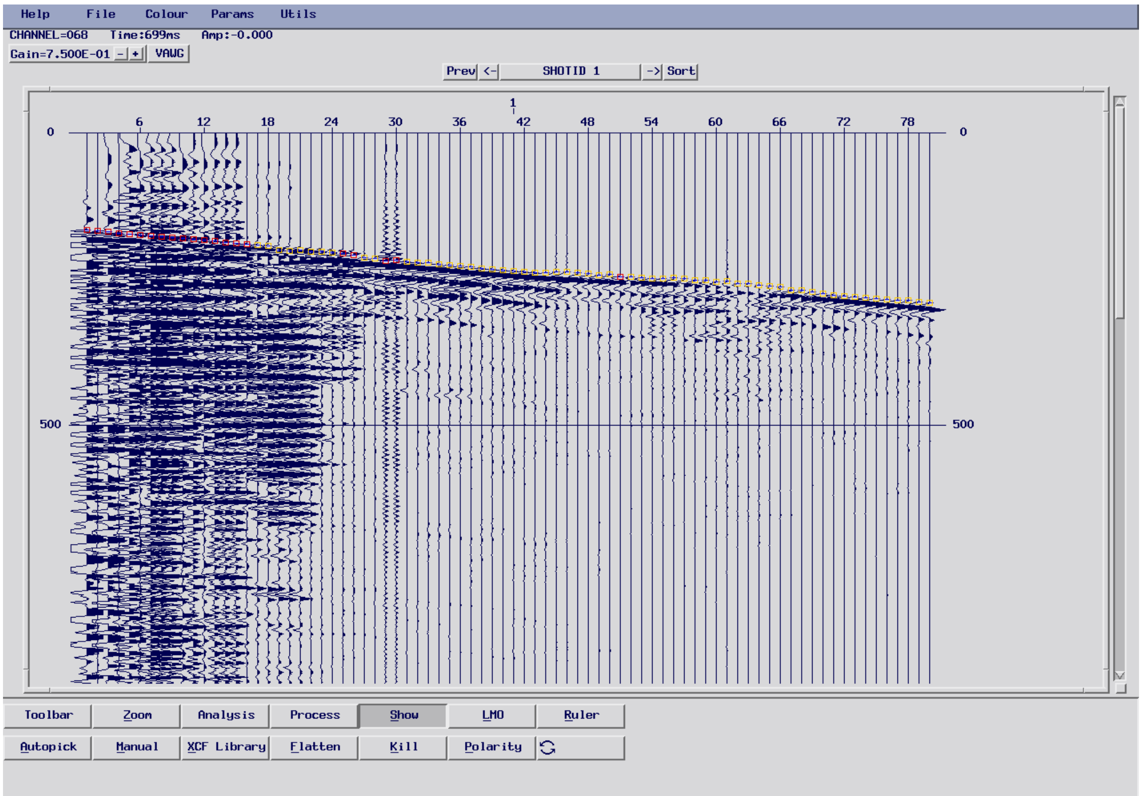


Figure A9 The pick first break tool in Claritas. Yellow picks represents automatically picks while red picks are manual picks.

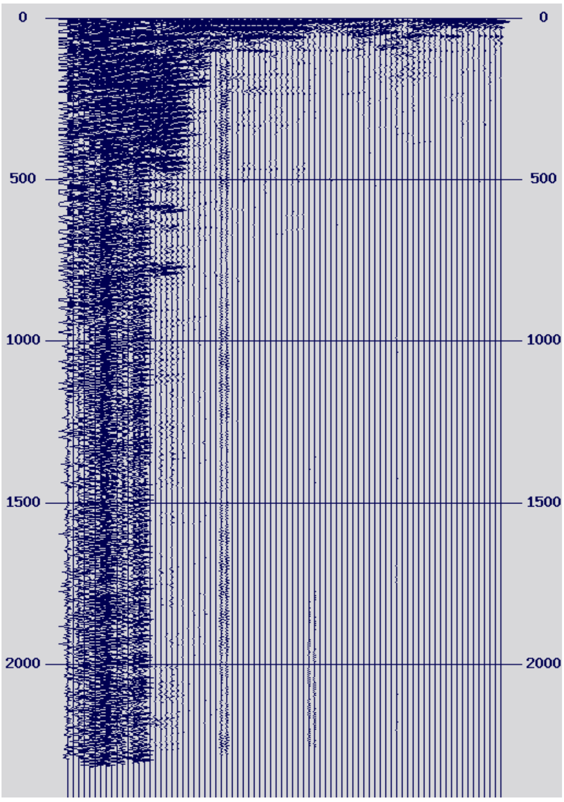


Figure A10 V component of shot 4010 after alignen coherent downgoing energy horizontal.

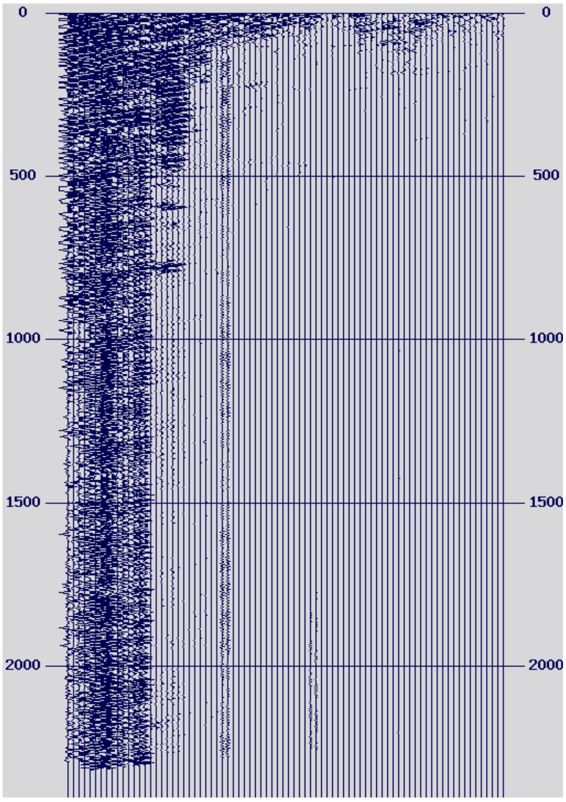


Figure A11 V component of shot 4010 after subtracting downgoing events by horizontal velocity filter.

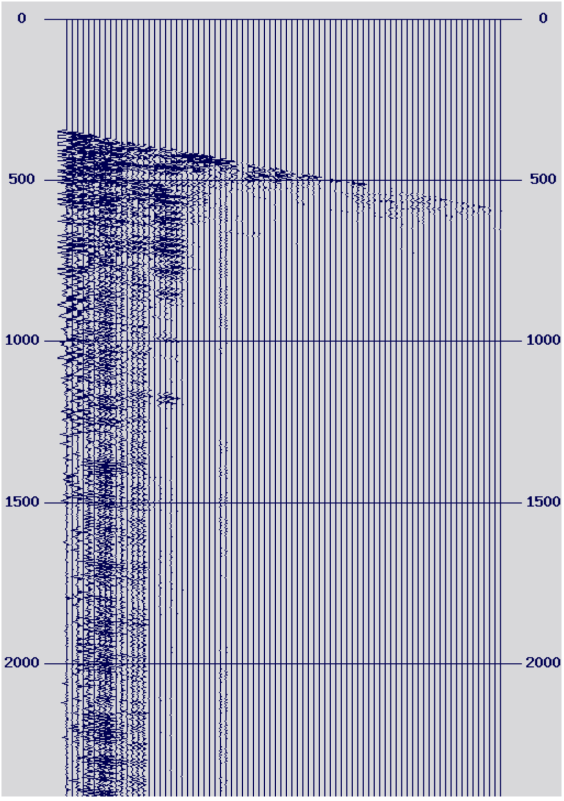


Figure A12 V component of shot 4010 after alignen coherent upgoing energy horizontal.

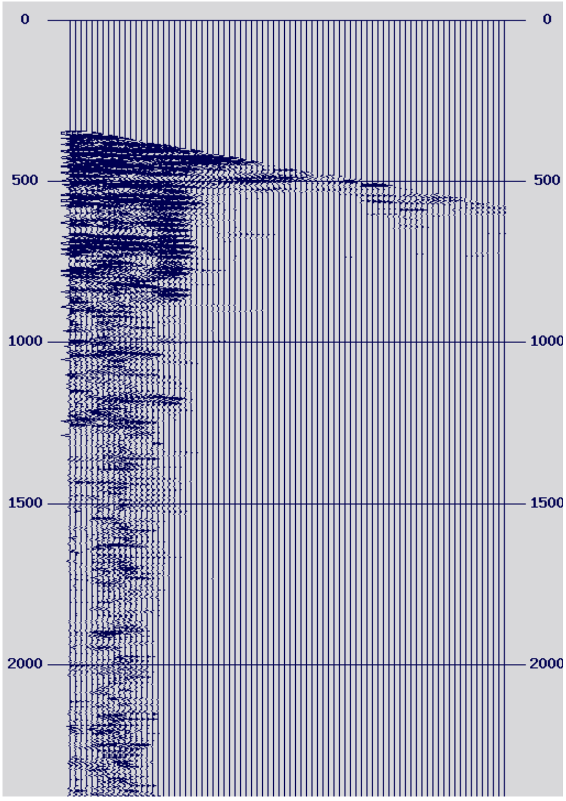


Figure A13 V component of shot 4010 after increasing upgoing events by horizontal velocity filter.

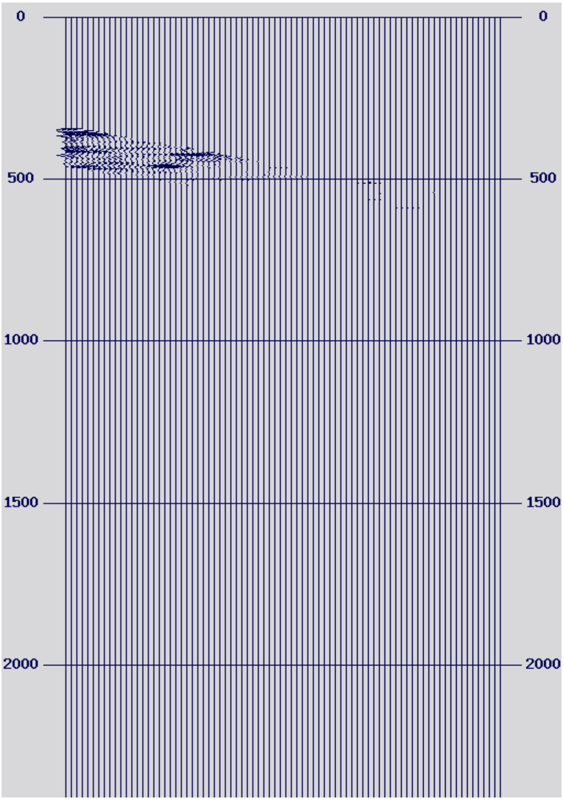


Figure A14 V component of shot 4010 after primaries-only mute.

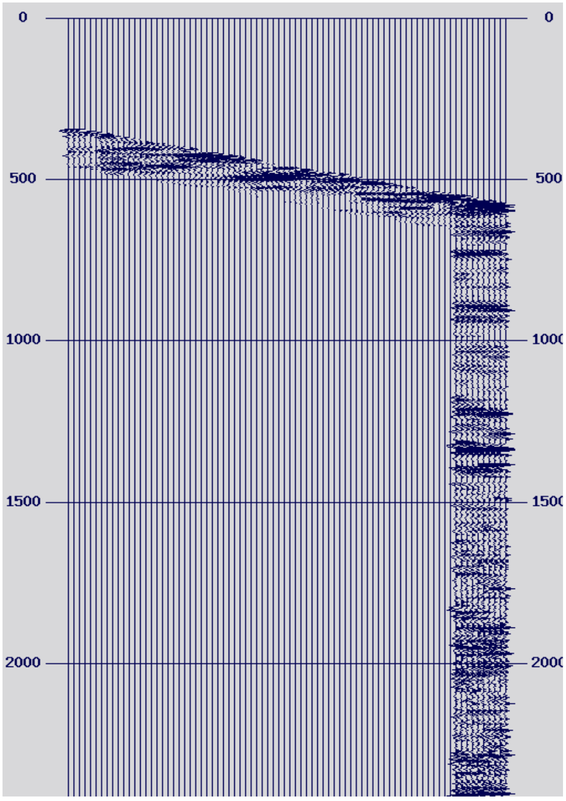


Figure A15 V component of shot 4010 after automatic gain control.

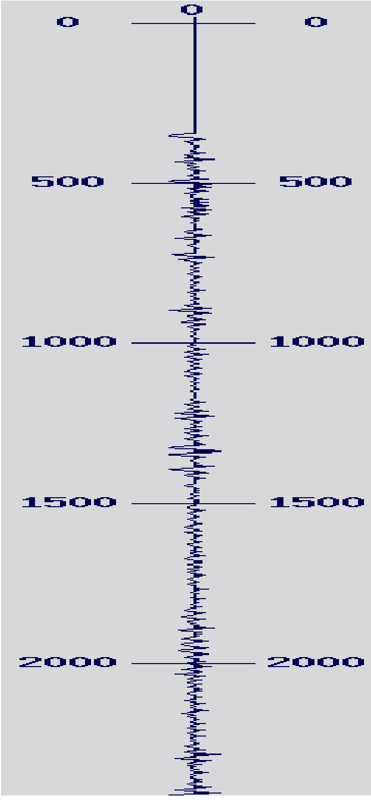


Figure A16 V component of shot 4010 after vertical stacking

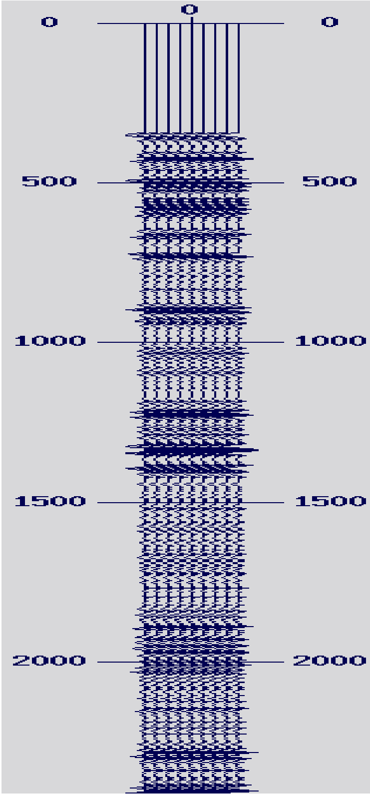


Figure A17 V component of shot 4010 after gather 9 copies of stacked section.

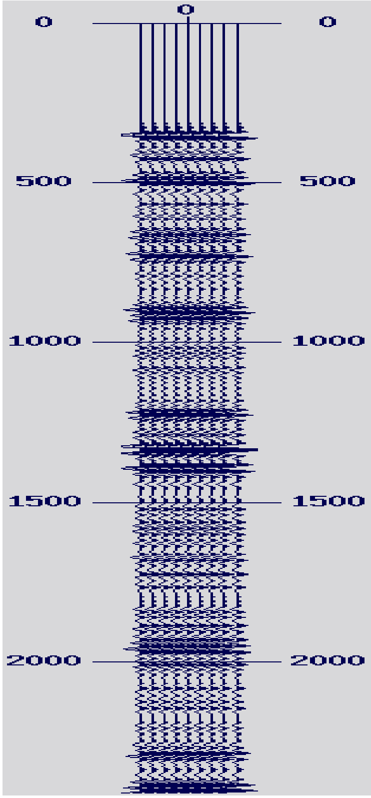


Figure A18 V component of shot 4010 after band-pass filter: 7-14-60-80 Hz