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ACOUSTIC MONITORING OF CO_2/METHANE MIGRATION IN COAL SEAMS

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ABSTRACT

The main objective of this project is to investigate enhanced production of methane and the related permanent storage and migration of CO_2 in the subsurface. The main tool is seismic tomography. At Delft University of Technology - Department of Geotechnology, traveltime and amplitude tomographic imaging techniques have been further improved to achieve high resolution (of the order of thickness of coal layers). Our aim is to validate this new theory on the real data set from the RECOPOL project ('Reduction of CO_2 emission by means of CO_2 storage in coal seams in the Silesian Coal Basin of Poland') or on a new ultrasonic measurements in a connection with it.

In this paper, we present results of a comparable experiment in the Alberta province of Canada where steam was injected in tar sand (heavy oil sand). Thereby, we confirm validity of our theory for time lapse tomography in a case of a physically very similar situation. Furthermore, we present preliminary experimental results of the ultrasonic measurements on a scaled model.

INTRODUCTION

As the main tool for the investigation of enhanced production of methane and the related permanent storage and migration of CO_2 in the subsurface we have chosen seismic tomography. Seismic tomography is an appropriate method for estimating seismic velocity structures from either observed travel times or amplitudes of direct waves. High-resolution geological images are obtained from multiple source - multiple receiver data, acquired in a borehole to borehole seismic survey known as crosswell tomography. Another option using borehole to surface configurations is called VSP tomography. Fig. 1 shows the geometry of crosswell acquisition, the first method mentioned. A real high-quality seismic data set is the first step towards high-resolution tomographic imaging. So far, a new theory has been tested on synthetic data. Our aim is to further validate it on the real data set from the RECOPOL project and on laboratory ultrasonic measurements. More details about RECOPOL project are given in the introduction of a chapter on the ultrasonic experiment.

As a starting point for our modeling for the ultrasonic measurements, we made a dual coal/overburden model which is followed by a realistic up-scaled physical model of the RECOPOL geometry with an aim to simulate CO_2 injection. The challenge is to introduce thin layers with low velocities, representing the (CO_2

saturated) coal seams, which later can be changed to some other value by rock physics modeling for $CH_4/CO_2/H_2O$ replacement, without changing anything else in the model. Time lapse monitoring should detect those changes in the velocity structure, but first of all acoustic measurements should clearly detect these thin layers. Hence, we are developing a method for an estimation of the gas/fluid (i.e., CO_2, CH_4 and H_2O) concentration in a subsurface, from real seismic data. Some preliminary experimental results of the scaled model are presented in that chapter.

In the next chapter we present results on a comparable velocity configuration of steam injection in tar sand. Here, we confirm validity of our theory for time lapse tomography monitoring of physically similar behavior. We have chosen to process data sets from this pilot project in Alberta, since RECOPOL seismic time lapse data are still not available. Injection of a steam in tar send is very similar to injection of CO_2 in coal seams if we consider impedances (and velocity changes) of the structures involved.

At the end, we conclude with the concluding chapter where we also give overview of the most important questions we will have to answer in the future.

ACOUSTIC MONITORING OF CO_2 INJECTION FOR ENHANCED CH_4 PRODUCTION

In coal field nowadays hot oily methane and water are produce, but also gases are injected to improve production rates and sweep effectiveness. Here, we propose the technique known as seismic tomography for acoustic monitoring of injected CO_2 in the subsurface. The word *tomography* is composed of the Greek words *tomos* meaning a *slice* and *graphi* that is translated to *write on*. Accordingly, acoustic monitoring by seismic tomography refers to the method in the academic field of seismology and the industrial area of exploration seismology where primarily compressional waves (i.e., sound waves) are used to compile images of the underground geology. In contrast to log data, seismic tomography provides information about the subsurface structures away from the wells.

In the case of acoustic monitoring of CO_2 injection for enhanced CH_4 production, the configuration consists of two downhole wells. In one well sources are installed to generate wave energy, while in the other well receivers are placed to record the propagating waves. The area between the two wells is known as the target zone. This kind of technique is called crosswell tomography since the 2 dimensional geological structure and properties (i.e., sound speed) of the target zone can be determined. The part over and under and on the sides of the target zone are called the over-, under- and sideburden, respectively. However, it is only possible to compile images of the target zone between the two wells. Fig. 1 shows a sketch of the crosswell experimental geometry. The sources and receiver positions are normally repeated for every few meters depth. The downhole wells are not limited to the vertical direction. Horizontal wells or non-straight tilted wells can be used as well.

An alternative to crosswell technology is an experimental setup with one well in which receivers are placed. The sources for wave energy generation are at the surface. The one well experiment is known as vertical seismic profiling (VSP). The resolution of VSP is inferior to that of crosswell tomography.

The dimensions of crosswell experiments are on the order of 100 meters. The wells are separated 50 to 150 meters, the distance between the top source/receiver and the bottom source/receiver is 100 to 300 m. The target zone is at depths from 150 m to 1500 m. For instance, crosswell tomography of steam injection in tar sand in the Alberta region of Canada is starts at 160 m depth. On the contrary, the Japanese pilot project on CO_2 injection in aquifer in the Niigata prefecture operates at 900-1230 m depth.

The nowadays seismic sources generate both compressional waves and shear waves (later arrivals with a different polarization) by using a highly repeatable mechanical tool. The primary arrivals come from an impulse source, while the shear waves are produced by a vibrator. The bandwidth for both compressional and shear wave sources is between 50 Hz and 1000 Hz. As wavefields propagate through the earth layers, the high-frequency part gets more attenuated than the lower frequency part.

Consequently, power spectra of the recorded energies have the most dominant frequency components for the lower frequencies.

There exist several approaches to describe the propagation of compressional and shear waves in the earth. Some of the wave theories are limited to the acoustic approximation, while others do include the interaction terms between compressional waves and shear waves. The latter theory is generally known as elastic wave propagation and by consequence is more complex than simplified acoustic wave theory where elastic propagation effects are ignored. In practice, the first arriving compressional energy is the part of the recorded wavefield that is most easy to recognize. Additionally, the compressional waves are mostly unaffected by the later shear wave arrivals. Therefore, we focus on an acoustic monitoring method based on the seismic tomography technique.

The traveltime of compressional waves is sensitive to the compressional wave velocity (i.e., sound speed) of the target zone. By estimating the traveltime from many (> 2000) recorded wavefields with different source and receiver positions in the downhole wells, most of the compressional wave velocity parameters in the target zone are sampled. These traveltime data are then converted in an image of the compressional wave velocity field in the target zone by a method called inversion. The inversion step is very similar to the old approach (before the radar Doppler method was developed) used by the police to estimate the velocity of vehicles. By laying out two cables on the road (e.g., the two wells) with a fixed distance, the police can register the time it will take a vehicle to pass from one cable to the next one. The vehicle velocity is then simply the cable distance divided by the recorded time. In seismic tomography, not only one traveltime is converted into a velocity measurement, but many traveltimes are combined to generate an estimate of the 2 dimensional velocity field between the two wells. More details on the finite-frequency wave theory for phase and amplitude attributes on which our inversion method is based on, can be found in [Ref 1, 2, 3]

Our acoustic method for the monitoring of CO_2 injection for enhanced CH_4 production goes one step further than seismic tomography. We apply two data sets recorded at different times instead of single data set alone to assess the CO_2 injection and CH_4 production. The data set first recorded is called the baseline data, while the repeated data are named the monitor data. This approach is known as time-lapse monitoring because the changes between the monitor and baseline data can be used to estimate the variation of the compressional wave velocity inherent to the injection/production process in the time between the two data acquisition surveys. Our acoustic time-lapse method works with traveltime and amplitude variations between the monitor and baseline data separately and combined. Similar to seismic tomography, the estimated traveltime and amplitude variation for many recorded time-lapse wavefields are converted into a 2 dimensional compressional wave velocity difference field. By assessing variations in the velocity field, it is possible to follow the migration of water, CO_2 and CH_4.

The resolution of velocity variation images obtained by this acoustic time-lapse monitoring technique depends strongly on the repeatability of the acquisition procedure to record the monitor data. The major non-repeatability is due to: *i)* variations in the source wavelet, *ii)* differences in source-receiver positions and *iii)* noise, which affects both the traveltime and amplitude part of the wavefields. As an example, only traveltimes can be used to monitor CO_2 injection in the Japanese pilot project in the Niigata prefecture. In the monitor survey, a different stacking procedure to enhance a strong compressional wavefield is used, resulting in unreliable amplitude data. Or, if the source or receiver positions are misplaced even by only half a meter in the repeated survey, small traveltimes shifts due to this non-repeatability cause are introduced in the time-lapse data. If the traveltime effect, inherent to the CO_2 injection and CH_4 production, is smaller than the non-repeatability effect due to shifted source-receiver positions, it is difficult to obtain an accurate image of the genuine time-lapse effects. A band-pass filtering of the time-lapse data can remove high-frequency noise components. In practice, the monitor and baseline data are processed in order to reduce the non-repeatability effects before the time-lapse monitoring method is applied. Then, after a proper data processing and inversion of the observed data differences, the images of the variation of compressional wave velocity are compiled. The maximum resolution power is about 3 to 5 meters.

Example of a real time-lapse data experiment with steam injection

This experiment was chosen because of its impedance resemblance with a coal seam and gas/liquid front. The time-lapse crosswell experiment, located in the Alberta province of Canada, is a pilot project where steam is injected in a tar sand formation through a horizontal pipeline between the source and receiver wells. The steam injection lasted 72 days between the baseline and monitor survey. The reservoir of heavy oil was heated up by conduction to make the bitumen less viscous. The crosswell experiment is configured with two source wells (i.e., CH1 and CH4) and two receiver wells (i.e., CH2 and CH3). A sketch of the acquisition geometry is presented in Fig. 2. The horizontal pipeline at 250 m depth with steam injection is indicated with the red arrows. In total, there are four cross-sections which make it possible to estimate a pseudo 3D time-lapse velocity structure. The sources and receivers are located between 160 m and 320 meters with a depth increment of 2 meter for both sources and receivers. The source energy is generated by a prototype source vibrator manufactured by Paulsson Geophysical Services. The source position is well repeated in the monitor survey, which contributes to minor non-repeatability effects in the time-lapse data set. In addition, the source signature is very repeatable. The 80 level receiver array is permanently cemented in the well casing, hence the coupling is good and the repeatability of receiver positioning in the time-lapse data set is perfect. In general, the time-lapse data set is of a high quality and there are few problems with non-repeatability effects due to differences in acquisition. Fig. 3 shows seismic data for a fixed source position recorded in the baseline and monitor survey, respectively. The compressional and shear waves are indicated. After removal of zero traces in the data set, more than 5500 traces with waveforms are available for the tomographic imaging method. The first arrivals with the compressional wave are very clear in the data. The strongest energy part is between 200 Hz and 600 Hz.

4D-velocity structure due to steam injection

The time delay and relative amplitude attributes from the time-lapse data were used to estimate time lapse velocity structure and strength inherent to steam injection between the baseline and monitor survey. A standard inversion technique is applied to generate the time-lapse velocity models from the time shift and relative amplitude variation attributes. The estimated time-lapse velocity models using the traveltime delay for all four cross-sections are presented in Fig. 4. By inspection, it is seen that the inverted models are similar in the sense that they show a negative velocity anomaly in the area near the horizontal pipeline. This is an encouraging result because it is generally known from rock physics modeling that a temperature increase is correlated with a velocity decrease in heavy oil sandstone reservoirs. Oil gets liquid thus time delays come in.

We also used the amplitude variation as input data for the tomographic image reconstruction for all cross-sections. Again the cross-sections show the presence of a negative velocity anomaly close to the pipeline location (not shown in the paper).

ULTRASONIC MODELING EXPERIMENT OF CO_2 INJECTION

Motivation for the physical modeling

Initially our aim was to understand RECOPOL data, process them and more general to investigate if time-lapse technique can be used in monitoring of carbon-dioxide injection.

The RECOPOL project is an EU co-funded combined research and demonstration project to investigate the possibility of permanent subsurface storage of CO_2 in coal. The project started in November 2001.

At a selected location in Poland a pilot installation is developed for methane gas production from coal beds while simultaneously storing CO_2 underground. The produced methane could become an alternative fuel that can be locally produced in Silesia. This installation is the very first of its kind in Europe. In that project CO_2 is injected into coal seams at a depth of 1050-1090 m. The CO_2 is adsorbed to the coal, which releases its methane gas simultaneously. Consequently, methane and water are produced. Daily 12-15 tons of CO_2 were injected with total of circa 760 tons into Carboniferous coal seams with a thickness of 1 to 3 m.

Our objective is to investigate if in the subsurface injected CO_2 and the produced coalbed methane can be monitored by the seismic measurements. To perform the seismic monitoring optimally, time lapse measurements are envisaged.

Within the RECOPOL project first survey has been done before injection has started. Immediately, many problems arose. Data were of poor quality, very noise and dominated by tube waves. First arrivals were almost unrecognizably. Furthermore, the exact location of wells was not precisely known at the time (wells are deviating). The main goal of first seismic measurement was to image the subsurface structures and geological settings. Additionally, rock properties from the acquired seismic data (together with well-log data) are derived.

A baseline cross borehole seismic survey was carried out in September 2003 and another problem is that up to now, a second survey has not been done yet. The initial plan was to do time lapse measurements at a certain time after the injection of CO_2 or at the very end. The challenge would be to detect seismic changes between the above mentioned time lapse measurements and to relate these to variations in rock properties. Therefore, a seismic method with high resolution and high repeatability is required.

Considering all these problems and the advantage that geological structure is well known, physical modeling seems to be a good idea to obtain more knowledge about the real field situation and to test applicability of our seismic inversion method.

In order to build a realistic model of the RECOPOL geometry more information about the geological structure, the well positions and the survey target zone need to be presented here.

There are two wells MS-1 and MS-4, 375 m apart, which were formerly used for a short period to produce CBM. Due to budgetary constraints it was not possible to put both existing wells back into production. It was therefore decided to clean up and repair the up-dip well (MS-4) and to drill new well between them, for the injection. The distance among the new injection well MS-3 and the production well MS-4 is 150 m. The intervals with the six major coal seams penetrated by MS-4 well were perforated in the 1990's. However, only the seams 357,364 and 401 were fractured. The thickness of those coal layers are 1.3, 2.9 and 3.3 m, respectively. The target zone of the seismic survey is from depth of 754 m to 1098m. Sources and receivers were placed on 2 m intervals, and used frequency was up to 2000 Hz. Some typical p-velocities measured from logs, for coal, sand and shale are given in Table1. The position of the wells, coal seams and target zone of the survey is shown in Fig. 5 (source is TNO-NITG).

Physical modeling and experimental requirements

Physical modeling is considered to be an attractive way of obtaining realistic 3D and 4D seismic data, though numerical modeling is still the most popular. The advantages of the physical modeling are obvious: It is not based on algorithms but on the laws of physics, hence, the wave propagation is real. Like in numerical modeling, the subsurface is completely known but one does not have to deal with the realms of approximations within wave equation itself (high-frequency approximation, acoustic rather than full elastic, 2D instead of 3D etc.) or boundary conditions or algorithm limitations (discretizing continuous reality) or limitations in the computer power and memory.

In physical modeling the seismic measurements are simulated on a laboratory scale. A scale model of the subsurface can be made from materials like rubbers, epoxies, plastics, metals, ceramics, etc. The seismic measurements are carried out with small sources and detectors, made from piezo-electric materials, using ultrasonic frequencies. The scaling factor is in the order of thousands (or tens of thousands) and need not necessarily be the same for distances and frequencies. Physically modelled data can be recorded in real acquisition geometry as well as in a time-lapse mode. The source and detector motion is in 3D so that crosswell or any other acquisition geometry can be simulated. Therefore, our aim is to make make as realistic as possible a coal-overburden model from artificial materials similar in velocities (and densities) to the real field situation (coal, send, and coal saturated with CO_2). The wells are located at the distance of 150 m from each other. Target zone of a survey is almost 350 m long. A scaling factor of 1000 determines dimensions of our model: 350 mm long and 150 mm wide. Instead of seismic frequency of 500 Hz, an ultrasonic frequency of 500 kHz should be applied. In other words, scaling factor of 1000 means that a spatial sampling interval of 2 m in a seismic scale corresponds to 2 mm on a model scale; similarly, a temporal interval of 2 ms corresponds to 2 μs and 500 Hz becomes 500 kHz. In that way, velocities remain unchanged. Technologies used in physical modeling are actually much more related to ultrasonic medical imaging than to seismic field acquisition taking into account dimensions involved.

The experimental setup in our laboratory is presented in Fig. 6. The main components are the signal generation system, the source and detector, the data acquisition system and the physical model itself. A short discussion is needed for all of these aspects.
As it can be seen from Fig. 6, the experiment has been performed in a water tank. The reason for that is to enable better coupling of transducers and a model.

Another aspect deserving attention is the motion system. Since the source signature is fully repeatable, a shot record can be acquired by measuring repeatedly with the source at a fixed location and a single detector at various offsets. This one-channel approach apart from advantage that any acquisition geometry can be acquired, has yet another advantage that common-receiver gathers (and common midpoint gathers etc.) can be obtained directly.

To simulate crosswell tomography, two positioning systems are needed, one for source and one for detector. So far in our laboratory we have only one positioning system for the detector while the one for the source is currently being installed. The positioning system has three degrees of freedom, which allows for simultaneous x, y and z motion. Those motions are controlled by PC. The input parameters are the trajectory of the detector, number of movements and the step interval. The motion controller triggers the data acquisition system when the prescribed positions of the detector have been reached.

The next key components of the acquisition system are transducers, since they determine the data quality for a large part. For sources and receivers, the requirements are: Large temporal and spatial bandwidth, high signal to noise ratio and small size. The small size is important since it minimize near offset gap (note that 2 mm 'scale' source corresponds to a 20 m 'real world' source). We use a focal transducer as a point source. Focusing is accomplished by curving the piezo plate. The spherically spot focusing transducer meets our requirements for the point source. By definition, the focal length of a transducer is the distance from the face of the transducer to the point in the energy field where the signal with the maximum amplitude is located. That is the place where we have our point source. The focal length of the transducer we used is 6 cm in the water and the central frequency is 500 kHz. As a receiver, we use a calibrated needle hydrophone (Onda Corporation SEA PZT-Z44-1000). It has high sensitivity and small size (frontal diameter is 1 mm).

The experimental measurements are recorded in the following way: The source signal is defined and generated in the waveform generator (Agilent 33220A), where it is converted from a digital signal to an analog signal. The analog signal is send to a power amplifier via an oscilloscope (Yokogawa DL9140) which serves for the visualisation mainly, and fed into the source transducer, which on its turn transforms electrical signal into an acoustic one. The echoes are received by the detector, amplified and digitized. Again via the oscilloscope, all data are saved in the form of binary files on the computer hard drive (using a Labview program). The signal-to-noise ratio is increased by stacking, i.e., each trace is an average of a number of individual measurements (1024). The averaging is also carried out via the oscilloscope. Each averaged trace is stored in a separate file.

The major focus of this paragraph is the physical model building. For that, steps that have to be taken are: Design of the model, selection of the best matching materials and actual production of the model. The design of the model is guided by the RECOPOL field situation. Fig. 7A represents sketch of the model which would be ideally fitted, and Fig. 7B is the model which is realistically more possible to obtain. Model A is more complex and very difficult to make since there are very thin layers that are inclined. Also, their thickness is in the limit of resolution power of our inversion method. To reach our goal, it is sufficient to realize and investigate the model at the right side of Fig. 7, since it already contains all necessary challenges: Thin layers of very low velocities, big velocities contrasts and also subtle changes that need to be detected (since all three layers have different but low velocities). Future project is to invent how to change velocity of one of the layers, without changing anything else in the model. Possible solutions are to inject some fluid in the layer, or alternatively to use an extra amount of the hardener and then aging of the model can already introduce changes of the velocity we need. That would represent the (CO_2 saturated) coal seam, which has changed its velocity to some other value due to $CH_4/CO_2/H_2O$ replacement.

Selection of the best matching material is first done by consulting data bases of many materials properties (p-wave velocity, s-wave velocity, density, attenuation etc.) and then by laboratory testing of the chosen material. Currently, we are at this stage of experiment. Materials that we test now are epoxies with various additives (like metal powders). The additives are used to control properties like densities and velocities. The result is wider range of material properties. Epoxies are initially fluids and only after hardener is added the chemical reaction is initiated which turns them into solids. Mixing of all ingredients of epoxy-based materials must be thorough in order to obtain a homogeneous substance. Furthermore, it is very important that the material is free of air. Even a small amount of air can increase the attenuation to unacceptably high level. Once material is prepared well, it is poured into a mould. We expect that one layer can be simply poured on the top of the next, but it might as well be that different parts of the model have to be built separately and then later glued together. That would result with some intermediate layer which may be extremely reflective or attenuating, and that certainly requires additional testing.

Preliminary results

Physical model shown in Fig. 6B is just a sample used to test velocity of epoxy raisin. Three different epoxy raisin samples (shown at the upper corner of Fig. 6B) are made (types: CY 219 (white), CW 2215 (transparent) and CW 2418-1 (black), all mixed with the hardener HY 5160) and their velocities are found to be 2990, 2680 and 2300 m/s, respectively. Taking into account velocities of layers in production and injection well from Table 1, we conclude that the black epoxy raisin is appropriate to represent coal layer in the physical model.

On the way to a realistic up-scaled physical model of the RECOPOL geometry which is suitable for the simulation of CO_2 injection, we start with the investigation of a dual coal/overburden model.
The acquisition includes one fixed source position and 52 different positions of the receiver. Spacing interval of the receivers is 2 mm. Consequently, the target zone is 104 mm wide. At both sides of the source, the area of 52 mm is scanned. The width of the two-layered model is 41 mm. Fig. 8 shows seismic data (common shot gather) for the baseline and monitor survey, respectively. Baseline survey is done in the absence of the model on the positioning table. Thereby, the acoustic wavefield propagates through the water only. The traveltime delay of the first arrivals in monitor survey is due to higher velocities of the model compared to the reference water velocity. The data are of a good quality since the first arrivals with the compressional wave are very clear. The central frequency of the transducer is 500 kHz, and the strongest energy recorded is between 200 and 600 kHz.

Durham ultrasonic experiment

As an example, we present here some of our results on the seismic data set, acquired on an epoxy scaled model (see Fig. 9). The model has been made and the data recorded at the University of Durham, United Kingdom [Ref. 4, 5]. As faintly can be seen in Fig. 9A and much more clearly presented in Fig. 9B, the model contains seven horizontal layers of different velocities and thicknesses, a single channel feature, and a single dipping layer with a small fault. The model is sufficiently wide in the out-ofplane direction to be considered two dimensional. The full survey consisted of a 51 source positions and 51 receiver positions, each at 2.5-mm intervals. In total 2601 traces were generated. The target region was 46.5 mm wide by 125 mm long.

Here, we illustrate advantage of our waveform inversion method over the more standard one, using those seismic data of a scaled epoxy raisin model.
For the inversion, as a reference model, we have used configuration without single channel feature, thus criteria for the quality of the inversion is how power is the resolution of that structure and how good is the estimation of its velocity.
Our method is based on the linear finite-frequency wave theory where single scatterings are accounted for, while more standard inversion approach is based on the ray theory. Ray theory is high-frequency approximation of the wave theory and therefore it is justified to be used only if wave field propagates through the sufficiently smooth medium. Fig. 10 shows wavefield inversion results using both approaches – ray theory and wave theory based inversion, respectively. It is clearly seen that Fig. 10A has a better resolution. Also, it can be seen that wavefield inversion based on the linear finite-frequency wave theory does not under-estimate velocity of the anomaly in the contrast to ray theory based inversion.

Furthermore, there is also possibility to apply time lapse monitoring on Durham data, since another model simulating post-flood has also been made [Ref. 5, 6]. There, only third reservoir layer (from the top) has been cut in two, and one part was replaced by the material with p-wave velocity 2147 m/s (see Fig. 11B) Initially, third layer had velocity of 2573 m/s, thus velocity difference that need to be detected is about 400 m/s. Our time lapse monitoring clearly reveled exact position of the post-flood region and accurately estimated velocity difference, as can be seen in Fig. 11A.

SUMARY AND CONCLUSSIONS

This paper illustrate richness and complexity of the problem we aim to solve, variety of approaches how to tickle it and it gives hope that soon we will be able to gain enough knowledge about CO_2 sequestration and enhanced production of methane.

We have proposed time lapse seismic technique for the monitoring of CO_2 injection and detection of all other changes in the subsurface which are thereby introduced. Using seismic data from a real field experiment on a physically similar configuration (steam injection in tar sand), we have proved that time lapse seismic monitoring indeed is a powerful tool.

Next, we have built experimental setup for ultrasonic modeling. By doing various testing, we have gathered enough knowledge to start building realistic scaled model which will successfully simulate CO_2 injection in the coal seams. In order to visualize thin coal layers and changes there in, we had to developed high quality seismic inversion method. To verify high resolution of our wavefield inversion method, we have compared images of layered physical model (prepared in Durham), obtained by inversion algorithms based on ray theory and on more complex wave theory. Obtained resolution is found to be satisfactory. Moreover, we also performed time lapse tomography using physical model data, and obtained result is accurately describing all changes between two models (pre-flood and post-flood).

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TABLES

Averaged P velocities [m/s]	coal	shale	sand
Injection well MS-3	2500	4250	4000
Production well MS-4	2250	4250	3750

Table 1. Averaged p-wave velocities for coal, shale and send in the production and injection well.

FIGURES

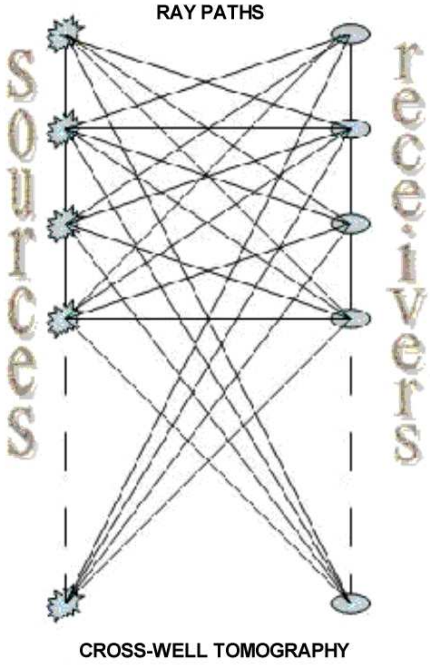


Fig. 1. General setup and concepts in a crosswell experiment.

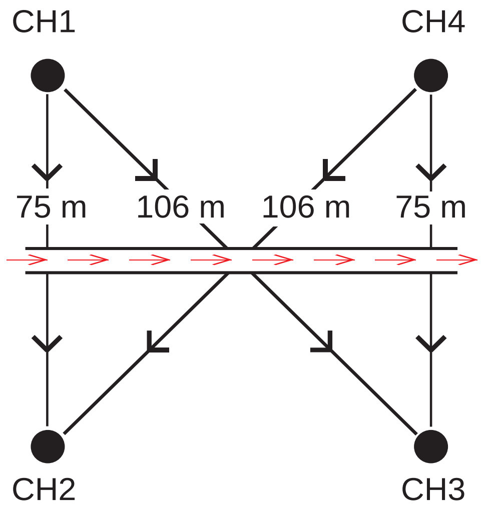
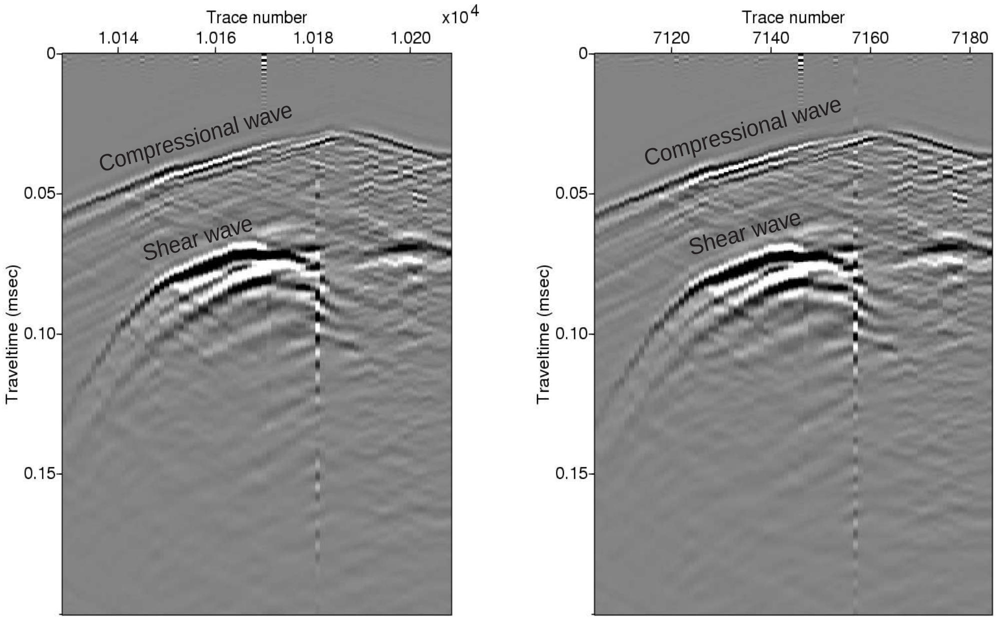


Fig. 2. Top view of the experimental configuration of wells and steam pipeline.



Reference survey, CH1CH2, comp. 1 **Monitor survey, CH1CH2, comp. 1**

Fig.3. Baseline and monitor seismic data for one fixed source position.

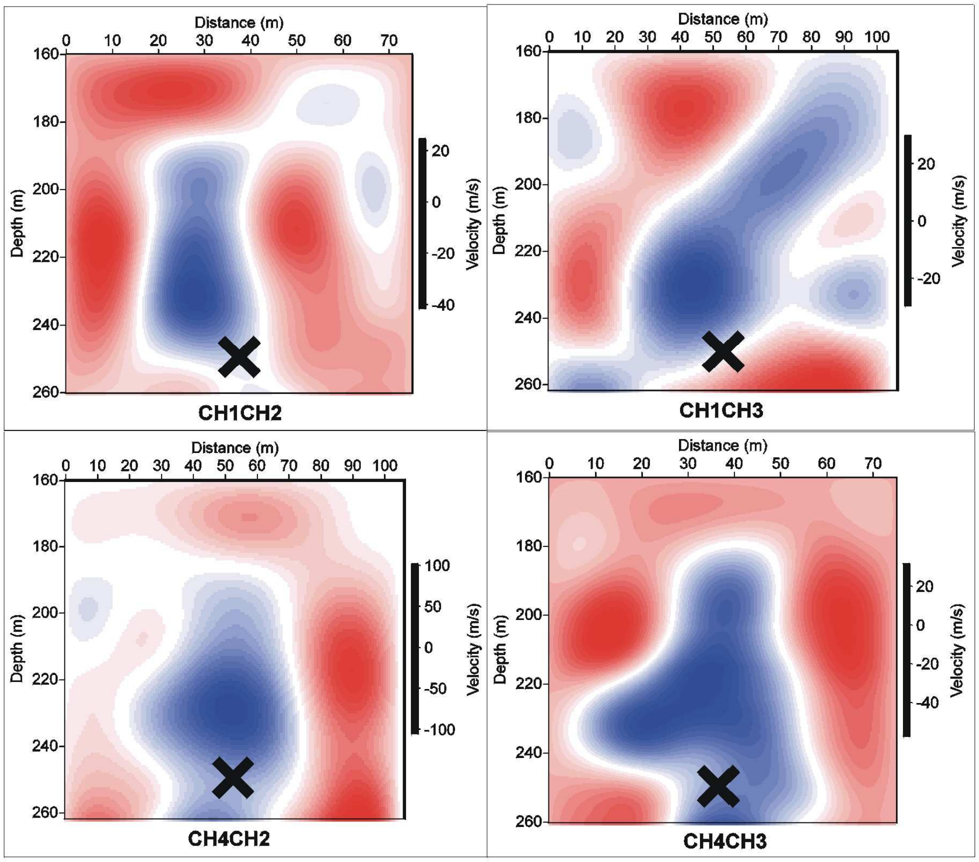


Fig. 4. Time-lapse compressional wave velocity images. The black cross indicates the location of the steam pipeline

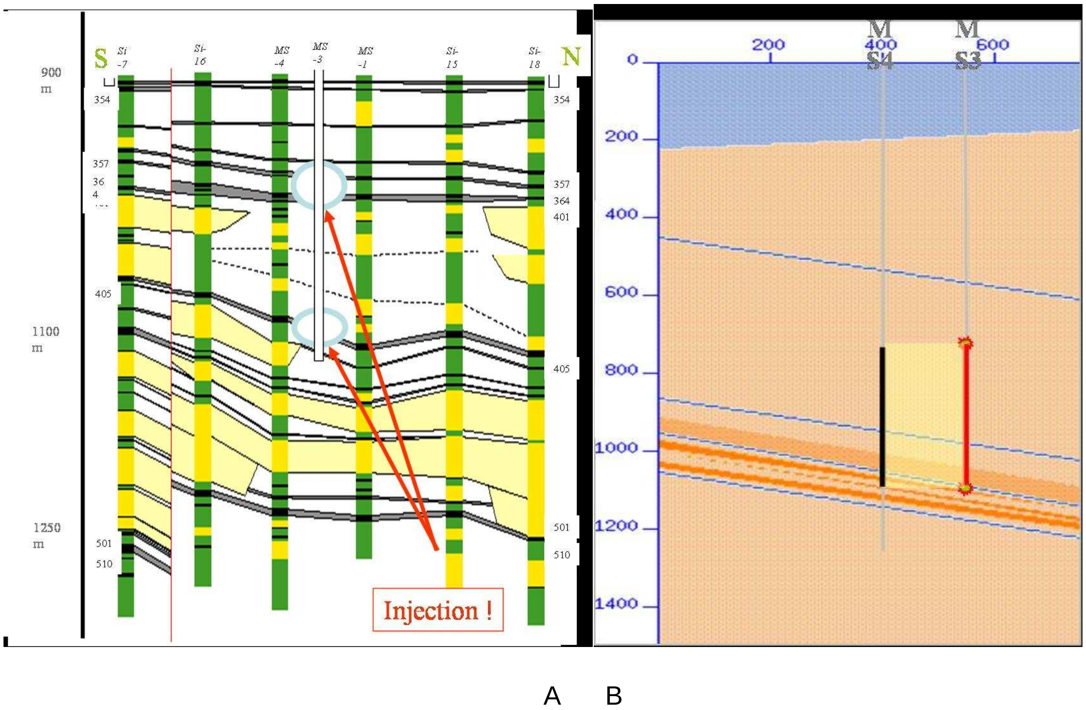


Fig. 5. A) The position of wells, coal seams and injection. B) The target zone of the survey. (Source: TNO-NITG).

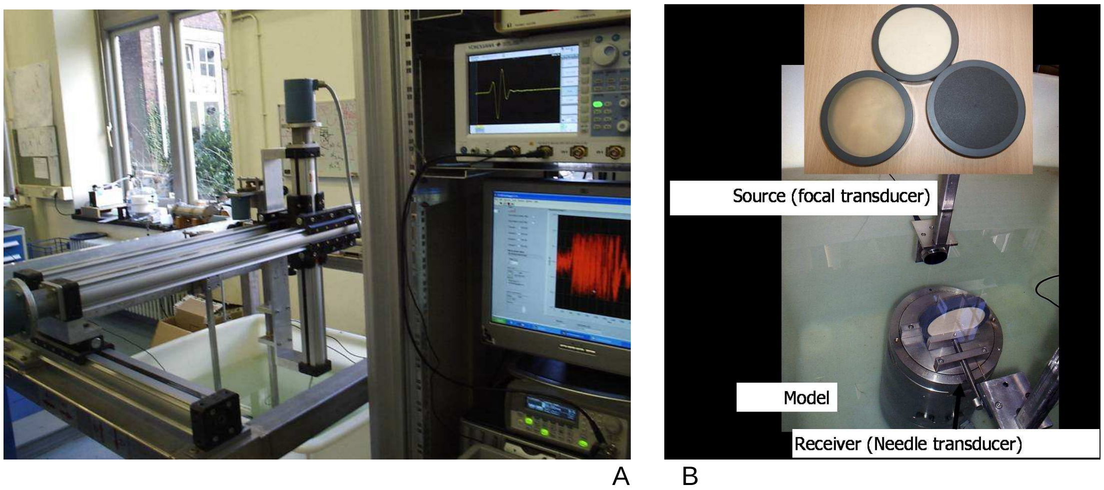


Fig. 6. Dietz Laboratory at TU Delft. A) Experimental setup: oscilloscope, computer, wave generator, water tank and motion system. B) Blow up of the part immersed in the water: source, receiver and the model situated at the positioning table. Small photo in the upper part represents 3 different samples of the epoxy raisin materials.

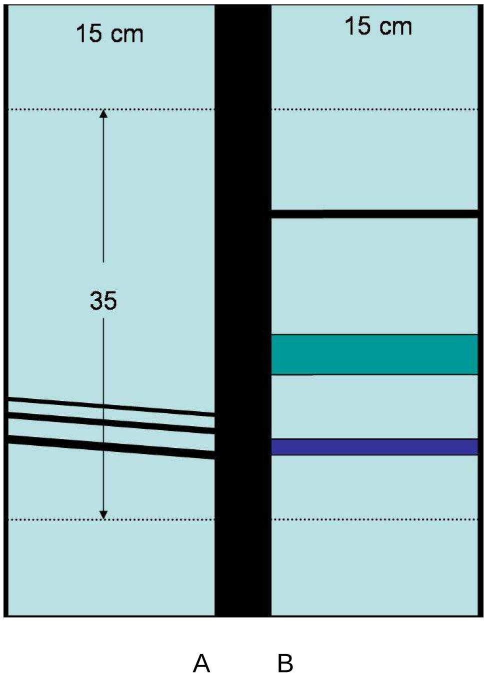
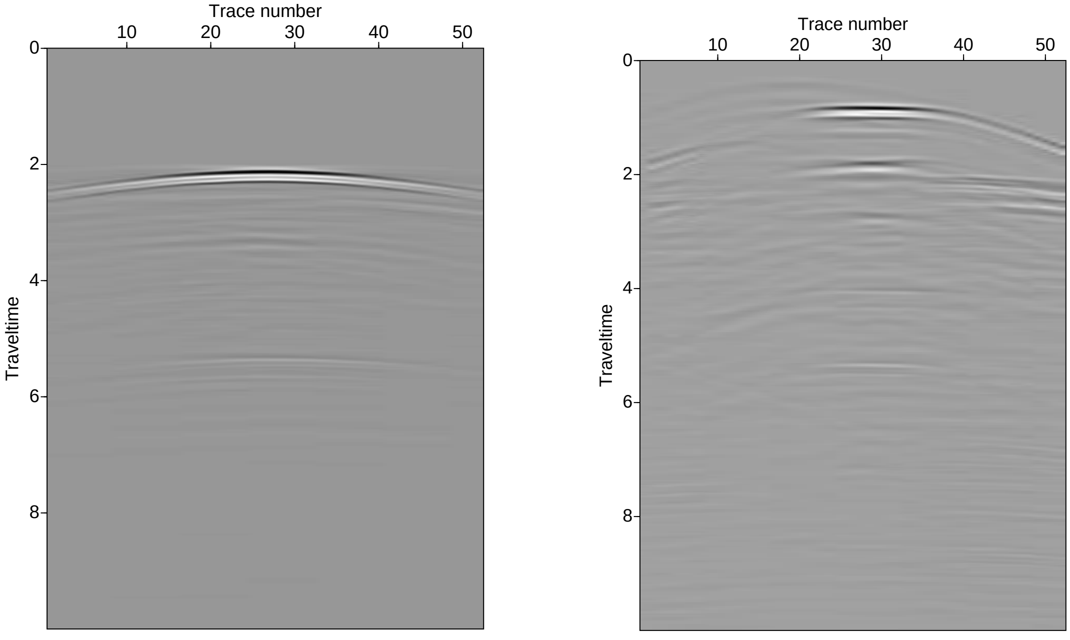


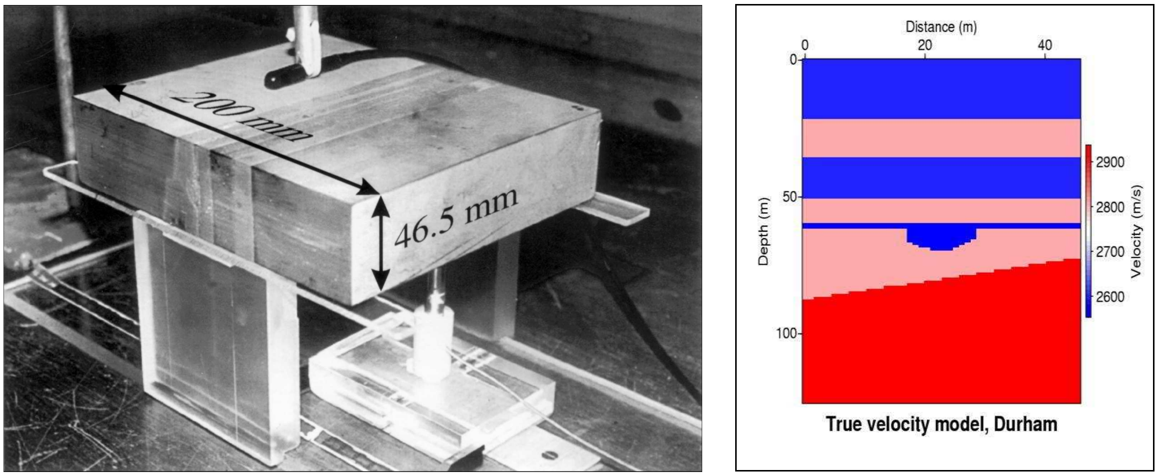
Fig. 7. Physical models of the RECOPOL geometry. Extended borders in order not to disturb survey. A) Complex one, difficult to make. B) Easier to make, but intrinsic complexity kept in.



water

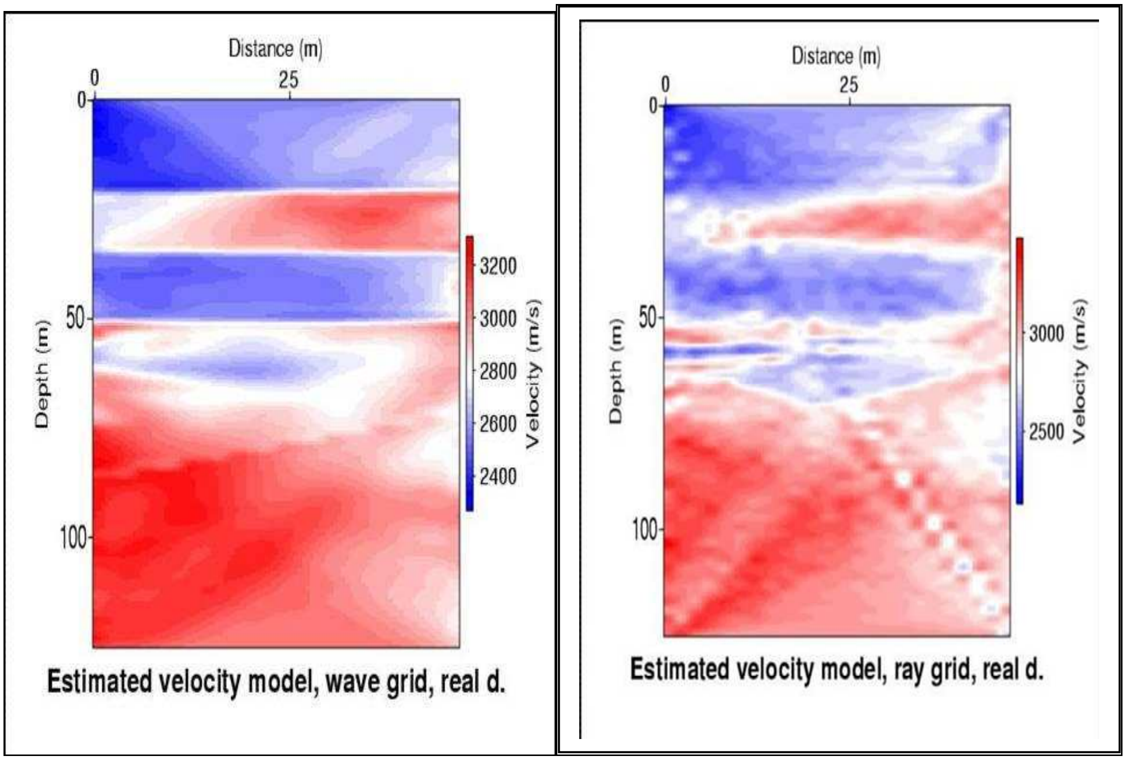
model 1

Fig. 8. Baseline and monitor seismic data for one fixed source position. Traveltime in μs.



A B

Fig. 9. A) A photograph of the Durham epoxy raisin model. The model has been tipped on one side in a preparation for the experiment. The top of the survey is at right end of the photograph.
B) Schematic section through the epoxy resin scale model.



A B

Fig. 10. Velocity tomograms. Image A) is obtained using wave theory and image B) using ray theory based inversion.

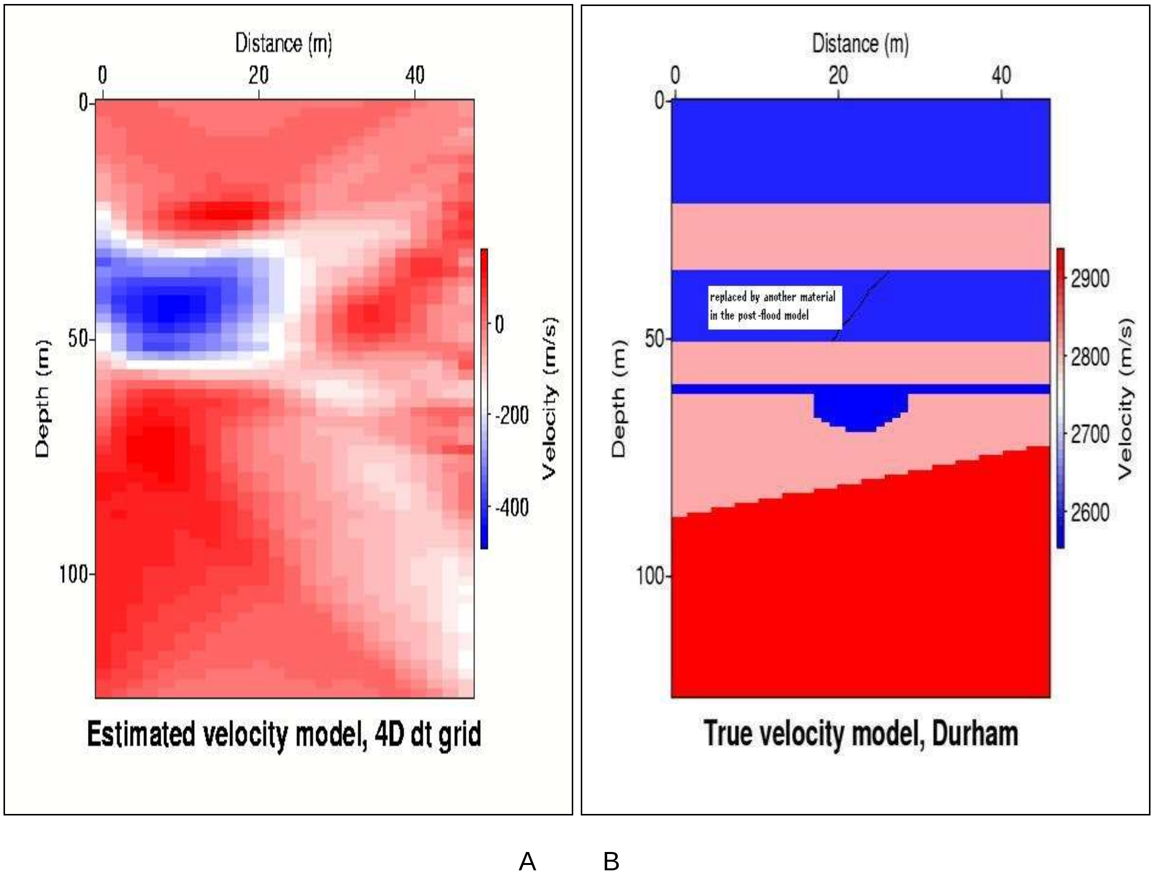


Fig. 11. 4D time lapse experiment. A) Result of time lapse monitoring detects lower velocity part of the post-flood model. B) Sketch of the physical model where left-hand part of the reservoir layer was replaced by low p-velocity material in the post-flood model.