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ScienceDirect
Energy Procedia 1 (2009) 2193–2200
Energy Procedia
www.elsevier.com/locate/procedia

GHGT-9

Designing a seismic program for an industrial CCS site: trials and tribulations

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Abstract

Designing a seismic characterization and monitoring program for a site with high levels of industrial and cultural infrastructure is by not trivial. At the MGSC Phase III project site, a combination of 3D surface seismic and VSP surveys will be used for site characterization and to monitor the injected CO_2. The sparse existing data have been carefully analyzed to design 3D surface seismic and VSP surveys that will fit within the surface constraints at the site and meet the greater objectives of the project. The seismic data will be used to map formation heterogeneities and characterize fractures.

Keywords: CO_2, seismic survey design, VSP, site characterization, monitoring, time-lapse, industrial site

1. Introduction

The Midwest Geological Sequestration Consortium (MGSC) Phase III project is located on the Archer Daniels Midland (ADM) Company property in Decatur, Illinois. The CO_2 source is the ethanol fermentation operation at the ADM plant. The current plans aim to inject one million tonnes of supercritical CO_2 over a three year period into the Mt. Simon Sandstone starting December 2009. The objectives of the project include characterization of storage formation and overburden, determination of the CO_2 injectivity and storage capacity of the Mt. Simon Formation, and effective monitoring of the CO_2 plume syn- and post injection. Two of the tools that will be used for site characterization and monitoring of the CO_2 plume are 3D surface seismic data and vertical seismic profile (VSP) data.

Designing a seismic program that meets the site characterization and monitoring objectives of the project is not trivial at an industrial site. The ADM plant is located on the edge of Decatur where there is limited site access for seismic surveys as well as high levels of industrial and cultural noise from surrounding plants, traffic, and trains. Several solution have been implemented or proposed to address these challenges. A detailed seismic survey design and evaluation (SED) study was completed to ensure that a 3D surface seismic survey was technically feasible. Data acquisition using a single sensor system has been proposed to adequately attenuate noise and increase data resolution. Time-lapse 3D VSPs have been planned as a high resolution and cost effective alternative to surface seismic data.

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doi:10.1016/j.egypro.2009.01.285

The results of the ADM project will have ramifications for commercial CCS operations in the Illinois Basin. The challenges faced in designing a seismic program at the site will be relevant to future commercial projects where CO_2 storage is co-located at a plant site with extensive infrastructure and site access issues.

2. Project geology and available data

The Cambrian Mt. Simon Formation is the thickest and most widespread saline aquifer in the Illinois Basin. The Mt. Simon Formation is underlain by Precambrian granitic basement and is overlain by a regionally extensive, low-permeability shale known as the Eau Claire Formation. Very little data were available within a 20 mile radius of the site to aid in site characterization. Rough estimates to the top and of the thickness of the Mt. Simon Formation were based on regional structure and isopach maps and two wells located 51 miles to the south and 37 miles to the north of the site respectively (Figure 1). Based on these data, the Eau Claire Formation was estimated to be at a depth of 4920 ft and have a thickness of 500 ft, and the Mt. Simon Formation was estimated to be at a depth of 5420 ft (+/-500 ft) and a thickness of about 1700 ft.

Two 2D seismic profiles (ADM-1 and ADM-2) were acquired along the east-west and north-south roads that pass by the ADM plant in the Fall of 2007. The seismic contractor was restricted to using two Envirovibes™ along the roadways due to the amount of industrial and residential infrastructure in the area. The purpose of these lines was to provide some preliminary information about the geologic structures and stratigraphy at the site. An anticlinal structure was identified at the top of the Mt. Simon Formation to the northwest of the proposed injection well in the 2D seismic data (Figure 2); however, a full 3D surface seismic survey or additional 2D seismic lines will be needed in order to properly define the structure and evaluate its impact on the movement of CO_2 in the subsurface.

Two additional sets of old well logs were identified and used to refine the depth and thickness estimates of the Mt. Simon Formation, and thereby assist in the drilling plans for the injector well. The N. Barnard well is located 7 miles to the east of the ADM site. While a full suite of logs was acquired in the well, it was drilled to a depth of 2650 ft and only provides shallow well control. The closest deep well control to the site is 17 miles to the southwest where the L. Harrison well penetrates the top of the Mt. Simon Formation at 6306 ft; the only logs acquired in this well were SP and resistivity. Pseudo-sonic and density logs were generated for the L. Harrison well and the pseudo-logs were spliced with the N. Barnard well logs. The spliced pseudo-sonic and density logs were used to create synthetic seismograms that were correlated to the 2D surface seismic data to improve the depth and thickness estimates for the Mt. Simon Formation. The new depth and thickness estimates for the Mt. Simon Formation were 5259 ft (+/-200 ft) and 1856 ft, respectively. These new estimates reduced both the uncertainty in the depth of the formation tops and had a direct effect on the drilling plans for the injector well. The pseudo-sonic and density logs were also used in the VSP modeling.

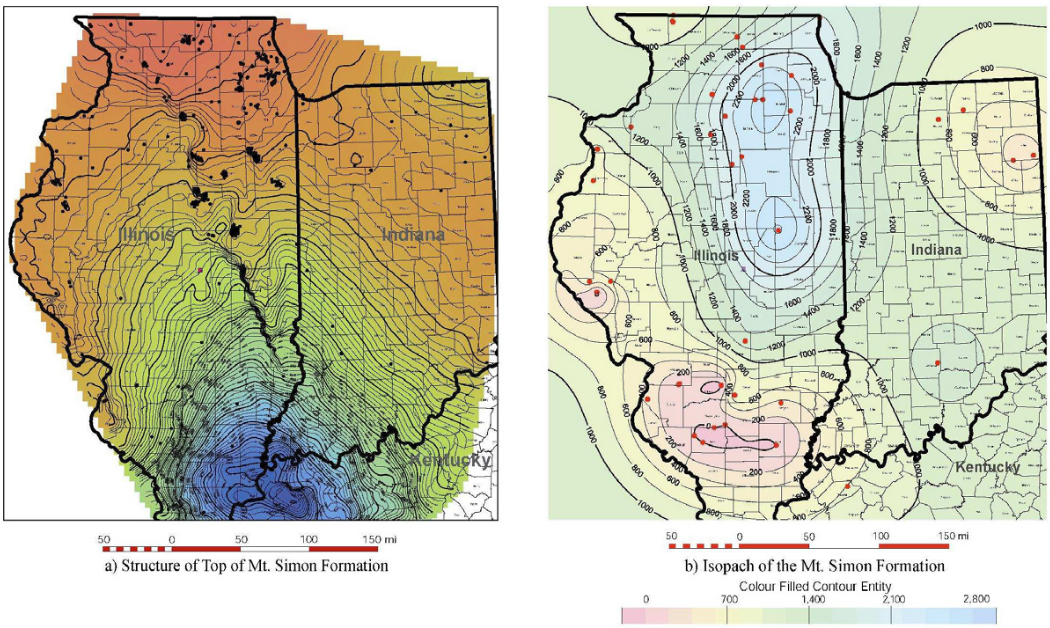


Figure 1: Regional maps of the Mt. Simon Formation. a) Structure at the top of the Mt. Simon Formation. b) Thickness of the Mt. Simon Formation (Courtesy of the Illinois State Geological Survey).

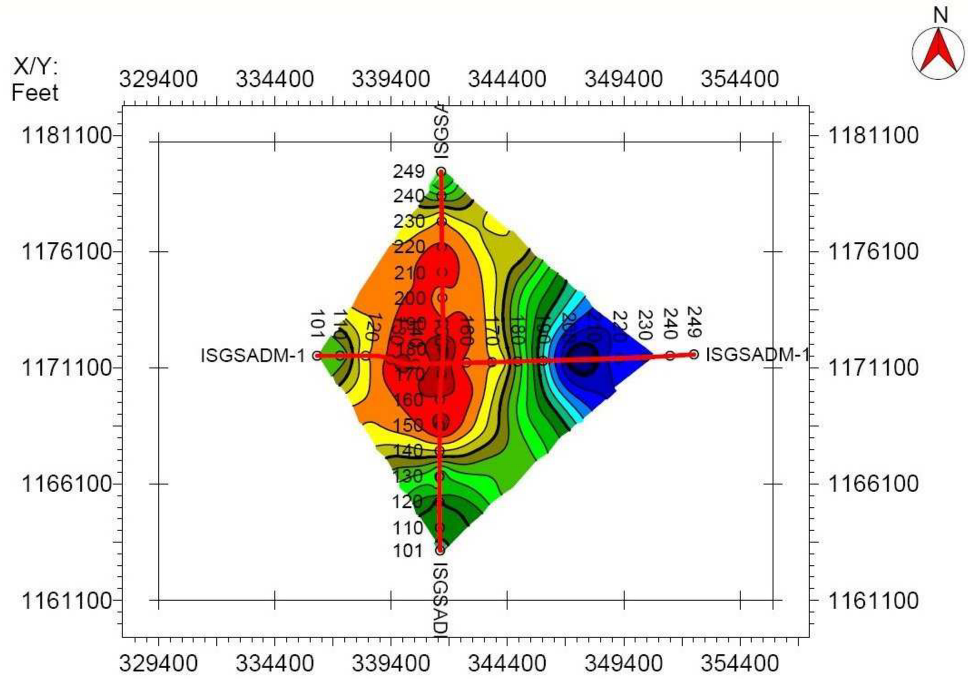


Figure 2: Anticlinal structure identified on the 2D surface seismic lines at the top of the Mt. Simon Formation. The crest of the structure appears to be northwest of the injection point. More seismic data will be needed to define the geometry of this structure and assess its potential effect on CO_2 movement.

3. 3D surface seismic survey design

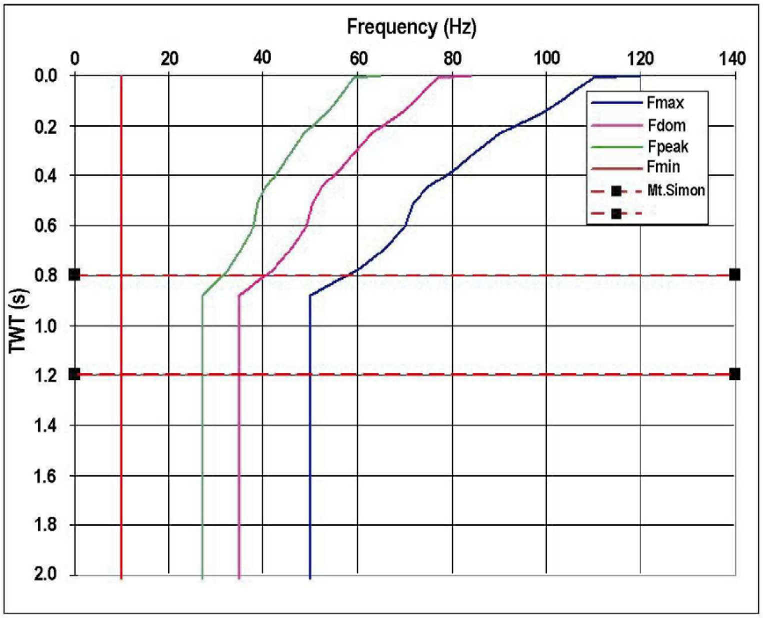
Ideally, the project should acquire baseline 3D surface seismic data for further site characterization prior to CO_2 injection and, if the project budget allows, a 3D monitor survey at the end of the project to map the distribution of CO_2 within the Mt. Simon Formation. However, given the restrictions on site access, the technical feasibility of acquiring a 3D surface seismic survey was in serious question. The SED study was the critical first step in designing a seismic program for the site given the obvious surface constraints because it ensured that the 3D surface seismic survey would meet the objectives of the project. The 2D seismic data was analyzed to determine the potential frequency bandwidth and resolution of new 3D seismic data as well as the required migration aperture needed to image the Mt. Simon Formation and overburden at the ADM site.

3.1. Resolution analysis

Figure 3a shows that the 2D seismic data has a dominant frequency of 40 Hz at 0.8 s, which corresponds to the top of the Mt. Simon Formation. The bandwidth and seismic velocity define the extent to which the seismic data will be able to image geologic features such as thin beds and faults. The vertical resolution analysis predicts that the seismic data should be able to resolve a thin bed that is about 80 ft thick at 0.8 s (Figure 3b), and fault resolution analysis predicts that the seismic data should be able to resolve a fault with a vertical displacement of 30 to 60 ft at 0.8 s. If the frequency bandwidth of the 3D surface seismic data can be increased beyond that of the 2D seismic data then the vertical and lateral resolution of the 3D seismic data will increase as well.

3.2. Migration aperture

It is necessary to record extra full fold data around the edges of the subsurface area you want to image so that the migration can properly position all of the reflection and diffraction energy in the area. Migration aperture is based on the larger of steepest geological dips in the area or the distance required to capture diffracted energy with a dip of 30°. At this site, there are no substantial geologic dips. The SED study estimated that a migration aperture of 5000 ft would be needed to image a target at 1.2 s based on a 30° diffraction aperture. The required migration aperture has a direct effect on the size of the actual acquisition footprint needed to image the area around the proposed injection well.



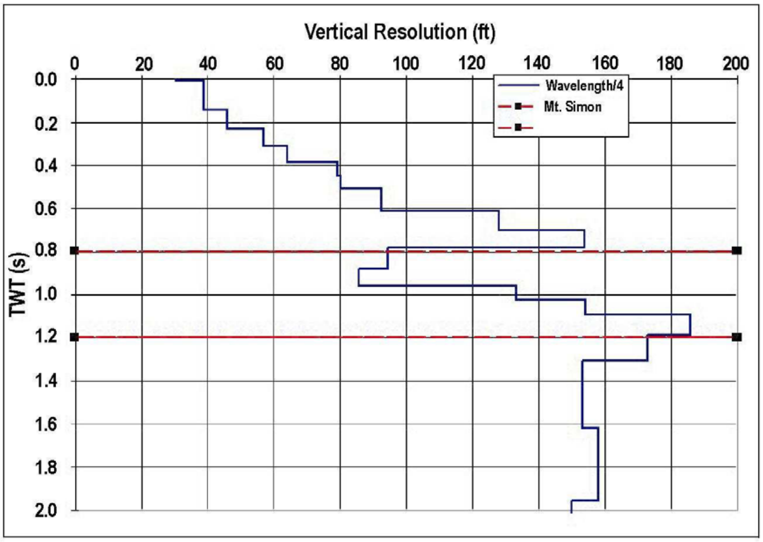


Figure 3: Analysis of bandwidth of 2D data and vertical resolution. a) Frequency content against depth. b) Variation in thin bed resolution with depth; vertical resolution is a function of the maximum interpretable frequency and velocity.

3.3. Field lay-out

Figure 4 displays the proposed source – receiver lay-out for the 3D seismic survey and the corresponding fold coverage based on a 40 x 40 ft bin size. Typical bin sizes used for seismic acquisition and processing usually range between 110 – 220 ft. The ideal migration aperture needed at the surface to image the top of the Mt. Simon Formation in the area surrounding the injector well has been highlighted. Surface infrastructure prevents the survey from obtaining source and receiver points over the entire area needed for the ideal migration aperture. This increases the risk that the 3D seismic data acquired will not be able to adequately image the area around the injector well. Extra source lines were added in the middle of the survey area where site access was already known to be a problem to increase subsurface fold coverage in that particular zone, but fold coverage still decreases to the south because plant infrastructure prevents the acquisition of source and receiver points in that direction. The fold coverage shows that a large portion of the subsurface image area will be full fold, and full fold data will be obtained well beyond the immediate image area north and northeast of the injection well. This scenario fits the needs of the project well as the CO_2 plume is expected to preferentially move to the northwest based on the expected dominant northwest fracture trend in the Mt. Simon Formation, the small regional dip at the top of the formation, and the anticlinal structure identified in the 2D seismic data. It should be stressed that Figure 4 represents a best case scenario, as there may be additional restrictions on source and receiver placement that will further reduce the subsurface coverage shown.

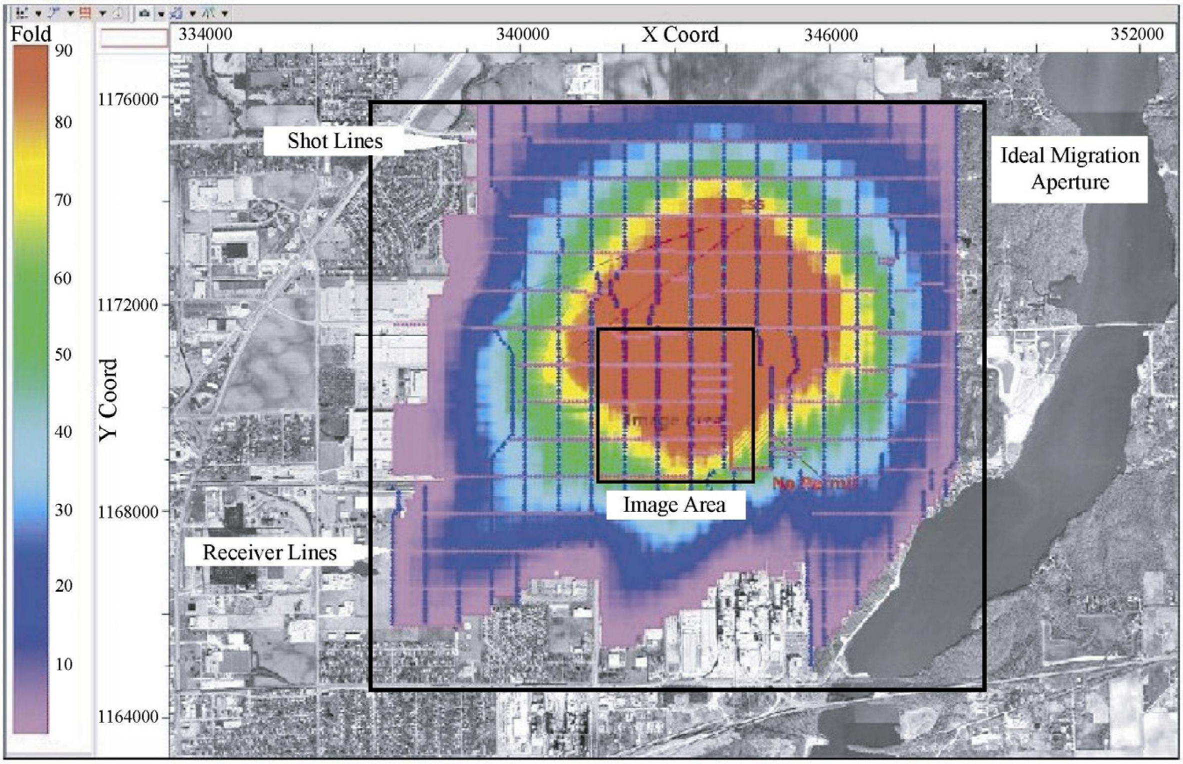


Figure 4: The best case source – receiver lay-out and fold coverage for the ADM site given surrounding surface constraints. Source lines are in purple, and receiver lines are in blue. Fold coverage is based on a 40 x 40 ft bin size. The ideal migration aperture and subsurface image area are highlighted in black.

The ADM site is on the edge of Decatur and is surrounded by industrial plants. As a result the 2D seismic data was heavily contaminated by industrial noise, mains power contamination, and cultural noise such as traffic, as well as by typical source generated noise (Figure 5). On some shot gathers, the amplitude of the noise is much higher than the amplitude of the seismic signal. and the noise is aliased. High amplitude, aliased noise presents a serious challenge to both data processing and imaging targets of interest because the processing will smear the aliased noise across the final image and obscure primary reflectors. Ideally, the acquisition lay-out should be designed to adequately record noise so that it can be removed from the data early in the processing flow. However, coherent noise recorded by conventional geophone arrays is often aliased [1].

Single sensor seismic acquisition improves random noise attenuation and ensures that coherent noise is adequately sampled, so it can be removed early in the data processing sequence [1]. Single sensor data also preserves the intra-array perturbations that distort the true seismic signal and reduce frequency bandwidth of the data so they can be corrected during processing [1]. The resulting single sensor data has a higher signal-to-noise ratio, increased frequency bandwidth, and an increase in image resolution as compared to conventional seismic acquisition systems that are based on geophone arrays [2]. An increase in the resolution of the image will help reduce geologic uncertainties during the site characterization phase of the project while the increase in the signal-to-noise ratio will mean smaller time-lapse changes can be detected during the monitoring phase of the project [3].

4. Monitoring with VSP data

VSP surveys have been planned to monitor the active CO_2 injection on an intermediate basis. 3D VSP surveys will provide even higher resolution images of the Mt. Simon Formation around the injector well than the surface seismic data [4]. A permanent geophone array will be installed so that frequent time-lapse 3D VSP surveys can be acquired to monitor the injected CO_2; these surveys will be more cost effective and have smaller acquisition footprints and deployment efforts than 3D surface seismic surveys. The parameters obtained during the VSP processing, such as anisotropy, Q factor, and multiple analysis, can also be used to improve the 3D surface seismic imaging [5, 6]. Again, improvements in the surface seismic imaging through the enhancement of frequency bandwidth and resolution will improve the site characterization and reduce uncertainties in the geologic models and simulations.

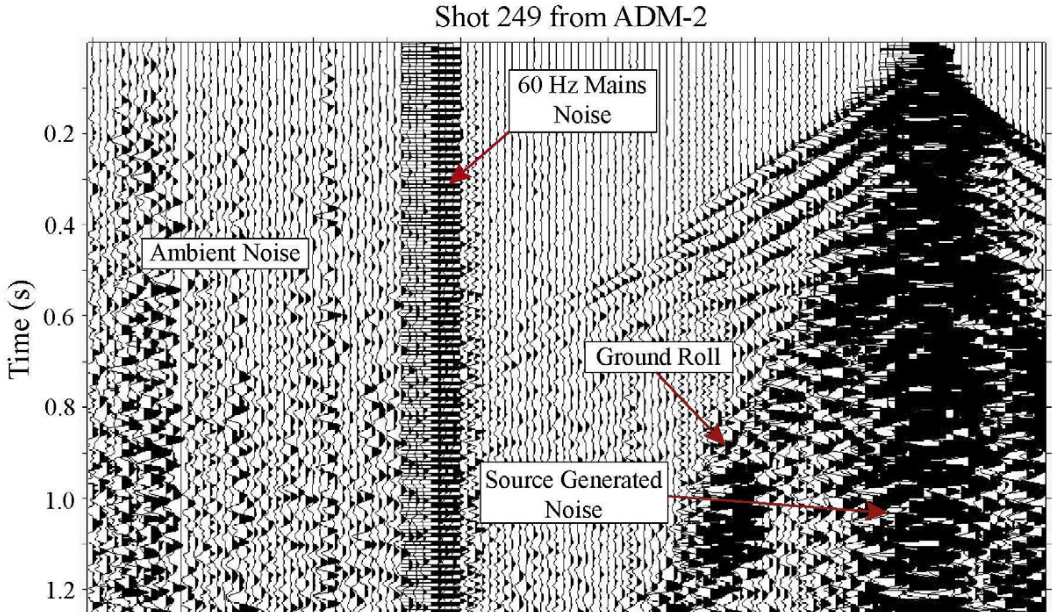


Figure 5: Example of the noise recorded in a shot gather at the north end of the north-south 2D line. Types of noise include ambient noise in the area, electrical noise from power lines, ground roll, and source generated noise. This is one of the shots farthest from the plant and is relatively quiet. Trace spacing is 110 ft.

4.1. VSP Modeling

Initially, the plan was acquire the baseline 3D VSP survey simultaneously with the 3D surface seismic data without adding additional shot points. The 3D VSP subsurface fold coverage at about 5500 ft was modeled using the shot points from the 3D surface seismic survey and a 31 level geophone array located between 1734 -- 2484 ft depth (Figure 6a). The modeling plainly shows that the shot and shot line spacing of the 3D surface seismic survey is too sparse to provide adequate 3D VSP images at the site. Instead, the 3D surface seismic source lay-out would result in a series of 2D walkaway VSP images. While the walkaway VSP images would be useful, they are not at the ideal azimuth to monitor the injected CO_2 plume. The ideal walkaway azimuths would trend NW-SE and NE-SW or be parallel and orthogonal to the anticipated direction of CO_2 movement within the formation.

A second model of the subsurface fold coverage for the 3D VSP was generated using a 100 ft shot grid over a 2400 x 2400 ft area around the monitor well (Figure 6b). This configuration gives subsurface fold coverage of 20 out to offsets approximately 500 ft from the monitor well. The area of the 3D VSP survey can easily be expanded to give greater subsurface coverage, and it would still be smaller than the footprint of the 3D surface seismic survey. The final 3D VSP survey size will be based on the CO_2 plume simulations that will be run once new well logs are acquired in the planned injector well. It should also be noted that the 3D VSP monitor surveys do not necessarily have to cover the entire footprint of the baseline survey but, instead, can cover a subset of the baseline survey based on the predicted plume expansion at a particular point in time.

5. Conclusions

Very little data beyond regional information has been available to characterize the deep geology around the ADM site and to provide depth and thickness estimates of the Mt. Simon Formation. Careful analysis of old well logs within a 17 mile radius of the ADM site and newly acquired 2D seismic lines allowed the depth and thickness estimates for the Mt. Simon Formation to be refined; thereby assisting in drilling decisions related to the injector well.

Given the industrial and cultural surface constraints at the ADM site, there was some doubt as to whether it was technically feasible to acquire a 3D surface seismic survey at the site. A dedicated SED study evaluated the frequency bandwidth, vertical resolution, noise content, and required migration aperture of the existing 2D seismic data to help design a 3D source – receiver lay-out that would fit within the surface constraints at the site. The SED study proves that a 3D surface seismic survey can in theory be acquired at the site that will have adequate fold coverage in the required image area and additional subsurface coverage to the north of the injector well where the CO_2 is expected to preferentially move.

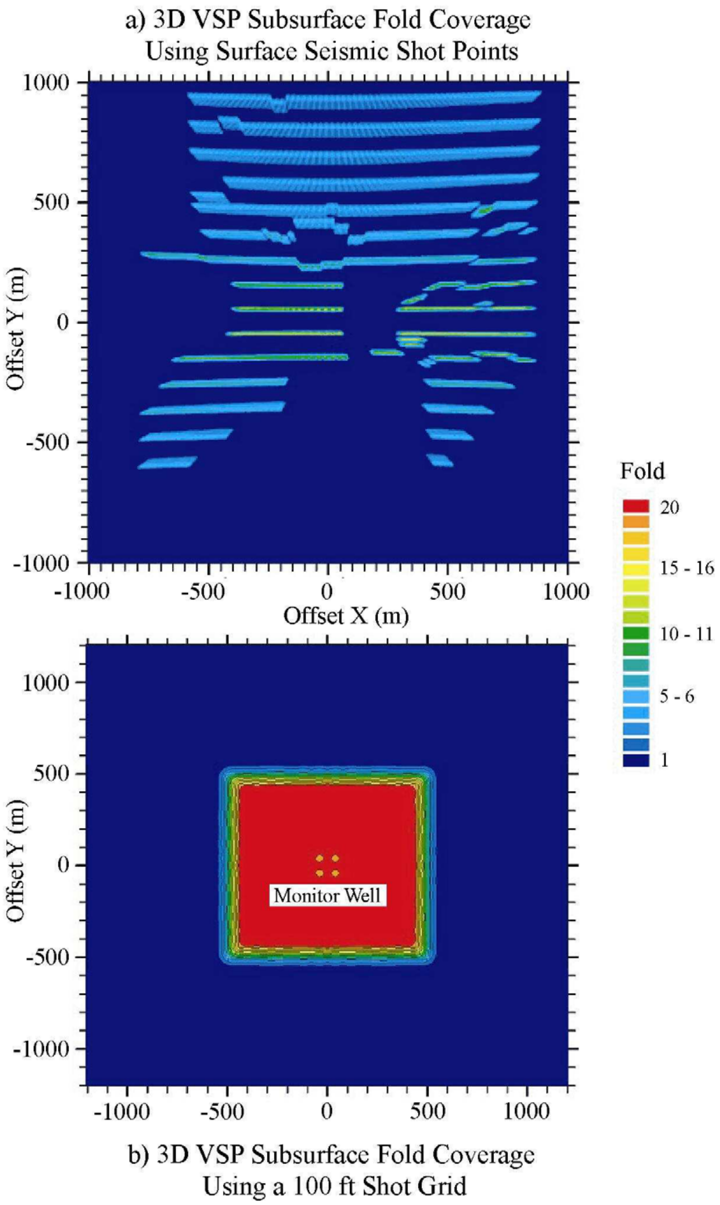


Figure 6: 3D VSP fold coverage modeling. a) The subsurface fold coverage obtained using the 3D surface seismic shot points. The shot points and shot lines result in 2D walkaway VSP images rather than 3D VSP images. b) 3D VSP fold coverage using a 100 ft shot grid.

Time-lapse 3D VSP surveys will be used monitor the injected CO_2 plume for the duration of the project as they provide a higher resolution and lower cost alternative to 3D surface seismic surveys. Plans are to install a permanent geophone array for the time-lapse monitoring. VSP modeling shows that the surface seismic survey shot points alone do not provide adequate subsurface fold coverage for 3D VSP imaging. At best, these shot points will provide 2D walkaway VSP images of the subsurface. A 100 ft shot grid over a 2400 x 2400 ft area would result in a 3D VSP with a fold coverage of 20 out to an offset of about 500 ft from the monitor well. Shot locations for the 3D VSP surveys will be refined based on surface limitations once new data has been obtained from the injector well.

6. Future plans

Once the injector well has been drilled and a full suite of logs has been acquired, the new data will be used to model the seismic response of the Mt. Simon Formation to CO_2 injection. Modeling the anticipated seismic response of the formation to specific volumes and saturations of CO_2 will assist in planning the time-lapse VSP surveys. Specifically, the magnitude of the modeled seismic response will help determine the optimal timing for the time-lapse VSP surveys. Without the fluid substitution modeling there is a danger that a monitor survey could be acquired before any measurable change has occurred in the formation as a result of CO_2 injection.

The baseline 3D surface seismic data and 3D VSP data should be acquired in the Fall of 2009. Prior to this, the ground at the site will be too wet to acquire good seismic data and crops in the surrounding fields will prevent site access. When the data has been processed, it will be calibrated using the new well log data and seismic inversion will be used to derive rock properties, such as lithology, porosity, and permeability, away from the injector well. Mapping rock properties away from the injector well will identify heterogeneities within the Mt. Simon Formation, such as high porosity zones, that may have a significant affect on the movement of CO_2. It will also help identify stratigraphic features in the Eau Claire Shale which may affect long term storage integrity at the site.

Finally, the 3D seismic data will also need to be analyzed for fractures in both the Mt. Simon and Eau Claire Formations, as the fractures will affect the movement of the CO_2 within the Mt. Simon Formation and the long term integrity of the cap rock. Heterogeneities identified by the seismic inversion and the results of the fracture characterization must be incorporated into the existing geologic models and simulations, as they may have a significant impact on the behaviour of the injected CO_2.

Acknowledgements

The Midwest Geological Sequestration Consortium is funded by the U.S. Department of Energy through the National Energy Technology Laboratory (NETL) via the Regional Carbon Sequestration Partnership Program (contract number DE-FC26-05NT42588) and by a cost share agreement with the Illinois Department of Commerce and Economic Opportunity, Office of Coal Development (contract number ICCI0303 DEV03 2RF).

SMT Software for their University grants to the University of Illinois and Brigham Young University.

Special thanks go to the following people at Schlumberger and WesternGeco: David Paddock and Mohamed Eissa for the log and depth estimation work, George El-Kaseeh, Eugene Gridnev, and Joe Seissiger for the surface seismic survey design, and David Patten for the VSP modeling.

Disclaimer

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