FINAL REPORT

A Non-Invasive Approach for Elucidating the Spatial Distribution of In-Situ Stress in Deep Subsurface Geologic Formations Considered for CO_2 Storage

DOE Award Number DE-FE0031686

Prepared by:

Battelle
505 King Avenue
Columbus, Ohio 43201

Principal Investigator: Mark Kelley
kelleym@battelle.org 614-424-3704
Project Manager: Christa Duffy
duffyc@battelle.org 614-424-5785

Authors: Mark Kelley[a], Bob Hardage[b], Andrew Bunger[c], Odd Andersen[d],

a. Battelle
b. Independent Consultant
c. University of Pittsburgh
d. SINTEF

Submitted to:

National Energy Technology Laboratory
Technology Development and Integration Center
Carbon Storage Team
Project Manager: William W. Aljoe
412-386-6569
william.aljoe@netl.doe.gov

Date: December 17, 2021

Acknowledgment:

This material is based upon work supported by the Department of Energy National Energy Technology Laboratory under Award Number(s) DE-FE0031686.

Disclaimer:

TABLE OF CONTENTS

Page

TABLE OF CONTENTS (CONTINUED)

Page

List of Figures

TABLE OF CONTENTS (CONTINUED)

Page

List of Tables

ACRONYMS, ABBREVIATIONS, AND SYMBOLS

Acronym	Explanation
3C	three-component
3D	three-dimensional
AAPG	American Association of Petroleum Geologists
AVA	amplitude-vs-incident-angle
CCS	carbon capture and storage
CIP	Current Industry Practice
CO_2	carbon dioxide
DOE	Department of Energy
DRA	Deformation Rate Analysis
EDX	Energy Data Exchange
FE	Fossil Energy
FEM	Finite Element Method
FOA	Funding Authorization Announcement
FORGE	Frontier Observatory for Research in Geothermal Energy
ft	feet
H1 wavelet	transverse geophone (VSP) wavelet
H2 wavelet	radial geophone (VSP) wavelet
MATLAB	"MATrix LABoratory" –a proprietary multi-paradigm programming language and numeric computing environment developed by MathWork
mi^2	square mile
mini-frac	mini hydraulic fracture
ML	machine learning
ML+VS	machine learning trained on velocity-vs.-stress laboratory data
MPa	megapascal
MRST	MATLAB Reservoir Simulation Toolbox
NETL	National Energy Technology Laboratory
P	compressional
PP and P-P	Downgoing illuminating P wave and upgoing P reflected wave
PSTM	pre-stack time migration
P-SV	P-SV data involve a down-going illuminating P wave and an up-going SV reflected wave
P-wave	compressional-wave
S-wave	Shear wave

Acronym	Explanation
SEG	Society of Exploration Geophysicists
SEM	static earth model
SHmax	maximum horizontal stress
Shmin	minimum horizontal stress
σ_{yy}, σ_{zz}, σ_{xx}	two horizontal confining stresses (σ_{yy} and σ_{zz}) and a vertical confining stress (σ_{xx}) used in the Task 3 laboratory TUV tests
SINTEF	Stiftelsen for industriell og teknisk forskning, headquartered in Trondheim, Norway, is an independent research organization
SOL	State Otsego Lake Michigan
SPE	Society of Petroleum Engineers
S_V	Vertical stress
SV-P	SV-P data involve a down-going illuminating shear (SV) wave and an up-going P reflected wave
S-wave	Shear-wave
TUV	Triaxial Ultrasonic Velocity
VEM	Virtual Element Method
Vp	Velocity of P-wave
Vp/Vs	Ratio of compressional-wave velocity to shear-wave velocity
Vs	Velocity of S-wave
VSP	vertical seismic profile
$V_{p,xx}$, $V_{p,yy}$, $V_{p,zz}$	P velocities in three propagation directions (x,y,z)
$V_{s,xy}$, $V_{s,xz}$, $V_{s,yx}$, $V_{s,yz}$, $V_{s,zx}$, $V_{s,zy}$	S velocities in three propagation directions (x,y,z) and two polarity directions each (i.e., two polarity directions per propagation direction, e.g., xy and xz)

EXECUTIVE SUMMARY

The primary objectives of this project were to: develop a new, non-invasive method to define the orientation and magnitude of in-situ stresses in deep geologic formations (depths that exceed 1500 meters) considered for carbon dioxide (CO_2) sequestration; to demonstrate the method at a real field site; and, to extend current technical capabilities and reduce costs of acquiring information about deep-stress fields. This investigation was segmented into five tasks, including Project Management (Task 1) and four technical tasks (Tasks 2 through 5). The results of the technical tasks are described in this document.

In Task 2, two methods were demonstrated that successfully extracted the azimuths (directions) of maximum horizontal stress (SHmax) and minimum horizontal stress (Shmin) in deep rocks from traditional seismic reflection data like the data that have been used for decades to explore for deep oil and gas reservoirs. The first method utilized a legacy vertical seismic profile (VSP) from the former FutureGen2 site in Morgan County, Illinois. This project showed that the azimuth where a polarity reversal occurs in a mathematically rotated, down-going, direct-S wavelet defines the azimuth of SHmax. Shear-wave (S-wave) data were emphasized in this VSP study because S waves are more sensitive to stresses and fractures than are traditional compressional (P)waves used in seismic reflection seismology. This vertical-vibrator, direct-S, wavelet-rotation method provided estimates of SHmax azimuth that agreed with mini hydraulic fracture (mini-frac) measurements of SHmax azimuth determined in the same well by a previous Department of Energy (DOE)-funded project (Cornet, 2014). The second method utilized three-dimensional (3D) seismic data from a site in Otsego County, Michigan. This second project demonstrated that S-mode reflections in the form of SV-P reflection events are available in surface-based 3D seismic surveys that are generated by P sources and recorded with only vertical geophones. This new concept of SV-P reflection seismology was used to determine SHmax azimuth by constructing azimuth-dependent SV-P trace gathers at 98,000 imaging bins across a Michigan Basin 3D seismic survey, and then analyzing each trace gather in each image bin to determine from which azimuth direction the SV-P reflection from a targeted formation arrived earliest. The SHmax azimuth direction defined by these novel 3D SV-P reflections agreed with SHmax azimuths determined earlier by others at the same site.

In Task 3, laboratory Triaxial Ultrasonic Velocity (TUV) tests were conducted on rock samples from the FutureGen2 characterization well (i.e., the same well where the VSP seismic survey was obtained that is discussed in Task 2 above), and from rock samples representative of the Michigan verification site (i.e., where 3D seismic data were used to define SHmax azimuth in Task 2). The main objective of this portion of the project was to employ non-destructive techniques to determine how P-wave and S-wave propagation velocities are related to triaxial-stress conditions in laboratory test samples taken from targeted reservoir rocks. The overarching principle is that such laboratory measurements can provide a basis whereby field measurements of wave-propagation velocities in CO_2 storage reservoir rocks can be used to ascertain the stress state that would be expected to generate the observed wave-propagation behavior.

Initially it was envisaged that data generated by these lab TUV tests would be applied to high-resolution seismic reflection data for the purpose of deriving truly non-invasive stress-magnitude estimates. However, through coordination with Task 2 during the execution of the project, it was found that even high-quality, high-resolution, field seismic data do not provide the velocity resolution that is required to detect the small velocity-versus-stress changes that are observed

in lab TUV measurements. Thankfully, open-hole sonic logs provide, typically, at least one additional digit of velocity precision compared to the velocity precision provided by field seismic reflection data. We show that sonic log data provide field measurements of wave velocities that can be used, in combination with lab TUV data, to derive estimates of stress profiles along drilled wellbores.

In Task 4, field testing was conducted to obtain input data needed to develop the site-specific geomechanical model for the Michigan site in Task 5 and to verify the model results (i.e., calculated stresses) for this site. The field work entailed collecting geophysical logs and core samples and conducting geomechanical stress tests in the Core Energy LLC State Otsego Lake (SOL 8-15A) well, located in Otsego County, Michigan. This well was selected for conducting the Task 4 field work because it is a partially completed well with an uncased (i.e., open borehole) section. The open borehole section allowed access to the geologic formations for logging, coring, and testing to be conducted without the expense of drilling a test well.

In Task 5, the focus was to demonstrate the use of numerical modeling of field scale stress by developing numerical, geomechanical models of test sites, calibrating them with data obtained from field measurements, and performing numerical simulations to estimate the full site-scale subsurface stress field. Sub-regional (site) scale geomechanical numerical models were developed for two project test sites (i.e., FutureGen2, Illinois and Otsego County, Michigan) that have both been considered as candidates for CO_2 storage. Model parameters (i.e., rock properties and boundary conditions) were calibrated to field measurements, including well logs, well fracture tests, and processed seismic data. The calibrated models were then used for numerical stress simulation to estimate the site-wide 3D stress tensor, which in each point of the model domain provides magnitudes and orientations of the three principal stresses. Also, modeling capabilities of the underlying open-software simulation solution, MATLAB Reservoir Simulation Toolbox (MRST), were enhanced and adapted to the needs of the project. These software modifications included routines for properly reading, processing, calibrating, and running simulations on earth model grids, as well as specially adapted routines for visualizing and interpreting results.

1.0 INTRODUCTION

1.1 Background

This document provides a summary of the research accomplishments achieved under Cooperative Agreement DE-FE0031686, which was awarded to Battelle by the U.S. Department of Energy (DOE) Fossil Energy (FE) on September 18, 2018. The title of the research project is "A NON-INVASIVE APPROACH TO ELUCIDATING THE SPATIAL DISTRIBUTION OF IN-SITU STRESS IN DEEP SUBSURFACE GEOLOGIC FORMATIONS CONSIDERED FOR CO_2 STORAGE." The period of performance for the project was October 1, 2018, through September 30, 2021.

This project was awarded in response to the U.S. DOE FE Funding Authorization Announcement (FOA) DE-FOA-0001826 (DEVELOPING TECHNOLOGIES TO ADVANCE THE UNDERSTANDING OF STATE OF STRESS AND GEOMECHANICAL IMPACTS WITHIN THE SUBSURFACE) Area of Interest 1 (Tools and Methods for Determining Maximum Principal Stress in the Deep Subsurface).

1.2 Objectives of the Project

This 3-year project is part of the U.S. DOE National Energy Technology Laboratory (NETL) Carbon Storage program that was implemented to research and address gaps that affect the economics of commercial carbon capture and storage (CCS) projects. One of these key gaps is the lack of certainty in predicting geomechanical impacts of pressure migration caused by carbon dioxide (CO_2) injection into a geologic storage complex. The overall goal of this project is to improve technical and economic performance of state-of-the-art methods for determining in-situ stresses. This project aims to develop methods for determining the spatial distribution, both laterally and vertically, of the magnitude and orientation of the three principal in-situ stresses in the deep subsurface (i.e., depths greater than 1500 meters), including conducting verification testing at a field site. In this project, verification testing was conducted at two sites. One location was the former FutureGen2 site in Illinois. The other was an area in Otsego County, Michigan, that encompassed a three-dimensional (3D) seismic survey referred to as the Perch 3D seismic survey that was made available by Core Energy, LLC of Traverse City, Michigan. The results of this work will lead to an increased understanding of the geomechanical impacts associated with a CO_2 injection operation and therefore decrease geomechanical risks throughout the life cycle of the project.

The project consisted of five tasks performed over a 3-year period from October 1, 2018, through September 30, 2021. The five tasks included Project Management (Task 1) and four technical tasks (Tasks 2 through 5) (Table 1-1). This project was led by Battelle Memorial Institute (Battelle) in Columbus, Ohio (Christa Duffy, Project Manager; Mark Kelley, Principal Investigator). The project team included Core Energy, LLC (Allen Modroo), The University of Pittsburgh (Prof. Andy Bunger, Delal Gunaydin, Navid Zolfaghari Moheb, Joshua Higgins, and Yunxing Lu), SINTEF (Odd Andersen), Battelle (Valerie Smith, Sanjay Mawalkar), and independent consultants Bob Hardage and Wayne Goodman. Other participants included Sterling Seismic & Reservoir Services (Richard Van Dok), Texseis (Mike Graul, Tim Hall, and Chris Hall), and Schlumberger. A summary of the project tasks is provided in Table 1-1 along with the involved organizations and individuals.

Table 1-1. Project Tasks and Involved Organizations and Individuals

Task	Task Description	Responsible Entities
Task 1	Project management	Battelle
Task 2	Seismic data processing for two field sites to determine the stress orientation (i.e., S_{Hmax} azimuth), anisotropy [Vs fast/Vs slow] and [Vp/Vs] in the area with seismic data coverage	Bob Hardage, Texseis, Sterling Seismic & Reservoir Services, Core Energy, Battelle
Task 3	Laboratory experiment to establish experimentally derived relationships between wave velocity/attenuation (anisotropy) and the triaxial-stress state (magnitude and direction)	Univ. Pittsburgh, Battelle
Task 4	Field well testing, logging, coring of the Core Energy LLC SOL 8-15A well in Otsego County, Michigan, to obtain stress-related measurements and mechanical rock properties to use to build geomechanical model (Task 5) and to verify the seismic-derived stress results from Task 2	Battelle, Core Energy, Schlumberger, Wayne Goodman
Task 5	Field scale stress modeling	SINTEF, Battelle

1.3 Purpose of this Document

The purpose of this document is to provide an overview of the research completed under this project. A detailed report for each of the four technical tasks has been prepared and uploaded to the DOE's Energy Data Exchange (EDX) website (EDXSupport@netl.doe.govhttps://edx.netl.doe.gov/) and are available to the reader who is interested in more details about the methods and results of the various tasks. In addition, all data generated by this project have also been uploaded to the EDX site and are available for anyone interested in reviewing or working with the data. The remainder of this summary document provides short descriptions of each of the four technical task efforts and accomplishments.

2.0 SUMMARY OF TECHNICAL TASKS

2.1 Extracting Stress Data from Seismic Data (Task 2)

This section briefly describes the work conducted in Task 2 of the project. A comprehensive discussion of the work performed in Task 2 and the results obtained is provided in the companion stand-alone report (Hardage et al., 2020):

> ***TASK 2 REPORT EXTRACTING STRESS DATA FROM SEISMIC DATA. A Non-Invasive Approach for Elucidating the Spatial Distribution of In-Situ Stress in Deep Subsurface Geologic Formations Considered for CO_2 Storage.***

In addition to the Task 2 report, three peer-reviewed publications were generated and are available. These publications are listed in the References section as Hardage et al., 2021a, 2021b, and 2021c. Expanded abstracts of the papers are provided in the Appendix.

We developed and demonstrated two new non-invasive procedures for extracting maximum horizontal stress (SHmax) azimuth information from legacy seismic data. In the first demonstration, we used legacy vertical seismic profile (VSP) data that had been acquired at the FutureGen2 site in Morgan County, Illinois, to demonstrate a new, simple method for determining the azimuth of SHmax. We describe the method as “simple” because the procedure requires only one down-going S wavelet. In the second demonstration, we used a new seismic wave mode, the SV-P mode, to extract SHmax azimuth information from legacy 3D, P-source, seismic reflection data that had been acquired several years ago by others at a CO_2 storage site in Otsego County, Michigan.

These two types of seismic data (i.e., VSP data and 3D data) have been used for decades to explore for deep oil and gas resources. Huge digital libraries of these data already exist and are well preserved by commercial firms. Some of these legacy seismic data are positioned in areas that will be investigated as future CO_2 storage sites. Our research results thus provide attractive low-cost (sometimes no-cost) options for accessing seismic data that can be used to define stress azimuths at specific target depths at other potential CO_2 storage sites.

2.1.1 Emphasis on Shear (S) Mode Data

We emphasized applications of shear-wave (S-wave) data in this project because S waves are far more sensitive to stresses and fractures than are traditional compressional (P) seismic waves. Three new S-wave concepts that we demonstrated will be important in future applications of S-wave seismic technology in carbon capture and storage (CCS) projects.

2.1.2 New Concept 1: P Sources Are Also Excellent S Sources

The first new S-wave concept that our work provides to the CCS community is that we show that it is not necessary to use a traditional, horizontal-displacement S-wave seismic source, such as a horizontal vibrator, to generate down-going illuminating S wavefields needed for S-wave analysis of deep-stress conditions. Effective horizontal-displacement seismic sources are rare and expensive to deploy. These two factors (i.e., scarcity and high cost of appropriate S sources) are the major reasons why S-wave reflection seismology has languished for years. Our work removes these barriers by demonstrating that effective S-wave illumination of deep geology can be achieved with common, low-cost, and widely available compressional-wave (P-wave) seismic sources.

Our research shows that common P-wave sources such as vertical vibrators or shot-hole explosives create effective, down-going, illuminating S wavefields directly at a P-wave source station. This important principle has been overlooked and uninvestigated by reflection seismologists. In project 1, we used illuminating S wavefields generated at the baseplate of a vertical vibrator to conduct deep-stress analysis with VSP data. In project 2, we used down-going direct-S wavefields produced at buried-explosive shot-hole cavities to conduct deep-stress analysis with 3D seismic. The basic physics that underpin this concept that P sources are also effective S sources are explained in this report.

Our work shows that common, low-cost, P sources produce down-going, direct-S wavefields that are suitable for imaging deep targets just as their well-known direct-P wavefields do. These direct-S wavefields can be used for investigating deep-stress conditions, and for detecting and quantifying fractures and subtle faults that cannot be detected by P-wave data. Our work thus introduces a simple, low-cost, non-invasive way to utilize S-wave data that will benefit the global CO_2 storage community. This advance is particularly important for stress and fracture analysis of deep targets.

2.1.3 New Concept 2: S-Wave Data Generated by P Sources Can Be Recorded with Vertical Geophones

The second new concept in S-wave reflection seismology that we demonstrated is that S-mode reflection data exist in 3D seismic surveys that are generated by P sources and recorded with only vertical geophones. This principle is quite important. Traditional logic has been that to capture an S-mode reflection with surface-based receivers, horizontal geophones must be deployed. This DOE-funded research shows that S-mode reflections can be recorded with simple vertical geophones.

At each reflecting interface, some of the energy carried by a down-going, direct-P, illuminating wavefield reflects as an up-going S-wave mode. Unfortunately, this up-going S reflection can be recorded only if horizontal geophones are deployed across the earth surface. This combination of a P-wave source and horizontal geophones is a field deployment procedure that has been used for 25 years to acquire P-SV data.

In this same manner, at these same deep interfaces some of the down-going illuminating S energy produced by a P source converts to up-going P reflection wavefield. This up-going converted-P wavefield is recorded by surface-based vertical geophones just as are traditional up-going P reflections produced by a down-going P wavefield. The new S-wave imaging mode we used in this study is this SV-to-P converted mode that is created by a surface-based P source and recorded by surface-based vertical geophones. We designate this wave mode as SV-P data throughout this report. Basically, SV-P data are simply the data that one creates when the ray paths that create popular, conventional P-SV data are reversed. We thus implemented one of the oldest principles used to study the physics of propagating wavefields; this being the “principle of reciprocity.” This principle states that if the positions of a source and a receiver are exchanged, he same data will be generated.

As a side note, our use of SV-P data in this project caught the attention of the Society of Exploration Geophysicists (SEG) to the extent that a manuscript describing our work, which we submitted to the ***Interpretation*** journal that is jointly published by SEG and American Association of Petroleum Geologists (AAPG), underwent a rapid peer review and was published only 2 months after we submitted it. That paper is listed as Hardage et al., 2021b in the References section that follows, and its abstract is provided as Task 2: Paper 2 in the Appendix that follows.

In this final project report, we show that in common 3D, P-source, seismic surveys, two images are embedded in vertical-geophone data. One image is the traditional P-P reflected wavefield that has been used for decades. The second image is an SV-P reflected wavefield, which carries stress-sensitive and fracture-sensitive S-wave information. We utilized both traditional P-P reflected wavefields and this new concept of SV-P reflected wavefields in this project. Our DOE-funded demonstration should encourage others to utilize SV-P reflections embedded in vertical-geophone data in their CCS investigations.

2.1.4 Study Site 1: Extracting SHmax Stress Azimuth from VSP Data

Our first seismic study was conducted in the Illinois Basin where we used legacy VSP data. These VSP data were acquired in 2013 at the FutureGen2 site in Morgan County, Illinois. No funds were spent in this present study to have access to the VSP data that were used for our deep-stress analysis. No well had to be drilled to deploy a vertical array of VSP receivers to record the data we used.

Common vertical-vibrator sources, arguably the most common P-wave source used to acquire seismic reflection data today, were used to generate down-going, illuminating, seismic wavefields at this VSP site. Down-going and up-going wavefields were recorded with a vertical array of standard three-component (3C) geophones that extended from the earth surface to basement. This same type of VSP data has been recorded in many wells positioned across all depositional basins. Some of these legacy VSP data now can be retrieved from digital storage and used in CCS deep-stress, deep-fracture investigations, just as we did in this project.

Using legacy VSP data is a non-invasive procedure for studying stress and fracture conditions in deep rocks because the earth does not have to be invaded with a new well to acquire the data. Our non-invasive VSP procedure can be replicated in many locations considered for CO_2 storage by simply analyzing existing legacy VSP data with the methodology we describe in this report.

If no legacy VSP data have been recorded at a location considered for CO_2 storage, but a well appropriate for VSP data acquisition already exists, one can argue that installing a receiver array in that existing well and recording new VSP data is also a “non-invasive” procedure. This argument is logical because a new well does not have to be drilled to acquire the VSP data that are needed. Unfortunately, the VSP strategy described in this report cannot be used at a location where there is no pre-existing well without violating the “non-invasive” requirement imposed by DOE.

2.1.5 New Concept 3: Define the Azimuth of SHmax Stress by Simple Mathematical Rotation of a Down-Going, Direct-S, VSP Wavelet

The third new concept introduced in this project is that the azimuth of SHmax can be determined at any target depth by conducting a simple, 360-degree, mathematical rotation of the down-going, direct-S VSP wavelet generated by a surface-based P-wave source. At Study Site 1, this down-going direct-S wavefield was produced at the baseplate of a common vertical-vibrator source. Down-going S wavelets thus traveled from the earth's surface, through stressed rocks, to a deep horizontal VSP geophone where it was recorded, and then was mathematically rotated to determine the azimuth of SHmax stress at that receiver depth.

The physics of this procedure is that the azimuths where polarity reversals occur in this mathematically rotated S wavelet define the azimuths of SHmax and minimum horizontal stress (Shmin). This new approach to monitoring SHmax azimuth at a CO_2 storage site is an upscaling, by a factor of several 1000s of the parameters used in a seminal 1998 laboratory test on small rock samples at Amoco's research campus in Tulsa, Oklahoma. The details of this Amoco rock physics lab experiment are documented in this report.

An example of our wavelet-rotation method applied to zero-offset VSP data is shown as Figure 2-1. The methodology that causes the rotated wavelet behavior to be displayed in this format is described in the Task 2 report. This mathematically rotated VSP fast-S wavelet reverses polarity on the H2 horizontal geophone at azimuths of 50^{o} +/- 5^{o} and 230^{o} +/- 5^{o}. These azimuths agree with the azimuths of SHmax found by traditional mini hydraulic fracture (mini-frac) tests conducted by others when the VSP receiver well was drilled. These tests indicated SHmax azimuth is 52^{o} +/- 4^{o} at this VSP well site. The polarity reversals marked on the H1 horizontal-geophone panel define the slow-S azimuth. Correct SHmax azimuths were indicated by this simple wavelet-rotation method when the vertical-vibrator source was stationed at zero-offset, at several far-offsets, and at different azimuths around this VSP receiver well.

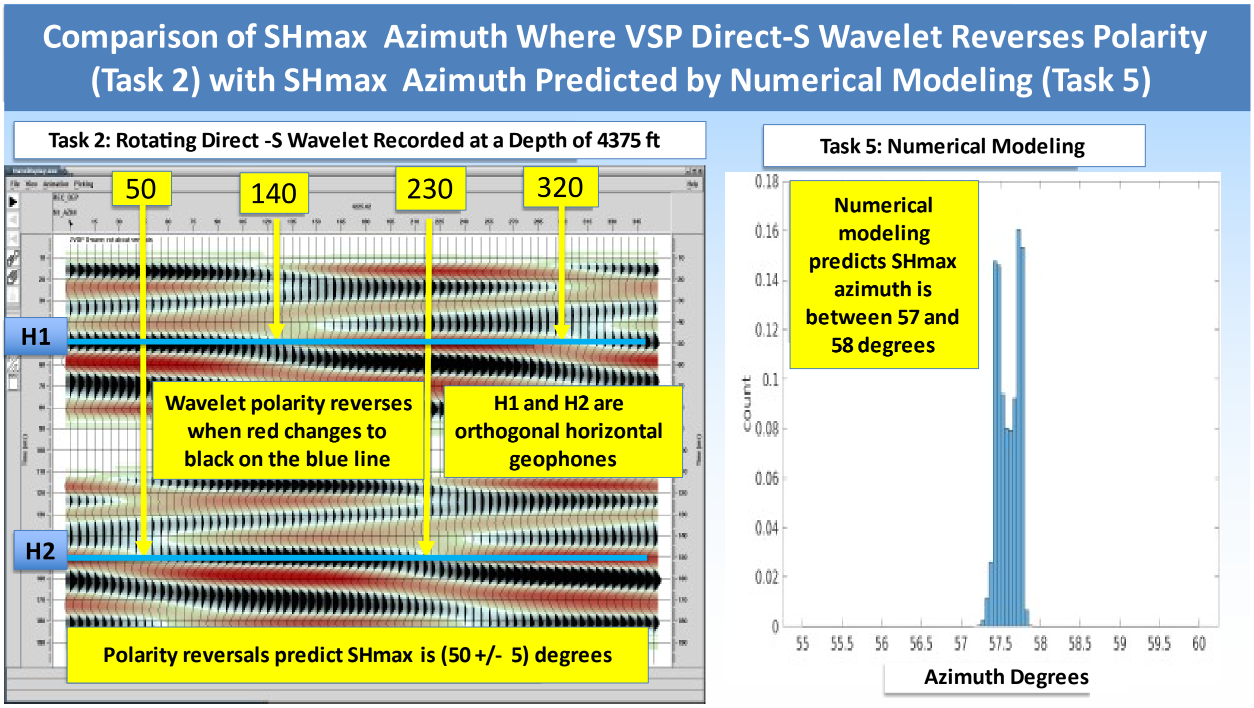

Figure 2-1. Comparison of SHmax azimuth determined by mathematically rotating a down-going direct-S VSP wavelet (left) and the SHmax azimuth predicted by numerical modeling (right). The left-side results were generated in Task 2; the right-side results were generated in Task 5, which will be discussed later. These two estimates of SHmax azimuth are in acceptable agreement. The direct-S wavelet that was rotated was produced at a vertical-vibrator baseplate offset only 195 feet from a VSP receiver well and was recorded by a 3C geophone at a depth of 4375 feet. Mini-frac tests done in this receiver well indicated SHmax azimuth is 52° +/- 4°, essentially the same results we found in Task 2 and Task 5. The H1 data panel shows rotated slow-S wavelets, and its polarity reversals define the azimuth of Shmin. The H2 data panel shows rotated fast-S wavelets, and its polarity reversals define the azimuth of SHmax. Polarity reversals occur on the blue phase-reference line where black peaks (positive polarity) switch to red troughs (negative polarity).

This simple, single-wavelet VSP data analysis procedure for detecting the azimuth of deep SHmax stress has never, to our knowledge, been reported or discussed in geophysical literature. A peer-reviewed paper describing this technique has been published in the ***Interpretation*** journal (Hardage et al., 2021a). An abstract of this paper appears as Task 2: Paper 1 in the Appendix.

The value of this simple field procedure for determining the azimuth of SHmax stress at target depths that span a CO_2 storage reservoir (or in the sealing units of a storage reservoir) at specified calendar times during the lifetime of a CO_2 storage reservoir should be helpful to the worldwide CCS community.

2.1.6 Study Site 2: Determining SHmax Azimuth from 3D Data Generated by Buried Explosives and Recorded by Vertical Geophones

Our second seismic investigation was conducted in the Michigan Basin where we used legacy 3D seismic reflection data, typical of data that have been acquired by the oil and gas industry for several decades, to predict the azimuth of SHmax stress. These 3D data were generated by buried, shot-hole explosives and were recorded by vertical geophones. Data acquired with surface-based seismic sources and vertical receivers, as these data were, meet the criteria of being an ideal type of non-invasive procedure for analyzing stress conditions in deep rocks.

These 3D seismic data were acquired several years before implementation of this current study. Thus, no new 3D data had to be acquired to conduct this non-invasive deep-stress investigation. There are thousands of similar sets of legacy 3D seismic data in digital data-libraries around the globe. The methodology demonstrated at this second study site can be replicated with any of these legacy 3D seismic data volumes. A peer-reviewed paper describing this technique has been published in the ***Interpretation*** journal (Hardage et al., 2021b). A second paper comparing our new reflection time technique to a second method that involves performing an amplitude-vs-incident-angle (AVA) analysis of the amplitude-gradient behavior of P-P reflection wavelets also has been accepted for publication (Hardage et al., 2021c). An abstract of both papers appears as Task 2: Papers 2 and 3 in the Appendix.

Our new *Concept No.1* and *Concept No. 2* (described previously in this report) were implemented at this second study site. SHmax azimuth was estimated by constructing SV-P trace gathers at imaging bins across a 24-mi^2 3D seismic survey where CO_2 is being stored in a carbonate reef at a depth of approximately 7500 ft. These SV-P trace gathers utilized source-receiver pairs that were constrained to be inside a narrow, 30^o-wide, azimuth corridor. That narrow stacking corridor was then rotated in a 360-degree compass circle to find the azimuth where an SV-P reflection from a deep target appeared at its earliest arrival time. The earliest arrival time of an SV-P reflection wavelet from a deep target layer defines the azimuth of the fast-S mode at that target depth. The azimuth of the fast-S azimuth is, by definition, also the azimuth of SHmax.

We conducted this azimuth-dependent rotation of SV-P reflection wavelets using wavelets that were generated at three depths (i.e., 3500 ft, 5500 ft, and 7500 ft). The 3D survey area covered 24 mi^2. Stacking bins measured only 82.5-ft by 82.5-ft, so approximately 98,000 stacking bins were required to span the 24-mi^2 image space. Six azimuth corridors, each being 30-degrees wide, were analyzed at each stacking bin. The positive and negative offset portions of these six corridors provided a full 360-degree azimuth analysis of SV-P arrival times at each image bin. Almost 1.8 million pre-stack time migrations (PSTMs) of SV-P traces had to be done (i.e., 98,000 bins x 6 azimuth corridors x 3 depths). This analysis was a massive computational effort. One result that focused on SV-P reflections from the reservoir formation at depth at 7500 ft is shown as Figure 2-2.

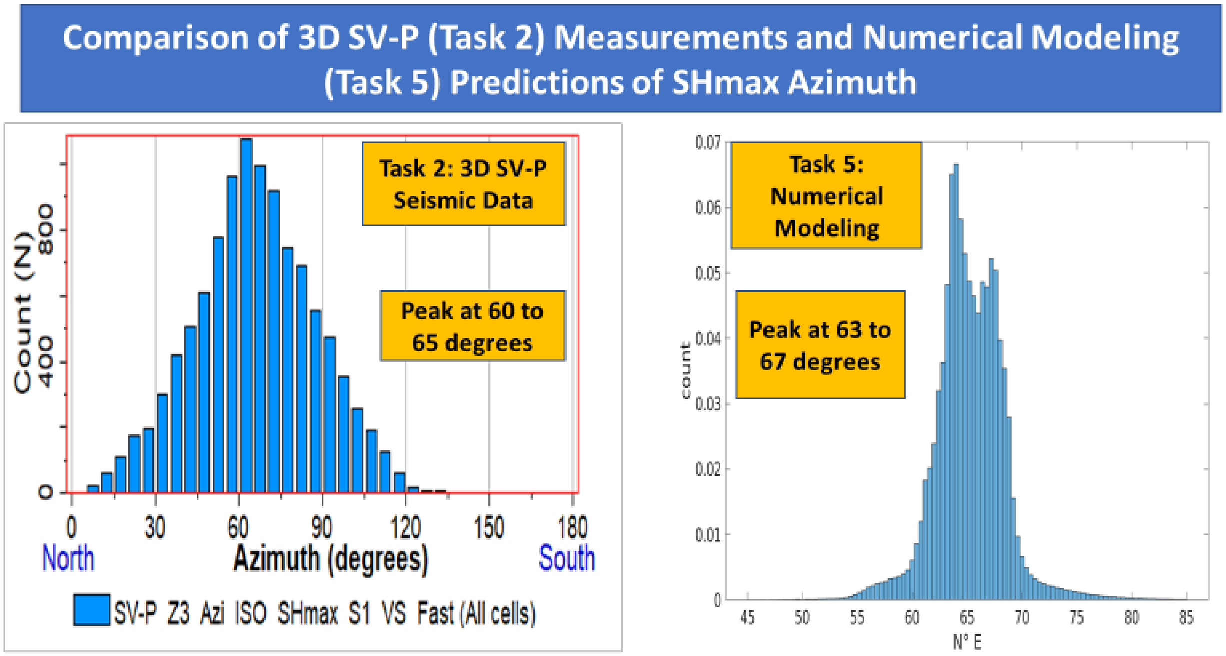

Figure 2-2. Comparison between SHmax azimuths determined by analyzing azimuth-dependent arrival times of SV-P reflections from a Michigan Basin CO_2 storage formation at a depth of 7500 ft (left), and azimuths predicted by numerical stress modeling (right). The left-side results were generated in Task 2; the right-side results were generated in Task 5 that will be discussed later. These two estimates of SHmax azimuth are in almost exact agreement with independent SHmax azimuth measurements made with mini-frac tests done by others.

The six azimuth-dependent SV-P wavelets positioned in each stacking bin at each target depth were cross-correlated to determine the consistency of their waveshapes. If the wave-shape correlation between the six wavelets was less than 0.5, their bin was not used to predict SHmax azimuth. The results were that at each target depth, SV-P data at approximately 30,000 of the 98,000 bins were used to predict SHmax. At each depth, these 30,000 predictions were combined to form a single histogram of the predicted azimuth of SHmax azimuth. These histograms gave a consistent prediction of 65^o +/- 15^o for the SHmax azimuth at all three depths (i.e., 3500 ft, 5500 ft, and 7500 ft).

In Task 4 of this project, conventional measurements of SHmax azimuth performed in a well at the edge of the seismic image area predicted values of SHmax azimuths that were centered around 60^o, just as is the SV-P arrival-time histogram in Figure 2-2. It should be stressed that Tasks 2, 4, and 5 were conducted independently, by different investigators, yet the results of all three tasks come to the same conclusion about the azimuth direction of SHmax at the Michigan CO_2 storage site. We conclude that analysis of azimuth-dependent SV-P reflection times is a new, valuable, non-invasive method for defining the azimuth of SHmax at deep depths.

Presently, we cannot estimate the magnitude of SHmax stress with SV-P data. The reason for this limitation is explained by the high-frequency rock physics testing that was conducted in Task 3. This laboratory testing is discussed in the next section of this report.

To summarize Task 2 results, we conducted two field demonstrations that showed that the down-going direct-S wavefield produced at a P-source station provides accurate estimates of SHmax azimuth. These are seminal demonstrations because they used common, widely available, seismic data generated by P sources and then are recorded (1) with horizontal geophones if VSP data are used; or (2) with vertical geophones if 3D data are used. The importance of these field demonstrations is that if CCS activities cause SHmax azimuth to shift, then either of the non-invasive S-mode seismic methodologies that we have introduced can detect that shift. The calendar-time monitoring of SHmax azimuth with these seismic field techniques will be invaluable for recognizing when CCS activity is altering stress conditions within, or local to, a storage reservoir and its sealing units.

2.2 Laboratory Experimental Characterization of Stress Dependent Wave Speed in Rocks and Application for In-Situ Stress Estimation (Task 3)

This section describes the work conducted in Task 3 of the project. A comprehensive discussion of the work performed in Task 3 and the results obtained is provided in the companion stand-alone report (Bunger et al., 2021):

> ***TASK 3 REPORT Laboratory Characterization of Stress Dependent Wavespeed A Non-Invasive Approach for Elucidating the Spatial Distribution of In-Situ Stress in Deep Subsurface Geologic Formations Considered for CO_2 Storage***

Task 3 was conducted at the University of Pittsburgh with assistance from graduate students. Portions of cores taken from wells (which were drilled at the same or similar sites in the Illinois Basin and Michigan Basin where Task 2 seismic research was conducted) were used in these lab measurements. The basic objective of the research in Task 3 was to determine whether P-wave and S-wave velocities in a CO_2 storage rock correlated in any way with the stress magnitudes in that storage rock.

Cubes were cut from well cores and instrumented with six sensors (i.e., one transducer per side of a sample). These sensors were positioned on the six sides of each test cube so that a source-receiver pair would measure P and S travel time in orthogonal X-Y-Z (i.e., two horizontal and vertical) directions through the cube. A true triaxial load frame (Figure 2-3) applied horizontal and vertical loads on the sample with hydraulic actuators in three directions, generating two horizontal confining stress (σ_{yy} and σ_{zz}) and a vertical confining stress (σ_{xx}). The magnitudes of the stress in any of these three directions could be identical, or the stress in each direction could differ in magnitude. The key components of the experimental setup are shown in Figure 2-3 and Figure 2-4.

Approximately 146 load combinations were applied per specimen ranging up to 30 MPa in each direction. By taking advantage of S-wave transducers with known polarity, both fast and slow S-wave polarizations were obtained for every load combination.

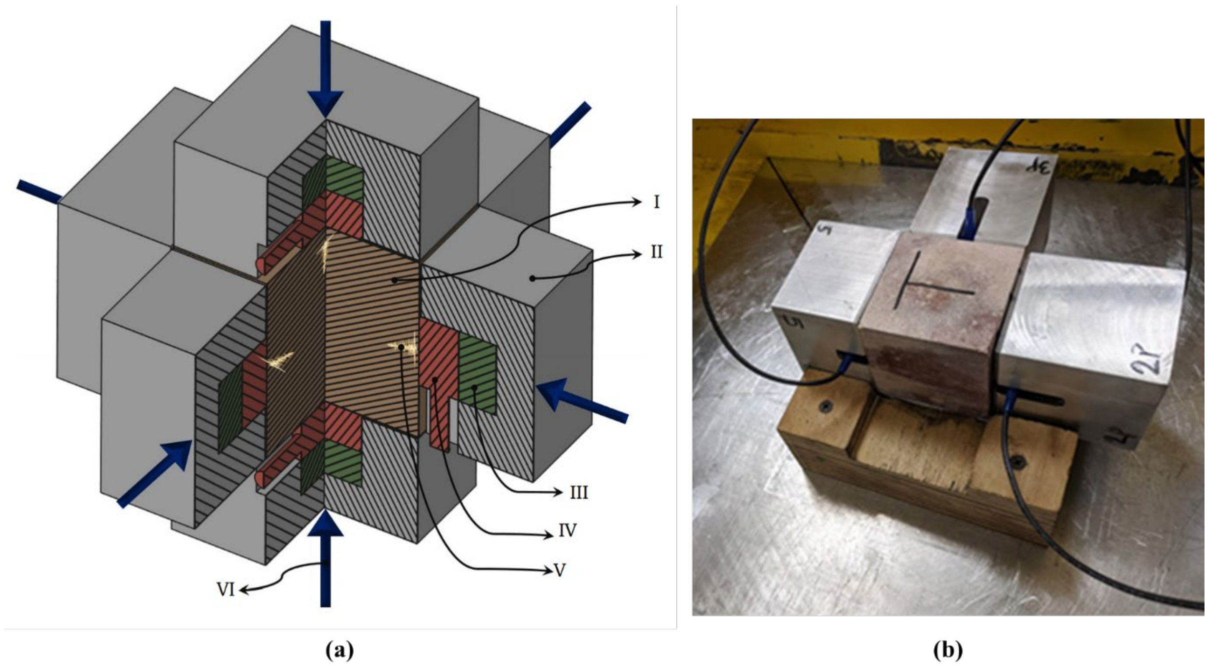

Figure 2-3. (a) A schematic showing a cross-sectional view of the arrangement of the rock sample, transducers, and aluminum blocks used in laboratory measurements of Vp and Vs in stressed rocks. Numbers on the schematic show rock sample (I), aluminum block (II), rubber layer (III), transducer (IV), signal generated by the transducer (V), and the stress loading directions (VI). (b) A sample, with transducers located inside the aluminum blocks, before it is loaded in the triaxial-machine that generates the three orthogonal stresses.

These high-frequency measurements showed that P and S velocities in the stiff rocks at the FutureGen2 site increased as stress magnitude increased, which will be an important principle in CCS management procedures. However, the low-frequency P-wave, fast-S, and slow-S seismic reflection times used in Task 2 (both VSP data and 3D data) did not vary with SHmax and Shmin stress magnitudes, even though those low-frequency data reacted strongly to changes in stress azimuth.

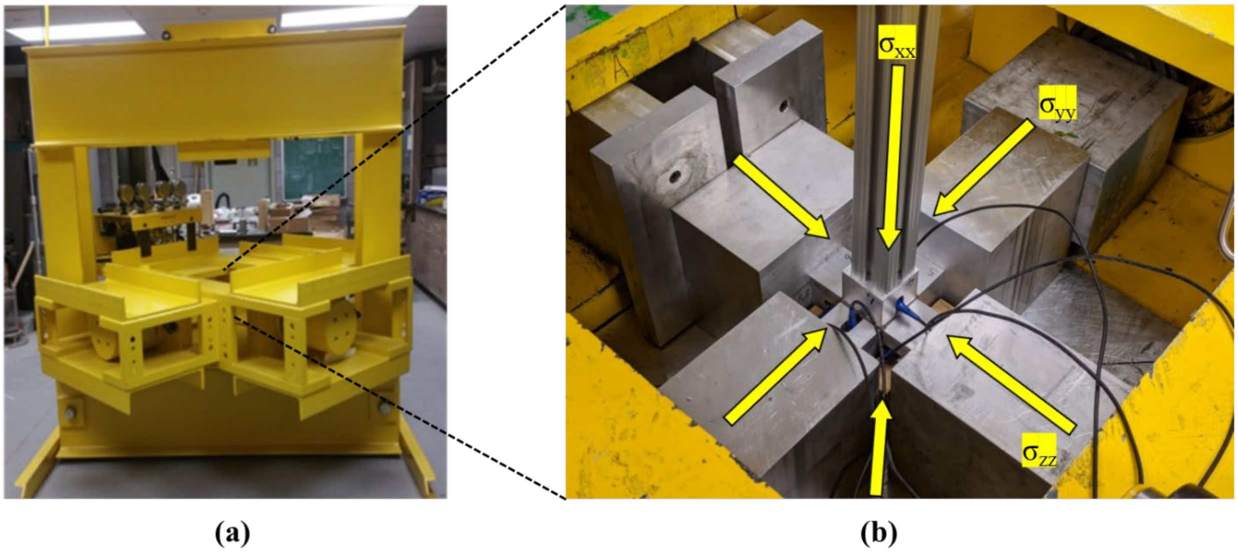

Figure 2-4. (a) Triaxial load frame. (b) Rock specimen under loading. Vertical stress is denoted as σ_{xx}. Horizontal stresses in two directions are shown as σ_{yy} and σ_{zz}.

This seemly contradictory result between P-wave and S-wave velocity behaviors observed in Task 2 and Task 3 has a simple explanation. The samples that were tested in Task 3 were stiff rocks. Thus, P and S velocities in these rocks are a four-digit number when velocity is expressed in units of meters per second. Any measurable reaction of low-frequency VSP and 3D wavelets to changes in stress magnitude in their propagating medium requires that velocity changes appear in either the first or second digits of this four-digit velocity number. In contrast, the velocity of high-frequency wavelets in laboratory samples reacts to stress magnitudes that cause a change in the third digit of this four-digit velocity number. There is thus at least one order of magnitude (and probably two orders of magnitude) improvement in sensing stress-magnitude changes in high-frequency lab-test velocity data versus using low-frequency 3D or VSP velocity data.

The velocity changes in the stiff rock samples used in Task 3 begin in the third digit of P and S velocity measurements. Based on the principles stated in the previous paragraph, Task 3 lab equipment thus had a sensitivity to changes in P and S velocities that cannot be matched by traditional 3D or VSP seismic data. Instead of any disagreement in the findings of Task 2 and Task 3 regarding correlations between P and S velocities and stress magnitude, there is perfect agreement. The lab measurements in Task 3 simply must be correlated with high-frequency sonic log velocity data rather than with low-frequency VSP and 3D seismic velocities when using rock velocities to infer rock stress magnitudes.

Extensive suites of velocity-versus-stress measurements were produced by the lab Triaxial Ultrasonic Velocity (TUV) experiments. Based on the arrival times of the pulsed-received waves, P velocities in three propagation directions ($V_{p,xx}$, $V_{p,yy}$, $V_{p,zz}$) and S velocities in three propagation directions (i.e., two polarity directions per propagation direction: $V_{s,xy}$, $V_{s,xz}$, $V_{s,yx}$, $V_{s,yz}$, $V_{s,zx}$, $V_{s,zy}$) at a given load configuration (σ_x, σ_y, σ_z) are calculated. These measurements are cataloged and presented graphically in the full Task 3 report (Bunger et al., 2021). Figure 2-5 shows an example matrix of nine plots showing P and S velocity data of Upper Mt. Simon sample with corresponding stresses applied on the sample during the experiments. All plots confirm and quantify the anticipated trend of increase in the velocity as the loads applied on the sample are increased.

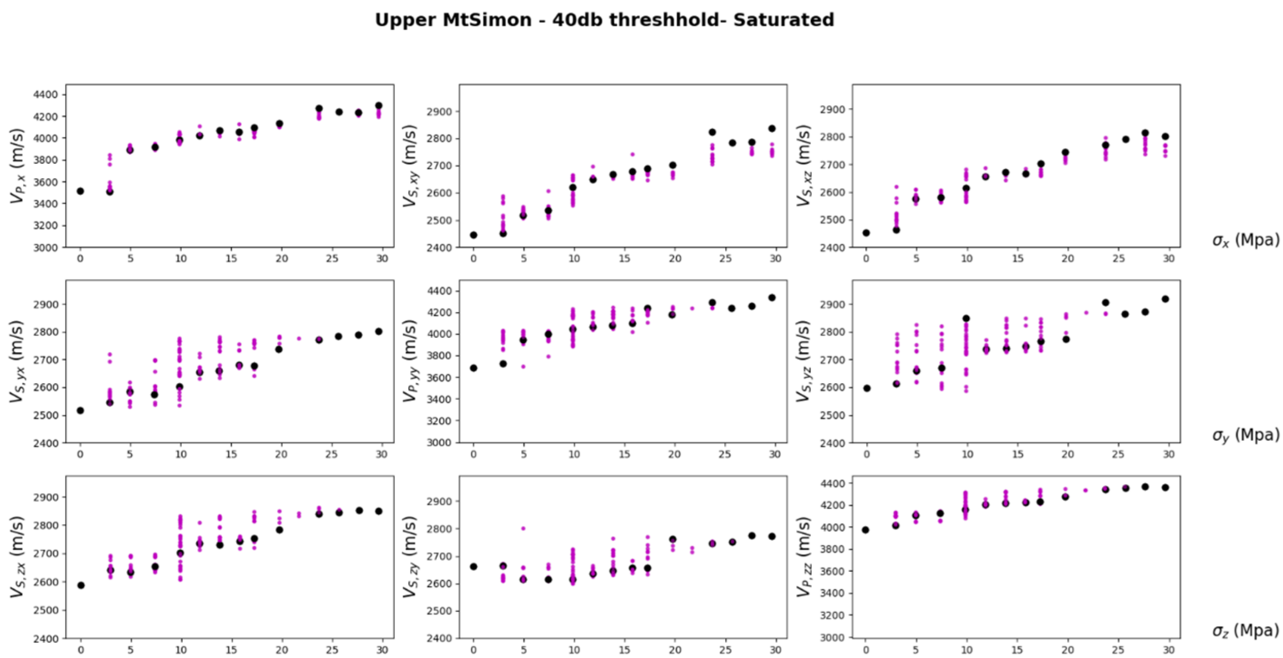

Figure 2-5. Results of experiments performed on Upper Mt. Simon sample is shown via correlation plots of wave velocities and stresses applied on the sample.

Once the necessary number of lab measurements were made, a direct, multivariate, regression using random-forest machine learning (ML) trained on 70-percent of the lab TUV experimental data that was generated to establish a relationship between triaxial stress and measured Vp and Vs velocities. This supervised (i.e., trained) ML was then applied to the other 30-percent of measured triaxial wave velocities, and the procedure satisfactorily predicted the laboratory stresses that were applied to produce those velocities. With this prediction accuracy, the procedure was then ready to apply to open-hole sonic logging data.

Stress predictions in the Upper Mt. Simon, based on this trained ML model, are the curves labeled ML+VS in Figure 2-6. The stress magnitudes estimated from current service-company methods of log interpretation are labeled CIP (Current Industry Practice). For each of the orthogonal stresses (panels a, b, c), the ML interpretation (ML+VS) exhibits more variation than does the conventional log interpretation. However, it is important to note that the average of each ML-estimated stress is approximately equal to the value given by the currently practiced industry procedure.

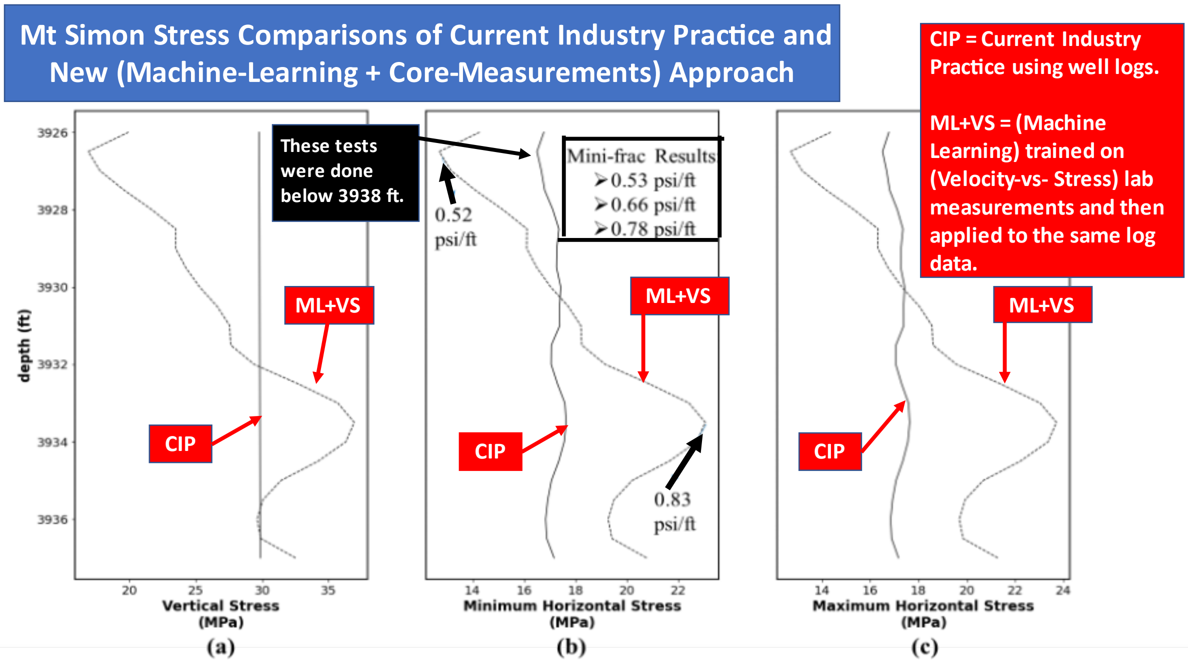

Figure 2-6. Comparisons of (a) Vertical stress, (b) SHmax, and (c) Shmin determined from well-log data at the FutureGen2 site by traditional industry practice (traces labeled CIP), and by the new method developed in Task 3 of this project (traces labeled ML+VS). This new method consists of two steps: (1) use supervised ML to relate triaxial stresses applied to core samples to lab measurements of Vp and Vs velocities in those stressed rocks (VS); and (2) then apply that trained ML relationship to real well-log data.

It is important to understand the assumptions that are embedded in the current industry practice of stress estimation from log data. Vertical stress is obtained by integrating the density log and then applying the assumption that vertical stress has no lateral variability and must always be the value given by the calculated weight of the overburden. This procedure is probably too restrictive in most cases. For horizontal stresses, industry practice is to assume (1) tectonic strain is the same in all layers (top to bottom); and (2) there is no lateral variation in horizontal stress. Both assumptions are over-simplified and inconsistent with reality.

Classical log interpretation thus makes assumptions about stress and strain uniformity that almost certainly differs from real-rock conditions, at least in many cases. In this FutureGen test case, the TUV-trained ML model predicts stresses that (1) are the same order of magnitude as classical log interpretations; but (2) show more variability. The results of mini-frac tests conducted at depths immediately below this FuturerGen2 test sample interval are included in panel (b) of Figure 2-6 to show that the range of mini-frac stress values is consistent with the range of the ML predictions. These mini-frac results validate and illustrate the usefulness of this new ML approach for predicting stress magnitudes and variations.

The TUV ML method was then applied to estimate stresses in all parts of the well with similar rock to the samples tested in the lab. Results are compared with stress estimates from Deformation Rate Analysis (DRA), which is a core-based stress estimation method also performed in Task 3. Results are also compared to mini-frac experiments previously obtained for the FutureGen well. These two aspects of Task 3 (i.e., applying the TUV ML method to similar rock and DRA) are discussed in detail in the full Task 3 report (Bunger et al., 2021).

2.3 Field Testing (Task 4)

This section summarizes the work conducted in Task 4 of the project. A comprehensive discussion of the work performed in Task 4, and the results obtained, is provided in a companion stand-alone report (Battelle, 2019):

> ***TASK 4 (FIELD TESTING) REPORT: Non-Invasive Approach for Elucidating the Spatial Distribution of In-Situ Stress in Deep Subsurface Geologic Formations Considered for CO_2 Storage***

Task 4 encompassed the field activities that were conducted to collect data needed to conduct research Tasks 2, 3, and 5. Task 4 was thus, chronologically, the first task performed in the project. Task 4 activities were performed in the Core Energy State Otsego Lake (SOL) 8-15A well in Otsego County, Michigan. This well was located inside the 3D seismic survey that was the focus of research at Study Site 2 that was discussed in the Task 2 portion. Field-testing activities focused on collecting cores, acquiring an extensive library of well logs, and conducting mini-frac tests. All rock data that were collected to support this project are cataloged in the Task 4 report (Battelle, 2019).

The mini-frac data collected in Task 4 were invaluable for demonstrating the accuracy of our new concept of using SV-P seismic data to predict SHmax at the Michigan study site. Our SV-P azimuth-dependent travel-time results predicted that SHmax azimuth at the Michigan site was 60^o +/- 15^o; in comparison, our new concept (i.e., using SV-P data generated by P sources and recorded with vertical geophones) provided the same estimate of SHmax azimuth as did mini-frac tests as shown in Figure 2-6.

The extensive well-log data base acquired in Task 4 was used in Task 5 to help calculate the elastic parameters needed to numerically model stresses at the Michigan verification site.

By providing these types of valuable rock physics data, Task 4 was the critical backbone of the entire project. Task 4 either provided crucial data needed by Tasks 2, 3, and 5, or confirmed that research results produced in Tasks 2, 3, and 5 did or did not agree with real-earth data.

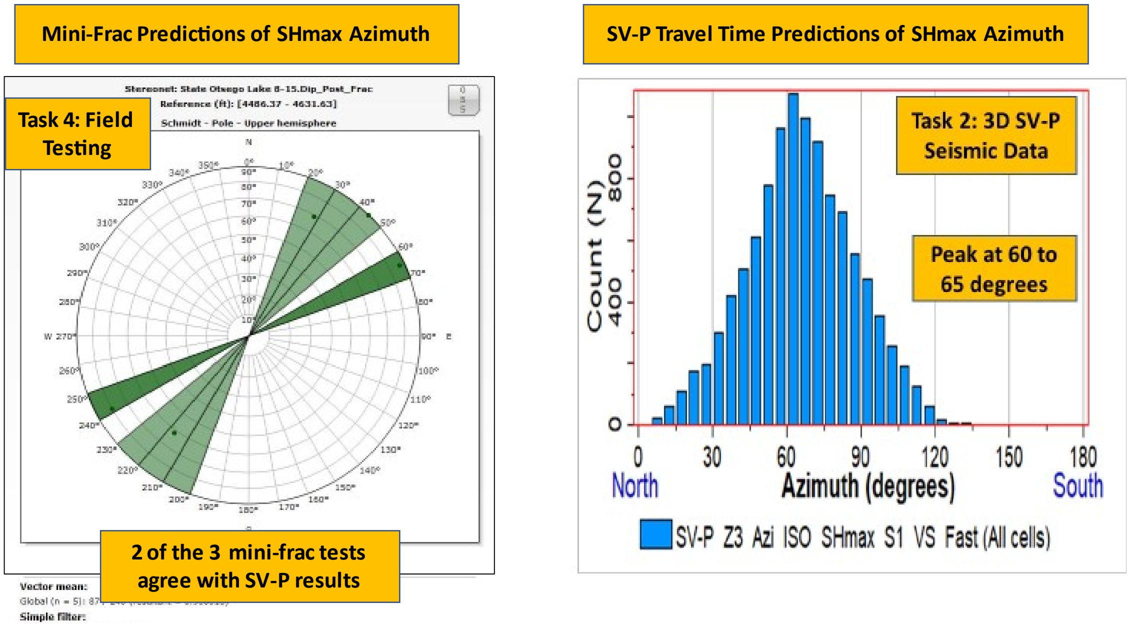

Figure 2-7. Comparison between SHmax azimuth predictions provided by mini-frac tests (left) and by azimuth-dependent SV-P travel-time measurements generated in Task 2 (right). The two strategies for estimating SHmax azimuth gave equivalent answers that the azimuth direction is 60° +/- 15°.

2.4 Stress Modeling (Task 5)

This section briefly describes the work conducted in Task 5 of the project. A comprehensive discussion of the work performed in Task 5 and the results obtained is provided in the companion stand-alone report (Andersen et al., 2021a):

> ***TASK 5 REPORT FIELD SCALE STRESS MODELING A Non-Invasive Approach for Elucidating the Spatial Distribution of In-Situ Stress in Deep Subsurface Geologic Formations Considered for CO_2 Storage***

In addition to the Task 5 report, a technical paper has been accepted for publication in the *SPE Journal* and will be available in 2022 (Andersen et al., 2021b). This information was also presented at the SPE Reservoir Simulation Conference in October 2021 (Andersen et al., 2021c).

In Task 5, estimates of SHmax azimuth were calculated by numerically modeling the rock system at each of the two sites described in Task 2 where seismic methods were used to detect SHmax azimuth. Model parameters were calibrated to a wide range of field measurements that included well logs, wellbore fracture tests, and processed seismic data local to each study location. These calibrated models were used in numerical simulations to estimate the 3D stress tensor field that extended across each study area. The model results in Task 5 provided magnitudes and orientations of the three principal stresses at each field demonstration site used in Task 2.

First, static earth models (SEMs) were developed for the two field demonstration sites discussed in Task 2. This SEM procedure expanded pre-existing models of the target formation at each site studied in Task 2 to include new rock layers that defined the under-burden and rock layers that extended the earth model to the surface. All earth layers were then populated with elastic properties (i.e., formation bulk density, Young's modulus, and Poisson's ratio) determined from local well logs.

Considerable time was invested in enhancing the modeling capabilities of the publicly available MATLAB Reservoir Simulation Toolbox (MRST) so that this popular modeling software would meet the needs of this project. These enhancements included routines that read earth parameters, executed processing procedures, properly conditioned the earth model, and ran simulations of the stress conditions. Specialized routines also had to be written for visualizing and interpreting model results.

The linear elastic equations embedded in MRST used the relatively recent Virtual Element Method (VEM), which provides certain advantages related to grid complexity over the Finite Element Method (FEM) used in most geomechanical stress modeling. VEM procedures allow irregular-shape grids, which is a valuable capability for building complex geological layering.

Model parameters that had to be determined included lateral principal-strain magnitudes, orientations of the maximum lateral principal strain, and modifiers that could adjust the material properties of the model that were initially assigned. Critical material properties that could be adjusted included Young's modulus, Poisson's ratio, and bulk modulus. Different calibration parameter groupings were implemented to control how physical properties were modified for comparison to real data results. These procedures are discussed in the full Task 5 report (Andersen et al., 2021a).

Key model products created in Task 5 are plots that describe the magnitude of the three principal stresses as functions of depth along a specified wellbore. An example of the modeled principal stresses at demonstration site 1 is shown as Figure 2-8. Other important Task 5 results include maps of stress-azimuth at each of the two seismic investigation sites. These stress azimuth maps and other results are provided in the full Task 5 report (Andersen et al., 2021a).

The principal values of the research conducted in Task 5 are that (1) it established a framework that allowed stress data from multiple physical measurements to be integrated into a unified geomechanical model by an automated calibration procedure; and (2) it provided estimates of the depth behavior of all three principal stresses (i.e., SHmax, Shmin, and Sv).

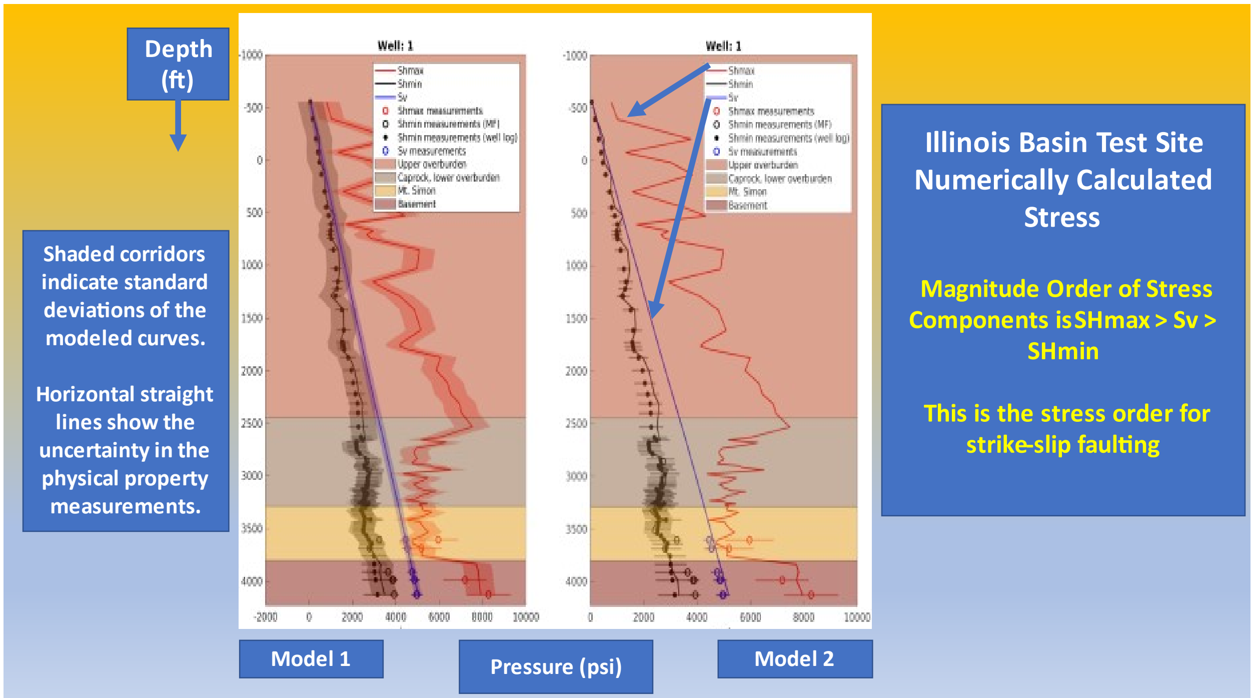

Figure 2-8. Task 5 modeling results at demonstration site 1 in the Illinois Basin. Important products created by Task 5 modeling are these types of depth curves of the three principal stresses (i.e., SHmax, Shmin, and Sv). The ranked order of the magnitudes of these three stresses defines the type of faulting that has occurred, or that will occur. The stress order at site 1 indicates that site is a strike-slip environment. In contrast, the stress order predicted at demonstration site 2 in the Michigan Basin is a normal-fault domain).

3.0 SUMMARY

The key achievements realized in each of the four technical tasks of this project are summarized below.

Task 2 demonstrated two methods to extract stress orientation data from two types of seismic data (i.e., VSP data and surface-sensor reflection data). In the first demonstration, we used legacy VSP data that had been acquired at the FutureGen2 site in Morgan County, Illinois, to demonstrate a new, simple method for determining the azimuth of SHmax. We describe the method as “simple” because the procedure requires only one down-going S wavelet. In the second demonstration, we used a new seismic wave mode, the SV-P mode, to extract SHmax azimuth information from legacy 3D, P-source, seismic reflection data that had been acquired several years ago by others at a CO_2 storage site in Otsego County, Michigan. Work performed in Task 2 emphasized applications of S-wave data because S waves are far more sensitive to stresses and fractures than are traditional P seismic waves. An additional outcome of Task 2 is the demonstration of the following three new S-wave concepts that are relevant to future applications of S-wave seismic technology in CCS projects:

- It is not necessary to use a traditional, horizontal-displacement S-wave seismic source such as a horizontal vibrator to generate down-going illuminating S wavefields needed for S-wave analysis of deep-stress conditions.
- S-mode reflection data exist in 3D seismic surveys that are generated by P sources and recorded with only vertical geophones.
- The azimuth of SHmax can be determined at any target depth by doing a simple, 360-degree, mathematical rotation of the down-going, direct-S VSP wavelet generated by a surface-based P-wave source.

All aspects of Task 3 were completed and the overall goal of generating lab TUV data, and connecting it to field interpretation has provided a new method for in-situ stress estimation. The results of Task 3 prove the feasibility of direct multivariate regression that uses random-forest ML, trained on lab TUV experimental data, to interpret stress that is based on P- and S-propagation velocities defined by open-hole sonic log data acquired in the same interval where the TUV data are generated. Our work provides a new approach to using sonic log data for stress estimations. These new stress estimations are more consistent with mini-frac measurements (typically considered highly reliable) and are more successful at estimating accurate maximum-to-vertical stress ratios than the present state of the art. Thus, the TUV ML approach pioneered through Task 3 opens the door for a new approach to well-log interpretation. This method has potential applications throughout the geosciences and geoengineering.

While it is acknowledged that the need to drill a borehole to obtain high precision sonic logs is not truly “non-invasive” as the original project goal stated, the approach would be compatible with future developments that would lead to non-invasive seismic data if these seismic data can generate velocity characterization that is about one decimal place more precise than the present state of the art. We consider our development of a new method for sonic log interpretation that outperforms, at least in this test case, widely used state-of-the-art log analysis, a significant accomplishment for a 3-year project. This work is also a fundamental advance in rock mechanics that forms the basis for ongoing development of lab TUV-based in-situ stress estimation and applications in other DOE projects, including Utah FORGE.

Task 4 encompassed the field activities that were conducted to collect data needed to support research Tasks 2, 3, and 5. Task 4 activities were performed in the SOL 8-15A well in Otsego County, Michigan, located inside the Perch 3D seismic survey that was the focus of research at Study Site 2. Field-testing activities focused on collecting cores, acquiring specialized well logs (image, sonc), and conducting mini-frac tests. All rock data that were collected to support this project are cataloged in the full Task 4 report (Battelle, 2019). The mini-frac data collected in Task 4 were invaluable for demonstrating the accuracy of our new concept of using SV-P seismic data to predict SHmax at the Michigan study site. Core data and well-log data acquired in Task 4 provided the elastic parameters needed to numerically model Sv, SHmax, and Shmin stresses at this project's two study sites in Task 5. Thus, by providing these types of valuable rock physics data, Task 4 was a critical component of the entire project.

Task 5 achieved its objective of establishing a modeling framework that demonstrates the ability to integrate often incomplete stress data from multiple sources into a unified geomechanical model through a fully automated calibration procedure, and in so doing, predict 3D stress distribution beyond the area where calibration data were obtained. Moreover, the approach also provides estimates of the associated model uncertainties and can be applied directly on SEM grids. It provides physically consistent estimates of the complete stress tensor field across the full domain. The ability to model stresses and fluid flow on the same numerical grids makes the approach well-suited not only for computing baseline stress fields (as presented in this report) but also to provide stress prediction and updated stress estimates during injection and post-injection phases through coupled reservoir (i.e., fluid) and mechanical simulation.

4.0 REFERENCES

Andersen, O., M. Kelley, and V. Smith (2021a), ***TASK 5 REPORT FIELD SCALE STRESS MODELING A Non-Invasive Approach for Elucidating the Spatial Distribution of In-Situ Stress in Deep Subsurface Geologic Formations Considered for CO_2 Storage***, Prepared by Battelle, DOE Award Number DE-FE0031686; Submitted to National Energy Technology Laboratory Technology Development and Integration Center Carbon Storage Team; May 30, 2021.

Andersen, O., M. Kelley, V. Smith and S. Raziperchikolaee (2021b), ***Automatic calibration of geomechanical models from sparse data for estimating stress in deep geological formations***, accepted for publication in SPE Journal (Manuscript SJ-0521-0075).

Andersen, O., Kelley, M., Smith, V., and S. Raziperchikolaee, (2021c). "Automatic Calibration of a Geomechanical Model from Sparse Data for Estimating Stress in Deep Geological Formations." Paper presented at the SPE Reservoir Simulation Conference, On-Demand, October 2021. doi: https://doi.org/10.2118/204006-MS.

Battelle, 2019. TASK 4 (FIELD TESTING) REPORT: ***Non-Invasive Approach for Elucidating the Spatial Distribution of In-Situ Stress in Deep Subsurface Geologic Formations Considered for CO_2 Storage***; Prepared by Battelle, DOE Award Number DE-FE0031686; Submitted to National Energy Technology Laboratory Technology Development and Integration Center Carbon Storage Team; December 30, 2019.

Bunger, A., D. Gunaydin, and M. Kelley (2021), ***TASK 3 REPORT Laboratory Characterization of Stress Dependent Wavespeed A Non-Invasive Approach for Elucidating the Spatial Distribution of In-Situ Stress in Deep Subsurface Geologic Formations Considered for CO_2 Storage,*** Prepared by Battelle, DOE Award Number DE-FE0031686; Submitted to National Energy Technology Laboratory Technology Development and Integration Center Carbon Storage Team; November 2021.

Cornet, F., 2014. ***Results from the In-Situ Stress Characterization Program, Phase 1: Geomechanical Tests Conducted in the FutureGen Stratigraphic Well (FGA#1)***. PNWD-4421. Battelle, Pacific Northwest Division, Richland, Washington.

Hardage, B., R. Van Dok, M. Graul, A. Modroo, V. Smith, and M. Kelley (2020), ***TASK 2 REPORT EXTRACTING STRESS DATA FROM SEISMIC DATA A Non-Invasive Approach for Elucidating the Spatial Distribution of In Situ Stress in Deep Subsurface Geologic Formations Considered for CO_2 Storage***, Prepared by Battelle, DOE Award Number DE-FE0031686; Submitted to National Energy Technology Laboratory Technology Development and Integration Center Carbon Storage Team; October 30, 2020.

Hardage, B. R. Van Dok, M. Kelley (2021a), ***Stress Analysis Using Direct-S Wavelets Produced by a Vertical Vibrator***, Interpretation, Vol. 9, No. 3 (August 2021); p. 1–10; http://dx.doi.org/10.1190/INT-2020-0220.1.

Hardage, B., M. Graul, T. Hall, C. Hall, M. Kelley, V. Smith, and A. Modroo (2021b), ***Determining fast-S and slow-S propagation directions with SV-P data produced by buried explosives and recorded with vertical geophones***, Interpretation, Vol. 9, No. 2 (May 2021); p. T599–T609; https://doi.org/10.1190/int-2020-0226.1.

Hardage, B., M. Graul, T. Hall, C. Hall, M. Kelley, V. Smith, and A. Modroo (2021c), ***Estimating SHmax Azimuth with P Sources and Vertical Geophones: Use P-P Reflection Amplitudes or Use SV-P Reflection Times?*** (Accepted for publication in Interpretation. Should appear in a volume issued in early 2022.)

APPENDIX A. ABSTRACTS FOR PEER-REVIEWED PUBLICATIONS CREATED BY THE PROJECT

Task 2: Paper 1

Hardage, B. R. Van Dok, M. Kelley (2021), ***Stress Analysis Using Direct-S Wavelets Produced by a Vertical Vibrator***, Interpretation, Vol. 9, No. 3 (August 2021a); p. 1–10; http://dx.doi.org/10.1190/INT-2020-0220.1.

Abstract

We have determined how to extract the azimuth of maximum horizontal stress (SHmax) in deep rocks by doing a simple 360° mathematical rotation of a down-going direct-S wavelet generated at the baseplate of a surface-based vertical vibrator. We worked with direct-S wavelets that travel through stressed rocks to a deep, horizontal, vertical-seismic-profile (VSP) geophone. We find that the azimuth where a polarity reversal occurs in mathematical rotations of this down-going direct-S wavelet defines the azimuth of SHmax stress in the overlying rocks. We tested this direct-S wavelet rotation method for determining the SHmax azimuth at a site in the Illinois Basin using legacy VSP data acquired in 2013. SHmax azimuths indicated by this simple wavelet-rotation method were determined when vertical vibrators were stationed at zero offset, at far offset, and at different azimuths around a VSP receiver well. These VSP-based SHmax azimuths agreed with the azimuth of the SHmax found by traditional mini-frac tests in the VSP receiver well. This simple VSP data analysis procedure for detecting the azimuth of maximum horizontal stress has never, to our knowledge, been reported or discussed in the geophysical literature. This technical finding should be of interest to the worldwide geophysical community, especially to people who need to monitor how stress fields shift when fluids are injected into, or extracted from, deep porous reservoirs.

Task 2: Paper 2

Hardage, B., M. Graul, T. Hall, C. Hall, M. Kelley, V. Smith, and A. Modroo (2021b), ***Determining fast-S and slow-S propagation directions with SV-P data produced by buried explosives and recorded with vertical geophones***, Interpretation, Vol. 9, No. 2 (May 2021); p. T599–T609; https://doi.org/10.1190/int-2020-0226.1.

Abstract

We have evaluated the concept of practicing S-wave reflection seismology with legacy 3D seismic data generated by a P-wave source and recorded with only vertical geophones. This type of S-wave imaging is based on the principle that seismic P-wave sources not only produce a down-going illuminating P wavefield, but they also simultaneously produce a down-going illuminating SV wavefield that, in almost all cases, is suitable for S-wave reflection imaging. The S-mode used in this study is the SV-P, or converted-P, mode. This mode involves a down-going illuminating SV wavefield and an upgoing reflected P mode that is recorded by vertical geophones. In flat-layered stratigraphy, the lengths of the SV and P ray paths in SV-P imaging are identical to the lengths of the SV and P ray paths in P-SV imaging with P sources and 3C geophones. P-SV imaging of deep rocks has been practiced for more than two decades; SV-P

imaging is a new concept. SV-P data should provide the same options for investigating deep rocks as do P-SV data. We have determined one of the equivalences between SV-P data extracted from vertical-geophone data and P-SV data extracted from horizontal geophones: that being that the propagation velocities of both modes react to azimuth-dependent variations in the S velocity in anisotropic rocks. Azimuthal variations in the SV-P travel time can be used to define the polarization direction of the fast-S-wave mode, which is also the azimuth of the maximum horizontal stress (SHmax). Our investigation demonstrates a noninvasive method for monitoring changes in the SHmax azimuth across a CO_2 storage reservoir, or any targeted porous rock, as fluids are cycled into, and then out of, that rock's pore space.

Task 2: Paper 3

Hardage, B., M. Graul, T. Hall, C. Hall, M. Kelley, V. Smith, and A. Modroo (2021c), ***Estimating SHmax Azimuth with P Sources and Vertical Geophones: Use P-P Reflection Amplitudes or Use SV-P Reflection Times?*** (Accepted for publication in ***Interpretation***. Will be assigned to a volume published in early 2022.)

Abstract

Two methods are compared for extracting the azimuth of maximum horizontal stress (SHmax) from 3D land-based seismic data generated by a P source and recorded with vertical geophones. The first method utilizes the direct-SV mode that is produced by all land-based P sources. P sources generate SV illumination that radiates in all azimuth directions from a source station and creates SV-P reflections that are recorded by vertical geophones. Unless stratigraphy has steep dip, SV-P ray paths recorded by vertical geophones are simply the reverse of P-SV ray paths produced by the same P source and recorded by horizontal geophones. SV-P data thus provide the same S-wave sensitivity to stress fields as popular P-SV data do. The second method retrieves P-P reflections and then performs an amplitude-vs-incident-angle (AVA) analysis of the amplitude-gradient behavior of P-P reflection wavelets. This analysis is done in narrow azimuth corridors to determine the gradient of reflection-wavelet amplitudes as a function of azimuth. This P-P AVA amplitude-gradient method has been of great interest in the reflection seismology community since it was introduced in the late 1990s. Each of these methods, AVA analysis of the gradient of P-P reflection amplitudes, and our azimuth-dependent arrival times of SV-P reflections, can be used to determine the azimuth of SHmax stress. The two methods are compared with ground truth measurements of SHmax azimuth at a CO_2 sequestration site in the Michigan Basin. SHmax azimuths were determined from P-P and SV-P data at three major boundaries at depths of approximately 3500 ft (1067 m), 5500 ft (1676 m), and 7500 ft (2286 m). Two estimates of SHmax azimuth (one using SV-P data and one using P-P data) were made at each stacking bin inside a 24-mi^2 (62-km^2) image space. The result was approximately 98,000 estimates of SHmax azimuth across each of these three boundaries for each of these two prediction strategies. Histogram displays of PP AVA gradient estimates had peaks at correct azimuths of SHmax at all three depths, but the spread of the distributions widened with depth and split into two peaks at the deepest boundary. In contrast, each histogram of SHmax azimuth predicted by azimuth-dependent SV-P travel times had a single, definitive peak that was positioned at the correct SHmax azimuth at all three boundaries.

Task 5: Paper 1

Andersen, O., M. Kelley, V. Smith and S. Raziperchikolaee (2021b), ***Automatic calibration of geomechanical models from sparse data for estimating stress in deep geological formations***, accepted for publication in SPE Journal (Manuscript SJ-0521-0075).

Abstract

In this study, we demonstrate geomechanical modeling with fully automatic parameter calibration to estimate the full geomechanical stress fields of a prospective US CO_2 storage site, based on sparse measurement data. The goal is to compute full stress tensor field estimates (principal stresses and orientations) that are maximally compatible with observations within the constraints of the model assumptions, thereby extending pointwise, incomplete partial stress measurement to a simulated full formation stress field, as well as a rough assessment of the associated error. We use the Perch site, located in Otsego Country, Michigan, as our case study. Input data consists of partial stress tensor information inferred from in-situ borehole tests, geophysical well logs, and processing of seismic data. A static earth model of the site was developed, and geomechanical simulation functionality of the open-source MATLAB Reservoir Simulation Toolbox (MRST was used to model the stress field. Adjoint-based nonlinear optimization was used to adjust boundary conditions and material properties to calibrate simulated results to observations. Results were interpreted through a Bayesian framework. The focus of this article is to demonstrate how the fully automatic calibration procedure works, and to discuss the results obtained, but not to do a detailed analysis of the stress field in the context of the proposed CO_2 storage initiatives. Our work is part of a larger effort to non-invasively determine in-situ stresses in deep formations considered for CO_2 storage. Guided by previously published research on geomechanical model calibration, our work presents a novel calibration approach that supports a potentially large number of linear or nonlinear calibration parameters, produces results that optimally agree with available measurements, and extends partial point-wise estimates to full tensor fields that are compatible with the physics of the site.