Seismic Characterization of the Decatur, Illinois (USA) Carbon Capture and Storage Site

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Abstract

To improve the detection of microearthquakes down to very small magnitude levels, we apply the empirical Matched Field Processing (MFP) method to 14.5 months of continuous borehole seismic data from the USGS seismic network at Decatur, Illinois and identify 95% more events than were detected in the original catalog. Improved microseismic event detection is one component of a new Microseismic Toolkit that aims to reduce specific technical difficulties that make seismic hazard assessments for CO2 injection and storage projects difficult. These tools can also allow for an improved understanding of the subsurface reservoir at the Illinois Basin – Decatur Project (IDBP) site as observed through changes in the dynamic microearthquake activity and in the more slowly-varying subsurface medium changes associated with CO2 plume growth.

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1. Introduction

The Illinois Basin – Decatur Project (IBDP) is a collaborative carbon capture and storage (CCS) project between the Midwest Geological Sequestration Consortium (MGSC), Archer Daniels Midland Company (ADM), Schlumberger Carbon Services, and several other partners. A major objective of the IBDP, which is managed by the
Illinois State Geologic Survey (ISGS), the Lead Technical Contractor for the MGSC, was to validate a fully integrated, large-scale geological carbon storage program involving the injection of approximately 1 million metric tons of anthropogenic CO₂ within the Mount Simon sandstone over a three-year period. Injection began on 17 November 2011 and successfully concluded on 26 November 2014, injecting a total of 999,215 metric tons of CO₂ at an ADM industrial facility at an overall rate of approximately 1,000 metric tons per day. Data from the IBDP microseismic monitoring network [1] and the United States Geological Survey (USGS) microseismic network in Decatur, IL [2] have enabled seismic interrogation of the subsurface at the Decatur site. Here we focus specifically on data obtained from the USGS seismic array, which is archived at the publically available Incorporated Research Institutions for Seismology (IRIS) Data Management Center (DMC), to improve the spatio-temporal resolution of passive microseismicity associated with the IBDP site.

The USGS installed a combination of surface and borehole seismic stations beginning in July 2013 [2]. Currently the archived borehole seismic data is available at the IRIS DMC starting from 15 November 2013. The current USGS borehole seismic network consists of three modified three-component Oyo Geospace S10g-2.0 borehole seismometers (Fig. 1). Microseismic event detection from manual inspection of the spectrograms resulted in a baseline catalog of 123 events between 15 November 2013 and 30 January 2015 ranging in moment magnitude (Mw) from -1.35 to 0.89 [2].

Fig. 1. Map showing the locations of microseismic events from the original USGS Decatur earthquake catalog as grey circles, sized by magnitude. Surface seismic stations are shown as dark grey triangles and borehole seismic stations as blue triangles. Topography is indicated by the shaded grey background and is taken from the ETOPO1 Global Relief Model [3].
2. Microseismic Toolkit

The goal of LLNL’s Microseismic Toolkit is to allow for an improved understanding of subsurface reservoir behavior and refined future seismic hazard analyses. The Toolkit is composed of five distinct but inter-related steps, the first of which is advanced seismic event detection, specifically Matched Field Processing (MFP). This paper primarily focuses on the application of the MFP method to the USGS Decatur borehole seismic data. The additional four steps (Ambient Noise Correlation (ANC) for high-quality 3D velocity model creation, BayesLoc for Bayesian microearthquake event location and uncertainty quantification, the Virtual Seismometer Method (VSM) for event microearthquake cluster analyses, and Empirical Forecasting for a moving short-term seismic hazard forecast will also be briefly outlined.

2.1. Matched field processing (MFP)

Limitations in seismic instrumentation or processing techniques can often exclude a substantial fraction of seismic events from official earthquake catalogs. These limitations can produce anomalously high seismic event detection thresholds and cause many microearthquakes to escape recognition entirely. Additionally, the amplitude of a microearthquake signal may be so small compared to the background ambient noise level that a simple location procedure may be impossible for the event, even if it was successfully identified.

Fig. 2. Map showing the number of new events identified by each master event. The filled circles are color coded to represent the number of new events identified. The red circles indicate master events that did not identify any new events.
Subsurface reservoirs however, must accurately map seismic activity through time to obtain a complete picture of the underground storage site, both for immediate reservoir management purposes as well as for long-term sustainability issues. To improve the detection and location of microearthquakes down to very small magnitude levels, we apply the empirical MFP method to the continuous USGS borehole seismic data to detect and locate more microearthquakes than can be detected using only conventional techniques, such as a short-term-average/long-term-average (STA/LTA) trigger algorithms. MFP in particular can be implemented into existing seismic workflows to quickly increase the fidelity of the seismic network output. MFP can increase the number of detected seismic events and the sensitivity of existing seismic network arrays using advanced processing techniques on the existing raw data without upgrades to the seismic hardware [4,5].

Using this advanced earthquake detection technique, we construct representative master templates from the previously identified microearthquakes within the USGS earthquake catalog. From this catalog, we identify 75 events with high signal-to-noise ratios (SNR) between M_w -1.35 and 0.89 to use as master template events. These master events are input into the MFP methodology and were able to identify new microearthquakes that had been originally missed within the continuous seismic data. Between 15 November 2013 and 31 January 2015, 113 more events or approximately 95% more microearthquakes were identified (Fig. 2). These new events occurred throughout the observation period, whether or not any events had been previously identified in the original catalog in any given month (Fig. 3). Interestingly, although the end of the injection program occurred at the end of November 2014, the greatest number of events occurred between August and September 2014, several months prior to the end of CO₂ injection.

Fig. 3. Bar graph showing the number of new events per month between 15 November 2013 and 31 January 2015 identified using the empirical MFP, shown as light grey bars, and the number of events in the original catalog, shown as dark grey bars.
An example of a newly identified event is shown in Fig. 4 along with the persistent low frequency noise (below approximately 30 Hz) and clearly anthropogenic noise (e.g., the constant 20, 40 and 60 Hz noise) prevalent across the seismic network that makes the identification of seismic events using only traditional earthquake detection techniques extremely challenging.

2.2. Ambient noise correlation (ANC)

ANC is a form of seismic interferometry, in which long periods of continuous background noise recorded by the seismic network array are used to estimate the 3D velocity and attenuation structure of the earth [6,7]. A major advantage of this noise-correlation technique is that it strips away the dependence on earthquakes and artificial seismic sources for the creation of 3D subsurface velocity models. Velocity models can instead be obtained beneath, preferably dense, seismic station arrays even in areas with low natural seismicity or lacking active sources. To date, ANC has been applied to several geothermal injection sites using both local-distance and regional-distances seismic stations [8]. An increase in subsurface velocity resolution was achieved and verified through waveform inversion of the observed data [8]. It should therefore be straightforward to apply this technique to a CO₂ injection site with adequate seismic station coverage.
2.3. BayesLoc

BayesLoc is an event re-location and uncertainty estimation tool that uses Bayesian inference to rigorously account for various potential sources of uncertainty in the data [9]. The analysis provides not only the most likely location of individual microseismic events, but also the confidence volumes indicating the intrinsic location uncertainty. As absolute location uncertainties can often be very large, a good understanding of these confidence volumes is essential to making informed decisions as to whether, for example, potential microearthquake trends are indicative of migration across true fault structures or simply an indication of event location uncertainty. Application of BayesLoc to microseismicity associated with geothermal injection programs have shown the utility of the method in separating out distinct regions of a subsurface reservoir that activated over the lifetime of the prescribed stimulation [10].

2.4. Virtual seismometer method (VSM)

VSM is another form of seismic interferometry that employs cross-correlations between pairs of microseismic events [11,12]. It is very sensitive to both the earth structure between the pairs of events and their source properties (earthquake location, mechanism and magnitude). As such, this technique is particularly powerful for event cluster analysis. Cluster analysis can distinguish between larger, coherent fault structures (e.g., a single large fault) and diffuse seismic sources (e.g., slip along multiple fracture zones). This in turn could feed into seismic hazard analyses since larger faults do in general pose a greater hazard than several smaller, discontinuous fractures. VSM can further be used to either directly tackle full moment tensor inversion or track differential moment tensor information, depending on how well constrained event locations are.

2.5. Empirical forecasting

The Empirical Forecasting algorithms use a statistical model to connect injection rate with observed seismic event frequency and magnitude distributions. This model has relatively few free parameters, but these parameters are continuously re-calibrated to observed data as injection proceeds. The calibrated model can then forecast future event frequency within a pre-determined forecast window. This tool provides a way to estimate both the current level of seismic hazard and how the hazard may evolve based on different injection scenarios. Application of this model to data from the Basel EGS project shows that it can provide a rough, but reasonable forecast of how seismic event counts will change when, for example, the injection well is shut-in [13].

3. Conclusions

Improved spatio-temporal resolution of both dynamic microearthquake occurrences, microearthquake source properties, and observations of the more slowly-varying seismic characteristics associated with plume growth in CO2 sequestration reservoirs can provide benefits for both reservoir management applications as well as seismic hazard analyses. Using the five techniques within the Microseismic Toolkit described here will allow for the extraction of additional, valuable information from passive microseismic datasets that are not commonly available using standard approaches.

We show that advanced earthquake detection and location techniques, such as the MFP method, can improve the spatial-temporal microseismicity map within the IBDP carbon sequestration storage reservoir. The significant 95% increase in microearthquake data availability that MFP can provide improves the statistical analyses of induced seismicity sequences, reveals critical information about the ongoing evolution of subsurface reservoirs, and better informs the construction of models for seismic hazard assessments.

Additionally, ANC can use background noise from passive seismic sensors to develop 3D velocity and attenuation structures beneath the seismic arrays. Re-location of both new and original events within a reservoir, and quantification of their uncertainty, can be handled by the Bayesian event re-location tool BayesLoc with integration of the ANC-developed velocity model. The VSM method is a powerful tool for event cluster analysis. Results from all of these techniques can then enhance the output from the Empirical Forecasting tool, which can rapidly integrate
statistical analyses of injection and microseismic data to estimate future seismic hazards and its correlation with injection.

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References