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Data integration, reservoir response, and application

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ABSTRACT

The microseismic activity observed in and around a geologic formation undergoing carbon dioxide (CO_2) injection is a combination of natural, or “background”, microseismicity plus that activity which is induced by injection operations. Since injection pressure within storage target formations are maintained safely below fracture pressure this induced activity typically originates at natural pre-existing zones of mechanical weakness presented by structural or stratigraphic features. The combination of mechanical properties and in situ stresses dictate the focal mechanism for microseismic emissions, an understanding of which facilitates the use of observed microseismicity for regulatory compliance and project management.

Under favorable conditions microseismic activity may be unambiguously correlated with structural and/or stratigraphic features directly observed in seismic data, thus providing strong constraints to interpretation of observed microseismicity for focal mechanisms. However, in many cases, such as at the Illinois Basin–Decatur Project (IBDP), this direct correlation is elusive and other indirect support is required. Analysis of microseismicity at IBDP has been performed within the context of the integrated reservoir and mechanical earth models developed as part of the site characterization and monitoring program. The IBDP integrated modeling workflow involved continuous and geotechnically consistent data integration for geologic modeling, calibrated flow simulation, three-dimensional (3D) mechanical earth model, and coupled hydro-mechanical simulation. Using the coupled model, scenario-based forward modeling of microseismicity was performed for hypothetical focal mechanisms inferred from observed data.

The experience gained at IBDP illustrates the importance of integrated modeling in the interpretation of microseismic activity for focal mechanisms and provides valuable insights into critical data gaps which could be the target of future basic research efforts.

1. Introduction

Seismic data acquisition, processing, and analysis have provided a deeper insight into the microseismicity at the Illinois Basin–Decatur Project (IBDP) site in Illinois, USA. The acquisition, processing and data analysis began in late 2009 and has continued past the one million tonne (and injection shut-in) milestone reached in November 2014 and into the post-injection site closure period. In this paper it will be shown how these data have been integrated with other geoscience and engineering data to form a multi-disciplinary and geotechnically consistent conceptual model of the microseismic source mechanism.

The importance of geological context as part of the IBDP microseismic monitoring and the process by which this has been developed is discussed. This is followed by a brief discussion of the hydro-mechanical “reservoir response” to carbon dioxide (CO_2) injection and the model-based workflow used to develop an initial working model for the microseismic source mechanism at IBDP. Finally, ways in which the resulting model is being used to support operational activities for a second project in Illinois are presented.

While having many intermediate milestones, one of the overarching objectives of the IBDP microseismic monitoring effort was to develop and demonstrate methods for technically rigorous and economically viable monitoring of microseismicity for CO_2 sequestration projects.

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Table 1
Model components and data sources.

	Structure/ stratigraphy	Discrete components	Properties
Well logs	• Geologic tops • Image log dip estimates	• Image log fracture interpretation	• Hydrodynamic properties • Mechanical properties
Core	• Formation breaks • Bedding planes	• Fault and fracture interpretation	• Hydrodynamic properties • Mechanical properties
Well Test	• Reservoir thickness (k-H)	• Sealing faults • Fracture flow	• Permeability (k-H) • Total compressibility
Seismic	• Horizon interpretation	• Fault interpretation • Inferred fracture sets (seismic anisotropy)	• Porosity (inversion) • Elastic properties (inversion)

Table 2
Static model development milestones.

	Structure/stratigraphy/discrete features	Hydrodynamic properties	Mechanical properties	Utility
2008 Preliminary	• Layer cake stratigraphy defined by well tops from analog well 60 miles away from proposed drilling location • No discrete features	• Uniform zonal porosity and permeability • Assigned using logs from analog well 60 miles away from proposed drilling location	• No Mechanical Earth Model (MEM)	• Site characterization • Basis for initial reservoir simulation model
2010 Update	• Layer cake stratigraphy: well tops from CCS1 • No discrete features	• Stochastic zonal porosity and permeability • Conditioned to CCS1 well logs	• 1D MEM for CCS1	• Updated site characterization • Basis for initial reservoir simulation plume predictions
2011 Update	• Stratigraphy: 2010 3D seismic survey and well top control from wells CCS1 and VW1 • No discrete features	• Stochastic zonal porosity and permeability • Conditioned to CCS1 and VW1 well logs and 2010 seismic inversion products	• 1D MEM for well VW1 • 3D stochastic zonal mechanical properties conditioned to well CCS1 1D MEM	• Update site characterization Basis for final Class VI permit reservoir simulation area of review (nb1) calculations • Basis for preliminary Finite Element Model (FEM) (nb2) modeling
2013 Update	• Stratigraphy: 2011 extended 3D seismic survey and well top control from wells CCS1, VW1, and VW2 • Provisional fault interpretation • Mechanical features inferred from microseismic data	• Stochastic zonal porosity and permeability • Conditioned to CCS1, VW1, and VW2 well logs and 2011 seismic inversion products	• 1D MEM well VW2 • Updated 3D stochastic zonal mechanical properties conditioned to well CCS1, VW1, and VW2 1D MEMs • Included mechanical features inferred from microseismic data	• Update site characterization • Basis for updated FEM and preliminary microseismic prediction research

2. Geologic context

2.1. The role of the geologic model

The geologic context in the interpretation and understanding of the microseismic data at the IBDP is imperative and foundational. The static model provides the framework for subsequent numerical computations of transient hydrodynamic and geomechanical processes. The microseismicity observed at the IBDP site is initiated at distance from the injection well where reservoir properties, hydraulic pressure, and stress–strain state are not directly measured. As a result, reservoir characteristics and hydromechanical conditions in the vicinity of the microseismic source may only be estimated by extrapolation within an accurate model.

While certain microseismic source mechanism characteristics may be inverted directly from microseismic observations alone through processes such as fault plane solution (FPS) analysis and moment tensor inversion, the results of such analyses lack sufficient uniqueness or completeness to solely form the basis of a geologically consistent interpretation of the source mechanism. This is particularly true when the features responsible for microseismic activity are not evident at the resolution of surface seismic data during site characterization. In such cases, the results of microseismic data inversions must be interpreted within as accurate a geological context as possible to help compensate for this lack of surface seismic resolution. Prior to the IBDP data acquisition campaign there existed little subsurface information in the area to support the development of such a model. Will et al. (2014) provide a historical review of the work done to integrate microseismic observations, indirect geologic and geophysical indicators, and forward modeling for development of a working conceptual model of the microseismic source mechanisms at the IBDP site.

2.2. Key elements of the static model

The modeling workflow utilized for microseismic analysis at the IBDP involved parallel development of static geologic and geomechanical models followed by coupled flow and geomechanical