The ACT4 SPARSE Project

Sparse Passive-Active Reservoir monitoring using Seismic, Electromagnetics, gravity, and surface deformation

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ABSTRACT

The overall aim of SPARSE is to facilitate large-scale (Gt) storage by establishing a reliable solution for long-term, low-cost conformance and containment monitoring based on sparse geophysical data, collected from sea-bottom or land nodes. These can serve as a background monitoring system to establish conformance with predicted behaviour or trigger target-oriented active (e.g., seismic and/or CSEM) surveys if/when and where needed. This will reduce the number of very costly and environmentally problematic, conventional large-scale 3D active surveys during the operational phase considerably, and it may remove the need for such surveys in the post-injection phase altogether. The main requirements for such a monitoring system are: 1) that sufficient information can be extracted from the sparse data so that relevant changes in the subsurface can not only be detected but also quantified; 2) high repeatability; 3) low-cost installation, operation, and maintenance over decades.

ACT 4 BACKGROUND AND SPARSE OBJECTIVES

ACT4

The ‘Accelerating CCUS Technologies’ (ACT) program is an international initiative to facilitate the emergence of CO2 Capture, Utilization and Storage (CCUS) via transnational funding of projects aimed at accelerating and maturing CCUS technology through targeted innovation and research activities. This fourth round of ACT projects, hence the name ACT4, involves the countries of Canada, Germany, India, Norway, and the United States, with funding for United States research entities provided by DOE’s Office of Fossil Energy and Carbon Management.

SPARSE Project Objectives

The project contains four technical work packages (WP) as follows.

WP 2: Geophysical Monitoring and Quantification

WP2 aims to optimize and further develop geophysical monitoring for sparse long-term and low-cost CO_2 monitoring, including active and passive geophysical data acquisition for reliable 4D monitoring, extraction and optimum use of information from sparse data, and quantification of relevant parameters for conformance and containment monitoring.

WP 3: Conformance Verification

WP3 aims to develop an approach for automatic conformance verification, based on the comparison between modelled behaviour and observed data including reservoir and geomechanical modelling and the automatic evaluation of conformance

WP 4: Node Design and Implementation

WP4 aims to determine the optimum implementation of SPARSE monitoring, including node design, positioning and cost, technical implementation, and automatic data processing, reduction, and evaluation.

WP 5: Application and Testing

WP5 aims to test the components of the SPARSE monitoring. WP5 includes the design, installation and validation of different components (e.g., semi-continuous seismic acquisition) and aspects of SPARSE monitoring at Canadian and Norwegian field laboratories. The project will evaluate the ability of nodes to demonstrate conformance and containment of CO_2 for large-scale CCS projects as they develop. This involves automatic data acquisition, management, distribution and analysis, and processing and analysis of SPARSE data collected at the CaMI field research station.

LBNL Involvement

LBNL involvement can be broken down into two principal tasks.

Task 1 - Numerical Modeling, Implementation, Testing, and Data Processing for Optimized Land-Vertical Source (VS) Electromagnetic (EM) measurements

This task revolves around design, testing, and implementation of a geophysical measurement configuration that has been made in marine environments, but not deployed for land CCUS. The task is associated with WP’s 2 and 4.

Task 2 - Machine Learning Inversion of Multi-Physics SPARSE Node Data for Monitoring

This task will adapt and apply a multi-physics geophysical imaging scheme developed under the DOE’s SMART Initiative to the geophysical data collected in this project. The task is associated with WP’s 2 and 5.

International Partners

R&D Institutions : SINTEF (Norway, Lead Institution), Carbon Management Canada and University of Calgary (Canada)
Industrial Partners: Horisont Energi, Neptune Energi, Quad Geometrics (Norway), 3P Technology Corp, Q-Eye Labs, GeoSoftware (Canada), Spotlight (France), Precision Impulse (UK), Chevron (US)

LBNL Task 1 : VSEM Implementation and Testing

Vertical Source EM History

The motivation for using vertical source time-domain EM system comes from the offshore oil-exploration industry, where in the mid 2000’s a Norwegian company Petromarker (now known as Allton or allton.com) pioneered the use of this configuration for use for exploration as well as reservoir monitoring. Figure 1 below shows how the data are acquired with the stationary source kept vertical via a ship that has dynamic positioning control, and seafloor electric field receivers that are recoverable. The source waveform consists of a ‘step-off’, and the signal of interest is the decaying electric field after the source current has been terminated. As shown in Figure 2, a ‘thin’ resistor at depth such as that produced by a hydrocarbon (HC) reservoir or injected CO_2 plume will cause a quicker decay in the electric field than if the resistor is absent.

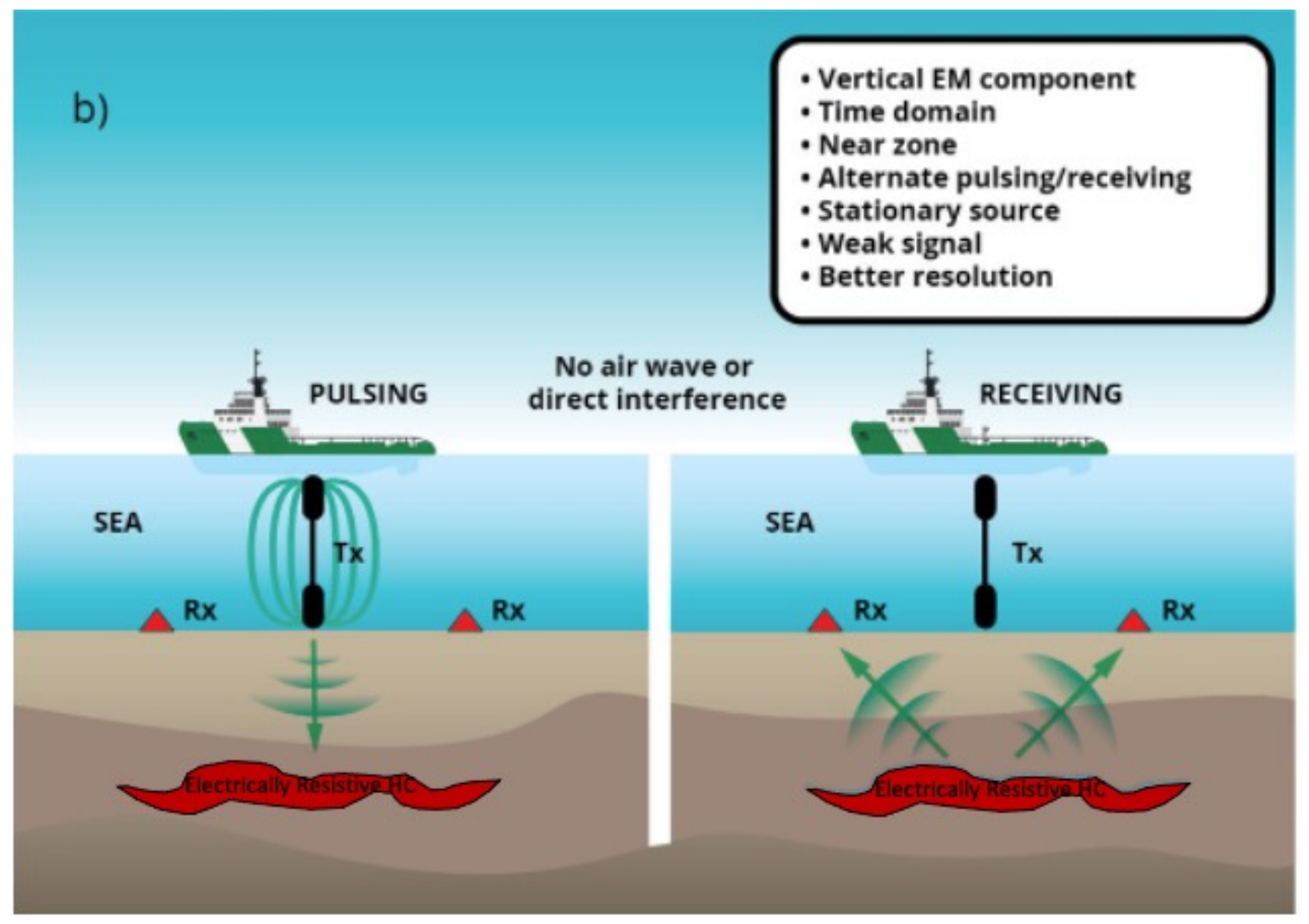

Figure 1 *Schematic illustrating the VSEM acquisition configuration in a marine environment. Figure from the Allton website (https://allton.com/csem/).*

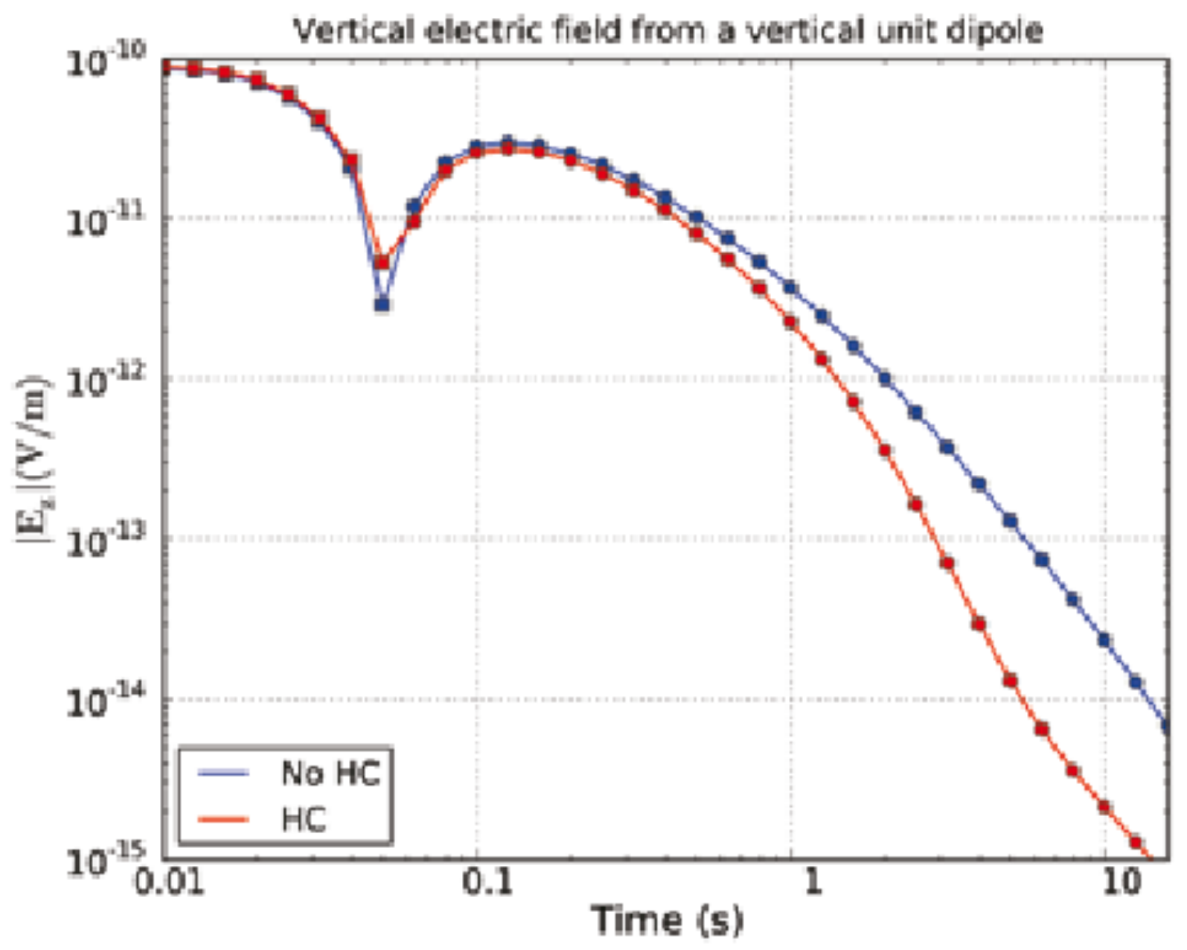

Figure 2 *The absolute value of the vertical electric field voltage at the receiver position computed from the 1D model of Constable and Weiss (2007). The transmitter dipole has a 1Am moment, and the receiver offset is 500 m. The red curve shows the result of the HC layer, the blue one without. The seawater has 0.3 Ωm resistivity, below there is a layer of 1 Ωm sediments with thickness 1000 m, and then there is a 100 Ωm HC layer of 100 m thickness above an infinite layer of 1 Ωm. (From Holten et al., 2009).*

The vertical source method tends to provide slower data acquisition compared to traditional horizontal source-reiver marine CSEM methods due to the fact that the vertical source must be stationary rather than continuously towed. However there exist three characteristics of this acquisition geometry that may provide advantages for node-based monitoring of CO_2 at depth. First, the measurement of the decaying electric field allows for close transmitter-receiver separations which is a necessity for nodal monitoring and allows for smaller target detection (Alumbaugh et al, 2010). Second, Frafjord et al. (2016) indicate that this configuration has greater depth sensitivity than traditional horizontal source techniques. And third this configuration does not generate an ‘air-wave’ which tends to mask responses from depth (Helwig et al., 2019).

LBNL Task 1 : VSEM Implementation and Testing

Land Implementation

For land implementation of VSEM measurements as part of the ACT4 SPARSE project, we envision installing the vertical source using 100m to 200m deep wells / boreholes where electrodes at the bottom of the whole and on the surface provide the contact points for the electric current injection as shown in Figure 3. The optimal receiver configuration will be determined via numerical modeling and will consist of a combination of horizontal electric field and / or three component magnetic field measurements. We will also investigate vertical electric field measurements using either a second shallow (10 to 50m deep) well or possibly even coincident measurements in the source borehole.

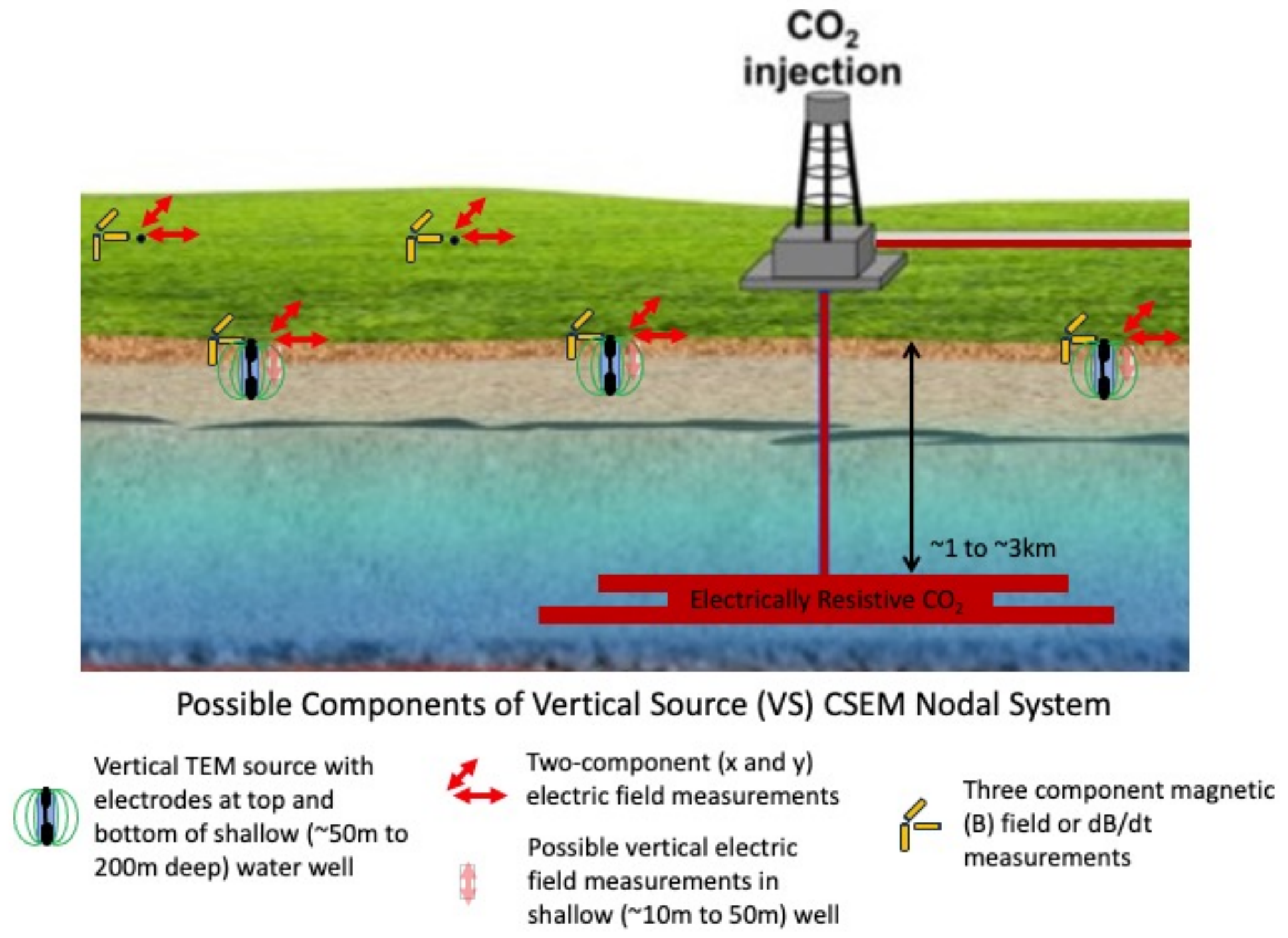

Figure 3 *Schematic illustrating the VSEM acquisition configuration in a terrestrial environment.*

ACT4 Implementation and Testing at the Carbon Management Canada’s (CMC) Newell County Facility (NCF) Test Site

LBNL’s Task 1 of the ACT4 SPARSE project will be to test the concept of VSEM at CMC’s Newell County Facility (formerly known as the CaMI test site). This activity can be broken in to three subtasks with sub-task 1 and 2, and 2 and 3 separated by a GO / NO GO decision point.

Subtask 1: *Numerical optimization of the nodal VSEM configuration for the NCF site*

Subtask 2: *Installation and testing of vertical source and associated receiver nodal systems, and collection/processing of first / baseline data*

Subtask 3: *Collection of six ‘time-lapse’ data sets on a quarterly basis*

Though the NCF does not provide a deep-supercritical CO_2 injection scenario, it does provide a location for testing of various technologies. The left hand side of Figure 4 shows a cartoon of the current injection experiment occurring at the site which was designed to simulate a shallow leak at 300m depth. The right side shows a map of the site with injection occurring in the well designated by the blue triangle, and the green circles representing water wells for possible VS deployment.

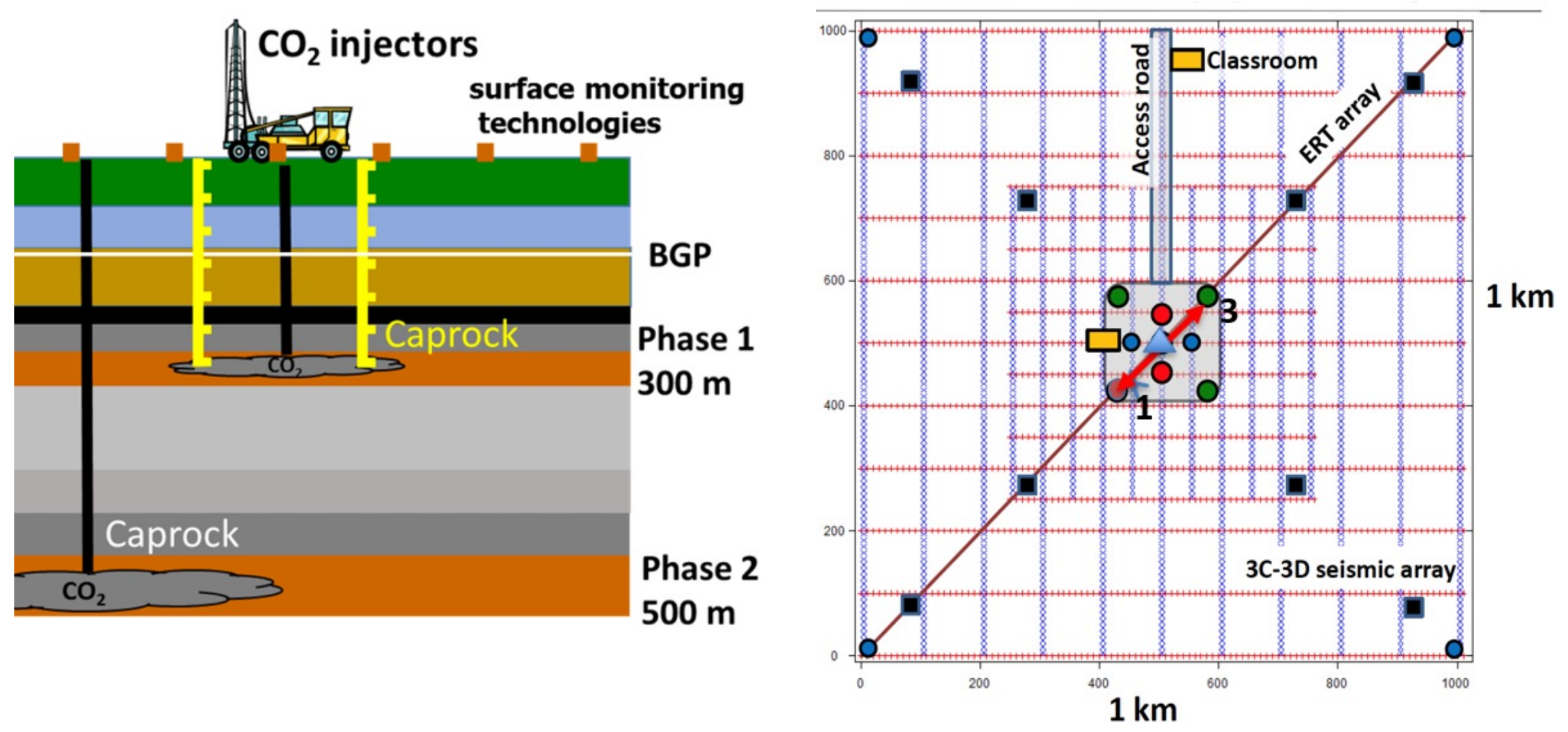

Figure 4 *Cartoon description of the NCF CO_2 injection experiment (right) and map of the site (left) showing position of the injector (blue triangle) and water wells (green circles).*

LBNL Task 2: Multi-Physics Machine Learning Data Imaging

Machine Learning (ML) Imaging

LBNL has developed a ML based geophysical data imaging algorithm with multi-physics capabilities under the DOE’s SMART Initiative. As described in Um et al. (2022), the algorithm uses site specific rock-physics transforms to convert an ensembles of reservoir simulations to geophysical property models which are then used to generate synthetic geophysical data that train the ML algorithm. The resulting algorithm not only produces images of reservoir properties of interest (i.e. CO_2 saturation) rather than geophysical properties (e.g. resistivity) but also estimates of uncertainty in the images.

Figure 5 below demonstrates the concept using the synthetic 2D Kimberlina data set of Alumbaugh et al.(2023) as a test case. The top row shows the CO_2 saturation model at 20 years after injection on the left, and a traditional seismic velocity image generated via full waveform inversion (FWI) on the right. The second through fourth rows show the ML generated CO_2 saturation on the left and uncertainty estimation on the right for the seismic only data, EM only data, and combined seismic and EM data, in that order. For the ACT4 SPARSE project this algorithm will be modified to use 1D models to generate training data. The use of 1D models is justified due to the close source-receiver offsets provided by the nodal measurements.

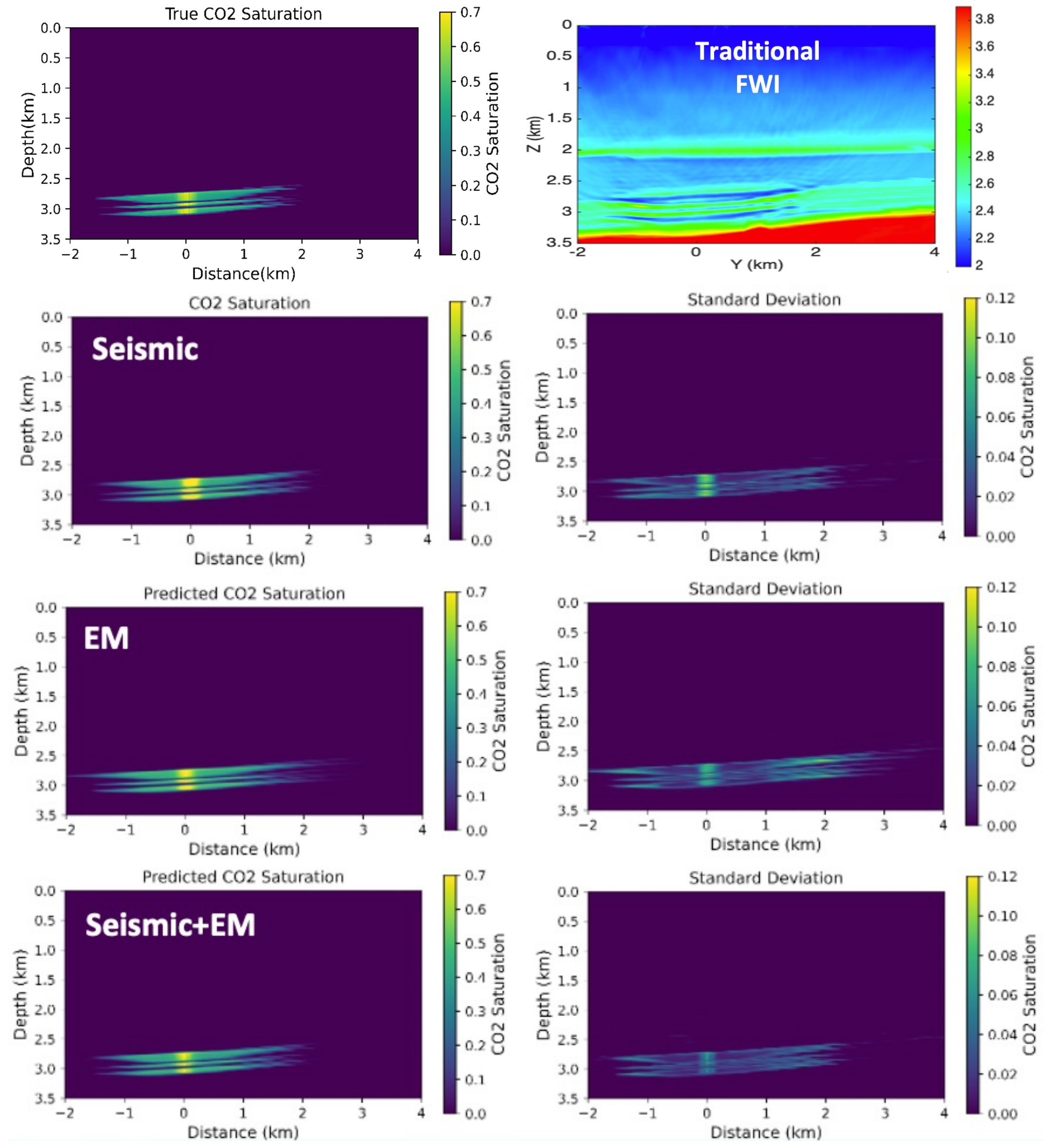

Figure 5 *Example from Um et al (2022) demonstrating the use of an ML algorithm for providing images of CO_2 saturation using multi-physics data. The top row shows the model (left) and results of traditional seismic imaging (right) and the second through fourth rows the results of applying the ML approach to different data.*

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