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ABSTRACT

After learning that the TDS value in the target injection formation at the Kevin Dome site is too low to qualify for an EPA Class VI CO_2 injection permit, the BSCSP project was re-scoped such that injection of CO_2 is no longer planned. With no injection planned, the Geomechanics project was closed. In this final report, we describe the objective and approach of the project as proposed, and the limited results obtained before stopping work. The objective of the proposed research was the development & validation of an integrated monitoring approach for quantifying the interactions between large-scale geological carbon storage (GCS) and subsurface geomechanical state, particularly perturbations relevant to reservoir integrity such as fault reactivation and induced fracturing. In the short period of work before knowing the fate of the Kevin Dome project, we (1) researched designs for both the proposed InSAR corner reflectors as well as the near-surface 3C seismic stations; (2) developed preliminary elastic geomechanical models; (3) developed a second generation deformation prediction for the BSCSP Kevin Dome injection site; and (4) completed a preliminary map of InSAR monuments and shallow MEQ wells in the vicinity of the BSCSP injection pad.

TABLE OF CONTENTS

EXECUTIVE SUMMARY

This project has been on a “hold work” status due to the lack of CO_2 injection at the targeted field site at Kevin Dome, Montana. In this final report, we describe the proposed plan work package and initial work completed before the work was stopped.

The objective of our proposed research was the development and validation of an integrated monitoring approach for quantifying the interactions between large-scale geological carbon storage (GCS) and subsurface geomechanical state, particularly perturbations relevant to reservoir integrity such as fault reactivation and induced fracturing. GCS systems are engineered to reduce the likelihood of seal failure by way of judicious site selection (e.g., avoiding seismically visible faults, redundant seals) and active monitoring systems (e.g., in-well pressure monitoring to avoid fracture generation). However, large-scale pore pressure perturbations induced by industrial GCS have the potential to interact with sub-seismic faults within the reservoir unit or seal as well as critically-stressed and seismically transparent faults in crystalline basement rocks.

A rigorously coupled monitoring approach was proposed which combined spatially and temporally resolved satellite deformation monitoring (InSAR) to detect geomechanical perturbations induced by injection and/or production. Microseismic (MEQ) monitoring was proposed to map interactions between induced stress changes and fault reactivation on the small scale. Surface deformation measurements, made by InSAR, would be inverted for changes in reservoir volume and pore pressure. The variation in pore pressure would be validated against core-calibrated impedance inversions derived from a 4D 9C seismic volume. If dipole signatures of surface deformation were to be detected, indicative of a tensile opening event, an attempt would have been made to evaluate the fractured zone using either scattered energy or anisotropy metrics in the 4D 9C volume. The temporal and spatial correlation of this pressure pulse with MEQ activity would allow delineation of induced events and potential analysis of stressed faults in the injection region. These measurements would have been integrated using a state-of-the-art coupled modeling framework (TOUGH-FLAC) to allow a detailed understanding of subsurface interactions and safe operating conditions.

The project was intended to have been executed at the planned Big Sky Carbon Sequestration Partnership (BSCSP) (DE-FC26-05NT42587) Phase III sequestration site located at Kevin Dome, Montana, to allow observations at injection rates truly relevant to commercial GCS deployment. The Kevin Dome storage pilot proposed was unique among current GCS pilots in that it encompassed spatially separated production and injection zones, allowing observation of both polarities of pore pressure perturbation during operation. The entire site would have therefore been analogous to a CO_2 hub, a location which functions as both a GCS repository as well as temporary storage facilities to supply the needs of enhanced oil recovery. Such sites, while typically yielding net storage of CO_2, will likely experience a wide range of pore-pressures during injection and draw-down periods, similar to the pressure histories exhibited by natural gas storage facilities. Thus, the project proposed to address geomechanical impacts of both sequestration and utilization activities. Had the project gone forward, an additional benefit of siting coupled InSAR/MEQ monitoring study at Kevin Dome would have been the extensive characterization and monitoring datasets which could have been used to constrain and validate the piloted techniques, including surface-to-TD sonic logs, core studies of elastic properties, VSP

constraints on seismic velocities, and most crucially a unique 4D 9C surface survey to provide a comparison to pore pressure maps derived from surface deformation measurements. Furthermore, this project as proposed included study of a carbonate reservoir, subject to potential reactive geochemistry which could cause creep compaction. Integrated modeling and monitoring would allow unique field scale constraints on such coupled geochemical/geomechanical processes.

In summary, this project would have directly benefited the DOE carbon storage program by providing an integrated framework for coupled monitoring, modeling and analysis of the geomechanical impact of CO_2 injection, a listed CO_2 storage science technology objective (DOE/NETL 2011) and MVA technology objective. In particular, our approach provides a cost-effective approach for monitoring surface deformation coupled to injection and the associated injection related MEQ activity. The combined system would provide an avenue for reservoir integrity assurance; the combination of a pressure triggered MEQ swarm would provide a trigger for more detailed investigation of reservoir pressure state and seal integrity, possibly including targeted 4D seismic, extended MEQ arrays or secondary monitoring protocols. The utility of InSAR inversions for mapping pore-pressure perturbations at the reservoir scale was validated; if this approach was shown to be effective, InSAR could provide an inexpensive monitoring alternative or complement to 4D seismic for pressure characterization and improve the temporal frequency of far-field pressure monitoring.

EXPERIMENTAL METHODS

A rigorous coupled monitoring approach was developed which combines spatially and temporally resolved satellite deformation monitoring to detect geomechanical perturbations induced by injection or production with microseismic monitoring to map interactions between induced changes and fault reactivation on the small scale. Surface deformation measurements, made by InSAR, were to be inverted for changes in reservoir volume and pore pressure, and the variation in pore pressure validated against core-calibrated impedance inversions derived from a 4D 9C seismic volume. If dipole signatures of surface deformation, indicative of a tensile opening event, were detected, an attempt would have made to evaluate the fractured zone using either scattered energy or anisotropy metrics in the 4D 9C volume. The temporal and spatial correlation of the pressure pulse with MEQ activity would have allowed delineation of induced events and potential analysis of stressed faults in the injection region. These measurements would then be integrated using a state-of-the-art coupled modeling framework (TOUGH-FLAC) to allow a detailed understanding of subsurface interactions and safe operating conditions. The project was proposed to allow observations at injection rates truly relevant to commercial GCS deployment.

RESULTS AND DISCUSSIONS

Task 1.0 Project Management

After learning that the TDS value in the target injection formation at the Kevin Dome site is too low to qualify for an EPA Class VI CO_2 injection permit, work was put on hold during quarter 2 of FY2015. Project Management activities were limited.

Lee Spangler, Laura Dobeck (MSU), and Jonathan Ajo-Franklin (LBNL) attended the NETL FOA 1037 Kickoff Meeting in Pittsburgh. Lee Spangler and Jonathan Ajo-Franklin presented an overview of the "Geomechanical Monitoring for CO_2 Hub Storage: Production and Injection at Kevin Dome Phase III" project on the first day of the meeting (November 12, 2014).

MSU Fiscal Director facilitated the issuance of MSU subaward G165-15-W5118 to GeoEnergy Monitoring Systems, Inc. (GeoEMS). GeoEMS was to provide ground monitoring for CO_2 storage at the Kevin Dome site. The issuance of a Contracted Services Agreement was also facilitated between MSU and TRE Canada, Inc. (TRE) to provide InSAR Ground Movement Monitoring over the Kevin Dome.

The overall project schedule and overlap with BSCSP activities was for potential conflicts and roadblocks.

Laura Dobeck and Jonathan Ajo-Franklin had begun discussions of what needed to be accomplished before final positioning of the InSAR reflectors and MEQ shallow bore holes could be determined.

Task 2.0. Permitting/Compliance

LBNL participated in subtask 2.1 (Infrastructure Design) within task 2.0. LBNL personnel researched designs for both the proposed InSAR corner reflectors and the near-surface 3C seismic stations. Key aspects of the design of the former include foundation construction decoupled from near-surface freeze processes and design of a reflector "shroud" which prevents snow accumulation within the reflector. A preliminary design for the reflector was completed. Specification of the 3C seismic station design was conducted in collaboration with the subcontractor (GeoEMS) LBNL anticipated using for the seismography deployment.

Beyond design of the physical installation, LBNL worked to determine optimal location of both the InSAR reflectors and the 3C seismic stations. Since the InSAR reflectors are designed to fill-in gaps in natural reflector distribution, LBNL obtained historical PS-InSAR data from TRE. This dataset, shown in Figure 1, revealed useful persistent reflectors around both the injector and producer pads with the worst coverage to the north east of the production well. Averaging of the entire dataset revealed a long-term 0.3 mm/yr subsidence trend between 1992 and 2002, likely related to shallow gas production activity. This background trend would have needed to be addressed if injection took place in order to allow isolation of CO_2 related displacements.

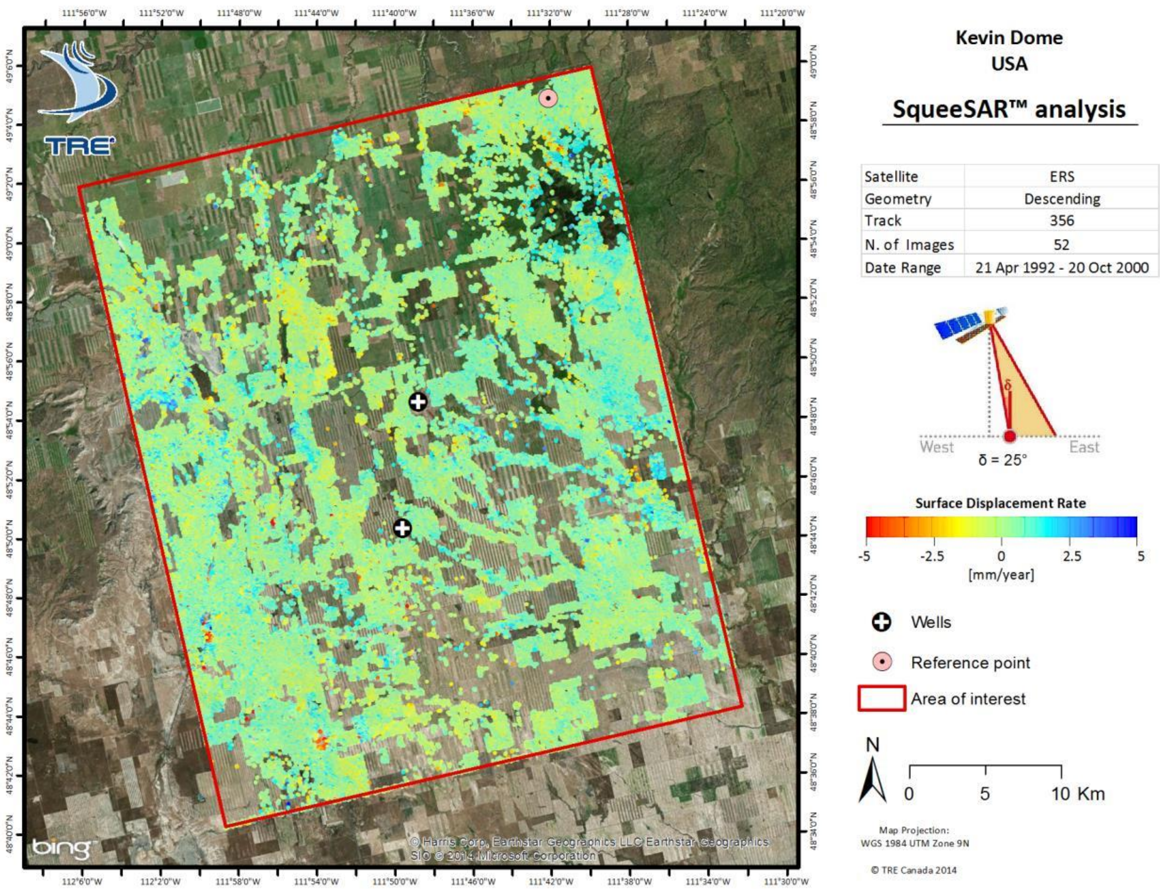

Figure 1. Historical PsInSAR analysis provided by TRE for 1992 to 2000. Danielson well location is lower cross while the Wallewein well is the upper cross.

During the third project quarter, LBNL participated in subtask 2.1 (infrastructure design) and completed a preliminary map of InSAR monuments and shallow MEQ wells in the vicinity of the BSCSP injection pad. Before this site selection process, LBNL used data provided by MSU to merge elements of the BSCSP GIS atlas with SQUEE-SAR scatterer information obtained from TRE. These GIS layers included cultivated lands, landownership, local roads, restricted areas, existing wells, infrastructure/buildings, National Wetlands Database, BSCSP well locations/pads, access roads to BSCSP wells, estimated injection location, EA project boundary, and the current surface seismic boundary. The results of our preliminary modeling efforts, Figure 2 shows the synthesis of these datastreams (A & B at different scales) with the modeled deformation iso-contours in black, road network in green, and transparent red in areas with abundant InSAR scatterers appropriate for deformation monitoring.

Two sets of locations were required in initial planning/permitting phases, the location of monuments to supplement gaps in scatterer coverage and the location of the planned shallow wells for MEQ seismic acquisition. Monument locations were selected in locations near roads (to provide access and avoid conflict with agricultural work) which exist in scatterer gaps, largely caused by planting and plowing activity. MEQ well locations were chosen to be close to road access, with offsets ~1.5 to 2 times the planned injector well depth (~1.3 km) (~0.8 miles), and with good azimuthal coverage of potential events. The shallow well network was to be supplemented by surface stations on the injection/monitoring well pads and potentially a fifth well near the injector. Figure 3 shows proposed locations of the InSAR monuments and MEQ wells. As can be seen, many of the 15 monuments are concentrated in the North and West quadrants to supplement poor scatterer coverage in these locations. The MEQ wells are clustered within 2-3 km of the injector pad.

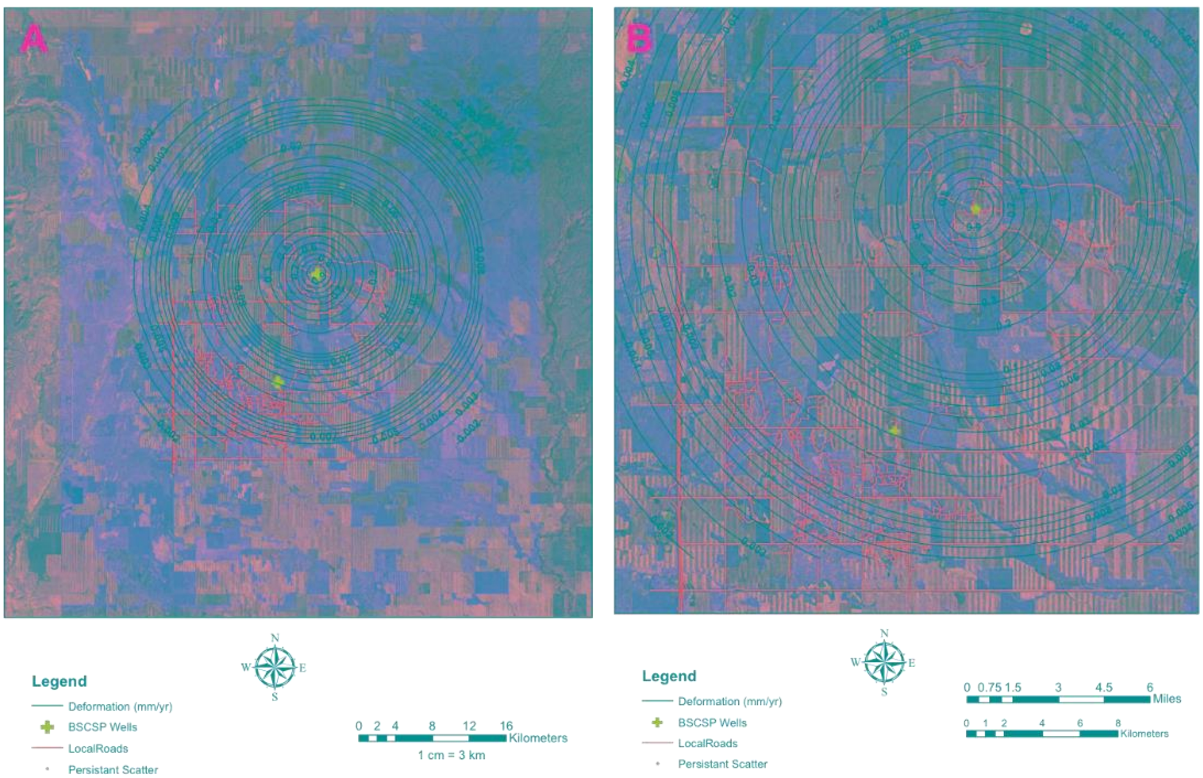

Figure 2. Maps of modeled surface deformation superimposed on TRE identified SQUEE-SAR persistent scatterers. Potential injection pad identified by blue cross at center of circles. Red areas are zones with sufficient scatterers for displacement measurements.

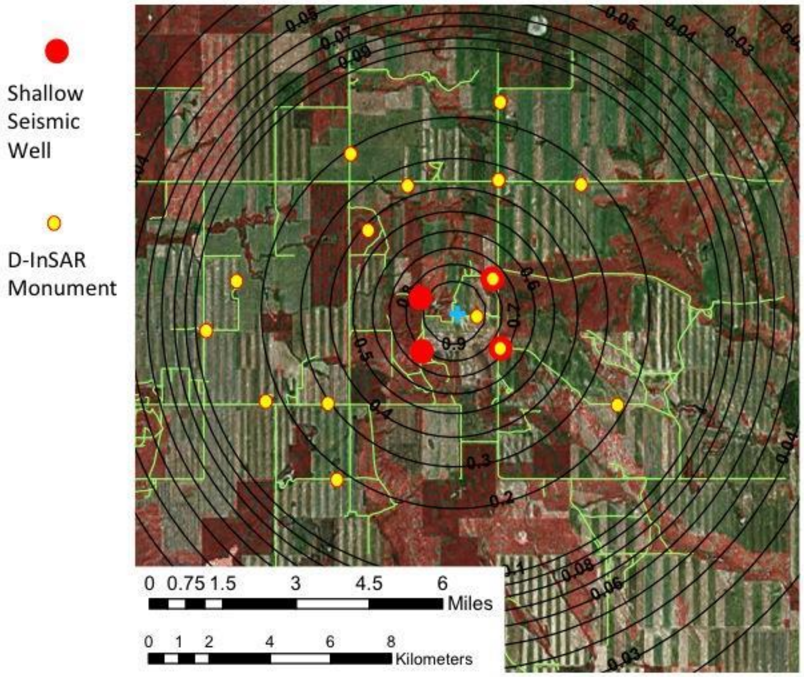

Figure 3. Preliminary map of shallow seismic wells and D-InSAR monuments.

Task 3.0. Geomechanical Modeling

During the first project quarter, LBNL participated in Subtask 3.1 which focused on developing preliminary elastic geomechanical models to provide guidance on infrastructure deployment. An initial 1D elastic model was constructed using existing well logs from the Wallewein and Danielson wells drilled by BSCSP. Several models were tested to predict surface deformation, one assuming inflation of a large (250 m height) (~273 yards) unmapped fracture zone and a second assuming purely elastic inflation of the reservoir. Both models used the pressure distribution predicted by the first generation of BSCSP reservoir flow models and predicted measurable displacements out to 5 km (~3 miles) radius from the injector assuming a 250 Kton/yr injection rate. A lobar distribution of displacement was noted in the fracture model suggesting that azimuthal InSAR coverage would be valuable in constraining such mechanisms. While the fracture model is unrealistic in that it would likely be detectable on 3D seismic, it provided an upper bound for predicted displacements and extents, hence a good constraint on the maximum InSAR reflector radius.

During the second project quarter, LBNL developed a second generation deformation prediction for the BSCSP Kevin Dome injection site. The original model, a 1D stack derived from the Wallewein 22-1 well logs, was replaced with a more geologically accurate model derived from the TOUGH-2 geomodel utilized for previous predictive flow calculations. Figure 4 shows the flow model (panel A) and the associated pressure perturbation at the middle Duperow after two years of injection (panel B).

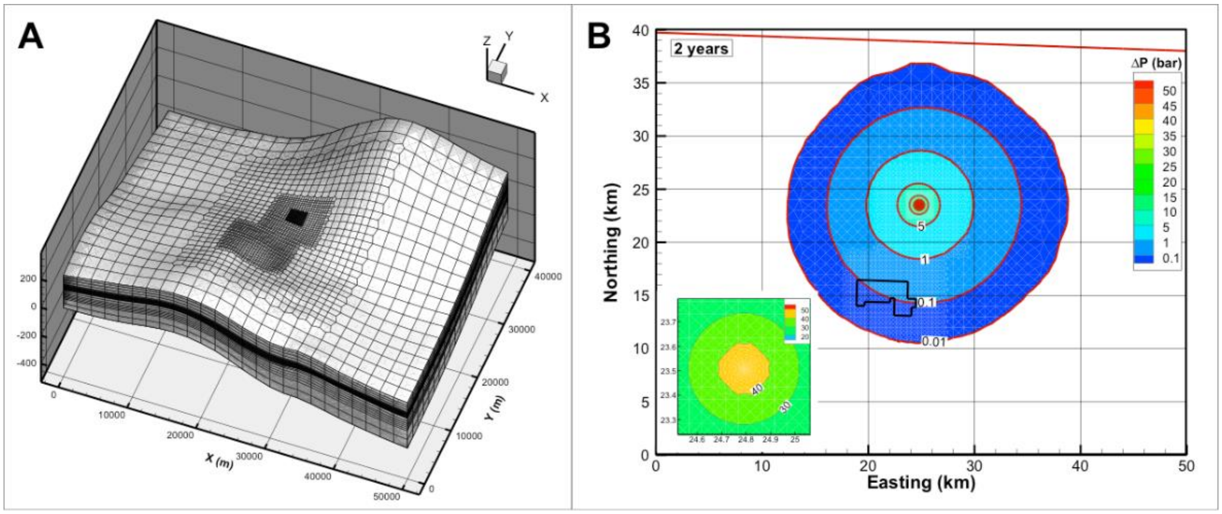

Figure 4. Second generation BSCSP Kevin Dome TOUGH-2 model and pressure predictions. Panel (A) shows the geomodel and panel (B) shows pressure predictions at the top of the middle Duperow formation.

The pressure perturbation results from the BSCSP TOUGH-2 model were coupled into a simplified elastic model to provide predictions of surface deformation at two years of injection from a single well at 250 kT/yr. Figure 5 shows the updated uplift predictions using the more complicated flow model. As can be seen, radial uplift at measurable levels should extend over 7 km (4.35 miles) from the injection location, slightly farther than was predicted during previous model runs.

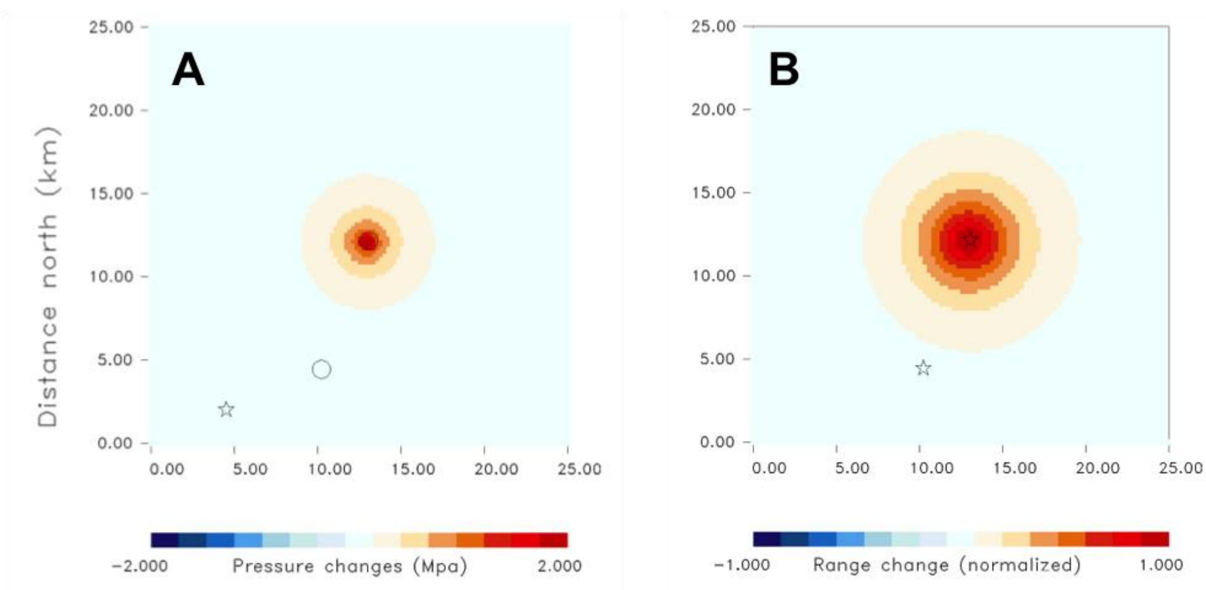

Figure 5. Updated pressure field (A) and resulting radial uplift (B) calculated using the updated flow model.

Task 4.0. Geomechanical Monitoring / Data Acquisition

With no planned injection of CO_2 at the Kevin Dome site, no monitoring equipment was deployed.

Task 5.0. Data Processing, Analysis and Integration

No InSAR or MEQ data was collected.

CONCLUSION

In the short period of work: (1) designs were researched for both the proposed InSAR corner reflectors and the near-surface 3C seismic stations; (2) preliminary elastic geomechanical models were developed; (3) a second generation deformation prediction was developed for the BSCSP Kevin Dome injection site; and (4) a preliminary map of InSAR monuments and shallow MEQ wells in the vicinity of the BSCSP injection pad was completed.

GRAPHICAL MATERIALS LIST(S)

REFERENCES

Wang, R., Lorenzo-Martin, F., and Roth, F., 2003. Computation of deformation induced by earthquakes in a multilayered elastic crust - Fortran programs EDGRN/EDCMP, Comput. Geosci., 29, 195-207.

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LIST OF ACRONYMS AND ABBREVIATIONS

3C	3-Component
4D 9C	Four-Dimensional Nine-Component
BSCSP	Big Sky Carbon Sequestration Partnership
DOE	Department of Energy
D-InSAR	Differential Interferometric Synthetic Aperture Radar
GCS	Geological Carbon Storage
GIS	Geographic Information System
InSAR	Interferometric Synthetic Aperture Radar
LBNL	Lawrence Berkeley National Laboratory
MEQ	Micro-Earthquake (or Microseismic)
MVA	Monitoring, Verification and Accounting
NETL	National Energy Technology Laboratory
SQUEE-SAR	Squeeze Synthetic Aperture Radar
TD	Total Depth
TDS	Total Dissolved Solids
TRE	A commercial provider of InSAR services
VSP	Vertical Seismic Profile

PUBLICATIONS

No publications were produced under this award.

PRESENTATIONS

No presentations were produced under this award.

OTHER PRODUCTS PRODUCED

No other products were produced.