In Salah CO_2 Storage Project

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Benefit to the Program

- This project combines sophisticated modeling tools with monitoring data sets to address fundamental challenges in interpreting storage system behavior.

- This program meets the Carbon Storage Program goal to "conduct field tests through 2030 to support the development of BPMs for site selection, characterization, site operations, and closure practices."

Objectives

- Project objective is to address four fundamental challenges:
  - Modeling of plume migration and prediction of partitioning among various trapping mechanisms
  - Uncertainty quantification of CO_2 distribution with the reservoir and potential migration pathways (e.g. damaged caprock)
  - Understanding of fluid-induced seismicity and associated risks
  - Definition of potential leakage source terms and their impact on a shallow groundwater aquifer

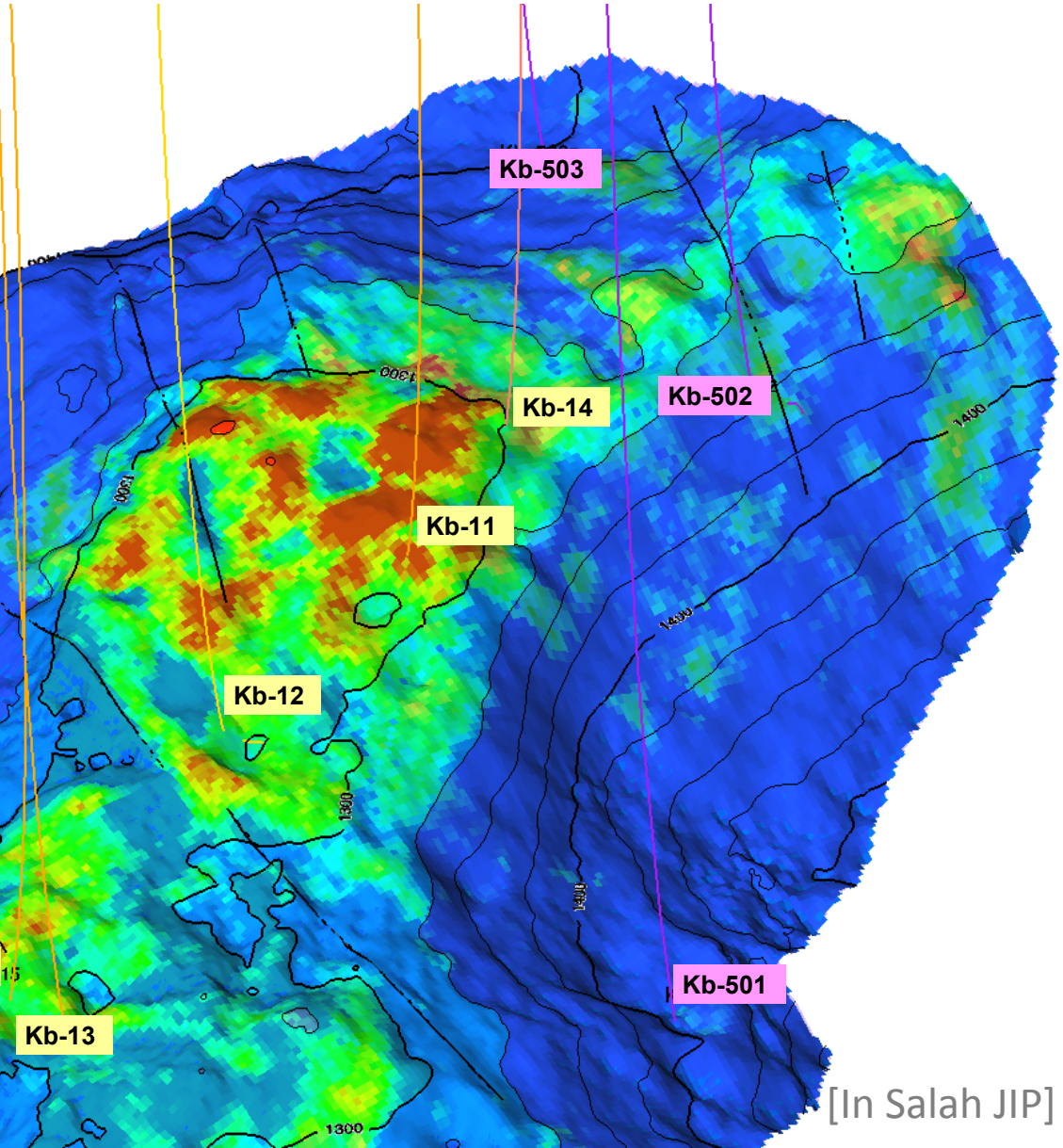
- Success is tied to the ability to provide useful guidance to the operator.

Technical Status

- The technical work is complete, and we are in the final reporting stage:
  - J.A. White et al., "Geomechanical behavior of the reservoir/caprock system at the In Salah CO_2 storage project", (under review by operator).
  - S. Ezzedine et al., "Assessing hydraulic fracturing of porous fractured media reservoirs: Application to In Salah", (in preparation)
  - A. Ramirez et al., "Stochastic inversion of InSAR data to detect penetration into the lower caprock at In Salah", (in preparation).

- In June 2011, injection operations were halted at the site to allow the operator to re-evaluate the injection strategy.

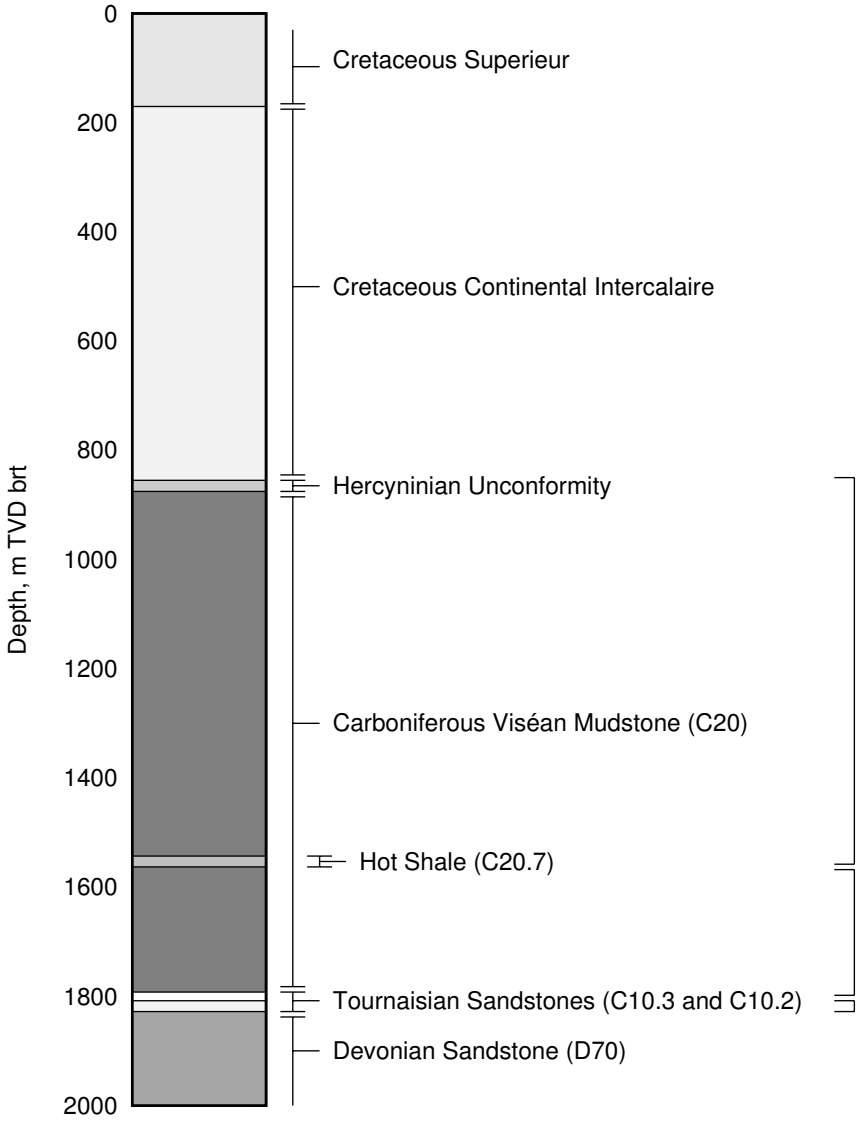
In Salah Storage Project



[In Salah JIP]

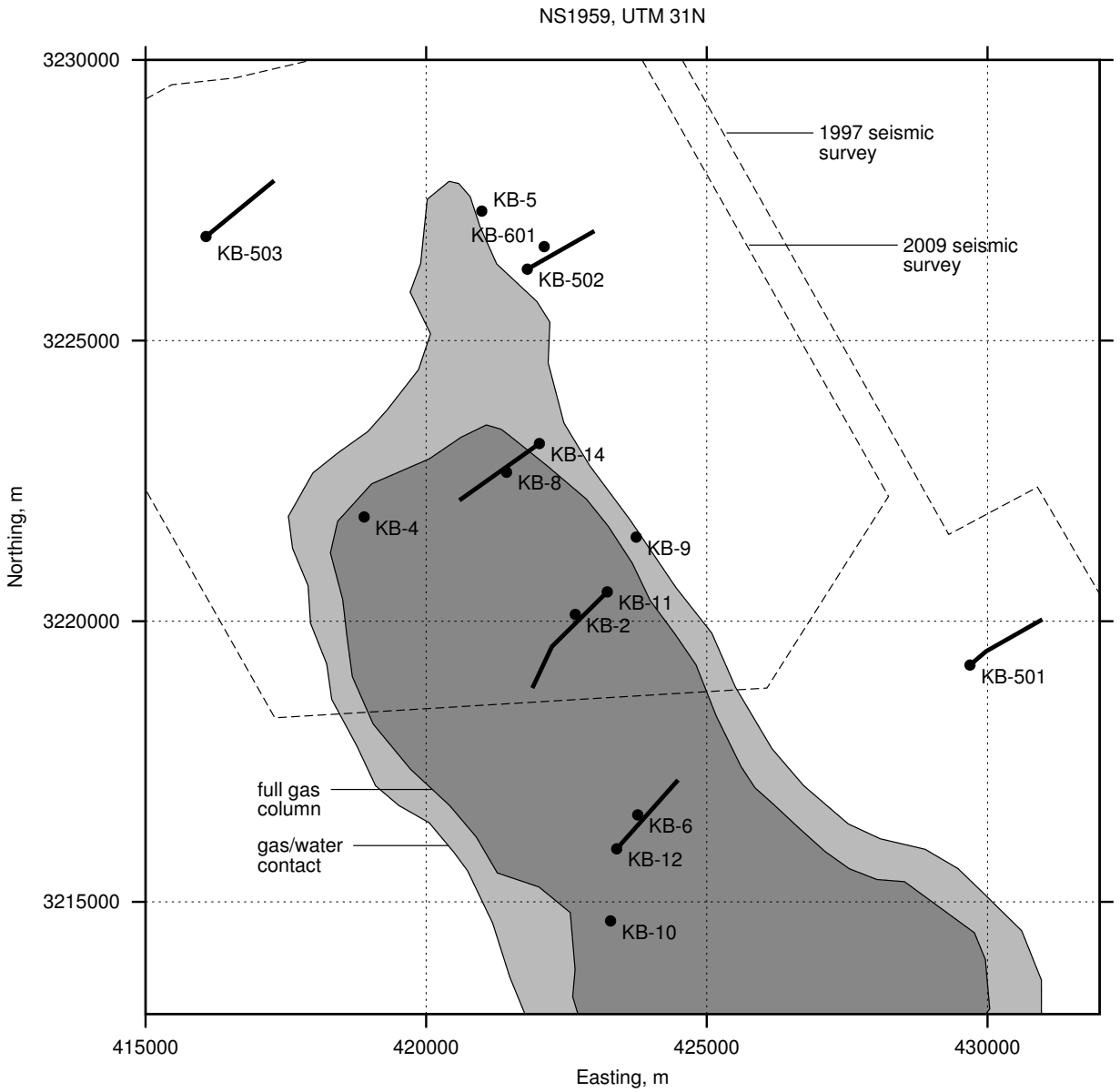
- Reservoir at ~1900m, ~20m thick
- Anticlinal structure
- Gas with high CO_2 content produced from the cap
- Separated and re-injected through three horizontal wells on the limbs

Storage Complex



- 950 m thick caprock
- Grouped into main caprock and lower caprock units
- Monitoring indicates that fluids have migrated into the lower caprock
- No indications that the main caprock has been affected

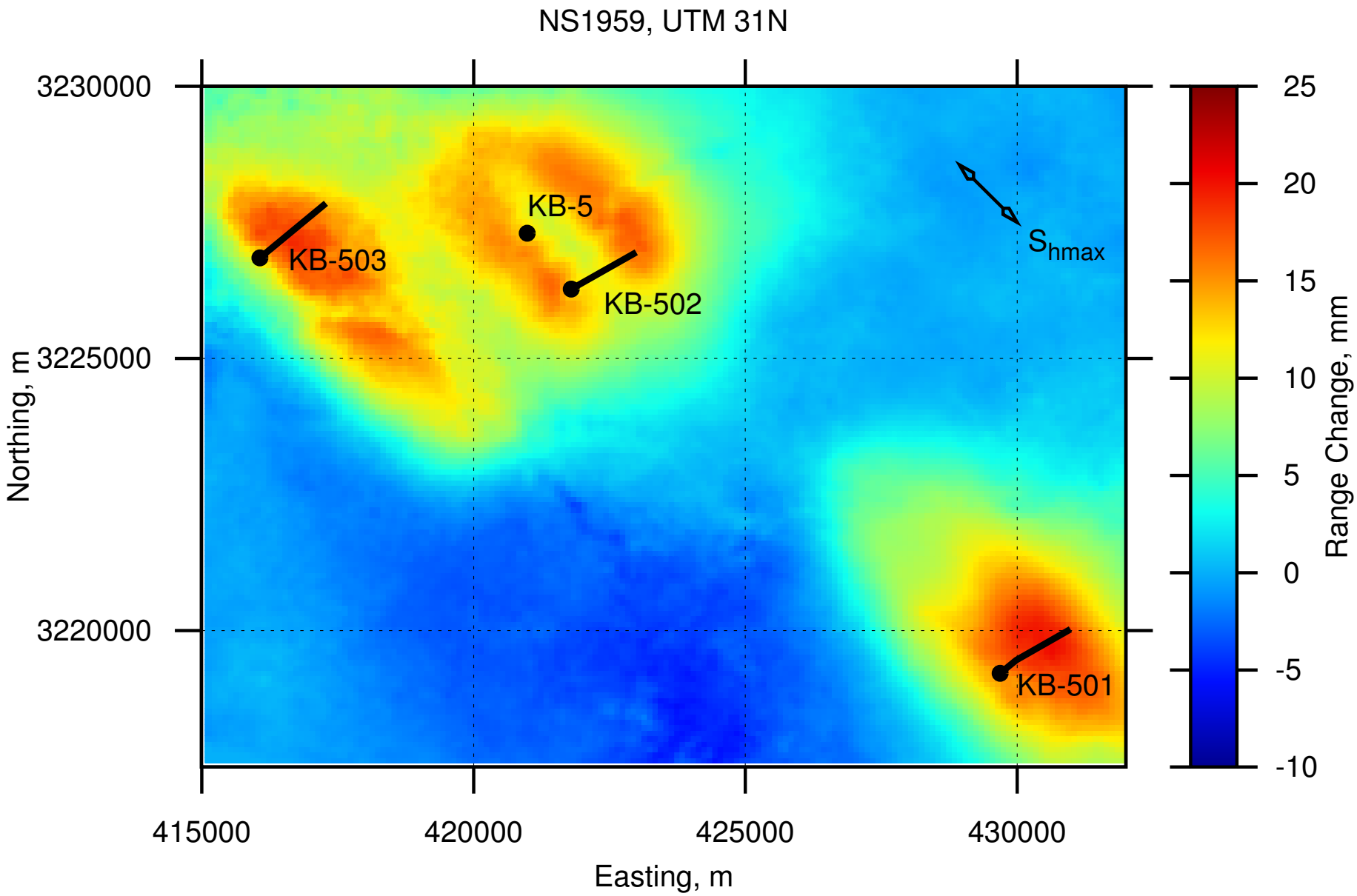
Characterization and Monitoring



- Co-located storage and production
- Seismic surveys
- InSAR
- Microseismic (limited).
- Surface and aquifer monitoring
- Others

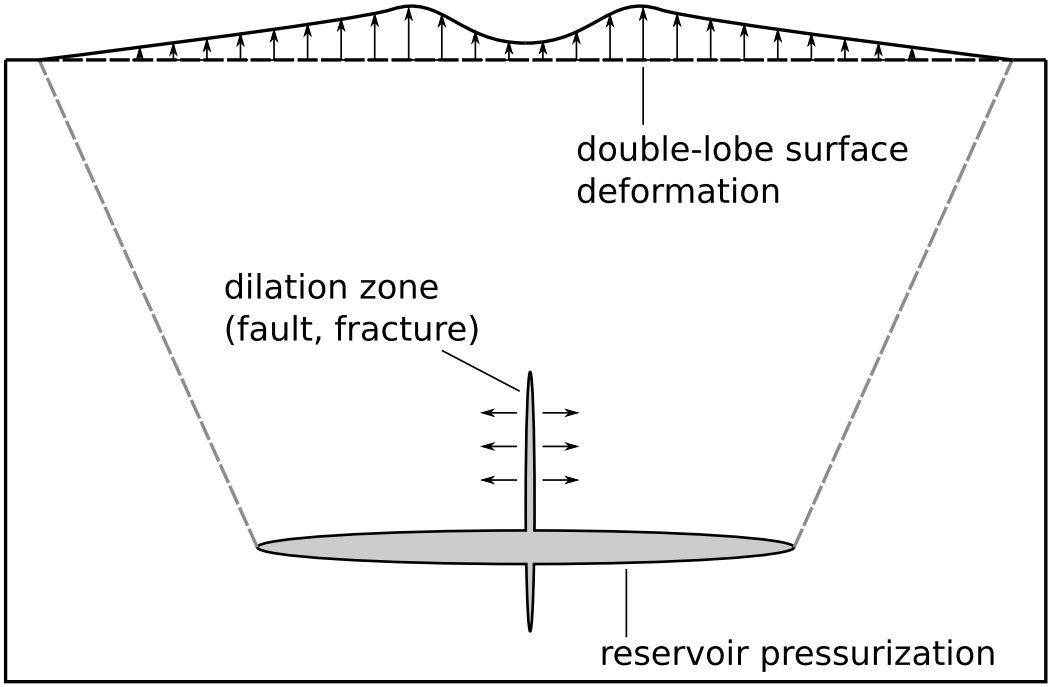
InSAR

March 2010



Possible deformation mechanism

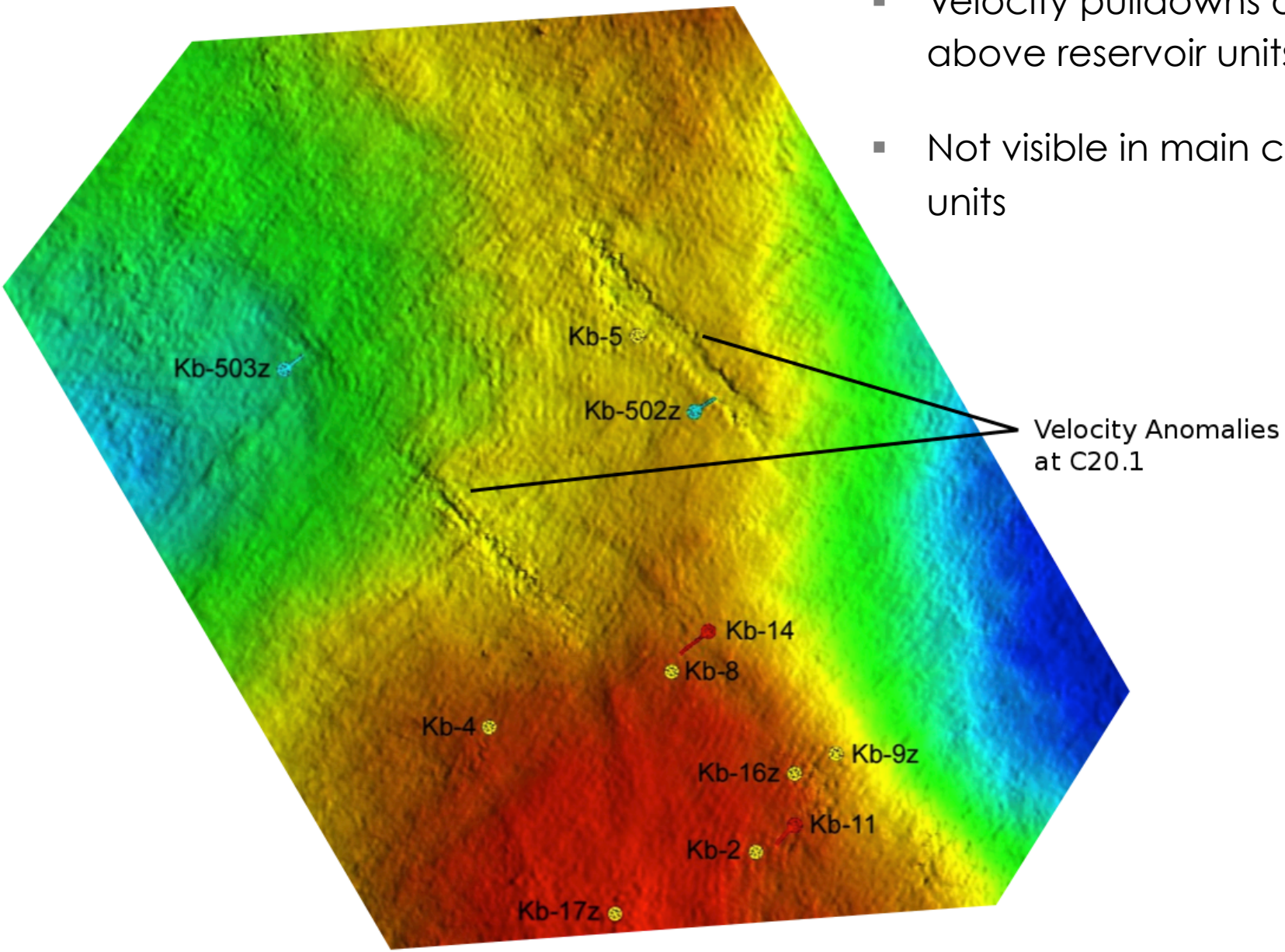
- Dilation of a vertical feature in the reservoir and lower caprock [*Davis 1983, Vasco 2010*]



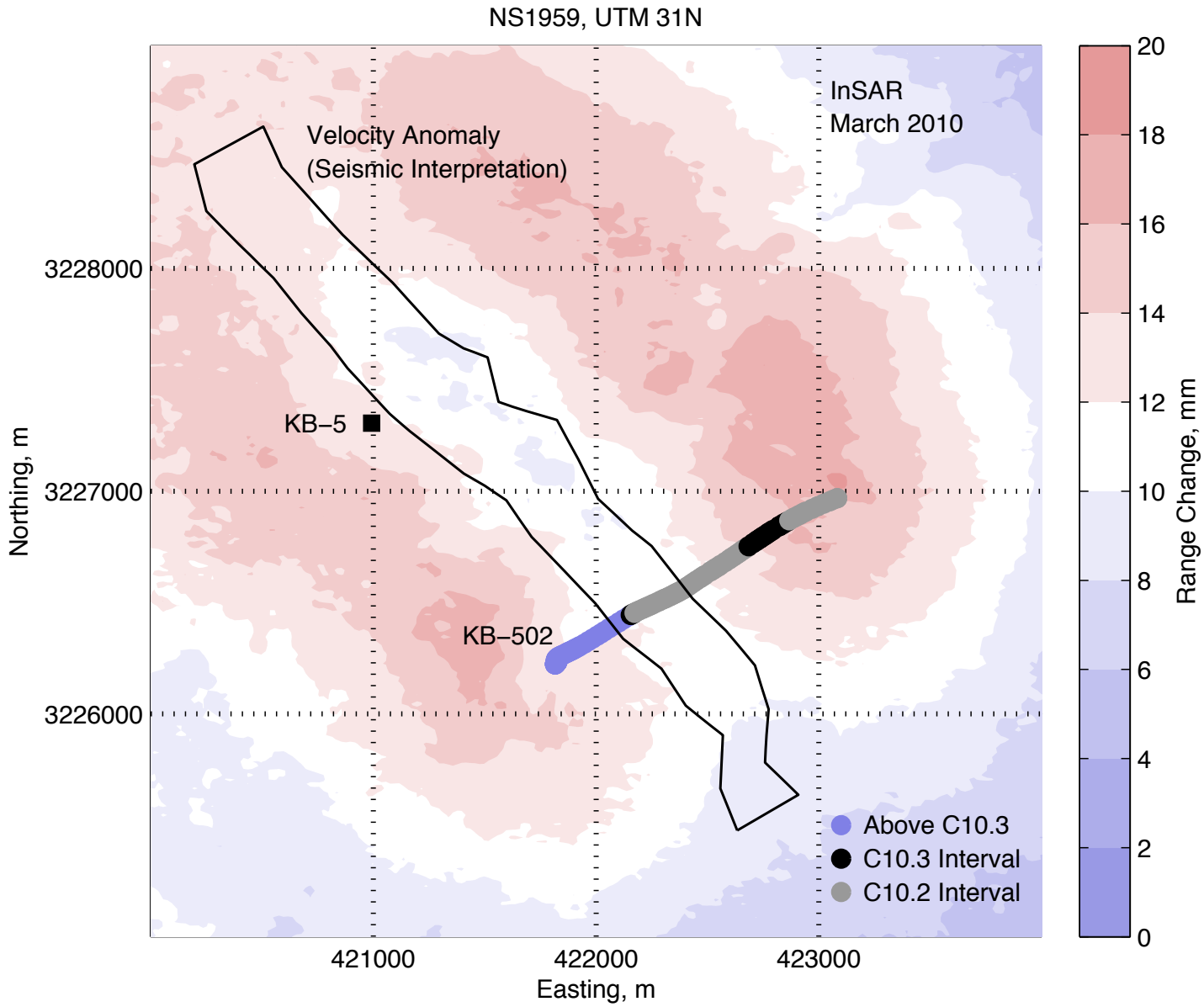
[not to scale]

Seismic velocity anomalies

- Velocity pulldowns observed above reservoir units
- Not visible in main caprock units



Comparison of InSAR and seismic



Hypotheses to explain monitoring observations

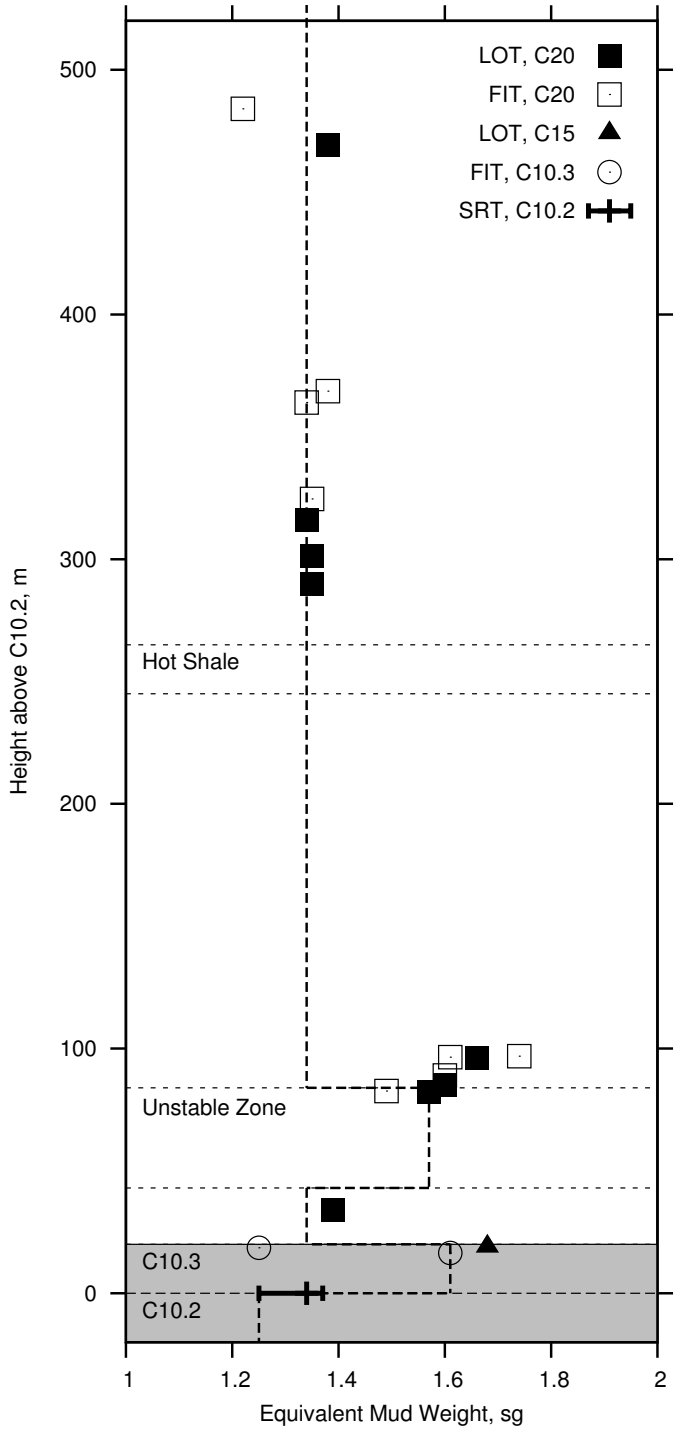
Table 1: Plausible hypotheses to explain available monitoring observations of the lower caprock. Combinations of these mechanisms are also possible.

No.	*Mechanism*	*Description*	*Evidence*
I	**Reservoir-only**	All observations are consistent with pressure and saturation contained in the reservoir interval.	*Weak*
II	**Fault(s)**	The wells intersect one or more pre-existing faults providing a vertical migration pathway.	*Weak*
III	**Hydrofracture**	Injection pressures have created new fracture pathways, through tensile hydrofracture.	*Strong*
IV	**Pre-fractured**	The lower caprock contains pre-existing fractures that are intrinsically permeable, or re-activated by pressure and/or dissolution.	*Moderate*

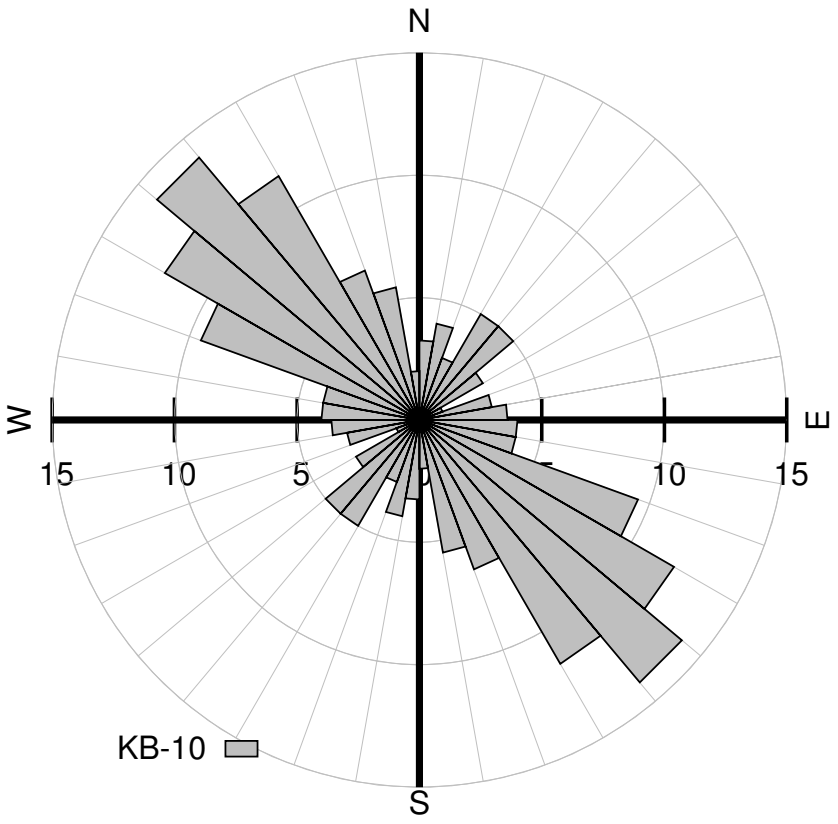
[White et al. 2013]

Hydrofracture hypothesis

- Explains narrow, linear features observed in seismic and InSAR response.
- Features run perpendicular to minimum in situ stress, and parallel to one another.
- Large uncertainties in LOT and FIT data, but injection pressures could have exceeded fracture gradient.
- Injectivity analysis and microseismic show indications of fracturing behavior [Oye et al 2012].



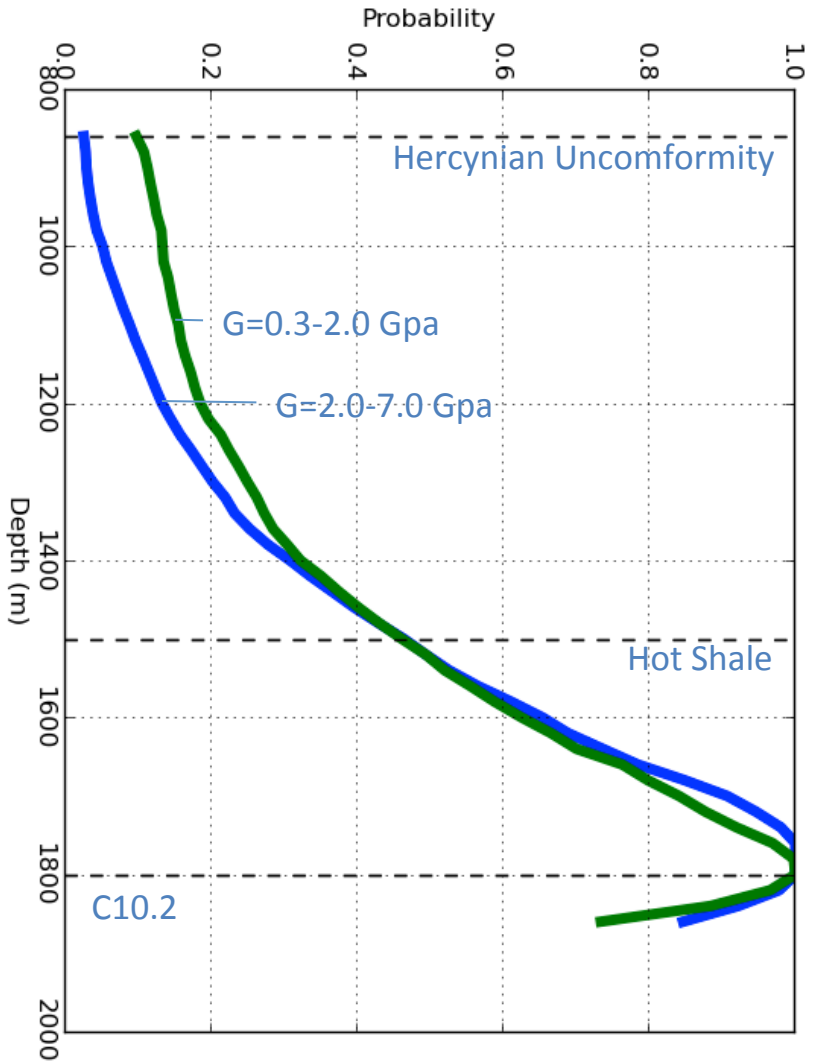
Pre-existing fractures likely played an important role



Fracture strikes observed in offset well kb-10.
Dips typically within 20° of vertical.

- Inferred stress regime at site is strike-slip (vertical stress is intermediate).
- Pre-existing fractures well oriented for tensile opening and shear.
- Could also extend and coalesce through hydrofracture and/or hydroshear.
- Extensive fracture characterization presented in [Iding & Ringrose 2010].

Stochastic inversion of InSAR data at kb-502



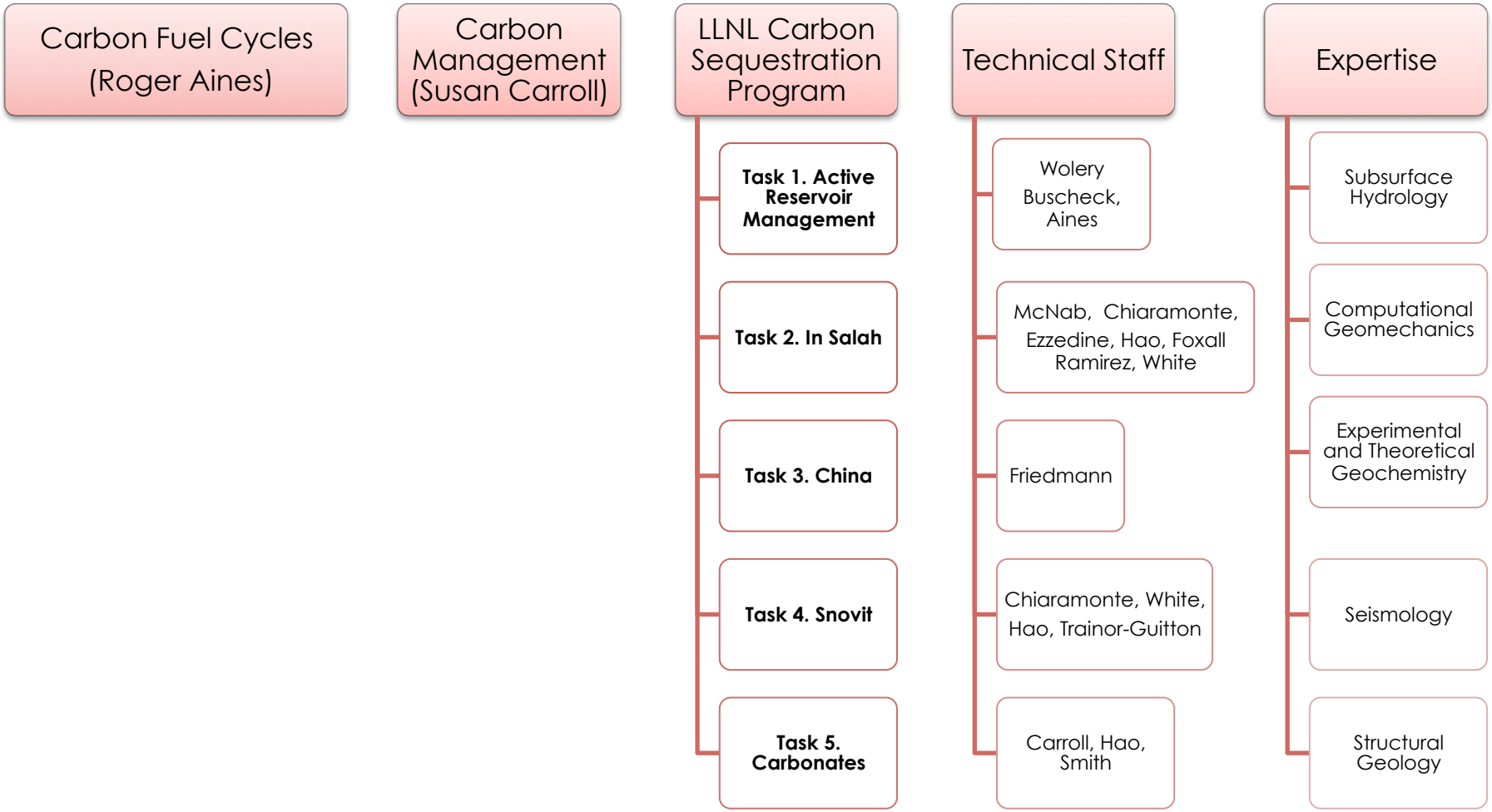
[Ramirez et al. 2013]

- Attempt to estimate probability that linear feature has reached a certain height, using InSAR data alone.
- Suggests moderate probability it has reached the Hot Shale, low probability it has exceeded H.U.C.
- Results independent but consistent with seismic observations of anomaly, which disappears above the Hot Shale.
- No monitoring data suggests the storage integrity has been compromised.

Lessons Learned

- Major risks often stem from uncertainty in formation properties. Co-locating multiple operations allows site characterization to be leveraged.
- It is useful to deploy multiple, independent monitoring tools. Interpretation of any one data set can be ambiguous, but together they form a clearer picture.
- The redundant nature of the seals at In Salah make it very robust, even if unexpected events occur. New CCS sites should prioritize this redundancy.

Organization Chart



Gantt Chart

	Task	FY2011	FY2012	FY2013
2.1	**Multiphase flow and hydromechanical modeling**	◆	◆	◆
2.2	**Stochastic inversion**	◆	◆	◆
2.3	**Induced microseismicity**		◆	◆
2.4	**Shallow aquifer geochemistry**	◆	◆	◆

key:

complete
on schedule
cancelled
◆ milestone

- Tasks 2.1, 2.2, and 2.4 were completed on schedule.
- Task 2.3 effort was shifted to other tasks due to delays in receiving the microseismic data.
- Remaining project funds are being devoted to final reporting and peer-reviewed publications.

Bibliography

- In preparation or review
  - J.A. White et al., "Geomechanical behavior of the reservoir/caprock system at the In Salah CO_2 storage project", (under review by operator).
  - S. Ezzedine et al., "Assessing hydraulic fracturing of porous fractured media reservoirs: Application to In Salah", (in preparation)
  - A. Ramirez et al., "Stochastic inversion of InSAR data to detect penetration into the lower caprock at In Salah", (in preparation).
- Journal publications
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  - S.A. Carroll, W.W. McNab, S. Torres. "Experimental study of cement – sandstone/shale – brine – CO_2 interactions". Geochemical Transactions 2011; 12:9 doi:10.1186/1467-4866-12-9.
  - J.P. Morris, Y. Hao, W. Foxall, and W. McNab. "A study of injection-induced mechanical deformation at the In Salah CO_2 storage project." Int. J. Greenhouse Gas Control 2011; 5:2 doi 10.1016/j/ijgcc.2010.10.004
- Numerous conference proceedings and abstracts.