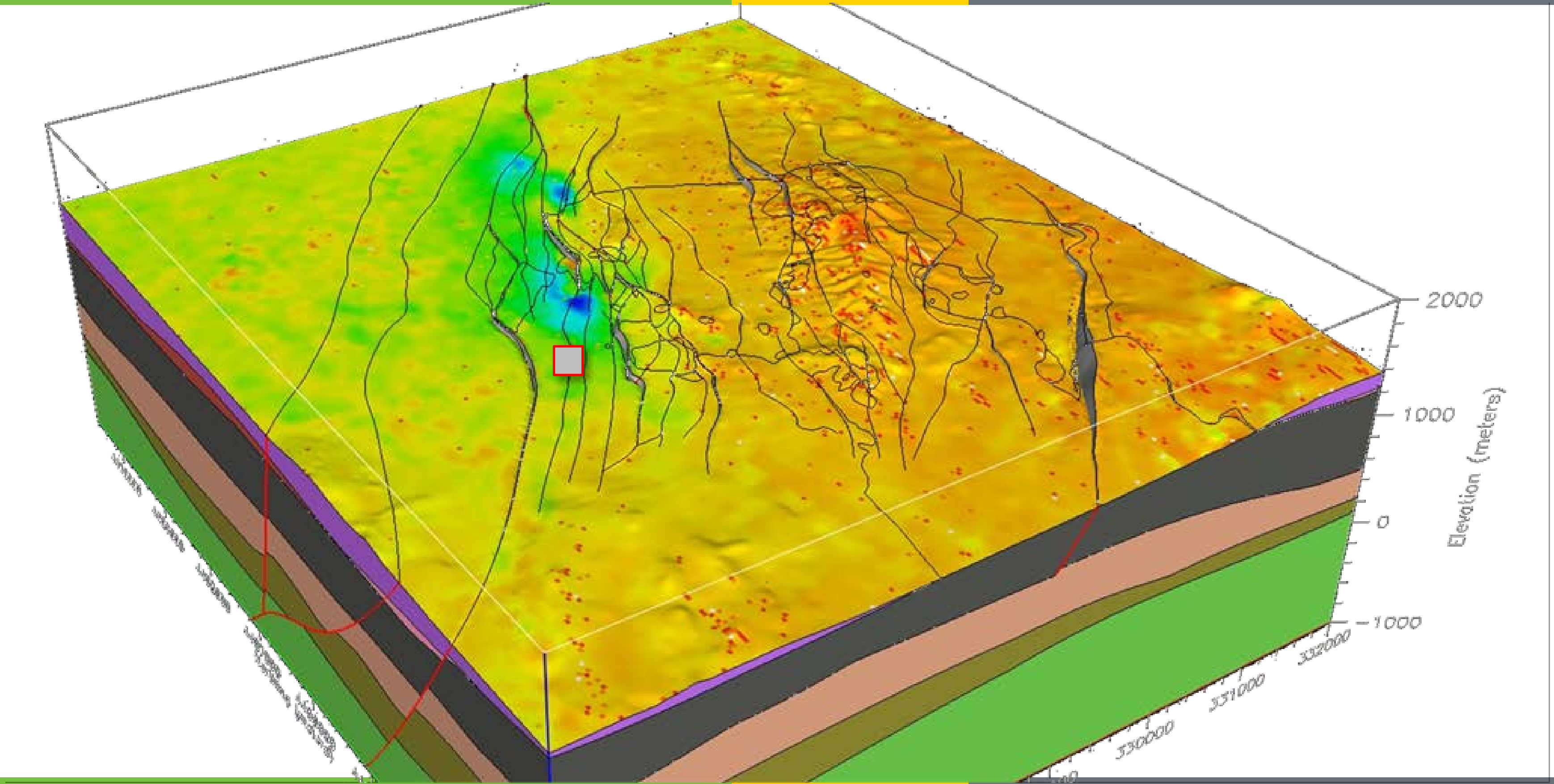

Monitoring EGS Stimulation and Reservoir Dynamics with InSAR and MEQ, DE-EE0005510

April 24, 2013

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Temple University

Topic 4: Observation Tools and Data Collection System for Reservoir Stimulation

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Relevance/Impact of Research

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Currently, no tool effectively provides direct monitoring of the progress of fluid pressure into the natural fracture network or surrounding formation.

- **Objectives:**
  - Improve monitoring of fluid pathways and subsurface permeability change to optimize injection/production design.
  - Explore the relationship of both seismic and aseismic deformation to fluid pressure and flow fields.
  - Develop integrated geologic/geomechanical model that matches seismic and aseismic responses to pumping.

- **Impact:** LCOE improvements primarily result from better definition of the reservoir geometry and pressure field
  - Improved management of injection/production strategies to more efficiently sweep heat and minimize fluid losses to the formation
  - Improved siting of new wells/reduced potential of failed wells by assessing the fluid volume in communication with existing wells
  - Assessing stimulation potential by determining the proximity of tight wells to the reservoir
  - Avoiding development of short circuits

Technical Approach

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Goal: *Map the evolution of the stimulated zone and pore pressure distribution in reservoir during stimulation and production phases of EGS.*

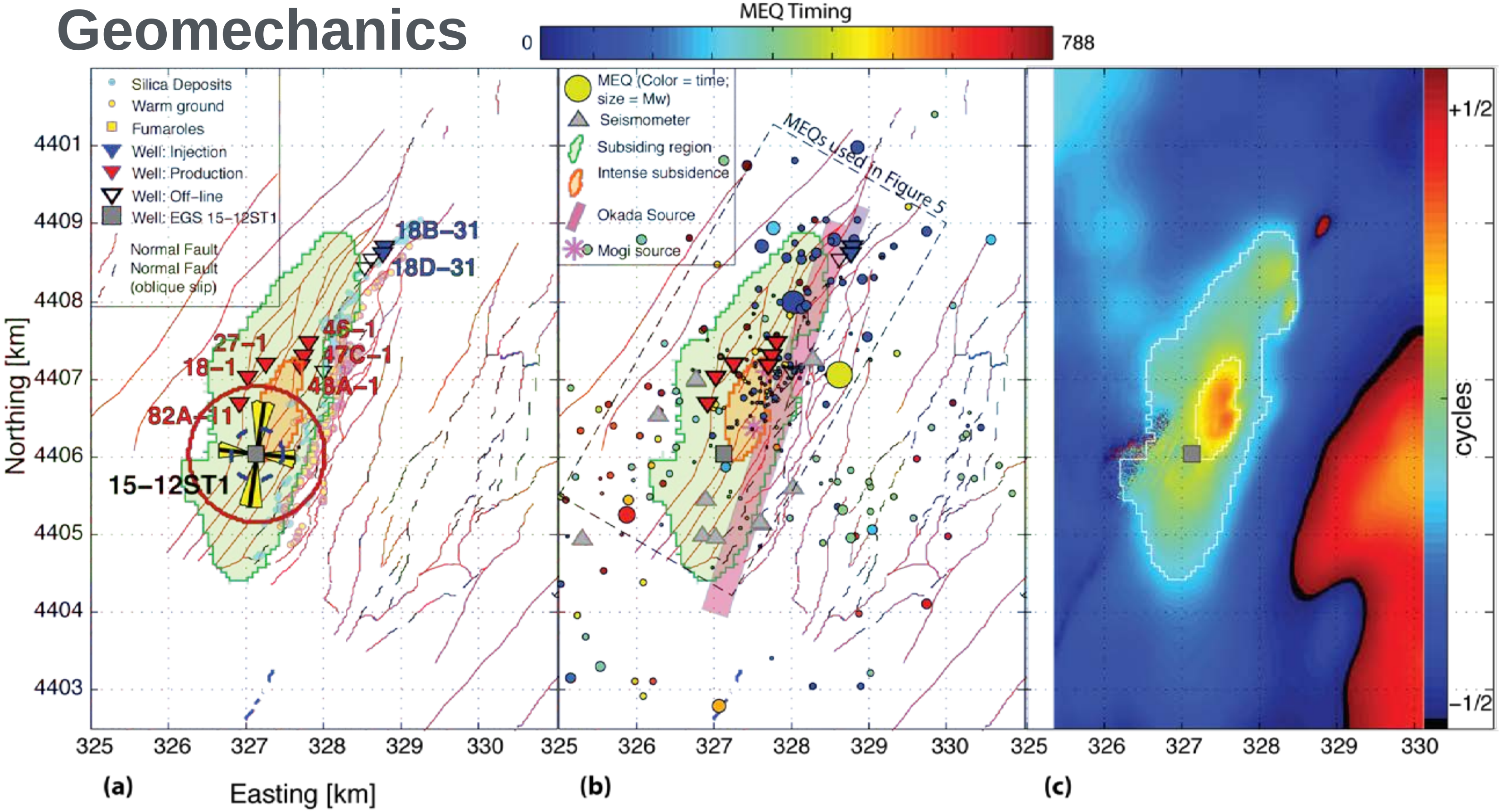
- Previous production at Brady displays associated seismicity and clearly defined surface deformation.
  - Assemble comprehensive dataset of historical seismicity and surface deformation.
  - Develop integrated geology and geomechanics model using FEM model.
  - Model link between injection/production, pore pressure, and associated deformation/seismicity.
  - Estimate stimulation volume and fluid flow from EGS using seismicity and surface deformation.
  - Provide procedure/toolkit to industry.

Team:

Surface deformation and seismic: Feigl, Mellors, Foxall
Geology, geomechanics: Davatzes, Wang (Ali)
Integration and management: Davatzes

Scientific/Technical Approach: Impulse & Response

Geology Geomechanics | MEQ | Surface Deformation



***Fault map**: Faulds et al., 2012*
***Hydrothermal**: Coolbaugh et al., 2004*
***Stress:** Moos et al., 2011 (un-published)*

***MEQ Catalog**: LBNL*

***SAR**: TerraSAR-X*
***InSAR**: GiPhT*

Scientific/Technical Approach: Impulse & Response Time Series

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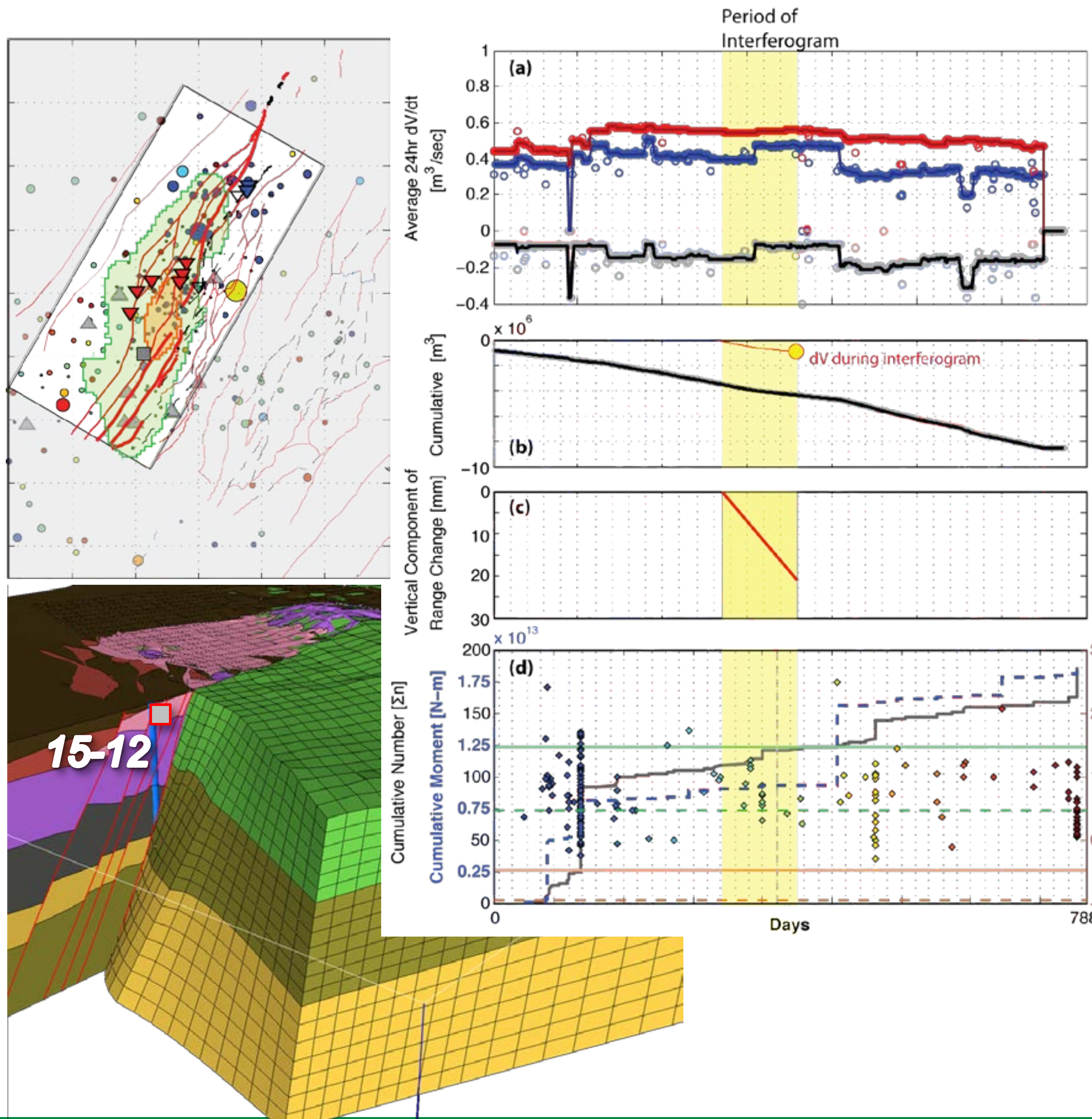
- Fluid injection is coupled to deformation
- Impulse:
  - Injection/production history
- Response:
  - InSAR: Surface deformation field
  - MEQs: Coulomb Friction Failure criterion
- Process is modeled analytically and in FEM (COMSOL & ABAQUS)
  - Geology, Structure
  - Physical Properties
  - Boundary Stresses



Scientific/Technical Approach: Impulse & Response

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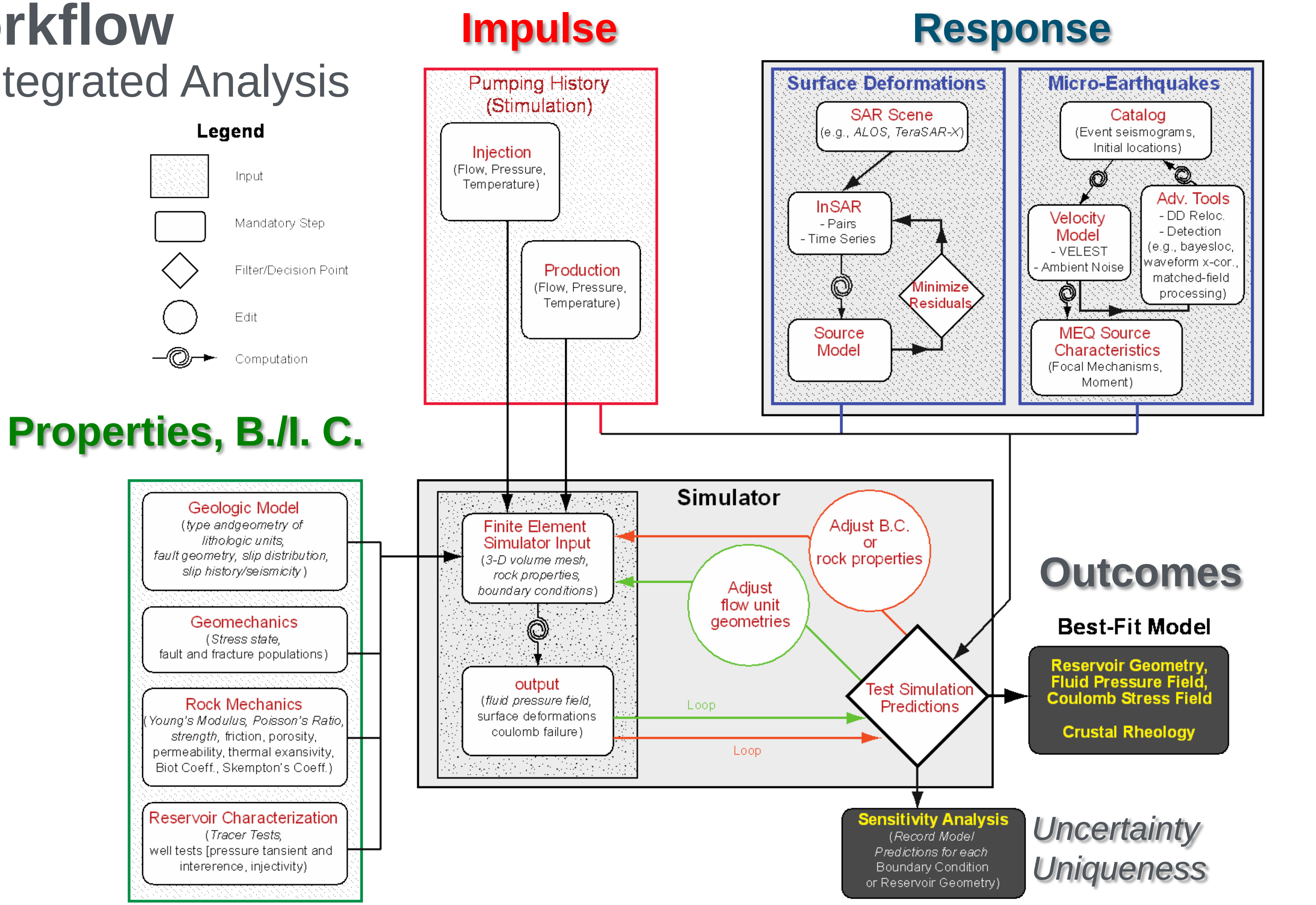
Workflow
of Integrated Analysis



Summary planned and actual Accomplishments, Results and Progress

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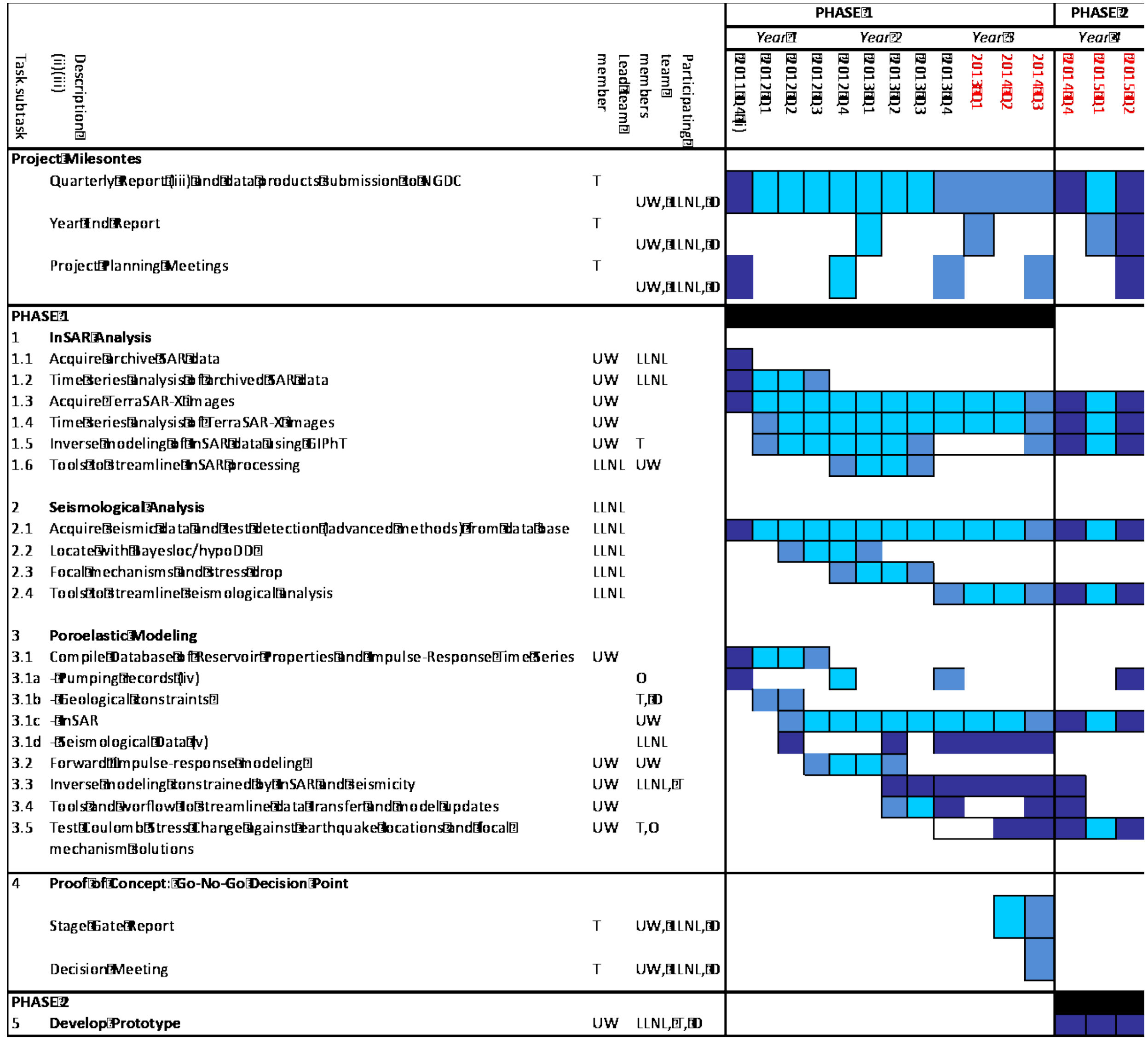
- Planned activities are summarized in the Gantt Chart
- Project timeline has been extended to match delay in Brady EGS Demonstration Project
  (NCE = 3 Quarters)
- Key data and initial analyses in place for monitoring EGS demonstration:
  - rapid acquisition of TerraSAR-X scenes
  - Improved seismic velocity model



Notes: T = Temple, O = ORMAT, UW = University of Wisconsin-Madison, LLNL = Lawrence Livermore National Lab

Summary planned and actual Accomplishments, Results and Progress

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Original Planned Milestone/ Technical Accomplishment	Actual Milestone/Technical Accomplishment	Date Completed
Monitor EGS Stimulation BR15-12ST1	NCE Sought 2012-10 (obtained 2013-03)	Planned 2013-03/04
Hire PostDoc	delayed	2013-04
Obtain/Analyze Archival InSAR	→	2012-12
TerraSAR-X Acquisition	→	2011-11 to now
MEQ data and station history	→	2011-11 to now
	Velocity Model: VALEST & Ambient Noise	2013-02
	GPS Monitoring (Kremer, UNR)	2012-01 to now
Team Database	→	2012-01 (updating)
Definition of data formats, reference frame & Identification of software tools		2012-03
Pumping Records	2004 through 2011-10 obtained	2012-09
Integration of Geologic Data	→	2012-11
Analysis Workflow	→	2012-12
Geologic Model in EarthVision	→	2012-07
Initial Meshing of Geologic Model	→	2012-09
Project Workshop	→	2012-12
Initial integrated examination of Geology, InSAR, MEQ and Pumping		2013-01
Submit initial interferograms NGDS	→	2013-03

Summary Slide:

Table of Key Technical Accomplishments

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	FY2012 Milestone/Tech Accom	FY2013 Milestone/Tech Accom
Analysis of Surface Deformation	- Acquired ALOS scenes - Acquisition of TerraSAR-X scenes - GPS monitoring (*added task*)	- Continue TerraSAR-X acquisition - Monitor stimulation of 15-12ST1
Result (status)	*- Initial models of subsidence in vicinity of production from 1992 to present: ~20 years* *- GPS data acquisition since 2012*	*- Time series analysis of InSAR*
Analysis of Seismicity	- Acquired MEQ catalog from LBNL - Velocity Model (*added task*)	- Complete updated velocity model - Begin advanced analysis
Result	*- Catalog background* *- Initial locations and moment release* *- Velocity model (VELEST & Ambient noise)*	*- Continue to refine velocity model as new MEQs are aquired* *- Advanced analysis on-going*
Geological Database	- EGS project analysis - Acquired and formatted production/injection data	- Expand pumping records pre 2004 - Continue acquisition of new pumping data including stimulation
Result	*- Geologic & Geomechanical model (formations, fractures, stress, phys. prop.)*	*- Integrated pumping record*
Analysis Framework	- Established Analysis Workflow - Established data standards	Establish workflow to enable "semi-automation" of joint analysis of InSAR and MEQ via poroelastic modeling
Result	*- Initial time series of Impulse-Response* *- Established relative of aseismic and seismic processes to pumping activity*	*- Build Workflow tools for analysis* *- Robust time series comparison*

Technical Results:
Spatial Correspondence (88 Days)

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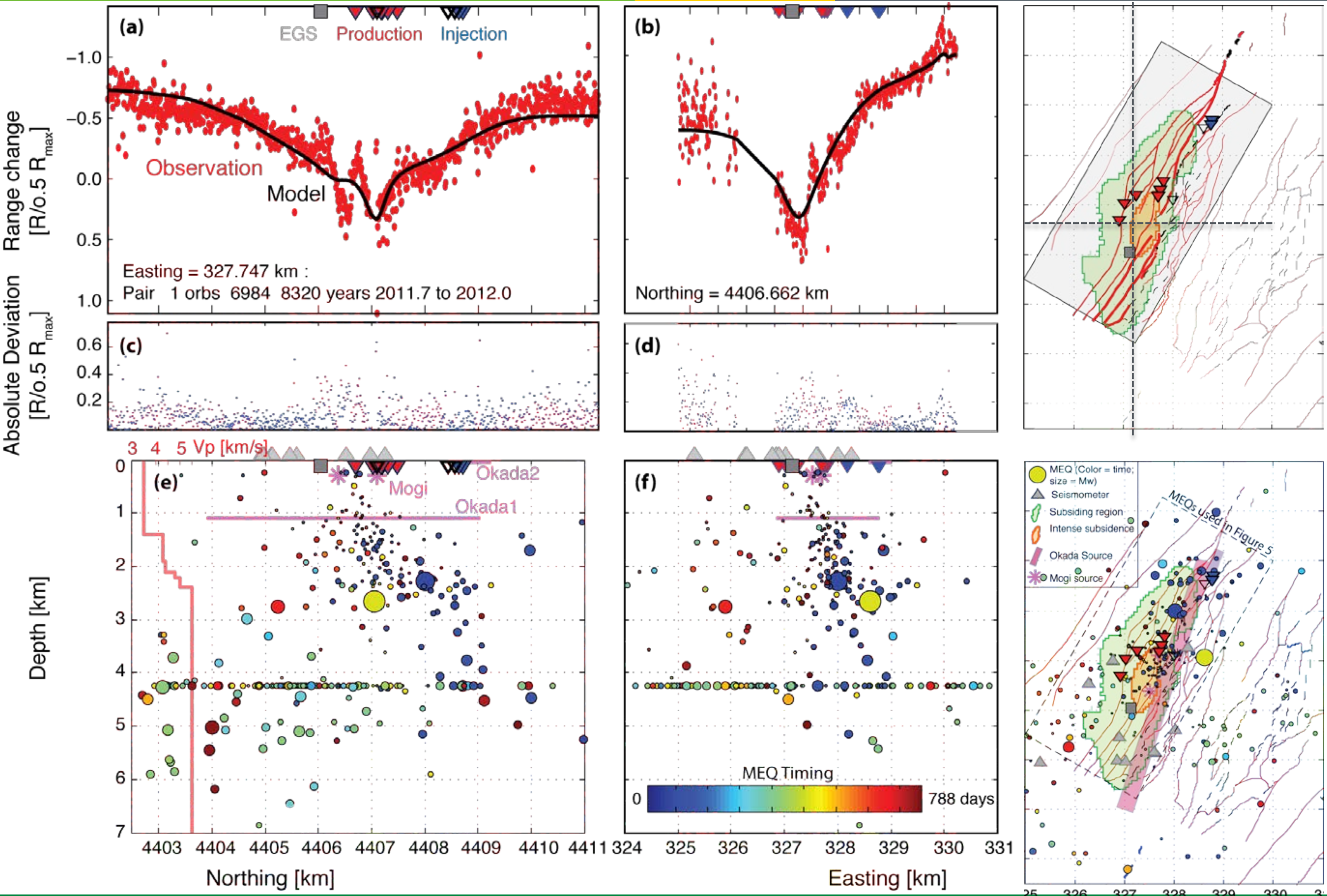

Summary Technical Results: Findings and Implications

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Impulse and Response:

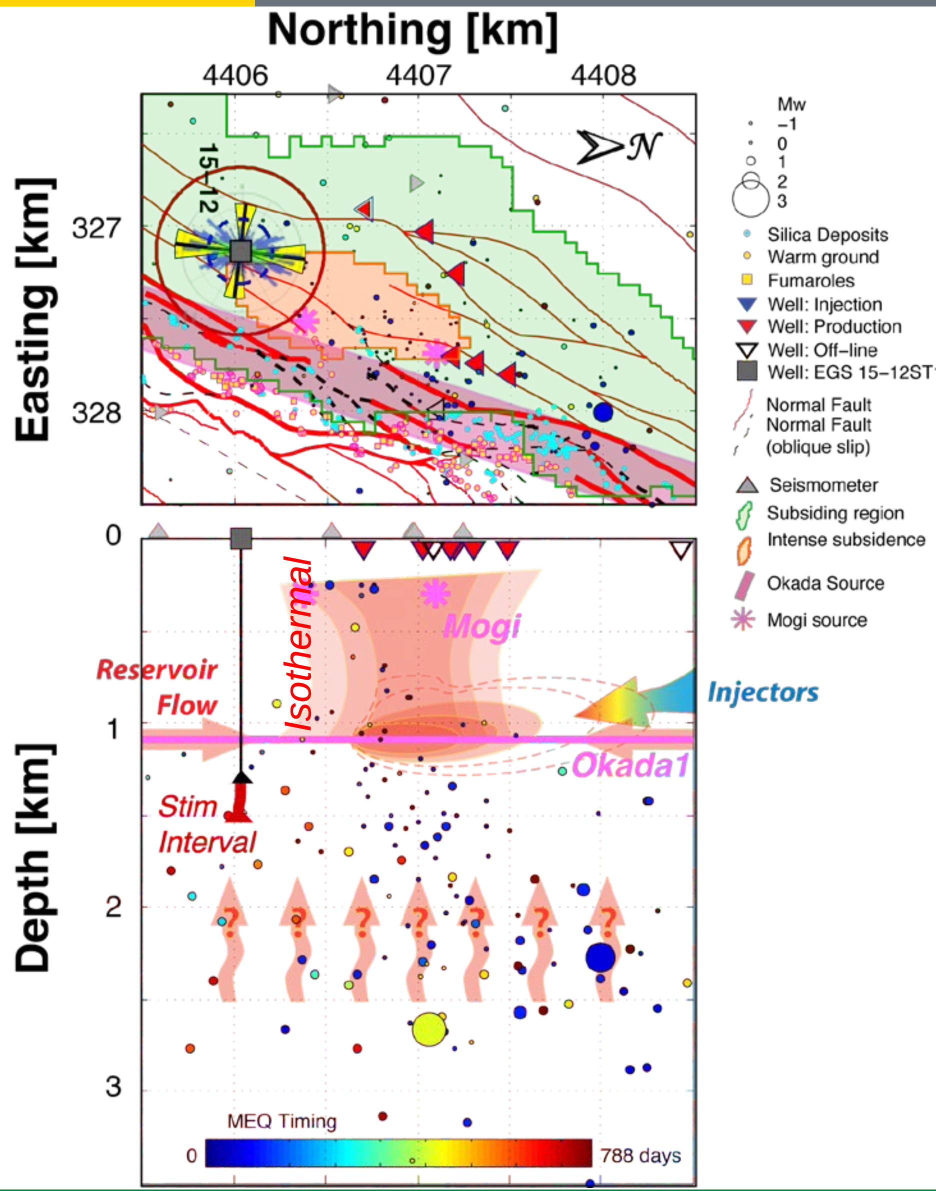
- Deformation is highly episodic (both surface displacements and MEQ)
- Most deformation is aseismic, and energy release through MEQs is too small to significantly contribute to the surface deformations
- The most intense Surface Deformations and MEQ activity are not co-located
- MEQs are generally below the reservoir as inferred from wells and from modeling of surface deformations, but outside the region of maximum subsidence
- Both effective normal stress decrease due to injection *and* solid stress change due to contraction caused by production induce MEQs, thus confusing their association with the permeable fracture network.

Brady Reservoir:

- The region of active pumping represents only a narrow vertical conduit of enhanced permeability tapping a deeper, extensive fault-hosted reservoir
- The orientation of the subsidence zone and elastic deformation source relative to the average fault strike suggest that multiple fault segments are combine to host the reservoir and the clear locus is the common bend (and associated branching) of these fault segments.
- Differences between modeled volume change at depth and cumulative volume extraction suggest a significant component of flow into the reservoir to support production.

Impact of Technical Results: Brady Reservoir and EGS

- Deformation sources consistent with upwelling of hot water evidenced by isothermal temperature profiles (Shevenell et al., 2012) along fracture zone localized at bend in Brady Fault
- Recharge preferentially along fault strike and consistent with SHmax direction
- *Well 15-12ST1 is well-positioned to connect through hot, untapped rock to the current set of producing wells*



Future Directions

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Milestone or Go/No-Go	Status & Expected Completion Date
Task 1: InSAR: obtain scenes from WINSAR archive	Complete: 2012, Q4
Task 1: InSAR: software tools to streamline analysis	Started (2014, Q2)
Task 1: InSAR: complete analysis of archived	Initial analysis of archived pairs: 2013, Q1 (2014, Q2): time series analysis
Task 1: InSAR: Analysis of TerraSAR-X scenes	Initial analysis of selected pairs: 2013, Q1 (2015, Q3): time series analysis
Task 2: MEQ: catalog of events with error estimates	Started (2014, Q2)
Task 2: MEQ: software tools to streamline analysis	Started (2014, Q2)
Monitor EGS Experiment	2013, Q3
Task 3: Modeling: Complete geologic and reservoir database	Database complete: 2012, Q4
Task 3: Modeling: software tools to streamline analysis	Started (2014, Q2)
Task 4: Phase 1 Report; Go/No-Go Decision	(2014, Q3)
Task 5: Brady Prototype passed to ORMAT	(2016, Q1)

Mandatory Summary Slide:
Key Attributes of MEQ and InSAR Study

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- The *Reservoir Monitoring using InSAR and MEQ* project:
  - Strong research team and dedicated field operator
  - Benefits from a 20-year record of reservoir deformation in the shallow subsurface (<1-2 km) and pumping records
  - Is integrated with an EGS demonstration project
  - Uses multiple mechanisms for monitoring fluid migration, change in stress, and deformation during EGS reservoir management including pre-, syn-, and post- stimulation behavior of the stimulated volume
  - Independently evaluates the relationship between MEQ and stimulation
  - Provides a database documenting these effects in response to both EGS stimulation and reservoir management practice
  - Provides rapid development of technology to monitor and guide stimulation during development of an EGS including evaluation of the longevity of the EGS flow pathways
  - Provides an integrated reservoir model with higher resolution than can be achieved from monitoring well responses alone
  - Ensures technology transfer is ensured by development of a prototype at the operating Brady’s geothermal field & open-source code development

Project Management

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Timeline:

Planned Start Date	Planned End Date	Actual Start Date	Actual /Est. End Date
10/1/11	9/30/14	4/1/12	12/31/15

Budget:

Federal Share	Cost Share	Planned Expenses to Date	Actual Expenses to Date	Value of Work Completed to Date	Funding needed to Complete Work
$1,463,000	$77,000	$645,000	$298,000	$366,500	$1,242,000

End of FY2013-Q1

- Management Activities and Approaches:
  - Annual Science Team – Industry Workshop (1st in December 2012)
  - Twice-Monthly technical conference calls (including participation by the industry partner, ORMAT, and coordination with EGS Demonstration)
  - Project organization through formal Work Flow
    - Established common data formats, reference frame, metadata
    - Hierarchy of identified software tools including import/export filters, etc.
    - Cloud project database

– Established NCE to sync project timeline with Brady EGS Demonstration

– Once data from the EGS demonstration is available research activity and the spending rate will also increase (facilitated by hiring of PostDoc + Summer research time)

Additional Information: Technical Approach

***Goal:** Map the evolution of the stimulated zone and pore pressure distribution in reservoir during stimulation and production phases of EGS.*

<u>**Measure**</u> history of deformation:

- *Surface*: **S**ynthetic **A**perture **In**terferometric **R**adar (**InSAR**)
- *Subsurface*: Seismicity

<u>**Model**</u> deformation history as ***response*** to ***forcing*** by pumping using poroelasticity to infer:

- Pore pressure field
- Fracture network hosting fluid flow
- Stimulated *vs* persistent flow paths

Develop an integrated set of <u>**software tools**</u> to ***monitor*** the evolution of permeability and fluid flow within an EGS during both the stimulation and production phases