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THMC Modeling of EGS Reservoirs – Continuum through Discontinuum Representations: Capturing Reservoir Stimulation, Evolution and Induced Seismicity

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Chemistry, Reservoir and Integrated Models

Mandatory Overview Slide

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- **Timeline**
  - Project start date: **January 1, 2010**
  - Project end date (3 years): **December 31, 2012**
  - Actual award date: **April 29, 2010**
  - Percent complete: **Just initiated**
- **Budget**
  - Total project funding: **$ 1,602,500**
  - DOE share: **$ 1,113,024**
  - Awardee share (AltaRock): **$ 489,476**
  - Funding received [FY09]: **$ 0**
  - Funding committed [FY10]: **$ 406,466**
- **Partners**
  - LBNL
  - AltaRock
- Barriers [Overleaf]

Mandatory Overview Slide [Barriers]

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- *Barrier F:* "*Modeling – Insufficient modeling and validation capabilities to effectively couple fluid flow, geochemistry, and thermal-mechanical phenomena for:*
  - *(1) stimulation prediction and*
  - *(2) reservoir simulation.*"[Tables 4.8 and 4.9]
- *Barrier B* (site characterization),
- *Barrier G* (stimulation technology) to "*mitigate reservoir short –circuiting,*" and
- *Barrier M:* "*Improve[d] understanding of rock-fluid geochemistry for scale and dissolution prediction*" both during "*stimulation and management of the created reservoir*" and in "*maintaining fluid flow and reservoir lifetime*" [Table 4.29 in GTP-MYRDD]. This includes both managing reservoir productivity through "*keeping flow paths open*", but also "*managing induced seismicity*" [Table 4.30 in GTP-MYRDD] through the determination of influence of chemistry on the slip and seismic attributes of rupturing fractures.
- *New GTP Goals: "Model the reservoir conductivity at an EGS system demonstration by 2011."*

Relevance/Impact of Research [1]

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Towards the routine development of long-lived, high-volume, low-impedance and high-heat-transfer-area reservoirs at-will and at-depth.

Develop a thorough understanding of complex THMC interactions through synthesis, modeling and verification:

- [Synthesis] Understand key modes of porosity, permeability evolution and the generation of reactive surface area, e.g.:
  - (i) mechanical rupture, concomitant dilation and the generation of flow-occluding wear products where dilation is thwarted;
  - (ii) healing and sealing of fractures by mechanically-mediated processes of stress-enhanced dissolution (pressures solution) and sub-critical crack growth; and etching or infill of fractures by free-face dissolution or precipitation.

Relevance/Impact of Research [2]

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Develop a thorough understanding of complex THMC interactions through synthesis, modeling and verification:

- [Modeling] Develop distributed parameter models for upscaling in time and space:
  - **Develop discontinuum models with relic fractures** capable of accommodating multiple modes of extensional and shear failure and the creation of new fracture-surface area including dilation, block translations and rotations. Such models are key in adequately representing stimulation through long-term production where aseismic and seismic rupture may be followed through rate-state evolution. We will develop a model linking the mechanical discontinuum code PFC3D to TOUGHREACT.
  - **Improve continuum representations of these coupled THMC behaviors** capable of more efficiently representing post-stimulation evolution of the reservoir through production. We will refine a model linking the mechanical continuum code FLAC3D to TOUGHREACT.
  - **Examine the relative strength, sequence and timing of the various THMC effects** in controlling the evolution of EGS reservoirs from stimulation through production to abandonment including the role of heterogeneities in either promoting or frustrating thermal sweeps and in stemming the propensity for short-circuiting.

Relevance/Impact of Research [3]

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Develop a thorough understanding of complex THMC interactions through synthesis, modeling and verification:

- [Verification] Demonstrate the effectiveness of these models against evolving datasets from EGS demonstration projects both currently (Soultz and Geysers) and newly in progress (Newberry Volcano).

- [Education] the next generation of geothermal engineers and scientists through integration of undergraduate and graduate scholars in science and in engineering in research and *via* the GEYSER initiative.

Scientific/Technical Approach [1]

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Approach

- Critically examine key THMC process couplings
- Extend distributed parameter reactive-chemical models
- Develop stimulation models (discontinuum)
- Extend coupled production models (continuum)
- Understand performance of past and new EGS reservoirs
- Educate the next generation of geothermal engineers/scientists

Progress

- Progress to milestones: Recently initiated

Go/No-Go Decision Points

- **Close of Year 1:** No-Go if change in permeability predicted from M or C models is within 80% of prediction using MC models.
- **Close of Year 2:** No-Go if process interactions suggest that existing independent THC or THM models can predict permeability evolution within 80% of predictions using THMC.

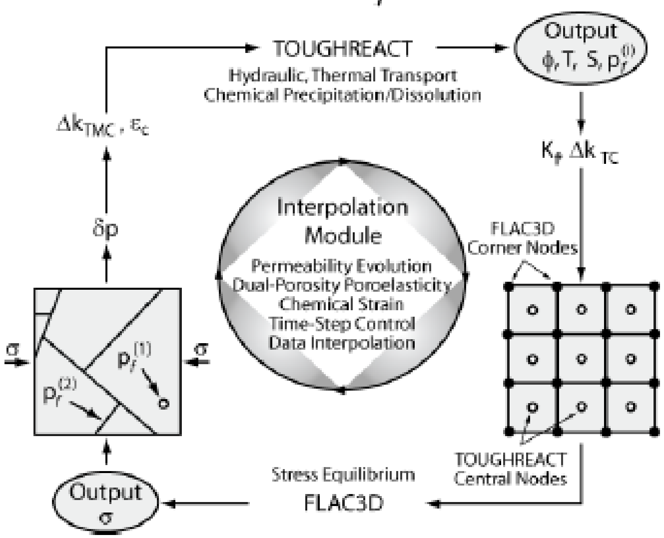
Coupled THMC Modeling

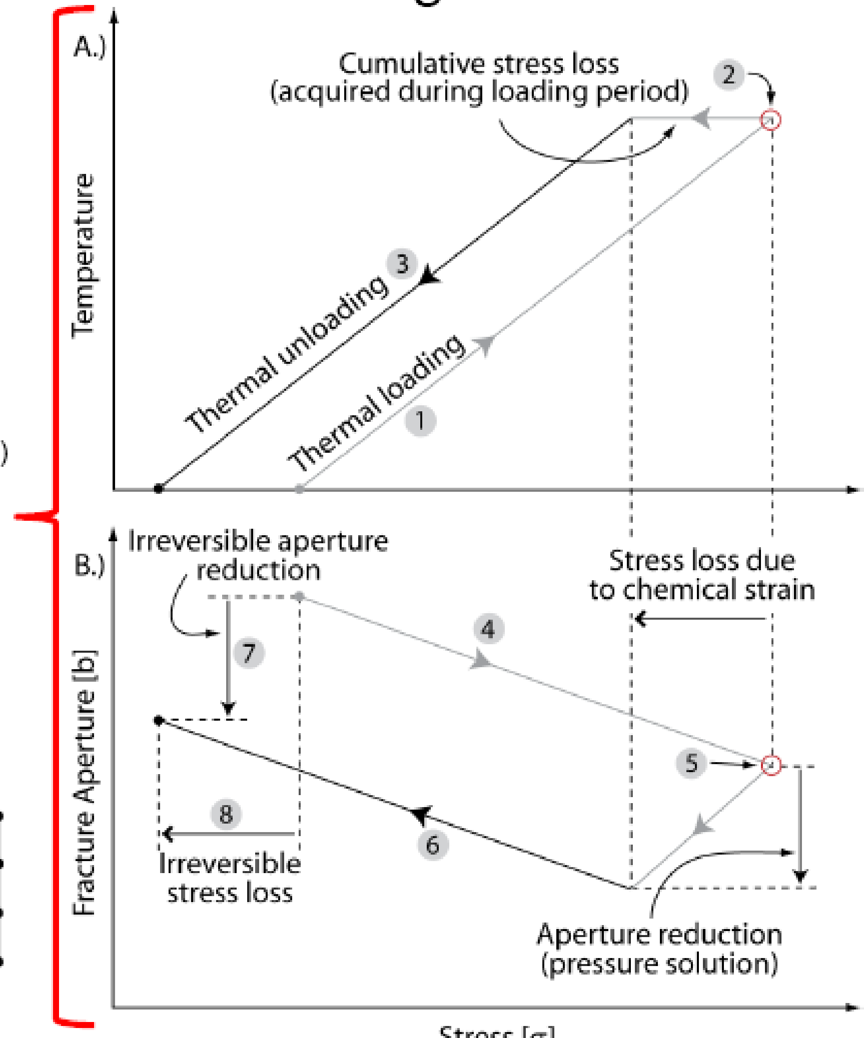
- **TOUGHREACT (THC)** – Accommodates non-isothermal, multi-component phase equilibria, pressure diffusion, multi-phase hydrologic transport, and chemical precipitation/dissolution (transient mass/energy balance)

$$\frac{\partial M}{\partial t} = -\nabla \cdot \mathbf{F} + q$$

- **FLAC3D (M)** – Mechanical constitutive relations (force equilibrium, capable of THM)

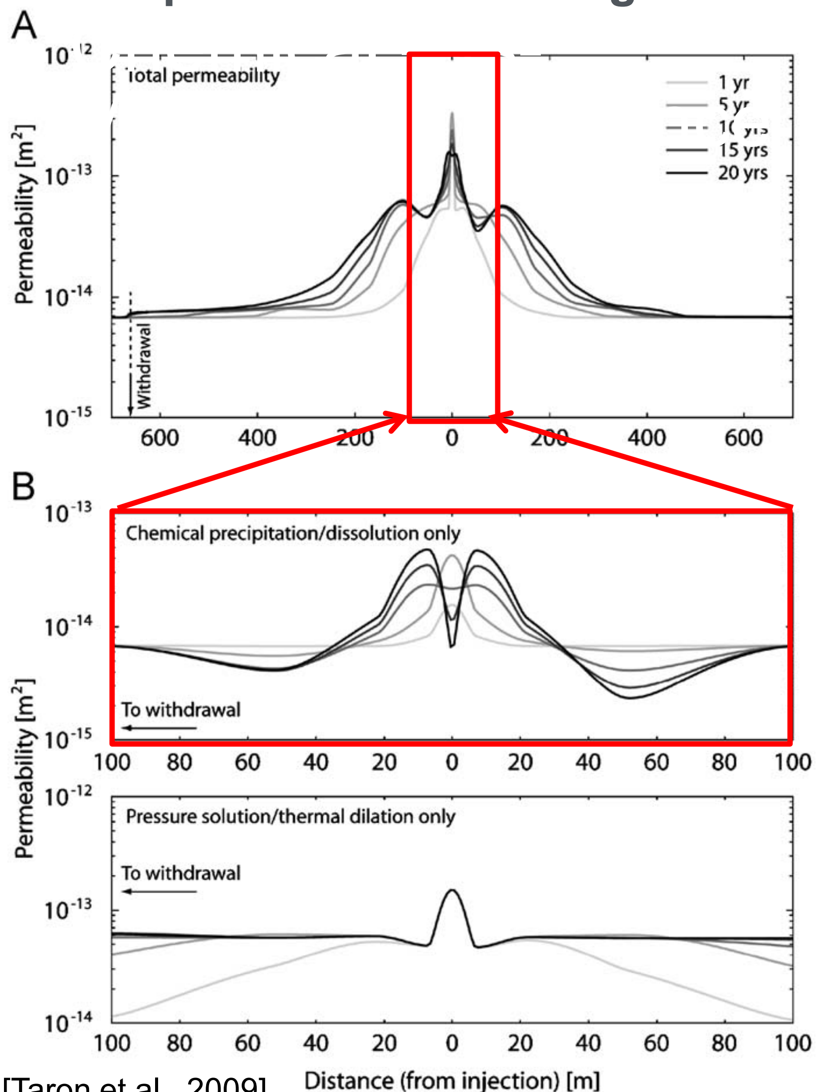
$$\nabla \cdot \boldsymbol{\sigma}^T = -\rho \mathbf{b}$$



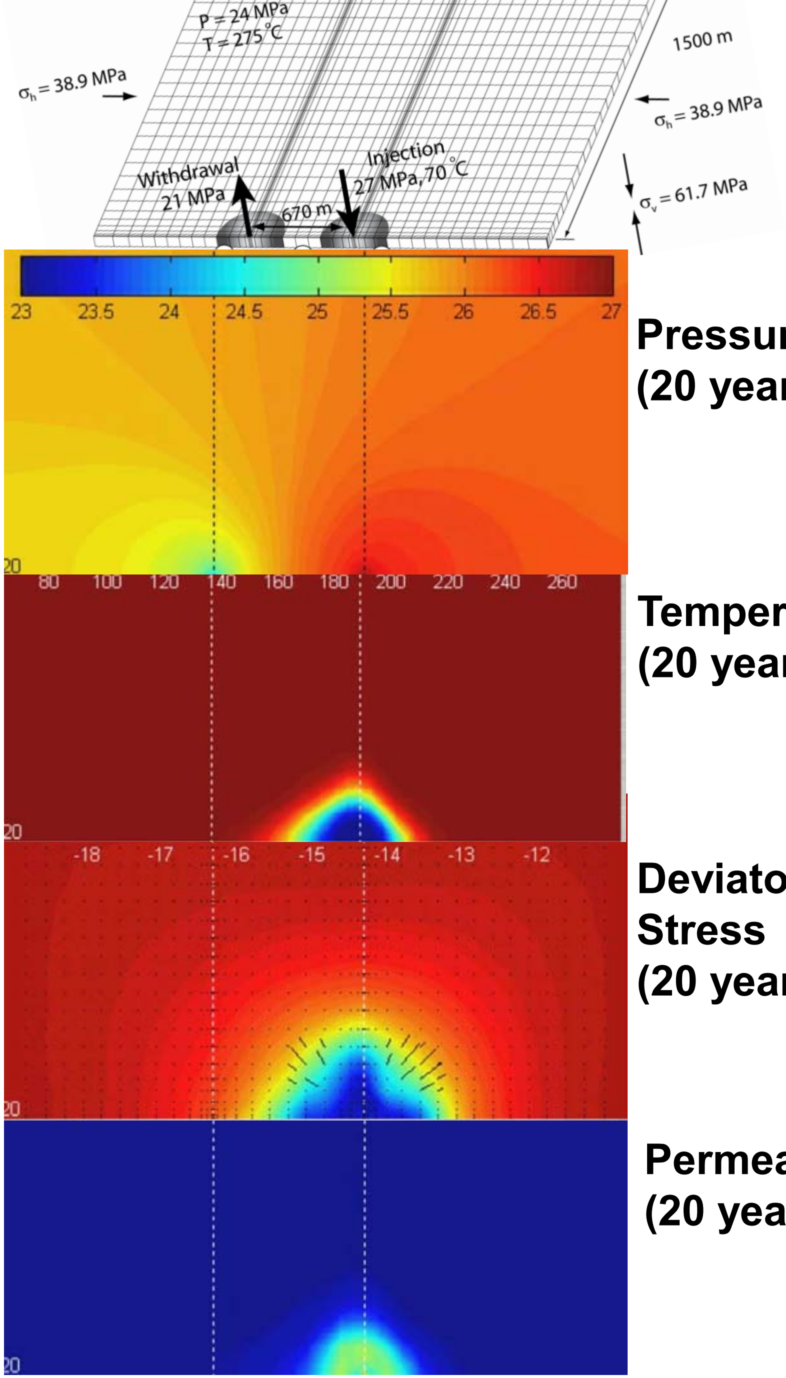


[Taron et al., 2009]

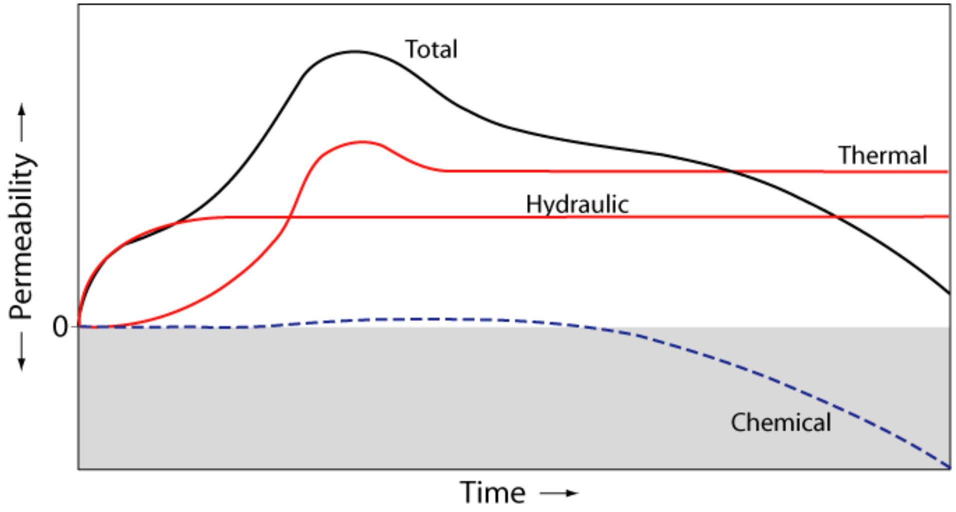
Coupled THMC Modeling

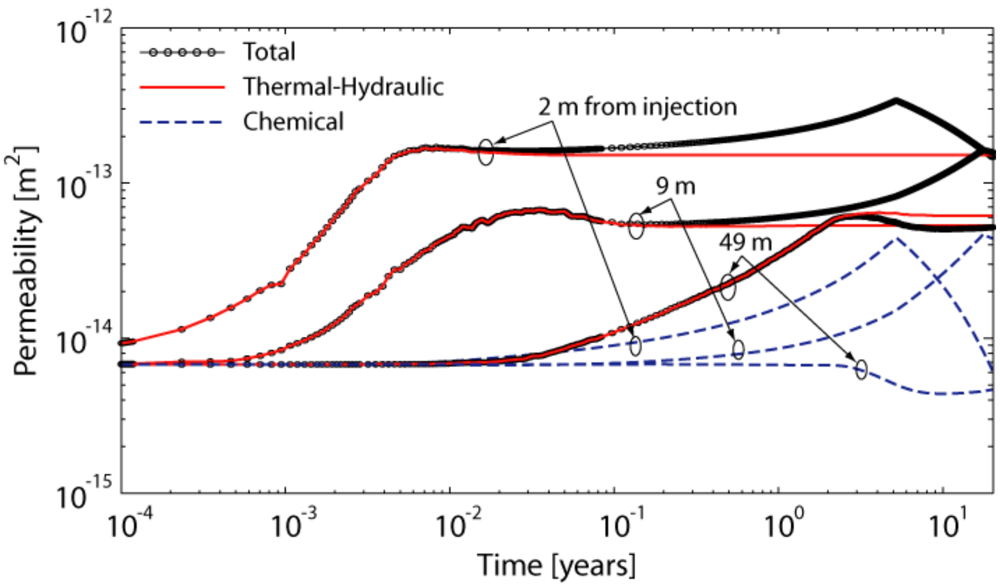


[Taron et al., 2009]



Scientific/Technical Approach [4]





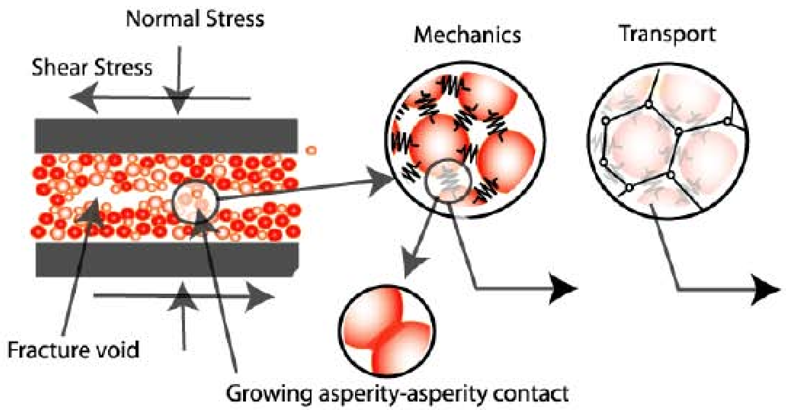
Timescales and Characteristic Times

- Thermo-hydraulic processes combined in this model.
- Onset of chemical permeability change a longer time-scale process.
- Sharp onset of chemical change due to complete dissolution of all calcite in veins (Coso analog)

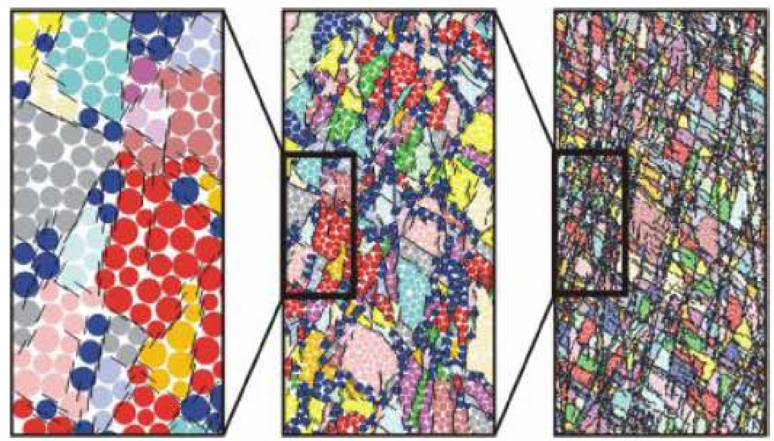
Scientific/Technical Approach [5]

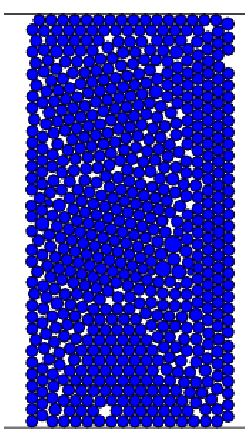
Granular Models for Synthetic Rock Masses

Micro-Model

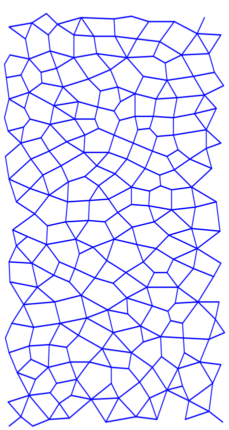


Nested Structured Model





Solid sample



Fluid network

Permeability distribution

Science questions:

Approaches to represent the complex failure and deformation response of structured media, e.g.:

1. Mechanisms of chemical compaction
2. Styles of failure
3. Levels of induced seismicity
4. Healing rates
5. Stress-mediated reaction rates
6. Feedbacks between processes
7. ………………

Accomplishments, Expected Outcomes and Progress

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Accomplishments So Far

- As noted

Additional Activities Planned – Education

- Educating the next generation of geothermal engineers and scientists
- Combined <u>**G**</u>raduate/Undergraduate <u>**E**</u>ducation in <u>**S**</u>ustainable <u>**S**</u>ubsurface <u>**E**</u>nergy <u>**R**</u>ecovery (<u>**GEYSER**</u>)
  - CAUSE: Two semester undergraduate research course with travel [Geysers (California, 2000), Nesjavellir and Svartsengi (Iceland, 2003) and the now abandoned Rosemanowes (UK, 2003) geothermal sites]:

    http://www.ems.psu.edu/~elsworth/courses/cause2003/index.html
  - Integrated design class for M.S. students http://www.ems.psu.edu/~elsworth/courses/egee580/index.html

Project Management/Coordination

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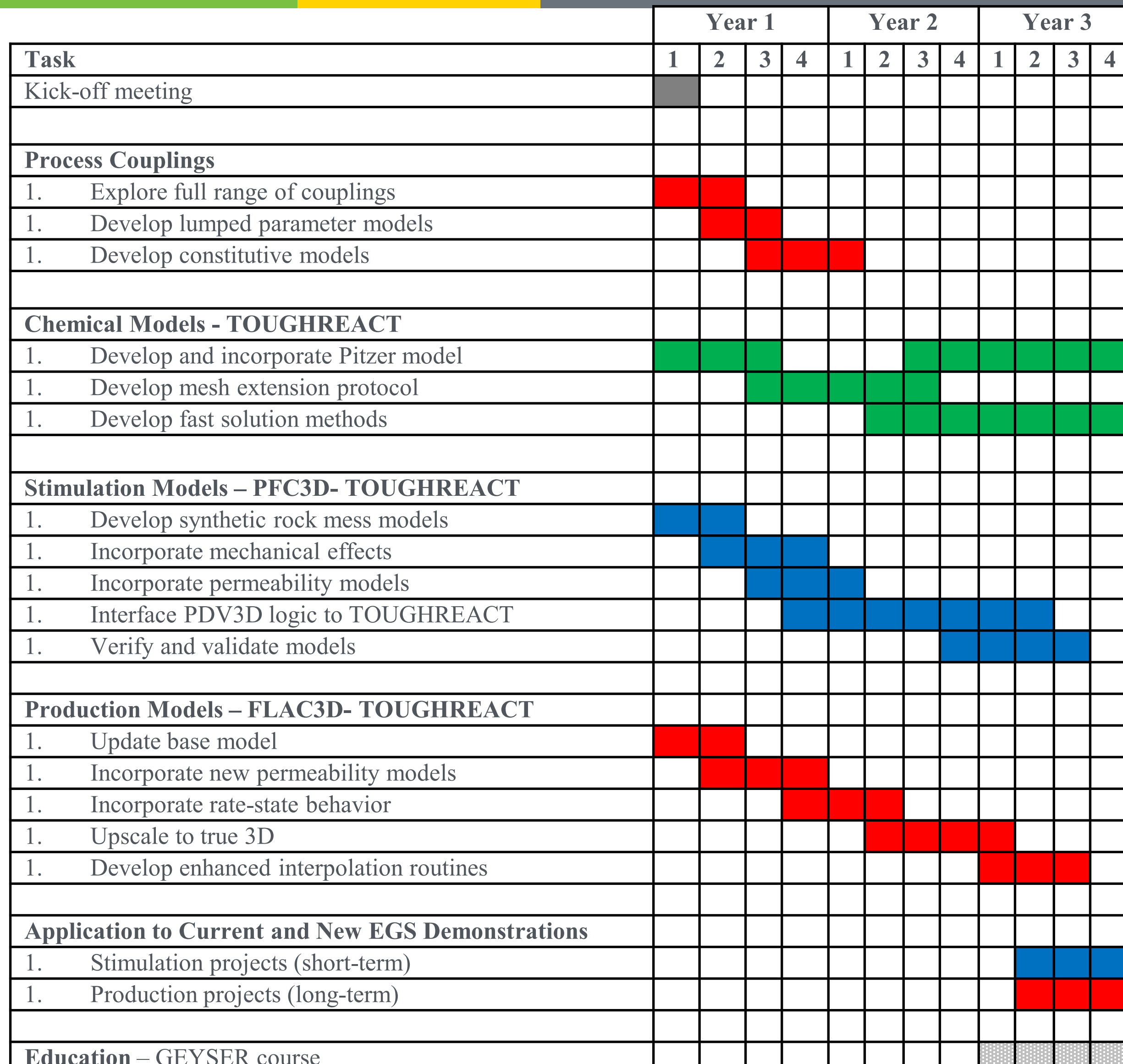
Personnel

PSU
- Elsworth
- Taron
- Student 1
- Student 2

LBNL
- Sonnenthal

AltaRock
- Various



Future Directions

As Previously Defined

- Critically examine key THMC process couplings
- Extend distributed parameter reactive-chemical models
- Develop stimulation models (discontinuum)
- Extend coupled production models (continuum)
- Understand performance of past and new EGS reservoirs
- Educate the next generation of geothermal engineers/scientists

Mandatory Summary Slide

- **Develop models to accommodate multiple modes of porosity, permeability and strength evolution and the generation of reactive surface area.**
- **Develop discontinuum models with relic fractures capable of representing stimulation.** Such models are key in adequately representing stimulation through long-term production including aseismic and seismic rupture.
- **Improve continuum representations of these coupled THMC behaviors** capable of more efficiently representing post-stimulation evolution of reservoir production.
- **Examine the relative strength, sequence and timing of the various THMC effects** in controlling the evolution of EGS reservoirs from stimulation through production to abandonment including the role of heterogeneities in either promoting or frustrating thermal sweeps and in stemming the propensity for short-circuiting.
- **Demonstrate the effectiveness of these models against evolving datasets** from EGS demonstration projects both currently and newly in progress (Geysers and Newberry Volcano).
- **Educate the next generation of geothermal engineers and scientists** through integration of undergraduate and graduate scholars in science and engineering through travel, data gathering and research via the GEYSER initiative.

Supplemental Slides

Related Publications

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Copies Available at: [www.ems.psu.edu/~elsworth/publications/pubs.htm]

1. Taron, J., Elsworth, D., Kolditz, O. (2010) Evolution of permeability in fracture networks: geophysical and geochemical effects in enhanced geothermal systems. Submitted for publication. Trans. Geotherm. Res. Council.
2. Lee, D.S., Elsworth, D., Yasuhara, H., Weaver, J., Rickman, R. (2010) Experiment and modeling to evaluate the effect s of proppant-pack diagenesis on fracture treatments. Submitted for publication. J. Petrol. Sci. and Eng. 26 pp.
3. Taron, J., Elsworth, D. (2009) Roles and timing of onset of various thermal-hydrologic-mechanical-chemical process couplings in EGS reservoirs. Trans. Geotherm. Res. Council.
4. Taron, J. and Elsworth, D. (2010) Constraints on compaction rate and equilibrium in the pressure solution creep of quartz aggregates and fractures: controls of aqueous concentration. Submitted for publication. J. Geophys,. Res. 35 pp.
5. Niemeijer, A.R., Marone, C., and Elsworth, D. (2010) Fabric induced weakness of tectonic faults. Geophys. Res. Lett., 37, L03304, doi:10.1029/2009GL041689.
6. Elsworth, D. and Yasuhara, H. (2010) Mechanical and transport constitutive models for fractures subject to dissolution and precipitation. In press. Int. J. Num. Meth. Geomechs. Vol. 34, pp. 533-549. Doi:10.1002/nag.831
7. Taron, J. Elsworth, D., Min, K.-B. (2009) Numerical simulation of thermal-hydrologic-mechanical-chemical processes in deformable fractured porous media. Int. J. R. Mechs. Vol. 46, pp. 855-864.
8. Taron, J. and Elsworth, D. (2009) Thermal-hydrologic-mechanical-chemical processes in the evolution of engineered geothermal reservoirs. Int. J. R. Mechs. Vol. 46, pp. 855-864.
9. Min, K.-B., Rutqvist, J., and Elsworth, D. (2009) Chemically- and mechanically-mediated influences on the transport and mechanical characteristics of rock fractures. Int. J. R. Mechs. Vol. 46, No. 1, pp 80-89. doi:10.1016/j.ijrmms.2008.04.002