State of Stress Beyond the Borehole: Predicting reservoir response to injection

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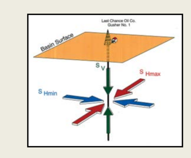
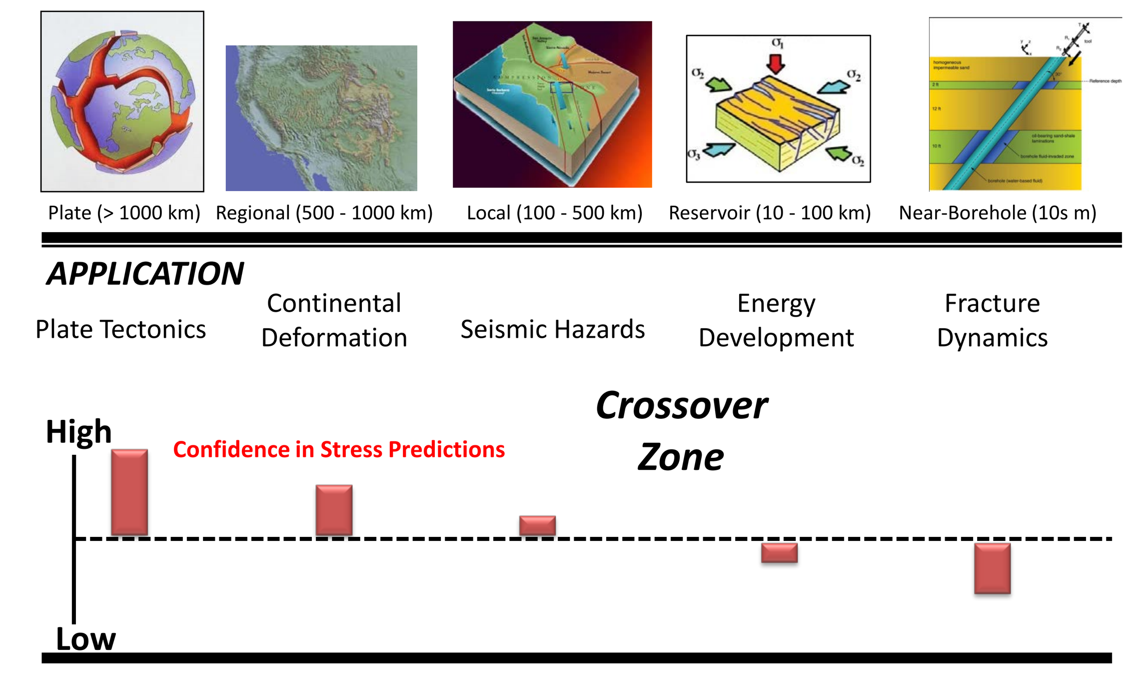
1. Abstract

The state of stress controls all *in-situ* reservoir activities and yet we lack the quantitative means to measure it. This problem is important in light of the fact that the subsurface provides more than 80 percent of the energy used in the United States and serves as a reservoir for geological carbon sequestration, used fuel disposition, and nuclear waste storage. Adaptive control of subsurface fractures and fluid flow is a crosscutting challenge being addressed by the new Department of Energy SubTER Initiative that has the potential to transform subsurface energy production and waste storage strategies.

Our methodology to address the above mentioned matter is based on a novel Advance Multi-Physics Tomographic (AMT) approach for determining the state of stress, thereby facilitating our ability to monitor and control subsurface geomechanical processes. We developed the AMT concept for deriving state-of-stress from integrated density and seismic velocity models and demonstrate the feasibility by applying the AMT approach to synthetic data sets to assess accuracy and resolution of the method as a function of the quality and type of geophysical data. With this method we can produce regional- to basin-scale maps of the background state of stress and identify regions where stresses are changing. Our approach is based on our major advances in the joint inversion of gravity and seismic data to obtain the elastic properties and density for the subsurface; and coupling afterwards the output from this joint-inversion with theoretical model such that strain (and subsequently) stress can be computed. Ultimately we intend to obtain the *differential state of stress* over time to identify and monitor critically stressed faults and evolving regions within the reservoir, and relate them to anthropogenic activities such as fluid/gas injection.



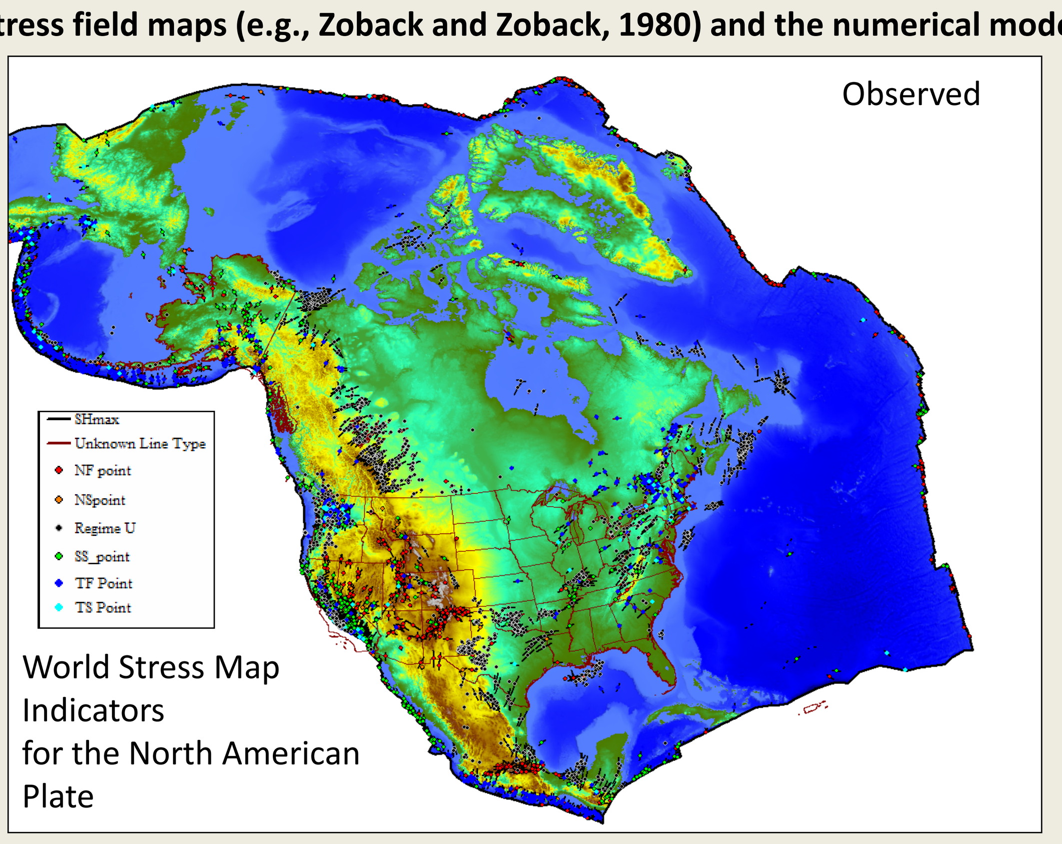
The State of Stress Spectrum



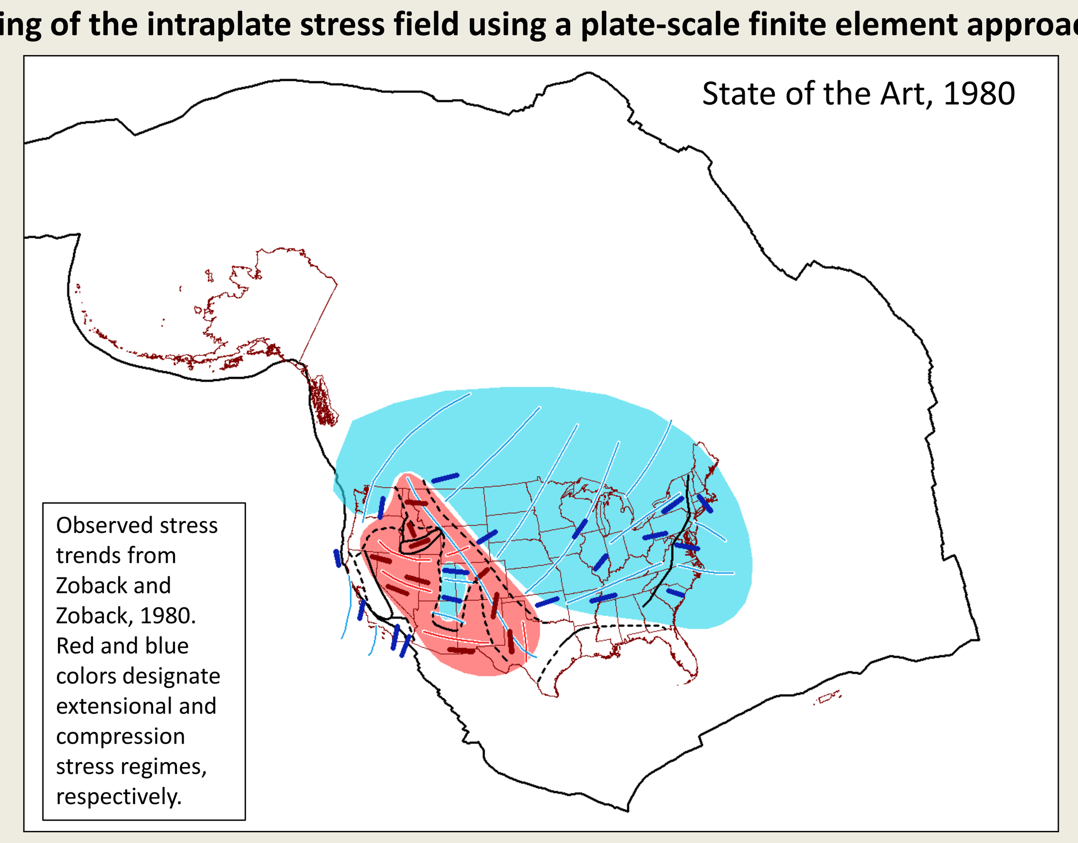
The Need: quantitative knowledge of the full stress tensor

2. Background (Tectonic) Stress State

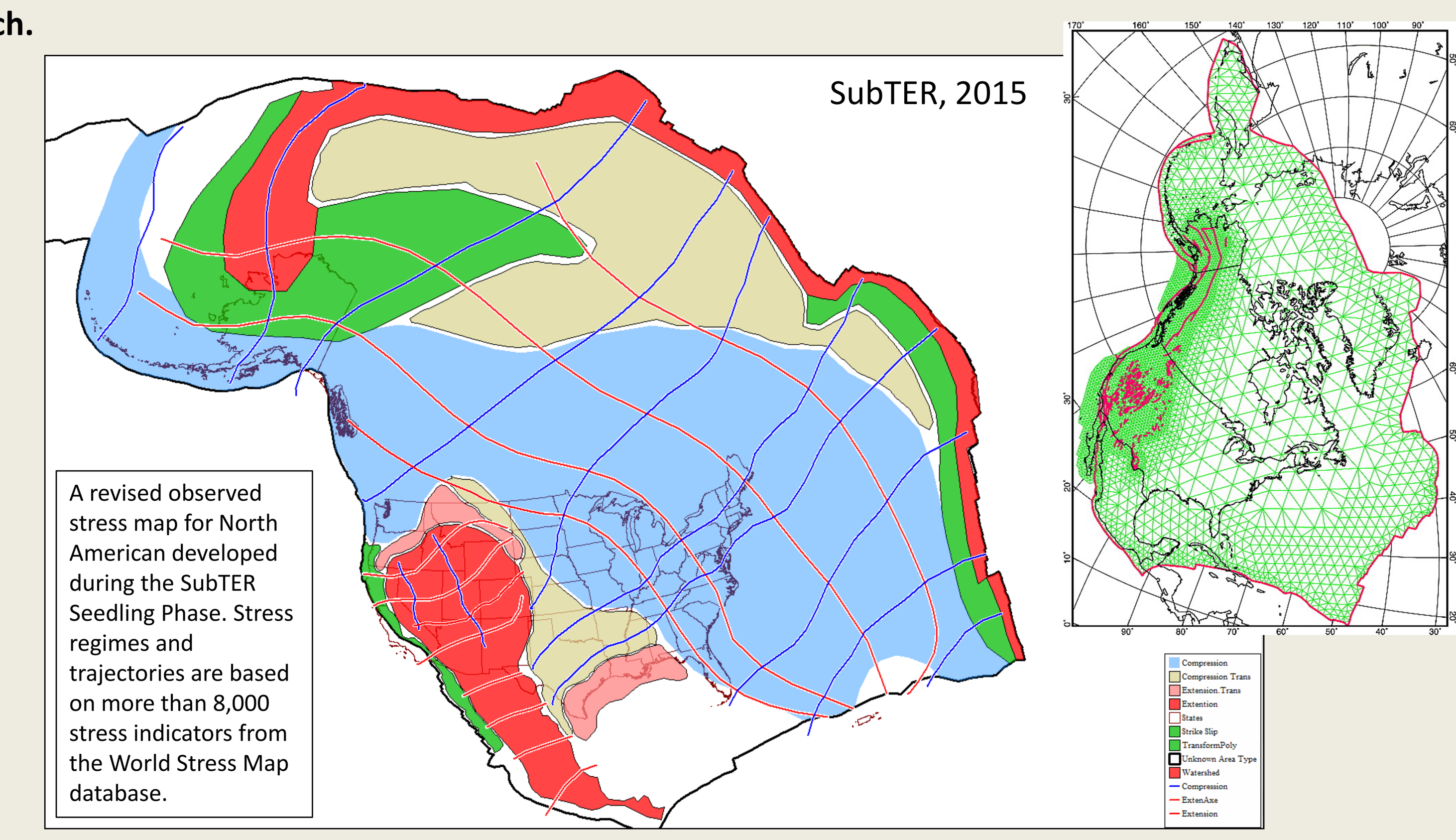
Knowledge of the present-day background (or tectonic) stress is essential for numerous applications in petroleum exploration and production and in civil and mining engineering, such as improving the stability of boreholes and tunnels and enhancing petroleum production through natural or induced fractures. The main source of information about this stress field is the World Stress Map (WSM) Project - a collaboration between academia, industry, and government that is building a comprehensive global database of present-day stress information to better understand the state and source of contemporary tectonic stress in the lithosphere. The WSM has provided key insights into the state of plate-scale and regional stress fields in the earth's crust and revealed that these are primarily controlled by forces exerted at plate boundaries, in particular mid-ocean ridges and continental collision zones. However, comparatively little is known about the state of stress at smaller regional-to-local scales, especially in sedimentary basins where knowledge of the local stress field is critical for improving borehole stability, designing hydraulic fracture stimulations and planning of water-floods. While some sedimentary basins exhibit roughly uniform stress fields (e.g., the Western Canada Basin), many others exhibit numerous small-scale variations in stress orientation (e.g., central North Sea). Local scale stress variations are believed to result from complex far-field forces, geological structures (e.g. diapirs, faults) and mechanical contrasts (e.g. evaporites, overpressured shales). **A key aspect of the SubTER Stress and Induced Seismicity Pillar is the refinement of observed stress field maps (e.g., Zoback and Zoback, 1980) and the numerical modeling of the intraplate stress field using a plate-scale finite element approach.**



World Stress Map Indicators for the North American Plate



Observed stress trends from Zoback and Zoback, 1980. Red and blue colors designate extensional and compression stress regimes, respectively.



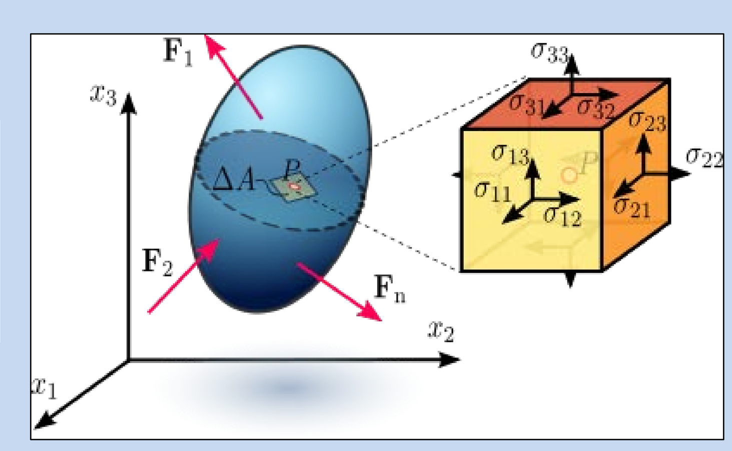
A revised observed stress map for North American developed during the SubTER Seedling Phase. Stress regimes and trajectories are based on more than 8,000 stress indicators from the World Stress Map database.

3. Stress at the Reservoir Scale

Data

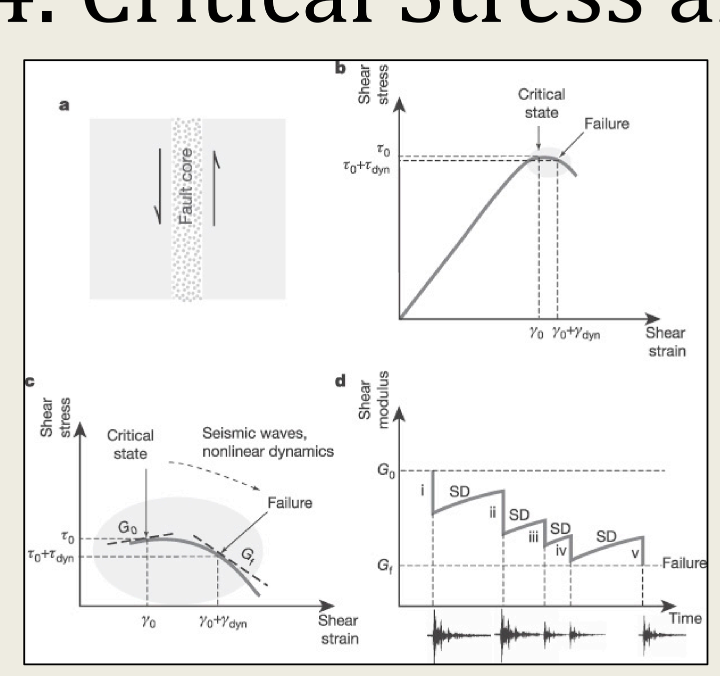
Gravity Seismic → Multi-Physics Joint Inversion → Density & Elastic Moduli → Stress Field from Internal Load + Background Stress Field

= Total Stress Field

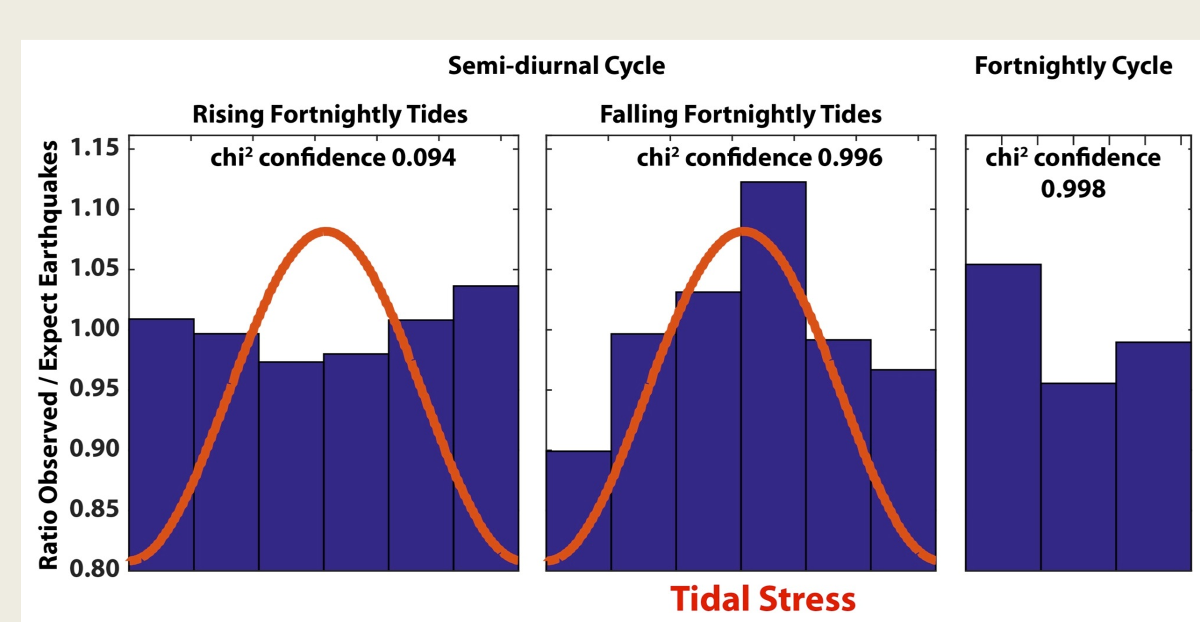


The total stress field is the sum of far-field tectonic stresses (background stress) and stresses due to internal loading on the local, reservoir scale. To obtain the stress field from internal loading, we use a multi-physics joint inversion of gravity and seismic data to obtain density and elastic moduli and use these values to determine stress and strain. An important component of this approach is calculating self-consistent models for density and elastic moduli, which drastically reduces uncertainties for this piece of the stress field. Additionally, we will use point measurements of stress in boreholes to calibrate and validate the contributions of tectonic and internal loading stresses to the full stress tensor.

4. Critical Stress and Faults



Dynamic loading, such as from seismic waves and solid earth tides, can weaken the shear strength of fault core material. If the fault is critically stressed (near failure), this can trigger an earthquake. Therefore, we can infer the presence of critically stressed faults by observing triggered earthquakes. We have shown that we can detect critically stressed faults in an active tectonic region (Parkfield, CA) and are currently analyzing seismicity near Raton, NM and Prague, OK (two regions with induced seismicity) for a similar signal.



Earthquakes preferentially occur at maximum semi diurnal tidal stressing, indicating a weakening of fault core material in critically stressed faults leading to failure (this process is shown in the figure at left).

5. Final product

Our ultimate goal is to develop a field deployable, real time monitoring system of stress measurement and analysis in support of the SubTER stress pillar. The monitoring system is comprised of seismometers, gravimeters and on-site or remote real time analysis capability.

Monitor stress and differential stress, critical stress state → Inform injection processes

Monitor stress and differential stress, critical stress state → Apply to hazard analysis

Our developments have direct application to CO2 sequestration for hazards assessment.

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