Subsurface Stress & Induced Seismicity

Introduction

Knowledge of the subsurface stress state is required to predict and control the growth of hydraulically-induced fractures, re-opening of faults, and induced seismicity potentially associated with subsurface energy production, storage and waste disposal applications. Current capabilities to directly measure or infer the in-situ stress are woefully inadequate. This limitation leads to significant uncertainties and lost opportunities to take advantage of the subsurface for energy production and waste storage, as well as public distrust in the subsurface energy sector.

To guide and optimize sustainable energy strategies while simultaneously reducing the environmental risk of subsurface injection, radically new approaches are needed to quantify the subsurface stress regime. New methods are needed to characterize the local and regional geology (lithology, tectonics, and seismic activity), the local and regional stress regime, the nature and presence of faults, the pressure and properties of existing fluids, and the mechanical properties of the rocks – over large spatial extents and with sufficient time/space resolution. Acquiring this knowledge at each site requires major improvements in the topics described below: interrogating and sensing stress state beyond the borehole and development of a fracture control risk assessment framework Adaptive control of subsurface fractures and flow requires pairing capabilities gained through this theme with new abilities to manipulate and predict subsurface responses to perturbations (as are described under the 'fractures and flow control' and 'fit-for-purpose modeling' themes).

Knowledge Gaps and Proposed Research

Interrogating stress state beyond the borehole

Current approaches to interrogating subsurface stress state either provide information about only a very small fraction of the relevant subsurface region (e.g., wellbore pressure transducers) or provide an unacceptably fuzzy interpretation of in-situ conditions (e.g., inversion of induced micro-earthquake data). Research associated with this topic will lead to new class of capabilities that will enable accurate quantification of the pre-injection and temporal evolution of in situ stress magnitudes and directions (full stress tensor) throughout the affected rock volume, including the reservoir and cap-rock, and from local to regional scales. Establishing the relation between the evolution of effective and poro-elastic stresses and the deformation, in particular the potential of shear slip along faults, will be essential for this endeavor.

Research in this topic aims to develop new approaches to quantify both local (reservoir) and surrounding (regional) stress state, both of which are important for adaptive control of subsurface fractures and flow. Different subsurface perturbations may provide useful information about the local stress state. Examples include well-designed injection, energetics, or push-pull tests that temporarily modify the local stress field in the vicinity of a wellbores. Small hydraulic fracture experiments (e.g., mini fracs) can be systematically employed to measure minimum stress directly and the understanding of instantaneous shut-in pressure, Such stress tests could be combined with temperature, geochemical, or other tracers that indirectly respond to pressure perturbations (see below). Meso- to macro- scale stress state, natural fracture networks, and permeability are strongly influenced by the tectonic stress field, which is particularly difficult to quantify. Entirely new approaches are needed to meet this challenge. An ensemble of boreholes, distributed around the volume of interest, could be used to perform purposefully designed, large scale pressure and flow perturbations. The design of the perturbation should be partially based on core studies of reservoir rock under relevant conditions. The induced subsurface field response, including micro-earthquakes and fluid flow, could be monitored using a variety of new instrumentation, as is described by the following topic. Research developments associated with this topic are expected to be critical for guiding the optimal management of new reservoirs as well as systems that have been subjected to multiple injection experiments.

Sensing stress state beyond the borehole

Existing methods for determining reservoir stress state are largely indirect or interpretive, typically involving the application of techniques, such as over-coring stress measurement, or combinations of techniques, such as min-ifracs and geophysical imaging of borehole fracture patterns. These methods also depend on assumptions of rock properties which are often overly simplified, such as homogeneity or isotropy, or are difficult to validate. Significant breakthroughs are needed to quantify both the local and regional stress states and their evolutions in response to perturbations. To meet this challenge, new approaches for measuring stress (and indirect effects on flow, temperature and reactions) as well as integration approaches are required. Examples of sensor advances include broadband 3-component seismometers that are placed inside of wellbores and at the ground surface to monitor background and induced seismicity; acoustic fiber optic sensor strings placed outside of casing together with tilt, INSAR, lidar and other deformation sensing performed elsewhere; seismoelectric and piezoelectric signatures; and nanoscale temperature, flow and pressure sensing devices that can be distributed throughout the volume of interest (refer to 'New Subsurface Signals' discussion). Development of new wireline logging tools for direct measurement of stress in high-temperature environments (e.g., integrated mini-frac logging tools / density / imaging) are envisioned. A new class of non-elastic approaches would be needed to jointly invert data from these diverse (direct and indirect) measurements, together with other information that is often available (such as from geological knowledge, wellbore breakout observations and geophysical monitoring).

Manipulating subsurface stress

Advanced knowledge of the stress state is not sufficient for optimal control of the fracture creation. A real and permanent control of the subsurface state of stress should become the new paradigm in order to optimize fracturing processes and ensure efficient and environmentally safe fluid pathways. Comprehensive designs of fluid injection systems (playing for example with the number, length and direction of horizontal wells) and various injection rate scenarios should be adapted to the existing local stress field. In order to locally release stress and balance the increase in pressure due to fluid injection, optimized water/brine pumping techniques could be deployed. Innovative techniques should also be envisioned including changing rock properties and/or temperature at depth to modify stress and exploring the effect of induced dynamic transients by energetic (e.g. explosions) means on stress.

Fracture Control Risk Assessment Framework

The number of seismic events induced by human activities and felt by the population in the United States has increased over the last decades. In some cases, 'nuisance' seismicity brought about by subsurface energy system manipulations has led to pubic alarm that has delayed production schedules. In other cases, seismicity, water quality and air quality pose real and significant threats to the environment and public. It is thus of primary importance to establish a framework and protocol for assessing key risk driver associated with fracture control. Similar in flavor to the DOE National Risk Assessment Program (NRAP) associated with identifying risks associated with geologic carbon sequestration, a systematic framework is needed to identify the risk factors associated with subsurface fracture control. Examples of risk contributors could potentially include the natural geological fabric and stress state, stimulation of existing fracture and fault networks, and wellbore and natural subsurface fastpaths that could potentially serve as conduits to environmental systems. The objective will be to develop an understanding of the probability of different risk factors for contributing to an overall probability of environmental risk under a variety of subsurface conditions and perturbations. As with the DOE NRAP project, it will be imperative to develop and test a fracture control risk assessment framework hand-in-hand with development of process understanding and simulation capabilities.