Subsurface Characterization
Letter Report

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EXECUTIVE SUMMARY

In response to a request from the Department, JASON recommends that DOE take a leadership role in the science and technology for improved measurement, characterization, and understanding of the state of stress of engineered subsurface systems in order to address major energy and security challenges of the nation. In addition to the engineered subsurface being important in several of DOE's mission areas, the science appears ripe for breakthroughs (*e.g.*, in applying laboratory-proven measurement techniques in the field), disparate research communities working in related areas can benefit from increased coordination (academia, industry, multiple government agencies), and DOE has specific capabilities that can effect these advances. In particular, we recommend: 1) coordinated research and technology development at dedicated field sites; 2) targeted use of dedicated government facilities for relevant laboratory studies; and 3) efforts to synergistically advance theory, modeling and simulation to provide a framework for laboratory and field measurements.

1 INTRODUCTION

The U.S. Department of Energy (DOE) asked JASON to conduct a short study of the science and technology enabling improved measurement, characterization, and understanding of the state of stress in engineered subsurface systems of the Earth's crust. The Study Charge reads:

> Successful utilization of the vast majority of U.S. energy resources fundamentally hinges on understanding and controlling the mechanical deformation of rocks in the upper crust. Examples include creating and sustaining fracture networks in enhanced geothermal systems (EGS) and unconventional oil and gas reservoirs; predicting and controlling geomechanical stability of reservoir rocks and seals in CO_2 storage reservoirs; and predicting geomechanical evolution at the interface between geologic media and engineered materials in nuclear waste storage and disposal settings. All of these efforts are governed by intrinsic rock properties and response to natural and applied lithostatic, tectonic, and hydraulic stresses at a variety of scales; from the stresses generated in single crystals, at grain boundaries, and at actively growing fracture tips, to field and crustal scales. Rock-property and stress heterogeneity further complicates interpretation of these systems. Understanding which scales are key to controlling fracture nucleation and propagation is particularly relevant to subsurface energy applications. Constraining orientation and magnitude of 3D stresses at these critical scales at desired locations within a rock volume is equally important.
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> In many cases current measurement techniques for characterizing the state of stress limit interrogation to scales broader than those of interest, or to the near-wellbore environment. Techniques such as GPS measurements, earthquake focal mechanisms, shear wave velocity anisotropy, wellbore breakout analysis, and hydraulic fracturing tests leave gaps in resolution of the changing stress field in

space and time during subsurface operations. This hampers their utility both for prediction and real-time monitoring of stress changes, with implications for tailoring operations and risk management. To address these gaps, new insights into characterizing the state of stress at key scales are needed to understand, predict, simulate, and monitor the dynamic response of the subsurface to changing stresses (e.g., fracture initiation and propagation, induced seismicity). The target capability is to measure stress at key scales at arbitrary spatial locations across reservoir-sized bodies in real time, towards dynamic control of subsurface conditions.

JASON was specifically asked to address the following questions on stress states in the subsurface to 5 km depths (*i.e.,* up to 1-10 km^3 bodies):

1. What are the key scales controlling stress changes that precipitate fracture nucleation and propagation?
2. Are the signals that we currently acquire adequate for characterizing the stress field at these key scales?
3. How can we improve interpretation of and/or instrumentation for acquiring these existing signals?
4. Are there signals of importance that we are not interrogating today?
5. What instruments and methods are needed to capture these new signals and resolve the state of stress?

JASON met with briefers on June 20, 2014, and engaged additional experts in discussions over the subsequent two weeks. Our overarching finding is that in addition to the engineered subsurface being important in several of DOE's mission areas, the science appears ripe for breakthroughs. Disparate research communities working in related areas can benefit from increased coordination (academia, industry, multiple government agencies), and DOE has specific capabilities that can effect these advances. We therefore recommend that DOE take a leadership role in the science and engineering needed for developing engineered subsurface systems. Support for this statement is provided in the remainder of this letter report, beginning with summary answers to the study charge questions in Section II and specific findings and recommendations in Section III.

2 ANSWERS TO STUDY CHARGE QUESTIONS

1. What are the key scales controlling stress changes that precipitate fracture nucleation and propagation?

There is a range of scales controlling the spatial and temporal distribution of stress in the subsurface, hence the stress conditions precipitating nucleation and propagation of fractures. Four spatial scales, spanning 3-9 orders of magnitude, are of foremost significance for the present purposes (Table 1).

Table 1. Length Scales Relevant to Subsurface Stress and Failure

Phenomenon	*Characteristics*	*Range*
Strength	Transition from strong (material-dominated) to weak (gravity-dominated) behavior of rock	10^{1}-10^{3} m
Failure	Scales at which failure is nucleated or localized, *e.g.*, at stress concentrations or pre-existing flaws	10^{-6}-10^{2} m
Composite heterogeneity	Stress inhomogeneity due to material heterogeneity and anisotropy within a rock	10^{-6}-10^{-2} m
Engineering perturbations	Zone within which stress is perturbed due to a probe (*e.g.*, borehole) or an engineered structure	10^{-2}-10^{2} m

Rock can be strong, but beyond a certain distance scale the force of gravity becomes overwhelming and the crust must be treated as intrinsically weak [1,2]. Laboratory experiments document crushing strengths for rock ranging from about 30 to 200 MPa, meaning that density variations of 1.5-2.5 g/cm^3 ($\Delta\rho$ of rock versus water or air) can only be supported over distances $l \approx$ 1.5-13 km before the differential stresses overcome material strength (using $\Delta P = \Delta\rho g l$ to estimate differential stress, with g being the acceleration of gravity). The tallest monolithic cliffs in the world are of order km (*e.g.,* El Capitan in Yosemite Valley), implying a transition from strong to weak behavior at ~10^3 m distance scales [3].

Alternatively, hard rock is commonly observed to be jointed (fractured) over distances of meters, such that it can be considered as effectively having no strength at scales greater than about 10^1 m (other than a frictional strength, as discussed below). This feature has been recognized since early applications of hydraulic fracturing to estimating stresses in the crust [4]:

> In any section of a well bore a few tens of feet in length, it is probable that many such joints have been intersected. It appears likely, therefore, that the tensile strengths of most rocks that are to be subjected to hydraulic fracturing by pressure applied in well bores are effectively zero, and that the pressure required to produce a parting in the rocks is only that required to reduce the compressive stresses across some plane in the walls of the hole to zero.

A current view is expressed by a leading expert [5]:

> Present day crustal terrains have been smashed into one another by large-scale collisions over the order of billions of years, continually being pushed to stress states at the limit of what they can withstand before some local region succumbs

to frictional failure or to other types of fracture. So, even in areas that show no seismicity on the time scale of modern human settlement, it is reasonable to assume that regions exist which are on the threshold of failure, and all it takes is a sufficient increase in $\tau / (\sigma - P_{fluid})$ to trigger a frictional rupture, *i.e.*, an earthquake. Here τ is the maximum shear stress on some ancient fault-like structure, σ is the compressive normal stress on the same feature, and P_{fluid} is the pore-fluid pressure.

Thus, rock has strength only at distance scales shorter than 10^1-10^3 m, and effectively has no strength over greater distances. This transition in strength behavior takes place over the spatial dimensions of engineered subsurface systems (*e.g.*, regions of fluid extraction or injection at depth), hence is of direct relevance to the study charge. For soils and other weakly consolidated matter, in contrast, the change from "strong" to "weak" can occur at length scales down to the order of μm. Even over the domain of "strong" behavior, both the stress field and the rock properties (elasticity, strength, distribution of flaws, etc.) can be extremely heterogeneous.

Accordingly, we focus here on distances ranging from the smallest scale of elastic heterogeneity, down to the μm dimensions of grain-boundaries and stress concentrations, up to the dimensions of pre-existing fracture systems – perhaps tens to hundreds of meters. This range includes the "process zone" associated with faults (*e.g*., Fig. 3.13 in Ref. [6]). One can visualize clouds of pre-existing cracks or pores that can be re-activated (opened and/or sheared) as stress is changed, either on geological timescales or due to human activity such as drilling, fluid injection or withdrawal, or otherwise modifying the subsurface. Therefore, extreme heterogeneity in general characterizes both the stress and the rock's constitutive properties at depth. This view is consistent with seismological studies at distance scales of 10^4 m and more (*e.g*., Ref. [7]).

Table 2. Elastic Properties of Mineral and Fluid Phases in Rock (STP) [8]

Mineral/Fluid Phase	***Bulk Modulus (GPa)***	***Shear Modulus (GPa)***
Quartz	38	44
Feldspar	55-85	28-40
Mica	58	35
Calcite-Dolomite	73-95	32-46
Water	2	0
Air	10^{-4}	0

At the smallest scales, cm to μm, stress varies because rock is a composite material, with differences in elastic properties between neighboring mineral or fluid phases. One can presume that stress variations within a rock may relax at depth over geological time periods, approaching a condition of spatially uniform stress (Reuss limit). However, the stress state is perturbed due to changes in elevation (*e.g*., due to uplift, erosion, and postglacial rebound), of typical magnitude 0.1-1 km per million years, let alone due to drilling or emplacement of engineered structures at depth. The initial response to engineering perturbations tends toward maintaining strain compatibility between neighboring phases (Voigt limit), and may depend on factors such as the orientation of stresses relative to mechanical layering. As bulk moduli vary by 50-100 percent (or more) between the primary mineral and fluid phases of the crust (Table 2), the initial stress change varies by a comparable amount. That is, a change in average stress of 20 MPa can initially cause stress differences of 10-20 MPa over sub-millimeter to centimeter distances of grain and pore dimensions. We note that, by analogy with observations on granular materials, maximum compressive stresses in rock might often be spatially distributed in the form of filaments ("force chains") of stress concentration [9].

In fact, stress changes can be larger by perhaps factors of 2-5 or more because i) the mineral grains are anisotropic, so differential stresses are determined by variations in the orientation-dependent elastic moduli (c_{ijkl}) – far larger than the variations in the average bulk or shear moduli; and ii) stress concentration significantly increases the stress around sharp corners of mineral grains or pores. This means that in the absence of plastic flow or crack nucleation, stress can locally increase by order 100 MPa or more over distances of μm to mm – stress gradients sufficient to initiate fracturing and even crystal-structural instabilities (the crystal structure collapses at the unit-cell scale). That is, yielding is initiated in pristine rock, whether through mineral grains or along grain boundaries and any available porosity.

The final length scale of importance is that associated with engineering perturbations of the subsurface (*e.g*., drilling), including emplacement of engineered systems. Current practice is to evaluate the magnitude and range of this stress "shadow" using elasticity theory, the result being that the stress field is most strongly perturbed to a distance comparable to the magnitude of the emplaced structure (*e.g.*, out to 1-2 borehole diameters, using the Kirsch 2D solution [10]). One can think of this perturbation as the stress concentration induced by emplacing the engineering system in a medium otherwise assumed to be homogeneous and subject to a uniform state of stress (despite the actual heterogeneities in place). Engineered systems are expected to range from cm (small boreholes) to perhaps 10^1-10^2 m, implying stress-field perturbations over comparable distances.

Thus, a variety of length scales are required to describe the stress state of rock in the top 5 km of the Earth's crust. Each of the above length scale regimes is compounded with key time scales. The shortest time scale is determined by the elastic-wave velocities ($\sim 10^{-3}$ to 1 s over distances of m to km), but longer time scales include those required for redistribution of fluid (a poro-elastic response) and heat, and for movement or healing of flaws at depth (which may well involve geochemical reactions): many are diffusive or chemical processes with poorly characterized (and probably highly varied) time scales, from seconds to millions of years (or longer) (*e.g.*, the 15 order of magnitude range of hydraulic diffusivities summarized in Fig. 2 of Ref. [11]; see also Fig. 12 of [12]. Frictional strength can have a time dependence over sub-second time scales (*e.g.,* Ref. [13]). There is also the semi-diurnal to bi-decadal (and longer) range of tidal timescales that influence crustal processes [14,15]. It is the vast uncertainty and range in time-scales characterizing stress distributions in the crust that presents one of the greatest challenges to natural earthquake prediction at the present time (*e.g.,* §6 of Ref. [16]).

2. Are the signals that we currently acquire adequate for characterizing the stress field at these key scales?

Signals are acquired for characterizing the stress relative to conditions of interest in Earth's crust, from documenting changes in stress locally at a borehole to mapping patterns at tectonic scales [17]. There are well-established techniques for estimating average orientations and magnitudes of stress components from borehole measurements at depth [18,19]. The vertical *normal* *component of stress* – "lithostatic pressure" – is determined by the density structure ($dP = \rho g dz$ for depth interval dz), although the effects of surface topography need to be taken into account and practical difficulties can arise due to scatter in field observations (*e.g.*, Fig. 3 of Ref. [19]). The pressure measured in hydraulic fracturing and leak-off tests can then be used to estimate the *minimum horizontal stress*, and – with further assumptions – tensile borehole fractures may reveal the *maximum horizontal stress*; over-coring and analysis of recovered cores provide complementary information [4,6,18]. Thus, there exist methods to determine, in many instances, the orientation and the 3 principal normal components of the stress tensor averaged over distances of meters to tens of meters.

These techniques for determining the relative magnitudes and orientations of stress components often show consistency from one site to another, and are important for understanding borehole stability as a function of orientation and location (*e.g.,* Figs. 18 and 21 of Ref. [19]). In our briefings and discussions we were told, however, that the measurements are rarely subject to absolute validation; their analysis is based on a simplistic, static model of a homogeneous material for how the borehole perturbs the pre-existing stress field (crucial for inferring the stress outside the process zone surrounding the borehole), and the results can be downright inconsistent and inexplicable (*e.g.,* Refs. [10,20]). In addition, laboratory studies do not support key assumptions used in the analysis, or in conceptualizing stress in the crust, such as the Mohr-Coulomb criterion (*e.g.*, all three principal stress components are needed to describe laboratory measurements of failure [21,22]) and the assumption that stress can be usefully average over space (cf. the geometry of force chains in model systems [9]).

In any case, questions surrounding measurement of the state of stress only address part of the study charge, which also includes predicting the stability and competency (*e.g.*, reliable containment) of subsurface engineered systems. Large regions of the crust are thought to be near critical stress for failure, as indicated by "weak" faults (normal stress close to fluid pressure) and the ease with which seismicity is induced by fluid pressure changes in the subsurface, *e.g.*, following fluid injection or withdrawal [23-25]. Borehole measurements generally assume the rock has zero strength, and it is exactly the transition from strong to weak domains – in both space and time (including in response to the subsurface engineering itself) – that is of key interest.

It is therefore the spatial heterogeneity in both *compressive and tensile strengths*, as well as *stress*, of rock in the crust that needs measurement and validation. Of especial importance is their relative magnitudes: How close is the system to the critical stress for sliding/failure? How do stress and strength change over time, whether due to tidal flexing, emplacement of an engineered structure, or movement of fluids at depth? Can the localization of strain be monitored, as the distribution of pre-existing flaws respond to changing stresses? Understanding these issues at distances of 10^0-10^2 m (see Failure Length Scale in Table 1), beyond those accessible in the laboratory, is especially lacking.

Currently acquired signals are not yet characterizing stress, strain and strength fields over the range of scales needed for quantitative understanding and prediction of regimes of critical stress that lead to failure in the top 5 kilometers of Earth's crust. The effects of failure, the spatial and temporal scales of fracturing events, and the possible redistribution of fluid that may trigger these events, are of direct relevance to the problem at hand. Currently acquired signals in the field and in the laboratory are not able to reliably predict how strain localizes, from perhaps a diffuse cloud of flaws to development of a narrow shear zone or fracture. Although compositional heterogeneity and residual stress can be measured with fine spatial resolution (*e.g.*, to below the μm scale) in recovered rock samples in the laboratory, there remains a question about what measurements are needed at these fine scales *in situ* beyond the borehole (*i.e.*, process zone) to achieve subsurface characterization aimed at understanding, or even predicting, failure. Signals required for characterizing the temporal response of the stress fields are not generally available, and could offer important insights toward quantitatively predicting the temporal response to subsurface intervention (*e.g.*, fluid injection and withdrawal).

3. How can we improve interpretation of and/or instrumentation for acquiring these existing signals?

The interpretation of existing signals would be improved by better validation of borehole stress measurements both in the field and through laboratory experiments. Experiments should include work with analogs to rock (*e.g.*, gels, model composites, glass), so as to properly scale to field dimensions the quantitative effects of stress, strain localization and initiation of failure in conducting laboratory breakout measurements with known (imposed) triaxial stresses. There is a gap in scales in going from laboratory experiments to the field (see Refs. [6,26] for the case of acoustic emissions). Scaling – relating phenomena over vastly different distance scales – from defects and fractures in the laboratory to large-scale fractures/faults in the field, as well as the broad range of strain rates, remains a major challenge due to limitations in size of laboratory samples. Scaling is further complicated by the heterogeneous nature of the environment and the lack of existing theory to integrate these property and structural variations into an understanding of the spatial and temporal changes in the stress.

Measurements using multiple, independent techniques are needed for cross-validation of field observations of stress and the critical state for failure. This is especially true for probing away from or between boreholes, where simplified models that lack stress and material heterogeneity are used. This could be done in an integrated effort to characterize different regions of the subsurface in small- to large-scale field sites. Much of the field validation can be carried out at relatively small scale, from meters to tens of meters, so mines and tunnels can provide a suitable locale for the necessary measurements. Additional information could be obtained from field sites with instrumented arrays of microholes and distributed sensors; advances in microdrilling can play a significant role in facilitating fast and therefore inexpensive probing. Small-scale sensors are available for deployment, though there is on-going need (and effort) for the sensors to be made useful under harsher environments, such as higher temperatures, than currently possible.

Improved interpretation of signals requires better understanding of rock properties at the relevant spatial and temporal scales described above. This in turn requires more extensive and better laboratory data, including fracture distribution, porosity, heterogeneity, grain size, chemistry, and fluid content. Laboratory methods have been developed for constraining residual stress in mineral grains from strain mapping of whole rock samples [27] (10s of MPa over 10s of μm), Information can also be obtained from studies of analog materials as well as rock, as shown in classic early studies [4]. An advantage of synthetic analog material is in principle the ability to control and more fully characterize the influence of pre-existing defects and microstructure, including a distribution of cracks, pore fluid, etc.

Theoretical models that are based on the appropriate materials physics and chemistry are essential for interpreting both laboratory and field measurements, and for giving a framework for integrating information at different length and time scales. These models are far from predictive, so must be further developed and validated against laboratory and field data. Approaches typically assume linear rock elasticity and ignore cracks and stress concentrations that could lead to failure [28]. As a result, there is a tendency to seek compatibility with existing models rather than independently documenting spatial and temporal heterogeneity that are key to testing different models.

Strengthening connections between currently disparate research communities would improve both interpretation of signals and instrumentation for acquiring signals. These connections include communities focusing on crustal deformation and stress (NSF-supported UNAVCO, PBO and SAFOD), space-based geodesy (NASA-supported InSAR, GPS), and seismology (USGS- and NSF-supported SCEC, Earthscope) (see Ref. [29]). Crustal stress measurements need to make connections with time-varying borehole strain measurements, geodetic and tide observations, seismic source modeling, and both theoretical and laboratory rock mechanics. In addition, a great deal of relevant data is collected by industry, both energy-related (*e.g.*, oil and gas) as well as mining and rock tunneling. Companies may also have useful sample repositories and of course own and/or have special access to field sites. Having access to these data would provide valuable information for synthesizing information about rock types and behavior at different depths and locations. In addition, access to industrial sites, including abandoned boreholes, for example for both sampling and passive instrumenting, would be useful. Leveraging mechanisms to promote industrial engagement could include tax credits and other incentives, anonymizing data, and requirements at the state level for data release. For each of these, potential legal issues would have to be recognized in advance.

4. Are there signals of importance that we are not interrogating today?

In principle, the range of signals that could be used span acoustic (Hz-MHz), electromagnetic (Hz-GHz, including magnetotelluric, source-controlled EM and ground-penetrating radar, GPR), and chemical signals. For each of these, there are issues of range versus resolution (kilometers-millimeters for acoustics, megameters-centimeters for EM) [30]. Commercial needs and interests have driven the development of numerous downhole logging tools. Many of the signals can be obtained with existing techniques but are not exploited fully to address the subsurface stress problems addressed here. Information can also be gained from combinations and correlations of signals, and the comprehensive use of sensor networks.

Signals of importance include those that provide information on the poorly understood localization of strain and (re-)initiation of failure, including their spatial and temporal dependence. There exist models for strain localization (*e.g.,* Ref. [31]), and it will be crucial for a successful program of research that such models be further developed and applied as guides for observation and experimental measurements; experiment and field measurement, in turn, should serve to test theoretical models. Although dilatancy is well established in the laboratory as an important precursor to failure, both in pristine rock and in samples with pre-existing flaws, this phenomenon is not well documented at field scales (*e.g.,* Ref. [32]). Efforts made several decades ago to document dilatancy associated with earthquake source regions proved inconclusive; the most productive approach would seem to involve focusing at short-range field scales (such as accessible in mines). Finding ways of detecting dilatant behavior – via changes in acoustic velocities, attenuation, harmonic generation (nonlinear response) or their anisotropies, for example – would represent a major advance, as would the alternative of understanding why dilatant behavior does not appear to scale from laboratory to field dimensions.

Despite the wide use of acoustic techniques in geoscience, acoustic signals are not fully utilized. Linear acoustic-wave propagation can measure the non-linear constitutive relations due to stress loading of cracked samples, as there is a strong dependence of velocities on stress and cracks [10]. Nonlinear acoustic wave mixing can be further exploited because it probes the effective stress and in principle allows imaging of the near-critically stressed region [28]. The range and attenuation of acoustic signals by fractures and faults needs to be examined. These signals could in principle be measured in horizontally branched (side) holes, though they may be limited to probing within the process zone, and be collected from dense arrays of boreholes, such as could be established using microdrilling (see below). All of these methods can of course be applied to recovered cores in the laboratory (including experimental simulation of borehole conditions).

Electromagnetic (from magnetotellurics to controlled-source EM to radar) and seismoelectric/electroseismic techniques appear to be underutilized. These methods are sensitive to the presence of water or other fluids, as permeability is likely to change where strain is being localized and failure initiated; and appearance of fluids can strongly influence the approach to critical loading. The strong dependence of the EM signals on the dielectric constant thus provides a probe of the presence of brine. This dependence also has limited methods such as ground-penetrating radar [28] to very shallow depths if the rock is not dry. The extent to which these techniques could be further developed and, for example, applied between boreholes and within a borehole from sensors at the surface remains to be explored. Seismoelectric (or electroseismic) signals provide information on the electrokinetic effects or streaming potential within the rock body. Developed methods appear to probe maximum depths of ~500 m. It will be important to keep abreast of industry developments (patents), and be aware of capabilities in both academia and industry for extending the methods to the kilometer depths.

Chemical and gas tracers can be used to measure porosity and the presence of fractures and faults [30,33], and as such, provide constraints on rock stresses and failure at depth. For example, noble-gas diffusivity measurements have shown that tidal effects can be important in movement of chemically inert fluid through the crust, as is the competency and vertical normal load of overburden on distance scales of tens to hundreds of meters [33]. This approach has been developed for validating nuclear-explosion monitoring techniques, and has proven invaluable for better understanding the physical pathways for mobility of fluids and gases at depth; however, far too few such studies have been completed to date. There are opportunities for judicious use of isotopic tracers for tracking the movement of other gases through the crust, whether He, CH_4, or perhaps artificially injected tracers such as SF_6.

The transport of CO_2 through the crust is complicated by still-poorly understood chemical reactions (including kinetics relative to timescales for transport). The chemical effects include deposition as well as dissolution, either of which can significantly impact subsurface permeability and lead to plugging of conduits in geothermal systems or leakage of a repository for CO_2 or nuclear waste. There is a need to first document the spatial-temporal characteristics of physical pathways (*e.g.,* by documenting transport of noble gases) before attempting to deconvolve the additional effects of geochemistry. Finally, there is awareness of the potential role of subsurface biological activity in underground storage sites; the extent to which subsurface biological activity affects local stress fields remains to be examined in detail. A particular challenge is imaging the chemical changes that affect subsurface stress, fracture, and failure.

To summarize, nonlinear acoustics as well as joint acoustic-electromagnetic techniques appear to be especially promising techniques that are currently underutilized with respect to engineered subsurface systems. These methods include sum and difference harmonics of regions insonified by more than one seismic beam, which is used in other disciplines and has been proven for rock in the laboratory, and seismolectric/electroseismic methods used in the oil and gas industry. In addition, chemical- or gas-tracer studies are also especially promising techniques to more fully document that range and spatial-temporal heterogeneity of fluid/gas mobility (diffusivity, etc.) through the upper crust. Other methods include measurements of changes in pore pressure and fluid production variation in reservoirs.

5. What instruments and methods are needed to capture these new signals and resolve the state of stress?

Three-dimensional sensor networks could capture a variety of signals with higher sensitivity and at higher spatial (and temporal) resolution than is now commonly done. Autonomous robots travelling along boreholes could be used for underground tomography. For example, for boreholes forming a square pattern (either horizontal or vertical), transmitter and receiver robots could travel along the boreholes transmitting ultrasound or electromagnetic signals. To obtain a more precise understanding of stress distributions underground, we would need to abandon the ray-optics approximation and study the propagation of ultrasound as a nonlinear process, but there is precedence for this approach in the seismology community.

There is a need for continued development of small deployable sensors for downhole monitoring. Downhole spectroscopic probes such as NMR (for water content) and Raman (for temperature, molecular identification) have been developed but need to be further advanced. Challenges include the high temperatures that prevail at the greatest depths considered here (to 600 K at 5 km). Fiber-optic materials become opaque at high temperatures, requiring new fiber materials to be developed. Sufficiently hardened electronics may also be needed. The development of cooling packages for these sensors could extend the range and allow still other probes to be successful deployed and used. Altogether new probes should be explored such as x-ray and neutron diffraction downhole to probe structural, compositional, and stress heterogeneity.

Small sensors can be emplaced *in situ* in microholes, which are less costly to drill, and so could be considered for a sensor network indicated above [30]. These developments include the continued development of intelligent but inexpensive nanosensors that could be injected in the subsurface systems [34]. Because of the cost of drilling, particularly in hard rock and to the depths required, microholes offer an alternative for subsurface characterization. How dense an array across surface is needed would need to be examined and will depend on the resolution sought or required. This in turn requires the continued development of a range of drilling technologies, including resonant drilling, fluid injection drilling, high-speed dual string drilling, and penetrometers [35].

Theoretical models of subsurface stress and failure have been growing in sophistication. At the large field scale, models have been useful for constraining reservoir stability and behavior [36]. At the more local scale, there are attempts to include appropriate microphysics such as anisotropic microstructural elasticity together with materials property data (*e.g.,* Ref. [37]). However, these models are far from predictive. Models of fracture propagation (especially nucleation) could be enhanced by improved understanding of the range of variations possible in a given rock type, the possible impact of poro-elasticity of the surrounding material, and the extent to which finer scale description (*e.g.,* $< \mu$m-mm scale) is required [6]. Improved understanding of the dissipative mechanisms responsible for seismic attenuation would improve the characterization of subsurface rock and stress. Understanding the underlying physico-chemical basis of anisotropic frictional strength is needed to characterize its strong dependence over different timescales.

3 FINDINGS AND RECOMMENDATIONS

We conclude with findings and recommendations, followed by our overarching finding and recommendation based on the above answers.

Findings

1. **A variety of length scales is required to describe the stress state of rock in the top 5 km of Earth's crust.** The transition from strong behavior at short distances ($<10^{-1}$-10 m) to weak behavior at long distances (>10-10^{3} m) is likely highly heterogeneous in the crust, occurs over a multitude of length and time scales, and is influenced by external forcings as well as internal changes (fluid flow, strain localization, etc.). The crust is near its critical stress in many places, so not much is needed to cause failure as evident from observations of induced seismicity following injection or withdrawal of fluids, as well as correlations between subsurface hydrological activity (*e.g*., as evidenced in changes in geyser eruptions) and distant seismic events. Thus, in many cases it is not the stress but the approach to critical loading that is of key interest.

2. **Our understanding of the state of stress and proximity to failure in the crust is not yet sufficient for confident design, control and sustainment of engineered subsurface systems**. The transition from strong to weak behavior is understood in general terms, but not well enough characterized (*e.g*., imaged) in space and time to assure DOE's mission addressing key national needs through engineered subsurface systems. Still, there exist promising methods for mapping rock properties sensitive to critical loading at spatial and temporal scales of interest. Laboratory and field data that are needed include information about what selects the modes of failure – compressive and shear strength, fracture toughness, sliding friction, etc. – and how crustal material is affected by faults, fractures, fluids, grain size and other defects. Nonlinear response to acoustic or seismic excitations contains useful information about the fractured state of rock, and induced seismicity can also be used to infer such properties as friction coefficients and pre-existing stresses.

3. **Field techniques are not yet sufficiently developed for reliable prediction and control of engineered subsurface systems.** Well-established techniques for estimating average orientations and magnitudes of stress components from borehole measurements provide important information about borehole stability at depth, but are generally insufficient to actively monitor and control the stresses associated with engineered subsurface systems. The overlapping effects of tides, subsurface fluid flow, atmospheric pressure, and shifting tectonic loads (*e.g.*, in response to earthquakes) are not well disentangled in current measurements of crustal stress and strain. There are confounding indications of sensitivity to small effects (*e.g.*, hydrologic responses to distant earthquakes; ease of triggering induced seismicity), and lack of sensitivity to large effects (lack of correlation between tides and seismicity). Field measurements are not generally well validated by laboratory studies and are rarely amenable to quantitative cross-check by independent field methods.

4. **Although there is considerable relevant information from past laboratory, field and theoretical investigations, there remain important gaps in our understanding of rock behavior**, **especially as pertains to engineered subsurface systems.** Stress distributions are not well characterized, either in space or time (*e.g.*, filaments of stress concentration at multi-grain scale to larger-scale stress concentrations associated with clouds of flaws). Localization of strain and stress (stress concentrations) in response to external loading, whether in pristine or in previously deformed rock, remains poorly understood. Dilatancy is documented in the laboratory prior to failure but not at field scale. There is a lack of relevant data on failure (re)initiation at length scales beyond meters, and there is a need to develop models of these phenomena in parallel with measurements at laboratory to field scales.

5. **Theoretical models provide an important framework for understanding laboratory and field measurements, but are limited and far from predictive for applications considered here**. Measurements are analyzed using simplistic models (*e.g.*, of the stress field in a homogeneous material around a borehole) that give consistent findings, in many instances. Most of the relevant properties of real fractured rock cannot be predicted with sufficient theoretical accuracy for the range of spatial and temporal scales of interest. Extensive experimental validation is required, and the development of more first-principles-based models requires improved understanding of the behavior of real rock over a wide range of length and time scales.

6. **Progress is limited by gaps between research communities**. There are considerable amounts of relevant data and expertise in communities outside DOE, including industry (oil, gas, water, mines, tunnels), academia (including affiliated institutes and centers), and other government agencies (*e.g.*, NSF, USGS, NASA, DoD, EPA). Improved coordination among these communities (academia–industry–government, field–experimental–theoretical), leveraging expertise in DOE laboratories as well as potential field sites and user facilities, could lead to significant breakthroughs in understanding subsurface engineered systems. Improved coordination could also enhance training in the appropriate skills and grow a future workforce.

Recommendations

1. **We recommend coordinated research and technology development at dedicated field sites.** Measurements are needed at field scale, from meters to hundreds of meters, with a premium on the smaller scale (cm to tens of m) so as to overlap laboratory scales and provide validation of theoretical models and simulations. Dense arrays of micro-boreholes for testing and development of monitoring techniques and sensor networks offer significant potential, and imply a focus on rapid/inexpensive drilling as well as development of small, inexpensive sensors with enhanced capabilities (*e.g.*, a greater variety of sensors with better resilience to high temperatures and other environmental challenges). This activity could take place at re-occupied existing structures (*e.g.*, abandoned boreholes, mines, existing field sites) or newly developed sites. DOE should play a leadership role in this effort. *Findings 1-4.*

2. **We recommend targeted use of dedicated government facilities for relevant laboratory studies.** The community would benefit from DOE's longstanding experience in operating user facilities by expanding relevant facilities at its national laboratories to become user facilities (from rock mechanics capabilities at Sandia National Laboratories to deformation rigs and related devices at advanced radiation facilities). Several of these facilities at DOE sites, perhaps along with complementary capabilities in government (*e.g.,* USGS [38]), academia and industry, could be linked to serve as a distributed user facility. The effort should take advantage of the different strengths of the governmental, academic, and industrial sectors in furthering the program. This coordinated program of laboratory measurements could include smart archiving of data and samples for the research community, as well as support strong connections between theoretical, simulation and observational (both laboratory and field) communities. The effort will also serve as an important training ground for the next generation workforce in this field. *Findings 3-6.*

3. **We recommend efforts to advance theory, modeling and simulation to provide a framework for laboratory and field measurements.** The link between observation, experiment, and theory should be strengthened, with theoretical predictions guiding empirical measurements and observations in turn testing theory. There is room for application of increased computational capability, but the main choke points for theory are in the development of conceptual models and in efficient ways to tackle the multi-scale nature of the problem. We recommend that resources of the DOE, including its expertise in theory, modeling, and simulation, be exploited for this effort. *Findings 4-6.*

Overarching Finding and Recommendation

We recommend that DOE take a leadership role in the science and engineering needed for developing engineered subsurface systems, addressing major energy and security challenges of the nation. In addition to the engineered subsurface being important in several of DOE's mission areas, the science appears ripe for breakthroughs, disparate research communities working in related areas can benefit from increased coordination (academia, industry, multiple government agencies), and DOE has specific capabilities that can effect these advances.

REFERENCES

[1] M. K. Hubbert, Theory of scale models as applied to the study of geologic structures, *Bull. Geol. Soc. Am.* 48, 1459-1520 (1937).

[2] M. K. Hubbert, Strength of the Earth, *Bull. Am. Assoc. Petrol. Geol.* 29, 1630-1653 (1945).

[3] G. M. Stock, N. Luco, B. D. Collins, E. L. Harp, P. Reichenbach and K. L. Frankel, Quantitative rock-fall hazard and risk assessment for Yosemite Valley, Yosemite National Park, California, *National Park Service and US Geological Survey* 92, (2012).

[4] M. K. Hubbert and D. G. Willis, Mechanics of hydraulic fracturing, *Trans. Soc. Petrol. Eng. AIME* 210, 153-168 (1957).

[5] J. R. Rice, personal communication (2014).

[6] A. Zang and O. Stephansson, *Stress Field of the Earth's Crust* (Springer, New York, 2010) 322 p.

[7] L. Rivera and H. Kanamori, Spatial heterogeneity of tectonic stress and friction in the crust, *Geophys. Res. lett.* 29, 1088 (2002).

[8] J. D. Bass, Elasticity of minerals, glasses, and melts, in *Mineral Physics and Crystallography, A Handbook of Physical Constants*, edited by (American Geophysical Union, Washington, DC, 1995), pp. 45-63.

[9] C.-H. Liu*, et al.*, Force fluctuations in bead packs, *Science* 269, 513-515 (1995).

[10] D. R. Schmitt, C. A. Currie and L. Zhang, Crustal stress determination from boreholes and rock cores: Fundamental principles, *Tectonophys.* 580, 1-26 (2012).

[11] A. J. Barbour and F. K. Wayatt, Modeling strain and pore pressure associated with fluid extraction: The Pathfinder Ranch experiment, *J. Geophys. Res.* 119, 5254-5273 (2014).

[12] M. Manga*, et al.*, Changes in permeability caused by transient stresses: Field observations, experiments and mechanisms, *Rev. Geophys* 50, 2011RG000382 (2012).

[13] G. Di Toro*, et al.*, Fault lubrication during earthquakes, *J. Geophys. Res.* 118, 447-458 (2011).

[14] D. C. Agnew, Earth tides, in *Treatise on Geophysics*, edited by G. D. Price (Elsevier, Amsterdam, 2007), pp. 163-195.

[15] K. Hodgkinson, J. Langbein, B. Henderson, D. Mencin and A. A. Borsa, Tidal calibration of plate boundary observatory strainmeters, *J. Geophys. Res.* 118, 447-458 (2013).

[16] H. Kanamori and E. E. Brodsky, The physics of earthquakes, *Rep. Prog. Phys.* 67, 1429-1496 (2004).

[17] M. L. Zoback, First- and second-order patterns of stress in the lithosphere: The world stress map project, *J. Geophys. Res.* 97, 11703-11728 (1992).

[18] M. D. Zoback, *Reservoir Geomechanics* (Cambridge University Press, Cambridge, 2010) p.

[19] M. D. Zoback*, et al.*, Determination of stress orientation and magnitude in deep wells, *Int. J. Rock Mech. Mining Sci.* 40, 1049-1076 (2003).

[20] B. C. Haimson, The effect of lithology, inhomogeneity, topography and faults on in situ stress measurements by hydraulic fracturing, and the importance of correct data interpretation and independent evidence in support of results, in *Rock Stress and Earthquakes*, edited by F. Xie (Taylor & Francis, 2010), pp. 11-14.

[21] B. Haimson, True triaxial stresses and the brittle fracture of rock, *Pure Appl. Geophys.* 163, 1101-1130 (2006).

[22] D. R. Schmitt and M. D. Zoback, Infiltration effects in the tensile rupture of thin walled cylinders of glass and granite: Implications for the hydraulic fracturing breakdown equation, *Int. J. Rock Mech.* 30, 289-303 (1993).
[23] W. L. Ellsworth, Injection-induced earthquakes, *Science* 341, 1225942 (2013).
[24] N. J. van der Elst, H. M. Savage, K. M. Keranen and G. A. Abers, Enhanced remote earthquake triggering at fluid-injection sites in the Midwestern United States, *Science* 341, 164-167 (2013).
[25] M. D. Zoback and S. M. Gorelick, Earthquake triggering and large-scale geologic storage of carbon dioxide, *Proc. Nat. Acad. Sci.* 109, E3623-E3624 (2012).
[26] S. D. Goodfellow and R. P. Young, A laboratory accoustic emission experiment under in situ conditions, *Geophys. Res. Lett.* 41, 3422-3430 (2014).
[27] K. Sekine and K. Hayashi, Residual stress measurements on a quartz vein: a constraint on paleostress magnitude, *J. Geophys. Res.* 114, B01404. doi: 01410.01029/02007JB005295 (2009).
[28] D. Schmitt and M. D. Zoback, Diminished pore pressure in low-porosity crystalline rock under tensional failure: apparent strengthening by dilatancy, *J. Geophys. Res.* 97, 273-288 (1992).
[29] *Advancing Experimental Rock Deformation Research: Scientific, Personnel, and Technical Needs,* White paper from a NSF-DOE-SCEC-USGS sponsored workshop, 69, 2012 (2012).
[30] Enhanced Geothermal Systems, *JASON Report,* JSR-13-320 (2013).
[31] J. W. Rudnicki, Failure of rocks in the laboratory and in the Earth, in *Proc. 22nd Int. Congr. Theor. Appl. Mech.*, edited by J. P. Denier and M. D. Finn (Springer, 2013), pp. 199-215.
[32] G. Chen and H. Speztler, Complexities of rock fracture and rock friction from deformation of Westerley Granite, *Pure Appl. Geophys.* 140, 95-121 (1993).
[33] C. R. Carrigan, R. A. Heinle, G. B. Hudson, J. J. Nitao and J. J. Zucca, Trace gas emissions on geological faults as indicators of underground nuclear testing, *Nature* 382, 528-531 (1996).
[34] J. Neal and C. Krohn, Higher resolution subsurface imaging, *J. Petrol. Technol.* 64, 44-53 (2012).
[35] For example, *Geoprobe:* http://www.geoprobe.com.
[36] J. White, *Presentation to JASON,* June 20 (2014).
[37] J. P. Verdon, D. A. Angus, J. M. Kendall and S. A. Hall, The effect of microstructure and nonlinear stress on anisotropic seismic velocities, *Geophysics* 73, D41-D51 (2008).
[38] http://earthquake.usgs.gov/research/physics/lab/