UT GeoFluids 2020 Research Plan

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1 Executive summary

The UT GeoFluids 2020 Industrial Associates Program will last 10 years and study the state and evolution of pressure, stress, deformation and fluid flow through experiments, theoretical analysis, and field study. The Institute for Geophysics (UTIG) at the Jackson School of Geosciences will partner with the Dept. of Civil and Environmental Engineering at Tufts University. The cost will be $50,000 and will increment at 2%/yr. The first payment will be due in May 2019. Our research will focus on the following.

- Develop and deliver pore pressure and fracture gradient workflows.
- Link poromechanics with pressure prediction and express in whole earth stress models.
- Include stress dependency and material anisotropy in poromechanical models.
- Develop synthetic seismic models of poromechanical models.
- Study material behavior under complex stress paths representative of geologic conditions.
- Experimentally examine the role of creep in mudstones at geological stresses.
- Compare material behavior of resedimented mudstone with intact material.
- Apply and test our approaches to field problems.

We aim to develop a unified approach that incorporates stress dependency, creep, mineralogical transformation, and loading path to illuminate the state and evolution of pressure and stress in basins. We already see evidence that this unified approach can improve well design and provide insight into a range of geological processes. These approaches will result in two and three-dimensional whole earth models that improve well design, real-time drilling, borehole stability, and reservoir simulation.
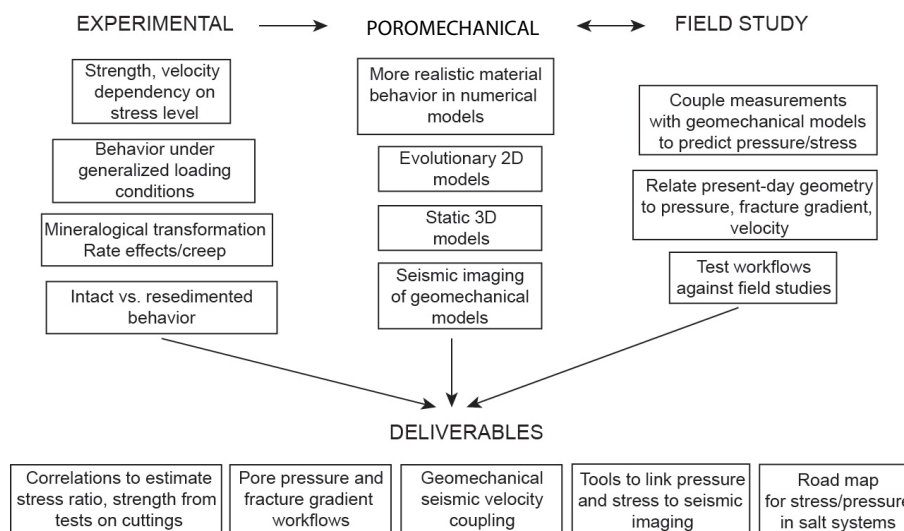

Figure 1. Interdependence of experimental, poromechanical, and field study variables.

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We produce innovative concepts that couple geology, mudrock rheology, and fluid flow to predict pore pressure and stress in the subsurface. Applications include pore pressure and stress prediction, the design of stable and safe drilling programs, and the study of hydrocarbon migration and entrapment. We study the state and evolution of pressure, stress, deformation and fluid migration through experiments, models, and field study:

1. **Experimental**: We analyze fabric, acoustic, electrical, hydraulic, and material properties of mudrocks: 0.1-100 MPa.
2. **Poromechanical Modeling:** We couple sedimentation, porous fluid flow, geologic and tectonic loading to predict pore pressure and the full stress tensor.
3. **Field Study:** We analyze pore pressure, stress, and deformation in thrust belts and in salt systems

2.1 Experimental

2.1.1 Overview

Our experimental program will characterize and quantify three important aspects of hydromechanical behavior: stress level dependence, anisotropy, and time dependence. Our goal is to better interpret field observations, calibrate numerical simulations, and provide a database to develop new models of mudrock behavior. During the past decade, we focused primarily on the stress dependent aspects of behavior during uniaxial and triaxial loading conditions and under constant loading rates. This has included various subthemes (temperature, salinity, type of mudrock, mineral transformation, etc.) but the central focus has been stress level. The next phase of the research will expand to compare intact to resedimentated behavior, the effects of loading direction, and the effects of creep.

2.1.2 Validate/calibrate resedimented behavior against intact behavior

Challenge: We have spent a decade developing material models for mudstones of different lithologies based on the resedimentation process. We will reconcile these systematic measurements against intact core samples. Does resedimented material behave similarly to intact material and, if not, is there a systematic mapping that we can use to transfer insights from resedimented to intact mudrock behavior?

Research Plan: We will work with industry sponsors to acquire intact core samples of unlithified, relatively high porosity, mudrocks and additional material for resedimentation. This will provide a one to one comparison using exactly the same laboratory test protocols with near identical materials. We will perform laboratory experiments (uniaxial compression, undrained triaxial shear, velocity, etc.) on the intact core and the companion resedimented specimens. We will also perform our typical suit of physical property tests. We will then move on to the more challenging lower porosity and higher stress lithologies.

We will systematically compare the resedimented behavior with the intact behavior (Figure 2), and with our extensive resedimentation database. We will then produce an approach, if possible, to integrate the intact and resedimentation database to develop generalized intact behavior. The results will allow our experimental work to more effectively be applied to subsurface problems.

Examples could include: 1) Stress X on resedimented sample creates a material with the same void ratio as intact sample from in-situ stress Y. 2) Resedimented sample with void ratio A behaves the same as intact sample with void ratio A (hopeful outcome); or, resedimented sample with void ratio B is necessary to match behavior of intact sample with void ratio A (possible outcome).
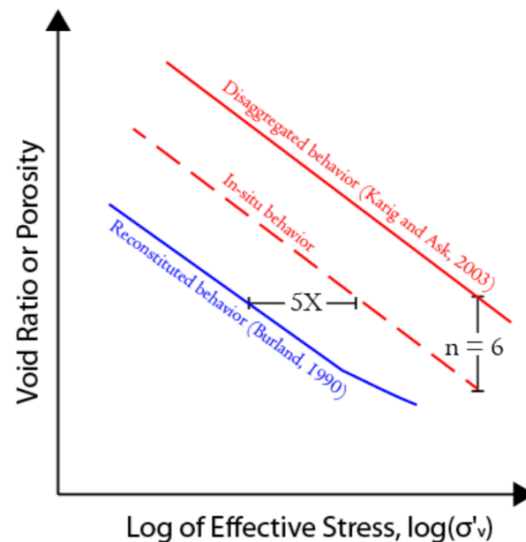

Figure 2. The relationship between material properties measured in the laboratory and intact field behavior is unclear. For example, Karig and Ask (2003) suggest that at given effective stress, an intact mudrock is more compacted than a synthetic specimen of identical composition made in the laboratory. In contrast, Burland (1990) suggests that the in-situ mudrock is less compacted than the laboratory-generated material. We will compare measurements of resedimented behavior against intact behavior. Other aspects of mudrock behavior may also be different (e.g. stress-strain behavior under shear, undrained strength, friction angle, velocities, etc.).

2.1.3   Poromechanical behavior under generalized load conditions.

Challenge: Mudrocks in many basins undergo complex stress histories. For example, sediment deposited outside a thrust belt under uniaxial strain (K_0) conditions is ultimately exposed to a large lateral stress as it is consumed into the thrust belt (Figure 3a). Alternately, sediment adjacent to a salt diapir may undergo extreme lateral stresses that are larger than the vertical stress (Figure 3b).

Most mathematical models for geological applications use relatively simple descriptions of material behavior. For example, we use the Modified Cam Clay model or Rockfield's SR3 model. These formulations are based on yield surfaces that are symmetric about the horizontal (mean stress) axis and remain as such regardless of the loading path. However, it is generally observed that yield surfaces rotate and align with the loading axis (Figure *4*b). A critical question is what is the shape of the yield surface and how it evolves during loading. This is important because the form of the yield surface at any given loading increment controls the amount of pore pressure generated.
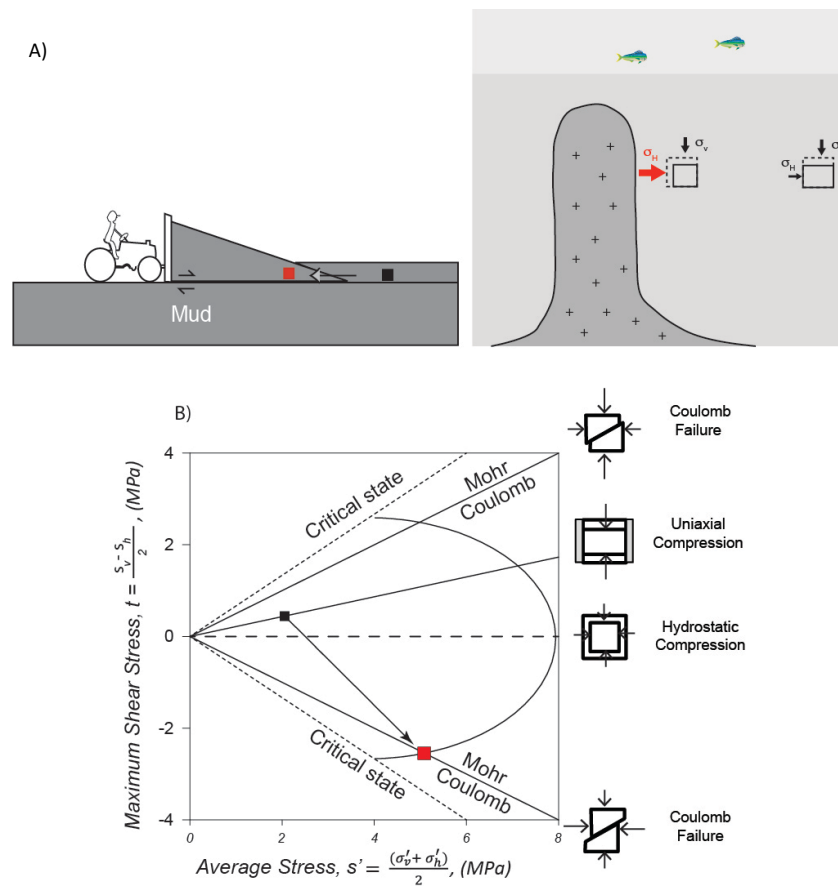
Figure 3: Basin sediments commonly undergo complex stress histories. In either a thrust belt (a) or a salt system (b), the stress path may shift from initial deposition along the K_0 trend (black square), where the horizontal stress is less than the vertical, to compressional failure (red square), where the lateral stress exceeds the vertical stress.

Research Plan:

Initially, we will investigate the shape of the yield surface at different stress levels, up to 100MPa, using our conventional triaxial apparatus (cylindrical specimens). We will also study yield surface rotation under compressional loading (horizontal major principal stress). We will next develop a 3-axis testing device capable of large normal strains in order to decouple the intermediate principal stress from the direction of loading. Such devices have been used for very low stress testing (<1 MPa) in geotechnical engineering and for rock testing at high stress, but with very limited strain capability (<5%). This will be a major advancement in technology that will allow investigation of compression and shear behavior as the material transitions from a K_0 state of stress to the more general stress conditions found around salt features or within thrust belts.
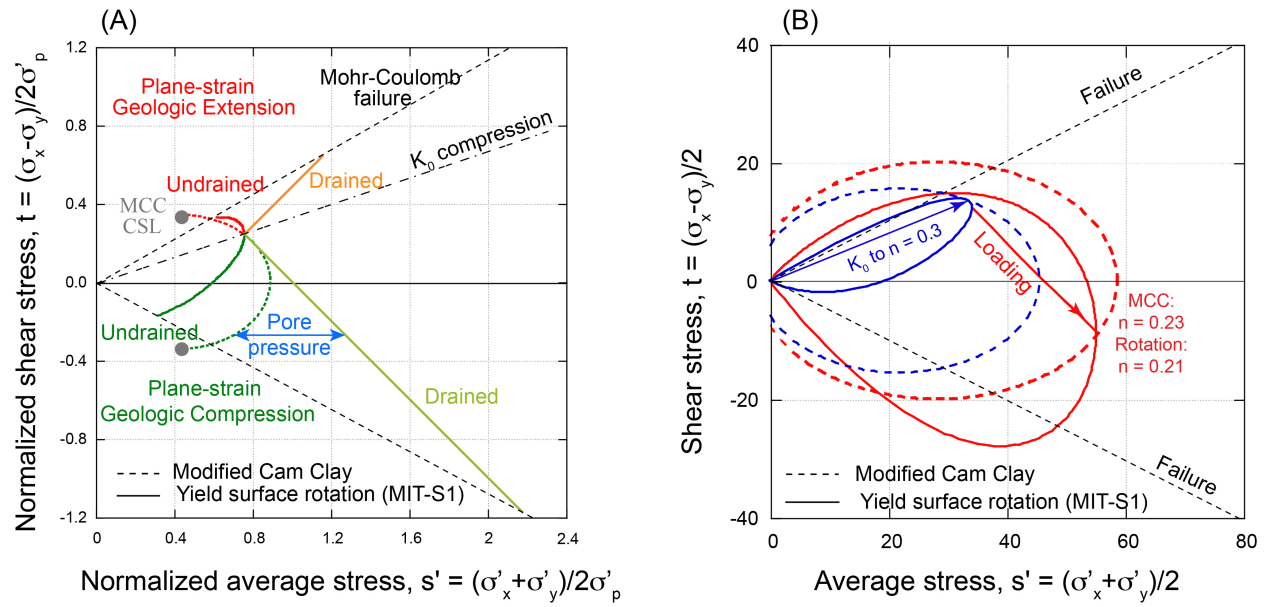
Figure 4*: A) Example loading paths following uniaxial compression for plane-strain conditions, predicted by Modified Cam Clay (dashed lines) and MIT-S1 (yield-surface rotation; solid lines). B) Compressional loading following uniaxial compression. Shape of iso-volumetric surface at the end of each loading predicted by MCC (symmetric with respect to x-axis) and MIT-S1 (asymmetric and rotating; Pestana et al, 2002).*

2.1.4 Wave Velocity Characterization:

Challenge: Wave velocities are a function of the elastic modulus and density of the material. Most sedimentary materials are considered to be cross-anisotropic (one symmetry axis) resulting in five independent elastic parameters. Anisotropy in the sedimentary section must be corrected for us to properly image the subsurface and to estimate subsurface properties (Nihei et al., 2011). We are developing complex forward poromechanical models and we wish to understand how they would be imaged in the subsurface. To do so, we need to determine the five elastic constants and how they vary with stress state and stress level.

Research Plan: We will measure the compressional (*P*) and shear (*S*) wave velocity anisotropy as a function of stress up to 100 MPa. The measured velocities will be used to compute the elements of the stiffness matrix, which are then used to determine the velocity in any direction (e.g. Figure 5). Velocity measurements require specific technologies designed for each stress level range. We have recently developed technology up to 10 MPa which allows measurement of a) *P* and *S* waves in the axial dimension (surface mounted piezoceramic crystals in the end caps); b) *P* and *S* waves across the specimen diameter (crystals mounted directly on the specimen under the membrane) and c) one inclined *P* wave (side of specimen to end cap). Our next technology increment will be developing a similar capability in the triaxial cell having a capacity of 100 MPa.

Elastic anisotropy (Young's modulus, Shear modulus, and Poisson's ratio) varies with stress level during K_0 consolidation and is also be dependent on the general stress state (non-K_0

conditions and proximity to the failure envelop). We will explore these velocities during different compression paths (K_0, isostatic, etc.) as well as during undrained shearing.
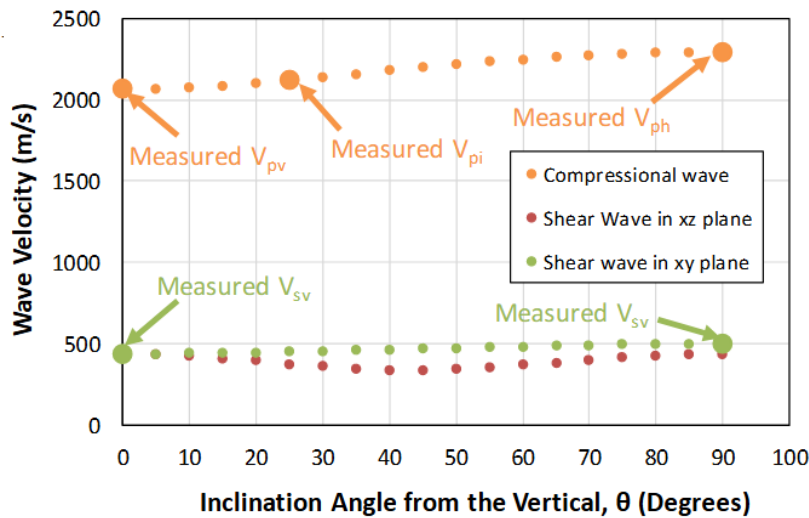

Figure 5. Compressional and shear wave velocity as a function of angle based on measurements of five independent velocities on a specimen uniaxially consolidated to 5.8 MPa

2.1.5   Visco-plastic behavior:

Challenge: Deeper, hotter, and older mudrocks are often more compacted than mudrocks at the same effective stress in the shallow section. It is also common for laboratory-measured compression curve using resedimentation technology to have a higher porosity than the in-situ porosity at the same stress level. Understanding the cause(s) of these differences is a primary objective of our research. We have ruled out the effects of pore fluid salinity, elevated temperature, and illitization. While unloading (reduction in effective stress) may account for some cases, it is unlikely to explain the ubiquitous behavior that is observed. We will now focus on creep as a cause for these effects.

All particulate materials experience time-dependent deformations (volumetric and shear) under constant effective stress conditions. Mesri (1974) found that the rate of creep was uniquely related to the slope of the compression curve and coined this "the 4th law of soil mechanics". Relaxation is the reduction in the stress state at fixed deformation, which is a closely related time-dependent behavior to creep. Creep is often referred to as secondary compression, drained creep, and undrained creep depending on the application. In the lab, creep follows primary consolidation. However, since rates of consolidation scale with the square of the drainage distance, field consolidation times are millions of times slower than the laboratory scale. It is unclear if creep occurs <u>after</u> primary consolidation or if it <u>coexists</u> with primary consolidation. Given the dramatic difference in time scales, these two hypotheses can lead to very different deformation and potentially pore pressure predictions.

Creep under uniaxial loading conditions has been studied extensively in the laboratory using both an incremental oedometer and constant strain rate compression testing. Creep deformations follow a linear log-time relationship. Figure 6 illustrates the potential effect of creep on

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compression behavior for different time scales up to 10 million years. While the numbers are approximate and based on lab measurements, Figure 6 clearly illustrates that creep may be an important factor in assessing field porosities. For example, at a 5% creep rate, a 10 m.y. old rock under a load of 100 MPa (14,500 psi) would compact 0.08 additional porosity units relative to a material recently deposited (solid red vs. dashed black lines, Figure 6).
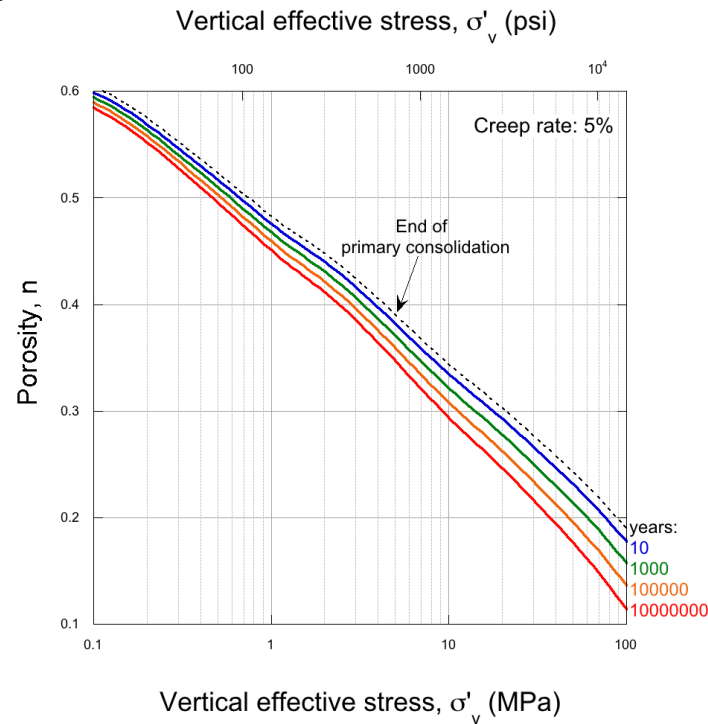

Figure 6. Effect of creep on compression behavior for different time scales up to 10 million years. End of primary consolidation (dashed black line) based on laboratory tests. Creep rate 5%.

Research Plan: We will perform uniaxial compression tests under varying strain rates as well as constant axial effective stress conditions (incremental loading) to characterize the creep rate and variation in the lateral stress ratio as a function of time and stress level. We will use rigid wall and triaxial devices to vary the drainage height and provide lateral stress measurements. The output of this study will be an understanding of how compression curves vary with strain rate. It will form the basis of a rate dependent mudrock model. We will also investigate how relaxation may alter the state of stress during uniaxial compression with a particular focus on how lateral stress (K_0) values change as a function of relaxation.

2.2   Poromechanical

2.2.1   Overview

The motivation of the poromechanical program is to study stress, pressure and deformation in complex geologic settings using field geometries and realistic material description. Our goals are to: a) estimate pore pressure and the full stress tensor under complex geologic loading; b) identify hazardous zones for drilling; c) advance our fundamental understanding of the interaction between pressure, stress, and deformation in basins; and d) develop a technical

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approach to address geological systems where large strains, pore fluids, and sedimentation interact. We will develop material models that describe the behavior observed in our experimental program (e.g., stress dependency, yield-surface rotation) and we will implement these models into numerical simulations. In addition, we will build 3-dimensional models of complex geologic systems and develop workflows to relate poromechanical results to velocity fields.

2.2.2   Incorporate more realistic material behavior within numerical models

Challenge: It is necessary to include this stress and path dependence in our poromechanical models to more accurately describe earth behavior. Simple critical state soil models assume a constant frictional strength, are insensitive to the rate of loading, and do not depend on the direction of loading. Our recent experimental work has demonstrated a systematic dependence of frictional strength, undrained strength, and lateral stress ratio on stress level. For example, the predicted stresses are fundamentally different when the material properties are strength dependent (Figure 7, right) relative to when they are not (Figure 7, left). We also observe a dependence of the yield surface and iso-volumetric surfaces on stress level and loading direction.

Research plan: We will develop an enhanced critical state model that will incorporate 1) the asymmetry (rotation) and evolution of the yield surface under complex geologic loading and high stress levels, 2) stress-level dependency of frictional angle, undrained strength, and stress ratio, 3) strain rate sensitivity. We will couple this new formulation with evolutionary numerical models.
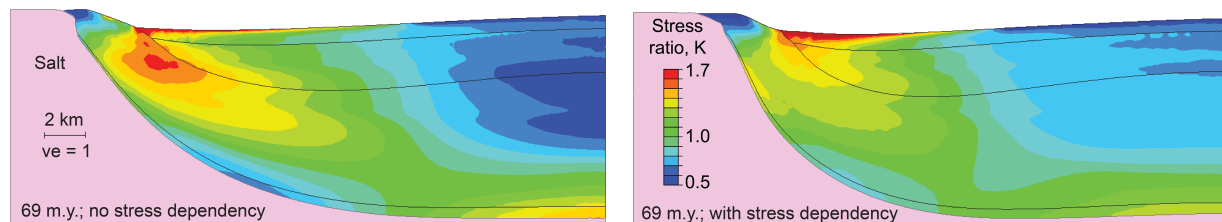

Figure 7. Preliminary study of the effect of stress dependency on a salt system. Decrease in the frictional strength with confining stress leads to a more uniform stress state near salt.

2.2.3   3-D models of complex salt systems

Challenge: We need to extend model results to three dimensions and understand under what conditions it is appropriate to extrapolate 2D results to 3D systems (Figure 8). A plane strain model significantly overpredicts the stresses relative to an axisymmetric model (Figure 9). Thus, while plane-strain and axisymmetric models may predict qualitatively similar behavior, the plane-strain approach predicts much higher values, because no deformation is allowed in the out-of-plane direction. At the same time the axisymmetric model may under predict stresses, because it cannot account for constrains in the circumferential (hoop) direction. Hence, neither approach fully represents the three-dimensional geometry of salt systems, which is complex.

Research plan: We will develop 3-dimensional models and study the effect of complex geometries to stress and pressure near salt. We will compare our results with plane-strain or

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axisymmetric models and provide criteria and guidelines for investing in a 3-dimentional study. We will work with industry to obtain real salt geometries, predict pressure and stress and compare with field data.
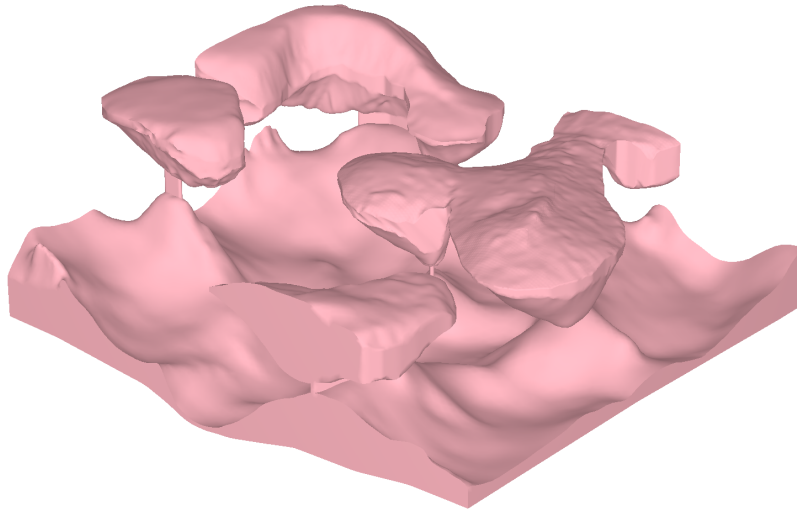

Figure 8. Salt system offshore West Africa, (courtesy of Repsol) illustrating the complexity of the 3D salt geometry.
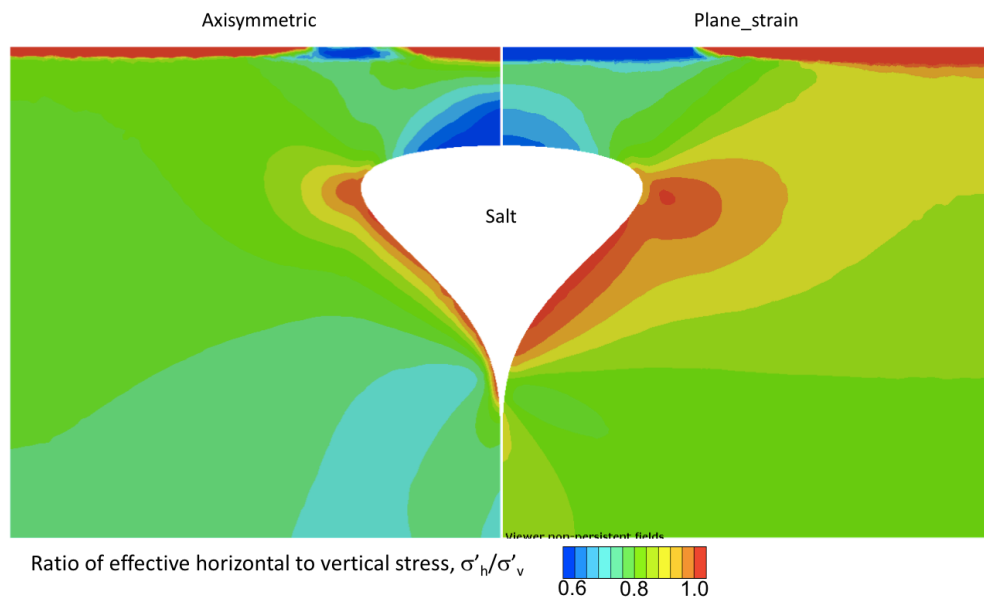

Figure 9. Axisymmetric vs. plane strain salt model. Both models predict qualitatively similar behavior, however the plane-strain model predicts much higher stress values.

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2.2.4 Synthetic Seismic of Poromechanical Models

Challenge: Our poromechanical models provide the full effective and total stress tensors, porosity and pore pressure predictions. We will develop seismic models of our poromechanical models to understand how pressure and stress are recorded in seismic data. The results may improve seismic imaging and ultimately allow inversion of pressure and stress from seismic data.

Research plan: We envision coupling poromechanical modeling, laboratory measurements, and seismic anisotropic-model building to develop the next generation of seismic analysis tools.

We will generate synthetic seismic data and images based on computed stresses (Figure 10A) and material properties from our poromechanical models. We will build anisotropic velocity models (Figure 10B) using published, and lab-measured, empirical and theoretical relations. We will use anisotropic models to create synthetic seismic shot gathers (Figure 10C) using the derived stiffnesses. A necessary intermediate step is the derivation of a rock-physics model to translate stresses to seismic velocities or elastic stiffnesses. Because the stress model is transversely isotropic (TI), the more convenient quantities to work in are the elastic stiffnesses. Initially, we will calculate directional-dependent velocities from the stiffnesses. Each cell in the TI model requires five independent stiffnesses. In this example (
Figure 10), the rock-physics used relates the effective stresses to the velocities. To derive this model, first, the well-log velocities are considered relative to the maximum principal stress along the deviated wellbore. The well deviation angle and the maximum principal stress angle dictate which anisotropic, angle-dependent velocity is measured along the wellbore. Once this is done, the range of fast and slow P-wave velocities expected throughout the model are known. The empirically derived rock-physics model relates the effective-stress components to elastic stiffnesses. It then transforms the poromechanical stresses to TI elastic stiffnesses at all locations (Figure 10B). The maximum principal stress direction determines the orientation of the fast and slow velocities.

For application to field data, we will use our effective stiffnesses for imaging using TTI reverse time migration. Resulting image gathers will be flat, which can be used for subsequent AVO analysis. Note that we estimate NMO velocity and η from anisotropic velocity analysis. These will be used together with velocity data (e.g., Figure 10) for quantitative interpretation (AVO analysis) and depth imaging of field gathers. Furthermore, we will develop inversion methods for directly estimating parameters other than NMO velocity and η, directly from field seismic data. We envision coupling modeling, lab measurements, and seismic anisotropic-model building to develop the next generation of seismic analysis tools.
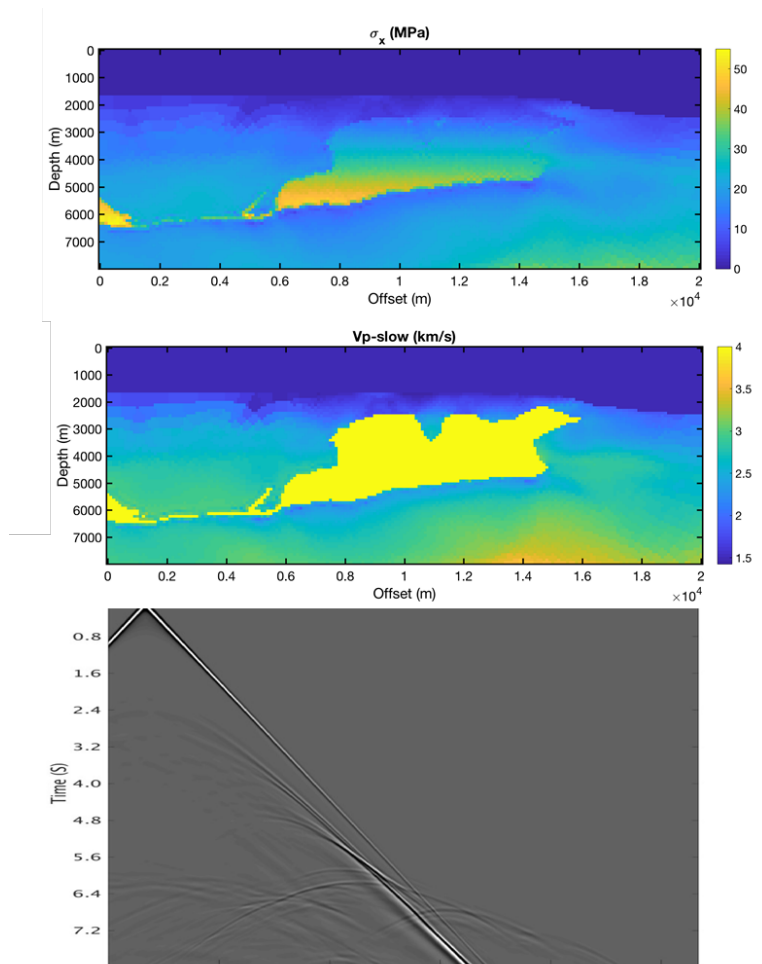
Figure 10. A) Stress field (in-plane horizontal stress) obtained from geomechanical model; B) slow quasi-P wave velocity obtained from (A); C) A synthetic seismic shot gather computed by finite differences using (B). All shot gathers will be processed and studied for AVO and anisotropic velocity analysis.

2.3   Field studies

2.3.1   Overview

We will continue to perform field studies in the Gulf of Mexico and elsewhere. Analysis of field data tests the effectiveness, approaches, and insights that we develop through our experimental and modeling work. It also trains the next generation of quantitative geoscientists.

2.3.2   Validation of poromechanical predictions with field measurements

Challenge: We have developed evolutionary poromechanical models that couple sedimentation with porous fluid flow and salt flow. We have also developed transient evolutionary models of fold-and-thrust belts. These models provide specific predictions regarding the state of stress, pressure, and deformation in complex systems. We will deliberate target data sets to test these predictions with field measurements.

Research plan: We will work with our industry members to obtain stress and pressure measurements in salt systems and in thrust belts. We will mine MDT and leak-off measurements from public databases. We will augment our estimate of stress state and pressure from borehole image logs. We will compare these field studies with poromechanical model predictions. This research will be instrumental in creating a road map that links porosity, overpressure, stress ratio, and mudrock strength with geometric features of salt systems.

2.3.3   Validation of pressure prediction workflows

Challenge: We have developed pressure prediction workflows that couple poromechanical modeling with seismic velocities. We have applied the workflow in a 2D transect in the Gulf of Mexico with limited well data. We will validate and test these approaches with analysis of field measurements in areas we apply these workflows.

Research plan: We will work with industry sponsors and service companies to release seismic data and pressure and stress data over specific fields with geometries that reflect our poromechanical model simulations. We will take advantage of newly released 3D seismic data available across the Gulf of Mexico. We will build static poromechanical models from present-day geometry and couple them with velocity data. We will validate our workflow by comparing pressure and stress predictions with available well measurements. We will use 2D and 3D poromechanical models and predict pressure across transects and across a three-dimensional area of interest. We will evaluate the relative benefits of investing into three-dimensional workflows.

2.4   Deliverables

1) Cuttings Protocol: We will deliver a protocol for on-site (on-rig) cleaning and testing of cuttings. We will provide correlations between liquid limits/clay fraction and stress ratio, friction angle, and undrained strength. This tool will allow quick estimation of least principal stress and strength during drilling.

2) Salt Pressure-Stress Atlas: We will build an atlas that relates salt geometry to pressure and stress predictions. This atlas will provide insights into qualitatively estimating stress, pressure, and hazardous zones near salt.

3) Road Map for Intact vs. Resedimented Behavior: We will build a database that compares intact with resedimented behavior.

4) Online Experimental Database: We will provide an online database containing our experimental measurements for use by the sponsors for internal evaluations.

5) Poromechanical Model Results: We will communicate and distribute poromechanical model results in standard industry software format and in excel spreadsheets, so that the insights are more easily applied.

6) Online Software: We will continue to build online software to communicate the concepts we are developing in UT GeoFluids.

7) <u>Workflows:</u> We will continue to develop our workflow to couple seismic models with poromechanical models to predict pressure and stress.

8) <u>Synthetic Seismic Images:</u> We will deliver tools and workflows to generate synthetic seismic datasets from our poromechanical models.

3   Logistics

The first payment will in May of 2019. The initial annual fee will be $50,000 and this will increment at 2%/yr. There will be no penalty for withdrawing from the consortium. Members who choose to join after the first year will be required to pay the previous year's consortium cost.

3.1.1   Current industrial associates
Industrial Associates which are currently members of the GeoFluids consortium, under the [Industrial Associate Agreement](#) will need to sign an Amendment.

3.1.2   Prospective industrial associates
Industrial Associates interested in joining the GeoFluids consortium will need to sign the original [Agreement](#) and an Amendment.

4   References

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