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SPWLA Young Professionals Newsletter

the bridge

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Throughout their career, FE specialists are expected to augment their interpretation capability and understanding of the subsurface through collaborations with a wide range of experts in other disciplines. To deliver integrated subsurface characterizations, it is especially useful to gain a basic understanding of these related disciplines. Therefore, as part of The Bridge's efforts to reach out to young professionals in the FE community, we would like to introduce and highlight some of the disciplines intimately related to petrophysics and formation evaluation. Dr. Nicolas Espinoza, a geomechanics specialist and an associate professor in the Hildebrand Department of Petroleum and Geosystems Engineering at The University of Texas at Austin, begins this series with the topic of geomechanics.

Dr. Espinoza earned his Civil Engineering diploma from Universidad Nacional de Córdoba in 2006, and his MS and PhD degrees from the Georgia Institute of Technology in 2008 and 2011. His primary research interests include the mechanics and physics of natural porous solids and granular media, including applications to advanced completion techniques, reservoir geomechanics, geophysics, and formation evaluation. The main fields of application of Espinoza's research are energy recovery from unconventionals and carbon geological storage. Dr. Espinoza has coauthored over 80 technical articles, served as an expert reviewer for several scientific and engineering journals, and given seminars at various leading research and educational institutions. Dr. Espinoza has made several contributions to the formation evaluation community, including the development of new acoustic methods to reveal the presence of fractures in shale formations, development of new methods to measure rock intrinsic mechanical anisotropy in a single tight rock plug, measurement and publication of petrophysical data of emerging unconventional formations, and identification and measurement of petrophysical properties of reservoir and seal rocks for safe CO_2 geological storage.

Geomechanics has had different meanings in the petroleum industry. Originally, it was related to drilling and wellbore stability. Then, its application broadened to encompass a wider range of reservoir issues, such as sand production and subsidence. In the last decade, geomechanics became intimately intertwined with oil and gas production efforts in unconventional reservoirs due to hydraulic fracturing. Geomechanics is relevant to all these issues and more! It should be considered each time rock deformation can have an impact on engineering and geoscience decision making in exploration, development, and production. In particular, geomechanics can be instrumental in optimizing decisions and resolving issues in the following situations:

(1) Exploration: Surface weathering processes and the movement of tectonic plates have changed the shallow lithosphere over millions of years. The current state of the subsurface is the result of the evolution of the Earth's lithosphere over geological time. Recent advances in geomechanics and structural geology have helped explain many features in the subsurface that, until recently, were not well understood. For example, current basin-scale geomechanical models can help predict pore pressure and the state of stress near salt domes, which are otherwise extremely challenging to estimate.
(2) Drilling and wellbore stability: Geomechanics helps minimize drilling and wellbore stability issues, thus saving operators millions of dollars by minimizing nonproductive time during drilling. Moreover, accurate geomechanical models and drilling techniques have enabled the drilling of HP/HT extended-reach wells in offshore environments.
(3) Hydraulic fracturing: In conventional reservoirs, petrophysicists focus on delivering interpretations to estimate storage properties. In unconventional reservoirs, understanding rock mechanical properties is at least as important as estimating storage properties because the reservoir stress state is the primary control for hydraulic fracture growth. Understanding the reservoir stress state significantly impacts well placement and well completion decisions.
(4) Production: Geomechanics helps prevent undesired phenomena such as excessive sand production and reservoir compaction and subsidence. Some of these not only affect production rates but also negatively impact surface facilities and adjacent wellbores. Geomechanics also plays an important role in EOR planning. Water or polymer injection may fracture wells and results in early breakthrough times with poor sweep efficiency. On the other hand, shale EOR can benefit from fractures when fracture geometry is used to set advantageous injection-production layouts.
(5) Waste disposal: Geomechanics has been of great help to reduce instances of induced seismicity due to the disposal of produced water. Such response is very site and rock specific, and recent advances have helped understand and control the link between pore-pressure increase and fault reactivation. Geomechanics is also helping transition towards a net-zero carbon energy scenario. Carbon geological storage is a key player to continue using fossil fuels while aiming for net-zero carbon dioxide emission. Similar to the injection of produced water, an excessive rise of pore pressure due to CO_2 injection can reactivate adjacent faults.
(6) Renewable energy: New breakthroughs in geomechanics are enabling a new era for deep geothermal energy production. Advances in hydraulic fracturing, directional drilling, and reservoir geomechanics are making possible geothermal systems with much higher power output than conventional single or double vertical well systems.

Many of the geomechanics applications described in the previous paragraph leverage log inputs and log-based interpretations. FE specialists, especially when working with unconventional assets, must therefore have a good understanding of rock geomechanical properties and their implications on reservoir stresses and hydraulic fracturing to collaborate with geomechanics experts, completion engineers, and drilling engineers. Geomechanics is also valuable in offshore environments with abnormal pore pressures. In these cases, LWD logging is critical to prevent well kicks and identify safe wellbore trajectories.

Therefore, the last section of this article introduces fundamental geomechanical concepts particularly useful for petrophysicists.

Solids deform when subjected to stress σ. The deformation (or strain ε) resulting from applied stress is inversely proportional to the material stiffness or elastic modulus, i.e.,

strain = (1/Modulus) * stress

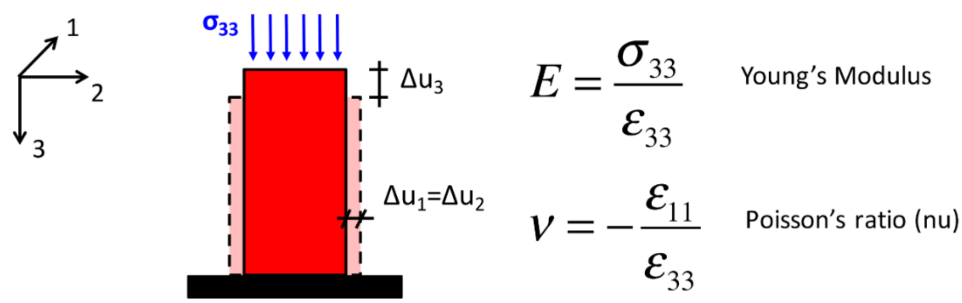

Fig. 1—Unconfined stress loading (compression) of a linear elastic isotropic solid.

Porous media are often filled with fluids at a given pressure. Hence, an appropriate correction for predicting solid strain is

strain = (1/Modulus) * (effective stress) = (1/Modulus) * (total stress – pore pressure).

When rocks are subjected to loading in one direction, as shown in Fig. 1, the elastic modulus is Young's modulus (*E*). 2D and 3D geomechanics applications require incorporating the perpendicular expansion effect resulting from the compression in the loading direction. This is quantified by the Poisson ratio, which is equal to the ratio between lateral strain and axial strain times –1.

Young's modulus characterizes the stiffness of a rock but does not tell us how strong it is. The rock strength is the maximum stress it can resist before showing significant irrecoverable strains or failure. For example, in Fig. 2, the strength of the rock under unconfined conditions is the peak stress ~3,800 psi, known as "unconfined compression strength." Rock strength can vary depending on in-situ conditions. Stiffer rocks tend to be stronger, but there is no universal relationship for such a trend.

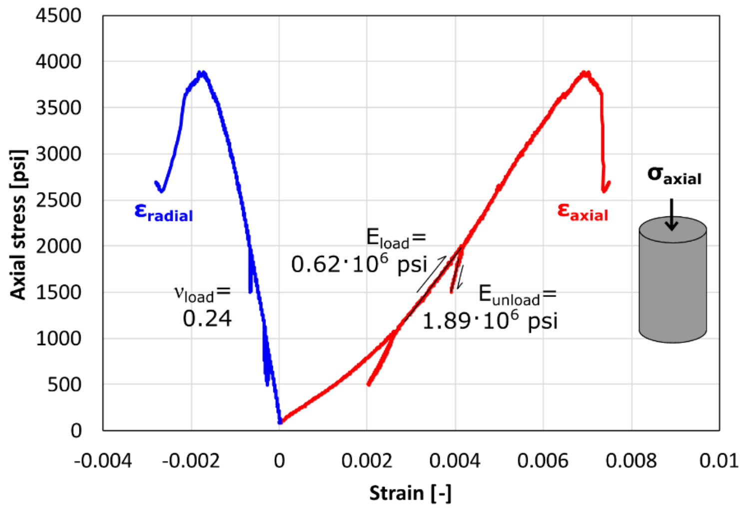

Fig. 2—Example of measurement of shale rock Young's modulus, Poisson's ratio, and strength under unconfined compression.

The equations above for stress and strain consider the rocks to be isotropic, yet many times this assumption does not hold for sedimentary rocks. Because of rock layering and particle orientation imposed in depositional environments, both stiffness and strength of sedimentary rocks are different in a direction parallel (horizontal) and perpendicular to bedding (vertical). A practical simplification for sedimentary rocks is the assumption of vertical transverse isotropy (VTI). Such extension requires quantifying two Young moduli (*E* vertical and *E* horizontal), two Poisson ratios (vertical and horizontal), and the vertical shear modulus. Usually, *E*(horizontal) > *E*(vertical) for intact rock, but the presence of vertical fractures can sometimes reverse this relationship.

Core measurements have paramount importance to accurately predict in-situ stresses and rock strength. Acoustic logs provide "small-strain" and high-frequency (fast-loading) elastic measurements. These are the so-called "dynamic mechanical properties." However, in-situ stress and reservoir response over long times depend on mechanical properties that reflect large strain and slow processes. Such loadings can be approximated through large strain and slow loading in the laboratory under triaxial conditions. These are the so-called "static mechanical properties." Correlations between dynamic and static properties are required to build and calibrate mechanical earth models and predict initial stresses and stress changes through time. Laboratory dynamic properties can also help establish these relationships, where $E_{static} = F_{ds} * E_{dynamic}$, with the empiric parameter F_{ds} ranging typically from ~0.4 to 0.8. Figure 3 shows an example of laboratory results for the relationship between static and dynamic properties for an unconventional shale formation. The relationships are site-specific and can be improved by working with a petrophysicist to recognize and group lithofacies.

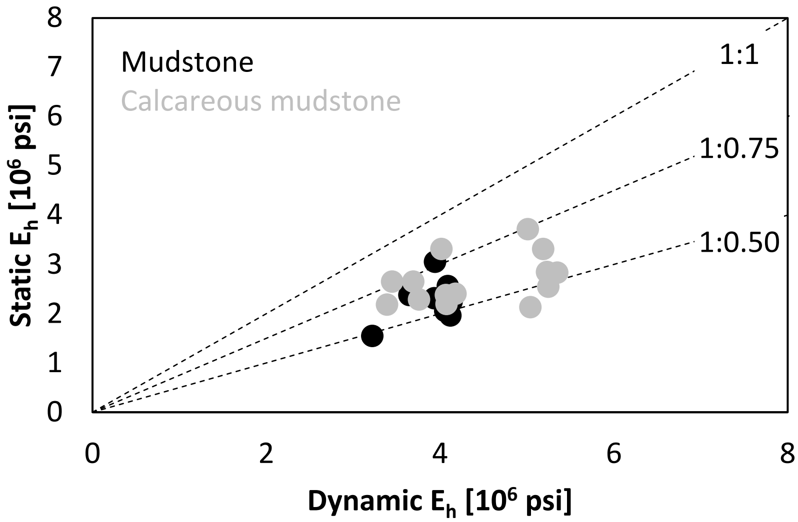

Fig. 3—Relationship between static and dynamic horizontal Young modulus for an unconventional formation. Static Young's modulus is usually 40 to 80% of the dynamic Young's modulus measured through acoustic traveltimes.

The workflow to build a geomechanical model from acoustic logs consists of the following steps (Fig. 4):

(1) Use the density log and directional survey to determine total vertical stress. The effective vertical stress must be calculated using direct or indirect pore-pressure measurements.

(2) Use the acoustic logs to determine the dynamic mechanical properties along the well (E and v for the isotropic case; E_h and E_v, v_h, and v_v for the VTI case). These values can be converted to the static Young's modulus and Poisson ratio using the static-dynamic correlations, i.e., parameter F_{ds}.

(3) Finally, the calculated mechanical properties along the well can be used together with a lateral loading assumption and the theory of linear elasticity to predict stresses as a function of "tectonic strains." The "tectonic strains" are calibration parameters that depend on the tectonic setting and can be adjusted based on field data such as DFIT tests and wellbore breakout angle measurements. The final stress calculation along the well is often called a "stress log."

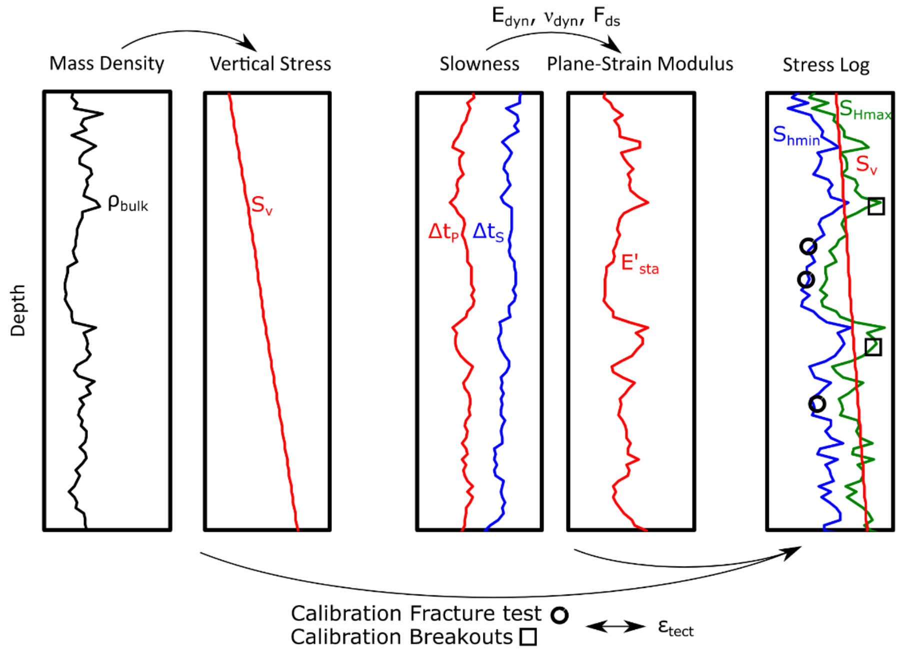

Fig. 4—Simplified workflow to calculate a stress log from wellbore logging data, field tests, and laboratory tests. The stress log permits identifying variation of horizontal stresses with depth and potential hydraulic fracture barriers.

Finally, we would like to end this article with a list of skills we believe petrophysicists should aim to acquire to become proficient in understanding and manipulating rock mechanical properties and geomechanics:

- Geomechanics core sample selection, planning, and interpretation of laboratory tests
- Interpretation of rock geomechanical properties from log measurements
- Estimation of pore pressure and understanding of disequilibrium compaction processes
- Fracture mapping from wellbore images and estimation of reservoir permeability in fractured formations from stress-based methods
- Fundamentals of stress profile prediction
- Fundamentals of wellbore stability to interpret fractures, breakouts, and washouts in borehole image logs and caliper measurements.

Nomenclature

E = Young's modulus
E_{dyn} = dynamic Young's modulus
E_{static} = static Young's modulus
E_h = horizontal Young's modulus
E_v = vertical Young's modulus
ν = Poisson's ratio
ν_{dyn} = dynamic Poisson's ratio
ν_{static} = static Poisson's ratio
ν_h = horizontal Poisson's ratio
ν_v = vertical Poisson's ratio
F_{ds} = static to dynamic correlation parameter
ε = strain
ε_{Tect} = tectonic strain
F_{ds} = static to dynamic correlation parameter
σ = stress
Sh_{Min} = minimum horizontal stress
Sh_{Max} = maximum horizontal stress
S_v = vertical stress
Δtp = compressional slowness
Δts = shear slowness
ρ_b = bulk density