What an engineer learned from applying geophysics to unconventional reservoirs

Ahmed Ouenes, FracGeo, The Woodlands, TX, USA

Introduction

The North American shale revolution has created many opportunities and operational challenges. While many of these challenges are often laid at the feet of engineers, the data and information which drives effective solutions however, comes from multiple disciplines. Geophysics remains the most affected discipline created by these challenges due to its lack of adaptation to the fast paced, low density and quality of data in unconventional reservoirs. Despite the lower for longer environment, geophysicists continue to have unrealistic expectations in terms of data availability and turn-around time of their deliverables thus missing the great opportunities that quantitative seismic reservoir characterization can bring to solving engineering challenges. These challenges can no longer be solved with the conventional approach where geophysics and other disciplines are disconnected and separated in different silos. The need for a true integrated approach where geophysics, geology and geomechanics are used simultaneously in new algorithms, workflows and a single integrated software is urgent. To better illustrate this urgency, an engineer who spent the last three decades developing and using geophysical algorithms to improve his engineering models shares his experience with geophysicists planning to work in unconventional reservoirs.

The two-major facts to remember when dealing with challenges in unconventional reservoirs are: 1) lack of data and 2) everything needs to be delivered in hours or days not weeks or months. Thus, any process that requires many advanced logs, high quality wide azimuth seismic, and efforts that are counted in weeks rather than hours is doomed from the beginning. The constant efforts to reduce costs and the fast-paced drilling of unconventional wells create a situation where a geophysicist requesting such working conditions will most likely have no job very soon. Given these tough constraints not commonly found in past conventional projects, combined with the perception found among all engineers that geophysics is not needed in unconventional reservoirs, what are the geophysical tools and workflows that could add value to engineers? To find these tools, one must first define the exact needs of the engineers dealing with unconventional reservoirs.

To drill and frac a successful unconventional well, an engineer needs to know 1) where to land and how to geosteer in his targeted zone, and 2) how to optimize his hydraulic fracturing while avoiding fracing hazards. Quantitative reservoir characterization provides answers to all these critical needs by using the appropriate new technologies adapted to unconventional reservoirs (Ouenes, et al. 2016). Below are some of the approaches that a geophysicist enabled with modern multidisciplinary software can deploy in few hours of work to add great value to the engineering challenges encountered in unconventional reservoirs.

Pre-stack inversion for landing and geosteering unconventional wells

Recently, most engineers and financial institutions bankrolling the unconventional shale revolution were surprised to find that unconventional reservoirs were not homogeneous reservoirs where all the drilled wells follow the same type curve. Thus, the concept of sweet spots became a priority and provided a unique opportunity for geophysics to shine. Since a sweet spot is defined as a rock that has a certain amount of resources that can be accessed through hydraulic fracturing (Ouenes, 2014), post and pre-stack inversion could be used to provide geophysical attributes that can directly or indirectly provide the necessary distribution of the rock properties contributing to the definition of the sweet spots.

Among the fast and efficient tools that could be used in post and pre-stack inversions is the colored inversion (Lancaster & Withcombe, 2000). A new variant of the original colored inversion quickly estimates an impedance model with a higher resolution than the original seismic thus providing a valuable engineering tool. The derived high-resolution impedance model could be transformed into

TOC, porosity and geomechanical properties through simple correlations, multivariate regression, or artificial intelligence methods using limited well data.

Another very powerful use of the colored inversion is with the facies constrained extended elastic inversion EEI (Kiche et al. 2016). In this process, the key geomechanical properties needed by the engineers can be derived quickly using pre-stack seismic data. The need to develop an improved version of the original extended elastic inversion EEI (Whitcombe et al. 2002) stems from the challenge posed by the lack of sufficient offset angles that rarely exceed 30 degrees in most of the seismic found for unconventional reservoirs. This fact creates major problems in the estimation of the density during the pre-stack inversion. To circumvent this chronic issue, the lack of information in the seismic data can be compensated by the provision of a facies model easily derived using decades old facies modeling technologies. In mathematics this technique is called regularization and in unconventional reservoirs it can be easily achieved using the gamma ray GR log which is found in every unconventional well. Unlike other techniques that attempt to estimate also the facies model from the pre-stack inversion (Naeini and Exley, 2017), this very quick approach uses all the available gamma ray logs and leverages them to define a facies model. A gamma ray model could be generated using geostatistics or neural networks and could be constrained by multiple post stack seismic attributes including the previously derived post stack impedance, multiple attributes derived from spectral decomposition and any other post stack seismic algorithm. Once one or multiple constrained gamma ray models are generated, the application of a simple cut-off could create one or multiple facies models. If actual facies are derived from available core or other conventional logs, then the Sequential Indicator Simulation (SIS) constrained by the previously derived post stack impedance could lead to multiple realizations of the needed facies model.

An illustration of this simple and quick approach based on gamma ray GR logs is shown for a Niobrara reservoir where we define three facies: Facies 1 for GR < 100, Facies 2 for 100<GR<120, and Facies 3 for GR>120 (Fig. 1A and 1B). Using the newly defined discrete facies log based on GR, a Sequential Indicator Simulation (SIS) geostatistical algorithm constrained by the post stack impedance derived previously with a colored inversion was used to populate the facies throughout the entire Niobrara reservoir. A cross section of one realization of the derived facies model is shown in Fig. 1C. A similar facies model could be derived by using the continuous GR logs and a neural network that uses as input multiple post stack attributes. Both techniques quickly provide the ability to create multiple realizations of a facies model while honoring multiple well logs that contain facies information as well as multiple post stack attributes derived from colored inversion, spectral decomposition and structural attributes such as volumetric curvature. A blind well (Fig. 2) shows the ability of the colored inversion to invert each angle stack thus enabling the facies constrained EEI to predict quickly dynamic elastic properties that have the appropriate magnitudes by facies. The extracted brittleness log (Fig. 2A) shows the low and high brittleness seen in the actual log (Fig. 2B). At the blind well, the correlation between the seismically derived and the actual brittleness log is 0.72 (Fig. 2C).

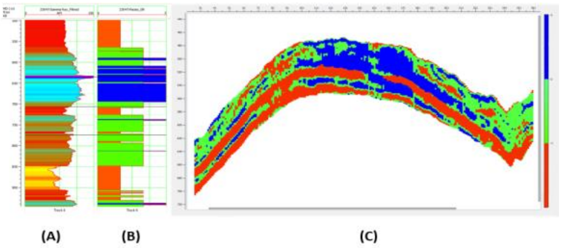

***Figure 1**:* (A) Original GR log and (B) discrete facies log derived by applying cut-off values to the GR log, (C) Cross section showing the facies model derived by using the Sequential Indicator Simulation geostatistical method to populate the discrete facies log in the entire 3D seismic survey.

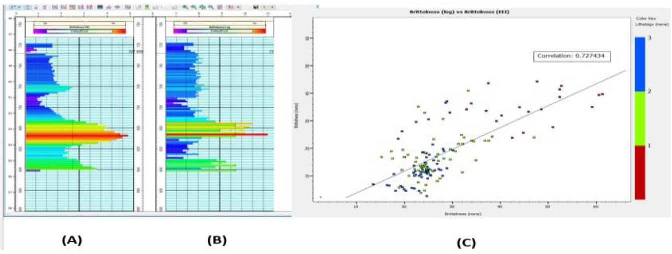

Figure 2 Seismically derived brittleness (A) compared to log derived brittleness (B). The correlation between the two logs is 0.72 (C)

The use of other inversion methods, such as stochastic inversion, instead of the colored inversion could be applied in the facies constrained EEI but will take few days instead of hours. This effort is reduced to few hours using a new fast stochastic inversion technology that will be released commercially in 2018.

The combined use of colored inversion, EEI and decades old proven facies modeling technologies cut down the time it takes a geophysicist to derive elastic properties using pre-stack seismic inversion from a few weeks to few hours. With such deliverables, the geophysicist could play a major role in helping the geologist and engineers pick the landing zone and geosteer in the targeted zone. The next step is to focus on the fracing of the correctly placed unconventional well. This fracing depends on the variable reservoir stresses along the wellbore. This variability in the localized stress field is created because of heterogeneous distribution in: 1) pore pressure, 2) elastic properties and 3) natural fractures. Let's examine how geophysics could help with the natural fracture modeling effort.

Seismically driven natural fracture modeling and subsequent geomechanical modeling of stresses

For many years geophysicists tried to use AVO concepts both for imaging natural fractures and more recently reservoir stresses (Gray et al. 2015). The drawbacks of this approach include the drastic and sometimes unrealistic assumptions made to derive the necessary equations, the need for wide azimuth seismic and the resulting poor vertical resolution of the deliverables. For multiple reasons related to costs and resolution, these techniques have contributed to the perception that geophysics does not add value to unconventional reservoirs development. To the contrary, geophysics could play a major role in creating value when estimating natural fractures and reservoir stresses if the proper methods are used.

An example of such value creation is the use of geophysical attributes to model the distribution of natural fractures. Since natural fractures measured along the wellbore or estimated from multiple proxies, including using surface drilling data (Jacques et al., 2017), could be available at multiple wells, geophysical attributes could provide the necessary information known in structural geology to influence the presence of natural fractures. For example, the density of natural fractures at a given point in the reservoir does not depend on poorly sampled statistics of various fracture sets measured through limited wireline data, but on the volumetric distribution and interaction of lithology, structural settings and distance to faults, porosity, and many other reservoir properties that compete to create the resulting natural fractures. These reservoir properties commonly called natural fracture drivers could all be estimated directly or indirectly through seismic processes that involve the post and pre-stack inversions described in the previous section along with multiple attributes derived from spectral decomposition and structural attributes such as volumetric curvatures. This seismically driven approach (Jenkins et al. 2009) has been successfully used during the last three decades and has provided engineers the necessary information needed to handle natural fractures including those found in unconventional reservoirs where their impact is significant. This impact could be positive through the creation of additional surface contact during hydraulic fracturing commonly referred to as frac complexity that can be sometimes imaged with microseismicity (Aimene and Ouenes, 2015). The contribution of the natural fractures could also be negative by creating frac hits through poro-elastic effects (Ouenes et al. 2017) that will often damage the production from child and parent wells. Thus the need for an accurate and validated natural fracture model and that can only be achieved when geophysics is used.

The cumulative effect of fractures and stresses will determine the outcome of the hydraulic fracturing. So, it is critical to first constrain the multiple sources of stress gradients in a reservoir, and simulate their interaction to understand local stress heterogeneity. In addition to elastic properties and natural fractures, the last reservoir property that has an impact on the reservoir stresses is the pore pressure which has been computed by geophysicists in multiple ways or estimated by engineers through reservoir simulation when dealing with existing depletion. With the help of geophysics, the three key factors affecting the stress gradients were computed and ready to be used as input in the continuum reservoir geomechanics (Aimene and Ouenes, 2015) workflow that provides the reservoir stresses.

The geomechanical model simulates the proper initial stress conditions resulting from the various sources of stress variability followed by the simulation of hydraulic fracturing in this heterogeneous stress medium. Since microseismic data is limited to only a few wells, the geomechanical approach using the seismically derived reservoir inputs, can predict microseismicity rather than use it as calibration, thus validating the geophysical inputs and the geomechanical approach that uses them simultaneously (Fig. 3). The resulting hydraulic fracture geometries and their subsequent use in production forecast provide engineers a more accurate representation of the stimulated volume and the resulting reservoir depletion.

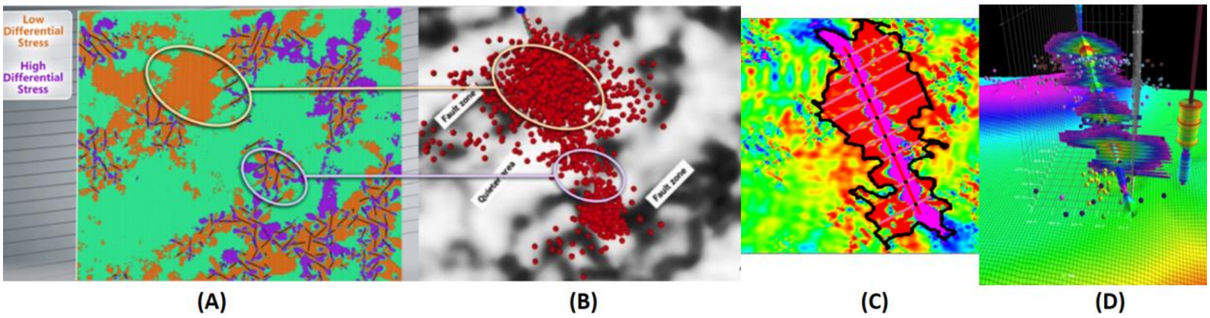

Figure 3: Differential stress (A) and strain (C) validated with microseismicity (B) and the resulting geomechanically constrained hydraulic fractures (D) that benefited from the geophysical input

Conclusions

Geophysical data plays a key role in understanding and developing unconventional reservoirs. Operational constraints however, often devalue these data, most often due to time and ability to be reconciled with engineering workflows. Through integration of multiple disciplines in a single software platform, the set-backs to using geophysical data for unconventional development can be overcome and provide timely deliverables to address various stages of unconventional exploration and development. This can be achieved through de-siloing asset teams, and integrating workflows to leverage all available data.

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