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Unconventional resource evaluation and applied geophysics utilising LMR

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SUMMARY

Over the last decade the oil and gas industry has delivered conceptual and technical changes that have entirely changed the fundamentals of natural gas supply in North America. Underpinning the step change in natural gas reserves and market ready supplies has been the change in the perception of fine-grained, organic rich rocks (i.e. shales – although of course not all shales are organic rich). No longer are such rocks viewed only as source and seal candidates, but also as source rock reservoirs or shale gas plays.

Although the geological continuity of shale gas plays have led to the production-line style operations seen across North America in mature unconventional plays, it is not "factory-style" efficiency improvements in isolation that allow the economic exploitation of shale gas. The large number of fit-for-purpose technologies, introduced by operators and service companies, has been critical in increasing production while keeping costs flat and/or reducing costs and time to production.

3D seismic data play a key role in unconventional developments as a unique look-ahead dataset. The role of seismic, however, has evolved to be far more than simply a tool for mapping major structures. For example, through AVO inversion we are able to make predictions regarding elastic properties of the formations of interest. The integration of AVO inversion data with engineering and rock physics data is providing new avenues of data exploitation. Seismic data are also being used to predict closure stress and stress anisotropy, which can be calibrated with data and analysis from hydraulic fracturing. Additionally, the integration of surface seismic data with microseismic provides a means of fine-tuning the estimation of stimulated rock volume.

Key words: Unconventional, shale gas geophysics, LMR, integrated workflows.

INTRODUCTION

Source Rock Reservoir (SRR) or "shale gas" plays, as they are almost ubiquitously known, can be produced at high rates through a combination of two key technologies, namely horizontal drilling and hydraulic-fracture stimulation. These `technological advances`, which led to the initial exploitation of the Barnett Shale in and around Dallas and Fort-Worth, were not new to the industry. This supports the notion that technological advances must be partnered with in-depth knowledge and understanding of a problem or challenge for maximal impact. To those that have entered the industry since the concept of shale gas was a given it is almost inconceivable that these technologies would not be routinely applied. Similarly, the increased application of micro-seismic monitoring in the field seems like an obvious technology to complement fracture stimulation treatments – however, such hindsight glosses over the deep expertise, foresight and understanding of the early proponents and adopters of this technology that has fundamentally changed the way fracture treatments are assessed.

SRR plays are often referred to as "resource plays" due to the perceived (and actual) reduction in geologic risk associated with their development. This reduction in geologic risk is, however, purely technical; the risk of achieving non-economic returns on a given development is of course much higher due to the large number of factors that impact life of field economics and the capital intensive nature of unconventional field development.

To be economically viable the scale of an SRR resource must be such that lifting costs can be driven down through fit-for-field technology and operational efficiency gains during initial development stages and that subsequent exploitation takes advantage of realised cost reductions. During these stages thousands of horizontal wells are drilled and tens of thousands of hydraulic fracture stimulation stages completed.

The intense focus in SRR plays on reservoir contact, Stimulated Rock Volume (SRV), and induced fracture networks has increased the attention paid to the rock physics or geomechanics within the reservoir. Whereas in conventional plays geomechanics studies were typically focused on wellbore stability or sand production, in shale gas plays it is the moduli of the rock (and any anisotropy in these moduli) and how the rock responds to fracture treatments that is of greatest interest. This is an expertise that has traditionally resided with a subset of geophysicists and provides further opportunity for collaboration between geophysics specialists and interpreters, geologists, engineers and other subsurface specialists.

METHOD AND WORKFLOWS

Geophysicists have leveraged the natural geometry of multi-fold seismic data to extract information about the shear properties of rocks for a number of decades using amplitude variations with offset or angle (i.e. AVO). AVO methods exploit variations in seismic compressional and shear wave velocities or impedances to infer changes in lithology, pore fluids or other changes in the subsurface. A number of industry standard methodologies for quantitative interpretation are commonly utilised, with interpreters leveraging existing paradigms regarding the meaning of certain seismic and AVO characteristics.

Understanding velocity or impedance measurements in Lamé parameter terms of incompressibility (λ) and rigidity (μ) provides an alternative interpretation methodology (Goodway et al., 1997). In addition to these two parameters Goodway et al. (1997) introduced two new attributes, LambdaRho ($\lambda\rho$) and MuRho ($\mu\rho$) or Lamé impedances, that could be calculated using AVO and referred to the method as Lambda-Mu-Rho or LMR. The calculation of $\lambda\rho$ and $\mu\rho$ from AVO outputs is relatively trivial (Equations 1 and 2) once compressional and shear impedance volumes are available.

$$\lambda\rho = Ip^2 - 2Is^2 \qquad 1$$

$$\mu\rho = Is^2 \qquad 2$$

...where Ip=acoustic impedance and Is=shear impedance.

Rock physics model (RPM) based interpretation templates for LMR or other elastic parameters can be used to facilitate interpretation and comparison of log or seismic derived elastic properties. Relatively general templates (Figure 1) can be used to gain rapid insights and compare log data and AVO inversion outputs, however, with additional information regarding mineralogy and porosity calibration points from core and log data templates specific to individual plays can be created.

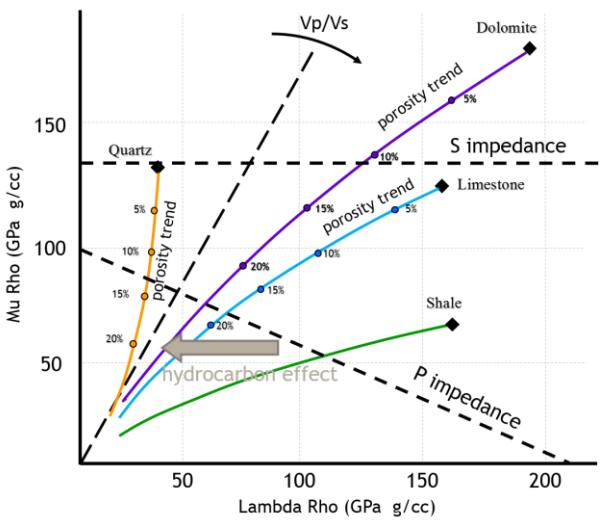

Figure 1. A general rock physics model interpretation template in the LMR domain. Porosity increases towards the origin, impedance and Vp:Vs iso-lines plot as indicated.

The creation of RPM templates requires assumptions regarding specific rock physics models. For example, Perez (2013) describes two distinct models for which seismic interpretation templates for unconventional evaluation can be created, one based on an additive granular model and another on a subtractive or inclusion based model. Of these two models the additive model is more intuitively relevant to the study of sedimentary rocks, however, due to the typically laminated and fine grained nature of source rocks and the resultant crack like porosity the subtractive model can also be appropriate. The diversity in textures of SRR plays has been well established through electron microscopy (e.g. Figure 2).

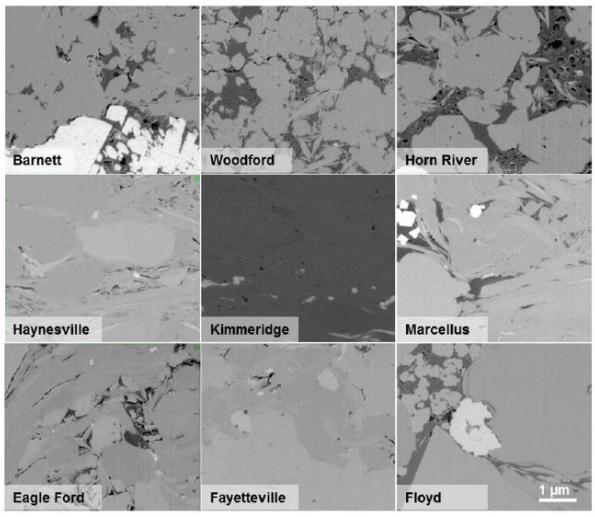

Figure 2. A collection of scanning electron microscope images of source rock reservoir plays from across North America illustrating the diversity in textures observed (Curtis et al., 2010).

The micro-scale heterogeneity of SRR plays, both in texture and mineralogy, contributes substantially to differences in the performance of individual wells, pads and areas within a play. Of fundamental interest to geophysicists is mapping changes in micro-scale properties to variations in elastic properties at the wavelet scale that can be detected or resolved through AVO inversion.

Close et al. (2012) illustrate a workflow to correlate instantaneous shut-in pressure data recorded during hundreds of hydraulic fracture stimulation stages with Closure Stress Scalar (CSS) estimates based on AVO inversion. The CSS is of interest as the minimum horizontal closure stress, defined as the minimum pressure required to open a pre-existing fracture or plane of weakness, must be exceeded to propagate fractures away from the wellbore after a fracture is initiated (typically at some higher pressure – the breakdown pressure) (McLennan and Roegiers, 1982). Accordingly, the minimum closure stress impacts stimulation efficiency and efficacy and is of substantial importance from an operational and economic standpoint. The closure stress equation given by Sayers (2010) was recast by Goodway et al. (2006, 2010) in terms of Lambda and Mu:

$$\sigma_{xx} - p = \frac{\lambda}{\lambda + 2\mu}\left[\sigma_{zz} - p\right] + \frac{\lambda}{\lambda + 2\mu}\left[2\mu\left(\frac{\varepsilon_{yy}^2 - \varepsilon_{xx}^2}{\varepsilon_{yy}}\right)\right] \qquad 3$$

...where

$\sigma_{xx} - p$ is the effective minimum horizontal closures stress

$\sigma_{zz} - p$ is the effective vertical stress (overburden stress)

ε_{xx} and ε_{yy} are the strains in the minimum and maximum horizontal stress directions respectively.

In the isotropic case, where the tectonic strain energy vectors (ε_{xx} and ε_{yy}) are equal, this equation reduces to simply:

$$\sigma_{xx} - p = \frac{\lambda}{\lambda + 2\mu}[\sigma_{zz} - p] \qquad 3b$$

From Equation 3b it follows that the minimum amount of pressure that must be applied to open a fracture ($\sigma_{xx} - p$) and overburden-pore pressure differential ($\sigma_{zz} - p$) are related by:

$$\frac{\lambda}{\lambda + 2\mu} \qquad 3c$$

Goodway et al. (2010) label Equation 3c the Closure Stress Scalar (CSS) or bound Poisson's Ratio. This term is effectively a rock quality factor.

Integrated geoscience-engineering workflows bring together disparate data sets from entirely different 'experiments', that is the elastic perturbation of the rock from a distal seismic source contrasted with the destruction of the rock from the high-pressure slurry pumped into the formation during hydraulic fracture stimulation. It should be noted that the scale of these experiments are in some respects quite similar, the amount of rock averaged by a seismic frequency wavelet is in many instances not substantially different to the amount of rock that is contacted through modern, large scale hydraulic fracture stimulations.

Utilising engineering data in the workflow of Close et al. (2012) provides a means of calibrating AVO data in an environment where traditional calibration tools are limited due to decreased logging frequency relative to conventional development wells and the lack of a direct correlation between production and a single point in the subsurface (as production is generally comingled from a horizontal up to 2 km long with up to 15 or more individually stimulated intervals). Figure 3 shows an example of the qualitative correlation of measured instantaneous shut-in pressures (a proxy for closure stress), mapped CSS estimates from AVO inversion, and production results, which supports a positive correlation between lower CSS values and improved fracture stimulation efficacy and correspondingly increased production (Close et al., 2012).

Geophysicists can also leverage standard interpretation workflows to assist in mapping major structures and horizons, providing full stack or azimuthal stack attribute volumes, such as curvature or coherency, to assist in mapping faults and other geohazards when drilling horizontal wells. Expertise in velocity modelling and seismic methods is also key to providing critical quality controls and insights into the interpretation of microseismic data. The growth in the microseismic monitoring industry is testament to the value placed on the insights provided by these data; but the accuracy of these data is highly dependent on assumptions about both vertical and horizontal velocities (e.g. Maxwell, 2009).

CONCLUSIONS

Shale gas plays present some unique challenges to geophysical interpretation. Impedance contrasts are often small relative to conventional reservoirs and structural height is not a primary control on well productivity. Additionally, the conventional means by which AVO inversions are quality-controlled, using blind wells or production results that can be associated to a specific reservoir interval, are less effective in these plays where long reach horizontal wells are rarely logged and production is comingled from kilometre's worth of reservoir. For these reasons it is necessary to attempt to use novel means of determining the validity and utility of AVO inversion data. AVO inversion results can be indirectly calibrated by using data from independent sources, such as completion engineering data and average production data.

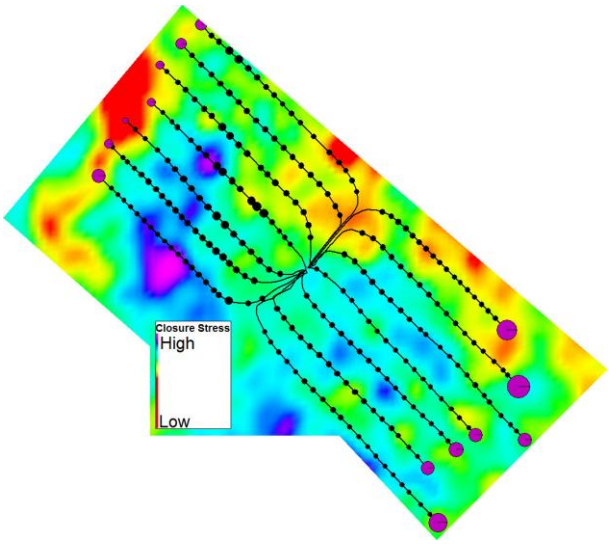

Figure 3. Closure stress scalar map extracted from an AVO derived volume compared to instantaneous shut-in pressure (ISIP) per stimulation stage (black circles where size is proportional to ISIP) and initial production (purple circles at well toes where size is proportional to initial production normalised by the number of stages).

Even without independent calibration, AVO inversion data illuminates heterogeneity and can be used to map sweet spots, laterally and vertically, using the relative differences in inferred rock properties. Templates based on rock physics models help understand how such sweet spots manifest in AVO inversion data. The templates and analysis of data from the Horn River Basin suggest that in general lower $\lambda\rho$, higher $\mu\rho$ and correspondingly lower CSS values are indicative of better reservoir – although it should be noted that for a quartz rich lithology an increase in MR is largely indicative of decreased porosity.

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