Global Cross Application of Shale Gas Development Work Flows Revealed

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ABSTRACT

China has seen its natural gas consumption rise significantly over recent years. As a result, unconventional energy, specifically shale gas, has become a focused alternative. However, major challenges to develop efficient shale gas extraction, such as the geology, undulating terrain, lack of water resources, immature expertise, prevail. Thus, large scale commercial production of shale gas remains in its infancy.

The Sichuan basin is a testament of this where exploration and production of unconventional reservoirs have taken place since the 1950s. With the basin resting in a major compressional tectonic area, part of the shale gas reservoirs is fractured, sensitive to abrupt structural dip changes and faulted standoffs. This complicates reservoir stimulation with unpredictable fracture orientations and growth. Lateral property changes within the reservoir and varying stratigraphic thickness adds to this shortcoming.

To shorten the learning curve, successful and established workflows from US plays such as the Eagle Ford, Marcellus and Barnett were introduced. From these plays, it was established that different shale plays retain distinct differences that were addressed through customization in the process and workflows. The differences were identified through detailed evaluations of reservoir quality (RQ) and completion quality (CQ). However, to address the local challenges during well construction, a new focus is needed with the introduction of drilling quality (DQ).

In this aspect, PetroChina South West Oil and Gas Company (SWOGC) operating in one of the Sichuan shale plays adopted the above workflow to accumulate and analyze the data with the objective to establish the main drivers for reservoir production towards recovery enhancement. Consequently, the customization of process and workflows to support large scale commercial shale gas development in the Sichuan Basin can be achieved.

INTRODUCTION

In recent years, shale gas took a pivotal role in the global gas market and it has created a gas revolution in North America. According to the US Energy Information Administration (EIA) report in June 2013, among 137 formations assessed in 41 countries outside the United States, China is listed as having the largest technically recoverable shale gas resources and third largest technically recoverable shale oil after Russia and US.

\begin{table}[h]
\centering
\begin{tabular}{|c|c|}
\hline
Rank & Country \ & Shale gas
\hline
1 & China & 1,115 \\
2 & Argentina & 602 \\
3 & Algeria & 707 \\
4 & U.S. & 665 (1,261) \\
5 & Canada & 573 \\
6 & Mexico & 545 \\
7 & Australia & 437 \\
8 & South Africa & 390 \\
9 & Russia & 285 \\
10 & Brazil & 249 \\
\hline
\end{tabular}
\caption{Top 10 countries with technically recoverable shale gas resources (EIA 2013)}
\end{table}

\begin{table}[h]
\centering
\begin{tabular}{|c|c|}
\hline
Rank & Country \ & Shale oil
\hline
1 & Russia & 75 \ (48) \\
2 & U.S. & 58 \\
3 & China & 32 \\
4 & Argentina & 27 \\
5 & Libya & 26 \\
6 & Australia & 18 \\
7 & Venezuela & 13 \\
8 & Mexico & 13 \\
9 & Pakistan & 9 \\
10 & Canada & 9 \\
\hline
\end{tabular}
\caption{Top 10 countries with technically recoverable shale oil resources (EIA 2013)}
\end{table}

According to the 2013 China Land and Natural Resources report, it is estimated that by 2020 China shale gas contribution will account for 26% of total natural gas consumption in the country and play an important role in China’s natural gas industry.
Background and Geological Setting

Sichuan basin is located in the central region of China and holds the largest shale gas reserve of the country with a total area covering 74,500 square mile. With existing gas pipeline and availability of water supply, the favorable infrastructure makes Sichuan basin the most promising shale gas region in China.

PetroChina started Sichuan shale gas pilot project in 2009 and is currently accelerating the development progress in order to achieve the aggressive production target. From the research and exploration data in the Sichuan basin, three sets of marine shale formations from the Paleozoic era were identified as the most promising shale gas reservoirs: Lower Cambrian Qiongzhusi Formation, Lower Silurian Longmaxi Formation and Upper Permian Longtan Formation. Among them, the Silurian Longmaxi and the Cambrian Qiongzhusi Formation are highlighted as the most perspective targets with thick rich organic formation and low clay content favorable for hydraulic fracturing stimulation treatment.

Log and core data analysis established that the Longmaxi has an average TOC between 1.2% to 8.65%, effective porosity of 5.1%, gas content of 5.2 m³/ton, with a general lithology composition of 48.9% quartz, 20.9% carbonate content and 28.3% of clay. The organic matter found is mainly Type I - II kerogen, with vitrinite reflectance (Ro) ranging from 2.0% to 3.6%.

Analog Formation

The United States and Canada have demonstrated significant success in shale gas development and are the main commercial producers in the world. However following the footsteps to copy the successes in North America is not as easy as it appears. More complex geological setting and lack of surface infrastructure in some locations makes China less favorable to shale gas development as compared to North America. With most of the shale basins in China located in tectonically active area with extensive folding and faulting, these challenging circumstances will potentially slow down the shale gas commercial development in China.

As all shale plays are not the same, looking for a global analog formation will depend not only on the rock composition, but also the mechanical rock properties with in-situ stresses and pressure, as well as presence of natural fractures and faults in the area. Comparing against the major shale plays in North America, the closest analog to Sichuan Longmaxi formation may be the relatively faulted part of central Marcellus shale in the Northeastern of United States. Both formations have similar deposition age, both are thick marine sedimentary rock with rich organic black shale, both shales have siliceous to calcareous mix, dry-gas prone, well documented faults and natural fractures with large horizontal stress anisotropy in faulted area.

Horizontal Well Evaluation

The success of shale gas development is mainly contributed to the advancement in horizontal well drilling and multi-stage hydraulic fracture treatment. To produce from these tight formations within economical limits, most horizontal wells are drilled with minimal
measurements. Although some wells are logged using advanced LWD tools, in most cases the acquired data are only used for real-time well placement application with very few datasets processed for formation evaluation. This is due to the simple reason that these measurements are generally poorly understood. In Wei 203-H1 horizontal well drilled in 2011, LWD data was acquired but not used for quantitative petrophysical analysis for this very reason (Lv 2013).

LWD logging was introduced more than 25 years ago applying the same measurement principles as wireline logging tools. This technology provides formation and downhole measurements in real-time for petrophysical evaluation and enables fast decision making during well construction for trajectory steering or well control. Successful examples are available that discuss how this information can be utilized for advanced interpretation (Han 2010).

In this study, detail comparison were made between wireline logging data acquired in a vertical well and LWD data acquired in a horizontal well. The most obvious difference between these two datasets comes from resistivity measurements. Knowing that propagation resistivity from LWD is affected by bed boundary effect in high angle wells, additional processing was run to derive true formation resistivity prior to petrophysics analysis. In the general perspective, LWD and wireline logging response kept within the same tolerance over the zone of interest. The histograms in Figure 2 provide detailed comparisons between LWD and wireline data.

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Figure 2: Measurements comparison between LWD data from horizontal well (on top row) and wireline logging data from vertical pilot well (on bottom row) over the same zone of interest

INTEGRATED HORIZONTAL WELL OPTIMIZATION WORKFLOW

As LWD logging becomes more popular in shale gas horizontal well in recent years, a new workflow was introduced to integrate all the measurements for formation evaluation and completion optimization. Real-time data is used for lateral landing and placing the horizontal borehole within the predefined geological target. Logging data is used for reservoir characterization computing rock properties along the lateral. This information can then be applied to customize staging algorithm and perforation design, to optimize fracture treatment with the aid of microseismic data, and to tie computed RQ and CQ to production results for production analysis or as an input for reservoir simulation. The overall workflow is illustrated in Figure 3 below:

While a portion of the workflow describes the well construction process, majority of the workflow concentrates on post well evaluation and stimulation treatments using the reservoir quality (RQ) and completion quality (CQ). Reservoir quality is defined by petrophysical parameters of organic shale leading to hydrocarbon storage and producibility. The key petrophysical parameters include organic content, thermal maturity, hydrocarbon filled porosity, effective permeability, hydrocarbon saturation and pore pressure.

Completion quality is defined by collective parameters that are required to effectively stimulate reservoir through hydraulic fracturing. The key geochemical parameters are elastic properties of rock, in situ stresses, mineralogy specifically on clay content and clay type, presence and orientation of natural fractures. These parameters will in turn have an impact on the fracture containment, fracture complexity, retention of fracture area and fracture conductivity.

From local drilling records in Sichuan basin, it is evident that most operators face borehole stability problems including loss circulation that often lead to stuck pipe
incidents while drilling shale gas wells. The complex geological setting with multiple faults and abrupt formation dip changes contribute to the high probability in drilling out of zone along the horizontal drainhole section. To address these additional challenges, a customize workflow that highlights on well construction is introduced. Drilling quality (DQ) emphasizes on risk mitigation to improve well drillability, increase drilling efficiency and successful well placement to maximize reservoir contact.

DEFINING THE THREE CORE QUALITIES

Drilling Quality (DQ)

Drilling for shale gas in the Sichuan Basin began since 2009 and is by far the most active shale leasing and drilling basin in China. Operators such as PetroChina, Sinopec and Shell have ventured into developing their leases (EIA 2013). Wells targeting the Silurian Longmaxi Formation in Weiyuan district normally range around 3500m in TVD and employ production laterals around 1000m to 1500m long. While the first horizontal well took up to 11 months to construct, improvements to well construction practices and drilling practices reduced this to approximately 2 months (Figure 5). Continuous improvement employing lessons learned, drilling the Longmaxi shale have effectively reduced well construction period down to 34 days in 2014.

However, this still exceeds the general construction time reported in most North America shale plays. Thus continued efforts to find ways to achieve “High Quality and Low Cost” targets to keep the unconventional gas development project profitable predominates science.
**Top Hole Section**

The main challenges in drilling the top hole section are mud losses, slow penetration rate, safety and keeping the borehole vertical. Drilling through the Leikoupo and Jialingjiang carbonate that consists of cave developments, surface faults and fractures unavoidably results in severe mud losses. In the beginning, water was used for drilling with the anticipation that the cutting will plug the formation. However, drilling records show that the plugging effect from cutting is poor while water supply is far and costly. Consequently, operators turned to aerated drilling, reducing drilling fluid density to less than water, thus preventing losses and improving drilling speed.

In some areas such as Changning district, to drill through harder formation such as Shiniulan, operators use underbalanced drilling to gain penetration rates of 5m/hr in comparison to 0.3 to 0.5m/hr overbalanced; however, this exposes the risk of getting a kick. It is fortunate that in the Weiyuan area, the Shiniulan is not developed, and is drilled predominantly overbalanced with water.

Formation drillability is a risk factor with shale breakout and hole collapse in the Longtan Formation. Slow penetration rate (ROP) is also encountered in Maokou and Qixia formations due to the presence of pyrite and chert. In these formations, the average ROP using tricone bit were in the range of 2 to 3 m/hr. Through studies, an optimized PDC bit was introduced that made improvements of 4 to 10 m/hr.

In addition to these challenges, hydrogen sulfide is also present in certain areas. For example, the Maokou formation can contain hydrogen sulfide in the range of 0.81 ~ 16.52 g/m³.

To maintain verticality of the top section, MWD guided drilling is employed to control deviation. This also contributed to the reduction of construction time whereby, the maximum deviation in inclination improved from 9.5deg to 3.2deg.

**Directional Section**

The main challenges the intermediate and horizontal section primarily suffers from are geological uncertainties and borehole instability that would directly lead to high cost of construction and the potential of poor production.

Geological uncertainty such as unknown formation dips, seismic and sub-seismic faults, hard and abrasive formation, low pore pressure are common challenges with Sichuan’s unconventional gas drilling. To provide a perspective of the local geological environment, LWD measurements such as images either from gamma ray or density offers a vision via near borehole interpretations, while rotary steerable system (RSS) technologies with high dog leg severity capability offers the ability to efficiently reach the geological landing target and step out the horizontal. This results in the reduction in time and increase reservoir exposure from a shorter vertical section to position the production lateral.

In some areas, to reduce the drilling problems, the Longmaxi formation is drilled underbalanced using Saraline Based Mud (SBM). Accidental penetrating to the lower Baota formation underbalance inevitably leads to severe kick. Hence it is paramount that the lateral is steereed within the Longmaxi formation.

In the Weiyuan district, high sick and slip conditions and sliding difficulties makes up the challenge in getting to the Longmaxi target. Thus, OBM is used overbalanced at 18ppg along with high dogleg severity RSS drilling tools in the curve section. It is also employed in the lateral section to provide well placement steerability.

Additionally, advanced and scientifically designed bits play a major part in the rock penetration efficiency. Nevertheless, the accumulation of technological wish lists would go against restraining construction costs where low cost, high quality boreholes and fast ROP are main considerations for unconventional shale gas development. It becomes obvious that advance technology and low cost contradicts, whereby operators and vendors very often struggle to find the critical balance between efficiency, cost, risk and safety.
Reservoir Quality (RQ)

Using LWD data for reservoir characterization in horizontal wells, the process can be divided into three distinct categories using the standard shale gas reservoir characterization workflow:

1. Formation lithology
2. Total organic carbon / Kerogen determination
3. Gas in place evaluation

Using this field calibrated model, LWD geochemical measurement was then employed to identify the main mineral content along the horizontal section including clay, quartz-feldspar-mica, carbonate and pyrite. The lithology derived from LWD spectroscopy data is consistent with the lithology derived using wireline data in vertical well which has an average clay content of 28.3%, QFM content of 50.5%, carbonate content of 19.8% and pyrite content of 1.4%.

Formation Lithology

The first step in unconventional log interpretation is to calibrate the evaluation model to the local formation using a known or physical source, generally the core data. The initial lithology derived from elemental yields acquired using logging data through conventional mineral model did not agree with X-Ray Diffraction (XRD) core analysis. Subsequently, a local calibrated mineral model was developed and validated using six vertical wells over the Longmaxi shale interval. A log plot showing core data imposed over calibrated log derived lithology is provided in Figure 8 below.

Total Organic Carbon (TOC) / Kerogen Determination

There are a few methods in the industry to quantify TOC content using conventional logging data. Among them, ΔLogR and Schmoker are the two most widely used and accepted empirical methods in shale gas evaluation. However, ΔLogR method can be affected by the presence of pyrite which is a common mineral in shale gas formation, while Schmoker method cannot differentiate the changes in density from TOC and/or porosity. Other common methods for TOC estimation include using uranium measurement or gamma ray logs as indicators of organic matter; however, these methods often require local calibrations.

Kerogen can be computed with a combination of triple-combo log (gamma ray, resistivity, bulk density and neutron porosity) and geochemical measurements. Using a petrophysical interpretation program such as ELAN, the matrix density calculated from the conventional data is compared to the matrix density calculated from geochemical data. Since geochemical measurement is insensitive to the presence of kerogen, the difference between these two allows simultaneous quantification of kerogen content and porosity. Once kerogen volume is calculated, it can then be converted to TOC for the known kerogen type and maturity (information from core analysis).
Gas in Place Evaluation

As described in the previous step, TOC and porosity can both be resolved using ELAN with calibration from core. Absorbed gas is calculated from TOC using Langmuir equation at a given pressure and temperature. From local experience in Longmaxi formation, Simandoux equation is utilized to compute water saturation and free gas volume. Combining the absorbed and free gas, total gas is calculated for the whole lateral.

Figure 10: Key petrophysical parameters computed using LWD data in horizontal well (on top row) compared to wireline evaluated data in vertical well (on bottom row) over the same zone of interest.

Due to the low permeability of shale gas formation and lack of core permeability for calibration in this area, permeability is not calculated in the horizontal well. The final shale gas evaluation is presented below:

Completion Quality (CQ)

Observing Hooke’s law, rock behaves like an elastic material under stress before its elastic limits are reached. Most of the rock mechanical properties can be measured using various tests in core laboratory. Nonetheless, it is unrealistic to core every well in the field. With the long turnaround time and high cost that make this option impractical, core to log integration technique is used to calibrate logging based equations for geomechanical properties.

Acoustic measurements are commonly used in combination with bulk density to enhance mechanical earth models and optimize drilling and stimulation designs. Mechanical properties that can be derived from acoustic data include bulk modulus, Poisson’s ratio, and Young’s modulus. These properties influence the closure stress and therefore directly impact the hydraulic fracture height in stimulation.

In most shale reservoirs, the variation of reservoir property in horizontal wells is primarily attributed by vertical variation in rock lithology as the wellbore penetrates different stratigraphic layers. High stress intervals, which normally correlate to high clay content intervals, find difficulty in retaining fracture conductivity during production because the proppant is more likely to be embedded in this ductile formation. This also highlights the importance of precise well placement to steer laterals within the desired low clay content formation.

In the Weiyuan horizontal well, LWD sonic data was logged after drilling. The acoustic measurements along with density and lithology derived from reservoir characterization were used to compute geomechanical properties along the lateral. Besides rock properties, the in-situ stresses also play an important role in determining fracture shape and hydraulic fracture growth during completion.

Although the calculated mechanical data compares favorably to core data in the surface, additional calibration is required to incorporate the in-situ conditions and strong regional tectonic stresses present in the Sichuan Basin. The initial shut in pressure (ISIP) form one of the nearby vertical well was used to calibrate the minimum horizontal stress. Combining the borehole enlargement and breakout phenomenon illustrated by the borehole image and caliper log, maximum horizontal stress was computed.

Overall, the CQ of the horizontal well exhibited similar characteristics compared to other vertical wells within the Weiyuan block. The three main principle stresses reveals a strike-slip to reserved fault relationship ($\sigma_H>\sigma_V>\sigma_H$) which corresponds to the geological
understanding in this area. The difference between maximum and minimum horizontal stress is relatively large, ranging from 10 - 20 MPa. This signifies that engineered fracture treatment designs are essential along the lateral.

![Figure 12: Mechanical properties calculated using LWD data along the lateral.](image)

As no high resolution image logs were acquired in this lateral, fracture and local structure curvature information could not be applied in the design. It is worth noting that the presence of natural fractures provide vital information that is can be used to optimize completion designs. The fracture orientation with respect to the stress direction relative to the horizontal stress would affect fracture initiation that would result in more narrow planar fracture growth or complex fracture growth for better coverage. Structural curvature can generate local strain due to deformation and would re-orient the stress direction. This differential strain may magnify, alter or reverse the far field stress changing locally along the lateral. The local curvature of bedding along with varying mechanical properties should be considered in future completion design to increase the percentage of completion stage contributing to production (Koepsell, 2011).

**COMPLETION DESIGN OPTIMIZATION**

Hydraulic fracture conductivity in tight shale reservoirs directly relates to well productivity. The main objective of hydraulic fracturing in shale formations is to create a complex network of conductive pathways in the rock to increase the surface area of the formation that is connected to the wellbore. The success in constructing these highly conductive fractures and keeping them open over long production period would significantly increase the gas production rates.

Experience revealed that adopting the North America shale multi-stage fracturing technology alone is not enough. Thus, customizing the technique with local reservoir characterization provides better stimulation results in the Longmaxi formation. By evaluating the RQ and CQ of the formation, slickwater was chosen as the fracture fluid with large scale, large displacement and use low to medium proppant concentration.

**Completion methodology selection**

After evaluating multiple completion methodologies available in the industry, multi-stage plug-and-perf system was chosen for this horizontal well as it is the most common applied system in North America with proven performance records. In a cemented casing or liner, the plug-and-perf system produces multiple hydraulic fractures along the lateral. This segmented fracturing system uses bridge plugs and limited entry technique to simultaneously stimulate multiple perforation clusters within a stage.

![Figure 13: Illustration of a plug-and-perf system](image)

**Distance between perforation clusters**

Multiple microseismic studies and modeling established that different shale plays retain different optimal perforation clusters spacing depending on local RQ and CQ. In Weiyuan horizontal well, production system and drainage period were also taken into consideration in designing perforation cluster spacing. With formation intrinsic permeability between 200 to 240nD, the optimized perforation clusters distance is between 25 to 27m.

![Figure 14: The optimal distance between perforation clusters.](image)

**Length between stages**

Determining the number of perforation cluster per stage will directly influence the efficiency of the stimulation treatment and associated treatment cost. To select the optimal number of perforation clusters within a stage, the objective is to fit as many clusters in a stage while permitting equal distribution of the stimulation fluid between the clusters.
Ideally, to ensure all perforation clusters are stimulated equally one could stimulate each cluster individually, but this obviously is not a cost effective approach. On the other hand, if a large number of clusters are treated together, most likely a number of clusters will not be stimulated. An effective way to determine the optimal cluster count is by running production logs in the existing horizontal well.

After considering the operational risk associated to running a long perforation gun and the cost effectiveness of reducing the number of stages, three perforation clusters for each stage were selected for Weiyuan horizontal well with 75m to 81m interval between stages.

Completion design optimization

With the understanding that stimulation efficiency can be achieved by grouping similar rock together for treatment, the position of each perforation clusters were optimized off the computed RQ and CQ. If the stress variations are high, limited entry calculations are performed to determine the distribution of perforations among fractures units. Limited entry designs can be specified stage by stage (even for stages with minimal stress variations), to promote the desired distribution of treatment fluid. Combined with completion quality information such as minimum horizontal stress profile and formation fracability analysis, the stimulation effectiveness, production, and ultimately shale gas play economics can be improved. Example on perforation placement is illustrated in Figure 16 below.

CONCLUSIONS

The customized integrated horizontal well optimization workflow was successfully applied in China horizontal shale gas development project. The list below documents the key objectives this customized workflow imparts:

1) The addition of drilling quality (DQ) was introduced to place significance on well construction to address the challenging local geological condition in Sichuan Basin. This focus helped improve the drilling efficiency and increase reservoir exposure within target formation with the introduction of RSS and LWD technologies.

2) In this case study, conventional and geochemical LWD data were used for quantitative formation evaluation via a locally core calibrated petrophysical model. Reservoir quality computed along the lateral correlated well against the pilot well data logged using wireline conveyance tool.

3) Unlike most shale play in North America, strong regional stresses are present along with active tectonic activity in the Sichuan Basin. To accommodate this, geomechanical properties were calibrated using nearby offset wells.

4) Perforation clusters position and stimulation treatment for the horizontal well is designed using RQ and CQ computed along the laterals.

5) In this project, advanced LWD, drill bit and RSS technologies were employed to improve efficiency, to acquire a better understanding to reservoir heterogeneity and to optimize completion design.

From the North America experience, integration and collaboration is the key to success in unconventional reservoirs. It is not just about technology. It is about applying the fit for purpose technology consistently to understand and predict the variability associated with these reservoirs. Unlike conventional reservoirs, a strong understanding of drilling quality, reservoir quality and completion quality is needed to be successful.

In this aspect, PetroChina SWOGC is adopting the new workflow in some of their shale projects with the objective of reducing their learning curve, to be more efficient and cost effective. Eventually, the customized workflow with proven technologies can be adopted to support large scale commercial shale gas development in the Sichuan Basin.

MOVING FORWARD

A field study was conducted in Marcellus using LWD measurements in horizontal wells for petrophysical evaluation and completion optimization. All 18 horizontal wells data were evaluated using a systematic
approach with a consistent workflow under the local calibrated petrophysical model. Customized completion design using rock mechanical and reservoir properties were carried out under the same guidelines. The “Petrophysics to Production” correlation technique revealed a relationship between better reservoir quality wells is tied to better production (Shim 2011). Linking these properties to 3D seismic data provided a detailed treasure map showing the best reservoir facies classes differentiated by colors. This multiple disciplines study allowed the operator to make crucial decision to maximize the value of their unconventional asset (Kaufman 2013).

By taking the mentioned case study above as an example, acquiring more high quality data in the field during initial development stages permit computation of RQ and CQ. This information can be used to explain varying production between laterals, better understanding on reservoir heterogeneity in the target area and identify the main production drivers for the specific field. While this integrated evaluation and modeling is beyond the scope of the paper, this holistic approach should be a standard practice in shale plays to identify the true field drivers between the observed production trends.

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