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Optimizing Unconventional Completions - An Integrated Approach

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Abstract

North American unconventional well completion design has evolved dramatically since 2013 in an effort to keep pace with the productivity gains realized in horizontal drilling. Several trends have emerged during the current industry downturn. Among these trends are a focus on core acreage with higher yield potential, the use of longer laterals, a movement towards higher proppant loading (pounds per linear foot), an increased reliance on plug and perf techniques, and decreased stage length and perforation cluster spacing (increased perf density). As a result associated improvements in well initial production (IP) rates and estimated ultimate recoveries (EUR's) have been highlighted in oil & gas operator's quarterly shareholder's reports during 2015 and early 2016.

Unconventional multi-stage completion designs have also quickly evolved along a path paralleling these trends. Horizontal well IP rates and EUR's have also been enhanced through the adoption of integrated completion designs. Recently introduced geo-engineered completions rely on cross-functional expertise and software to integrate petrophysical, geomechanical, drilling, and production data into a completion design. In cases where geo-engineered designs were used, wells showed improvements in EUR's over those associated with increased lateral lengths, proppant loading and stage counts. In one recent case using a geo-engineered design it was demonstrated that fewer stages and clusters achieved higher production than offset wells while injecting less proppant and fluid; thus achieving lower completion cost.

The use of *engineered* workflows in tight or unconventional reservoirs is not new. Multiple case histories have been published in recent literature illustrating the use of stress variability/contrast or mechanical specific energy (MSE) to generate brittleness or other *fraccability* indices to group stages with similar rock characteristics. In contrast to engineered designs, newer geo-engineered designs integrate multiple inputs (attributes) to determine basin and formation-specific weighted algorithms that correlate to stage and cluster production contribution improvement. The geo-engineered approach has proven repeatable and can be accomplished even when key wireline or LWD data is not available.

This paper will document how *geo-engineered completion* designs evolved from *engineered* workflows. Multiple inputs (e.g. production, wireline/LWD/mud logs, core analyses, and *big data* from national and state data bases) can be combined to determine stage length and perforation cluster positioning. Case studies will demonstrate that geo-engineered horizontal completion designs deliver superior well production results when compared to geometric, high-intensity plug & perf designs.

Introduction

As noted above current trends in North American horizontal completion designs include:

- longer laterals in conjunction with multi-well pad locations
- larger volumes of lighter weight sand/proppant (e.g., 100 and 40/70 mesh)
- high volume slickwater and hybrid fluid systems using larger volumes of water
- increased numbers of stages and perforation clusters

Many operators adopted higher intensity completions (longer laterals, higher proppant loading per foot, more stages, and more perforation clusters) from 2013 – 2016. The trends towards higher intensity geometric designs are shown in Figures 1 and 2. Some authors, including Filloon (2016), use the description "mega-fracs". Operators referenced in the article include Pioneer (PXD), Continental Resources (CLR), Matador (MTDR), and Devon (DVN) with exhibits taken from operator's quarterly shareholder presentations.

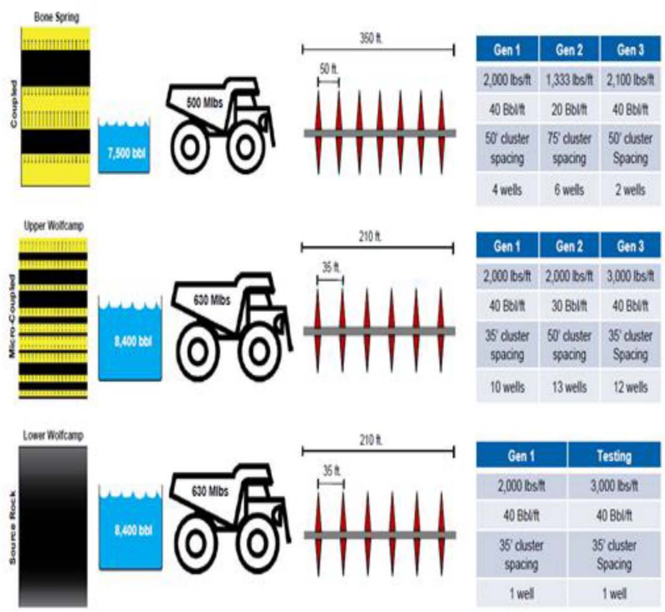

Figure 1—Madator Resources - Delaware Basin Frac Job Evolution

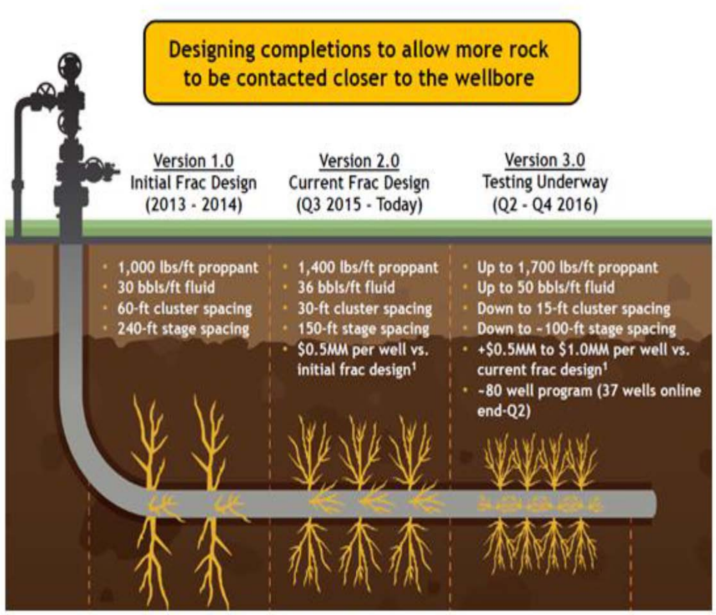

Figure 2—Pioneer Resources - Midland Basin Frac Job Evolution

The combination of these trends have helped to deliver better EUR's which in turn have increased project net present values (NPV's) for operators. Multiple operators in 2016 quarterly earnings presentations point to production type curves changes and improved economics in all basins – particularly in the Permian.

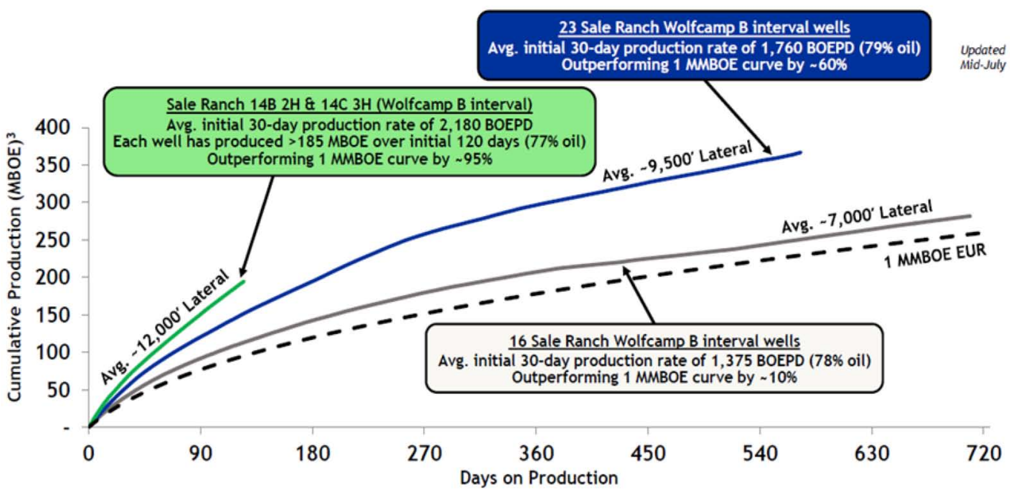

Figure 3—PXD - Midland Basin Type Curve Evolution

Between 2013 and 2016, operators also benefitted from lower pricing for hydraulic stimulation services, proppant, water disposal, and related services such as flow back/testing to achieve lower completion cost per lateral foot. This benefit is illustrated across the major U.S. unconventional basins in Figure 4.

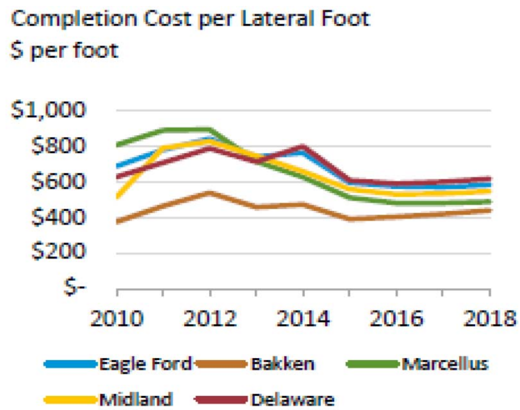

Figure 4—EIA – March 2016 Trends in U.S. Oil and Natural Gas Upstream Cost

Yet, against this backdrop of higher fracture intensity, lower completions cost, and improved average well EUR recovery factors for unconventional horizontal wells remain in the 3.5 to 10 % range (King, 2014). After more than 12 years of unconventional development, North American operators and service providers have acquired sufficient data and reservoir experience to learn a few lessons about lowpermeability mudstone completions. Each unconventional formation has a unique set of attributes. The attributes that drive production in Bakken wells are different from those driving production in Wolfcamp wells. Further, Wolfcamp A wells are different from Wolfcamp B wells. Likewise, Bakken completion practices by nature should be different from Wolfcamp completions to achieve optimal results.

This study looks at a few examples of where consideration of all available data regarding formation attributes made a difference in completion efficiency. Going forward operators will continue to unravel the source code of each unconventional formation to improve recovery factors. Comments regarding the latest advances in optimizing horizontal completions will be included in the conclusion of this paper.

History of Engineered Completions

Poor production in unconventional wells is often attributed to two challenging issues: low stage and perforation cluster efficiency (Miller et al., 2011) and incorrect lateral placement. This paper will primarily deal with the first challenge of low stage/cluster efficiency. The issue of progress being made in better lateral placement, however, is also briefly discussed in the summary section.

As input to Miller's study, Schlumberger released PLT results analyzing over 100 horizontal wells in six U.S. shale basins and indicated perforation efficiency was approximately 70%. Stated differently, about 30% of clusters contributed little or nothing to production. The same logic held true for stage contribution: not all stages contributed equally to a well's production.

As a result *engineered completion* designs aimed at tailoring completion stages to minimize lateral variability (primarily stress) were introduced. Indices for "fraccability" and "brittleness" were also introduced and described by Apache (Ponce, 2011). Based in large part on acoustic logging measurements, *engineered completions* initially relied primarily on logging results for stress calculations such as Poisson's Ratio and Young's Modulus.

Though not specifically using the term *engineered completion* the seminal work published by Cipolla (Cipolla et al., 2011) also relied on grouping rocks of similar properties during stage placement. Cipolla's study introduced algorithms and work flow logic to position stages and perforations clusters in both vertical and horizontal wells. Figure 5 illustrates the terms Completion Quality (CQ), Reservoir Quality (RQ), and Composite Quality Index (CQI).

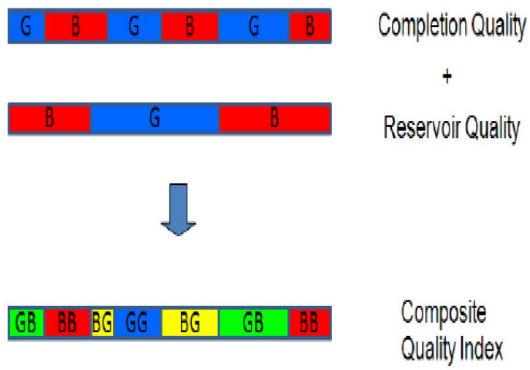

Figure 5—Cipolla 2011

The term *engineered completion* has been extended to other approaches. In horizontal wells where neither core nor open-hole or LWD logs were obtained to aid in completion design, proxies for unconfined compressive strength input have been put forth that use mechanical specific energy (MSE) estimates (Logan, 2015) derived from drilling data (WOB, TOB, ROP, bit wear, etc.) to produce facies logs.

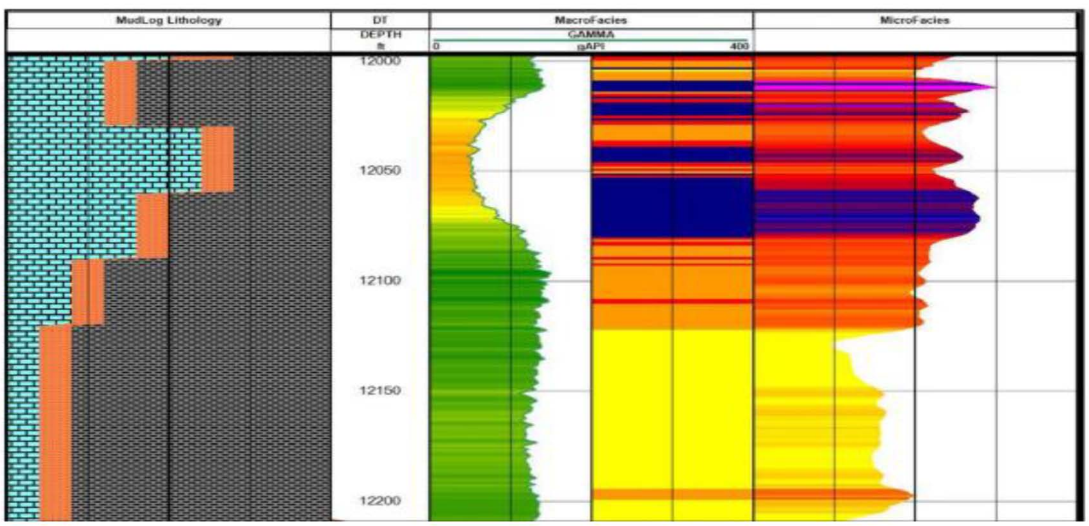

Figure 6—Facies log based on vertical drilling data (Logan, 2015)

A similar approach was described (Lehman et al., 2015) using neural networks from previous wells to populate the model with matched sets of measurements from open hole and drilling data. On subsequent wells in the same area, where neither wireline nor LWD logs were available, drilling data was combined with gamma ray logs and survey data using the neural network to derive synthetic shear, compressional, and density logs to enable *engineered completion* designs. In the concluding section of a follow-up study (SPE -181273-MS) published in 2016, Lehman, et al. noted that biodegradable diversion was also a viable method to enhance perforation cluster efficiency. However, the recommendation of the authors was to use the methods separately in early wells rather than using both engineered completion designs and degradable diverters at the same time. It is possible that using both in combination could be additive, but isolating the impact of each would be difficult to discern.

Figure 7. Illustrates the synthetic logs used to determine stage and cluster placements suggested for use in a Bone Springs well in the Delaware basin.

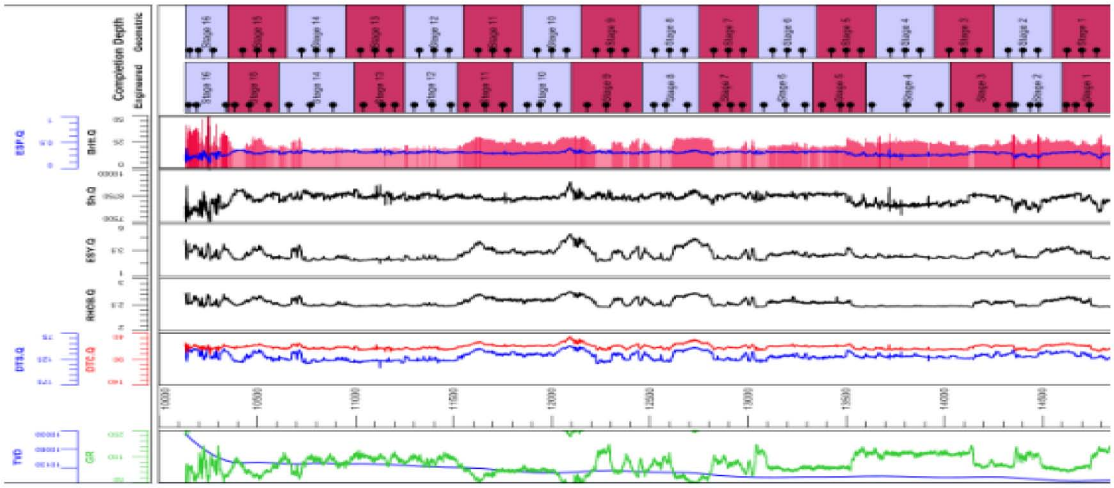

Figure 7—Synthetic shear, density log courtesy of Quantico Energy Solutions (Noblett, 2015)

More comprehensive methods and software for planning *engineered completions* (Ajayi et al., 2013) furthered the work of Cipolla (2011) in the use of reservoir (RQ) and completion (CQ) quality factors to ultimately determine a Composite Quality Index (CQI). The CQI was employed in the repositioning of horizontal stages and perforation clusters. This approach was based on wireline and/or LWD data and validated with microseismic results.

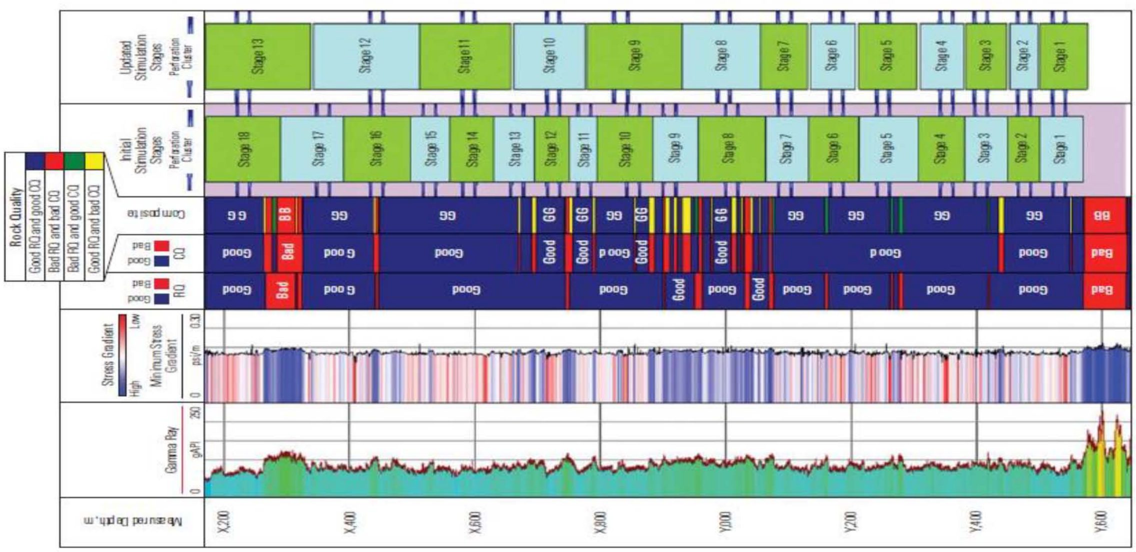

Figure 8—Ordos Basin Engineered Completion (Ajayi et al., 2013)

A study published by Parker et al. (2015) described a systematic engineering completion workflow used in designing a hydraulic fracturing program for Wolfcamp wells in the Delaware basin. The integrated engineered approach described by Parker et al., considered such factors as natural fracture saturation, mid-field fracture complexity, mechanical fracture interaction, and transverse fracture production interference to develop a multi-cluster/multi-stage *engineered completion*. This study provided evidence that by integrating proven engineering practices with diagnostic data, fracture modeling, and production history matching, horizontal well completions were optimized.

In another 2015 paper [URTeC 2153591] further enhancements to the completion design workflow first described by Cipolla et al., in 2011 were detailed in (Shahri et al., 2015) "…*a fully automated stage design algorithm … run on multiple parameter combinations and available data according to the nature* *and diagenesis of a reservoirs' environmen"t.* Shahri's paper described a workflow capable of automating horizontal stage design by minimizing the intra-stage variability of fracture potential index subject to specific constraints.

Further, Shahri's workflow provided the flexibility to deliver automated stage designs in the absence of key data without resorting to proxy or synthetic logs. Similar in some respects to the multiple indices described earlier in (Cipolla, 2011), Shahri's approach employed multiple indices including a composite index in the workflow, Integrated Fracture Potential (IFP), based on weighted attributes. As Shahri et al. point out, fracture potential is not a material property as is commonly thought. Fracture potential as defined by the authors considers

> "…*Current industry practice involves using logs to perform quick look analysis along wellbores to unlock this potential. This analysis usually results in a general fraccability or brittleness indicator. Stage locations, number and size selection are based on parameters that are not appropriately integrated and correleated to the fracturing potential. In order to fully characterize the fracture behavior and optimize stimulation design, key attributes that control fracture initiation, propagation, opening and closure need to be identified, their relative impact/weight(s) need to be quantified and integrated".*
>
> *(Shahri et al., 2015.)*

Among the weighted attributes considered in Shahri's model are: multiple elastic properties, unconfined compressive strength, fracture toughness, mechanical/stress anisotropy, natural fracture networks, reactivation of natural fractures, petrophysical attributes such as permeability, porosity, lithology and hydrocarbon potential. To distinguish Shahri's method from previous completion workflows the term *geo-engineered design* will be used henceforth in this paper.

The distinction between *engineered completions* and *geo-engineered completions* may seem pedantic but it is made in no small part because of recent industry criticism regarding engineered approaches. Cannon (2016) and others correctly point to an over-reliance on near wellbore logging measurements for *engineered completions* in the low-energy deposition and thinly bedded sedimentary environments characteristic of most U.S. basins. This over-reliance can lead to design errors caused by the interference of near bed boundaries, particularly with sonic measurements (Market, et al., 2016). In an effort to account for and manage near wellbore interference, *geo-engineered completions* rely on inputs other than wireline and LWD data exclusively.

Early Success in the Application of Geo-Engineered Completion Methods

The work of Shahri, et al. was a significant step in updating the established engineered completion paradigm. An example of a stage design using Shahri's automated workflow (from Mejia et al., 2015) is seen in Figure 9. The track towards the top in red [*Optimized Stage*] is the geo-engineered stage recommendation selected to be implemented by an independent operator.

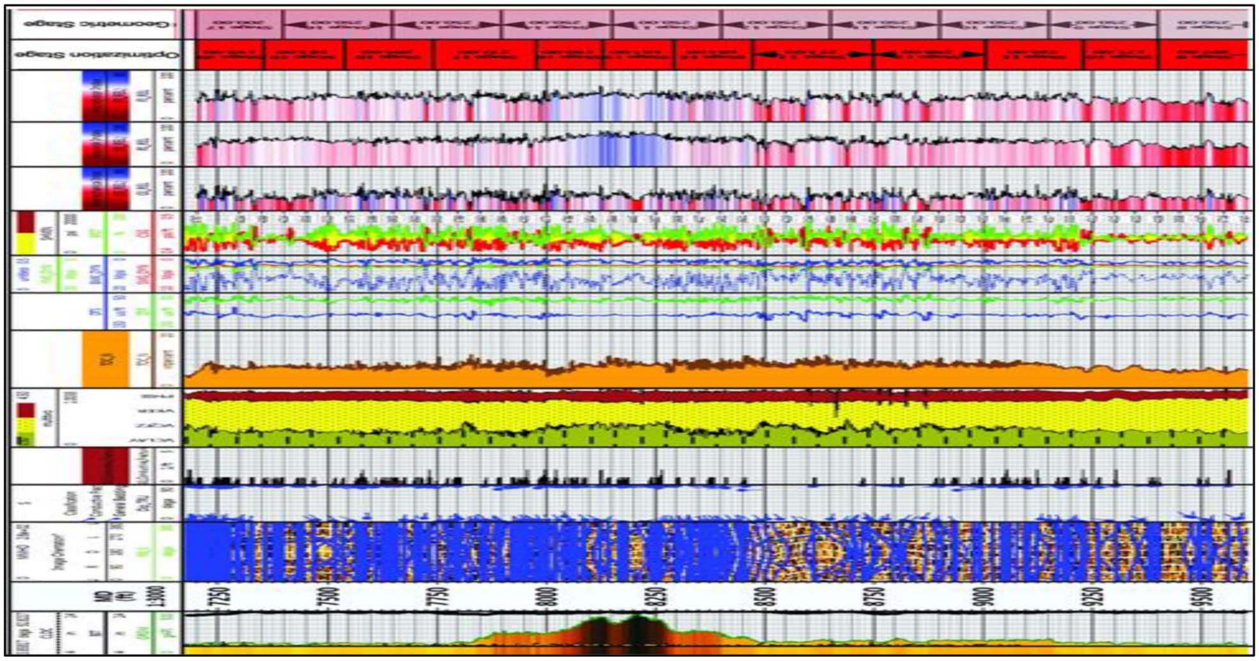

Figure 9—Optimized geo-engineered stage design (Mejia et al., 2015)

An early case study in the Woodford Shale using the automated geo-engineered workflow resulted in dramatic performance improvement with more than 16,700 additional barrels (BOE) produced during the first 60 days of production compared to a nearby well that the operator completed using a purely geometric design. figure 10 illustrates a production comparison of the first 60 days for each well.

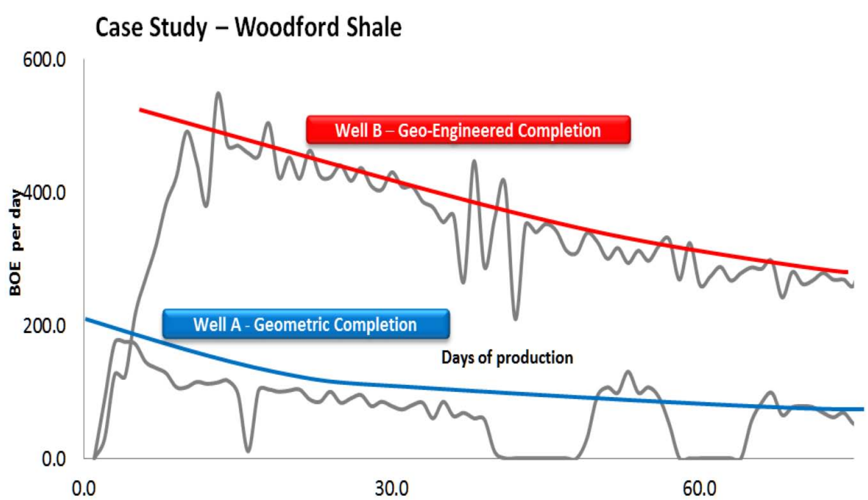

Figure 10—Logan County, OK geo-engineered completion

Shahri's automated stage design workflow was a breakthrough for *geo-engineered completions.* The methodology was proven during 2014 and 2015 by well production results in field applications. Later in 2015 the original work done by Shahri et al., brought about the introduction of a new generation of *geo-engineered completion* designs. Integrating perforation cluster/sliding sleeve & packer placement, frac simulation modeling, and the use of public domain "big data" to determine the best existing practices for proppant and fluid use enabled Shahri's methods to gain additional technical credibility within the industry. The latest geo-engineered completion design workflow is discussed in the next section.

Geo-Engineered Completions: 2nd Generation

The validity of any completion design methodology centers on the accuracy, efficacy, and repeatability of the workflow. Although comprehensive in the number of inputs capable of being integrated into the model, the original automated stage design methodology lacked several elements desired by operator's asset teams. Among the elements most requested were a recommendation for perforation cluster placement using the same data inputs, a side-by-side comparison of stage designs (e.g. geo-engineered versus geometric), a hydraulic fracture simulation using the recommended positioning of stages and clusters, and an associated stage-by-stage treatment schedule. Figure 11 illustrates the additional data elements incorporated into the latest geo-engineered completion design log format.

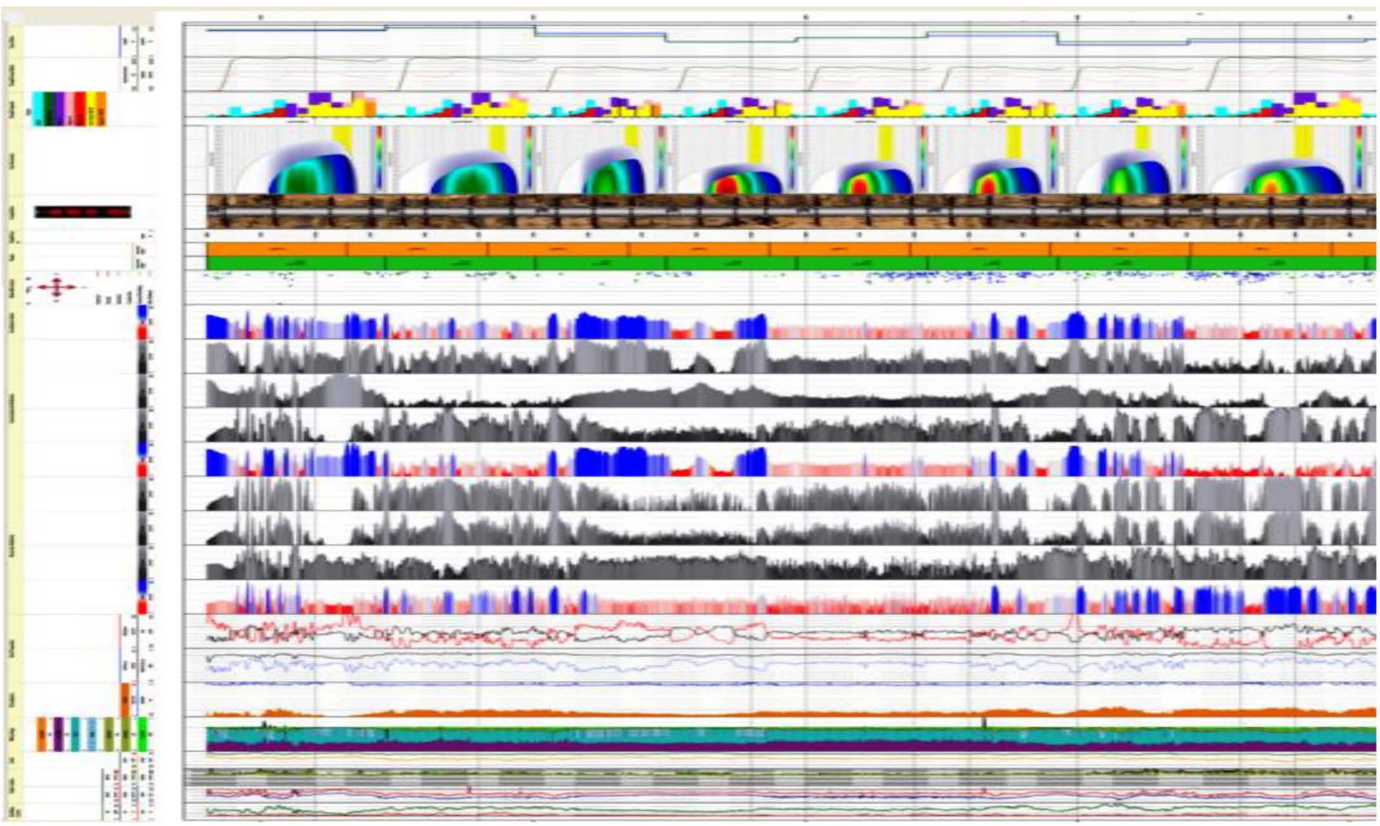

Figure 11—A wide format Geo-Engineered Completion Log used for integrated geo-engineered completion designs includes reservoir, geo-mechanical, composite indices, completion tools, stage comparisons, stimulation modeling, and treatment schedule in a log format.

A single integrated planning document (log) such as the one above contains a large, diverse data set. The log was intended for horizontal multi-stage completion design and was created in an attempt to make stage and perforation cluster decision making easier for cross-functional asset teams. If any particular data set is not available (e.g., cross-dipole sonic or micro-image log, etc.) either a synthetic proxy can be inserted or a substitute track such as hi-resolution gas ratio chromatographic analysis can be used. The next section will focus on perforation placement workflow using the same data.

Geo-Engineered Completions – Perforation Placement

In SPE 155485 Wutherich et al., (2012) point to three considerations to optimize perforating strategy when using a limited entry approach:

(1)Perforations should not cause an excessive restriction to flow,

(2)Perforations are optimally designed when every perforation receives an equal volume of fluid to ensure connection with the reservoir, and
(3)Perforation placement strategy should provide sufficient reservoir drainage.

Wutherich also cited Fisher (2004) and Jacobs et al. (2010) regarding optimal spacing of perforations. A later work by Baihly et al. (2010) definitively made the case for understanding lateral heterogeneity prior to adopting a horizontal completions design. Furthermore Wutherich cited Cipolla et al. (2011) where the case was made for optimal positioning of perforations within stages in areas of similar stress so that induced fractures can be distributed effectively. Geo-engineered completion designs account for similar stress considerations as well as the possible interaction with natural fracture networks.

As previously described such tools as automated stage algorithms and workflows (Shari et al., 2015) result in a geo-engineered stage design, where the length and placement of the stages is based on *minimizing the intra-stage variability of fracture potential* based on a combination of reservoir and geo-mechanical attributes. However, given the heterogeneity typically observed in these attributes along the length of a deviated or horizontal wellbore, a degree of variation is still observed within each stage. This *remnant* intra-stage variability (Figure 12) can be used as the basis for the placement of the perforation clusters within each geo-engineered stage.

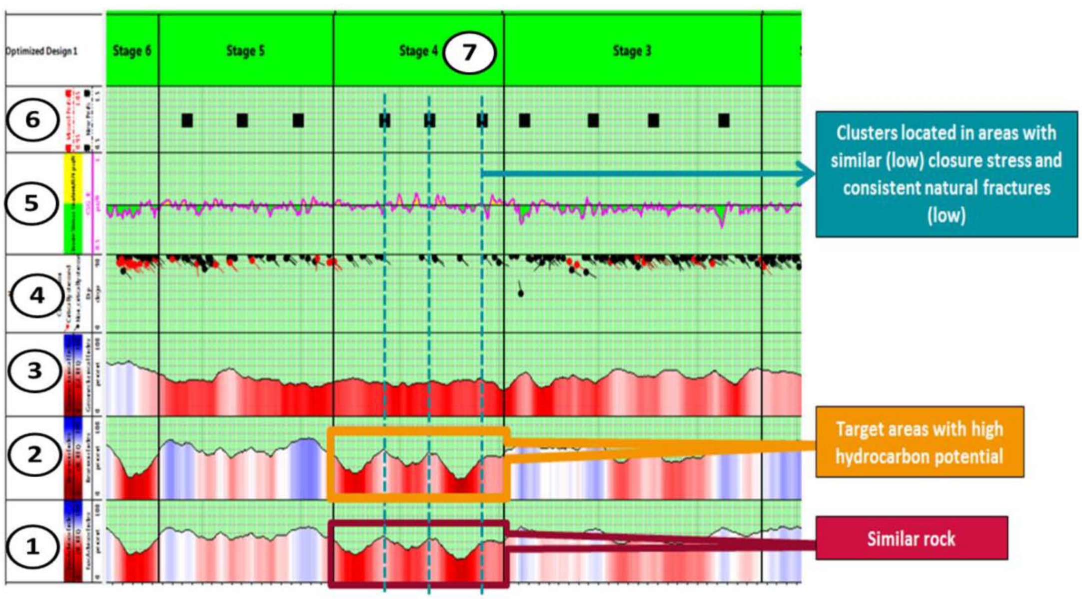

Figure 12—Geo-engineered completion illustrating both stage design based on minimizing intra-stage variability based on the combination of both reservoir (Track 2) and geo-mechanical (Track 3) and remnant variation within a stage (integrated fracture potential – Track 1). Track 4 shows the presence of natural fractures (red color representing fractures with the probability to be reactivated). Closure stress gradient is show in Track 5)

The presence of natural fracture networks and their current stress state can be important attributes in choosing the location of perforation clusters. The question "are natural fractures good or bad?" frequently arises in discussions regarding completion design. The answer is that they can be both. Natural fractures can provide points of "weakness" that promote the initiation of hydraulic fractures and can be targeted to promote fracture height and half-length. However if these fractures are open or their stress state is such that they will be reactivated when the pore pressure is increased during hydraulic stimulation, these points of relative "weakness" can cause the hydraulic fractures to propagate out of zone and potentially connect with adjacent aquifers above and more deep-seated gas rich formations, resulting in high water and gas cuts during production.

It may also be desirable to target intervals without natural fractures and fractures with a low or no possibility to be reactivated within a stage to promote complexity in the hydraulic fracture network in "fresh" rock. The presence and location of natural fractures and faults can be interpreted from seismic and confirmed using a variety of formation evaluation techniques, image logs being one of the most common and robust methods, but includes drilling parameter variations and advanced gas detection methods. Once the presence or absence of natural fractures has been confirmed, their current stress needs to be evaluated together with an assessment of the likelihood that they will be reactivated.

One method of analysis of the current stress state is described by Shari et al in their 2016 paper on "Stress Inversion via Borehole Log Image and Fracturing Data: Integrated Approach" (URTEC 2461241). An *accurate estimation of in-situ stress magnitude and direction is a prerequisite for robust and reliable geomechanical analysis.* This method combines *fracturing and image log data for determining the complete stress field using data from a single wellbore. Fracturing data (e.g., leak-off tests) and image log information (i.e., tensile fracture characteristics) are utilized to determine the in-situ stress field using a novel inversion algorithm capable of efficiently sampling from the complete in-situ stress solution set conforming to the input data and satisfying a priori domain constraints*.

In-situ stress magnitude and direction can then be used as inputs to critically stressed fracture analysis (Figure 13) to evaluate the probability that natural fractures will be reactivated during hydraulic stimulation. For example in figure 12, natural fractures are pervasive throughout most of stage 5 (Track 7) and the perforation clusters (Track 6 – black squares) were located to avoid those natural fractures that were assessed to have a higher probability (colored red – Track 4) of reactivation to restrict propagation of the hydraulic fractures within the reservoir interval.

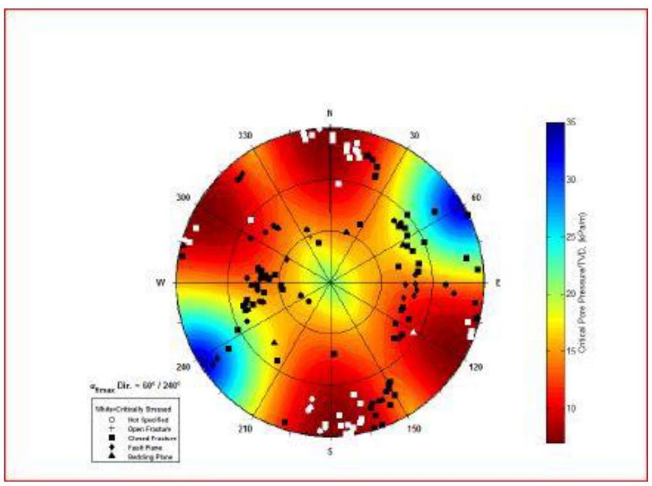

Figure 13—Critically stressed fracture analysis. Sonic shear data are used to determine the azimuthal stresses and these data are combined with image log interpretation to understand how the stress network will be affected by hydraulic fractures and which natural fractures will contribute to production and fluid movement (Market et al., 2016)

In the absence of a natural fracture network, the placement of perforation clusters can be based on minimizing the intra-stage contrast in other reservoir and geo-mechanical attributes, such as closure stress gradient as described in Cipolla et al. (2011). Placement of the perforation clusters in Stage 4 (Figure 12) was based on the absence of natural fractures (Track 4) and then minimization of the contrast in closure stress gradient across the three perforation clusters.

While a degree of automation can assist in selection of the location of individual perforation clusters, given that the attributes that control their location can vary greatly from stage to stage, formation to formation, play to play and county to county, and the complex interplay that exists between each attribute, a detailed workflow in combination with human intelligence and experience can result in repeatable and verifiable perforation cluster design.

Geo-Engineered Completions – Impact of Big Data on Completion Design

A specific definition of a term such as *big data* is difficult. The same holds true regarding the methods of data analytics used in production optimization. For instance the paper by Schuetter et al. (2015) discusses the trend toward statistical and machine learning methods for production optimization. However, this paper will consider the use of *big data* in a more limited manner. For the purpose of this paper the authors have chosen to apply the term *big data* to all the available data obtained from outside the operator's normal channels (e.g. measurements obtained via seismic acquisition, wireline and LWD logging, core and drill cutting analysis, etc.).

In addition to the wellbore logs and drilling data used in planning completions many operators and service companies today also rely on the vast amount of information available via public data bases to provide key information. For instance, nearly every state with drilling activity allows free access to view permits, completions, and production records for all wells. In addition, access to the chemical disclosure registry data base, FracFocus, was first begun in 2011 and provides details on proppant, fluids and chemicals used in completing each well. Since 2011, information on more than 112,500 horizontal wells has been made available for to the public via FracFocus.

In August of 2015 a Devon Energy press release announced that a "Game Changer for Completions" was now being used by Devon engineers. Tony Vaughn, Devon's executive VP of Exploration and Production, described a tool to "… accumulate and digest information we need to determine which completion practices are the most successful in any given area." Vaughn went on to describe a data base tool with mapping functionality to show where Devon wells were being outperformed by competitors so that completion designs could be quickly adjusted to achieve "best in class" results.

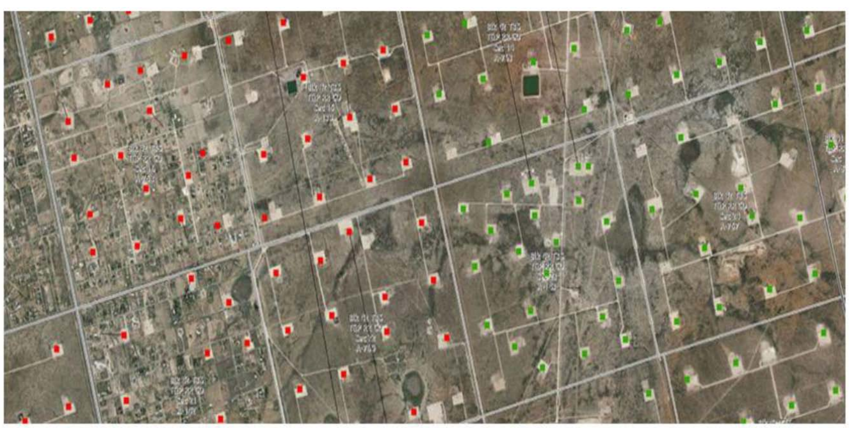

Figure 14—Devon's August 2015 press release announced the competitive advantage gained by using a data base tool to compare the methods and volumes (proppant and fluids) used in thousands of wells in the U.S.

The advantage of accessing public data to make better completion decisions was somewhat fleeting. By 2016, the playing field has been leveled for operators and service companies alike. Realizing that searching through public data records can be tedious, business intelligence firms, such as DrillingInfo, IHS, and NavPort, now provide search engines that access multiple *big data* sets and provide analytics tools that allow completion design teams access to the most up-to-date information. It is now easy to determine which nearby wells have produced the most hydrocarbons, used the most proppant, employed a new fluid design, or changed to a different surfactant. Figure 15 is a 2016 download example.

4/1/2013 to 4/1/2015 Depth: 7251 to 8512 ft Radius: 8 miles from

API Number	Operator	State Count	Well Service Prov	Total Vertical Depth (ft.)	Proppant Ty	Prop Mesh	Fluid Ty	Total Proppant Mass in ST	Total Proppant Mass (lbs)	Lateral Length (ft.)	Lbs/ft	Total Water Volume (gals)	Total Water Volume (bbls)	Bbls/Ft.	Stages	30 day Cum Oil (bbls)	30 day Cum Gas	Oil IP (bbls)	Calc Water (bbls)	Gas/Oil Ratio	IP Flowing Tbg
42-041-32266-00-				7404	Sand Only	20/40	SW/Xlink	3418.62	6837240	6378	1072	4110204	97862	15		5485	2977	575	193	0.33	325
42-041-32298-00-				7252	Sand Only	20/40	SW/Xlink	5232.61	10465220	6996	1496	6852552	163156	23		3895	1233	202	581	0.55	522
42-041-32226-00-				8187	Sand + Resin	20/40	Xlink	3110.55	6221100	5751	1082	3316320	78960	14		3684	5695	837	690	1.75	250
42-395-31914-00-				7724	Sand Only	100M_40/70_20/40	SW/LinG	5932.84	11865680	5987	1982	11129076	264978	44	34	3545	759	864	556	0.26	1583
42-313-31094-00-				8347	Sand + Resin	30/50_20/40	Xlink	3562.67	7125340	6909	1031	3700856	88116	13		3398	5730	527	350	2.03	190
42-395-31913-00-				7320	Sand Only	100M_40/70_20/40	SW/LinG	9346.16	18692320	8715	2145	15243060	362930	42	36	3221	1094			0.49	
42-313-31005-00-				7260	Sand Only	100M_20/40	SW	4158.07	8316140	8802	945	4660236	110958	13	20	2602	0	432	792	0.25	338
42-041-32303-00-				8119	Sand + Resin	20/40	Xlink	3787.26	7574520	6709	1129	3752910	89355	13		2472	5712	550	538	2.26	110
42-313-31004-00-				7264	Sand Only	100M_20/40	SW	3371.11	6742220	7429	908	4216716	100398	14	17	2318	0	384	720	0.25	574
42-041-32180-00-				7768	Sand Only	20/40	Xlink	2759.16	5518320	5690	970	2823702	67231	12		1614	378	605	811	0.35	533
42-313-30974-00-				8015	Sand + Resin	100M_30/50_20/40	Xlink	3177.95	6355900	7918	803	6912696	164588	21		1487	575	312	624	0.36	160
42-041-32194-00-				7770	Resin Only	20/40	SW/Xlink	1998.09	3996180	4375	913	3480906	82879	19		1438	425	262	105	0.34	176
42-041-32171-00-0				7324	Sand Only	20/40	Xlink	2732.14	5464280	5957	917	2732814	65067	11		1226	325	204	444	0.30	
42-185-30813-00-				8471	Sand + Resin	20/40	Xlink	3062.92	6125840	6900	888	3625272	86316	13		1173	2209	140	1560	2.38	233
42-041-32274-00-				7838	Sand + Resin	20/40	Xlink	2784.43	5568860	6396	871	2776242	66101	10		958	268	385	382	0.52	125
42-041-32136-00-				7757	Sand Only	20/40	Xlink	2798.47	5596940	5609	998	2741298	65269	12		859	731	490	388	0.76	280
42-313-31129-00-0				8388	Sand + Resin	20/40	Xlink	2629.57	5259140	6089	864	2789724	66422	11	21	807	544	294	275	0.56	100
42-041-32186-00-				7750	Resin Only	20/40	SW/Xlink	1609.43	3218860	5234	615	3075335	73222	14		777	258	510	260	0.34	1352
42-041-32188-00-				7755	Resin Only	20/40	SW/Xlink	1841.73	3683460	5043	730	3374484	80345	16		526	175	346	369	0.34	1183
42-041-32126-00-				7705	Sand Only	20/40	Xlink	2784.3	5568600	5480	1016	2765196	65838	12		266	266	129		0.74	180
				7771				**3505**	**7009808**	**6418**	**1069**	**4703980**	**112000**	**17**	**26**	**2088**	**1468**	**424**	**535**	**0.76**	**456**
				8156				2474	4948060	4827	1020	3285633	78229	16	24	1404	817	508	644	0.45	480
42-313-31221-00-0				7851	Sand + Resin	20/40	Xlink	3004.89	6009780	6639	905	3661571	87180	13	33			160	248		116
42-313-31093-00-				7951	Sand + Resin	20/40	Xlink	3356.41	6712820	6738	996	3839302	91412	14	34	2985	1137	720		0.29	532
42-041-32242-00-				7882	Sand + Resin	20/40	Xlink	1110.85	2221700	2221	1000	1317249	31363	14	11	1087	581	461		0.28	270
42-041-32235-00-				8032	Sand + Resin	20/40	Xlink	1098.53	2197060	2283	962	1289441	30701	13	12	1244	108	456	264	0.31	260
42-041-32225-00-				8118	Sand Only	20/40	SW/Xlink	2712.26	5424520	5342	1015	3042047	72430	14	27	1427	1437	624	1032	0.94	850
42-313-30992-00-				9100	Sand Only	20/40	Xlink	3561.24	7122480	5741	1241	6564188	156290	27	29	276	820	624	1032	0.43	850

Figure 15—Typical Excel download of nearby proppant, fluids and production well records. Courtesy NavPort

The information supplied by business intelligence firms comes in many cases with analytical tools such as maps, area search functions, EUR estimations, and decline calculations, etc. This method of preparing for a completions design takes the guesswork out of deciding which proppant loading to consider or fluid type to use at the onset of a project.

More importantly, because the data is tied to production records, it is also possible to know which combination of proppants, fluids, and chemicals yields "best in class" performance within a particular area. Production and proppant loading are even provided in formats normalized for easy comparison of wells with varying lateral lengths. Currently these data bases are available in the U.S. and Canada and there are plans to provide similar business intelligence in Argentina.

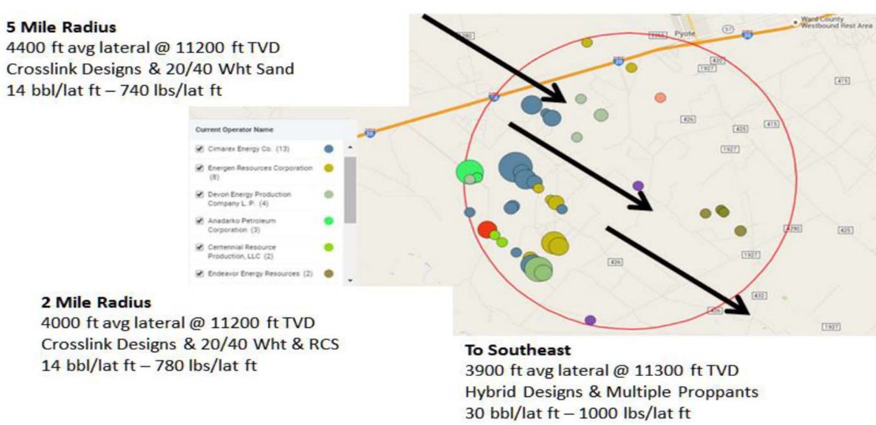

Figure 16—Typical search near a planned completion location. Image courtesy of NavPort.

As mentioned previously, a geo-engineered completion begins the hydraulic fracturing design process by considering which practices are currently providing the best results in a given area. By this point in the geo-engineering process the majority of design elements have been formalized. Stage placements and lengths have been determined, perforation clusters have been positioned, proppant loading and types selected, fluid and chemistry (biocide, friction reducer, gelling agents) are known. The next step in the workflow is modeling the hydraulic fracture behavior in a simulation capable of interpreting the complex nature of unconventional formations.

Geo-Engineered Completions – Integrating Fracture Simulation Models

Nearly all unconventional oil & gas operators have a preferred stimulation modeling software. Service companies typically offer a choice of software to enable the exchange of compatible data with clients. All fracture simulation software plaforms have some positive features. For example the software may have an easy to use interface, quick run times, both asymmetric and symmetric simulation capability, and single or multi-well options, the ability to manage complex formations layering, or the functionality to account for interaction with natural fracture networks, etc.

There are no perfect hydraulic frature simulators. Each fracture modeling software has some negative features. Examples include mandatory inputs that are difficult to obtain, the inability to make an adjustment to a single-stage element without re-running the entire well model, inflexibility regarding cluster length/ stage length variability or positioning, and slow run times brought on by layering issues or other causes. Accommodating changes and rapid processing times are high on the list of preferred characteristics. As geo-engineered design workflows have gained traction another desired characteristic is the flexibility to interface with multiple software models.

During geo-engineered completion design preparation, multiple fracture simulations are run. Simulations are commonly done to compare geometric and/or engineered designs with geo-engineered stage plans, or to determine the sensitivity to various cluster positioning concepts. Simulations are often needed to compare potential well performance from mega geometric frac and geo-engineered designs. With many comparisons to model, it follows that run-time speed is a critical factor in simulator selection.

Simulations are typically included as a part of the frac treatment schedule report. By incorporating the multiple simulation images (half length, or other) as part of horizontal geo-engineered log format, it is easier for teams designing completions to see the impact of stage and perf cluster decisions visually.

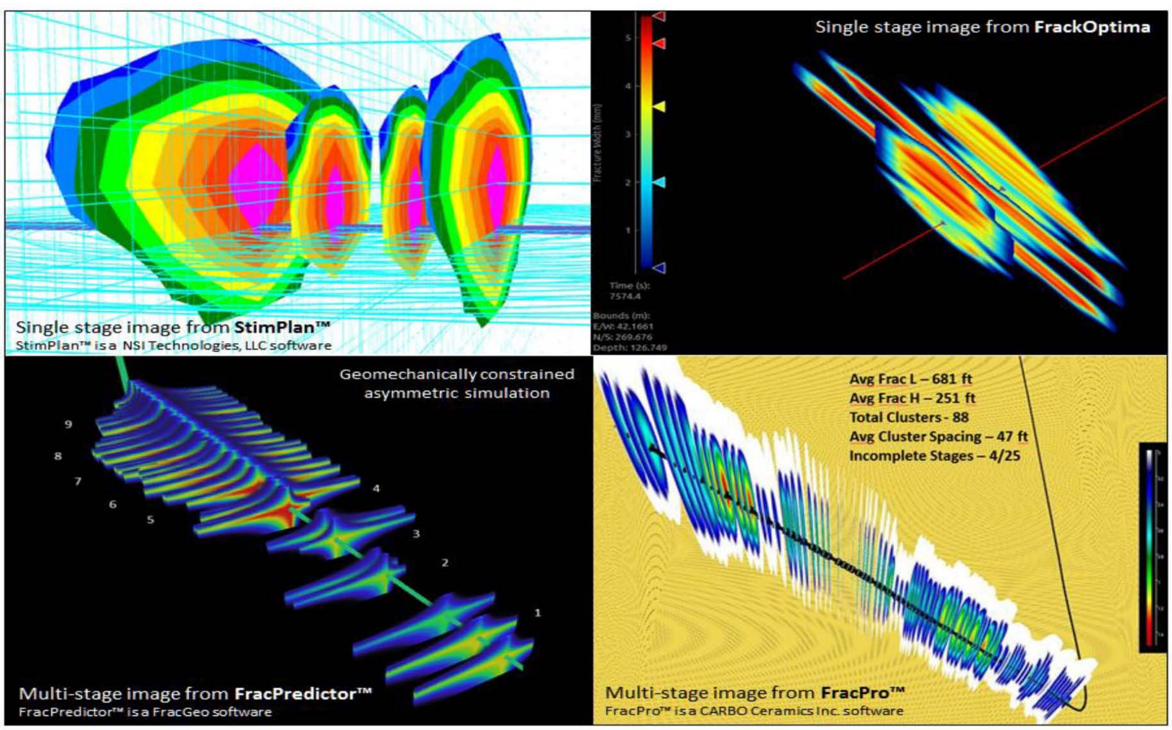

Figure 17—Geo-engineered completion designs integrate with 2-D and 3-D frac software output for single and multi-stage symmetric and asymmetric simulations

Three tracks in the geo-engineered integrated log format **(Figure 11.)** depict the hydraulic fracture design after simulations are done. The track immediately adjacent to the stage model image track is an easy to view representation of fluid and proppant treatment. The data gleaned as part of the big data search described earlier documents current best practices for proppant and fluids. Figure 18 shows the proppant and fluids selected for a single stage produced after the frac simulation. These selections are displayed in the easily read steps depicted in color bar chart image in the geo-engineered log.

Heavy Stages - 52; 4-21, 32-34. 37-67											
Step #	Description	Fluid Type	Rate (bpm)	Stg Vol (gal)	Stg Vol (bbl)	Prop Conc.	Prop Type	Stg Total (lbs)	Stg Slurry (gal)	Stg Slurry	Stg Pump Time (min)
1	Pump Down	SW	14	8,200	195				8,200	195	13.9
2	Breakdown	SW	12	500	12				500	12	1.0
3	Spearhead Acid	15% HCl	14	1,000	24				1,000	24	1.7
4	Pad	SW	50	40,000	952				40,000	952	19.0
5	0.50 ppga SW	SW	50	50,000	1,190	0.50	100 mesh	25,000	51,140	1,218	24.4
6	1.00 ppga SW	SW	50	45,000	1,071	1.00	100 mesh	45,000	47,052	1,120	22.4
7	Sweep	SW	50	20,000	476				20,000	476	9.5
8	1.50 ppga SW	SW	50	30,000	714	1.50	100 mesh	45,000	32,052	763	15.3
9	Sweep	SW	50	20,000	476				20,000	476	9.5
10	1.75 ppga SW	SW	50	15,000	357	1.75	100 mesh	26,250	16,197	386	7.7
11	2.00 ppga SW	SW	50	20,000	476	2.00	100 mesh	40,000	21,824	520	10.4
12	2.00 ppga SW	10# Linear Gel	50	40,000	952	2.00	40/70 White	80,000	43,648	1,039	20.8
13	2.50 ppga SW	10# Linear Gel	50	40,000	952	2.50	40/70 White	100,000	44,560	1,061	21.2
14	Flush	SW	50	15,000	357				15,000	357	7.1
				344,700	**8,207**			**361,250**	**361,173**	**8,599**	**184**

Stage Summary		
15% HCl	1,000	gal
SW	263,700	gal
10# Linear Gel	80,000	gal
100 mesh	181,250	lbs
40/70 White	180,000	lbs
Total Proppant	361,250	lbs
Total Fluid	344,700	gal
	8,207	bbl

Stage Density	**2890**	**Lbs/Lat/ Ft**

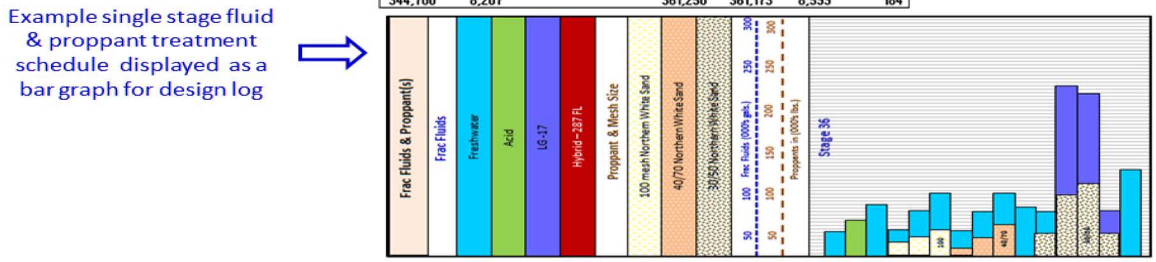

Figure 18—Fluid and proppant volumes in log based format by stage - adjacent to simulation image track

In a similar manner the track adjacent to the proppant and fluid column displays pressure and pumping rate data as part of full treatment schedule displayed in the log format as shown in **Figure 11**.

Geo-Engineered Completions: Delaware Basin Case Study 2016

In early 2016 a well was selected for completion in the Wolfcamp formation in the Delaware Basin. Data from four nearby wells was used as input for a trial of a new design. Among the offset data made available were a variety of logs, surveys, tracer, and production measurements for the geo-engineered analysis. The candidate well selected for completion was down dip to nearby producing wells and thus not considered a high potential candidate.

The use of a geo-engineered completion method to select stage lengths and to position perforation clusters resulted in the well's performance significantly exceeding the operator's expectations and delivering approximately the same hydrocarbon production as another operator's nearby well. The performance improvement occurred despite stimulating the candidate well with approximately 50% of the fluid and proppant volumes of the comparison well. Figure 19 compares the performance of the geo-engineered well with that of the operator's other wells in the same area.

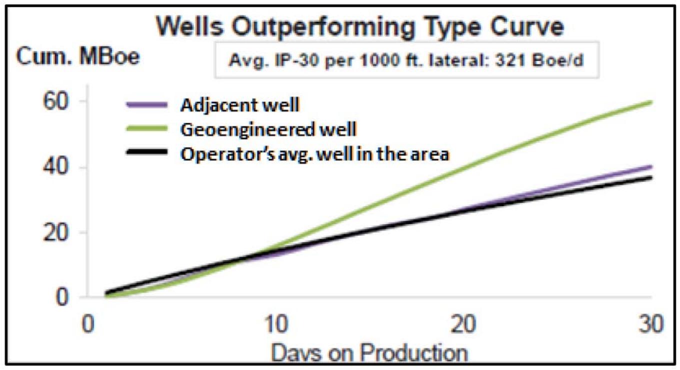

Figure 19—Well performance in a Wolfcamp completion in the Delaware Basin 2016

The geo-engineered well performed better than anticipated; achieving the first goal. The second was to see stages and perforation clusters contributing on a more equal basis. Oil soluble tracers were run on the well which provided part of the answer. Figure 20 shows the relative equal contribution recorded for each stage. Unfortunately cluster contribution was not determined as PLT's were not run.

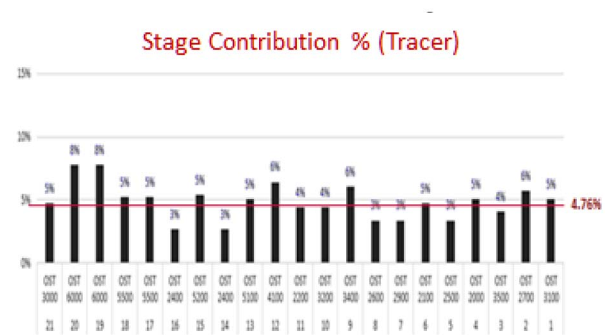

Figure 20—Tracer Data for Geo-engineered well

Horizontal Multi-Zone Completions Design: What's Next?

Geo-engineered completion designs continue to prove their value in horizontal completions. From 2011 to 2016 the design algorithms derived by Cipolla and the weighted attribute methodology described by Shahri and others have contributed to advancing the science and engineering behind horizontal completion design. Geo-engineered completions represent another step in the progressive path toward more efficient completions. Yet the path towards completion efficiency is only one branch of a complex tree. As stated in the introduction section, the quest to improve recovery factors, EUR's and associated net present values in unconventional reservoirs continues and involves at least two recognized challenges. Geo-engineering designs and degradable diverters mentioned earlier address perforation cluster and/or sliding sleeve placement to improve completion efficiency. The remaining challenge is that of lateral placement, which this paper did not specifically address.

However, lateral placement is being addressed by many within the industry. More importantly the larger issue of an integrated repeatable workflow coupling lateral placement and completion design optimization may be closer to reality than ever. Recent presentations from the West Texas Hydraulic Fracture Test Site (HFTS) consortium project reveal new breakthroughs in understanding unconventional production. Located in the Midland Basin the project concluded most of the testing early in 2016. Other longer term testing remains ongoing according to the project host, Laredo Petroleum.

The ambitious project involved a series of data acquisition and testing on eleven wells (see layout below in Figure 19) provided as a test lab by Laredo Petroleum. Among the information acquired and shared among the participants were:

- Pilot hole logs/core
- Horizontal DFITs
- RA & fluid tracers
- Microseismic data
- Cross-well seismic
- Marked proppants
- Drilling data
- Pressure monitoring
- Fiber optics via coil
- Open hole logs

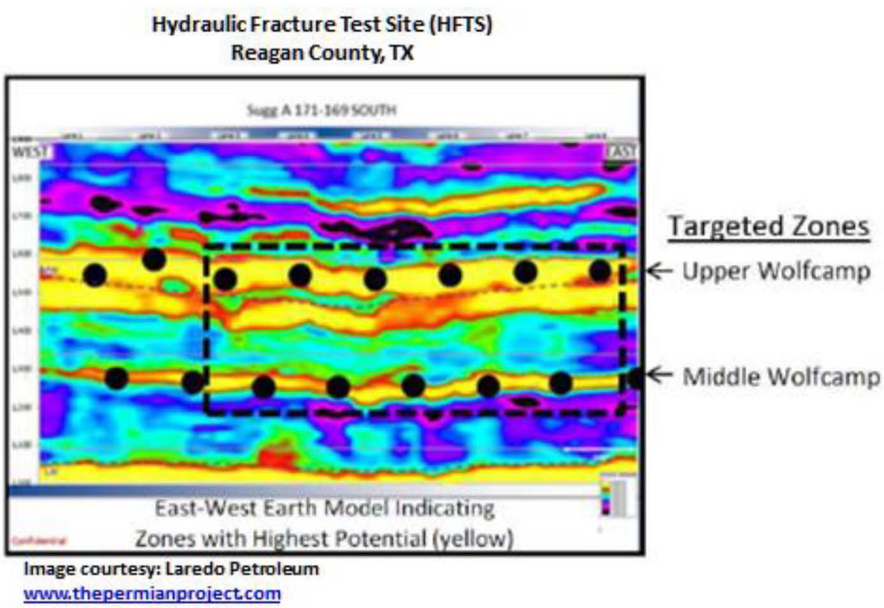

Figure 21—Well layout for HFTS

Previous work done by Laredo Petroleum in the Midland Basin convinced the operator of the need for a comprehensive earth model. In trying to determine the attributes driving production in the first six months of a well's life, they had found a low correlation with bivariate statistical analysis. It was assumed that no single variable was capable of predicting production. Laredo's adoption of an earth model coincided with the collection of data regarding 180 geoscience and engineering attributes during the project. That yielded the opportunity to perform "big data" multivariate analysis to determine and predict well performance. Among the findings announced by Courtier (2016) are the results in Figure 22 revealing that 11 of the 180 attributes identified as part of the multivariate analysis had a 97% correlation coefficient with actual production. Complex integrated completion workflows were paying dividends with the caveat that the workflow has a voracious appetite for reservoir and engineering data.

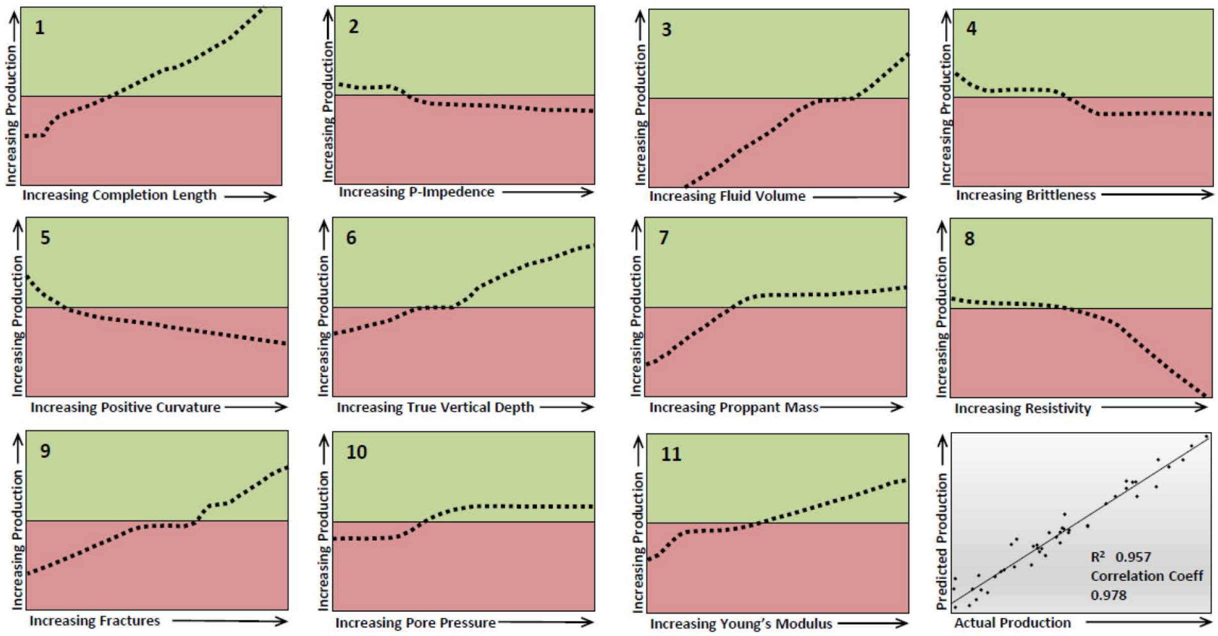

Figure 22—Results of multivariate analysis on data from a grouping of Midland Basin wells courtesy of the Laredo Petroleum consortium study with GTI, et al. in the Permian Basin published as part of the 2nd Quarter 2016 Investor Meeting presentation

By 1998, only 3% of the the human genome had been sequenced; fully 35 years after the 1953 discovery of the double helix by Watson and Crick. After more than 15 years the keys to unlocking the secrets of unconventional hydrocarbons still remain just out of reach. Each year the mystery unravels by a few more strands - but the progress seems agonizingly slow. As more is published in the coming months, our industry may find the 2016 testing done by the Permian consortium has contributed to the understanding of unconventionals more than we could have imagined.

Concluding Comments

The implementation of geo-engineered designs as described in this paper have shown field success and represents another achievement in completion design workflows for single well applications. Advances in horizontal completion design are rapidly evolving. Recent advances in horizontal completion designs have demonstrated the following:

1. Mega-frac jobs with high proppant loading and large fluid volumes work in nearly every basin.
2. Geo-engineered completions and degradable diversion improve cluster efficiency.
3. A proven 3D earth model is essential in determining lateral landing sweet spots accurately.
4. Big data has value. The current trend towards statistical modeling and machine learning are helping to determine a reservoir's unique DNA attributes which lead to optimizing production.
5. Determining the factors/attributes driving production requires large amounts of data from multiple wells as input to perform multivariate analysis for each potential interval.
6. In the absence of large amounts of data (e.g., exploration settings) the combination of high proppant loading, geo-engineered design and the use of degradable diversion are logical steps in establishing baseline performance to approximate *best in class* production within a given area.

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Glossary of Technical Terms

Big Data – The use of large amounts of data in determining the relationships between inputs and outcomes

CQ - completions quality; an index of key attributes used in determining completion stage placement

CQI – composite quality index; a combined index of key attributes used in completion design

EIA – Energy Information Administration; a U.S. entity monitoring oil & gas productivity and efficiency

Engineered completion design – a completion design which takes into consideration the lateral heterogeneity of a formation

EUR – estimated ultimate recovery; an estimate of a well's total output over its life

Geo-engineered completion design – a completion design which considers lateral heterogeneity, reservoir properties, geomechanical properties (including the interaction of natural fracture with induced fractures), and big data analysis of current best practices for a defined geographic area

HFTS – the West Texas Hydraulic Fracture Test Site sponsored by Laredo Petroleum

Integrated Fracture Potential (IFP) – a consolidated index of reservoir quality used to plan fracs

IP rate – initial production rate = the first day's total output from a newly completed well

LWD – Logging while drilling tools used to acquire formation measurements during drilling operations

MSE – Mechanical specific energy is a value for the energy required to remove a unit volume of rock

NPV – Net present value is an economic calculation used in comparing multiple investments

Perf density – separation distance between the perforation clusters within a stage

PLT – Production logging tools are typically wireline measurement devices to record a well's output

Plug & Perf – a completion techniques using internal frac plugs and wireline placed perforations

ROP – rate of penetration

RQ – reservoir quality; an index of key attributes used in determining completion stage placement

TOB – torque on bit

TVD – True vertical depth is a measurement of a well's depth relative to the surface depth

WOB – weight on bit

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