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AV Optimization in U.S. Shale Plays: Emerging New Techniques and Technologies*

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Search and Discovery Article #110214 (2015)**
Posted August 31, 2015

*Adapted from article prepared for distribution at AAPG/DPA Midland Playmaker Forum, January 14, 2015, and from oral presentation at the Forum in Midland, Texas. Text and slides were originally posted as Search and Discovery Article #80442 (2015).

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Abstract

In times of oil price instability and low gas prices, the capital-intensive technologies that made shale plays possible must be re-evaluated to see if there are ways to reconceptualize them to make the plays economic. This article presents the results of an analysis of the current state of shale play development in the United States to determine the recent advances in the understanding of reservoir behaviors and the most effective uses of new techniques and technologies. My presentation emphasizes reservoir optimization, and the application of the new technologies and techniques to reduce costs and to improve recoverability of hydrocarbons in order to improve ultimate recoverable reserves. It specifically addresses issues of decline curves, stranded pay between laterals, stacked pay logistics, and pad drilling. In addition, the presentation looks at sweet-spot optimization, effective investments, hydraulic fracturing, and geomechanics. Finally, it presents an overview of some of the emerging best practices in North American shale plays and the results of new optimization-focused technologies and techniques, including refracturing, whipstocking, geochemistry, and integrated imaging.

Introduction

Steep decline curves, inadequate drainage, and variable production histories have been a major concern in shale plays in North America. In times of low oil as well as natural gas prices, reservoir optimization with the best possible use of technology and new techniques becomes “mission critical.” For many producers, the easiest approach would be to emphasize bypassed and/or stranded pay where the cost to recover the marginal reserves (since the infrastructure is already in place) may be as low as $20 per barrel. In this case, it is important to recognize that there exists bypassed and stranded pay in multi-stage hydraulically fractured wells where there are “sweet spots” (that is to say, preferentially enriched zones within the heterogeneous reservoir rock) that were not adequately produced due to a number of factors. Many of the factors have to do with the fact that the formations being produced are extremely heterogeneous and also that the actual well design and execution can be less than ideal due to factors such as inadequate “plug and perf” stimulation, drilling out of zone when geosteering, proppant and fluid problems, fracture interference, and poor cluster efficiency. First, however, it is necessary to know how to identify and target the bypassed and stranded pay. Then, one must review approaches to effectively targeting and producing the pay, ranging from whipstocking the laterals, sidetracking, refracturing, pinpoint perforating, and radial drilling. Further, it is necessary to build a knowledge base and good teams to effectively analyze a reservoir, gather the correct data, build a model, and develop a drilling and production plan.

Part I: Next Phases of Shale Play Development (oral presentation**,** pages 3-13)

Optimizing shale plays is no longer just a North American concern. In China’s Sichuan Province, which contains the Fuling Field, companies such as Sinopec, in conjunction with Chengdu University of Petroleum, and the State Key Labs, and partners such as Chevron and ExxonMobil, are diligently seeking ways to overcome the very significant logistical challenges. Further, the conventional wisdom of “bigger is better” is challenged as costs escalate.

Across the border from prolific Eagle Ford shale wells in south Texas, teams of Mexican geologists have focused on the potential for exploiting the stratigraphic equivalents in northern Mexico (Peschier, 2010). The newly passed Energy Reform has opened the possibility of significant investment in these plays. But, no one wants to repeat costly errors, or to persist in using technologies and approaches that result in vast percentages of the oil in place being left behind.

For the global community of geoscientists, it is necessary join forces to solve technical problems. Certainly there will always be issues of intellectual property and also ownership of property, or market-making events in the case of a public company. Those issues notwithstanding, it is necessary to find ways to accelerate the development of and transfer of knowledge.

Stranded Pays: Between the Laterals (oral presentation**,** e.g., page 4)

Despite efforts, the decline curves for oil and gas production from shales continues to be steep and rapid. Within 36 months, many wells are no longer producing, despite the fact that a single horizontal well may penetrate many sweet spots directly, and in other cases, may drill through the edge of a lenticular, isolated sweet spot “pod.” The sweet spots that are on the edge of the laterals are not easily produced, and as a result, there may be pay that’s left behind. It could be considered “stranded pay.”

Stranded pay” denotes pay that might be technically recoverable, but it is not economically recoverable. Here are a few key points:

- The concept of “stranded pay” is not reserved for mature fields or uneconomic isolates
- There is stranded pay between and alongside laterals.
- To recover stranded pay in within the laterals, it is best to return to the first laterals drilled in a pad, which are mainly depleted ones. It is important to begin with the depleted laterals in order not to disturb ongoing production.
- “Offsets” or “whipstocks” out from the laterals to enter the sweet spots that contain “stranded pay” often identified by microseismic or geochemical methods (Broussard et al., 2009).

For example, a pad may have 10 laterals, if the pad has been there for 3 or 4 years, it is likely that at least one or two of the laterals is no longer productive, since declines tend to be steep and are essentially at less than 10 barrels of oil per day within 36 months.

For example, some formations are extremely heterogeneous, and in a 5,000 foot lateral, there may be a 300-400 foot section that is on the edge of a very nicely fractured “pod” that has excellent accessible porosity thanks to induced fracture. However, the lateral just grazed the edge of it. It did not drain well.

The pod (lenticular unit) has what we can safely call “stranded pay.” The question becomes: how can we recover the oil and/or gas that has been left behind due to geosteering errors, poor communication, and low connectivity of permeable zones?

That is where innovative drilling and completion can play an important role. The crux of the challenge is this: how is it possible to recover the oil and gas we know is in relatively porous and permeable zones on the edge of a lateral?

Sweet Spot Optimization: Whipstocked Laterals (oral presentation**,** e.g., page 7)

The “stranded pay” are sweet spots. The can be imaged fairly accurately when there are XRF, XRD, microseismic, geochemical analyses, mudlogs, and more available. The fact that they’re available after the fact of completion could present an advantage of sorts if it is possible to re-enter the lateral, and then whipstock off into the core of the sweet spot.

The ideal approach is to drill a directional offset through a lateral, and/or whipstock into a highly fractured sweet spot (fractured in the original completion), it will not be necessary to re-stimulate the well by refracturing it, which would include using chemicals such as hydrochloric acid to dissolve some of the carbonates and clear the facture networks (French, 2014).

To summarize, here are some of the techniques needed in sweet spot optimization:

- Better integration with sequence stratigraphy, geochemistry, imaging, XRF, etc.
- Under development: Whipstocking the Sweet Spots
- Whipstock directional drilling for better penetration of sweet spots
- Whipstock off the lateral where microseismic indicates a fracture pod
- Packers or sliding sleeves to perf within the whipstocked part of the lateral?

Cost Reductions

If one looks at the Analyst Day presentations of companies that are operating in shale plays, you'll find a common theme, which tends to center on cost reductions. Companies such as SandRidge Energy have been able to reduce drilling, completion, and operating costs significantly (SandRidge, 2014). Some companies have invested heavily in core studies in order to focus their efficiencies in the completion / stimulation phases. Others have looked ahead to stacked pays, and have invested in taking the time to study the other uphole potentially producing zones.

- Fracturing efficiency improvements (better pressure management, frac height control)
- Proppant, fluid, water management, pad drilling, logistics improvements
- Water management / water re-use
- Stacked pays (Bakken, Permian, Oklahoma)

Cost Intensifications

In a very counter-intuitive manner, some companies such as Continental Resources, have aggressively attacked the concept of technology and efficiencies and have decided to invest in additional technologies that will improve recoverability, and will allow additional zones, new laterals, new stages, and whipstocks to be utilized. So, their costs seem to be very high, but in the end, the ROI could be significantly higher if the ultimate recoverable reserves can be increased by an additional 5-10 percent, at a relatively low cost.

Here are a few of the technologies that cost more money, but pay off in the end:

- Microseismic sensor arrays (10-well installation)
- 3D visualization
- Goal: improve hydraulic fracturing, determine frac heights.
  - Find where the sweet spots are (lenticular units with communication).
  - Return to drill additional laterals, or whipstock into the heart of the pods.

Other factors include:

- Managing drilling fluids to minimize formation damage and optimize completions (oral presentation**, e.g.,** page 11)
- Addressing the problem of steep decline curves requires a multi-pronged approach. One of the reasons for the steep decline rate in shale plays is due to the clay mineral content and the fact that clay minerals can swell or bind with other chemicals, which can destroy permeability and porosity. Thus, both drilling and hydraulic fracturing fluids can cause the clay minerals to behave in a way that creates formation damage.
- Developing a water-based mud that inhibits shale swelling is a critical part of making sure that there is minimal formation damage in drilling a shale well, and also in developing completion fluids. Shale inhibitive drilling fluids help reduce swelling of clay minerals, which are grouped in five groups: kaolinite, smectite (montmorillonite), illite, chlorite, and vermiculite. Smectite is the most reactive to water, while clays such as illite having a low cation exchange capacity (CEC) swell through surface hydration (Al-Arfaj, Hossain et al., 2014).

Additives include pH controllers, fluid loss additives, viscosifiers, salt, and oxygen scavengers. Inhibitors include chrome and ferrochrome lignosulfonate, potassium chloride, amines and polyamines, and methyl glucoside, depending on the type of clay minerals in the shale (Al-Arfaj, Amanullah et al., 2014).

- Surface hydration: typically occurs in clays that have a low CEC values, such as illite. Cation substitution takes place in illites within the outer tetrahedral layer.
- Ionic hydration: hydration shells formed around the compensating ions, and occurs in clays with high CEC values.
- Osmotic hydration: due to the difference in salinity fo the shale rock fluid and the drilling fluid. If the shale rock fluid salinity is higher than the drilling fluid, the shale will hydrate.

Understanding the CEC helps develop the “best fit” drilling fluid and determine the best mud formulations. Water-based muds (WBMs) with additives (including glycol) are options, as well as oil-based muds and those with potassium chloride (Emadi et al., 2014).

Refracturing

Although hydraulic fracturing techniques continue to evolve, many operators who have drilled shale plays have come to realize that many wells have not been stimulated in a way that is effective. The main problems are fracture interference and cluster efficiency, which result in the fact that there are significant portions of unstimulated pay in typical shale play completions such as in the Woodford (French et al., 2014; Figures 1, 2, and 3).

In fact, many shales exhibit steep productivity declines – as high as 60 – 80 percent in a year (Jayakumar et al., 2010). Additional factors include proppant crushing, embedment, low reservoir permeability, and ineffective initial fracturing (Arnold et al., 2014).

In order to be effective with refracturing, the following tools can be used in a horizontal well:

- Sliding sleeve
- Coiled Tubing tools
- Perforation Squeeze (perf squeeze)
- Mechanical and Chemical Diverters

A case study in the Marcellus shale in southwestern Pennsylvania involved using a new temporary sealing agent along with chemical and mechanical diverters. The diverting agents entered the perforations and bridge-off and resulted in a long seal that accommodated the multiple shut-downs during existing perforations. The diverting agents directed the fracture fluid to the new clusters (Arnold, 2014).

Pre-Stack Seismic Inversion & Reservoir Characterization in Unconventionals

The two key properties derived from seismic are Young’s modulus and Poisson’s ratio. In addition, azimuthal inversion and AVO can be used to determine both the principal stresses and the differential horizontal stress radio. Specifically, wide-angle, wide-azimuth (WAZ) seismic data can be used to determine principle stresses (vertical, maximum and minimum horizontal), along with rock strength (Gray et al., 2010)

The benefits include:

- Sweet spot identification
- Well location optimization
- Completions optimization
- Geochemistry (reservoir characterization – what do you have?)
- Basin analysis (big picture)
- XRD / XRF (while drilling)
- Drilling fluid optimization

New Reservoir Stimulation Approaches

Geochemistry and geomechanical data should be integrated in order to develop effective reservoir stimulation. Currently, research is being directed in the area of nano-stimulation; that is, charged nano-particles are sent into the interstices of the clay minerals in order to stimulate them and accelerate the process of adsorption, and releasing gas molecules. Recent studies have demonstrated that nanoparticle-stabilized emulsions and forms can be utilized to recover oil and gas, particularly in mature fields. .

A summary of current areas that have shown high potential for having a positive impact on reservoir stimulation include the following areas:

- Cation exchange capacity (stabilizing fluids introduced into the reservoir in order to avoid behaviors of clay minerals)
- Simulating charged particles (nano-stimulation)
- Production issues (focusing decline curves)
    - Pressure controls / gas drive maintenance
    - Punctuated refracturing at certain intervals
    - Cluster spacing analysis to optimize induced fractures
    - Fracture interference by design to optimize fracture networks

Part II: North American Plays: "Best Practices"

A brief review of key shale and unconventional plays in North America allows one to see the emergence of certain "best practices." The following plays are reviewed briefly in terms of new develops and lessons learned.

- Bakken and Three Forks
- Eagle Ford (oral presentation, pages 14-15)
- Marcellus
- Mississippian Lime (oral presentation, page 17)
- Woodford Shale (oral presentation, pages 18-42)

Bakken and Three Forks

The Upper and Lower Bakken shales constitute source beds for the entire petroleum system (Bakken) in the Williston Basin of Montana and North Dakota. Optimizing the production in the Middle Bakken formation that lies between the Lodge Pole and the Three Forks formations has been achieved by taking a multi-disciplinary approach (Hardriker et al., 2014).

- Extend the limits of pad drilling & laterals by altering the horizontal landing targets and increasing wellbore lateral lengths.
- Optimize completion techniques: control and refine pump-down procedures and flush procedures,
- Optimize completion design
  - Proppant optimization (higher strength, ideal size)
  - Frac fluid optimization
  - Frac height determination
  - Frac interference determination

Eagle Ford

Because of its complexity and high degree of heterogeneity, the Eagle Ford requires an emphasis on optimizing reservoirs by means of identifying sweet spots, and then developing drilling and completion programs that maximize induced fractures, fracture networks, and fluid flow. The first priority is to identify sweet spots, which are characterized by relatively high Total Oil Content (TOC), relatively high brittleness, relatively high porosity, low clay content (which tends to create ductility), mineral filled natural fractures (for better possibilities of induced fractures, and an optimal stress regime.)

A sweet spot in the Eagle Ford is also an area of preferential enrichment, and the initial production levels can be average 2,000 barrels of oil per day in the first months of production, while a relatively barren area might produce only 200 barrels per day.

Geosteering using “logging while drilling” and image logs is very important. In addition, techniques to identify sweet spots can include the following:

- XRD / XRF: Geosteering in the laterals for sweet spots, as well as in pilot holes: The XRD data is particularly helpful in the determination of total clay, while the XRF measures 10-12 major elements, as well as trace elements (trace metals may indicate areas of high TOC (Tonner, 2012).
- Chemostratigraphy: using major, minor, and trace element geochemistry to classify strata and to characterize them by means of correlations to sweet spots. It can be used to detect and evaluate subtle yet rapid change in superficially homogeneous rocks (Tinnin et al., 2014).
- Geomechanical data derived through pre-stack seismic inversion (Tinnin et al., 2014)
- Redox-sensitive metals are an excellent proxy for organic richness (Dix et al.,2010).
- Microseismic for determining fracture heights
- Pyrolysis includes determining free hydrocarbon, remaining hydrocarbon generation potential, organic richness (TOC), and Thermal Maturity (Tmax).
- Sequence Stratigraphic correlations: 3D seismic & depositional modeling

As a result, the main performance determinants for the Eagle Ford are the levels of Vclay (ties to brittleness) and TOC, metal trace elements (proxies for organic content), mechanical elements (from inversion and mapping) , multi-attribute analysis to determine best locations for induced fractures.

Marcellus and Utica

Optimizing the Marcellus requires a deep understanding of the geology, particularly the depositional history, the thermal history of the basin, and also the structural history. The history combined with all available data can help one gain an ability to pinpoint sweet spots and also design programs with the right types of fluids. Using petrophysical data, core information, as well as seismic, it is possible to build 3D shared earth models, which can serve as static models for reservoir simulation (Yang et al., 2013).

In the Marcellus geochemistry is critical, particularly when targeting an ideal mix of gas and liquids. A few of the “must have” elements and the “best practices” in the play are:

- Gas-Liquids boundary determinations

- Gas typing and understanding the migration history / patterns / mixing
- Accessible and non-accessible porosity
- Pore typing (tie back to regional studies)
- CT scans of the cores

Mississippian Lime

The Mississippian Lime in Oklahoma and Kansas is highly heterogeneous, and there is significant variability of oil saturation. For example, it is not unusual for a well to encounter 15% oil cut, but less than a mile away, a well completed in the same zone will encounter 2 percent oil cut. Watney (2014) has investigated the distribution of oil saturation and has found that a knowledge of the geological history is critical in determining patterns for preferential enrichment. Higher oil cut is generally found in areas with fracture networks that include open fractures, and these communicating fracture networks correspond to areas of repeated tectonic activity, resulting in structural deformation (Watney, 2014).

Much of the variability has to do with hydrothermal fluid flow. Goldstein and King (2014) have found that there were three distinct pulses of hydrothermal fluid flow, each of which is associated with fracturing, silica dissolution and carbonate dissolution. Further, the hydrothermal fluid flow resulted in significant diagenesis, which allowed porosity to develop, as well as fracture networks. The combination of factors resulted in differential / preferential enrichment of oil and gas in the reservoir rocks (Goldstein and King, 2014).

In order to characterize the reservoirs, the following are needed:

- Image Logs for Fracture networks
- Basin-Level Analyses
    - Petroleum Generation
    - Expulsion / Flow
    - Structure (Faults / Fracture Networks)
    - Convergence with Mississippi Valley-Type Mineralization

Woodford Shale

The Woodford shale is found over a large geographical extent, and must be studied very carefully to identify the limits of fracability as well as the extent of the oil window (Cardott, 2014).

- Geomechanics
  - Pore pressure regimes
  - Nano-geomechanics (cation exchange capacity)
  - Fracture typing / characterization
  - Fracture networks
  - Brittleness & Fracability determination

The productive extent of the Woodford has been expanded recently, thanks to an enhanced understanding of the relationship between different types of kerogen and thermal maturation (Cardott, 2013). In order to determine the prospectivity of an area, certain geochemical evaluations can be very helpful. They include the following:

- Geochemistry
  - Total Organic Content (TOC) evaluations
  - Kerogen typing
  - Maturity / Vitrinite reflectance
  - Gas fingerprinting
  - Migration patterns
  - Indicator minerals / deformations
  - Adsorption factors
  - Pyritization

Conclusions

- New technologies and new techniques are being evaluated every day.
- New approaches to sweet spots (whipstocked laterals and refracturing) can result in optimized reservoirs.
- New reservoirs and also stacked pays are possible, particularly when migration paths can be traced by means of understanding fracture networks.

- Manipulating the clay minerals on a nano level can"unbind" the matrix and allow more accessible porosity.
- Managing drilling fluid chemistry can be done to avoid formation damage and to enhance brittleness and effectiveness of stimulation (including hydraulic fracturing).

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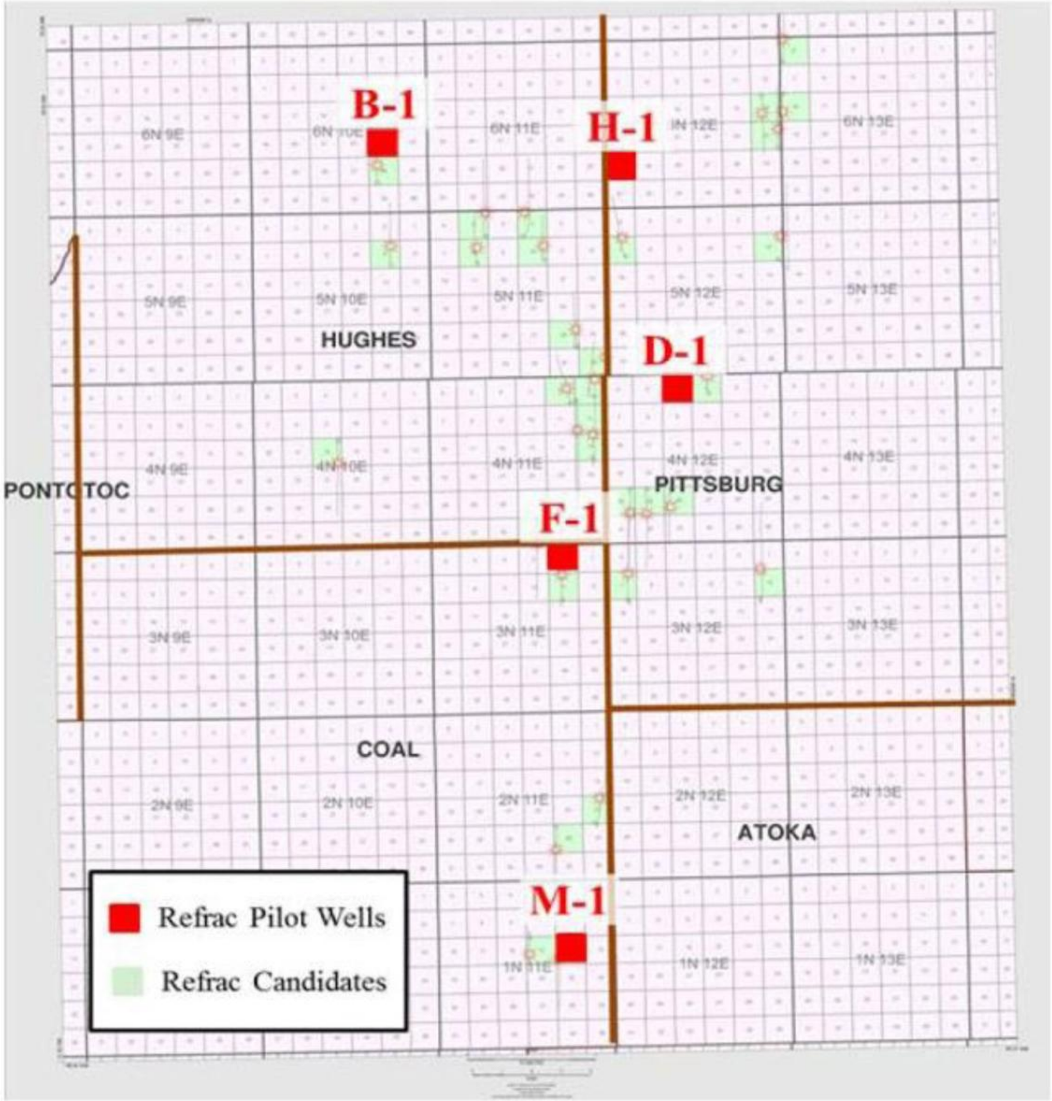

Figure 1. Location map of refracturing pilot wells (from French et al., 2014).

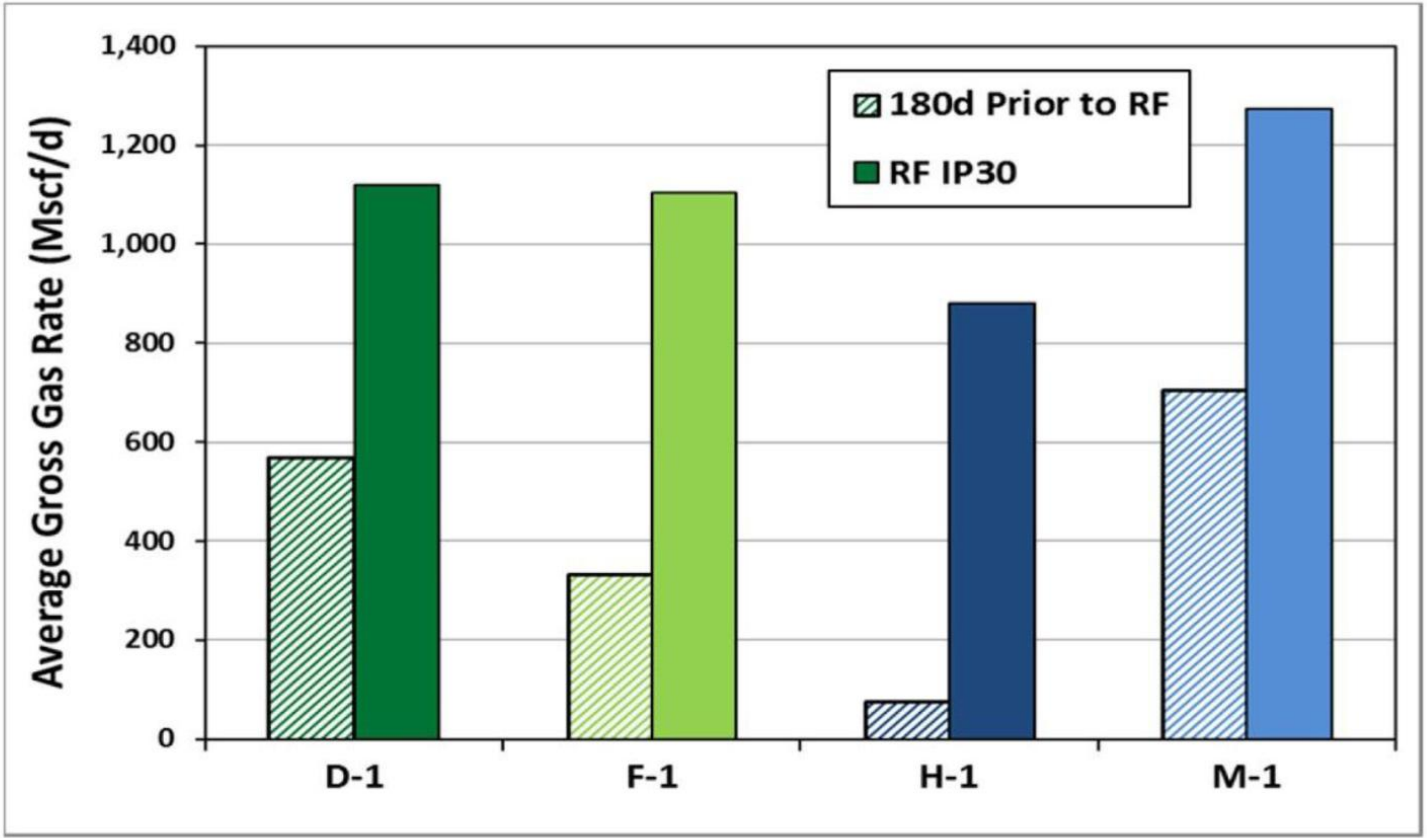

Figure 2. Plot of pre-and post-refracturing production rates (from French et al., 2014).

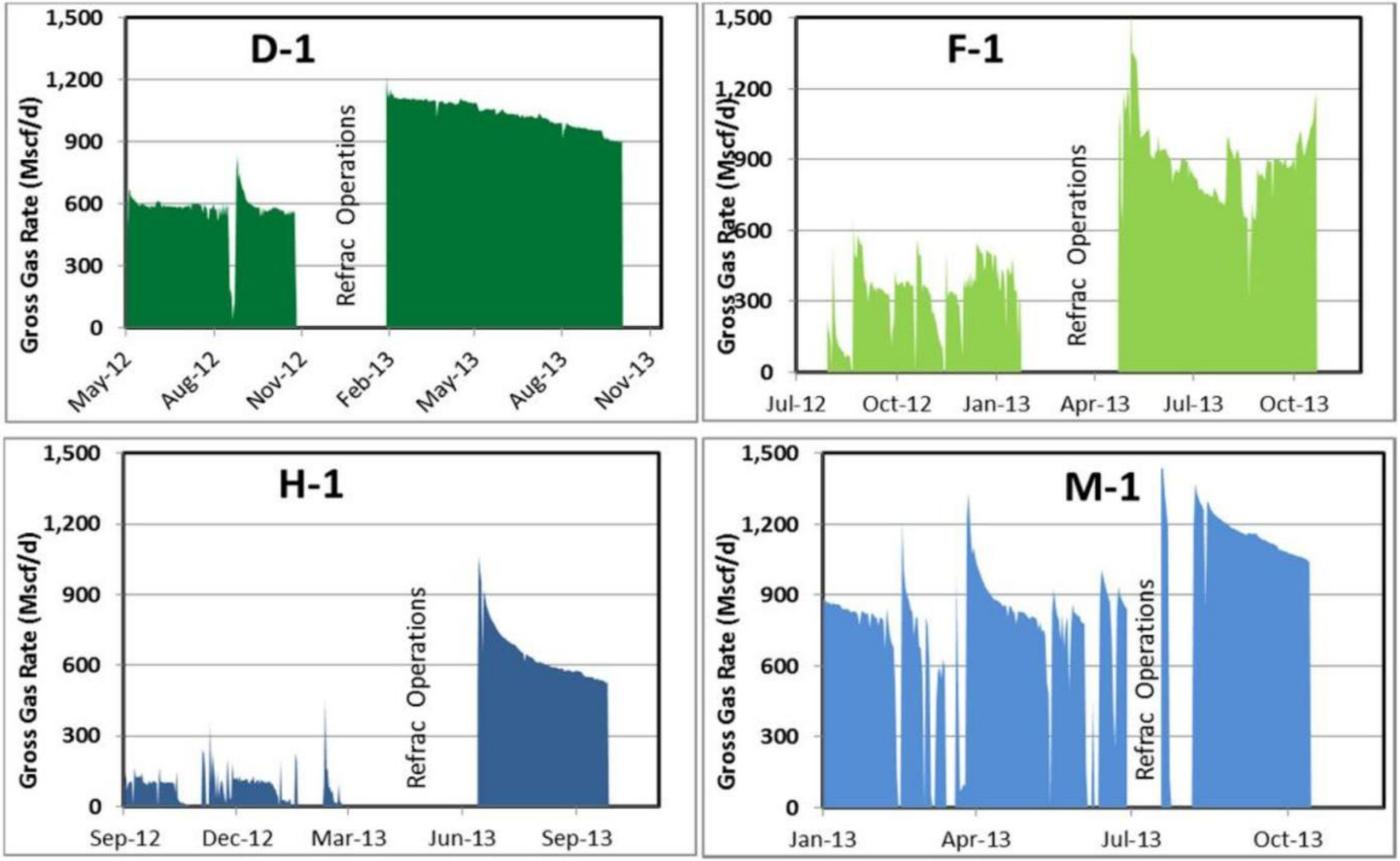

Figure 3. Pre- and post-refracturing production rates by well (from French et al., 2014).