SPE SPE-159838-PP

Rapid Work Flows for Accurately Determining Optimal Horizontal Well Spacing and Fracture Cluster Spacing

James L Buchwalter, Gemini Solutions Inc., Mark Craig, Devon Energy, Richard Wardlow, Devon Energy

This paper was prepared for presentation at the 2012 SPE Hydrocarbon, Economics, and Evaluation Symposium held in Calgary, Alberta, Calgary, 24–25 September 2012.

Abstract

This paper will discuss how accurate infill well development strategies for horizontal wells are efficiently developed using production and pressures from vertical discovery wells.

The work flow requires developing pattern* models for the vertical wells using best engineering assumptions for parameters, and then improving the reservoir description in the models using computer assisted history matching. The resulting rock properties are mapped between wells using a Kriging geostatistic algorithm. In the final step, different horizontal well locations and completion strategies are investigated to create an optimal well spacing and completion strategy. Close agreement between model production forecasts and recent horizontal well production and pressure records validates the accuracy of the approach.

Description of the Work Flow

The modeling is applied to an area of the Barnett Shale with nine vertical wells and four horizontal wells drilled recently. The map below highlights the location of the vertical and horizontal wells. The horizontal wells are drilled along the maximum principle stress plane to allow intersection of induced well fractures with natural fractures residing in the formation.

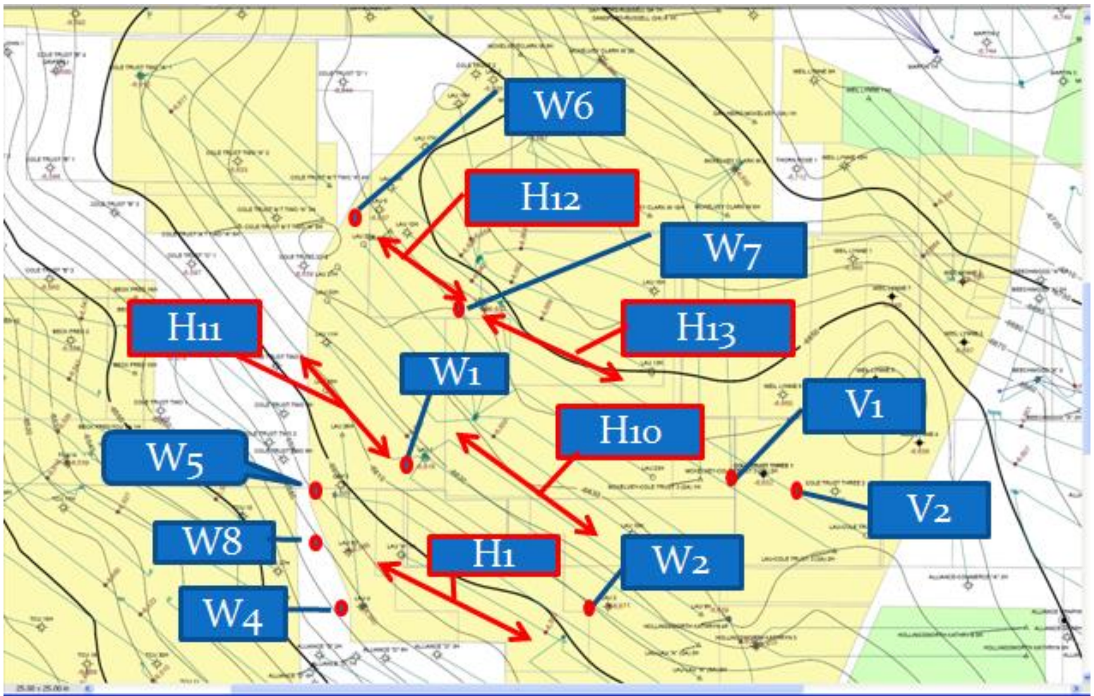
In the first step, vertical fracture well models are built using a black oil model with volatile oil/gas condensate modeling capabilities. Next, tubing curves are built independently using nodal analysis, imported into the pattern models, and assigned to the each well. Tubing curves give the models the capability of controlling wells by rates or tubing head pressures, and matching recorded history for both of these parameters.

The geology and fracture descriptions are then optimized using an assisted history match process that modifies fracture half-length, conductivity, fracture volume, permeability between clusters, rock permeability, and porosity. Normally this is a very labor intensive task. History matching 9 vertical wells and 4 horizontal wells without a history match tool requires an expert engineer with history match experience, and days to weeks of trial and error searches for solutions. The same task is completed using a user assisted history match algorithm in a few hours per well. This faster history matching process allows time to investigate multiple solutions with different starting parameters to find the best possible solution for each well.

Next, a Kriging algorithm estimates rock properties between wells and develops maps of permeability and porosity for the horizontal well locations.

In the last step, iterations on horizontal well locations and fracture spacing are used to optimize the completion strategy for future infill wells.

Figure 1 – Location of Vertical and Horizontal Wells in Study Area



The vertical wells have between 8 and 10 years of historical performance prior to drilling the infill horizontal wells.

History Match Approach Overview

The computer algorithm used for history matching replicates the traditional work flow engineers use for history matching, but automates the time spent manually setting simulation runs with simple statistical algorithms.

A brief description of the match algorithm is as follows. The engineer first specifies which parameters he would like to vary, with minimum and maximum ranges for each parameter. The convergence algorithm then initiates a set of simulation runs varying the parameter to test for improvement. If the model improves, the algorithm continues to test parameters further in the same direction until the match worsens. The process is repeated until convergence is reached or the maximum number of iterations is reached.

The algorithm converges on the solution very rapidly with a minimum number of simulations as the algorithm initially tests a broad range of values before testing progressively finer ranges of values as it closes in on the solution. In most instances, an accurate solution for three parameters takes less than 20 simulation runs, while testing all combinations of three parameters can take up to 2000 runs.

Discussion of Vertical Well Matches

A summary of the vertical well match parameters are listed in Table 1.

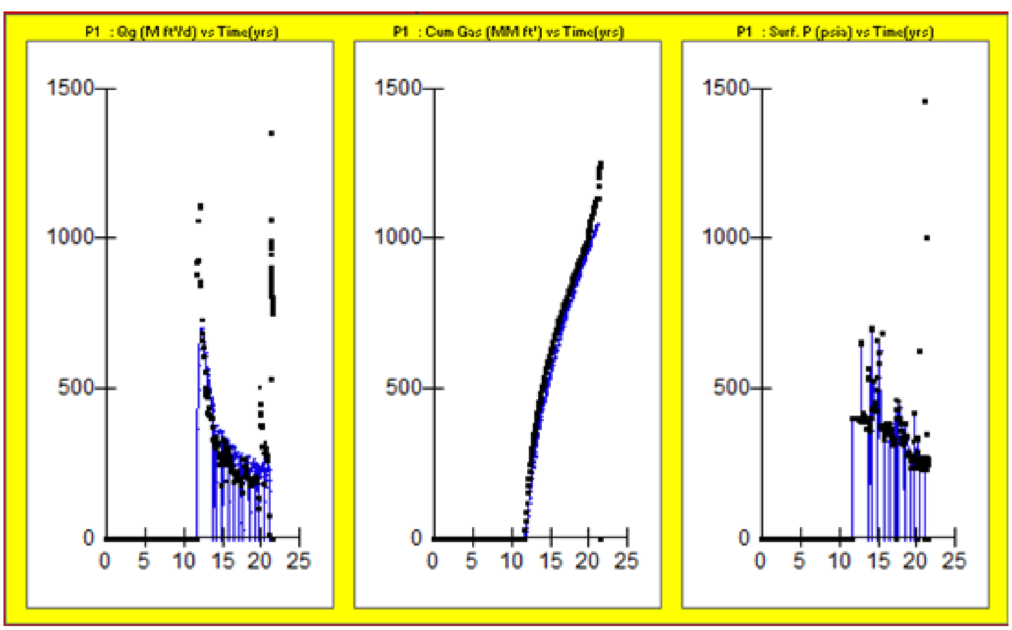
Table 1 –Vertical Well Matches

Area	Well	Fracture Half Length	Rock Permeability	Permeability in Fracture	Porosity	Equivalent Fracture Width
		Ft	**Nanodarcies**	**Millidarcies**	%	Ft
South	W1	410	660	10,000	6%	5
South	W2	750	480	10,000	6%	5
South	W4	759	700	10,000	6%	5
South	W5	460	600	10,000	6%	20
South	W8	500	231	10,000	6%	5
North	V1	317	392	10,000	6%	5
North	V2	310	289	10,000	6%	5
North	W6	350	350	10,000	6%	5
North	W7	369	196	10,000	6%	5

Fracture half-length varies from 310 to 759 feet with an average length of 469 feet. Rock permeability varies from 196 to 700 nanodarcies with an average permeability of 433 nanodarcies. The equivalent fracture width represents each fracture stage as a volume with a constant width extending the entire length of each stage.

A sample match of rates and tubing head pressures for one of the vertical wells follows:

Figure 2 – Match of Rates and Tubing Pressures for Sample Well

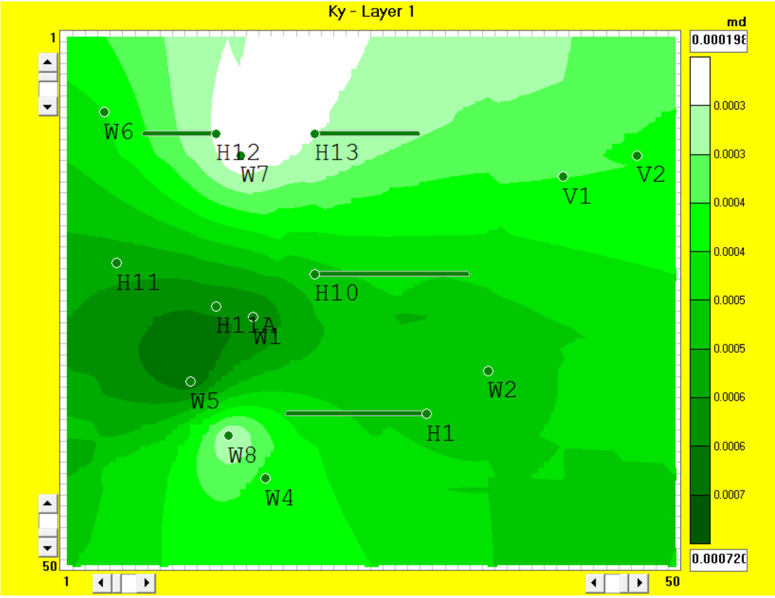


In this instance, the recorded tubing head pressures and historical rates serve to control the well while the assisted history match tool varies the parameters in Table1 (permeability, porosity, and fracture length). Note: The data points around day 8000 reflect a recompletion in the well and were ignored during history matching.

Creation of Permeability Map over the Model Area

Individual well rock properties taken from assisted history matching at each well were used to interpret maps for the area of interest. A Kriging* algorithm generates the interpretation between wells, shown in Figure 3.

Figure 3 – Permeability Map over Area of Interest



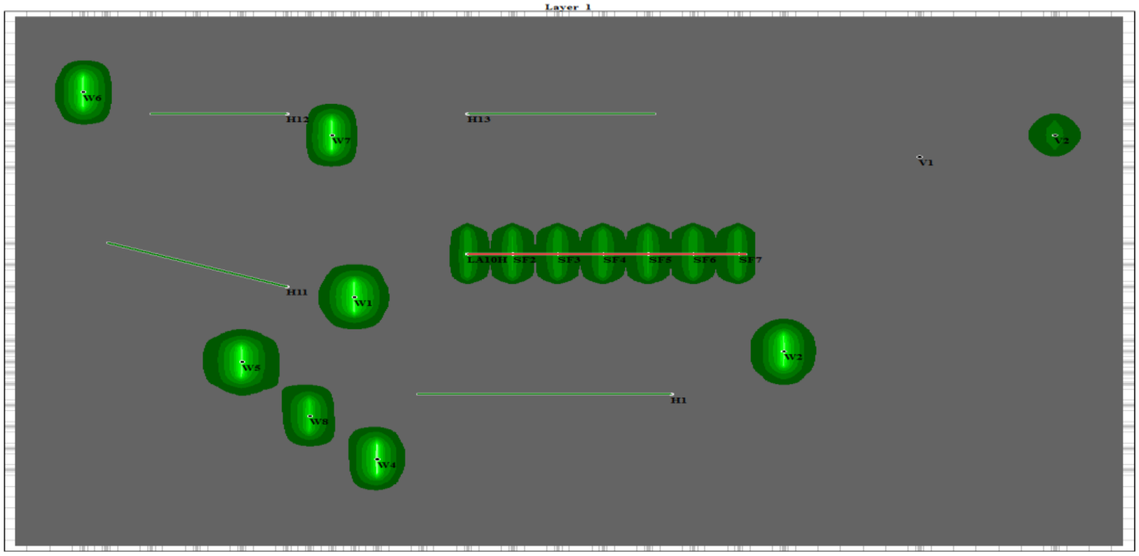
Permeability varied from 200 to almost 700 nanodarcies. The three fold permeability contrast illustrates the permeability variability seen in many tight assets, and the need for accurate permeability maps as optimal economic well spacing is strongly dependent on permeability.

The Kriging algorithm interpolates between the data points using a default variagram. The variagram has a user specified correlation length that adjusts interpolated data between know map data points. The map interpretation above assumes excellent correlation between known data points, and the result is a relatively smooth map interpretation.

Investigation of Interference between Wells

To test for interference, a model of the entire area was constructed and geological maps generated from the pattern history matches were integrated. Production was then integrated into the new full field model and run to present time. A pressure difference map at the present time is displayed in Figure 4.

Figure 4 – Pressure Difference at 1/11/2011



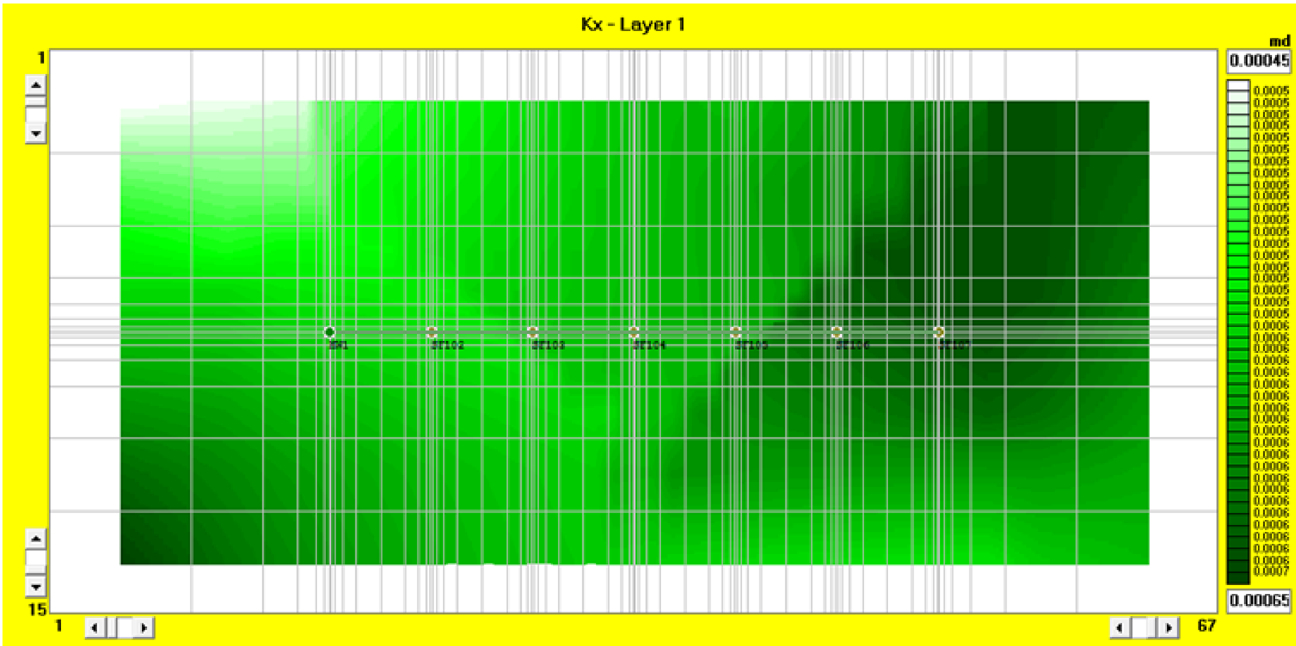
The pressure difference map shows no appreciable inter-well pressure interference. Production and pressure records confirm negligible interference between the vertical or horizontal wells.

The negligible interference between wells shows that the single well models used for this study are a good approach. Larger models with multiple wells are required when there is significant inter-well interference.

Building Horizontal Well Models

Next, pattern horizontal well models are integrated into the geological maps. A sample permeability field around one of the horizontal wells is shown in Figure 5.

Figure 5 – Permeability Map around a Sample Well, 450-650 Nanodarcies



The grid in Figure 5 is refined to 5 feet around the fracture stages and fracture tips to accurately model pressure and saturation changes immediately surrounding the stages.

Although single fracture adjustment was not required in this study, in certain cases changes in fracture half-length and conductivity for different stages and times may be required to achieve acceptable history matches, and to model inter-well interference.

Discussion of Horizontal Well Matches and Validation of Permeability Maps

The assisted history match work flow used to match the vertical wells was applied to each horizontal pattern model. The only parameter selected for adjustment in the horizontal wells was fracture half-length. The fracture half-length for a horizontal well with staged fractures is typically less than the fracture half-length for vertical wells drilled in the same area. This happens because in most instances adjacent horizontal well staged fractures are close enough to permit some interference reducing the effective completion fracture half-length. Two sample matches for horizontal well matches are shown below. Each match was achieved in fewer than 8 runs and 3 minutes CPU using the assisted history match tool.

Figure 6 – Match of Well 10 Horizontal Well, 255 ft Half Length

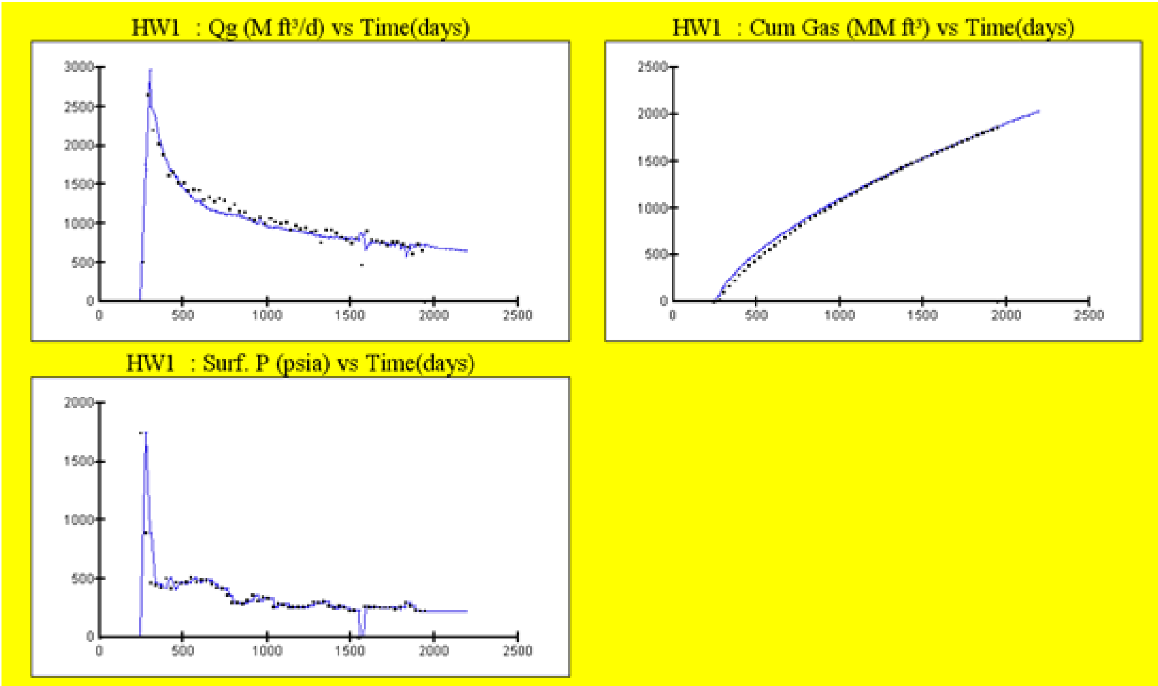
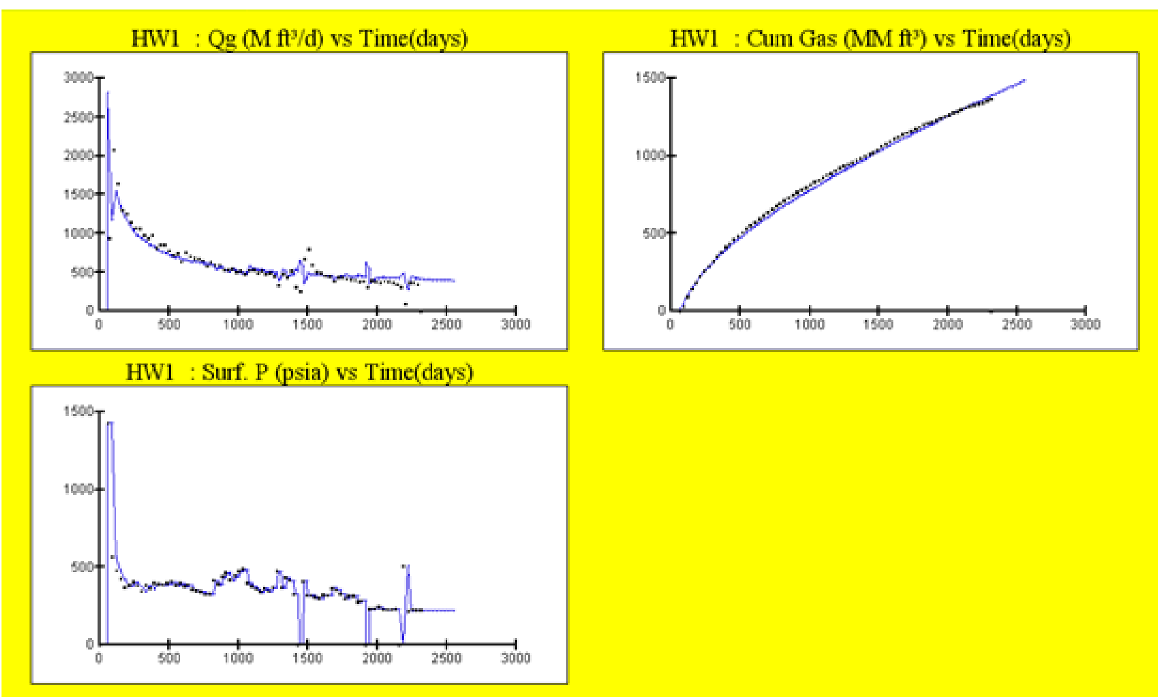


Figure 7 – Match of Well 11 - 240 ft Fracture Half Length



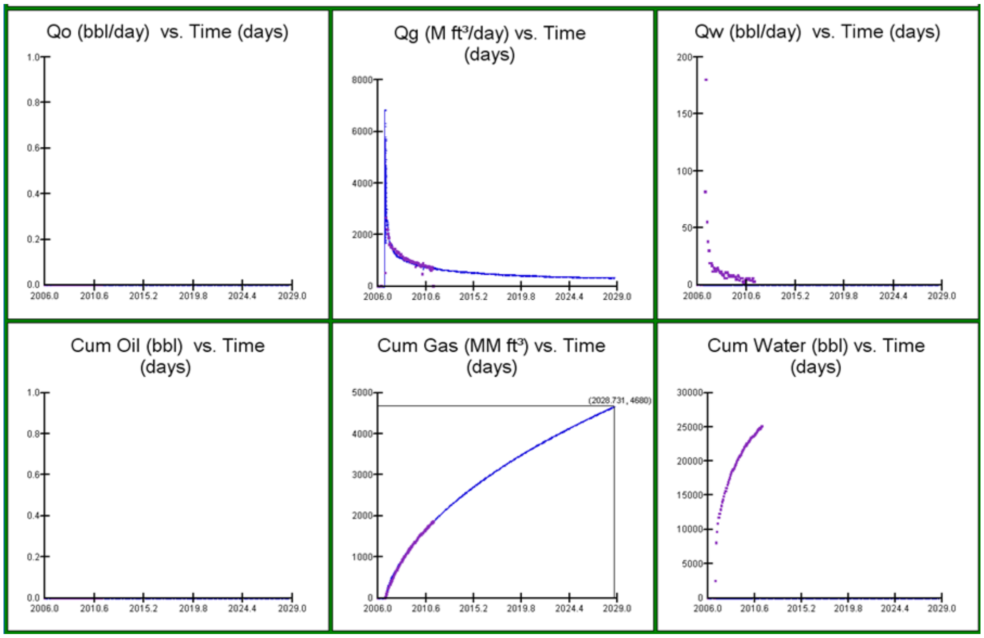
The matches of rates and tubing pressures for all of the horizontal well models are nearly perfect. Indirectly this validates the average permeability map created from the pattern vertical well matches. It is impossible to achieve matches of this quality without having accurate average permeability around each horizontal well.

The average fracture half-length of all the horizontal well models is 230 feet in comparison to 459 feet for the vertical wells. The reduction in fracture half-length as discussed earlier is a result of fracture interference between the fracture stages

Horizontal Well Forecasts

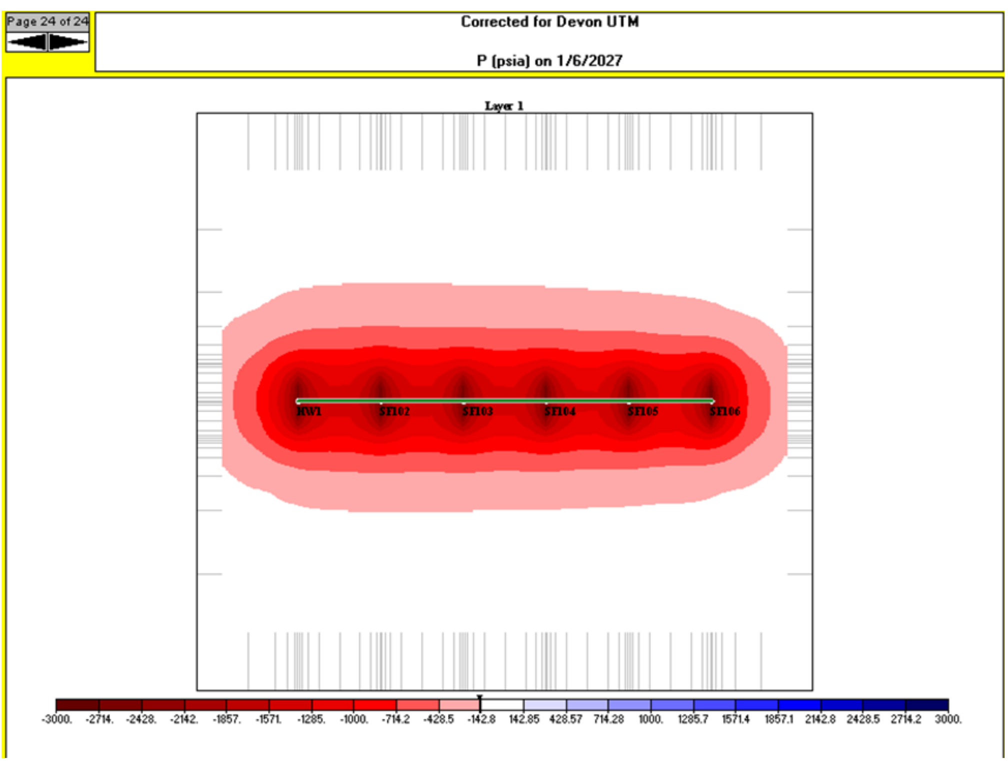
The current horizontal wells are spaced far enough apart to have minimal interference surrounding wells as evidenced by the pressure difference map discussed earlier. As a result, reasonably accurate production forecasts are possible for all of the wells using the pattern models constructed for history matching. A sample forecast for one of the horizontal wells is shown in Figure 8.

Figure 8 – Sample Horizontal Well Forecast, 4.6 Bcf through year 2028



The corresponding pressure difference map at the end of the forecast time is shown in Figure 9.

Figure 9 – Pressure Difference Map around Sample Well after 25 Years of Production



The pressure difference map is not symmetric at each fracture stage because the permeability varies along different parts of the horizontal well.

In the final step, several adjacent 640 acre sections are modeled to investigate optimal well spacing. The results of the simulation runs show that the optimal well spacing is approximately twice the average half-length for the horizontal wells (400 to 500 feet). Assuming a 5000 foot horizontal well length this corresponds to 60 acres per well and a 10:1 aspect ratio for the developed area. Models with any tighter fracture spacing show significant inter-well fracture interference, thus poor economics.

Note the spacing predicted by the modeling is only approximate as the model built for the study uses the average fracture half length, when in reality each individual stage may have longer or shorter half lengths than the average. As a consequence, real wells typically exhibit more or less interference than the model because of varying fracture lengths. Nevertheless, the model provides a good estimate for the average well spacing needed to make sound economic decisions for producing the field.

Conclusions

The sample study shows that building and history matching vertical and horizontal well models with staged fractures are completed much faster and more accurately using assisted history matching workflows. Additionally, using geostatistics to interpret rock properties between wells generates the variable permeability maps necessary to history match tubing head pressures from existing and future infill wells. As is the case in most tight assets because there is little inter-well interference between early discovery wells single well models provide an excellent approach for evaluating rock parameters. The history matched model provides an understanding of the optimal fracture and well spacing, and can be used for calculating future flow streams for vertical and horizontal wells.

Acknowledgements

The authors would like to thank Devon for allowing the publication of this work. The authors would also like to thank Ray Calvert from Gemini Solutions for developing the assisted history match tool used in the study.

Nomenclature

Pattern model - single well model without full field geologic data
Kriging - a group of geostatistical techniques used to interpolate the value of a random field at an unobserved location from observations of its value at nearby locations.