Journal of Natural Gas Science and Engineering 20 (2014) 109–120

Contents lists available at ScienceDirect

Journal of Natural Gas Science and Engineering

journal homepage: www.elsevier.com/locate/jngse

Evaluating gas production performances in marcellus using data mining technologies☆

Qiumei Zhou [a, b, *], Robert Dilmore [b, 1], Andrew Kleit [a], John Yilin Wang [a, b]

[a] The Pennsylvania State University, Petroleum and Natural Gas Engineering, Department of Energy and Mineral Engineering and EMS Energy Institute, 3 S Laboratory for Petroleum Research, 202 Hosler Building, University Park, PA 16802, USA
[b] U.S Department of Energy, National Energy Technology Laboratory, 626 Cochrans Mill Road, P.O. Box 10940, Pittsburgh, PA 15236-0940, USA

ARTICLE INFO

Article history:
Received 16 May 2014
Received in revised form 14 June 2014
Accepted 16 June 2014
Available online 5 July 2014

Keywords:
Gas recovery
Stimulation effectiveness
Data mining
Marcellus Shale

ABSTRACT

Shale gas development – enabled by the advent of advanced horizontal drilling and hydraulic fracturing technology - has become, over the past several years, a very important energy resource. The estimated ultimate recovery of natural gas from the Marcellus Shale in West Virginia alone has been estimated to be between 98 and 150 trillion cubic feet (Tcf). In 2008, 25 billion cubic feet (Bcf) of natural gas was produced from 41 horizontal wells in West Virginia. By 2012, that gas production reached 301.7 Bcf from 631 horizontal wells. However, the hydraulic fracture stimulation of horizontal wells with multiple stages mechanism, by which that natural gas is produced from shale, is complex. Significant uncertainty about production performance in these unconventional reservoirs represents significant risk for whether resource development will lead to favorable technical and economic performance.

The objective of this paper is to use post-hoc analysis techniques to identify correlations between gas production performance of a well and attributes of its completion and geological setting, and to identify those factors most important to predicting gas recovery performance. To accomplish this, the geological attributes of Marcellus Shale in West Virginia were characterized through literature review. Then, the set of 631 wells was down selected to a representative subset of 187 wells for which complete data are available, including well location, completion data, hydraulic fracture treatment data and production data. The wells were classified into four groups based on geological setting. For each geological group, engineering and statistical analyses were applied to study the correlation between well performance and well completion attributes through traditional regression methods. Important factors considered to affect gas production include number of hydraulic fracture stages, lateral length, vertical depth, proppant volume, and fracture fluid volume and treatment rate. The numbers of hydraulic fracture stages and lateral length have relative large influence on well performance. With these analysis results, it was possible to estimate well-scale ultimate natural gas production performance as a function of known geological conditions and completion parameters.

The results lead to a better understanding of the trends in Marcellus Formation well performance. These approaches could, in the future, help to optimize stimulation treatments and well completions and improve resource recovery in the Marcellus, and other unconventional hydrocarbon formations.

1. Introduction

The Marcellus Formation is the Devonian, organic-rich black shale located in the Appalachian Basin of the northeastern part of the U.S., which covers an area of approximately 95,000 square miles at an average thickness ranging from 50 to 200 ft. The depth of the Marcellus Formation ranges from 4000 to 8500 ft. It has been estimated that 1500 Tcf of natural gas is in place in the whole play area, and that approximately 489 Tcf of that gas is recoverable (NETL, 2010). In most areas, the Marcellus is overlain by the Hamilton shale member of the Hamilton Group and underlain by the Onondaga Limestone formation (Sweeney et al., 1986). Marcellus shale matrix consists primarily of quartz, clay, calcite, and organic material, with common minor constituents including pyrite

☆ This paper was prepared for presentation at the Unconventional Resources Technology Conference held in Denver, Colorado, USA, 25-27 August 2014.

* Corresponding author. Tel.: +1 814 865 8474
E-mail addresses: qxz126@psu.edu (Q. Zhou), robert.dilmore@netl.doe.gov (R. Dilmore), ank1@psu.edu (A. Kleit), john.wang@psu.edu (J.Y. Wang).
[1] Tel.: +1 412 386 4984.

http://dx.doi.org/10.1016/j.jngse.2014.06.014
1875-5100/

and chlorite (Cunningham et al., 2012). The composition of minerals determines the brittleness of the formation, with higher quartz content and lower clay content yielding a higher brittleness quotient. That brittleness corresponds to the ability to hydraulically fracture shale matrix (Enderlin et al., 2011). Fig. 1 shows the isopach map of the brittle lithology of Marcellus in West Virginia. The depositional setting is variable throughout the whole basin. Porosity of the shale matrix is most typically in the range of 0.5–5% with a highest-level of 9% in West Virginia (Lee et al., 2010). However, the matrix pore spaces in Marcellus are poorly connected; thus the successful extraction of natural gas depends largely on the fracture porosity of the shale. Matrix permeability is on the order of 10^{-4} md and very strongly stress dependent (Soeder, 1988); the permeability decreases by nearly 70% by doubling the net stress (Soeder, 1988).Organic content ranges from 2 to 14% but averages 3–6% in most areas (Cunningham et al., 2012). Fig. 2 shows the isopach map of the organic-rich lithofacies. The organic matter is primarily composed of type II algal marine kerogen (Ward, 2010), which is formed from marine animal and plant during thermal evolution. We find that thickness, thermal evolution and maturity of organic content, and formation pressure gradients vary significantly though all wells in the study area. Thermal maturity generally increases from west (where the reservoir is oily) to the east (where the reservoir produces natural gas with no oil) (NETL, 2010). The thermal maturity, as estimated using vitrinite reflectance (Ro), is low in the south-western part of West Virginia and high in the north-eastern part. Generally speaking, the northeast central spatial subset is thick and the southwest part is thin. The Marcellus is under pressured to the southwest and it has been postulated to be normal to potentially over pressured to the northeast with a transitional area in between. As we know, all of these are important parameters for reservoir evaluation and prediction of production performance. Formation thickness is an important parameter for evaluation of the original hydrocarbon in place. Also, thermal maturity impacts pore network characteristics and matrix flow mechanisms, which significantly affect production.

Figs. 3 and 4 show the geographical distribution of Marcellus gas and liquid production in West Virginia in 2012. The gas producing wells are concentrated in certain countries, while liquid producing wells are concentrated in other countries. As of the end of 2012, 2089 wells with production data were reported in West Virginia, including 1458 vertical wells and 631 horizontal wells, with cumulative gas production reaching 301.7 Bcf, and liquid production reaching 715.6 kbbl (Earl et al., 2013). Shale gas production could increase to around 12 Tcf annually in 2035; production in the entire Marcellus could reach 6 Tcf per year in the same year (Mason, 2012).

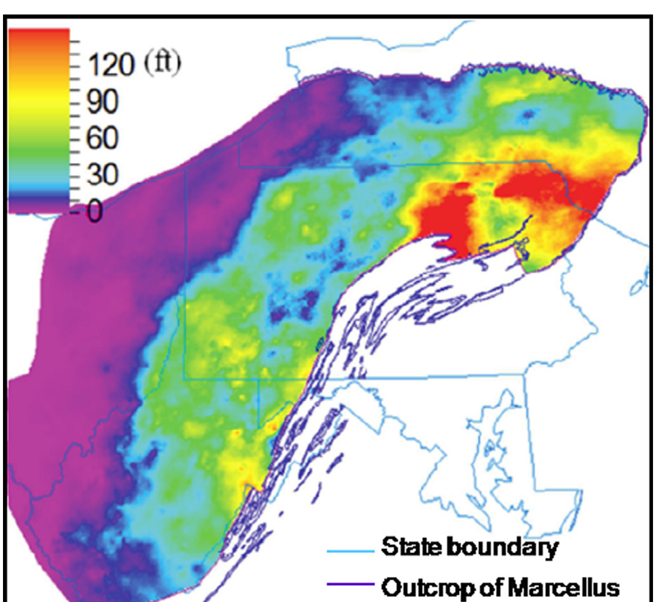

Fig. 1. Isopach map of brittle lithofacies (Carr et al., 2013).

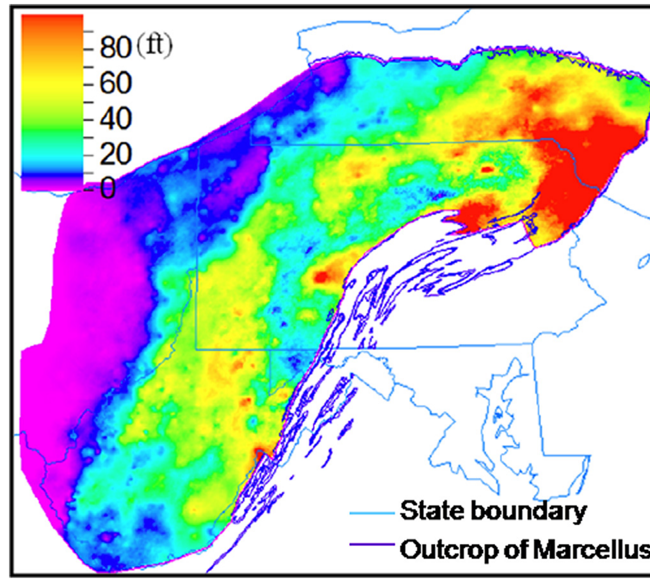

Fig. 2. Isopach map of organic-rich lithofacies (Carr et al., 2013).

Well production performance is determined based on the amount of original hydrocarbon in place and the fraction of the hydrocarbon that can be technically and economically extracted. Both of these factors can be explored by analysis of reservoir characteristics and well development methods. Industry experience provides practical evidence that drilling multi-fractured hori zontal wells (MFHW) is a very effective method to unlock the hydrocarbon reserves of shale formations. In the Marcellus Play, for example, the current practice is the stimulation treatment with application of large volumes of fracturing fluid and mass of proppant per hydraulically fractured stage. However, it can be difficult to determine which factors are most effectively predicting recovery performance.

Data mining is one approach that can be applied to extract implicit and interesting information from data in large databases, and reveal patterns in those data. Data mining has, in recent years, been widely employed in the oil and gas industry for analysis and optimization of controlling factors in complicated reservoirs. Common approaches used for data mining include artificial intelligence and neural network, fuzzy logic, classification and regression trees (CART), and data clustering. Artificial Intelligence or neural network is the most commonly used approach to analyze non-linear relationships between input and output data. In neural network analysis, inputs and outputs are connected by neurons, which represent the activation function for transferring the signal from input to output. Input data are weighted as initial condition, and that weighting value will evolve during the self-learning processes of neural networks. Once the neural network is adequately trained, the controlling factor can be identified through sensitivity study according to the weighting value and the structure of the neural network (Esmaili et al., 2012a,b). In CART analysis, a model is created to predict the value of a target output variable (such as gas production in this study) based on several input variables. A