The Distribution of Sector-Scale Permeability from Production Data within Naturally-Fractured Folds of the Canadian Foothills*

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Search and Discovery Article #41874 (2016)**
Posted September 6, 2016

*Adapted from extended abstract prepared in relation to an oral presentation at AAPG 2016 Annual Convention and Exhibition, Calgary, Alberta, Canada, June 16-22, 2016

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Introduction

The advent of horizontal drilling and hydraulic fracturing of Unconventional resources was the beginning of the demise of Foothills exploration in Western Canada. The increasing scarcity of new opportunities that relied primarily on structural closure meant that this well established play could not compete with the vast regional extent that Unconventional resources promised. A consequence of the maturity of Foothills plays meant that there was a deep understanding of the controls on production performance. However, the competitive landscape at that time also precluded industry-wide sharing of much learning.

Rationale

With Foothills development spanning over seventy years, Shell Canada's wealth of data, both *dynamic* (i.e., flow) and *static* (i.e., rock) is probably unparalleled. In particular, folds in the Livingstone (or Turner Valley) Formation are highly productive; including the Moose Mountain, Jumping Pound and Waterton fields. Because the depositional facies and depositional thickness within the Livingstone Formation are relatively uniform over the length-scale of a fold, lateral variability in matrix permeability is minimal. This formation, therefore, provides an ideal opportunity to evaluate changes in open-natural-network connectivity using pressure and production data.

Results

A large discrepancy between core-permeability (several mD) and well test permeability (hundreds of mD) highlights the importance of natural fractures to flow rate. Analysis of data from core and image logs is useful in constraining the timing, intensity, and morphology of discrete fractures. These data were used to guide drilling azimuth but were typically poor at predicting long-term production performance of wells, with inflow into wellbores commonly dominated by a small percentage of features, a problem recognized early on in western Canada by Cooper (1992). Dynamic data, such as pressure build-up tests and *sustained* flow rates, however, are more indicative of fracture connectivity, essential for longer-term production behavior-like estimated ultimate recovery (EUR).

Figure 1 shows the range in permeability-height (k.h) values measured from pressure build-up tests in several sheets within the Waterton duplex with a clear trend of larger values from wells in higher thrust sheets. The vertical trend in k.h between the sheets reflects the fracture-network connectivity developed by two processes; layer-parallel extension due to back-rotation of older sheets during emplacement of younger, deeper sheets; and increasing confining stress with depth restricting fracture apertures.

With enough wells, values of k.h can also be used to characterize the fracture network connectivity within an individual sheet. Figure 2 shows the distribution of k.h from predominantly vertical wells within sheet IV in the Waterton duplex where the enhanced system permeability along the crestal domain is due to layer-parallel extension perpendicular to the fold axis and the creation of a dominant axial-parallel set of fractures. However, correlation with structural elevation alone does not explain the range in k.h laterally within sheet IV, as some of the best-connected wells proved to be in doubly-plunging parts of the fold, where multiple fracture orientation sets can develop enhancing the system permeability.

There is a reasonable chance of predicting natural fracture connectivity in the Foothills by understanding the distribution of well-test data in association with the structural geometry from 3D seismic. Structural domains extracted using dip and curvature (at appropriate length-scales) from 3D seismic, proved to be sufficiently granular to correlate with permeability derived from flow data; a technique used to delineate the most connected and most productive parts of many Foothills fields. The robustness of the seismic interpretation is increased by balanced cross-sections, utilizing geometrical rules, specific to the stratigraphy in the Western Canadian Sedimentary Basin.

The Moose Mountain field also produces from the Livingstone Formation and is covered by 3D seismic. The production performance was characterized using a methodology outlined by Wei et al. (1998) and further described with practical application by Rogers et al. (2006), in which the character of pressure transient tests is used to determine the relative fracture connectivity within the reservoir. A map of flow domains (Figure 3d) was derived from a simple map of structural dip (Figure 3b) by defining areas in which wells had similar flow behavior (Figure 3c). The permeability anisotropy in each flow domain can be constrained from borehole image data of conductive fracture orientation sets (Figure 3a) and appropriate curvature calculations.

Validation of this flow-domain model was achieved through attempts to history match production data with a simulation model using several different scenarios of natural fracture distribution, in which areas of predicted fracture connectivity were translated into areas of enhanced transmissibility between grid cells. The flow domain model with axial-parallel fractures over the crest could best account for the production differences observed by the wells (see also Stephenson et al., 2007). Quantification of production-interference proved to be highly useful for the assessment of well-spacing and competitive drainage.

Conclusions

In conclusion, the key to understanding fracture connectivity in Foothills fields was to place less emphasis on the discrete fracture data-set, as observed from image logs and outcrops, and more emphasis on the information contained within flow data, such as variability in rates, well-tests and production communication between wells.

This compilation of sector-scale permeability and corresponding flow domains from various fields is useful for global conventional exploration, providing ranges of flow metrics for wells in analogue fields. Also, because the fields in western Canada are so mature, the results are well constrained. Furthermore, documentation of these data may provide reference for future Canadian Foothills exploration in step-out areas; potentially triggered when the Unconventional resources boom has run its course.

References

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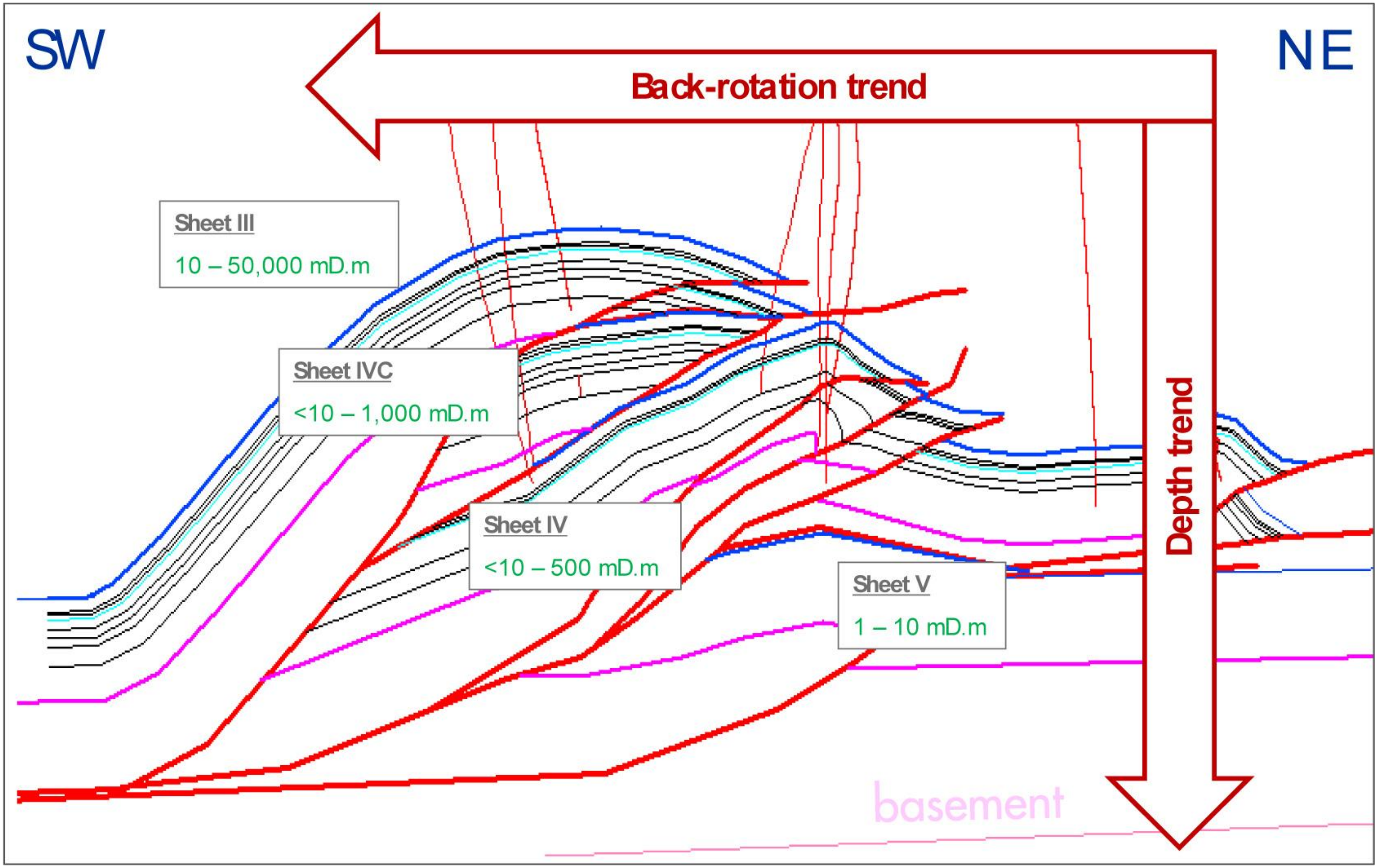

Figure 1. Cross section through the Waterton mega-scale duplex, formed by sheets III, IV, IVc, and V. The range in k.h values (mD.m) derived from pressure build-up well-tests in each sheet is shown.

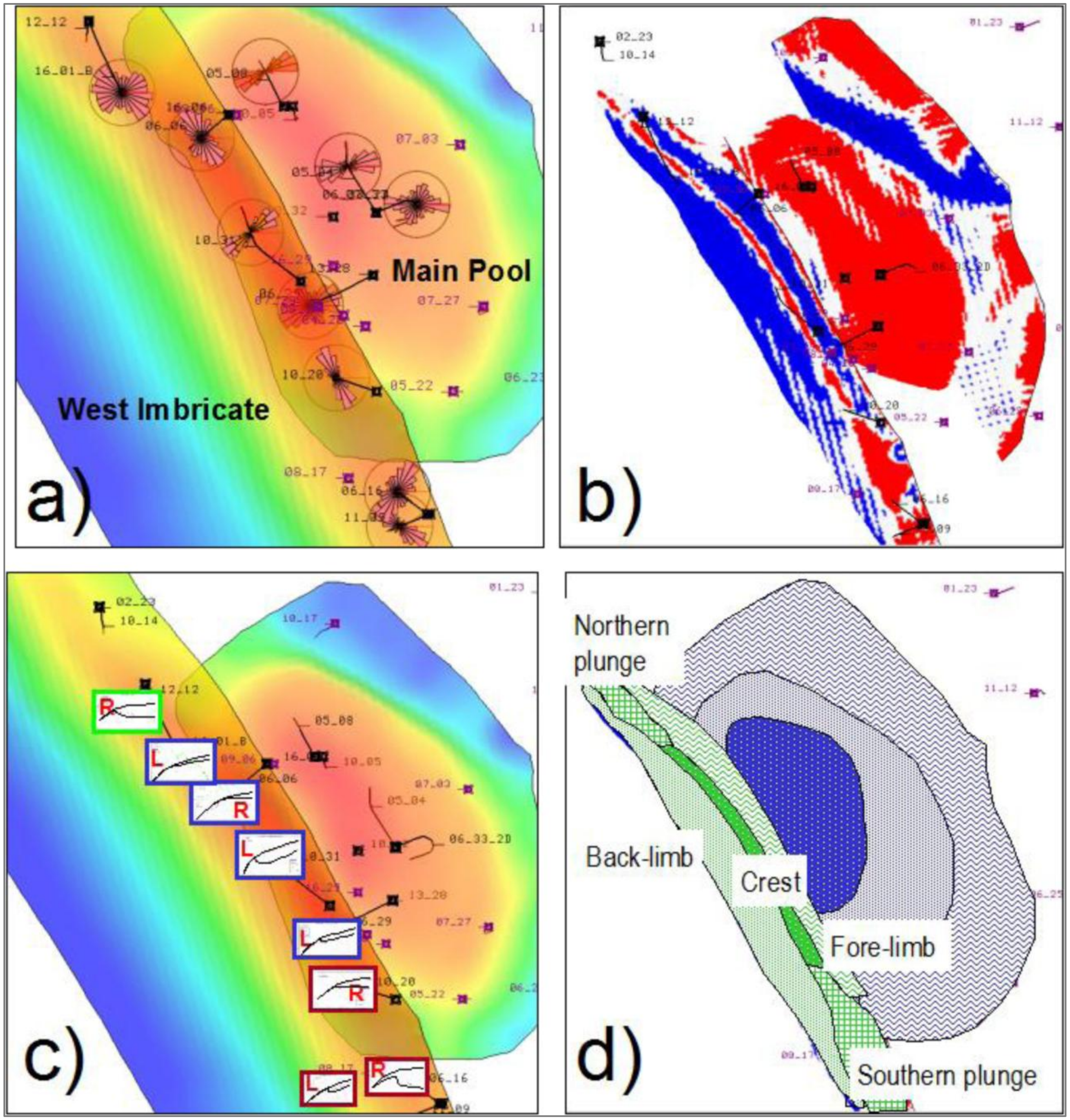

Figure 2. Top structure map from Sheet IV in the Waterton duplex. Bubbles show the value of k.h (mD.m) derived from well-tests and are centered on the location where the well intersects the top Livingstone Formation. Most wells are sub-vertical.

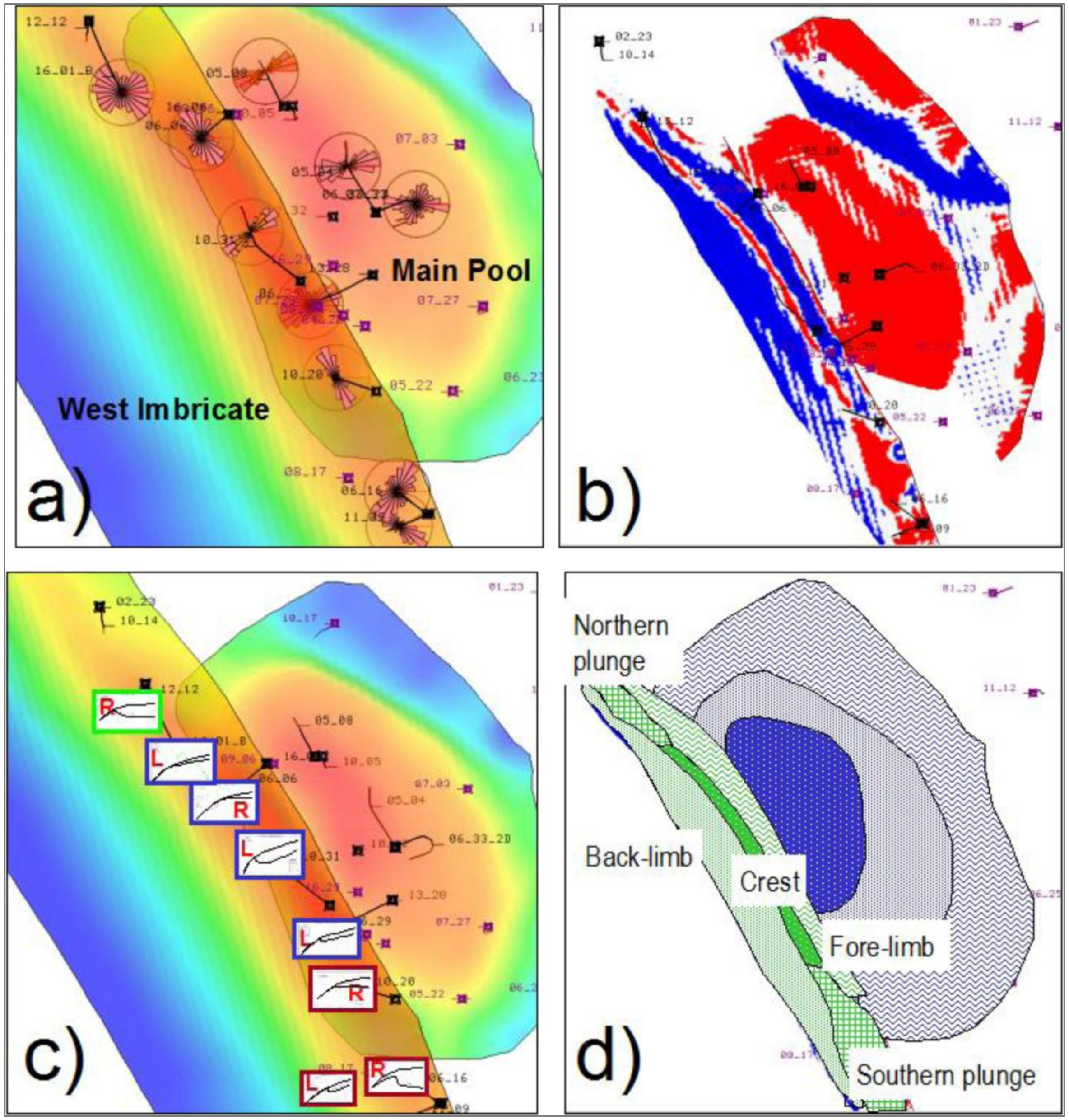

Figure 3. a) Depth map and rose diagrams of conductive natural fractures for the *West Imbricate* and the *Main Pool* at Moose Mountain. b) Dip domain map across the structure (red = 0-10°, white = 11-20°, blue = 21-30°). c) Pressure build-up data located in map view and coloured based on similar pressure response (L = linear flow; R = radial flow). d) Interpreted "flow domains" based on integration of all of the data.