Permeability Index of Vugs and Fractures in Heterogeneous Carbonate Gas Reservoirs from High-Resolution Electrical Images*

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Abstract

In the carbonate gas reservoirs of the Precambrian Dengying Formation, Sichuan basin, southwest China, the production performance does not match the reservoir properties obtained by conventional formation evaluation. A few wells with good reservoir properties have poor production performance, but some wells with general reservoir properties have good gas production. The carbonate reservoir storage is predominantly from secondary development of vugs and fractures. Therefore, the conventional formation evaluation method is not applicable to these complex heterogeneous carbonate gas reservoirs.

A new method that determines the permeability index of vugs and fractures was used for the reservoir characterization of the heterogeneous carbonate gas reservoir in 38 wells. The associated data were conventional openhole logs and electrical image logs; core data were available from seven wells. The permeability index from electrical images correlates to the unfilled vugs and fractures on the images. Conductive vugs and fractures from electrical images could be filled with mudstone or conductive materials. Core observation of the unfilled vugs and fractures are used to create a dataset of the conductivity value of unfilled vugs and fractures from electrical images. The dataset is used to automatically recognize the unfilled vugs and fractures on the electrical images. Image processing techniques are used to extract a quantitative measure of important reservoir properties from high-resolution borehole electrical images by the calibration of electrical image logs to core.

The 18-well production performance indicates that most of the reservoir zones with higher permeability index correspond to good gas production, and most of the reservoir zones with lower permeability index have poor productivity. The seven-well core data analysis shows that the permeability index from electrical images is proportional to reservoir rock permeability. However, the dataset of the conductivity value of unfilled vugs and fractures from electrical images should be further improved by coring in new wells.

Introduction

The Dengying Formation in Sichuan basin, southwest China, formed in the Late Precambrian marine carbonate depositional environments of platform margin and mound shoal (Zou et al., 2014). The lithologies of the Dengying Formation are mainly algal dolomite and crystalline dolomite, with occasional saddle dolomite. The Dengying Formation is one of the oldest petroleum reservoirs in the world. A long period of deep burial and diagenesis occluded porosity. The diagenetic processes included penecontemporaneous dolomitization, burial dolomitization, and hydrothermal dolomitization. However, silicification was the main process that made the Dengying Formation tight (Shi et al., 2013).

A long period weathering and erosion formed karst features, with locally well developed solution vugs and caves in the Dengying Formation. The carbonate reservoirs of the Dengying Formation are fracture-vug reservoirs and vug reservoirs. The average porosity of the reservoirs is 2.2% to 3.9%, and the average permeability is 0.59 md (Wei et al., 2015).

Conventional log evaluation practices fail to identify differences in production performance from wells drilled into the Precambrian Dengying Formation. The porosity and permeability within these heterogeneous carbonate gas reservoirs required for commercial production exists in the form of vugs and natural fractures and are difficult to quantify without high-resolution borehole electrical images.

Method

The quantitative identification of unfilled vugs and fractures on high-resolution electrical images comprises the following steps (Figure 1):

- Depth shift core to the images.
- Match unfilled vugs between core and the images.
- Set-up the dataset of the conductivity value of unfilled vugs from the images.
- Quantitatively identify unfilled vugs and fractures along the borehole wall.

Image processing techniques use the conductivity values in the image logs to automatically recognize unfilled vugs (green) on the images along borehole wall. The image processing extracts the connectedness curve (blue) of the unfilled vugs from the electrical images and provides the surface proportion curve (red) and size curve (black) of the unfilled vugs (Figure 2).

The dataset of the conductivity value includes unfilled-vug conductivity and conductivity contrast between unfilled vug and matrix (Figure 3). The unfilled vugs matched between core and the images in seven wells were used to create the dataset of the conductivity value of the unfilled vugs from the electrical images. The dataset was used in the other uncored wells for the quantitative identification of unfilled vugs and fractures in this case study.

Case Study

Well 5 had two gas production tests separately in the upper section (well 5-U) and the lower section (well 5-L). The gas production rate in well 5-U is 54.3×10^4 m^3/day, and the rate in well 5-L is 124.19×10^4 m^3/day. The main contributors to gas production in well 5-U are unfilled vugs (Figure 4). Unfilled fractures, however, could be significant to higher gas production in well 5-L (Figure 5).
The connectedness indicates the conductive intensity of the mud-filled vugs and fractures; this is used as a permeability index in this case study. The higher the conductive intensity, the better the connectedness and permeability of unfilled vugs and fractures. The 18-well production performance suggests that the reservoir zones with higher connectedness correspond to good gas production, and the reservoir zones with lower connectedness have poor productivity (Figure 6).

Conclusions

High-resolution electrical images are better able to identify vugs and fractures than are conventional logs, especially in tight reservoirs. Image processing techniques applied to core-calibrated image logs can help extract important reservoir properties, such as a relationship between vug connectedness and permeability index, the surface proportion equal to the porosity index.

To recognize and extract the unfilled vugs and fractures on the images, the dataset of the conductivity value from the seven wells in this study should be further improved by coring in new wells.

Besides the connectedness, the surface proportion and thickness of unfilled vug zones should be considered as another important factor in gas productivity in the very heterogeneous carbonate reservoirs.

Acknowledgements

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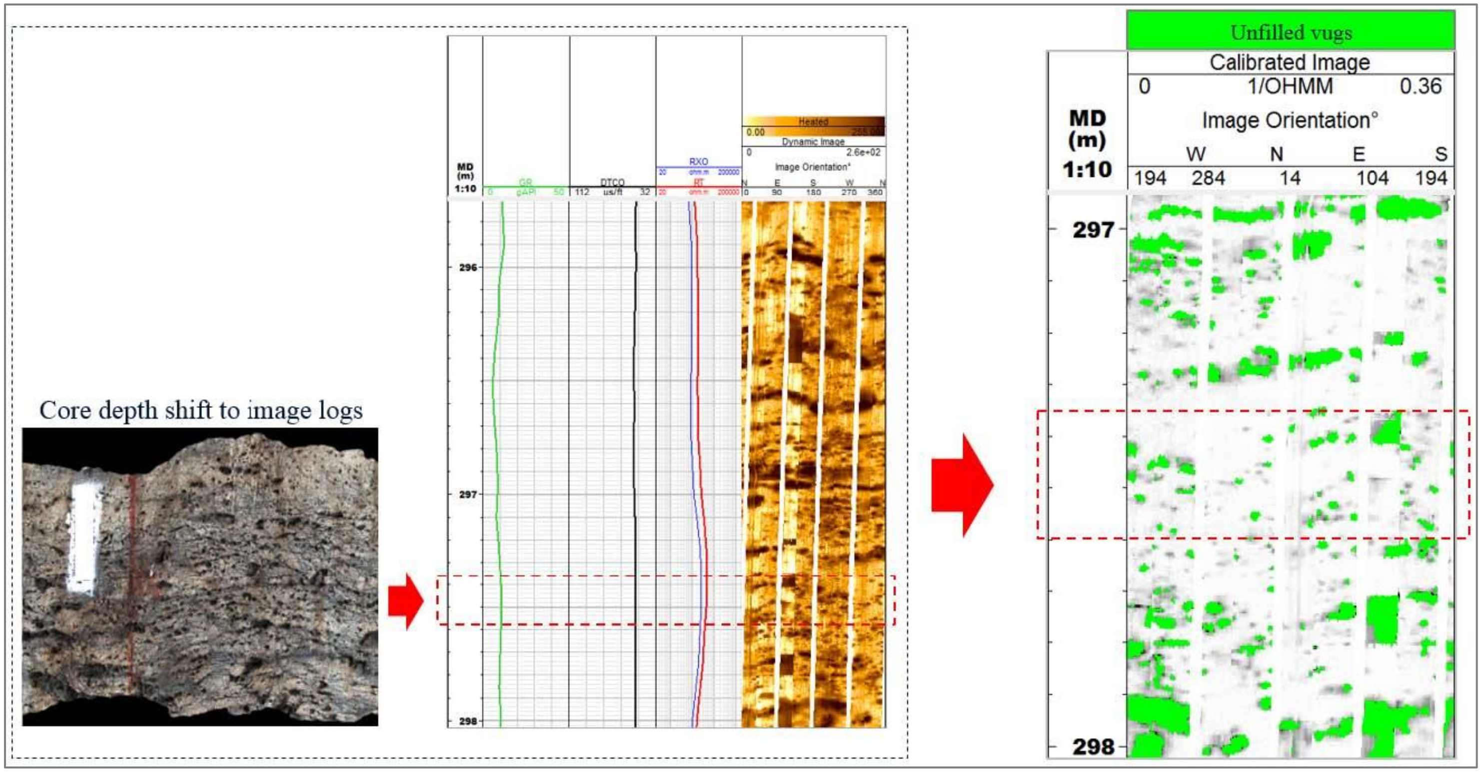

Figure 1. General procedure of the quantitative identification of unfilled vugs in well 16.

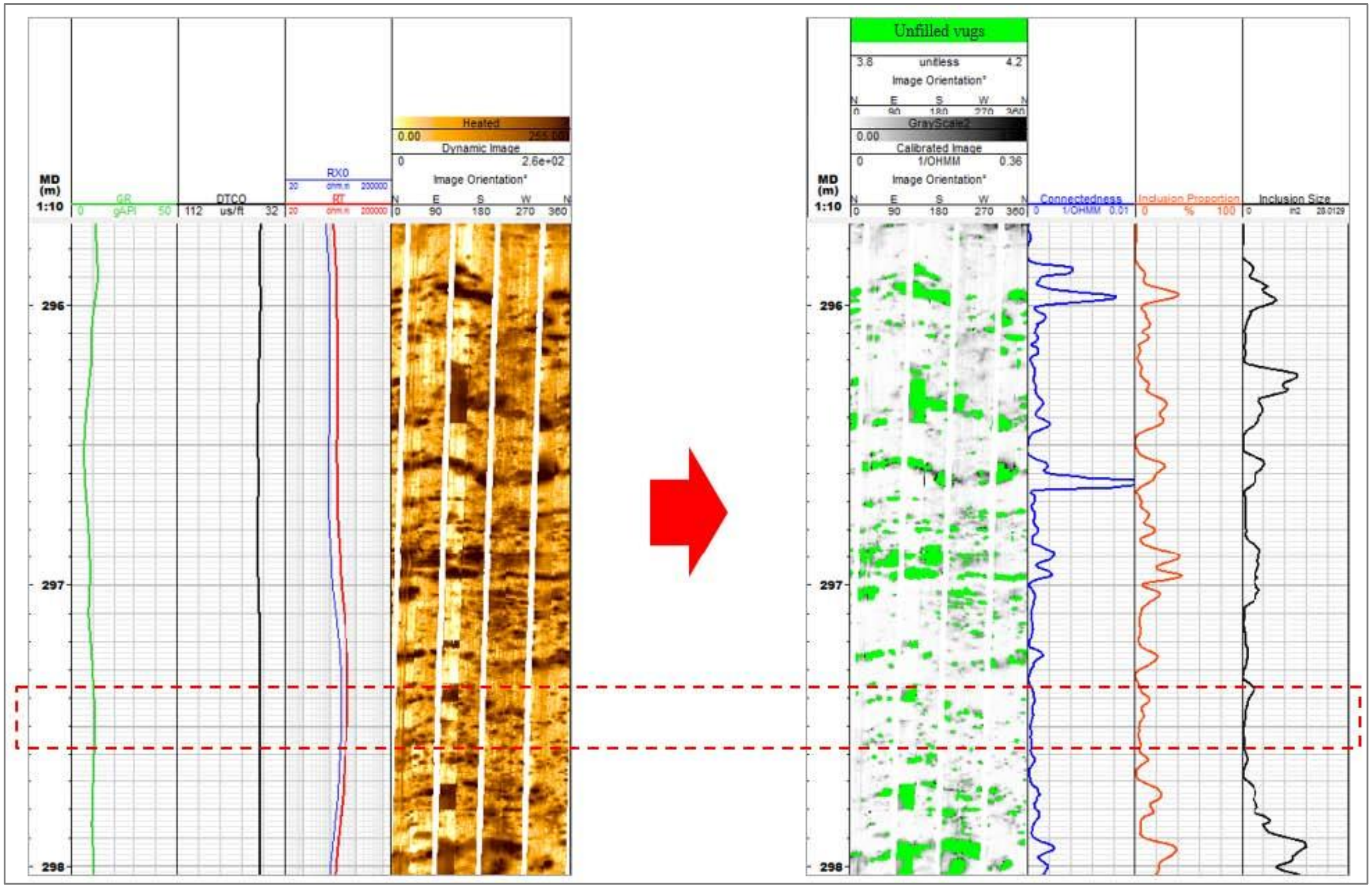

Figure 2. Quantitative identification of unfilled vugs along borehole wall in well 16.

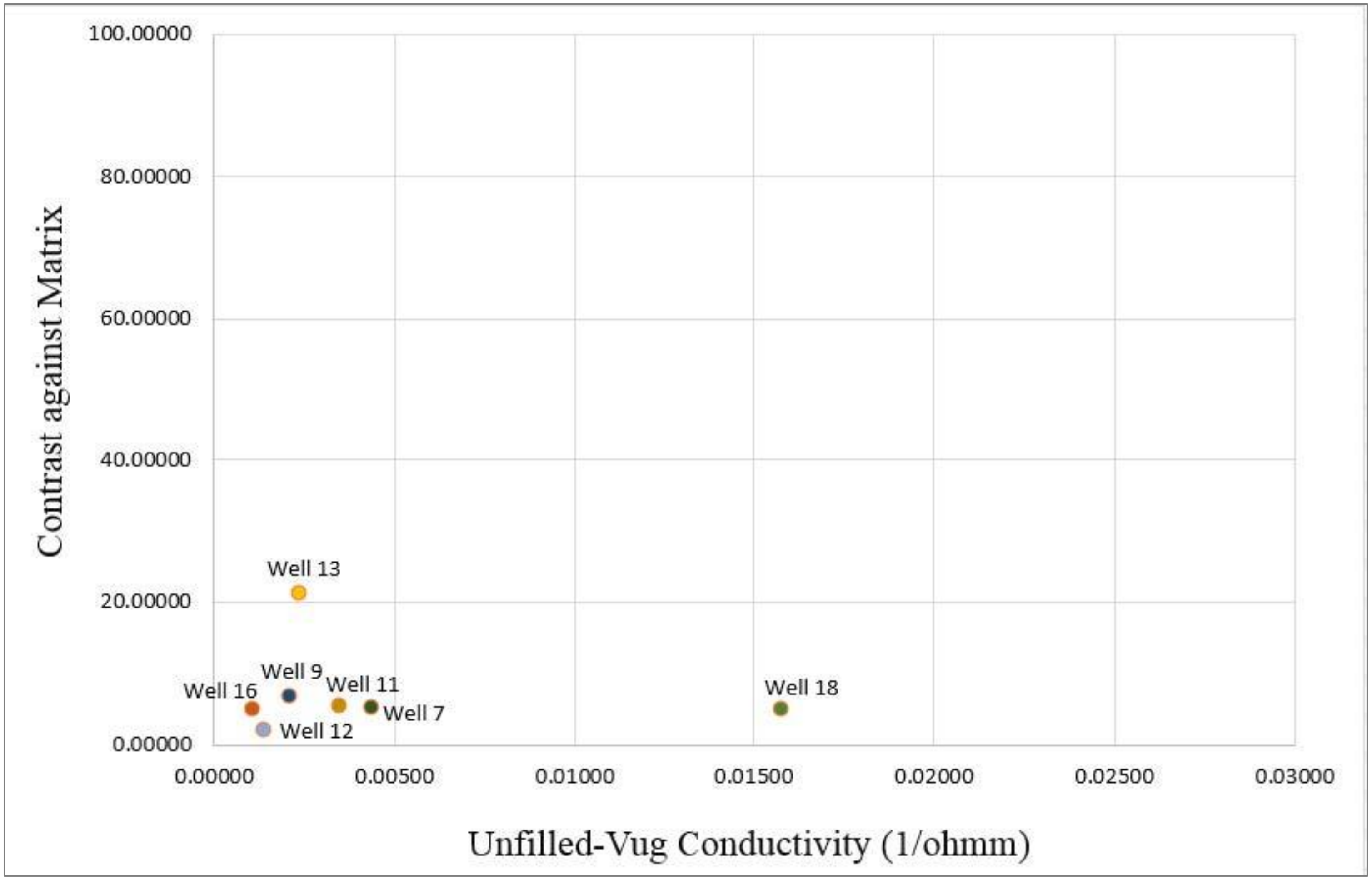

Figure 3. Dataset of the conductivity value of unfilled vugs in seven wells.

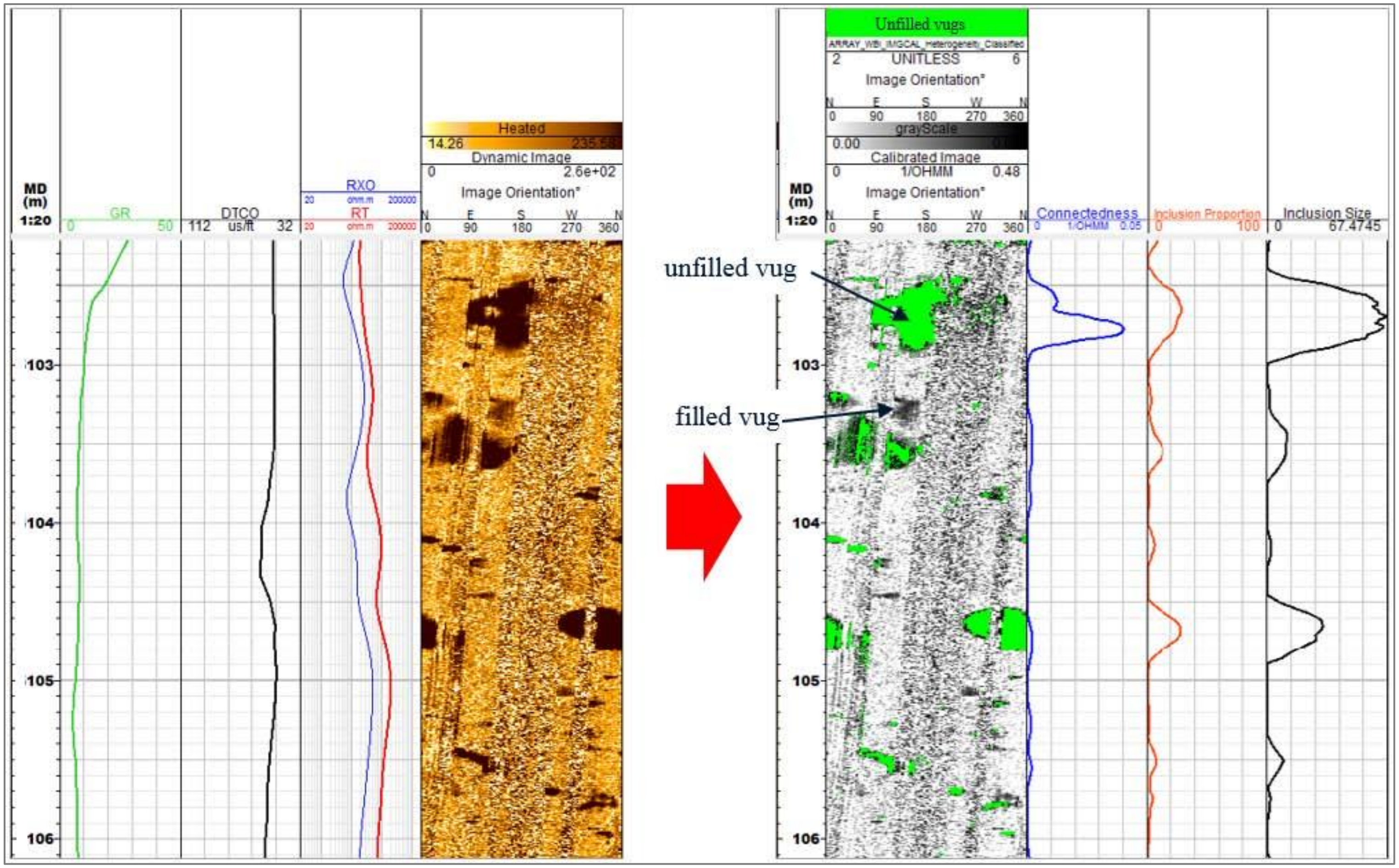

Figure 4. Example of the quantitative identification of unfilled vugs in well 5-U.

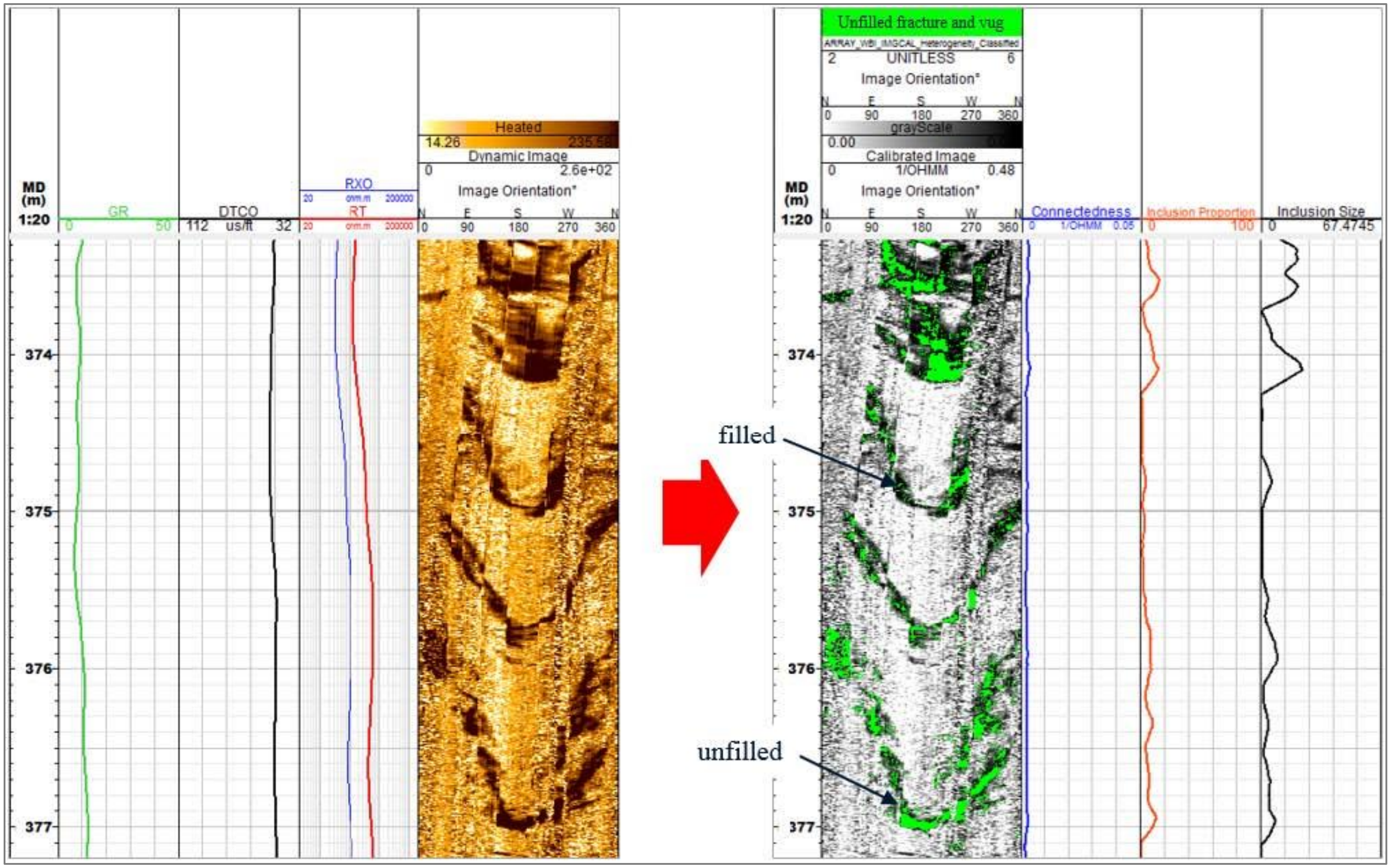

Figure 5. Example of the quantitative identification of unfilled fracture traces in well 5-L.

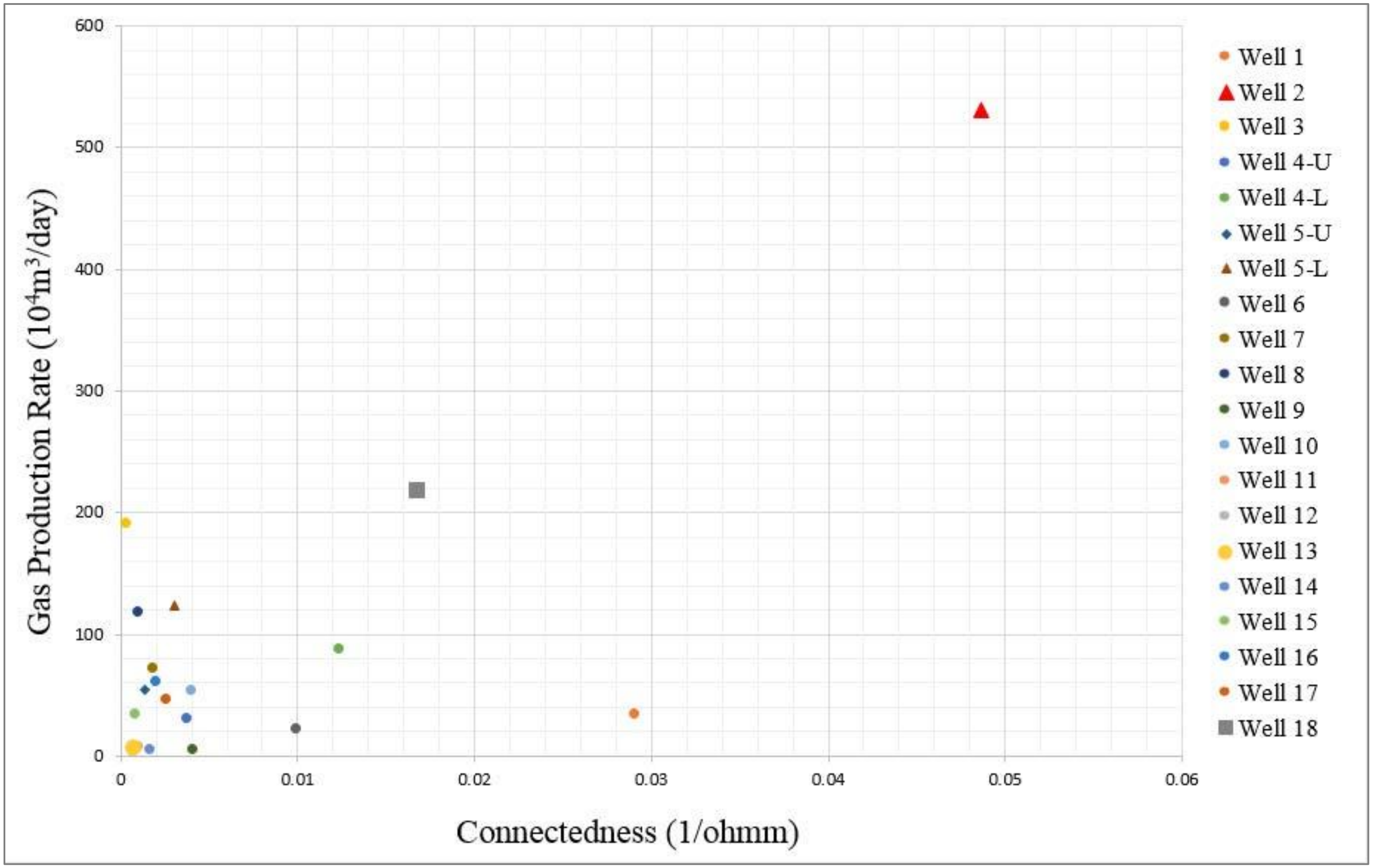

Figure 6. Crossplot of gas production rate versus connectedness from 18 wells.