Introduction

The electric well logging image plays an important role in oil and gas exploration for the evaluation of fractured formations. Because of the complexity and randomness of the fracture distribution and their pore structures, there are no ubiquitous method that can be used to extract fractures from well logs or seismic profiles. However, electric conductivity images show high resolution to the detail structures of sedimentary and/or fractures on the borehole wall. Many published papers have concentrated on themes of identification and extraction of fractures and vugs from electric conductivity images and Hough transformation is one of the most classic technique that can be applied to fracture recognition and extraction which is flexibly suitable for low-dip cracks with complete sinusoidal characteristics.

This study developed a new fractures’ extraction method that includes first step of identification of fractures and their edges by incomplete path morphologic scheme, and the second step of pattern recognition of the electric well logging images through a correlation with a family of sinusoidal functions prepared for the picking up of fracture parameters for high dip fractures and the Hough transformation for low dip fractures, then the statistical step has been applied to parameters extraction for the quantitative assessment of fractures and vugs.

Theory

Fracture parameters are key points to consider the behaviour of the underground formations from the geomechanical or hydrodynamical point of view (Cornet et al., 2003). Up to now, electric conductivity image is considered to be one of the most effective tools for studying the spatial distribution of formation fractures. In the electric conductivity image, fractures often present sinusoidal curves, with some exceptions of non-sinusoidal conditions of non-planar fracture surfaces. In the following research, we mainly focus on sinusoidal fractures. Assuming that the wellbore is vertical and the fractures are all aligned in the same planes, the intersected trajectory of fractures in the electric image conforms to a sinusoidal curve, as shown in figure 1 and it is satisfying the following formula which represents the fractures (Cornet et al., 2003)

\[ y = A \sin(\omega x - \varphi) + D \]  (1)

Where \( A \) is the amplitude, \( \varphi \) is the azimuth or phase, \( \omega = \frac{2\pi}{T} \) is the radial frequency, and \( D \) is the centric depth of fractures. For the specific borehole diameter, the spatial period is a constant, and the amplitude could be replaced by the dip angle of one fracture and its centric depth. Therefore, as long as a set of parameters (dip angle \( \alpha \), azimuth \( \varphi \) and centric depth \( D \)) are fixed, the distribution of fractures could also be determined.

\[ \begin{align*}
(a) & \\
(b) & 
\end{align*} \]

*Figure 1* A schematic diagram of the distribution of fractures underground. (a) is the 3D model of the intersection of the fracture plane and the wellbore, where \( \theta \) is the azimuth Angle (0 azimuth Angle in the direction due North), \( \alpha \) is dip Angle between the fracture plane and the horizontal plane and \( A \) is the amplitude of the fracture. (b) Sketch showing that a fracture intersecting a well shows on an unwrapped image as a sinusoid.

Incomplete Path Opening Process

The fracture and vug can be automatically derived from electric imaging logging FMI image by using the incomplete path opening morphology operation, as is shown in figure 2. There are two prime
parameters during the process: the length of the path $L$ and the number of admissible missing pixels $k$.

The expression of calculating the incomplete path opening transform is in the following. If the binary value $b[p]$ of $p$ pixel is false (Talbot and Appleton, 2007):

$$
\lambda^* [p,k] = \begin{cases} 
\lambda^* [(p^1, p^2 + 1), k - 1] \\
\lambda^* [(p^1 - 1, p^2 + 1), k] \\
\lambda^* [(p^1, p^2 + 1), k - 1] \\
\lambda^* [(p^1 - 1, p^2 + 1), k] \\
\end{cases}
\quad \text{else} \\
\lambda^* [p,k] = 1 + \max \left( \lambda^* [(p^1, p^2 + 1), k] \right) \\
\lambda^* [(p^1 - 1, p^2 + 1), k] \\
\right)
(2)
$$

Where $\lambda^* [p,k]$ is the path opening length that across $p$ pixel from one direction, $\lambda^*$ is the opposite direction, $L = \lambda^- + \lambda^+$, $k$ is the number of admissible missing pixels.

When $b[p]$ is false, it means that in the binary graph, the value of point $p$ is 0. Then we penalize the path and inherit the path length from the path with $k-1$ gaps. Analogously, we can calculate the vertical adjacency and the diagonal adjacency that is from upper left to lower right or from upper right to lower left.

Figure 2
The incomplete path opening morphology operation. (a) Adjacency relation of set $a$ and $b$, where $a$ is the successor of $b_1$, $b_2$, $b_3$, and $b$ is the predecessor of $a_1$, $a_2$, $a_3$. (b) The green area is a vug. The red area is a line fracture and the blue area is a sinusoidal fracture with missing pixels in it. (c) Fracture–vug formation model with 2% salt and pepper noise and the result of the incomplete path opening operation.

Hough Transform for Sinusoidal Fractures

Hough transform purposefully picks up sinusoidal curves in electric conductivity images through converting of the image data into parameters domain and shows the unknown parameters of the target curves. During the process of converting, multiple points belonging to a curve in the electric image are transformed to intersecting curves and their intersecting points correspond to the parameters of the curve in the image domain (Vincent, et al., 1979). In the well-logging processing, the Hough parameter domain is set up as an accumulator and the points of the curves generated by the transform are voted according to the coordinates. At the end of the poll, the coordinates of the high values give the parameters of the curves representing the amplitude and phase of a fracture separately.

Figure 3
(a) Three synthetic fractures. (b) Different time windows at the parameter domain of Hough transform. (c) The reconstruction fractures using Hough transform. (d) The comparison of the model and its Hough transform parameters.
In order to validate the suitability of Hough transform in image log, we design three fractures (Figure 3(a)) with gaussian white noise. The ‘bright spots’ in the edge map correspond to the parameter spaces of Hough Transform. The different time windows represent different depths of the fractures, as shown in Figure 3(b). Then we use the parameters of fractures obtained by Hough transform to reconstruct the original fractures (Figure 3(c)). The compass is the comparison of the initial model and its Hough transform parameters (Figure 3(d)). The length of the arrows represents the dip angle and the direction represents the azimuth angle of the fracture. The result of the Hough transform extraction algorithm looks very good because even though there is a lot of noise the algorithm still accurately extracts the correct sinusoids thanks to the voting procedure.

**The cluster of sinusoid**

From the previous section, we know that the fractures in image logging could be described by formula (1). Therefore, in this paper, the cluster of sinusoid function was used to fit the actual fractures. All fractures satisfied with formula (1) could be found in the cluster of sinusoid theoretically. Formula (3) represents this 2-Dimension correlation method (Delhomme, 1992).

\[
 r = \frac{\sum_{m,n} (A_{mn} - \bar{A})(B_{mn} - \bar{B})}{\sqrt{\left(\sum_{m,n} (A_{mn} - \bar{A})^2\right) \left(\sum_{m,n} (B_{mn} - \bar{B})^2\right)}}
\]

(3)

Where \( r \) is the 2-Dimension correlation coefficient, \( A \) is the input image of actual image logging curves, and \( B \) is the sinusoid function, \( \bar{A} \) is the mean value of \( A \) and \( \bar{B} \) is the mean value of \( B \).

Here we just consider low and high dip angle fractures (horizontal and vertical fractures can also be processed in this way). The basic parameters of the cluster of sinusoid are set as follows: the dip angle: -75° ~ 75°, and the phase: 0° ~360°. When the well radius is known, the amplitude can be calculated using the dip angle and the depth can also be obtained based on the actual FMI data. Thus, the cluster of sinusoid function could be constructed. In the actual calculating process, the parameters should be adjusted to balance the calculation accuracy and time spending according to the well-logging data.

Figure 4 shows three incomplete fractures. We try to use different methods to reconstruct the original fracture. The parameters derived from the cluster of sinusoid match better with the initial model parameters just as the compass shows. However the amplitude of fractures restored by Hough transform obviously exceeds the actual model. The parameter domain also does not converge. Therefore, we guess that the Hough transform results have a low accuracy because the initial model has less validly information and the fractures are incomplete. We verify with the actual imaging logging data as is shown in Figure 5. We can tell that the middle fracture is reconstructed in a wrong way by Hough transform while the result of the cluster of sinusoid is good.
Figure 5  (a) The original electric imaging logging data. (b) The extraction by incomplete path opening operation with \( L=40 \) and \( k=5 \). (c) The reconstruction fractures using Hough transform. (d) The reconstruction fractures using the cluster of sinusoid. (e) The comparison of Hough transform and the cluster of sinusoid results.

Conclusions

The method proposed in this paper based on the incomplete path opening process and the cluster of sinusoid can realize the fractures extraction automatically. With the suitable combination of parameters can we derive complete fractures and vugs that may have admissible missing pixels. The precision of this method relies heavily on the building of the cluster. As long as the cluster covers all phases and amplitudes, we could accurately extract conforms to the parameters of all fractures theoretically, but due to the computational efficiency in practical process and the cause of the computer's memory, it is often difficult to cover all the cases. We establish the cluster within a certain bounds to achieve the balance of computational efficiency and precision. At the same time, this method has advantages in the processing of actual imaging logging data. It can make up for the deficiency of Hough transform in the extraction of high dip angle fractures and incomplete fractures, and overcome the weak robustness of Hough transform to noise.

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