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RESEARCH PAPER

A fracture evaluation by acoustic logging technology in oil-based mud: A case from tight sandstone reservoirs in Keshen area of Kuqa Depression, Tarim Basin, NW China

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Abstract: To solve the problem of poor fracture identifying effect on electrical logging in oil-based mud, the application of acoustic logging to the quantitative characterisation of fractures is expanded from three aspects, namely, Stoneley waves, longitudinal and transverse waves and cross dipole acoustic waves, and a fracture logging evaluation model closely related to production capacity is established considering the radial extension characteristics of fractures. The Stoneley reflection coefficient is used to determine fractures locations to help detect fractures during normal micro-resistivity imaging logging. Based on the experiment on the relationship between fracture width and acoustic attenuation coefficient, empirical formulae for calculating fracture width have been established by primary wave and shear wave energy information considering the effect of porosity. The new parameters, including spectrum correlation coefficient and energy difference from cross dipole array acoustic logging data, can be used for fractures evaluation. The more developed the fractures are, the greater the energy difference becomes, and the smaller the spectrum correlation coefficient is, the higher the production is. The fracture effective evaluation parameters can be separated into two components, specified as the degree of fracture vertical opening and radial extension. Combining the conventional logging and array acoustic logging (including cross dipole array acoustic logging), a fracture radial extension evaluation model is presented closely related to productivity.

Key words: tight sandstone reservoir; fracture evaluation; acoustic logging; oil-based mud; radial extension; Kuqa; Tarim Basin

1. Survey of the study area

The sandstone reservoirs of the Cretaceous Bashijiqike Formation in the Keshen area of the Kuqa Depression in Tarim Basin is generally over 6 000 m deep, and commonly $(0.01–0.10)\times10^{-3}$ μm^2 in permeability, representing typical tight sandstone reservoir, but the gas production rate of a single well is more than 30×10^4 m^3/d. Previous studies show that tectonic fracture development is the main reason of the high yield of this reservoir[1–3] (Fig. 1). Although the fracture description of core is the most credible method[4], but the costs are high and discrete coring cannot complete the comprehensive evaluation of objective layer section. Fracture evaluation by using well logging technology can not only reduce costs, but also obtain continuous fracture data in the vertical direction, thus, this approach is favorable to most oilfield companies for detecting fracture in formation.

With the development of unconventional oil and gas exploration, logging technology has become a popular research tool to evaluate deep fractured tight sandstone reservoirs[5–6]. Lu Yuzhou, Xu Chaohui, et al. discussed identification of fracture in sandstone reservoir and the influence of fractures on water-

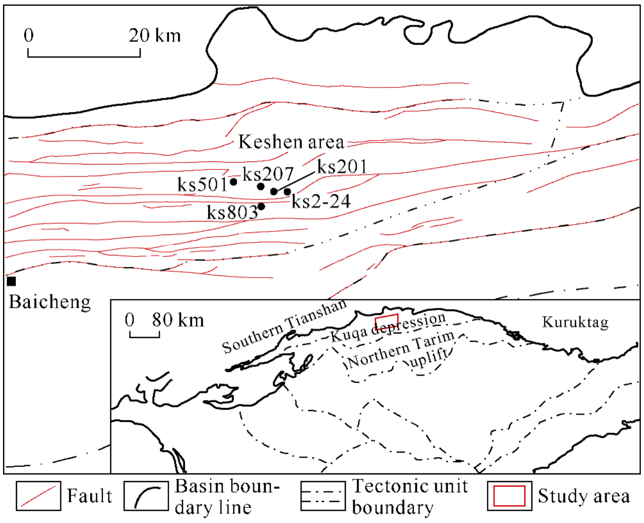

Fig. 1. Location of the Keshen area in the Kuqa Depression, Tarim Basin.

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flooding development on oil and gas filed by conventional well logging curves[7, 8]. Using the conventional well logging method in combination with micro-resistivity imaging well-logging data, Guan Ju, Li Jun, Xiao Li, et al. looked into the factors controlling fracture development and put forward an effective evaluation method that considering fracture effect for the reservoir[9, 10]. The fracture identification methods based on well logging mentioned above are all for water-based drilling fluid condition. To reduce reservoir pollution caused by drilling fluid, oil-based drilling fluid is mostly used in the Keshen area. As a result, the fracture identification effect of well logging methods based on fluid conductivity has become poorer. The contribution of fractures to the production capacity of an objective layer section should be analyzed from three dimensions. In addition to characteristic parameters, such as fracture width and density along the well-axis, the influence of fracture extension along the wellbore radial direction (the direction of wellbore diameter) should also be considered. In this study, logging evaluation techniques for fracture space distribution have been classified, and the fracture identification with logging under the condition of oil-based drilling fluid has been investigated, the application of acoustic logging in quantitative characterisation of fractures has been expanded from three aspects, namely, Stoneley wave, compressional and shear waves and cross dipole acoustic wave, and the radial extension of fracture has been taken into consideration to establish a fracture logging evaluation model more closely related to production capacity.

2. Classification of fracture logging evaluation parameters and problems presented by oil-based drilling fluid

2.1. Classification of fracture logging evaluation parameters

From a 3D space distribution perspective, the evaluation of fracture effectiveness comprises two components: the fracture opening along the well-axis direction and radial extensibility along the horizontal direction. Fractures near borehole wall are filled with filtrate of the drilling fluid, which leads to difference in the physical responses of the fractures and stratigraphic framework; this difference is the basis of fracture identification with well logging. Various fracture characteristic parameters evaluated with well logging can be divided into two categories according to the fracture space distribution: (1) characteristic parameters based on the fracture opening degree, which mainly describe fracture width characteristics in the well-axis direction (including multiple sets of equivalent width of fractures), the majority of the parameters evaluated are of this type because they are closely related to reservoir quality, it is generally believed that the better the fracture opening, the larger the fracture width, the higher the production capacity will be. (2) Characteristic parameters based on fracture extensibility along the radial direction, although fracture extensibility has great effects on the connection and stable yield of reservoir, the evaluation methods and parameters of this type are currently limited (Table 1). The parameters related to fracture radial extension in Table 1 only reflect volume-based significance, i.e., they are a comprehensive reflection of fracture opening and extensibility.

The characteristic parameters of fractures can be set up by digital signal processing method besides using logging response directly. New parameters reflecting fracture characteristics can be obtained through secondary processing for some parameters listed in Table 1. Fig. 2 presents the processing results of the fracture logging evaluation parameters of Well ks207 in Keshen area, in which the fifth column is the porosity difference calculated from density logging curve and sonic transit-time logging curve, the conductive efficiency of the sixth column reflects the formation connectivity. for tight sandstone reservoirs, the more abundant the fracture, the better the connectivity will be[11]; the seventh column shows the fractal dimensions calculated according to the density-acoustic wave porosity difference, the higher the value, the more abundant the fractures, and the more obvious the formation anisotropy will be[12]; in the eighth column, the Stoneley wave permeability (red) reflects the overall formation connectivity, and the permeability calculated according to the conventional porosity-permeability relationship reflecting the matrix permeability (green filling curve), if the formation has developed fractures, the Stoneley wave permeability must be greater than the matrix permeability. The processing results reveal that the porosity difference, conductive efficiency, fractal dimension, and difference between the Stoneley wave permeability and conventional permeability of two sections (6 788–6 828 m and 6 870–6 888 m in Well ks207) are basically identical to the fracture development identified by formation micro-resistivity imaging (FMI).

Table 1. Classification of fracture logging evaluation parameters

<table>
<tr><th rowspan="2">Classification of fracture parameters</th><th colspan="2">Conventional well logging</th><th rowspan="2">Imaging logging</th><th colspan="3">Array acoustic logging</th></tr>
<tr><th>Deep and shallow resistivity</th><th>Density, acoustic wave and neutron</th><th>Stoneley wave</th><th>Primary and shear wave</th><th>Dipole shear wave</th></tr>
<tr><td>Opening</td><td rowspan="2">Conductive efficiency, difference of deep and shallow resistivity, FVPA</td><td rowspan="2">Density-acoustic porosity difference, density-neutron porosity difference, FVPA</td><td>Fracture width, fracture hydrodynamic width, FVPA, fracture length</td><td>Stoneley wave permeability, reflection coefficient, frequency offset, time delay</td><td rowspan="2">Primary and shear wave velocity, attenuation coefficient and energy, fracture porosity</td><td rowspan="2">Energy, anisotropic parameters of time lag</td></tr>
<tr><td>Extensibility</td><td></td><td></td></tr>
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