Open and closed fractures from image log interpretation

Fractures, in their most basic description, are mechanical breaks where a rock has been displaced across a surface or series of surfaces. This displacement and the intervening materials (or lack thereof) in these breaks are of particular interest in reservoir investigations as they can have a significant effect on the flow of fluid within and through the reservoir. This state can be simplified to being open, with some amount of space being present between the two surfaces of the fracture, or closed, with either no space or minerals filling the space between the two surfaces of the fracture. If fractures are open, they can contribute significantly to the permeability of a reservoir to fluids, and if it is closed, it can have either no effect or be subtractive to the permeability in a reservoir. Either way, it is important to understand the state of fractures in reservoirs.

One of the methods for determining the state of fractures in a reservoir is imaging the borehole with downhole geophysical tools, commonly called image logging tools. These tools are developed to measure a given property of the rock circumferentially around a borehole as well as vertically and at a resolution high enough to produce a usable image. Although in some cases the 3D image of the wellbore is used, the cylindrical image is generally sliced along a given orientation and presented as a 2D image for interpretation (Figure 1). From these images the presence, orientation, and shape and state of a fracture may be inferred.

Figure 1: 3D images are presented in 2D by slicing the image along a specific orientation and presenting an unwrapped image. Because the image orientation and dimension are known, accurate determination of the orientation of linear features can be calculated from the amplitude and trough position of the resulting sinusoid.

Three types of imaging tools have the resolution to give this type of information. These are optical based tools, electrical based tools, and acoustic based tools.

Optical tools are, in their simplest form, downhole cameras that take a continuous image of the wellbore wall as the tool moves. They provide high resolution images but rely on a clear wellbore fluid (or air) to see features on the wellbore wall. Because of this, they see limited use in typical wellbores.
As with all imaging tools, the images they produce can be converted to 2D images from which measurements can be made. Because we are used to observing fractures in core and outcrop, optical images are simple to interpret. In Figure 2, we can see an optical image of a section of the borehole. Open fractures appear as linear dark features, represented by sinusoids on the 2D image. Unless the fractures are filled with a material of sufficient optical variance from the surrounding rock, closed fractures are not typically visible in optical images. Although the wellbore wall can be affected by the drilling process, it is sometimes possible to infer information such as fracture surface rugosity and aperture from optical images in a relative sense.

Figure 2: Optical borehole image in grey scale and with enhanced color. Dark regions represent increased wellbore diameter. The sinusoidal shapes highlighted with dark blue on the enhanced color right image indicate open fractures. The darker region in the middle of the image is a large void intersected by the wellbore. The enhanced colored image to the right also has sinusoids representing planes intersecting the borehole. The scale to the right with the “tadpoles” shows the magnitude (0 degrees on the left and 90 degrees on the right) and direction (tail points to dip direction of the features with north being up and south being down).

Acoustic tools use high frequency reflected sound waves to map the wellbore wall. Typically, a transducer and receiver pair are rotated in the wellbore as the tool moves along the length of the borehole. The reflected ultrasonic waves measure the distance to the wellbore wall at a level and stacked as the tool moves to form a continuous measurement along the well path (Figure 3).
The measurements are scaled to a color (usually dark being further and white being closer) and presented as an image. The image represents the distance to the borehole wall primarily but also the reflectivity of the borehole wall secondarily. Open fractures will appear as dark sinusoids on the image, as will any linear feature that causes an interruption in the wellbore wall. Figure 3 is an acoustic image with a few features that can be interpreted. Low angle sinusoids in the image are likely bedding planes where the reflectivity of the borehole wall has changed, or a soft material has been plucked from the borehole wall by the drilling process. A wide linear feature on the left of the image is likely where the drill pipe rotation has smoothed that portion of the wellbore and removed most of the mud. The higher angle somewhat continuous sinusoidal features are likely fractures. From this image, they are like a combination of open (continuous sinusoids) and partially open (discontinuous sinusoids) fractures. Because the acoustic tool relies on changes in the wellbore wall, portions of a fracture that are close or fractures that are fully closed are generally not interpretable on these types of images. Mineral filled fractures, if they contrast sufficiently with the surrounding rock, may be interpretable. Like optical tools, images from acoustic tools indicate the shape of the wellbore wall and inferences on fracture surface rugosity and relative apertures may be made.

Figure 3: Acoustic image of a section of wellbore. The low amplitude sinusoids represent bedding places where drilling has caused irregularities along bedding boundaries at the wellbore wall. The higher amplitude, dark sinusoids indicate fractures.
There are two types of electric imaging tools. Direct current tools are the most common and are used to image wellbores with conductive mud systems. Induced current electrical imaging tools are less common and can be used where nonconductive mud systems (oil-based muds etc.) are used. Both types of tools create a resistivity image of the wellbore wall.

Induced current tools are used in oil-based muds where current cannot efficiently be transmitted into the formation and returned to the tool with sufficient focus to create a usable image. The measurement principle is the same as an induction log but are made on the very shallow portion of the wellbore adjacent to the tool. Images are scaled from dark for conductive portions of the image to white for resistive portions of the image (Figure 4).

*Figure 4: Image from induction imaging tool. Sharp light-colored sinusoids distinguish fractures from the underlying changes in resistivity due to bedding.*

Generally speaking, fractures cannot be classified as open or closed using the induction imagers. Open fractures, which will be filled with nonconductive mud, will appear as bright sinusoids. Closed fractures are difficult for the induction imager to detect, and mineral filled fractures also appear as bright, resistive features. For this reason, induction imagers can detect fractures but cannot infer the state of fractures. - Cont’d
If it is combined with another imaging tool, however, the combination can be used to make a better interpretation. In Figure 5 an acoustic imager and an induction imager were run in tandem. As they use different measurements to interpret fractures, more information can be gained. In this case, the fractures interpreted in the induction image are interpreted to be open on the acoustic image. The induction image differentiates the bedding and eliminates that as a possible source of the features on the acoustic image. Since the induction image measures a small distance into the rock, one can be more confident that the features on the acoustic log are fractures and not drilling features.

The Resistivity (or micro-resistivity) image tools are another class of electrical imagers. Resistivity imagers focus electrical current into the formation and continuously measure the resistivity of the formation at discrete points around the wellbore. Since they need to transmit current into the formation, a conductive mud system must be present for this class of tool to work. The images they produce are the best of all the imaging devices for detecting and defining the presence and state of fractures. The images from this tool are displayed with dark representing low resistivity and light representing high resistivity (Figure 6). Open fractures, or those filled with conductive mud or materials, will appear as dark sinusoids on the image.

Figure 6: Direct current resistivity tool image. Bedding is clearly visible as the light and dark low angle sinusoids. In the lower middle, a fold is developed above an apparent fault. Open fractures can be identified as the dark partial or complete sinusoids cross cutting the bedding features. Some of these have been highlighted with a blue sinusoid trace on the image to the right.

Closed, non-mineralized fractures are difficult to discern with any imaging tool (as they are in outcrop or core) however the direct current imagers are the most likely to image small aperture fractures as the signal from a relatively small low resistivity feature (i.e., conductive mud in a fracture) still produces a resistivity contrast that can be seen on the images. If the closed fracture is closed by mineralization, the fractures are well imaged. They will show as either high resistivity sinusoids (Figure 7) or as low resistivity (dark) sinusoids with bright “halos” at the tips of the sinusoid.

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While high resistivity sinusoids are understandable (mineralization formed in fractures tends to be high resistivity in contrast with the surrounding rock) the low resistivity sinusoids with the bright halos are a little less so. The key in the explanation of the halos is that the resistivity tool measures the micro-resistivity sightly into the formation from the borehole wall. Since the fractures are intersecting the borehole at an angle (creating a sinusoid) the portions of the fracture closest to the borehole (at the tips of the sinusoids on the image) can affect the image. If the fracture is mineralized, the image will measure a combination of the formation resistivity and the fracture resistivity, producing a halo that loses intensity as the distance of the fracture from the borehole wall increases. The darker sinusoid portions (Figure 7) are due to the resistivity contrast of the fracture fill material and the formation.

Figure 7: Closed fracture images from a direct current imaging tool. On the left image a high resistivity plane (sinusoid) is clearly visible and traced by the pink sinusoid. On the right image, a bright “halo” can be seen at the trough of the sinusoid indicating the interpreted fracture is mineralized.

While imaging tools can be used to describe the state of fractures, it should be kept in mind that, as with all geophysical logging tools, images are measuring a property of the rock and inferring a state from that measurement. Depending on the tool, open fractures interpreted from images are more correctly visible fractures, interruptions in the rock surface, or conductive fractures. Similarly closed fractures are not visible, do not interrupt the rock surface, or are resistive. So, while we can infer the state of a fracture, images are just one tool used to help describe reservoir properties.

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