Acoustic and optical borehole-wall imaging for fractured-rock aquifer studies

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Abstract

Imaging with acoustic and optical televiewers results in continuous and oriented 360j views of the borehole wall from which the character, relation, and orientation of lithologic and structural planar features can be defined for studies of fractured-rock aquifers. Fractures are more clearly defined under a wider range of conditions on acoustic images than on optical images including dark-colored rocks, cloudy borehole water, and coated borehole walls. However, optical images allow for the direct viewing of the character of and relation between lithology, fractures, foliation, and bedding. The most powerful approach is the combined application of acoustic and optical imaging with integrated interpretation. Imaging of the borehole wall provides information useful for the collection and interpretation of flowmeter and other geophysical logs, core samples, and hydraulic and water-quality data from packer testing and monitoring.

Keywords: Geophysical logging; Borehole-wall imaging; Acoustic televiewer; Optical televiewer; Fractured-rock aquifer; Borehole; Ground water

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1. Introduction

Borehole-wall imaging for fractured-rock aquifer studies has undergone significant advancements since Paillet et al. (1990) provided a state-of-the-art overview. The first acoustic televiewer (ATV) was developed by the petroleum industry in the late 1960s (Zemanak et al., 1970). Although used by some researchers earlier (Paillet et al., 1985), widespread application of acoustic imaging for ground-water studies did not occur until the mid-to late 1990s with the development of ATV tools directly compatible with common slimhole geophysical logging systems. The first optical televiewer (OTV) was developed as a stand-alone system in 1987. Application of optical imaging for ground-water studies was uncommon until the recent development of OTV tools compatible with the more widely used logging systems.

Imaging with acoustic and optical televiewers results in continuous and oriented 360° views of the borehole wall from which the character, relation, and orientation of lithologic and structural planar features can be defined (Fig. 1). The combined application of acoustic and optical imaging provides critical information for water-supply development and source water protection and characterization and remediation of contamination in fractured rock. This paper describes recent developments in the acoustic and optical imaging methods and their application and integrated analysis for ground-water studies.

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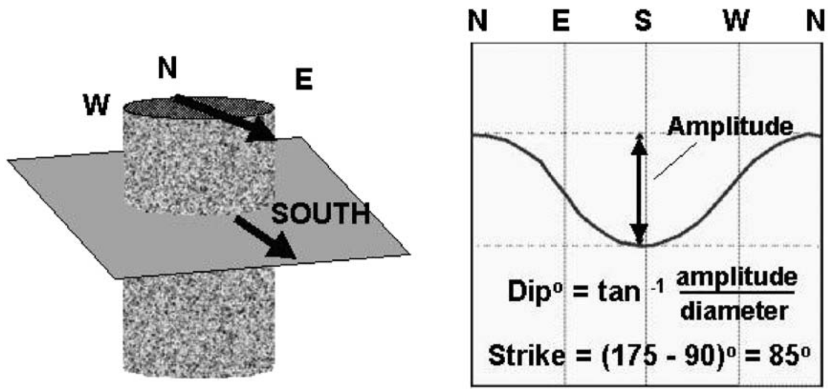

Fig. 1. Oriented, 360° image of the borehole wall and calculation of strike and dip of planar feature.

2. Acoustic televiewers

ATV imaging systems use an ultrasonic pulse-echo configuration with a 0.5 – 1.5-MHz transducer (Fig. 2). The transit time and amplitude of the reflected acoustic signal are recorded as photographic-like images, and the transit-time data can be used to generate high-resolution caliper logs (Fig. 2). Commonly used ATV tools are 1.7 – 3.7 m in length and 40 – 50 mm in diameter. Earlier ATV systems sent an analog signal up the logging cable that was displayed and photographed on an oscilloscope. In more recent systems, the analog signal is digitized downhole, and the digital signal is sent uphole for display and analysis on a computer. A comparison of ATV images from analog and downhole-digital systems is presented in Fig. 3.

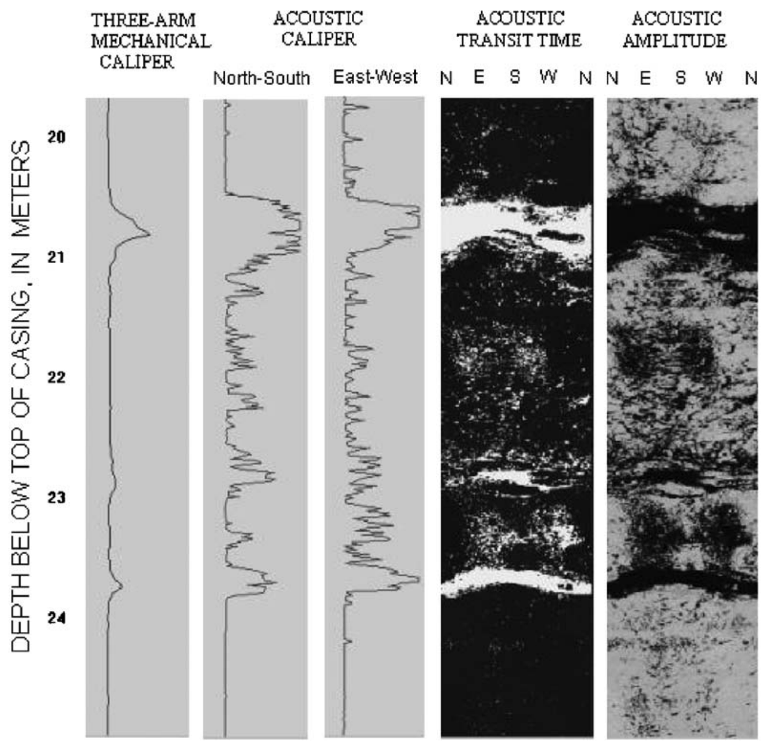

Fig. 2. Three-arm mechanical and acoustic caliper logs and acoustic transit-time and amplitude televiewer images in a 150-mm diameter borehole completed in metabasalt.

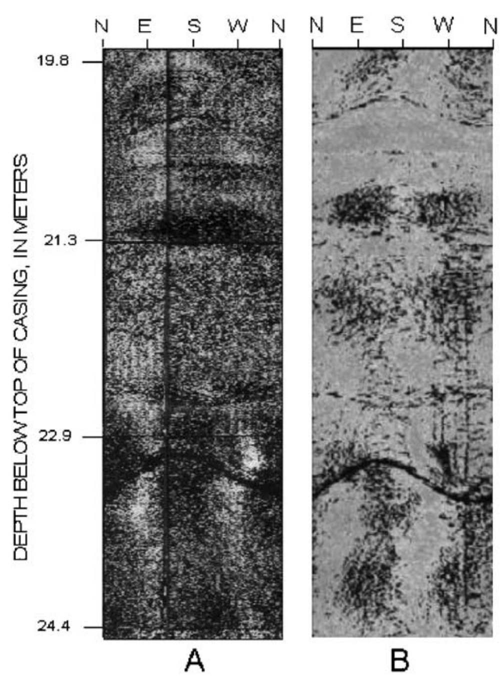

Fig. 3. Amplitude images from acoustic televiewers in a 150-mm diameter borehole completed in schist with pegmatite: *(A)* analog (note vertical line where image was spliced to correct for an orientation error found after log collection); *(B)* downhole digital.

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In a conventional ATV system, the transducer is rotated on a motor-driven shaft while the tool is pulled uphole. In a fixed transducer system, the acoustic beam is bounced off a rotating convex reflector. Vertical resolution of downhole-digital, rotating low-frequency transducer systems is on the order of 5– 7.5 mm and maximum borehole diameter generally is 230 mm or less. Fixed high-frequency transducer systems have vertical resolutions of 1– 2 mm and can be used in boreholes as large as 400 mm in diameter. A comparison of ATV images from downhole-digital, fixed high-frequency and rotating low-frequency transducer systems are presented in Fig. 4. Logging speeds for collection of ATV images is slow compared to conventional geophysical logs, 1– 3 m/min.

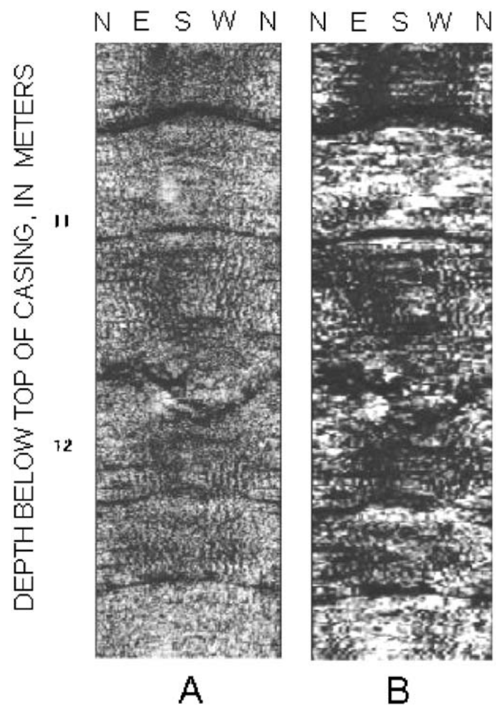

Fig. 4. Amplitude images from acoustic televiewers in a 150-mm diameter borehole completed in gneiss: *(A)* fixed high-frequency transducer; *(B)* rotating low-frequency transducer.

ATV images can be collected in water-or light mud-filled intervals of boreholes. Borehole enlargements related to structures such as fractures, foliation, and bedding planes scatter energy from the acoustic beam, reduce the signal amplitude, and produce recognizable features on the

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images (Paillet et al., 1990). Acoustic impedance contrast between the borehole fluid and the wall indicates the relative hardness of the borehole wall. Lithologic changes, foliation, bedding, and sealed fractures may be detected even when there is no change in borehole diameter if there is sufficient acoustic contrast. Multi-echo systems, which were first described by Broding (1982), record the full wave train of the reflected acoustic signal and are capable of imaging behind plastic casing (Fig. 5). Such systems are useful for imaging poorly competent intervals that will not stay open without being cased, and for inspecting annular grout seals.

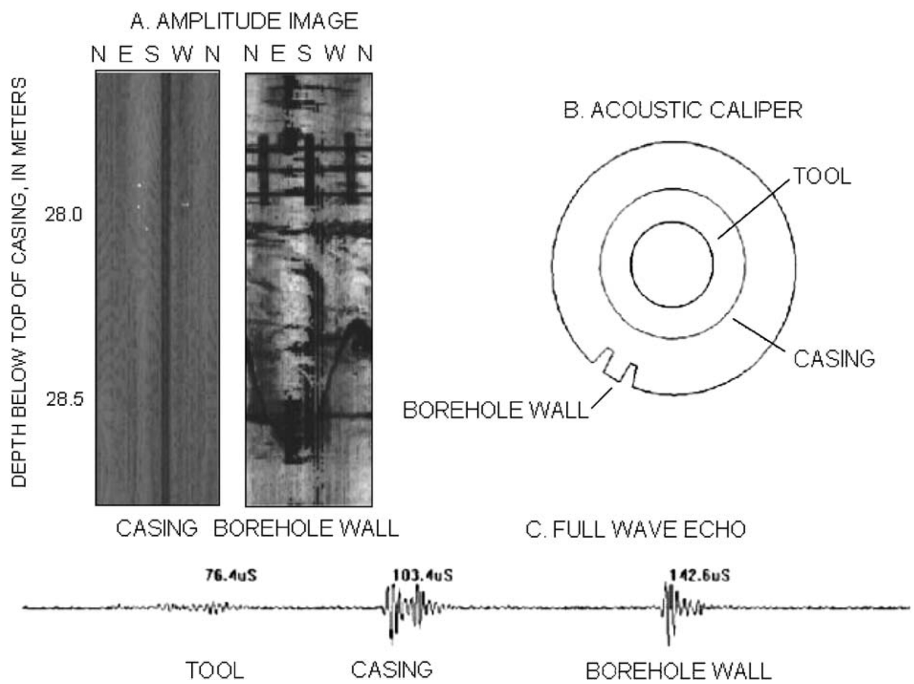

Fig. 5. Multi-echo acoustic televiewer log from 125-mm diameter borehole with 75-mm diameter plastic casing: *(A)* amplitude images of plastic casing and borehole wall behind the plastic casing (vertical and horizontal bands above 28 m are steel centralizers attached to outside of casing); *(B)* cross-sectional view of acoustic caliper; *(C)* trace of full wave echo.

3. Optical televiewers

OTV imaging systems use a ring of lights to illuminate the borehole, a CCD (charge-coupled device) camera, and a conical or hyperbolic reflector housed in a transparent cylindrical window. Commonly used OTV tools are 1.4 – 2.8 m in length and 40 – 50 mm in diameter. The

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CCD camera measures the intensity of the color spectrum in red, green, and blue. The reflector focuses a 360jslice of the borehole wall in the camera's lens. Light intensity is either preset prior to logging or, in some systems, may be adjusted while logging. The optical image scan is either sent up the logging cable as an analog signal and digitized uphole or digitized downhole and sent up as a digital signal. A comparison of images from uphole-and downhole-digital, conical and hyperbolic reflector OTV systems is presented in Fig. 6. Maximum borehole diameter in which OTV images can be collected typically are 300 mm or less. Common vertical and horizontal resolutions of OTV images are 0.5, 1, or 2 mm and 180, 360, or 720 pixels per line, respectively. The logging speed for OTV images is dependent on the selected vertical and horizontal resolution and the system design and cable type. Typical logging speeds for most systems are on the order of 1 m/min. Downhole-digitized systems necessitate slower logging speeds than uphole-digital systems but can be used on greater lengths of cable and on a wider range of cable types including single conductor. The fastest logging speeds, 3 m/min for 1 mm and 720 pixels per line data, are attained by a system that simultaneously transmits multiple scanned slices of the borehole wall uphole as an analog signal on coaxial cable.

Lithology and structures such as fractures, fracture infillings, foliation, and bedding planes are viewed directly on the OTV images. OTV images can be collected in air-or clear-water-filled intervals of boreholes. Unflushed drilling mud, chemical precipitation, bacterial growth, and other conditions that affect the clarity of the borehole water or produce coatings on the borehole wall impact the quality of OTV images. Acceptable OTV images commonly are obtained in boreholes intervals where conventional fish-eye camera images may be poor as a result of cloudy water because of the shorter focal length for the side-looking OTV as opposed to the downlooking camera. In air-percussion holes, it may be beneficial to wet borehole walls above the water level to remove dust left from drilling.

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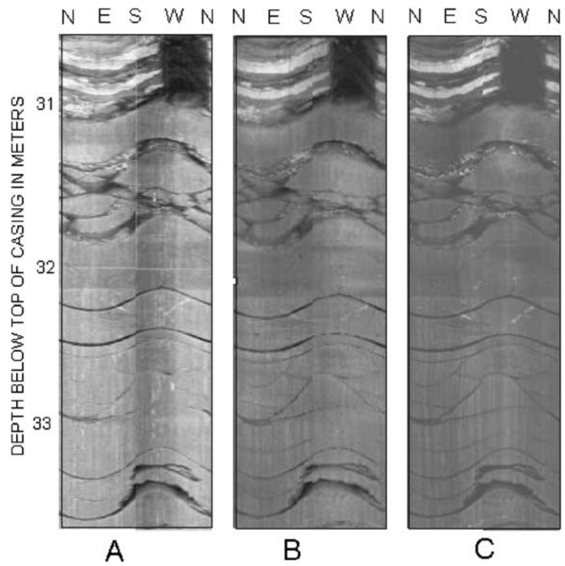

Fig. 6. Optical-televiewer images of a 150-mm diameter borehole completed in sandstone: *(A)* uphole-digital conical reflector; *(B)* downhole-digital conical reflector; *(C)* uphole-digital hyperbolic reflector.

4. Orientation and centralization of acoustic and optical televiewers

Orientation of acoustic and optical televiewers is accomplished by a three-axis fluxgate magnetometer and three accelerometers, which provide an oriented borehole-wall image and true three-dimensional location of the measurement. ATV and OTV images are oriented to geographic north by adjusting for magnetic declination during acquisition or during post-acquisi-tion processing. Orientation of identified planar features relative to the axis of the borehole can be reoriented in true space by compensating for the borehole deviation (Lau, 1983; Kierstein, 1984). The magnetometer and accelerometers are calibrated in the laboratory with a deviation stand. ATV and OTV image orientation and ATV caliper are checked in the field with a compass and oriented cylinder of known diameter.

In many studies of fractured-rock aquifers, imaging of the borehole interval just below the base of steel surfacing casing is important. To provide oriented images for the interval in which the magnetometer is affected by steel casing, the interval plus some overlap is rerun with the

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magnetometer turned off, and then the rerun image is matched and spliced into the oriented image for the rest of the borehole (Fig.7). This same technique can be used for borehole intervals in which the orientation of the image is affected by the presence of ferromagnetic minerals.

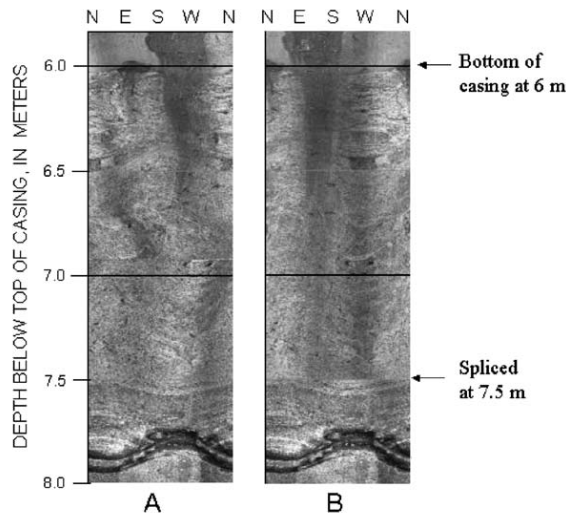

Fig. 7. Optical-televiewer images in an interval in which the magnetometer is affected by steel casing: (A) magnetometer turned on; (B) magnetometer turned off and spliced into the oriented image.

Tool centralization is critical for good-quality image data and accurate structure orientation. Centralization in boreholes that are 10 cm or greater in diameter is accomplished through the use of stainless steel or brass sliding end bowsprings. In boreholes less than 10 cm in diameter, plastic or rubber centralizers are used. Decentralization on ATV images is indicated by vertically striped transit-time and amplitude images. Similar light and dark bands are observed on OTV logs when the tool is decentralized.

5. Comparison and analysis of acoustic-and optical-televiewer images

OTV images allow for direct viewing of the relation between lithology, foliation, bedding planes, and fractures, whereas the relation between lithologic and structural features is not always clear on ATV images (Figs. 8 and 9). Foliation, bedding planes, and changes in lithology may not be apparent on ATV images if they are not associated with sufficient borehole relief or acoustic contrast. Fractures generally are recognizable on both ATV and OTV images. However, in darker rocks, fractures that are readily apparent on ATV images are difficult to distinguish from dark-colored zones on OTV images (Fig. 10). Iron staining and other chemical precipitation, free product, and bacterial growth that may be indicative of ground-water flow and (or) contamination are readily apparent on OTV images (Fig.11) but not ATV images.

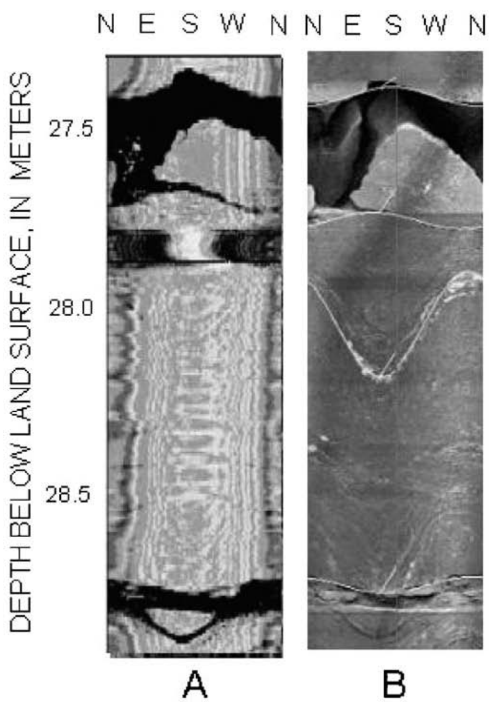

Fig. 8. Televiewer images of a 75-mm diameter borehole completed in gneiss: *(A)* acoustic; *(B)* optical (Stumm et al., 2001).

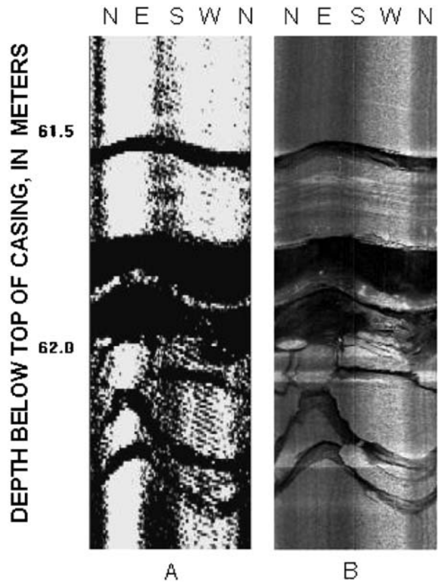

Fig. 9. Televiewer images of a 75-mm diameter borehole completed in sandstone: *(A)* acoustic; *(B)* optical (Williams et al., 2002).

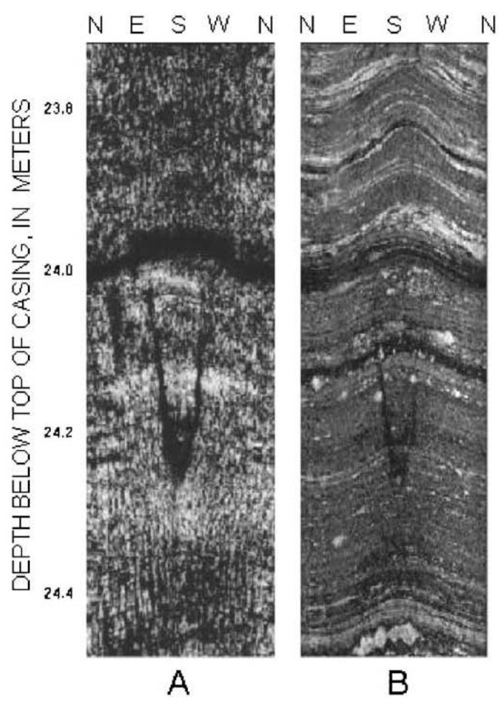

Fig. 10. Televiewer images in a 150-mm diameter borehole completed in dark-colored gneiss: *(A)* acoustic; *(B)* optical.

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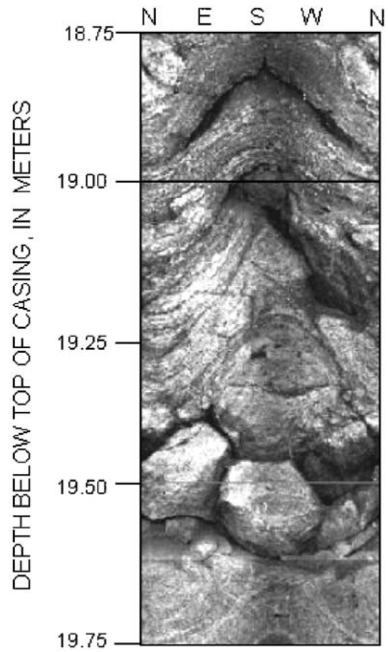

Fig. 11. Optical-televiewer image in a 150-mm diameter borehole completed in gneiss.

Drilling-related gouge affects the appearance of fractures on both ATV and OTV images. The drilling process typically gouges out fractures and increases their apparent aperture (Paillet et al., 1985). The top and bottom of steeply dipping fractures typically are gouged and appear to have a greater dip (Cohen, 1995). Fractures infillings may be gouged out so that sealed fractures may appear open. Closely spaced fractures may be gouged out and appear as a single large zone, in which the orientation of only the top and (or) bottom fracture may be determined.

The most efficient and powerful analysis of ATV and OTV images is done with computer programs that allow for simultaneous and integrated interpretation. Integrated analysis of ATVand OTV images displayed side by side at the same scale and orientation provides complementary and synergistic results. Experience has shown that independent analysis of ATV and OTV images produces data sets with multiple discrepancies in fracture location and orientation. Although some discrepancies are expected because of the inherent difference in the response of the tools, many apparent inconsistencies are readily resolved by integrated image analysis.

Structural and lithologic planar features are classified and fitted interactively with sinusoidal traces, and the true orientation is calculated using analysis software. The classified fractures and other planar features and their orientation commonly are displayed on tadpole and stereo plots. Tadpole plots (Fig. 12) provide a depth-dependent display of fracture orientation that can be readily compared with other conventional geophysical logs. Stereo plots (Fig. 13) provide a means for the graphical display of the distribution of fracture orientation for a borehole, selected depth intervals, or multiple boreholes. Additional information on the analysis of fracture-orientation data from boreholes and approaches for correcting for bias is presented by Martel (1999).

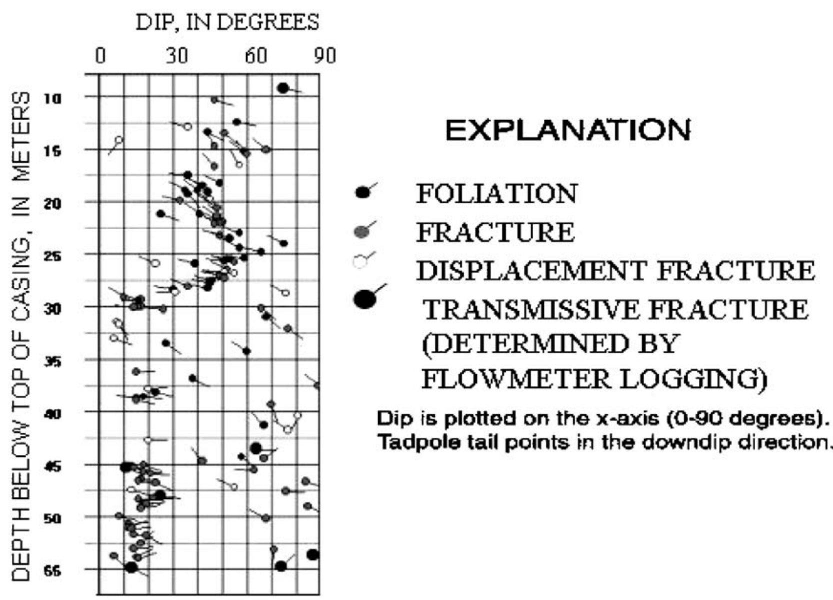

Fig. 12. Classification and orientation of structural features displayed in a tadpole plot for a borehole completed in gneiss.

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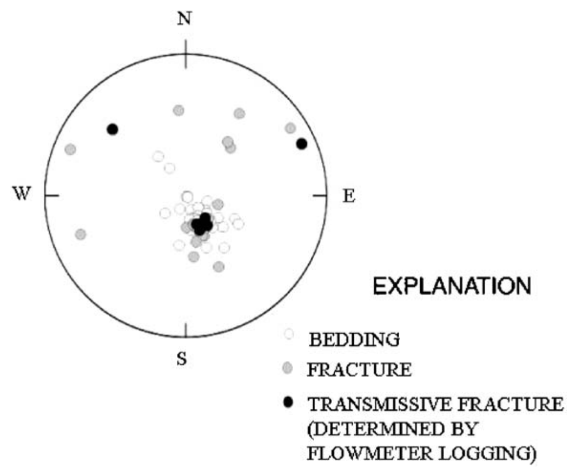

Fig. 13. Classification and orientation of structural and bedding features displayed in a stereo plot for a borehole completed in sandstone and mudstone (Williams et al., 2002).

6. Integration with other geophysical logs, core samples, and hydraulic measurements

Because the ATVand OTV images are oriented and continuous, they are extremely helpful for the analysis of core samples that commonly are not oriented and contain missing intervals, especially in intensely fractured intervals that are of critical interest. Gamma and resistivity logs are interpreted with the image logs to to help characterize lithology and water quality. Fluid resistivity, temperature, and flowmeter logs (Paillet et al., 1987) commonly are used to define which fractures identified on the ATV and OTV images are transmissive. The ATV and OTV images are used to target zones that stationary flowmeter measurements should bracket. The acoustic caliper is used to identify competent zones in the borehole that will allow for good seals with flow restrictors typically used with low-velocity flowmeters. The distribution and orientation of transmissive fractures are displayed on tadpole and stereo plots, which allows for a direct comparison of the relations between transmissive zones and lithologic and structural features identified on the ATV and OTV images (Figs.12 and 13).ATV and OTV images also provide critical information for placement of inflatable packers for testing and monitoring and for interpretation of resulting hydraulic and water-quality data.

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7. Conclusions

Conclusions ATV and OTV imaging results in continuous and oriented 360j views of the borehole wall. Fractures are more clearly defined under a wider range of conditions on ATV images than on OTV images including dark-colored rocks, cloudy borehole water, and coated borehole walls. However, OTV images allow for the direct viewing of the character of and relation between lithology, fractures, foliation, and bedding. The most powerful approach is the combined application of ATV and OTV imaging with integrated interpretation. ATV and OTV images provide a combination of qualitative and quantitative information that can be used to characterize fractures and lithology penetrated by boreholes; potentially identify contamination; help in the collection and interpretation of hydraulic and water-quality data and other geophysical logs; and provide insight for conceptual models of fractures, ground-water flow, and contaminant transport.

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