Combined Processing of BHTV Traveltime and Amplitude Images

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Abstract: Borehole scanner tools deliver high-resolution images of the borehole wall. These tools have become popular in a wide range of logging applications. A quantitative interpretation of image data requires consideration of the physics of the measurement process, quality control and data corrections. In this paper emphasis is placed on the processing and interpretation of BHTV traveltime images. It will be shown how more reliable information can be extracted from the traveltime and amplitude image by a combined processing of both images. Also, the synoptic presentation of both images assists in the interpretation of the acoustical data. Examples are given on high-precision calliper evaluations and on breakout analysis.

Introduction

Imaging tools

Borehole scanner tools which measure physical properties in different directions in a borehole allow one to derive the directional dependence of rock properties in the case of anisotropic formations. Among the scanner tools, borehole image tools produce images of the bore hole wall which are influenced by the surface of the borehole wall or a very small depth of penetration of only a few millimetres. One fascinating aspect of these image tools is that the data obtained can be presented on a computer like a core. Then, it is possible to display and interpret on screen these virtual core images with the associated virtual optical images of real cores created by an optical core scanner (Deltombe, 1999).

Acoustical imaging tools

The first borehole image tool was the acoustic borehole scanner called BHTV. This tool creates two images, an amplitude image which reflects the acoustic impedance of the borehole wall, and the traveltime image which reveals the borehole calliper. The BHTV tool was used in the beginning mainly in oil exploration. Since then the tool has become a standard tool in geotechnical exploration because the tool is superior in detecting fractures and thin weak layers. Moreover, the acoustic impedance is directly related to rock hardness (Schepers, 1996). Slimhole versions of the tool (40 mm) have helped to introduce the tool into the geotechnical market.

Electrical imaging tools

The electrical borehole imager, known as FMI, was developed for the oil market and it is still mainly used there. The tool is very good to detect bedding sequences in sedimentary rock.

Optical imaging tools

Optical borehole image tools were developed directly for the geotechnical and hydrogeological market, where wells filled with clear water are often available. The main applications are in hard rock formations as long as borehole stability in fractured zones is not a major problem.

Scope of paper
Acoustic image tools measure simultaneously two different images, i.e. an amplitude log which is directly related to geotechnical rock properties, and a traveltime log which allows one to derive a very precise borehole calliper. Even though finally two different physical parameter are recorded the two image logs are related to each other. We want to point out in this paper which information can be extracted by a combined processing of the two acoustic images and their synoptic interpretation. But our emphasis is placed on the processing and interpretation of traveltime image logs.

Process of traveltime measurement

Acoustical signal description

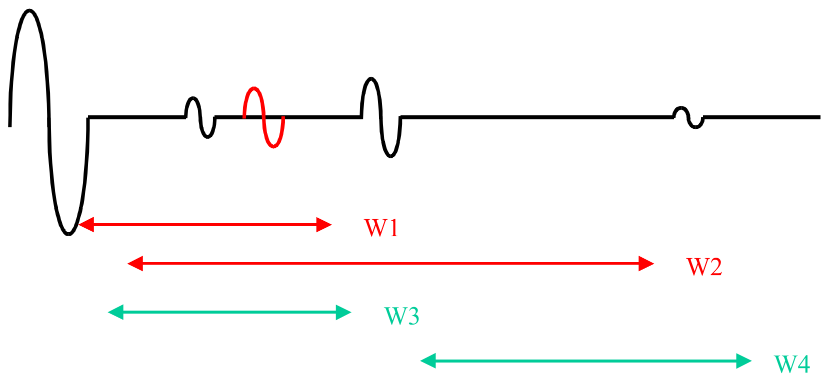


Figure 1

A typical signal send out and received by the acoustic transducer is schematically drawn in figure 1. The black line should be the signal which is recorded if there is no reflector. The first high amplitude wavelet is the transmitted signal followed by three coherent noise wavelets due to imperfect back damping or due to internal reflections inside the acoustic system. We assume that any incoherent electrical noise is always considerably smaller than any coherent acoustic noise. The level of such acoustic noise will limit a correct detection of traveltime in case of weak reflections from the borehole wall.

Effect of noise
The noise will, of course, depend on the acoustic components and the construction of the tool. But noise will also depend on the measurement window used during the recording of the image data. E.g. in figure 1 the window W1 is too close to the transmitted signal such that high amplitude values at the tail of the transmitted signal will result in a high noise level. A fixed long time window like W2 does not suffer from a potential wrong setting (W1) but it always includes the maximum coherent noise amplitude. The better approach is the individual optimal setting of the measurement window in accordance with the expected borehole calliper (W3 and W4). If the anticipated traveltimes fall into the gap between W3 and W4 and if reliable traveltime readings in areas of low reflection amplitudes are essential, an acoustic head with a different noise pattern can be used.

Detection process
Once a measurement window is defined the next influence on the traveltime measurement is given by the detection process of signals reflected at the borehole wall. An assumed weak reflection is overlayed as a red wavelet on the noise signal of figure 1. If a simple trigger level detection is used the reflected signal will not be detected in windows W1 and W2, and it will be very unlikely that it is detected in W3. The red wavelet will be properly detected if a maximum detection process is used. Modern BHTV tools record the full wave form of the reflected acoustic signal. As transmission of the full signal to the surface is not possible due to the limited data capacity of standard logging cables, fast on-line processing is therefore applied to realise a more sophisticated reflection signal detection. Such processing can use knowledge about the noise pattern and expected traveltimes to optimise the detection. Even the variation of the noise pattern with depth can be taken into account. Practically, such processing further reduces the length of the measurement window and moves the position of the window in an adaptive manner. In principle, this will allow one to detect the red wavelet in Windows W1, W2 and W3. But the situation depicted in figure 1 is fairly simple. The problem is more complex if the reflected signal is moving close to a noise signal. Finally constructive or destructive interference will change the signal form. If such a signal is detected at least the traveltime is close to the correct traveltime. On the other hand the amplitude is influenced considerably.

Faulty detection
Generally, we can state that in all cases where a wrong traveltime is detected, the amplitude is also wrong. On the other hand, the traveltime should be correct, if the amplitude is well above the noise level. As explained above the amplitude value can be wrong, even if the traveltime is correct. But this influence is only considerable at low amplitude values were relatively large amplitude variations can be assigned also to a number of other factors which are difficult to estimate properly.
It is obvious that from the traveltime image an amplitude quality image can be derived which defines for each pixel, if the amplitude is reliable or if the amplitude is wrong. The procedure incorporates the definition of wrong traveltime reading so that in parallel a traveltime quality image is created. In addition, the amplitude image is used to further refine the traveltime quality image. But the traveltime quality image is still subjected to some ambiguity. Both quality images are used later during data processing and aid in a synoptic way in data interpretation procedures.

Influence of directional resolution

The performance and the usefulness of BHTV tools depend highly on their directional resolution. This resolution is defined by the width of the acoustic beam at the reflecting point, i.e. the borehole wall.

Focused acoustical beam
Figure 2 explains the principle features of a finely focused acoustic system. In the upper part of figure 2 the planar cross-section through the centre of a circular beam pattern is shown. Underneath the amplitude variation along the central axis of the beam is displayed. In the near field close to the transducer interference of acoustic energy results in rapid amplitude changes. From a certain distance on, the beam width and the amplitude stay more or less constant. The design goal for a good acoustic borehole system is to make the length (focal depth) of constant width and amplitude as long as possible. Optimum resolution and quantitative exploitable results are achieved if the reflection interface (borehole wall) is within the focal

depth. The end distance of the focal depth depends on the frequency of the emitted signal and the aperture of the acoustic system. After the end of the focal depth the beam is spreading out at an angle of about 5^0 and the amplitude is decreasing rapidly. Slim hole BHTV tools with a typical acoustic frequency of 1 MHz allow one to realise beam width of 3mm and to expand the focal depth to 100mm.

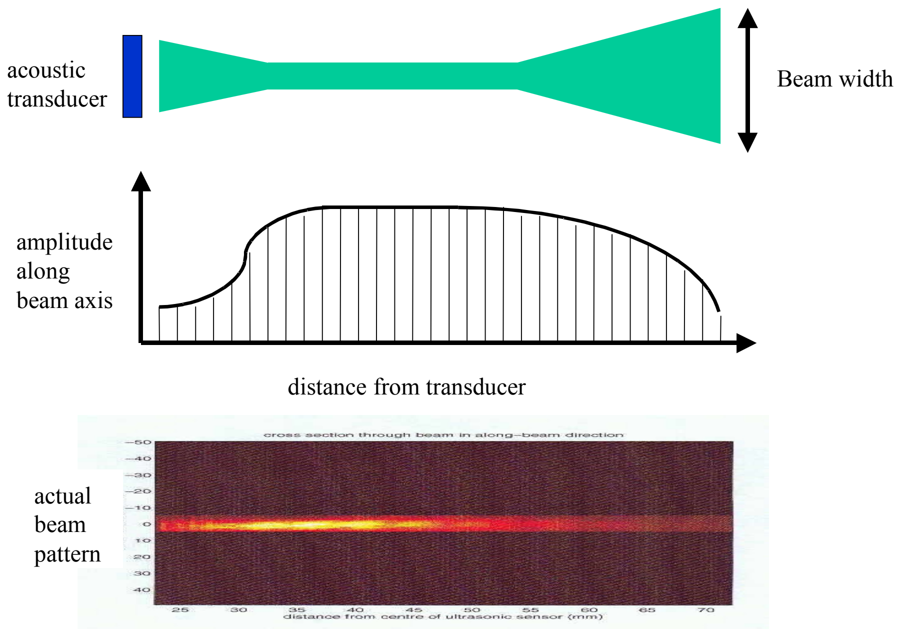


Figure 2

The lower part of figure 2 shows an actual beam pattern gained from laboratory experiments. The constant beam width spreads out from 25mm to 75mm. The amplitude along the beam is indicated by colour variations.

Spike in travel time image

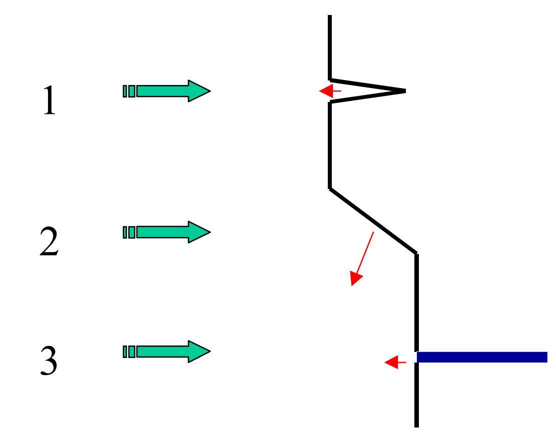


Figure 3

Such highly focused acoustic systems are in a positive sense very sensitive to borehole conditions. We have referred already to wrong traveltime readings. Often it is argued that a good BHTV tool should not produce spiky traveltime images. This is definitely wrong. The physics of acoustic wave propagation require that under certain borehole conditions only very weak reflection can be expected and consequently no correct traveltime can be measured if the reflected amplitude is below the noise level. This means, the higher the dynamic range is of the acoustic system, the less spikes we get. But spikes cannot be avoided under all conditions. In figure 3, three situation are shown which will yield very weak or no reflections.

Case 1 is an open fracture where most of the energy is refracted into the rock and only a very small part is reflected back to the transducer.
Case 2 is a steeply dipping interface. The total energy is reflected downwards without reaching the transducer.
Case 3 represent a thin zone of very low impedance which could be a very soft rock, a fracture or a mylonite zone. These zones are often accompanied by borehole washouts such that only some diffracting energy from the corner of the hard rock will reach the transducer. The better the resolution of a BHTV system, the more sensitive it is to not receive reflected energy in these cases described above. If a BHTV receives reflected signal in these cases the reflected energy can not come from the described structures. This means the real features are not correctly imaged.

Comparison of good focused and bad focused system

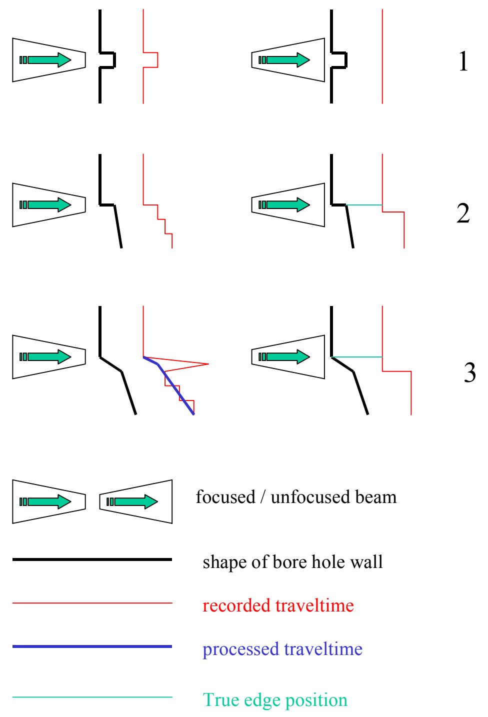


Figure 4

Figure 4 shall explain this with respect to a good focused and a bad focused system.

In **case 1** the thin washed out zone is not detected by the unfocused system. In **case 2** the position of the edge and the transition zone is not properly imaged by the unfocussed system. The same is true for **case 3**. In this last case we can expect the focused system to create one of those undesired spikes. But the spike tells us that the recorded amplitude is wrong and it gives a good estimate of the true position of the edge. As will be discussed later processing of the traveltime data can remove the spikes from the data and can help to reconstruct the true borehole shape. The blue line illustrates this.
Figure 5 compares the traveltime images (TT) and the amplitude images of a high-resolution BHTV tool (HR) with those of a low-resolution BHTV tool (LR). All structural features are considerably clearer in the HR amplitude image. E.g. a thin fracture at 12.8m is only visible in the HR image. The black dots in the HR-TT traveltime image indicate wrong traveltime readings. With respect to the LR-TT image one can rather speak of black areas, because faulty traveltimes spread out all along each detected fracture. With reference to the discussions above this can only be explained by a low dynamic range of the low-resolution system. The actually small calliper variations along the fractures are very well resolved by the HR-TT image.

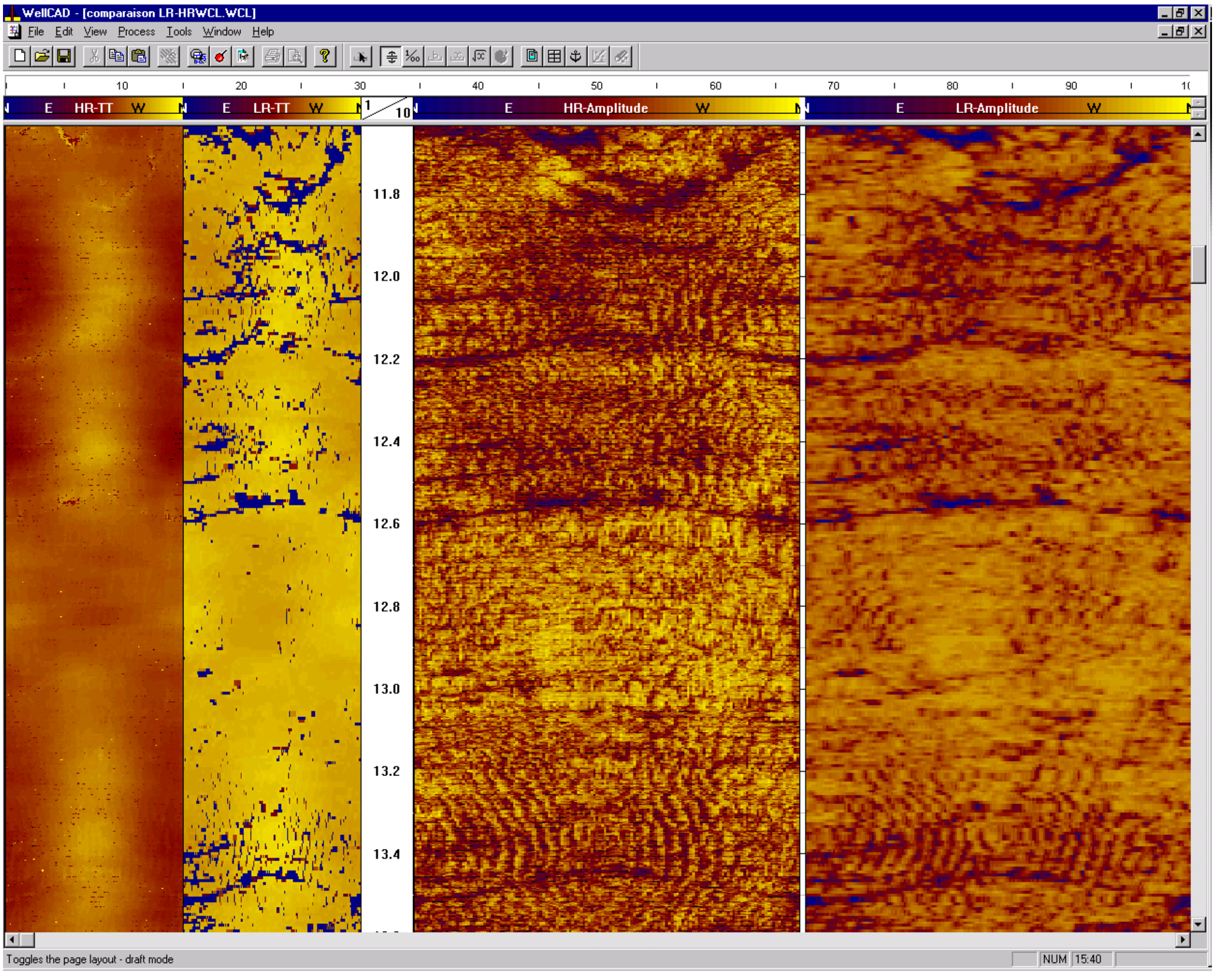


Figure 5

Traveltime corrections

Correction for faulty detection

In most cases the detection of wrong traveltimes is a fairly simple and unique process. This is due to the fact that the surface of the borehole wall is highly oversampled with respect to calliper variation as the sampling interval is defined by the desired high resolution of the amplitude image. Oversampling of the traveltime image makes a lot of sense with respect to detection of true edge positions and the definition of the amplitude quality image which is important for the quantitative interpretation of the amplitude image.

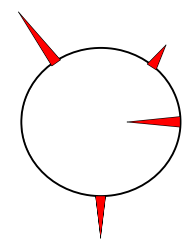
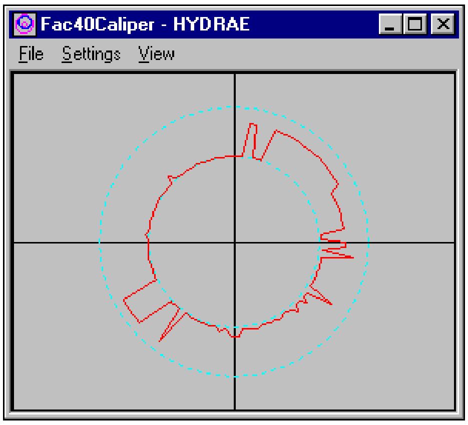


Figure 6a

In figure 6a, a borehole cross-section of a more or less circular borehole is drawn. The dark circular line gives the true shape of the borehole. Some of these typical spikes occur in the cross-section display of the measured traveltime data if e.g. a fracture along the borehole creates low reflection amplitudes. As can be explained by figure 1 the spikes can go to the inside (case W1) or to the outside (case W2). The length of the spikes depends on the actual calliper and on the measurement window settings. No sophisticated processing is necessary to detect wrong traveltime data in this very common case



The situation is more complicated if along a larger portion of the circumference there are many wrong readings and the true and wrong reading lie relatively close together such that a decision on wrong or right is difficult. The problem is illustrated by a cross-section display (figure 6b) as it is continuously monitored during field data acquisition. E.g. the traveltime readings in the upper right quadrant can be wrong but they may as well indicate a real breakout of the borehole wall. In this case a second run should be made where the traveltime quality image is refined by analysis of the amplitude image.

Figure 6b

Correction for decentralisation

Detailed information about the borehole shape can be derived from the traveltime image. The BHTV tool does not really measure borehole calliper, rather it measures multiple distances from the tool to the borehole wall. Calliper is only defined with respect to the centre of a regular shaped borehole.

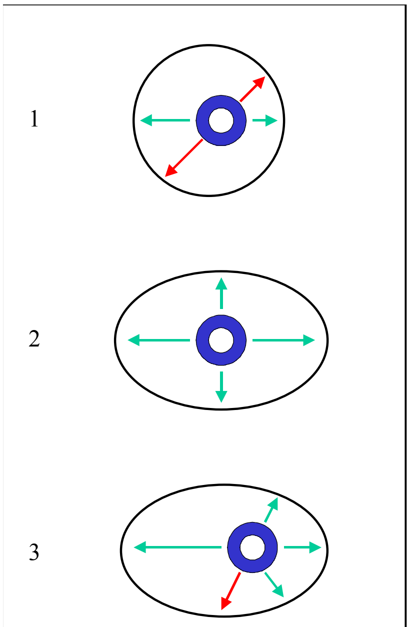


Figure 7

Influence on travel time

In figure 7 three different situation are schematically presented. In case 1 the tool is decentralised in a circular borehole. The two green arrows indicate the two direction where the acoustic beam hits the borehole wall perpendicularly. Only at these two direction we get maximum reflection amplitudes and the addition of the two opposite traveltimes gives us the true borehole calliper. In the direction of the two red arrows we measure a secant. The length of the secant depends on tool position. In case 3 the tool is decentralised in an elliptical borehole. The borehole wall is hit perpendicularly in four directions. But it is quite obvious that the addition of the distance given by the red arrows and distance in the opposite direction (green arrow) does not give a meaningful calliper value. Again, in case 2 the beam is perpendicular to the borehole wall in four directions. Calliper values can be calculated in all directions, because the tool is in the centre of the borehole cross-section. In case of an irregular shaped borehole a “centre” is not uniquely defined. We will discuss later how the traveltime data can be used to define a centre in such a case.

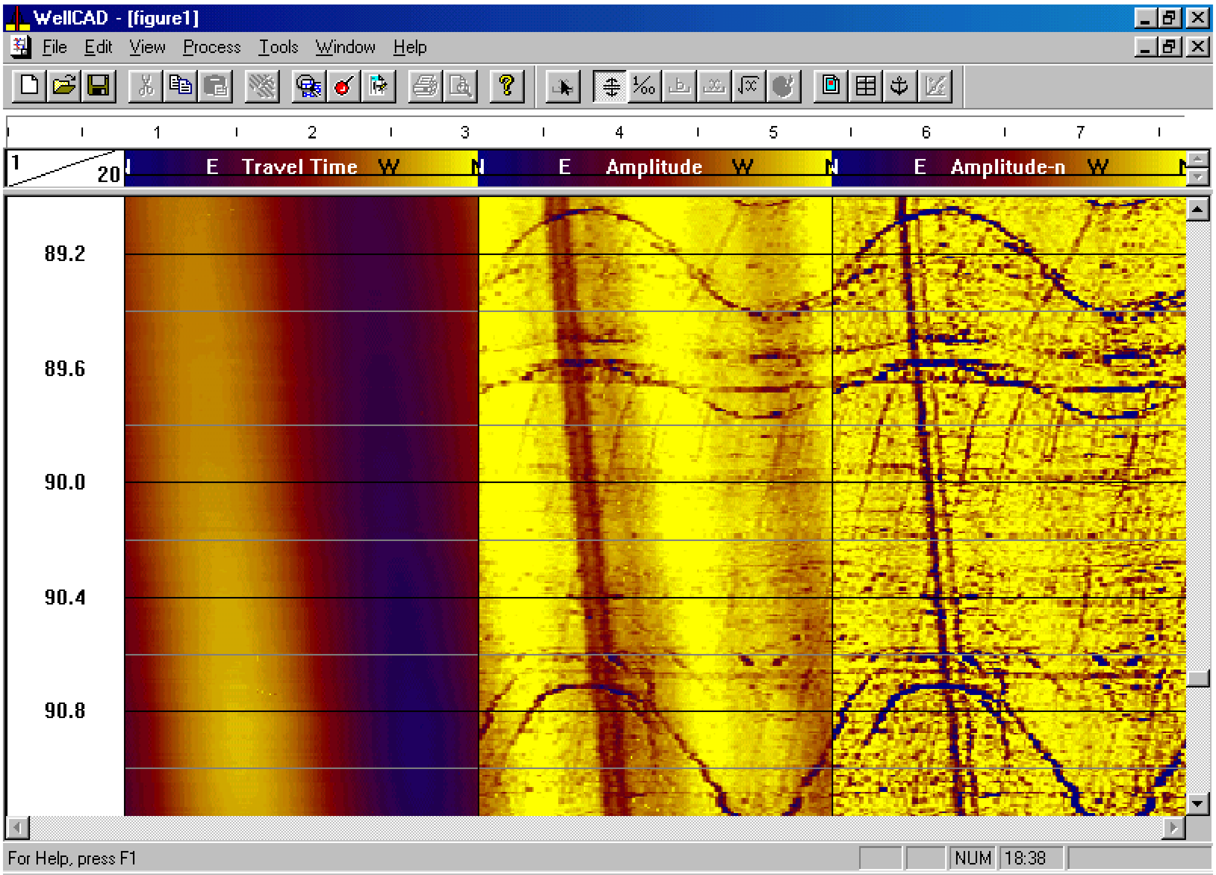


Figure 8

Influence on amplitude

As explained above the measured traveltime image depends on the position of the BHTV tool in the borehole. Figure 8 shows a typical result of a BHTV measurement. The traveltime is displayed in the left image track. We see a clear maximum (yellow) and minimum (blue) in the traveltime image. The difference between maximum and minimum is changing and also the direction of maximum and minimum. It is very likely in this case that the tool is not running along the centre of a more or less circular borehole (case 1 of figure 7). The amount of decentralisation and its direction is changing with depth. The traveltime image of figure 8 does not tell us much about the borehole shape besides that we may assume a relatively smooth borehole wall.

The information about decentralisation has its value with respect to the amplitude image. The influence of decentralisation (see figure 7) on the amplitude image in the middle track of figure 8 is visible as two broad shades (light brown) running parallel to the variation of the traveltime image. The narrow dark brown line in the amplitude image is due to tool construction. The shades and hence the influence of decentralisation can be removed to some extent from the amplitude image by a 2D high-pass filter. The result of the process is shown in the left track of figure 8. This image does not preserve the absolute variation of the amplitude values. Also, artefacts can be created in areas of rapid changes of the traveltime and amplitude image. Therefore, a crosscheck with both original images is recommended.

Knowing the position of the tool we can add another information to the amplitude quality image. It marks the direction where the acoustic beam was perpendicular to the borehole wall. This information can be later used to derive a rock hardness log based on a reliable estimation of the reflection amplitude for each depth.

Borehole shape calculation

To come to the borehole shape, the first thing to do is to transfer the traveltime data into distance data relative to the centre of the borehole. Then, we can directly see the borehole shape if we display cross-sections of the distance data. Such an approach is not adequate if an overview over longer borehole intervals is required. Furthermore small details of borehole shape may not be visible as the display range of the traveltime data is governed by the amount of decentralisation.

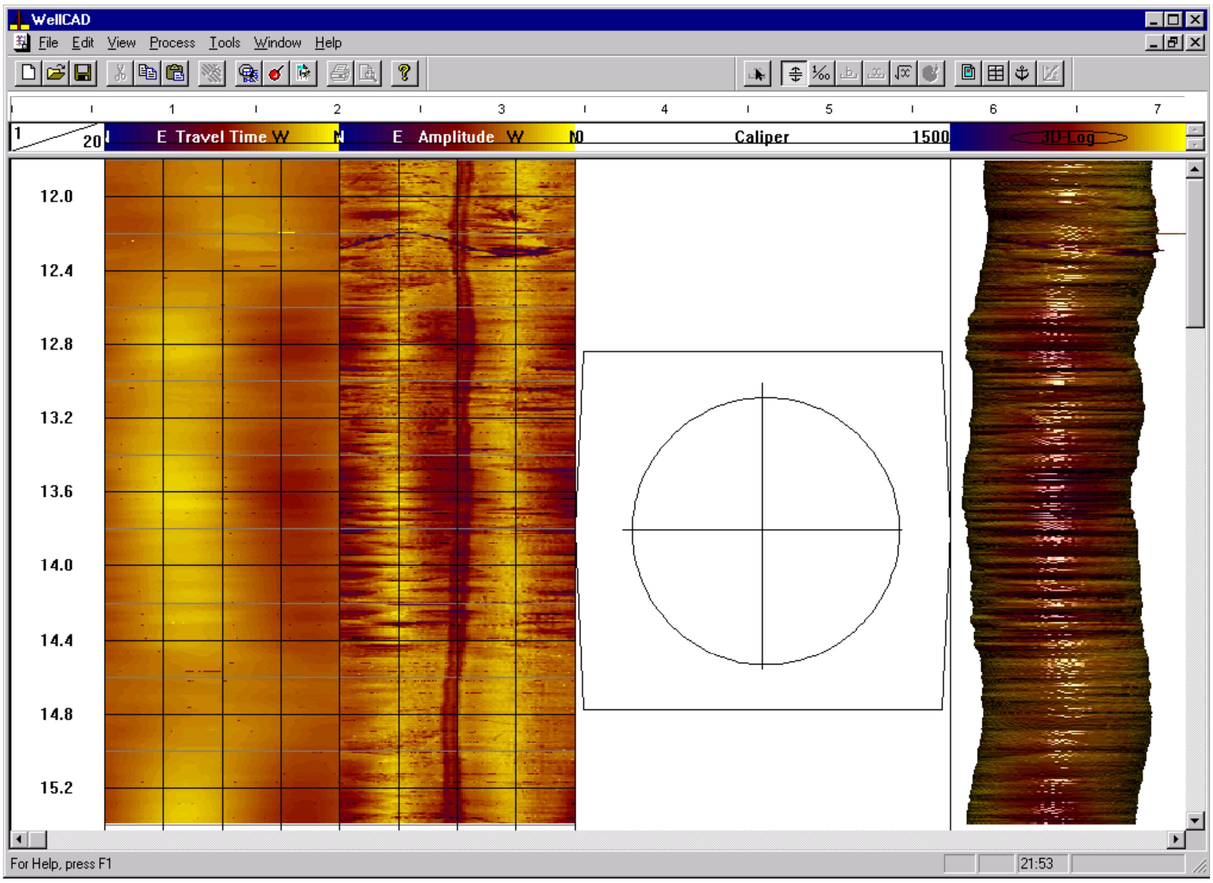


Figure 9

Figure 9 shows some BHTV data with three different presentations of traveltime data. The first track on the left is a standard unrolled display of the traveltime image. According to the borehole cross-section in the third track the borehole is more or less circular. The track on the right shows a 3D displays where the distance image is use to create a perspective 3D view of borehole geometry. The amplitude data of track two is projected onto the 3D body. You may think: what a crooked hole the drillers have made. But you are wrong. The hole is perfectly straight. The borehole geometry appears to be so crooked because the distances are calculated relative to the actual tool position which is not constant. There are some small scale feature visible along the borehole. But it is difficult to decide if they are real or not. This example

may point out how important it is to apply corrections to the distance image before a realistic 3D display can be generated.
We know the position of the tool relative to the borehole cross-section. This gives us the possibility to simulate in the computer the movement of the tool from its actual position to the centre of the borehole. The correction task is then to calculate the effect of such movement on each distance value. After the corrections are applied the distance image will look as if the tool has moved perfectly along the centre of the borehole. In the case of a regular borehole it is easy to define a centre of the borehole. The problem of the correction procedure is to adapt a practical approach for the calculation of the borehole centre.

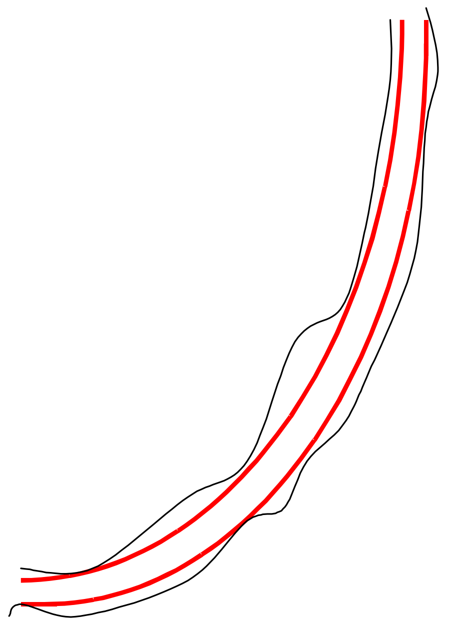


Figure 10

In figure 10 a vertical projection of an inclined and irregular hole interval is indicated by two dark lines. Boreholes are drilled with a drill bit of a certain size and with drill strings with some rigidity and hence a minimum radius of curvature. Therefore, we define the centre of the borehole as the central axis of a pipe with the diameter of the drill bit which is fitted into the borehole with maximum curvature. One possibility to calculate the path of the virtual pipe has been described by Menger and Schepers, 1988. In all such calculation algorithm the information of the traveltime quality image should be implemented. A result of a pipe fitting process is presented in figure 10 by red lines.

Traveltime interpretation and presentation

High resolution calliper

The result of a high resolution BHTV survey is shown in figure 11.

The amplitude image on the left side exhibits many thin fractures. The uncorrected traveltime image in the middle indicates that along some fracture material is broken out, e.g. along the steeply dipping fracture at 42m. The amplitude image and the traveltime image were used to create the 3D display on the right side. Many spikes are visible along the borehole. As explained above the appearance of spikes under special borehole conditions (like open fractures) can be considered as a proof of the high resolution capability of the BHTV tool and the spikes identify pixels where no true amplitude is measured. Of course, in the final display of traveltime data we would like to present the true borehole shape without spikes. Also, this will be necessary to see small calliper variations. Using the traveltime quality image prediction and interpolation algorithm can be applied to calculate the distance value at those pixels where spikes occur. In many cases a 2D low-pass filter can help to remove the spikes and to reconstruct the borehole shape. If the preservation of edges is of importance (e.g. in breakout analysis) 2D medium filter (Castleman, 1979) –or more general 2D percentage filter- should be applied.

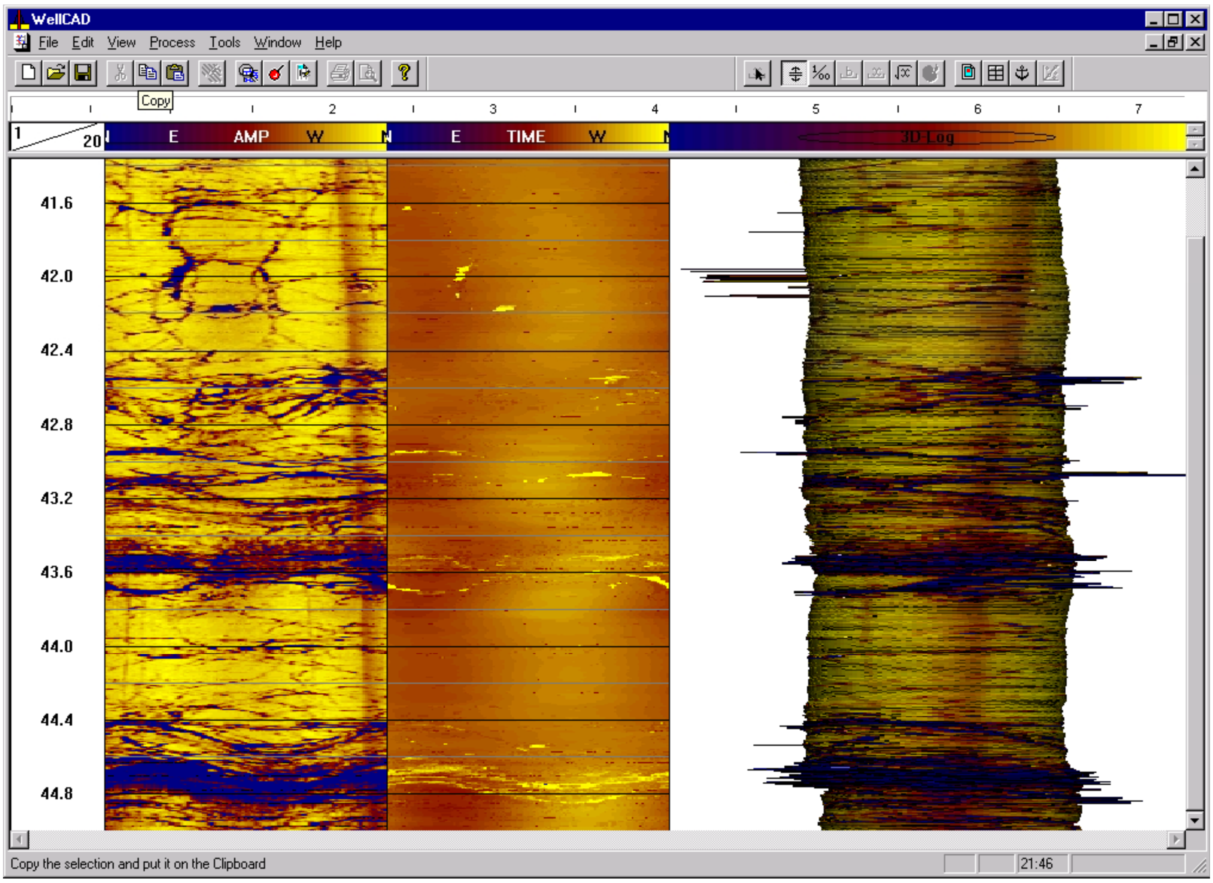
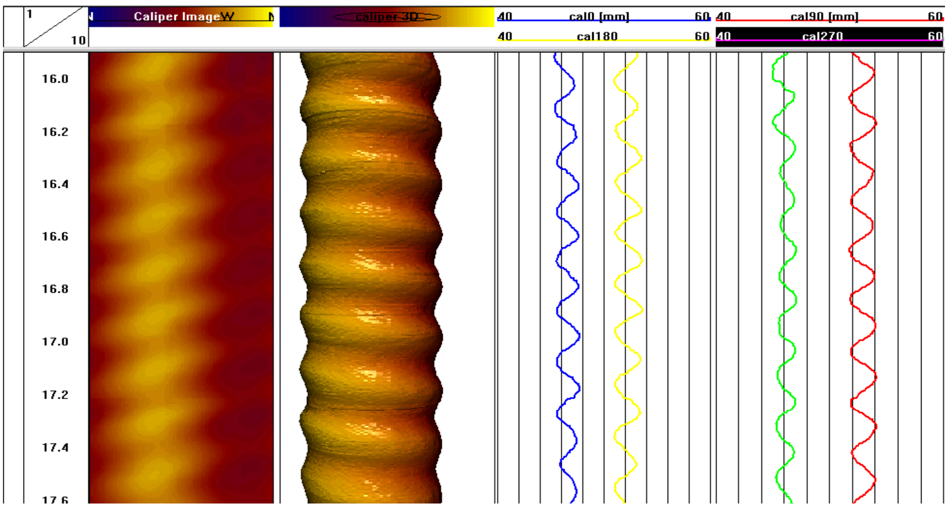


Figure 11



Presentation of very small (2 mm) bore hole caliper undulations induced by the drilling process

Figure 12

The results in figure 12 are a good example how much details of the borehole shape can be made visible after correction of the distance image for tool decentralisation and after removal of the spikes. The calliper image – or more correctly the distance image – is shown on the left side of figure 12. The amount and the good resolution of the calliper variations can be derived from the four tracks on the right which display individual calliper logs at four directions. As the scaling is from 40mm to 60mm the variations are in the range of only 2mm. The shape of the borehole is nicely revealed by the 3D display in figure 12. The scale is expanded such that the centre of the 3D display does not correspond to the centre of the borehole. Not the amplitude image but the calliper image is projected onto the borehole shape. The now clearly visible spiral along the borehole was created by the drilling process.

Breakout analysis

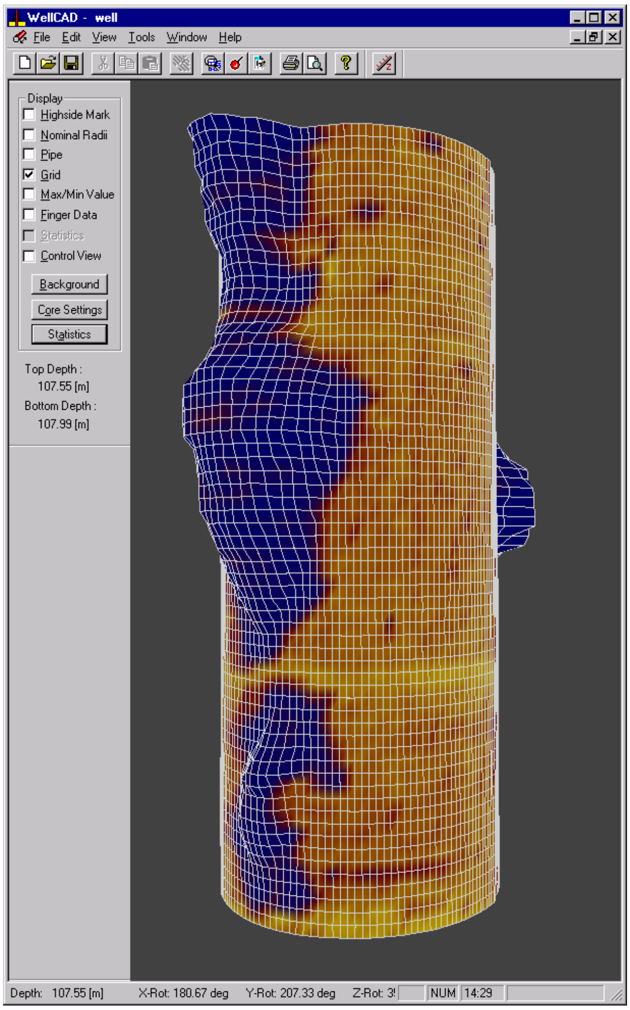


Figure 14

If the magnitude of maximum and minimum horizontal stress differ considerably from each other the borehole is deformed. These deformations lead to stress concentration and breakouts of the borehole wall occur in those intervals where the stress exceeds the strength of the rock (Barton, 1988). Typical for breakouts is that they develop on opposite sides of the borehole. The direction of the breakouts defines the direction of minimum horizontal stress.

A very exciting way of breakout presentation can be realised with 3D presentation software which allows the user to move into all positions inside and outside the borehole and to look in all directions. Figure 13 displays one snapshot of such a presentation of a borehole section with breakouts.

The 3D nicely reveals that breakouts are also visible on the amplitude image. This is due to the fact that the stress concentration has lead to deterioration of the rock. Acoustic measurement are very sensitive to detect defects in the rock. The blue colour (low amplitudes) in the amplitude image indicate these weak zones which are wider than the breakouts itself. This means that some material is already partly destroyed but not yet broken out. Therefore, the amplitude image can be considered as an additional tool not only to see existing breakout but also to detect potential breakout areas. In the light of this new result the determination of the width of breakouts has to be carefully considered.

Conclusion

The high information content of BHTV images can be used in a wide range of logging applications where quantitative data evaluation is required. But prior to any quantitative interpretation it is essential to apply quality control, corrections and processing of the image data. Additional information is gained by a combined processing of the BHTV traveltime and amplitude images. Proper presentation and evaluation tools should assist the further interpretation process. New aspects of borehole breakout analysis could be revealed by adequate processing and presentation.

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