# Enhanced Casing Evaluation: Longitudinal Borehole Casing Strain from Ultrasonic Imager Logging

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**Abstract**

*Over the last five years repeated ruptures of borehole casings connecting underground salt caverns to the surface have occurred. The ruptures pose a high risk to field operation of the caverns used as storage facilities. Apparently, the casing failures may result from lengthening of the borehole casing. At the moment there is no practical method for predicting this kind of casing lengthening and potential final failure. Logging based distance measurements between borehole casing shoe and well head are not sufficiently precise and reference measurements were not carried out. The installation of permanent optical fibre sensors was not considered a feasible option some ten years ago. The idea in this study was to analyse ultrasonic signals from standard cased borehole imager logs – backscattered from the borehole casing – for their frequency content which is possibly influenced by longitudinal borehole casing strain resulting from lengthening of the borehole casing. Standard ultrasonic imagers are usually used for the evaluation of casing-ID, casing wall thickness, and casing-cement connection. The suggested effects of varying frequencies resulting from longitudinal casing strains were expected to be relatively small, but the high data density of the powerful sonic imagers allowed a statistically based attribute analysis. In some of the S-shape boreholes a shift of the frequency content is in fact observed in sections of minimal radii of the cemented casing, which would be expected by increased longitudinal strain. First results and an outlook to further developments of this method are presented.*

## Introduction

Solution mined salt caverns have been used for large-scale storage purposes for decades. Due to the ductile material behaviour of rock salt these caverns experience a regular shrinkage over time. The associated movement of the rock mass may cause additional strain on the cemented casing, which may contribute to casing rupture as experienced with some salt caverns in the past. Presently there is no practicable technical method for direct or absolute measuring of this increasing longitudinal strain or the lengthening of the last cemented casing in boreholes without built-in optical fibre sensors.

In borehole logging methods, ultrasonic imaging has become a powerful standard procedure to determine the casing wall thickness and to verify the quality of the bond between casing and cement. This procedure is often applied as part of workover activities, usually after some periods of borehole operation as a kind of "time-lapse" borehole integrity study. Additional to the standard geophysical interpretation, for this study the frequency content of the full waveform of the ultrasonic signal received was investigated. The idea behind the analysis was that the backscattered sonic signal is influenced by the longitudinal strain of the casing in a sense that most easily can be explained analogous to the string of a music instrument. The more a string of a violin is stretched the higher is the resulting pitch. This effect, known to everybody, translated back to a borehole could suggest that a borehole casing under specific strain conditions, caused from lengthening, shows a modified backscattered sonic signal than it had before the lengthening took place. The search for



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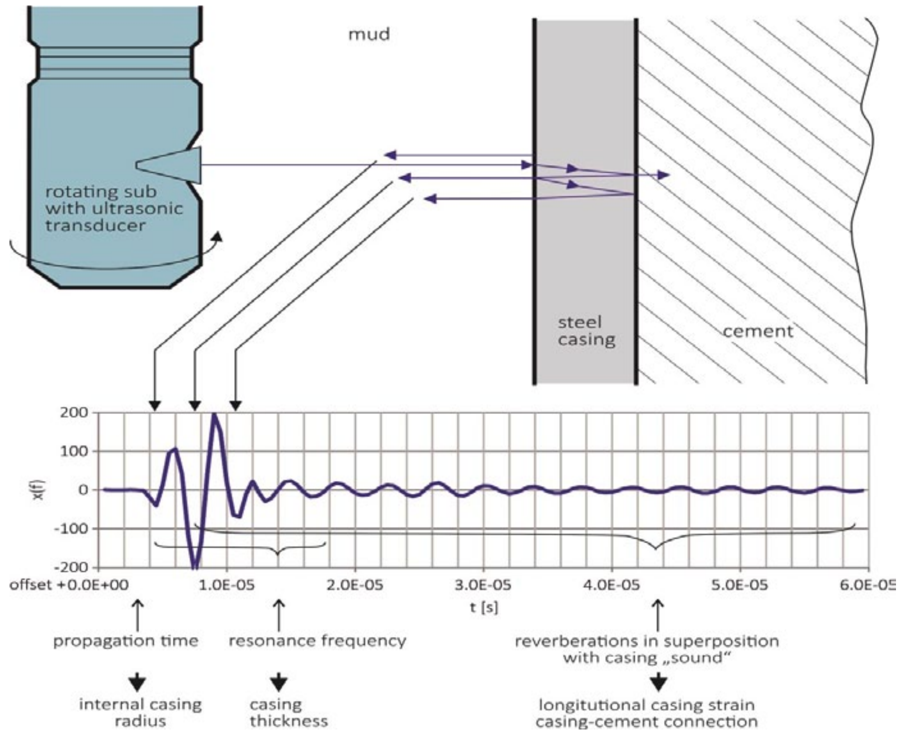


**Fig. 1** Schematic of ultrasonic wave propagation from transducer to borehole casing, interaction with the casing (reverberations), backscattering of the signals to the transducer. From the received full waveform information on internal radii, thickness, casing-cement connection and longitudinal casing strain are deduced [1]

**Tab. 1** Models for sound objects and their applicability to Enhanced Casing Evaluation [2–4]

| Sound Object / Theoretical Model | Applicability to Enhanced Casing Evaluation |
|---|---|
| differential string element<br>$$f_G \sim \frac{1}{2\,L\,R} \cdot \sqrt{\frac{\psi+\psi_i}{\pi \cdot \rho}}$$<br>$f_G$ base vibration frequency [s$^{-1}$]<br>$L$ chord length [m]<br>$R$ chord radius [m]<br>$\psi$ chord strain [N]<br>$\psi_i$ additional chord strain, analog to longitudinal casing strain [N]<br>$\rho$ density of chord [kg/m$^3$] | - simple model, considering the entire casing length<br>- does not constitute the demanded kHz-frequency range<br>- change of timbre via changes of chord strain, material density, length: doubling of the resulting frequency requires quadrupling of the chord strain<br>- differential string element not suitable to describe the vibration of a high frequency “knocked on” borehole casing string<br>- fastening of the string element at two fix points is necessary<br>- free vibration cannot take place due to cement bond<br>- macroscopic: frequency echo dependents on casing strain |
| bell<br>$$f_G \sim \frac{W_D}{R^2} \cdot \sqrt{\frac{E+\sigma_I}{\rho\,(1-\nu^2)}}$$<br>$f_G$ base vibration frequency [s$^{-1}$]<br>$R$ radius [m]<br>$W_D$ wall thickness [m]<br>$E$ modulus of elasticity [N/m$^2$]<br>$\sigma_I$ inside tension, from longitudinal casing strain [N/m$^2$]<br>$\rho$ density [kg/m$^3$]<br>$\nu$ Poisson number | - transversal vibrations in ring level and perpendicular (vibration patterns) not influenced form changes in length<br>- vibration can be measured, but not analytically modelled<br>- varying timbre via changes in material elasticity, density, radius, thickness and by an additional inside tension: “casing sound“ will follow a lengthening of 0.2 % with an increase of frequency of also 0.2 %.<br>- no fastening at two fix points necessary<br>- vibration can take place also while partly cement bonded<br>- macroscopic: frequency echo dependent on casing tension |

these effects was performed, knowing that a cemented casing of more than 1 km length, hit by ultrasonic pulses is not directly comparable to a violin string. Changing casing strain is also altering the elasticity module of the material. A ringing bell or hollow cylinder – the “casing sound” – would change its sound frequency in a low but audible per mille variation.

This study aims at the analysis and description of the frequency content of ultrasonic waveforms, its superposition with the casing sound and its change in time as well as the correlation to different borehole conditions. Spectral attributes of the recorded signals along the casing string are projected against the borehole-deviation. From that correlation, an attempt was made to deduce the local geomechanical stress field as a probable cause of casing ruptures.

The great advantage of the Enhanced Casing Evaluation is that it makes additional use of already available ultrasonic logging data. Being aware that the changes caused by mechanical casing strain are extremely low, there is, however, a chance that the high data density of modern sonic imagers can be analysed statistically. To be proven in further studies, the investigation method could be a significant step forward to detect potential casing intervals prone to casing rupture.

## Ultrasonic Imaging – Short Background

The ultrasonic imaging tool also named circumferential acoustic scanning tool has been developed as a wireline logging method for cased borehole logging. During the logging operation a transducer mounted on a rotation sub emits ultrasonic pulses between 200 and 700 kHz and registers the returning signal reflected from the internal and external casing interfaces. In the standard application the travel time of the echo gives the inner radius, the main resonance frequency delivers the high resolution casing thickness and the decay of the waveforms relates to the bond between casing and cement. In addition the superposition of reverberations and “casing sound” may give information on the longitudinal strain of the borehole casing. Figure 1 shows the measurement principles.

## Database and “casing sound”

Prior to the analysis of ultrasonic wave measurements the available log database had to be analysed with respect to log suitability for the Enhanced Casing Evaluation. The largest number of ultrasonic measurements for this study is derived from two different gas storage sites in Germany. At both locations ultrasonic logging has been generally done to evaluate the integrity of the last cemented casing. But during the screening process it soon became clear that data from measurements prior to 2008 could not be used, as the sample length of the individual shots was too short (32 samples/shot). Nonetheless, a total number of 17 measurements done after 2008 were

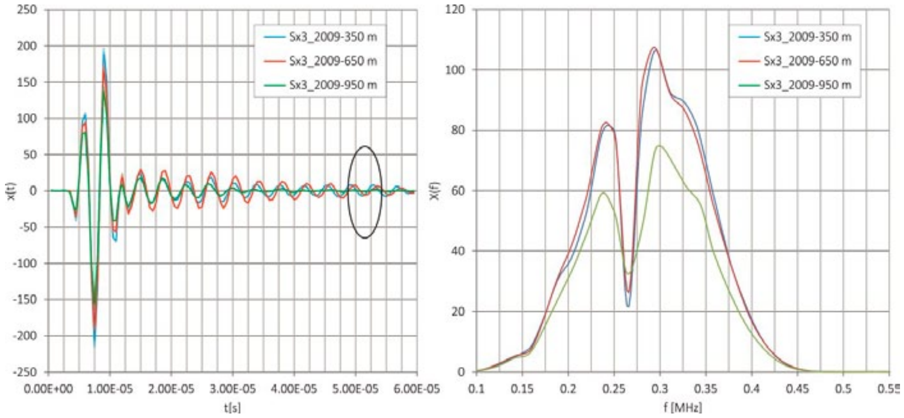


Fig. 2 Signal processing of cavern Sx3 for three single traces in different depths: amplitude vs. time (left) and spectral amplitude vs. frequency. In the tail part of the time-signal (marked) there is a phase shift detectable. In the cone-like spec-tra of these traces both the resonance frequency of 0,270 MHz and a frequency shift especially on the lower-frequency flange are detectable

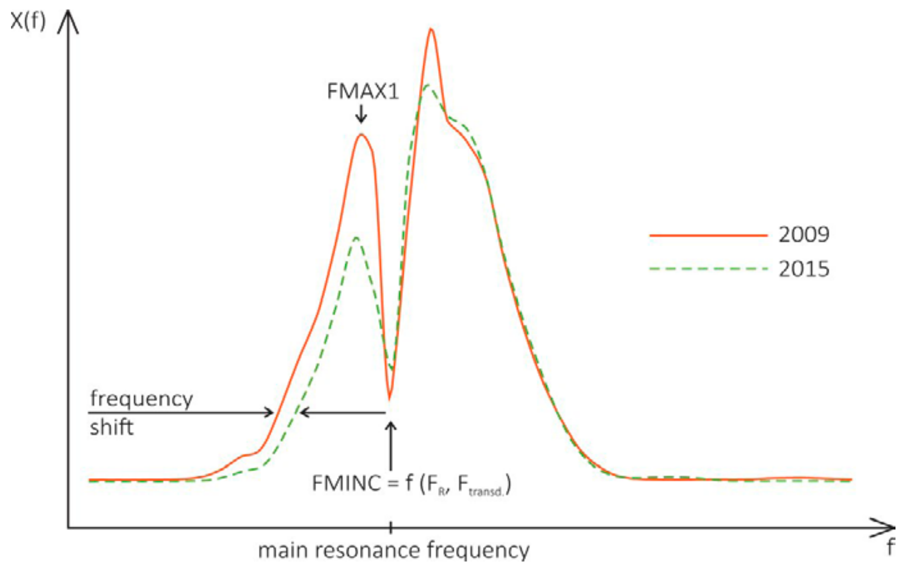


Fig. 3 Frequency spectra from cavern Sx3 logged in the same depth at different times. The frequencies for FMAX1 and FMINC are invariable. At lower frequencies there is a frequency shift between 2009 and 2015 towards higher frequencies detectable

found to be qualified for further analysis (119 samples/shot). Two logs are repeat measurements, both carried out in a workover campaign six years after the first logging. Such repeat measurements are of particular interest, as they allow time dependent analyses.
The aim in the first step of Enhanced Casing Evaluation was to find an applicable physical model that can describe the relationship between tension and frequency change known from strings or hollow cylinders. An answer had to be given to the question if such a model could be applied to a cemented casing with respect to energy and frequency content of the available ultrasonic data. Two primitive sound objects, which are able to generate a "casing sound" influenced from longitudinal casing strain are considered in Table 1.
With respect to the investigation target, possible frequency shifts in the reverberation signals due to mechanical tension changes of the borehole casing are caused by partial overlaying of both sound effect models. The signal registered by the borehole sonic log is superposed by high frequency reverberation and low frequency "casing sound". The effects of frequency shifting are extremely small and demand statistic spectral attribute analysis.
FEM simulation should be considered to get more clarity on the vibration phenomena.

## Signal Processing

The idea behind the signal processing is to extract and process the observed shifting of the frequency content of the registered waveforms, used for an interpretation of changes in the longitudinal casing strain. In the time domain this frequency shift can be identified as phase shifts in the tail parts of the registered signals (Fig. 2, left). In the frequency domain – calculated by Fast Fourier Transform [5] – changes in the low frequency content of the cone-like frequency spectrum are recognizable (Fig. 2, right). A typical frequency spectrum is characterized by a dominant minimum. This minimum is the main resonance frequency (FMINC). It results from the interference of the signal and the reverberations and it is used to calculate the wall thickness. In borehole casings with constant properties it should be constant. In addition it can be seen that the frequency FMAX1 of the amplitude maximum below the main resonance frequency is also constant under these conditions. However, the frequency content on the edges of the cone (Fig. 2) is not constant, giving indications of frequency shift effects as a target for this study.
Comparing the frequency spectra of echoes from original and repeat measurements, logged some six years later in the same borehole and at the same depth, show analogous effects with fixed FMINC and FMAX1 and also frequency shifts on the edges of the spectral cone (Fig. 3).
The aim of the second step in the Enhanced Casing Evaluation is to extract these moderate frequency shifts by signal processing and to compare them in relation to borehole depth or to repeat measurements years after the first logging.
For the quantification of the moderate frequency shift, several types of spectral attribute analysis were developed. One effective method is to quantify the energy content of the lower and upper fre-quency band divided by the FMINC and FMAX1 fixed frequencies (Fig. 4 left and middle). Although these spectral attributes do not change their central frequency defined by constant geometric casing conditions, the energy content changes due to frequency shift effects. Besides these two attributes a third attribute, named FMAXF, was developed constituting the maximum of the envelope of the spectral cone. The frequency spectrum envelope curve as the essential element of this spectral attribute can be calculated by Hilbert transformation or as a polynomial function (Fig. 4, right).
In the context of spectral attribute analysis the parameter Differential Frequency Ratio (DFR) is introduced. This is the quotient of the energies containing upper and lower frequency bands of any of the spectral attributes. The bandwidth is limited by $\Delta E1 = \Delta E2$ and the energy content is calculated by integration within these limits. The advantage of this procedure is that also the shape of the envelope curve is taken into account and is useful for comparison of different depths within one borehole log or for repeat logs in time-lapse analysis.

## Results

The spectral attribute FMAXF of borehole Sx3, logged at different times in the years

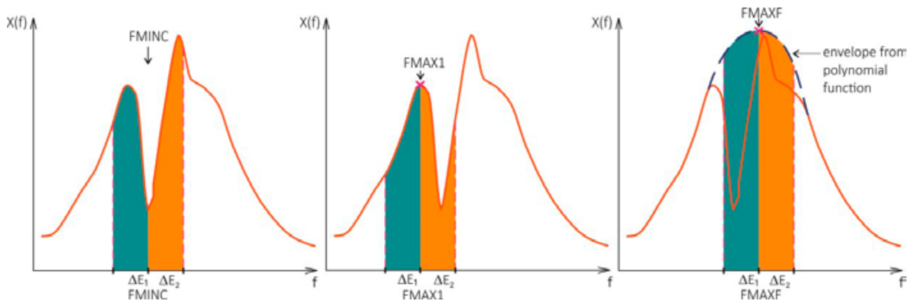


**Fig. 4** Definition of criteria for spectral attribute characterization based on fixed frequencies: FMINC, main resonance frequency (left); FMAX1, first local peak below the main resonance frequency (middle); FMAXF, frequency of the peak envelope (right). The quotient of the energy containing the lower and upper frequency bands is called Differential Frequency Ratio (DFR)

2009 and 2015, is shown in Figure 5. This time-lapse analysis clearly shows a change in the spectral attribute within this 6 year interval. The older log from 2009 (full line) is almost over the entire depth interval smaller in value than the newer log from 2015 (dashed line). The newer log fits the older log only in the upper part form the surface to a depth of 450 m, in deeper zones their values diverge significantly.

The borehole path from surface to the cavern Sx3 has a deviated S-shape. That results in a maximal longitudinal strain in those segments of the borehole casing that are maximally curved (maximal dog leg severity). In the second derivative of the S-shape borehole path these segments are characterized by larger values, as shown in Figure 6.

The comparison of FMAXF (2009, Fig. 5) from the older log and of the second derivative of the borehole path show a strong correlation between the spectral attribute and borehole path over the entire borehole length. Apparently the older log seems to be harnessed to the mechanical load of the casing. The striking accordance has to be superimposed on a number of influential factors such as corrosion or mud density, which all may severely shift the frequency content of the ultrasonic waveforms. The newer log FMAXF (2015, Fig. 5) fits with the older log only in the depth interval from the surface to a depth of 450 m. At higher depths of 450 to 900 m the correlation between spectral attribute and borehole path is much less pronounced, but still cognizable. From significantly higher values of the spectral attribute at greater depth an increased longitudinal strain can be deduced. Most striking is the rapid increase below 900 m, which is possibly caused by local rock movement.

Results of the Differential Frequency Ratio of the spectral attribute DFR(FMAXF) of four S-shaped boreholes located in the same cavern-field is demonstrated in Table 2 and Figure 7. Normed to zero at a depth of 800 m the DFR(FMAXF) graphs diverge with increasing depth, mostly developing a positive trend. A reason for that behaviour may be both an oriented local stress field and a movement of rock mass induced by cavern shrinkage, affecting the distance between the cavern roof and its surface installations. In the case of parallel oriented stress field and dogleg severity some lengthening or shortening of the borehole casing takes place. Especially at caverns Sx2 und Sx3 a lengthening can be concluded from positive values for DFR. They are deviated in a NW-SE direction parallel to the mapped stress field [6] and the casing weight seems to be overlaid by parallel local stress, which causes lengthening. Cavern Sx1 was drilled in N-direction, nearly perpendicular to the local stress, resulting in a nearly constant DFR without lengthening effects. In the cavern field some caverns show deformed neck contours potentially resulting from these rock movements. A simple principle sketch explaining the lengthening of the borehole casing, especially the deformation of the neck of the cavern (originally a vertical borehole section of diameter 19”) caused by the local stress systems [7] is shown in Figure 8.

## Summary

Enhanced analysis of data from standard high-frequency sonic imager logs could demonstrate that the frequency content of the ultrasonic waves consists of steady spectral attributes, such as main resonance frequency (FMINC) and variable elements, such as FMAXF changing along the borehole path, while geometric conditions are unchanged. The examined frequency shifting could be observed especially in longitudinal strain intensive sections of minimal radii of the cemented casing in S-shaped boreholes and in time-lapse analyses comparing measurements from different logging campaigns.

For gathering the frequency shift of the cone-like frequency spectrum of the ultrasonic wave backscattered reverberations a statistic based spectral attribute analysis was developed. The method is based on comparing the energy content of small upper and lower frequency bands around a spectral attribute.

Having quantified the gathered frequency shift of for example two measurements in the same borehole with a time lapse of six years, the following results were provided:

- *Old log:* strong correlation of spectral attributes and borehole path over the entire borehole length from the surface to a depth of 900 m
- *New log:* coincidence of spectral attributes with old log only in the depth interval from surface to 450 m, at greater depth significant rise of the attribute as an indication of increased longitudinal

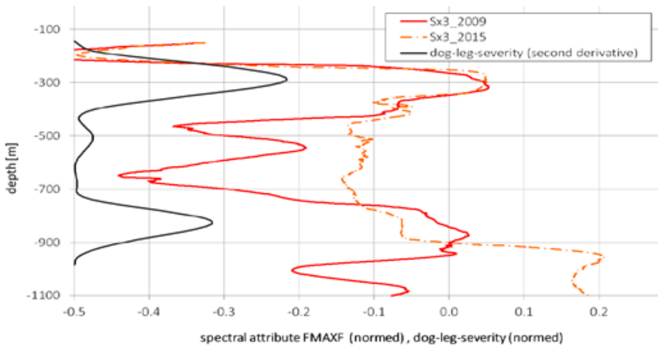


**Fig. 5** Spectral attributes FMAXF of borehole Sx3. The log from 2009 (full red line) does follow the dog-leg severity (black line, see Fig. 6). The log from 2015 fits with the older log from the surface to a depth of 450 m, at higher depth the values increase significantly (dashed line)

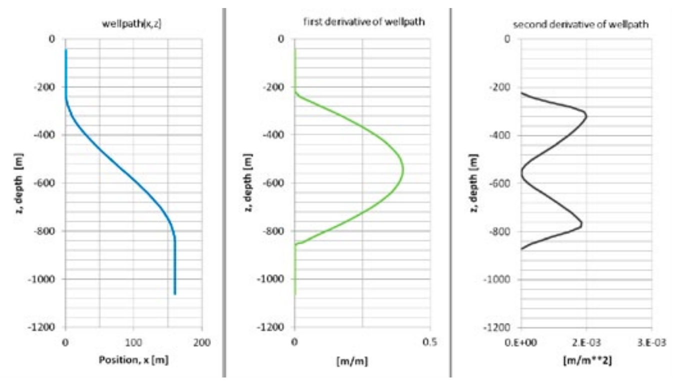


**Fig. 6** Simplified example of the first and second derivative of the borehole path (x,z) of a S-shaped borehole

Tab. 2 Development of spectral attribute DFR(FMAXF) as a function of azimuth of deviation for four boreholes

| Cavern | Azimuth of deviation | DFR(FMAXF), normed, 800 - 1,100 m depth |
|---|---|---|
| Sx1 | S – N | -0.03 |
| Sx2 | NW – SE | +0.20 |
| Sx3 | NW – SE | +0.12 |
| Sx4 | SW – NE | +0.05 |

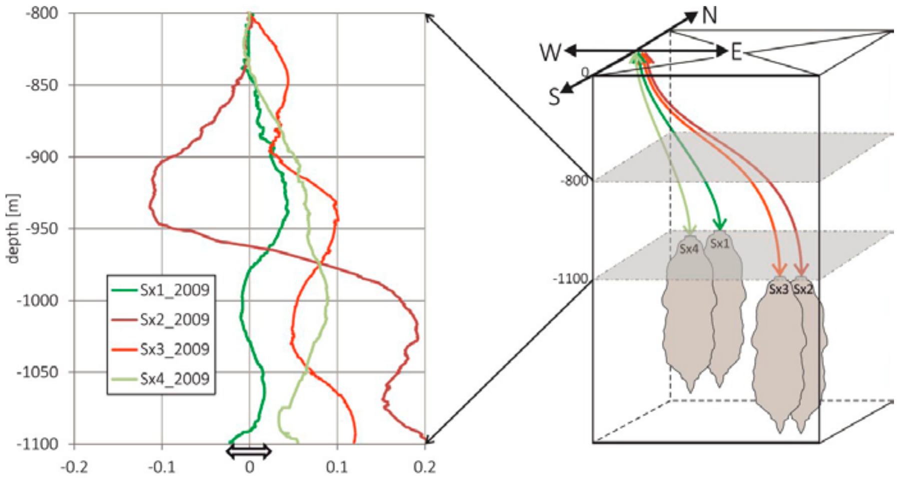


Fig. 7 Comparison of spectral attribute FR(FMAXF) vs. depth in the interval 800–1100 m for four borehole casings. At a depth of 1100 m there is a clear separation of values (Sx1< 0, Sx2, Sx3, S4>0) detectable. Spectral attributes greater than zero are understood as lenthening of the borehole casing. Their drilling paths following NW–SE direction which are overlaid by local stress in the same direction.

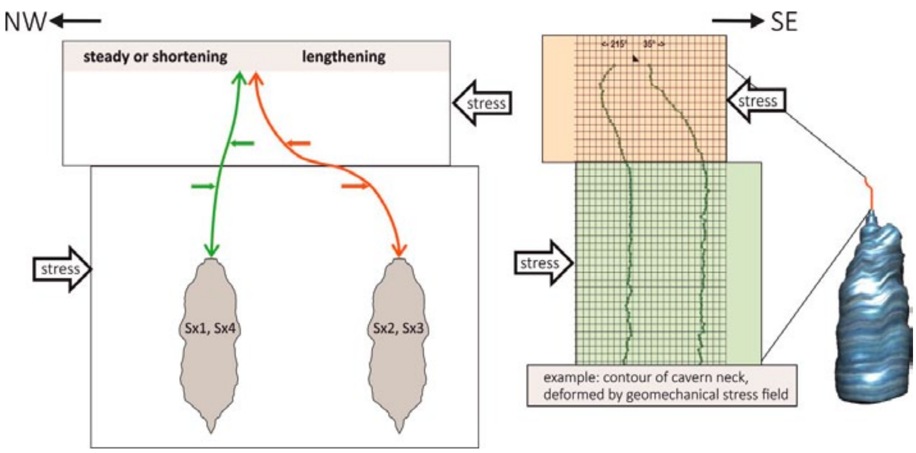


Fig. 8 Geological situaton: local stress field from NW to SE causes lenghtening of SE-deviated borehole casings (Sx2, Sx3). Boreholes deviated in N or NE direction (Sx1, Sx4) are less influenced by local stress field resulting in shortening or constant casing length. On the right the result of measured cavern neck deformation of a neighbored cavern in the same field is shown. Originally the cavern neck was a vertical borehole section of diameter 19"

strain. Even though amplitude variation becomes less pronounced the correlati-on of spectral at-tributes and borehole path is still recognisable in the depth interval 450–900 m.

- *Both logs:* prominent increase of the spectral attributes in depths below 900 m. The reason for that common behaviour could be associated with an oriented local stress field and rock mass movement induced by cavern volume convergence.

The influence of this stress field is also visible in neighbouring boreholes, which allow correlation between the stress amplitude and the azimuth of the deviated boreholes. The project is now going into its second phase including improvement of analysis procedures and sectorial analysis of the 3D-boreholes. It is planned to calculate the changing stress intensity of the casing along the borehole using a geomechanical modelling approach. Verified in further studies the method could be a significant step forward in detecting borehole casing intervals prone to rupture.

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