

## Accuracy and Convergence Considerations Regarding Ultrasonic Cavity Surveys Using the ECHO-LOG Technique

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### ABSTRACT

The accuracy of ultrasonic cavity surveys using the ECHO-LOG technique from Prakla-Seismos GmbH is first presented. Subsequently the errors are discussed regarding the individual parameters such as travel time and velocity of ultrasonic waves within the cavity media as well as depth determination. Based on average errors derived from such parameters, an error estimation is given for the cavity volume determination which refers to an idealized cylindrically-shaped cavity. The results show that the accuracy of travel time determination greatly influences the quality of the volume computation of cavities.

Parameters such as the compass deviation, magnetic declination and coriolis force are briefly discussed regarding their influence on the determination of distance from the point of emission of ultrasonic waves to the reflection point on the cavity wall. Differences that occur when measuring across the leaching strings are also considered.

The determination of convergence in gas-filled cavities is discussed from two different points of view: comparison of horizontal cross-sections measured at the same depth but at different times; and outlook on the determination and comparison of so-called best cavity "fits". Such fits are derived from two 3D high resolution measurements carried out several years apart in one and the same cavity using the SPIRAL-LOG technique. In this case the ultrasonic transducer system is continuously moved up-hole and slowly rotated. In doing so the cavity is sampled with a very high point density and the filigree structure of the cavity is resolved.

Thus the difference in volume between the two cavity measurements is a more accurate measure of the volume convergence because, for instance, errors regarding both depth determination and azimuthal orientation are eliminated.

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### INTRODUCTION

The ECHO-LOG technique has been a recognized part of cavity surveillance for the last 30 years. The continual technical improvement of the survey method and the associated increase in survey accuracy mean that today convergence determinations can be carried out very successfully using ECHO-LOG data. In the following these aspects are dealt with in detail.

### ACCURACY CONSIDERATIONS

#### General remarks

The ECHO-LOG technique is based primarily on the measurement of a travel time, i.e. the time it takes for a monofrequent signal to travel from the emitter (ultrasonic transducer) to the reflection point on the cavity wall and back. Knowledge of the acoustic velocity of ultrasonic waves in the propagation medium allows the distance to be determined from the equation

$$s = \frac{1}{2} v \cdot t \quad (1)$$

where  $s$  is the distance travelled,  $v$  is the acoustic velocity, and  $t$  is the travel time.

Consequently the accuracy of the travelled distance depends directly on the accuracy with which the parameters  $v$  and  $t$  can be determined. Also of interest is how accurately the survey tool can be positioned regarding depth and direction. The errors which occur can be considerable particularly in cavities with bizarre shapes, and this is especially critical when results measured at different times are to be compared with one another.

#### Accuracy of individual parameters

##### Distance

The accuracy of the distance determination is defined — besides by the technical effects which are corrected by calibration — mainly by the sampling rate with which the echo signals are recorded. Thus

$$g = \frac{1}{2} v \cdot n \cdot \Delta t \quad (2)$$

where  $g$  is the accuracy,  $n$  is the number of samples, and  $\Delta t$  is the sampling interval.

In the ECHO-LOG technique the minimum sampling interval is at present 20  $\mu$ s. Depending on the shape of the echo signal the travel time can be calculated to within  $\pm 2$  to  $\pm 10$  samples (for measurements in oil up to 15 samples). The maximum value of the envelope curve of a monofrequent signal is assumed to be the beginning of the echo signal, because its true start time cannot be determined exactly. Using this as a basis, the theoretical and practical accuracies in different media are given in Table 1, considering the acoustic velocity to be correct.

#### Acoustic velocity

The acoustic velocity is determined by means of a special tool solely in the measurement axis prior to the actual cavity survey. At each measurement point along two defined travel paths ( $s_1$  and  $s_2$ ) the differences in travel times are measured at high speed.

Referring to equation (1) the average acoustic velocity  $v$  is given as

$$v = \frac{s_2 - s_1}{\sum_{i=1}^n n^{-1} (t_{2i} - t_{1i})} \quad (3)$$

This type of measurement of travel time differences has the advantage of being able to determine the acoustic velocity with great precision over a specifically defined range. The accuracies obtained are of the order of <0.1%.

#### Depth

The final result of every cavity survey is a volume determination using all measured data. Total volume is determined from the individual cylinder segments which in turn are calculated from the horizontal sections. It is therefore necessary to investigate closely the accuracy with which the depth can be determined. The following quantities have an effect:

- accuracy of the depth recording system, <0.05%
- accuracy of the depth tie-in,  $\pm 20$  cm
- accuracy of surveyed length from depth tie-in point, <0.05%

#### Other causes of error

Other noteworthy factors which can give rise to errors are:

- compass deviation, approx.  $\pm 2^\circ$
- magnetic declination, approx.  $\pm 1^\circ$
- Coriolis force effect, approx.  $\pm 20$  cm.

TABLE 1

Accuracies

Medium	v(m/s)	g theor (cm)	g pract (cm)
		n = 1	n = 2 ... 10 (15)
Brine	1820	1.82	3.64 ... 18.20
Oil	1300	1.30	2.60 ... 13.00 (19.50)
Gas	440	0.44	0.88 ... 4.40

TABLE 2

Overview of errors

Parameter	Mean value	Mean absolute error	Mean relative error
	v, t, $\Delta h$	mv, mt, $m\Delta h$	mv, mt, $m\Delta h$
v	1820 m/s	1.82 m/s	$\pm 0.10\%$
t	50 ms	0.20 ms	$\pm 0.40\%$
$\Delta h$	600 m	0.30 m	$\pm 0.05\%$

#### Total error evaluation

Referring to the above individual error quantities of acoustic velocity, travel time and depth, an error evaluation is now made for the volume determination applying the law of error propagation.

Table 2 shows the individual error quantities for a brine filled cavity with a radius of 45 m and height of 600 m. The above accuracies for the parameters  $v$ ,  $t$ , and  $\Delta h$  are accepted as valid. It is assumed that the determination of the true signal start is accurate to within about 10 samples.

Starting with the formula for determining a cylinder volume

$$v_z = \pi r^2 \cdot \Delta h \quad (4)$$

where  $r$  is the radius of circular base,  $\Delta h$  is the height of cylinder, and applying equation (1) gives

$$v_z = \frac{\pi}{4} v^2 \cdot t^2 \cdot \Delta h. \quad (5)$$

According to the law of propagation of errors the following holds for the mean relative error

$$(mv_z)_{rel} = \pm \left[ \left( \frac{2mv}{v} \right)^2 + \left( \frac{2mt}{t} \right)^2 + \left( \frac{m\Delta h}{\Delta h} \right)^2 \right]^{1/2} \quad (6)$$

where  $v$ ,  $t$  and  $\Delta h$  are to be replaced by the corresponding mean values  $v$ ,  $t$  and  $\Delta h$  of Table 2. It follows that

$$(mv_z)_{rel} = \pm 8.3 \cdot 10^{-3} \approx 0.83\% \quad (7)$$

That means that every determined cavity volume is associated with a mean relative error of about 1%. Measurements in oil and gas filled cavities have errors of the same order.

### Measurement through the casing

Special further developments of the ECHO-LOG system have enabled the shape of cavities to be determined through one or even two casings. The quality of the survey results is greatly dependent on the media inside and outside the casing as well as on the condition of the casing itself, for example, whether it is corroded or there are surface deposits on it. The following sources of error have also to be considered.

### Direction determination

Generally the shape of the cavity is obtained from horizontal sections, the directions of which are measured with a synthetic compass. To obtain directional agreement between the sections they are turned and compared with previous sections or ones measured in parts of the cavity without casing. Directional errors greater than  $\pm 15^\circ$  cannot be ruled out.

It is also possible to use a gyro compass. In this case the accuracy of the direction determination is about  $\pm 15^\circ$ .

### Signal aliasing

As a result of ringing of the casing and defocusing of the echo beam, caused by the casing wall curvature and reflections inside the casing, multiple echoes occur dependent on the condition and type of casing. These can be attenuated or eliminated by signal correlation during the survey or by comparing the interpretation of all data referred to one direction of measurement.

### Acoustic velocity

As the acoustic velocity of the medium in the casing is normally different to that of the medium in the cavity, the velocity in the cavity is estimated by referring to past values. Comparisons between measurements with and without casing indicate total errors of about 1–5% depending on the properties of the casing.

## DETERMINATIONS OF CONVERGENCE IN GAS STORAGE CAVITIES

### Convergence

ECHO-LOG surveys are carried out nowadays in gas storage cavities at regular intervals to control convergence and shape stability. After completion of

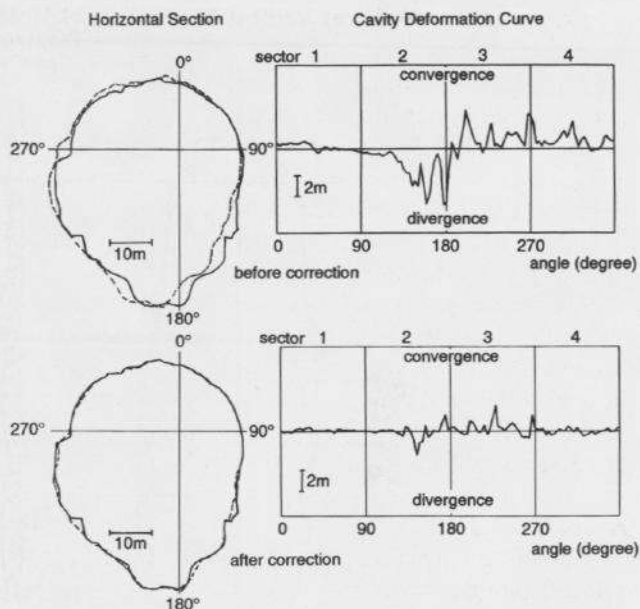


Fig. 1. Determination of convergence before and after correction.

each ECHO-LOG survey the interpreted cavity data are available in digital form as:

- horizontal sections, depth-sorted in polar coordinates with 120 angle and distance values, angle increment  $3^\circ$ ,
- vertical sections, angle-sorted in Cartesian coordinates with depth and distance values.

In order to visualize the development of the whole cavity the related horizontal and vertical sections of an old and a new survey with different signatures are plotted one on top of the other. Significant alterations of the cavity shape can be clearly recognized in this display.

The left part of Fig. 1 shows such a comparison of horizontal sections from two ECHO-LOG surveys (new: solid, old: dashed). This comparison is not suitable, however, for calculating the convergence as the amount is usually too small. Instead a numerical comparison is performed between two horizontal sections of a new and an old survey with the change in shape being plotted as the difference of the cavity radii above the measurement angle (Fig. 1, right).

In order to be able to include 'undisturbed' parts of the cavity in convergence determinations the horizontal section is divided into 4 or 8 sectors and the average displacement (convergence positive) as well as scatter of each sector are calculated. In addition the mean wall displacement for the entire horizontal section is calculated.

It is possible that between the two surveys, which are often separated by a period of more than six years, there are systematic errors, for example a

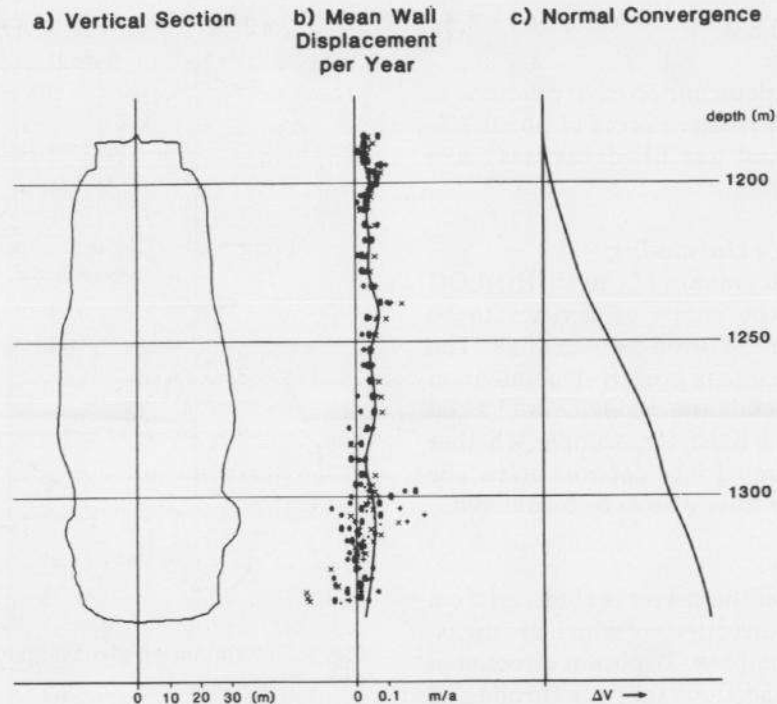


Fig. 2. Cavity shape and convergence versus depth.

shift in the survey axis or an angular rotation.

The advantages of digital processing of cavity survey data are highlighted particularly well here. Use of trial and error enables the optimum shift or rotation, which must be the same for all horizontal sections, to be quickly calculated and corrected. In the interpretation method developed by Pipeline Engineering GmbH only the old survey results are rotated or shifted as the new survey data are better than the old both technically as well as by definition.

In Fig. 1 the individual sectors exhibit considerably less convergence after an angle correction of  $-7^\circ$  than they did before the correction.

Figure 2b shows for the eight  $45^\circ$  sectors the wall displacement calculated from the horizontal sections after applying the corrections as well as the mean value of the whole section as a function of depth. These new mean values were plotted in four different signatures, ie in each case the values of two related  $45^\circ$  sectors were subjected to the same signature. If the mean is divided by the period between the two surveys the amount of wall displacement per year is obtained. In this case it is of the order of centimetres. By interpreting the calculated wall displacement and its scatter, which amongst other things is a measure of the wall roughness, the typical annual wall displacement can be found as a function of depth. For control purposes the so-called normal convergence for the whole cavity is calculated from this (Fig. 2c). Using a trial and error method the

mean wall displacement, and with that the cumulative normal convergence, is made to agree with the observed difference in volume. This is worthwhile only if no sloughing is indicated; this is discussed below.

A comparison of the shape and convergence of the symmetrical cavity shown in Fig. 2 indicates that:

- the cavity shape is very stable,
- the average wall displacement as a function of depth is not simple,
- the most scatter occurs in cavity zones which greatly deviate from the vertical,
- measurement errors, such as small differences in depth between the surveys, show up particularly in zones where the cavity walls are steeply inclined.

#### Shape stability and convergence

Until now the cavities considered have been in salt deposits with near horizontal layering. In salt domes, however, the conditions are different; here steeply dipping salt layers are predominant. Determination of convergence is now described for such conditions in cavities at depths from 1500 to 1800 m. As a result of these greater depths and the higher ambient temperatures larger convergence occurs.

Figure 3 shows an example of convergence determination in cavities with irregular cross-sections. Comparison of two horizontal sections indicates a change in shape to the east (Fig. 3a, dashed). To clarify whether or not this is associated with slough-

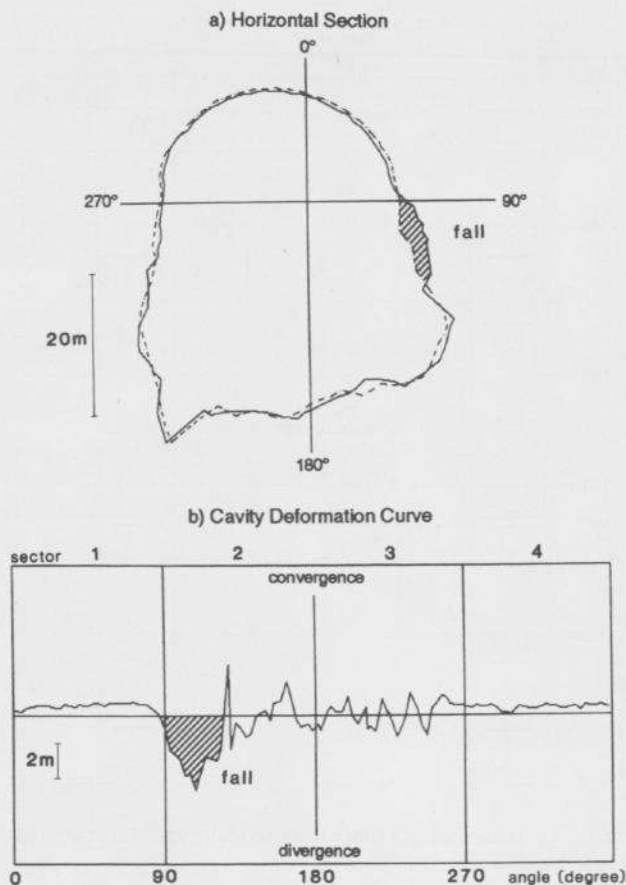


Fig. 3. Determination of convergence for irregular cross-section cavities.

ing, reference must be made to the overlying and underlying horizontal sections to see whether this change could have been caused by inconsistent interpretation or by any systematic differences in the measurements.

Inconsistent interpretation can be detected by comparing the respective raw data. If necessary the horizontal sections are reinterpreted. This work is justified because, to determine the convergence and shape stability, and with that the salt behaviour, it is necessary to eliminate as many error sources as possible. This in turn helps to improve the convergence model of the cavity.

Checks revealed that sloughing did in fact exist in the cavity of Fig. 3. If sloughing or changes in shape are indicated by interpretation, then the size of horizontal sections to be compared must be numerically determined (partial or total area). This enables sloughed areas to be calculated and also, by considering the depth, the sloughed volume.

The unsymmetrical cavity shape in Fig. 3 with a maximum extension to the south causes the measurement accuracy and quality of interpretation to vary considerably; in the north it is good, in the south

poorer. The corresponding wall displacement curve (Fig. 3b) shows the sloughing in sector 2 as divergence. A nearby convergent point is mainly the result of a small difference in the angle of the two measurements (angle tolerance and compass deviation).

This clearly demonstrates the limitations of the ECHO-LOG method for determining the convergence. At the same time it is realized that useable wall displacement values can be determined from sectors 1 and 4. Even in structured parts of the cavity the described interpretation technique enables the typical annual wall displacement to be determined as a function of depth.

Figure 4 shows the typical wall displacement for two adjacent cavities in a salt dome; both cavities were subjected to comparable stresses during injection and recovery procedures. The change of convergence with depth is different in both cavities, which indicates that the flow characteristics of the salt vary throughout the region. Such information makes it possible to determine optimum injection and recovery procedures in gas storage cavities for given operating gas movements.

In principle the normal convergence can be determined even when intense sloughing has taken place.

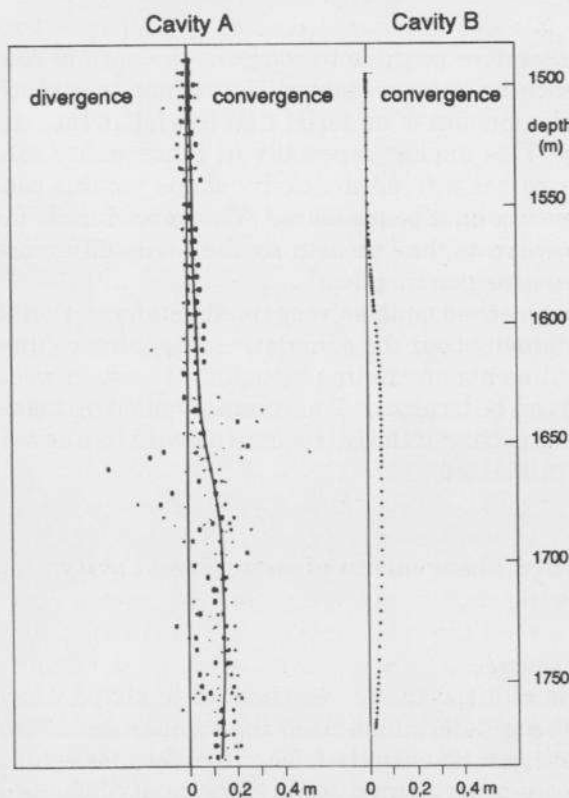


Fig. 4. Typical wall displacement per year for two cavities in a salt dome.

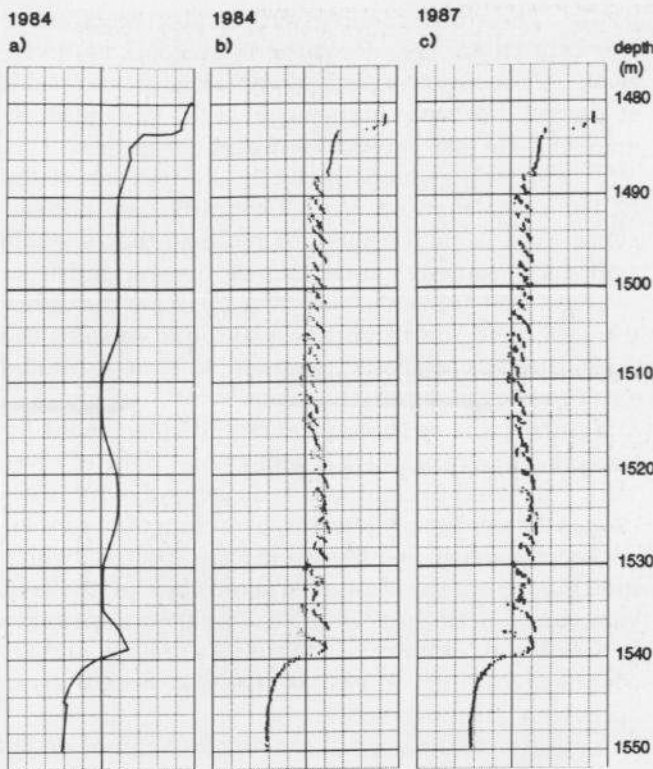


Fig. 5. Structured cavity wall area vertical sections for detailed investigations.

It is therefore possible to compare the normal convergence and the measured divergence to investigate the amount of material that has fallen into the cavity. This applies especially in zones where convergence has altered the cavity shape yet this convergence cannot be measured. This procedure is far more accurate than measuring the cavity difference at the corresponding depth.

This method enables very reliable information to be obtained about the cumulative sloughing volume as well as about existing sloughing zones, i.e. weak zones can be localized. The volume of piled up material at the base of the cavity can likewise be numerically calculated.

#### Detailed observation of structured cavity zones

##### *Cavity wall*

It is realized that some changes in shape which have been determined from the comparison of two surveys can be entirely false. Therefore for control purposes in structured zones of the cavity Echo-profile-logs are measured in one direction which yield a detailed image of the cavity wall.

Figure 5 shows an example of a detailed investiga-

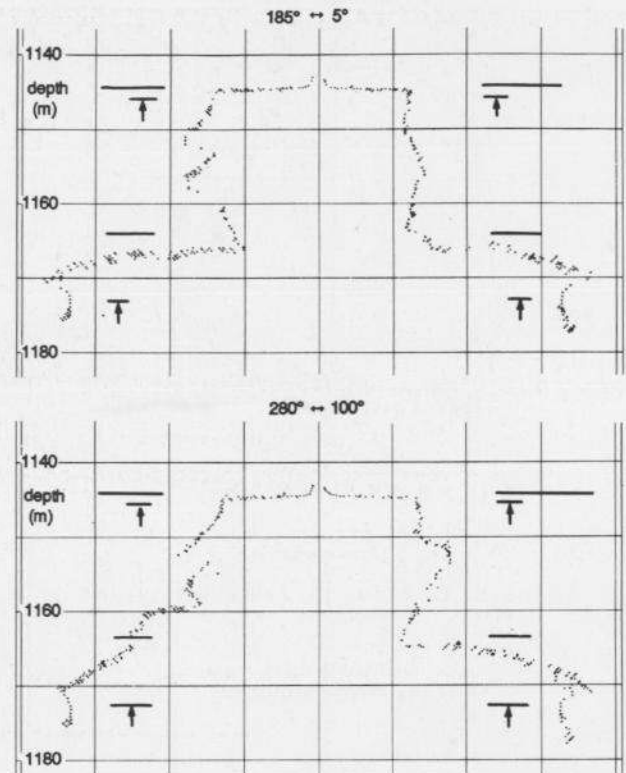
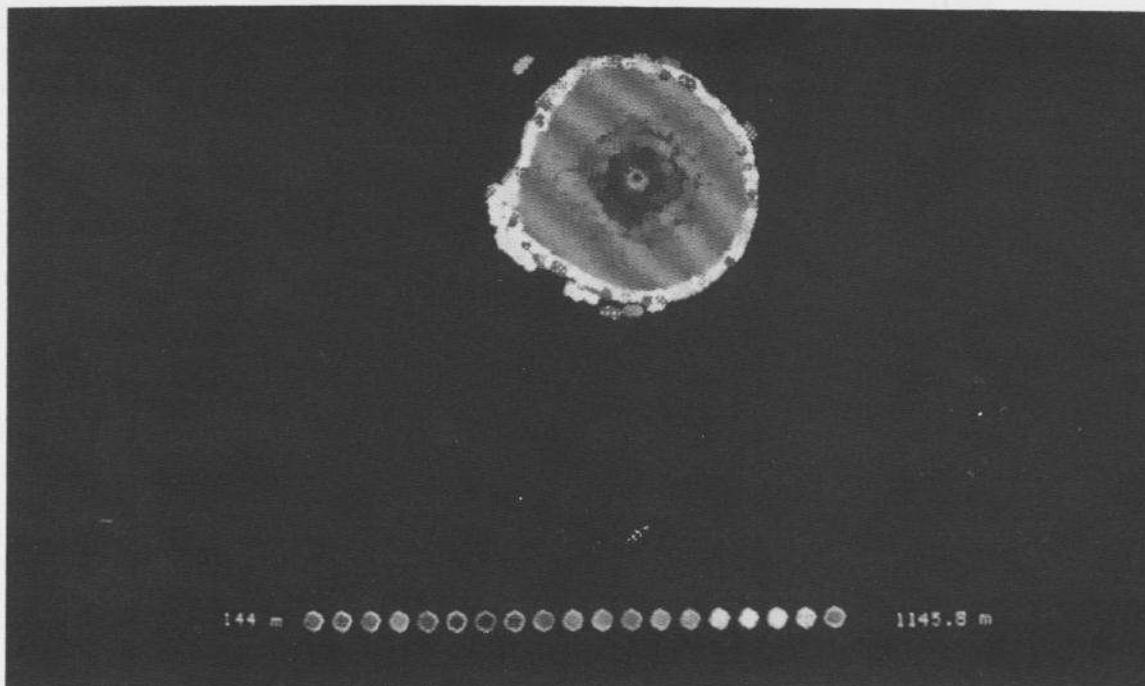


Fig. 6. Structured cavity roof area vertical sections for detailed investigations.

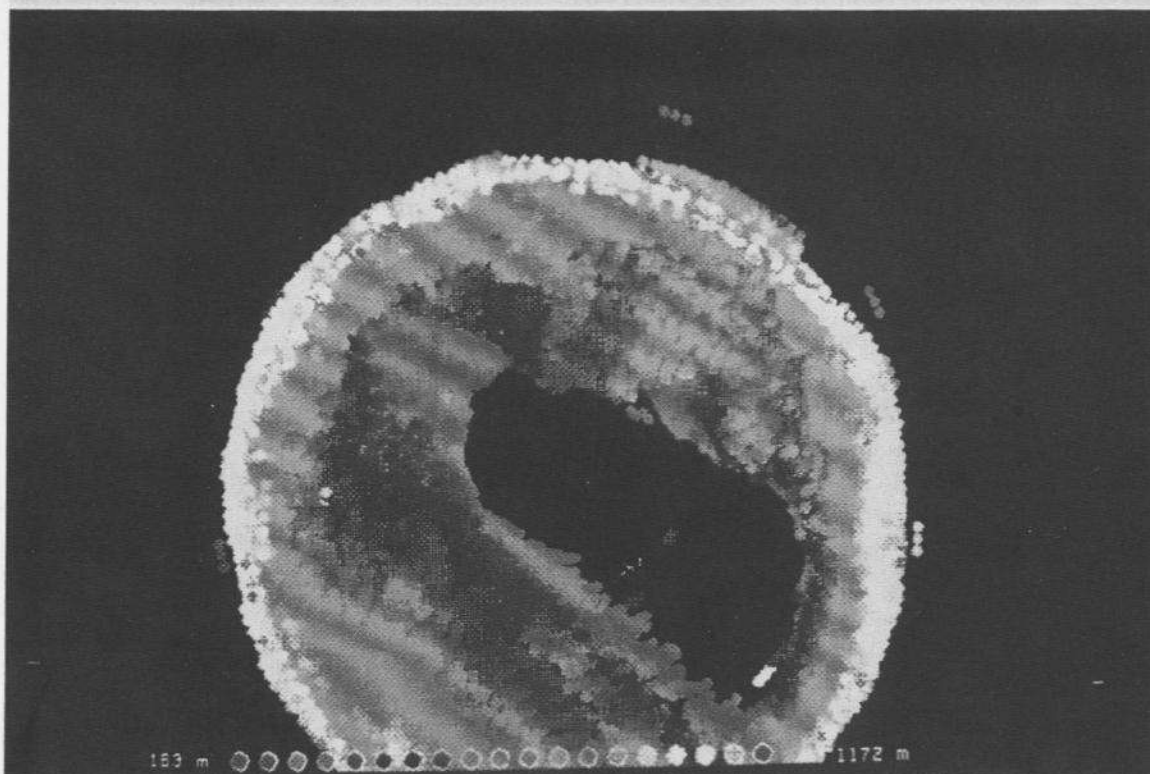
tion of a cavity wall. Two surveys are compared here that were recorded in 1984 and 1987.

The curve in Fig. 5a shows the conventionally surveyed cavity wall obtained from the interpretation of horizontal sections in the vertical part of the cavity and inclined sections in the cavity roof area. A detailed view (Fig. 5b) yielded by measuring the wall at 20 cm depth intervals and a 20  $\mu$ s sampling rate with the horizontal transducer reveals the flaky structure of the cavity wall. The salt flakes protrude by as much as 2 m from the wall at inclinations of 40–60°.

A follow-up survey three years on was carried out to establish whether or not this zone of the cavity was liable to sloughing or rock falls. The detailed survey of 1987 confirmed the stability of the cavity wall (Fig. 5c). However, just a small difference between the measurement depths of the two surveys would give completely different results if just the image gained from the interpreted horizontal sections were used. These results depend on whether the reflections return from the front or rear edge of the flake structures. Changes in shape would then be apparent; the detailed examination proved these to be non-existent. Despite strongly a structured wall the cavity is stable. This underlines the usefulness of such detailed investigations.



a) Contour Map for Depths between 1144,0 m and 1145,8 m,  $\Delta z = 0,1$  m



b) Contour Map for Depths between 1163,0 m and 1172,0 m,  $\Delta z = 0,5$  m

Fig. 7. Contour maps of structured cavity roof.

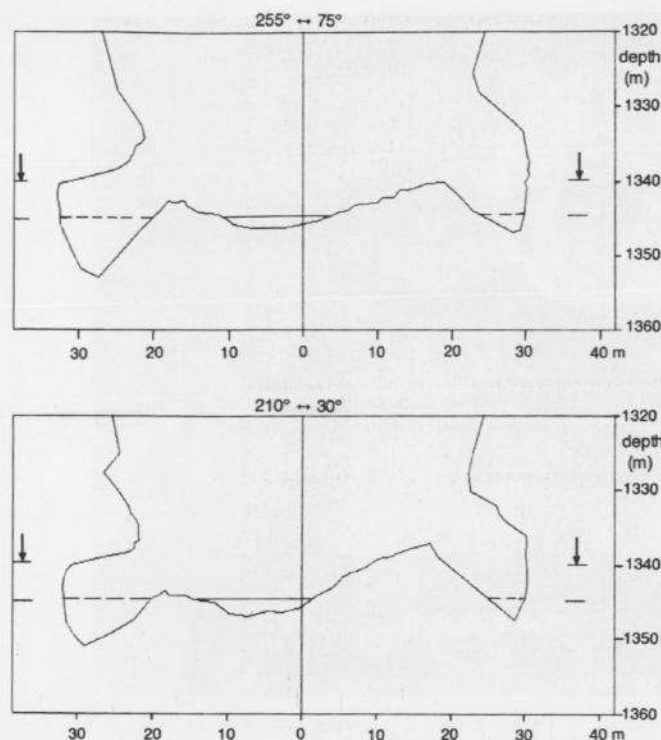


Fig. 8. Structured cavity bottom area vertical sections.

#### Cavity roof area

Particularly interesting areas of a cavity can therefore be closely examined by detailed surveys. When more than just a specific azimuth range is of interest SPIRAL-LOG measurements (continuous vertical movement and simultaneous rotation of the survey tool) of parts of the cavity have proved valuable. The required measurement point density of the part of the cavity of interest can be regulated through the tool speed. SPIRAL-LOG measurements can be made with the transducer horizontal or with it tilted upwards or downwards.

Detailed surveys of a complicated, structured cavity roof area were made using SPIRAL-LOG measurements with the ultrasonic transducer tilted and horizontal. The resulting data-set comprised more than 30 000 values. From this vast amount of results vertical sections were calculated; two directions of which are shown in Fig. 6.

Although these are raw data the complicated cavity shape can be easily followed. Such additional information proves to be of use also for interpreting the horizontal sections. And of course any possible changes in shape in this part of the cavity can be recognized and evaluated only when the original shape is known.

To obtain an even better overview of this part of the cavity it is possible to move about as an observer inside and outside the cavity with computer aid and

examine specific surfaces (marked by arrows).

Figure 7a shows the cavity roof in 18 colours each with a thickness of 0.1 m between 1144.0 and 1145.8 m. Leaching has been very even, as can be seen from the almost concentric depth rings.

In Fig. 7b the individual depth layers at intervals of 0.5 m in the intermediate roof area between 1163 and 1172 m can be well recognized. With the aid of depth layer curves it is possible to determine the surfaces and volumes of complicated shapes considerably better than before.

#### Cavity floor area

The question that needed to be clarified here was whether in the structured cavity floor, of which two vertical sections are shown in Fig. 8, the gas/brine interface had settled to the same depth over the whole floor area after the cavity was filled with gas. This is very important for the determination of the gas-filled cavity volume. Measurements were carried out using the SPIRAL-LOG technique with the measuring head tilted downwards by about 45°. The tool was then raised from a point just above the gas/brine interface at a speed of 0.5 m/min until the entire floor of the cavity had been sampled. Determination of the brine distribution in the cavity floor area was calculated from a so-called depth layer map.

In Fig. 9 ten depth layers each 0.5 m thick between 1340 and 1345 m are shown in different colours. As in this case the ultrasonic signals from the gas/brine interface are reflected away from the axis of incidence no reflections can be assigned to this depth range if brine exists.

#### SUMMARY AND OUTLOOK

By considering the accuracy it is possible to show that the development of the convergence as well as the stability of a cavity can be observed by means of ECHO-LOG measurements. Computer-aided interpretation of large amounts of data enable unequivocal statements to be made about the displacement of the cavity wall and consequently the behaviour of the salt at various depths can be derived. This information allows a prediction to be made about the long-term changes in the cavity shape.

If a cavity is completely surveyed a number of times with the SPIRAL-LOG technique over a period of time, best fits of the cavity can be formed. In each case the volume difference, which is equivalent to the volume convergence, is computed from the best fit of two individual highly resolved 3D cavity configurations. In this way errors in the depth determination as well as in the azimuthal direction determination can be minimized. These investigations are still to be completed.

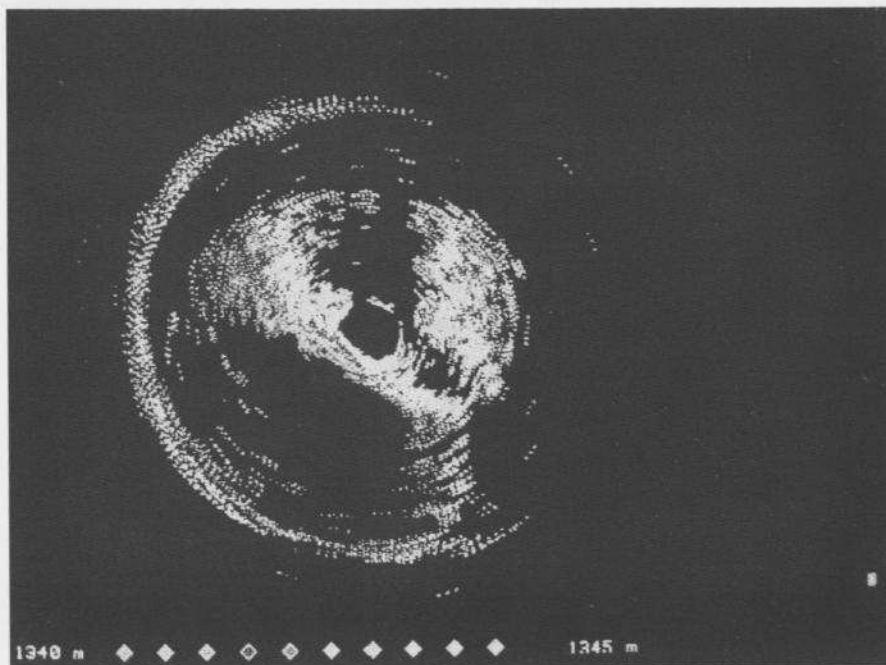


Fig. 9. Contour map of structured cavity bottom area for depths between 1340 m and 1345 m,  $\Delta z = 0.5$  m.