Mining Subsidence in the East Netherlands

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ABSTRACT

A method for forecasting the vertical and horizontal movements of points at the surface owing to mining subsidence has been developed for the special case of the Hengelo field. All possible data were collected and studied of a first case of caving-in of cavities created by the solution mining of salt. A theory was set up to explain two striking differences with other subsiding areas, i.e. the duration in time of the subsidence and the small area influenced at the surface in relation to the depth of the cavity mined out. Special attention is paid to the behavior of the Triassic claystone formation ("Red Beds") above the salt layer. In 1973 this theory was used to predict the rate of subsidence of a second case for the forthcoming 10 years' period. This second area of subsidence was situated just under a new brine purification and vacuum plant. For each part of the installation within this area the predicted movement was calculated in time. With these figures it was possible to arrange a long-term planning for preventive maintenance and by doing so to keep the complete plant operating.

INTRODUCTION

In 1918, KNZ started solution mining of salt in the Boekelo area, East Netherlands (Fig. 1). In 1933, KNZ moved to the nearby Hengelo area because of better transport facilities available after the Twente-Rijn canal had been dug during the time of the economic crisis.

The total production of salt in Boekelo amounted to about 1,445,000 metric tons from eight single production wells. The production in Boekelo was ceased in 1952. In our 1977 leveling no subsidence whatsoever was measured.

In Boekelo and Hengelo the geological profile down to the base of the salt is about the same and given in Figure 2. The Quaternary and Tertiary formations consist of an unconsolidated very plastic clay with only some sand in the upper thirty meters. The Triassic begins directly under this clay at a depth of about 120 meters with the Muschelkalk marl. Only in the northern part of the Hengelo concession is this Muschelkalk missing. Below the Muschelkalk we find the Upper Bunter claystone or "Red Beds" with the Rötsalt Formation at their base with an average thickness of 50 meters. The Red Bed claystones are dry, tight and impermeable. This formation is very consistent throughout the whole concession with a thickness of 180 meters. Figure 3 gives an idea of the depth, strike and dip of the top of the salt. The strike is northwest - southeast with a dip of about six degrees towards the southwest.

In 1963 the first subsidence was measured at area 1 (Fig. 3), just within the Muschelkalk border. Ten years later a second case of subsidence occurred in area 2 just a few hundred meters to the north and just outside the area of the Muschelkalk deposit. Unfortunately this second subsidence was situated under the new brine purification and vacuum plant.

The ten years' lapse between these two cases provided an opportunity to thoroughly study the behavior of area 1. Armed with this knowledge, it was possible to predict the second subsidence and to prevent severe damage to the salt production plant.

SUBSIDENCE CASE 1

Well number 18 was drilled in area 1 in 1949 and followed in 1951 by well number 24 at a distance of only 25 meters (Fig. 4). Both wells were taken out of production in 1958, 5 years before any subsidence was measured. It is difficult to trace accurately the production of salt from each individual well because of the numerous connections existing between the cavities of neighbouring wells. In total the wells 16 to 22, plus well 24, all more or less situated in area

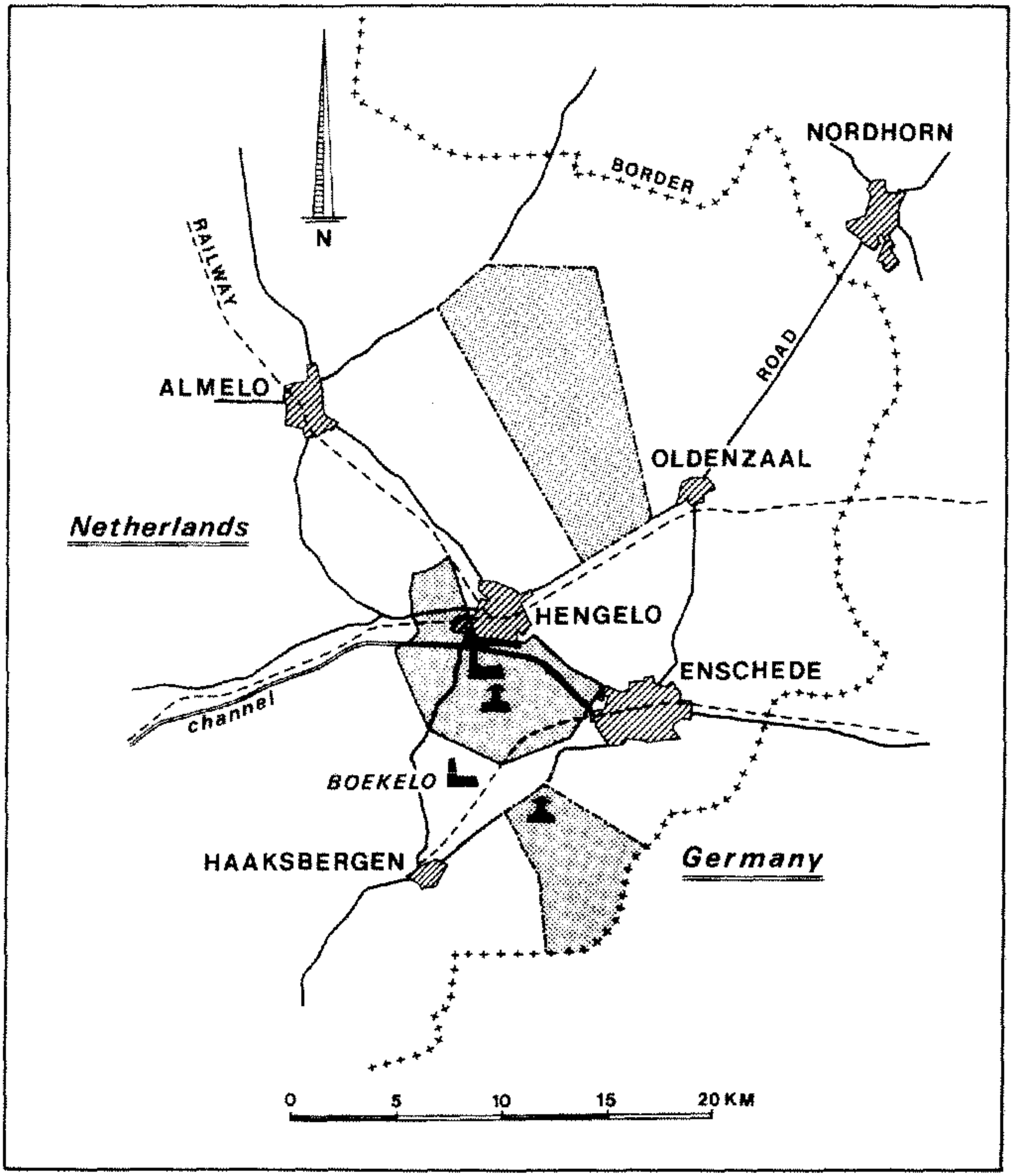

Figure 1. Akzo salt concessions in east Netherlands.

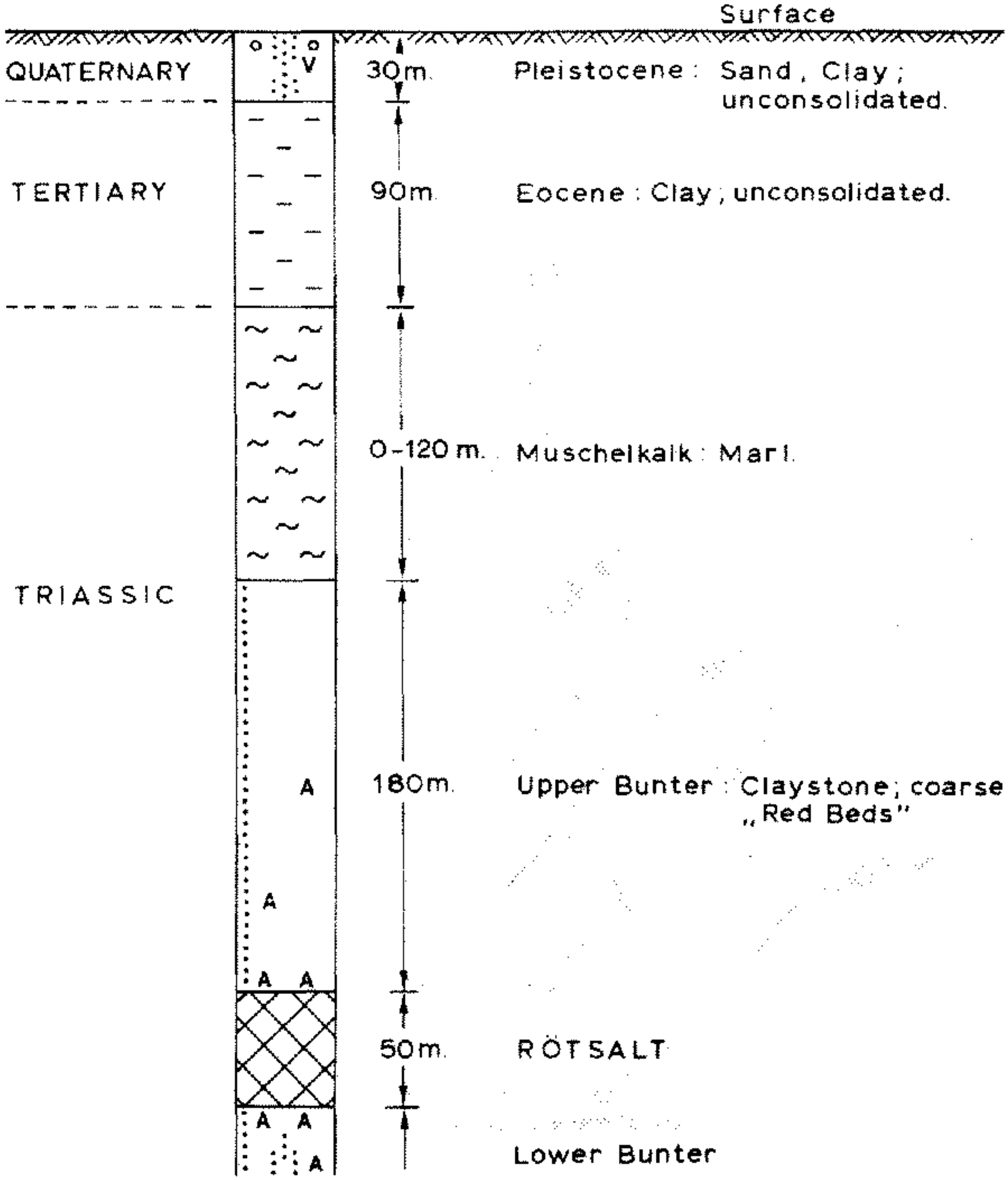

Figure 2. Geological profile of the Akzo concession "Twenthe Rijn", east Netherlands.

1, have produced 1,385,000 tons of salt. This is about the same tonnage of salt from an equal number of wells in Boekelo, but in Hengelo the production rate is higher and the cavities are interconnected as can be seen in Figure 4. In this figure the cavity diameter is also reproduced on the basis of calculations after production figures, while assuming the shape of an inverted cone. Then in our second half-yearly periodical measurements in 1963, a subsidence of 30 centimeters or 12 inches was found in comparison with the first measurement in 1963. In Figure 5 the results are given for the first four years. The bench marks 44 to 56 pass through the center of the subsidence bowl at centers of about 20 meters. The vertical movements are given in millimeters. In 1966 the subsidence measured in the center was about 64" or 1,625 mm. The horizontal displacement of the bench marks or the strain is given in millimeters per ten meters of length. The measurements showed similarities with subsidence figures for the Dutch coalfields under static conditions of the winning front, as can be seen in this figure by the stable zero strain point.

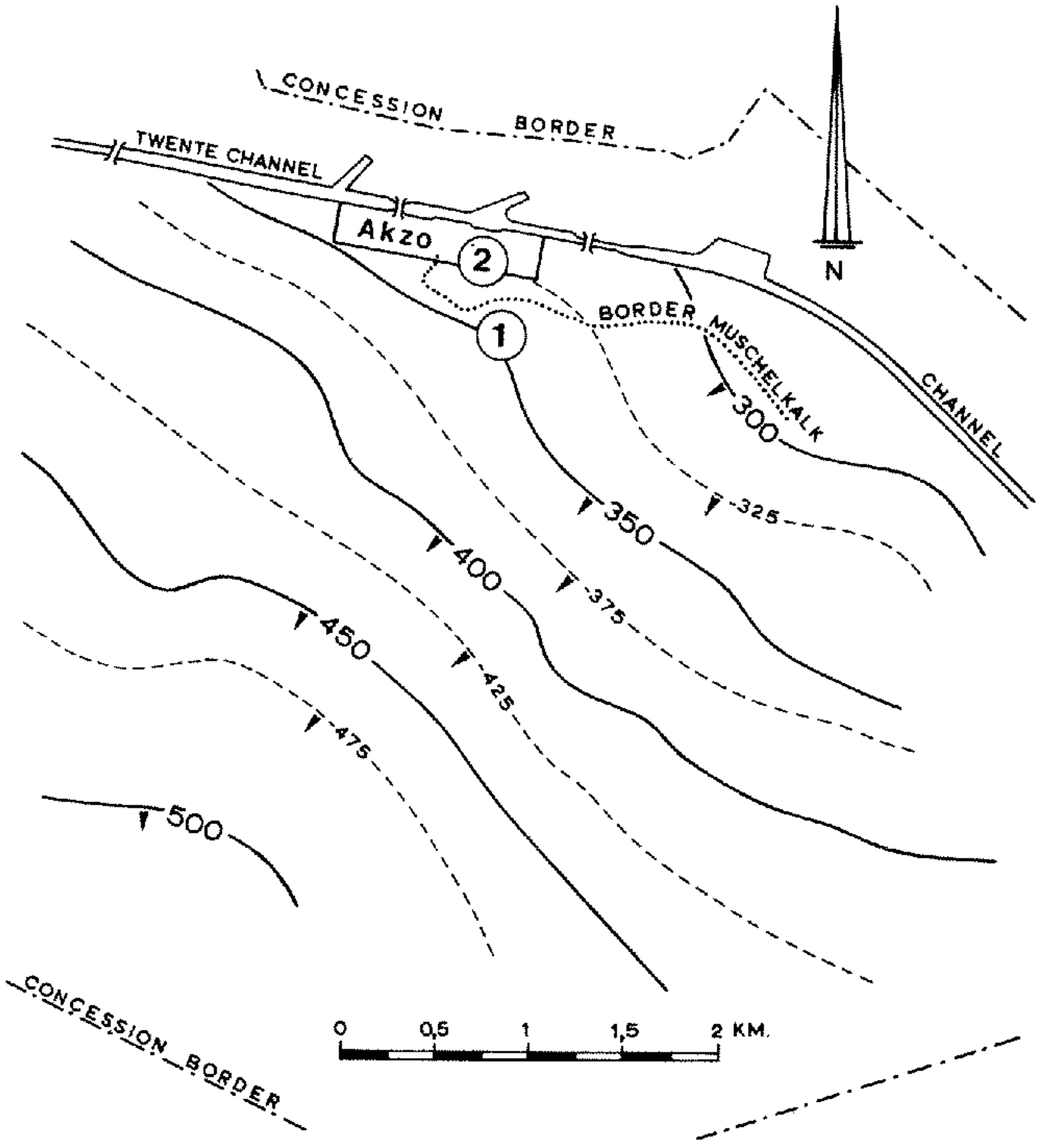

Figure 3. Structure map on top of the Hengelo salt with the areas of subsidence 1 and 2.

There were, however, two great differences, the duration in time of the subsidence and the small area influenced at the surface in relation to the depth of the cavity. As the coalfield practice showed movements at the surface ended after about two years. In the Hengelo case however, the subsidence has lasted for years. At this very moment, after 15 years, a vertical displacement of about 5 cm or 2" is still measured in the center of the bowl every year.

Unfamiliarity with what actually was happening in the underground made KNZ decide to drill an exploration well between wells 18 and 24 in this area. After the Triassic formation had been reached, great difficulties were encoun-

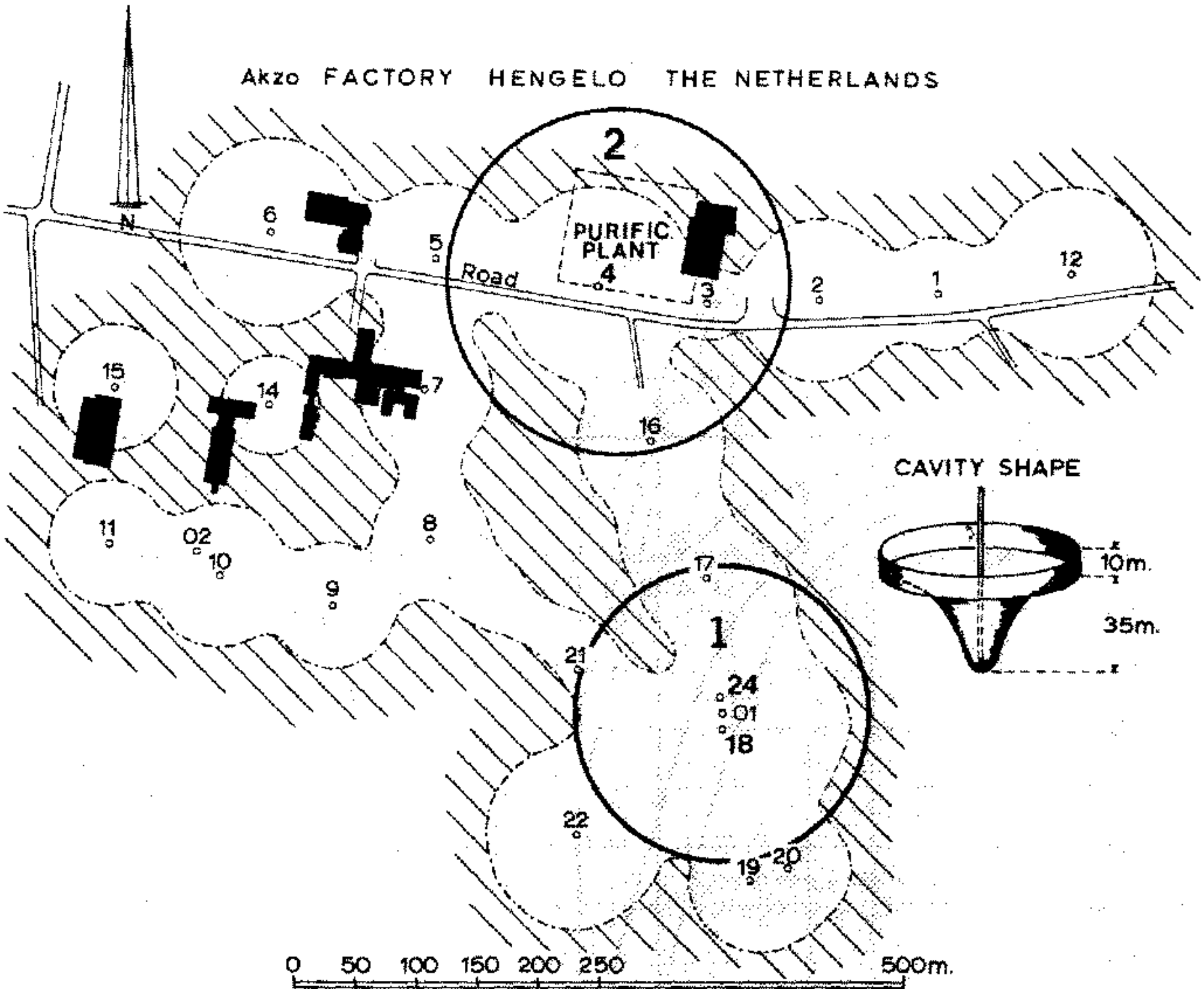

Figure 4. Reconstructed cavities based on salt production figures, Akzo Hengelo, Netherlands.

tered owing to a complete loss of circulation. As consequence no cuttings reached the surface. Several cores were taken to trace the guide horizons. In total 68.40 meters were cored with a recovery of 65.3%, whereas normally a recovery between 95% and 100% is obtained in these formations.

The drilling was even successful in reaching the undisturbed and still undissolved base of the salt, as can be seen in Figure 6. Between wells 18 and 24 some 8 meters of rock salt were found. Figure 6 shows the reconstructed original geological profile between wells 18 and 24 before any subsidence, in comparison to the profile actually found in this exploration well 01. The most noteworthy guide horizons have been marked in this figure. In this well a vertical displacement of about 26 meters was found at a depth of 340 meters, whereas the subsidence at the surface amounted to only 1.85 m at the same time.

The following conclusions could be made after completion of the exploration well 01:

1. The Quaternary and Tertiary clay formations are plastic enough to avoid rupture or faulting.
2. The Triassic formations Muschelkalk and Upper Bunter are completely broken. Open spalts and small cavities of several meters could be traced during drilling and logging.
3. A cavity in the salt layer was not found because of the collapsed roof.

Because the cavity collapsed several years after the shut-down of the wells, the structural failure of the roof rocks is due to more than the big span of this roof. There must be another reason. The Bunter Red Beds can easily be

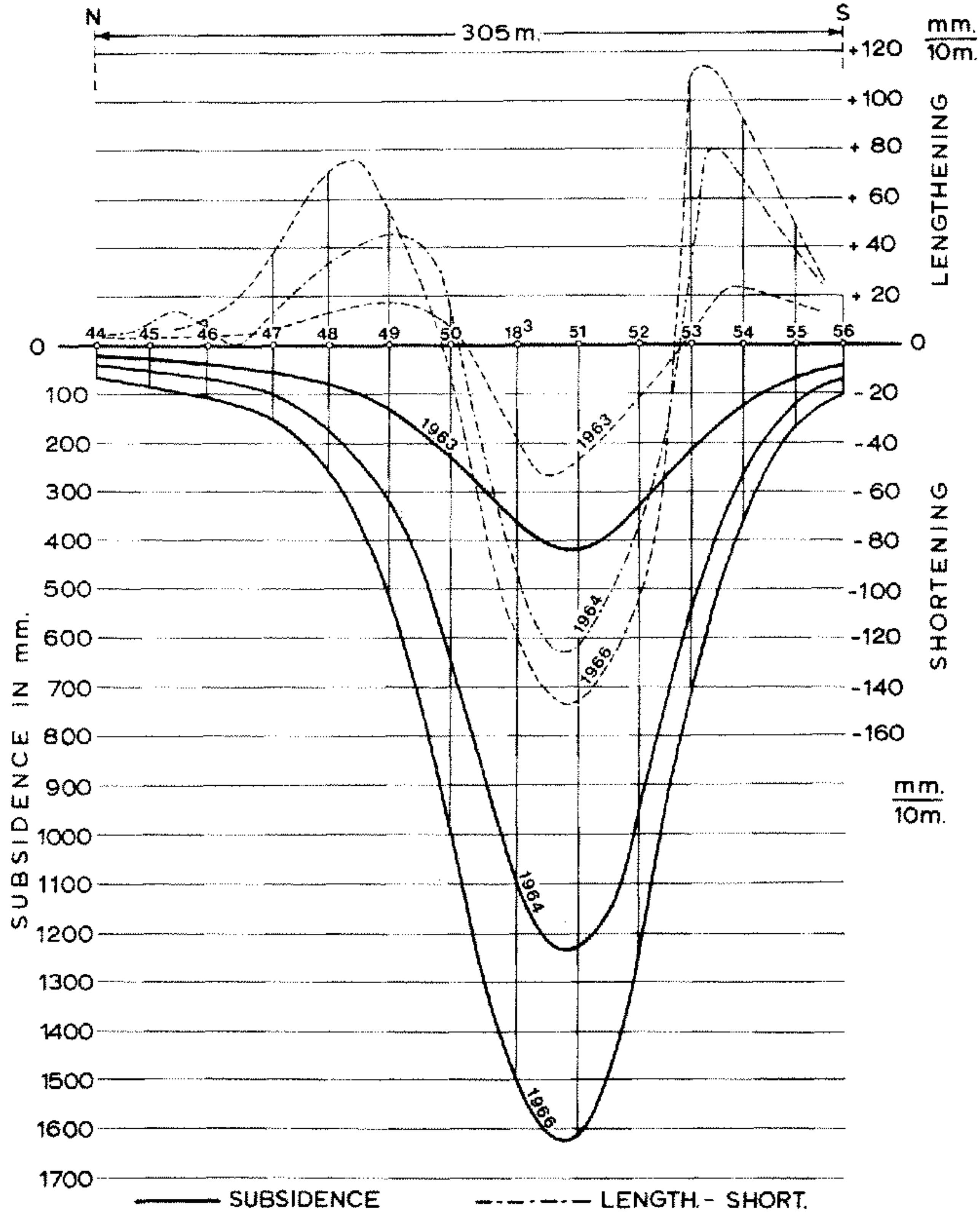

Figure 5. Results of measurements of the horizontal and vertical displacements of bench marks in area 1 during the period 1963–1966.

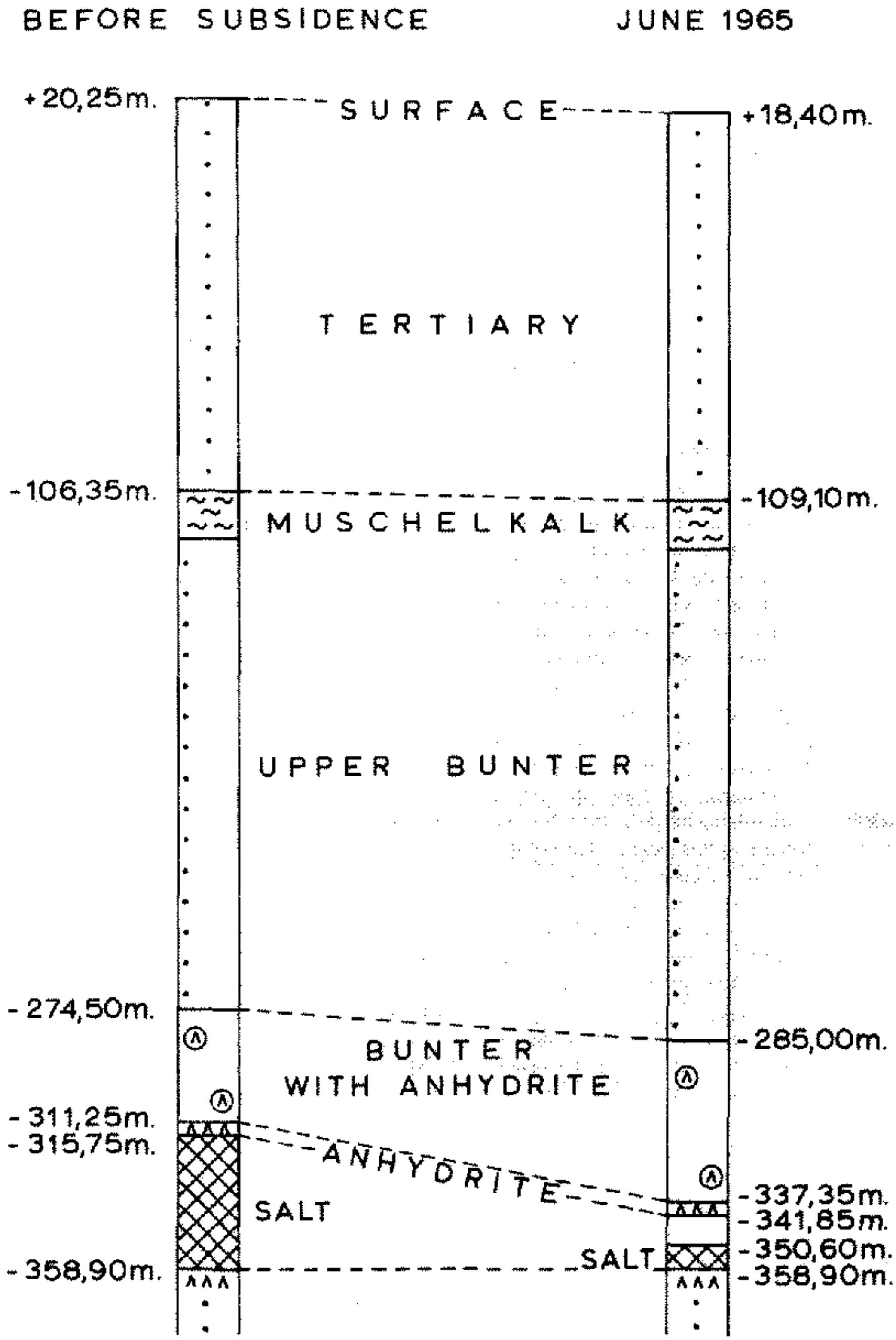

Figure 6. Geological profile of the Akzo Well 01 after 2½ years of subsidence.

moistened by water or brine so that the claystone loses its structural strength. As has been noticed before in other abandoned but not plugged wells, the roof of the cavities will collapse in beds of about 10 to 30 meters thickness over the years.

In 1963 the caving could finally reach the unconsolidated Tertiary clay. From that moment on a pronounced subsidence was measured on the surface. After a certain amount of time the subsidence is no longer directly related to the caving of the roof formations. The compaction of the rubble in the disturbed layers will be responsible for a very slow decreasing but long-lasting subsidence at the surface. Nevertheless the small area influenced at the surface with a diameter of only 270 meters could not be explained in relation to the depth of the original cavity at 340 meters (angle of draw).

SUBSIDENCE CASE 2

In 1973 subsidence was measured in a second case during the periodic leveling. The center of this new area was situated near the old well 4. After a year of thorough measuring this new situation could be judged and the similarities and differences be seen between this case and case 1. The geological profile of well 4 is about the same as that of wells 18 and 24. Only the 15 meters of Muschelkalk are absent here.

Well 4 was taken out of production in 1959. By that time this cavity had connected to several other cavities and was situated in the middle of a T-crossing (Fig. 4). From the salt production figures and the history of repair jobs on this well, it was known that the dissolving height in the salt layer had been lost very fast. Because of this fact the shape of the cavity will look like a small inverted cone. The connections to the neighbouring wells were made just under the roof of the rock salt. This means that the cavity of well 4 had less space for storage of broken rock material. It was no surprise, therefore, that a much slower rate of subsidence was measured at the surface in this area.

Figure 7 shows the difference in the subsidence rate of two similar bench marks in both areas. By similar bench marks are meant bench marks at the same distance from the center of the subsidence bowl. As can be seen in this figure, the subsidence rate of area 1 is much higher in comparison to that of area 2 for the first three years. After three years the rate in area 1 has decreased to a more or less constant figure of about 80 mm a year. In area 2 the rate of subsidence has stabilized for the time being at a figure of about 60 mm a year after the same period of three years. In area 2 the same comparably small area of influence was found also.

From laboratory experiments on cores, a maximum advisable diameter of about 80 meters was calculated for the cavities in the Hengelo field. However, in these calculations changes in the mechanical properties owing to wetting of the roof formations, and especially the Red Beds, were not considered. Now it is known that water or brine will penetrate into the normally tight and impermeable claystones owing to capillary forces. But it is thought to be possible only in an upward direction where the internal stresses are more or less released owing to undercutting by the open cavity. The walls of the cavity are still under the influence of the overburden pressure and not accessible for penetrating fluids. This process will creep slowly but steadily upwards depending on the height of the capillary action, and bed after bed of the roof formations will collapse into the cavity. There is some proof from logging in old, but still accessible wells, that this process actually takes place.

Eventually this leads to the following picture of the underground developments (Fig. 8). The moistening of the roof rock above the existing cavity will create a chimney filled with broken rock material. Depending on the storage capacity of the cavity, this chimney either will reach the unconsolidated formations or not. If the unconsolidated clay is reached, a normal subsidence bowl will develop with a slope equal to the angle of draw of 45 degrees for this kind of rock. This explains the relatively small area of influence in relation to the depth of the original cavity. The plane of break or fracture has been found at a much steeper angle. This plane intersects the surface at a line connecting the points of the largest extension. This angle is about 80 degrees in the Hengelo field. If one reckons with a 15% swelling of the claystone by moistening, with a cavity shape of an inverted cone and the calculated volume of 360,000 cubic meters for well 4, this cavity can just store the whole Triassic cylindrical column. So in this case, the slow rate of subsidence measured is caused by the compaction of the rubble pile above the cavity. The base of the unconsolidated Tertiary clay is found at a depth of 135 meters. Using the angle of draw of 45 degrees (more or less the same angle as has been found in the Dutch coalfields), the radius for the area influenced can be calculated to be about 135 meters. This figure is in extremely good correspondence with the figure actually found in both cases.

Considering this theory and the differences between the two cases, an attempt was made to forecast the vertical and horizontal movements at the surface in area 2 for the subsequent ten years' period. This task was of utmost importance in keeping the salt factory running. The purification plant, quite an intricate plant, is built on an overflow principle and flow directions would be reversed due to the subsidence. Numerous pipelines would be subjected to horizontal forces so that measures had to be taken to avoid rupture of these pipelines.

Table 1 shows some of the predictions made in 1974. In the first column the measured subsidence of bench mark 18^3 in area 1 is shown, while in the next column it is compared with the predicted subsidence of bench mark H in area 2, both for the first ten years' period. Finally, the last column gives the actual measured subsidence of bench mark H until

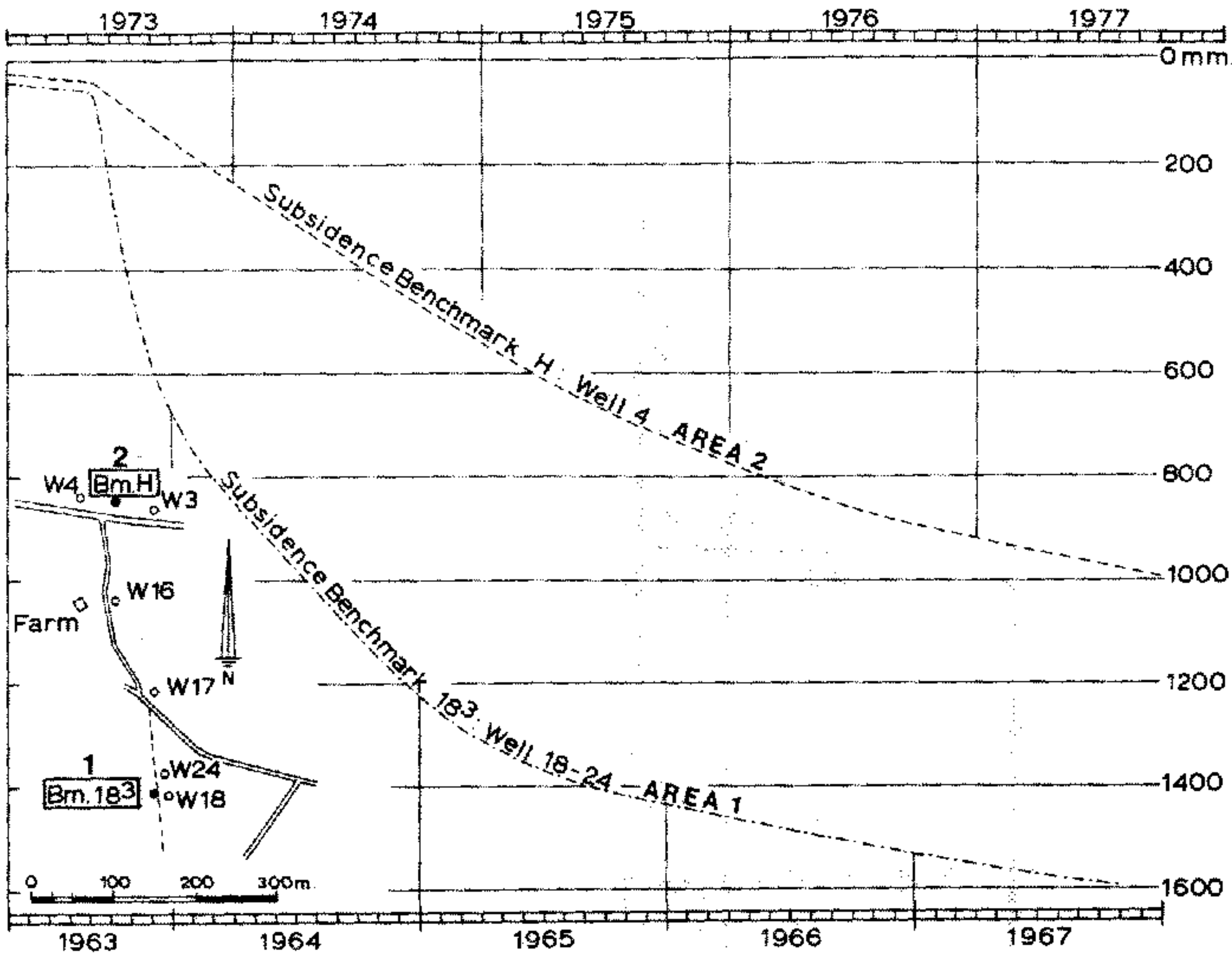

Figure 7. Comparisons of the rate of subsidence of bench marks in the two subsiding areas, Akzo Hengelo, Netherlands.

1978. Of course, there was no prediction for only one point in the subsiding area. Figure 9 gives the predicted subsidence for a line from the center of the bowl towards the east compared with the subsidence profiles actually measured over the same line. The subsidence in this area started in May 1973, so the September 1977 line is already nearly half the prediction. However, by this time the volume of the subsidence bowl is only 17% of the volume of the original cavity.

Figure 10 is a very simplified layout of the purification and the vacuum plant. In this plan the predicted figures are given for the angle of tilt in minutes and for the shortening and lengthening in millimeters per five meters of length at the surface. The figures are given for circular areas around the center of subsidence. It is an idealized situation, because in reality the subsidence bowl has more or less the shape of an ellipse with its longest axis in the northeast-southwest direction. This direction coincides with the direction of dip of the salt layer.

TABLE I
Prognosis of the Subsidence of Bench Mark H (Area 2) Over the Period 1973–1983 in Comparison with the Subsidence Actually Measured of Bench Mark 18^3 (Area 1) in the Period 1963–1973

Bench Mark 18^3		Bench Mark H		
Year (1a)	Actually Measured (1)	Year (2a)	Prediction (2)	Actually Measured (3)
1962	21 mm	1972	21 mm	21 mm
1963	653 mm	1973	311 mm	311 mm
1964	533 mm	1974	300 mm	299 mm
1965	207 mm	1975	200 mm	113 mm
1966	99 mm	1976	125 mm	94 mm
1967	82 mm	1977	75 mm	
1968	82 mm	1978	64 mm	
1969	81 mm	1979	60 mm	
1970	81 mm	1980	60 mm	
1971	80 mm	1981	60 mm	
1972	80 mm	1982	60 mm	
1963 thru 1972	1,978 mm	1973 thru 1982	1,315 mm	

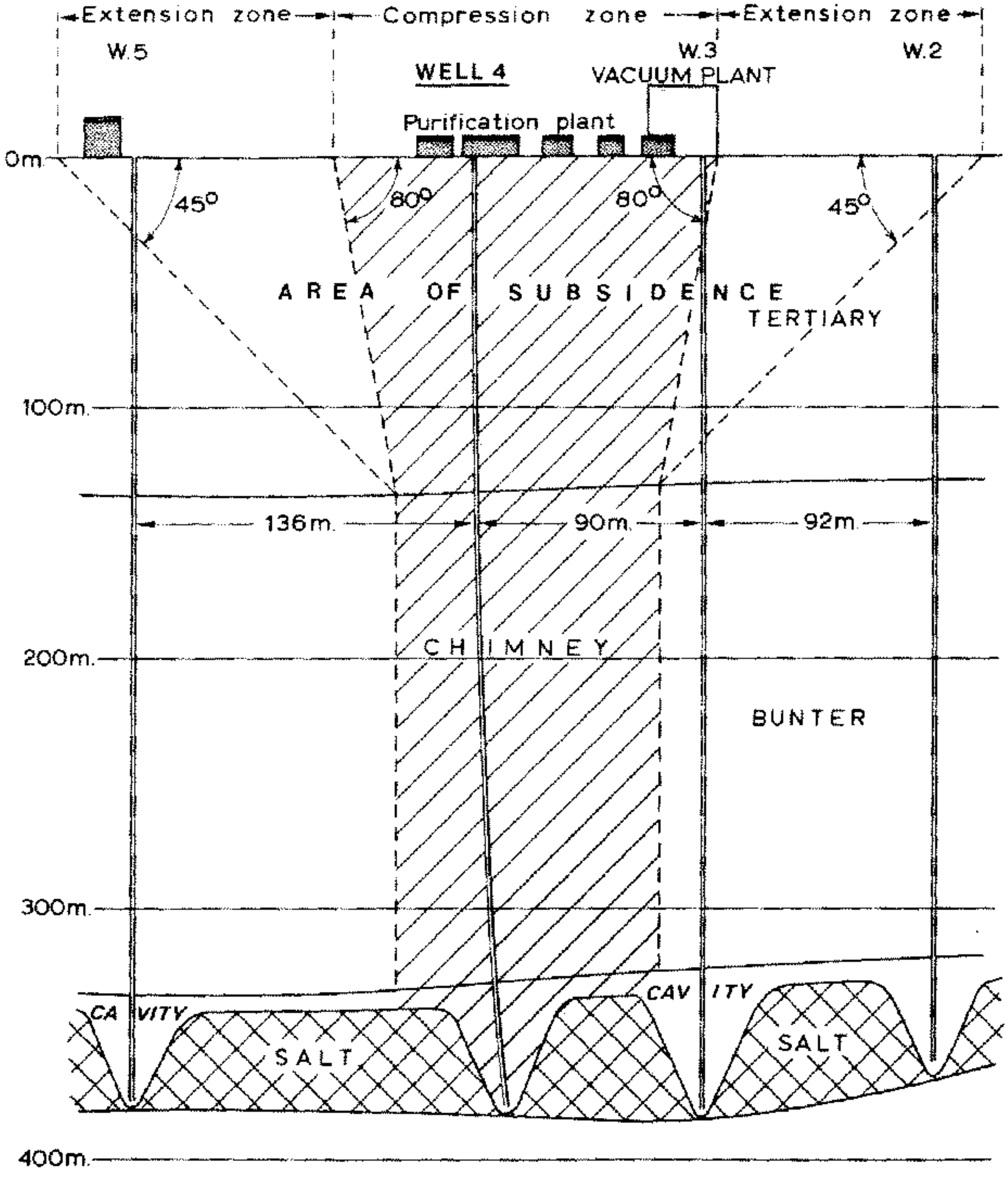

Figure 8. Idealized section over subsidence area 2 of Well 4.

What can be done with these results? The purification tanks have numbers that correspond with the numbers in the first column of Table 2. The next two columns of Table 2 give some more information about these tanks, such as their diameters and the distances from their nearest and farthest point to the center of the bowl. From the map, the average tilt in minutes of the tank can be easily read and this figure can be recalculated to a tilt in centimeters on the basis of the diameter of the tank. All the expected movements of construction features on the surface within this area can be found from this kind of table. With these figures it was easy to arrange a long-term planning for preventive maintenance. For example, the purification tanks were jacked up and put on a mound of stabilized sand to restore the flow direction between the tanks. The height of these mounds was calculated from the tables, as was the expected tilt. All tanks

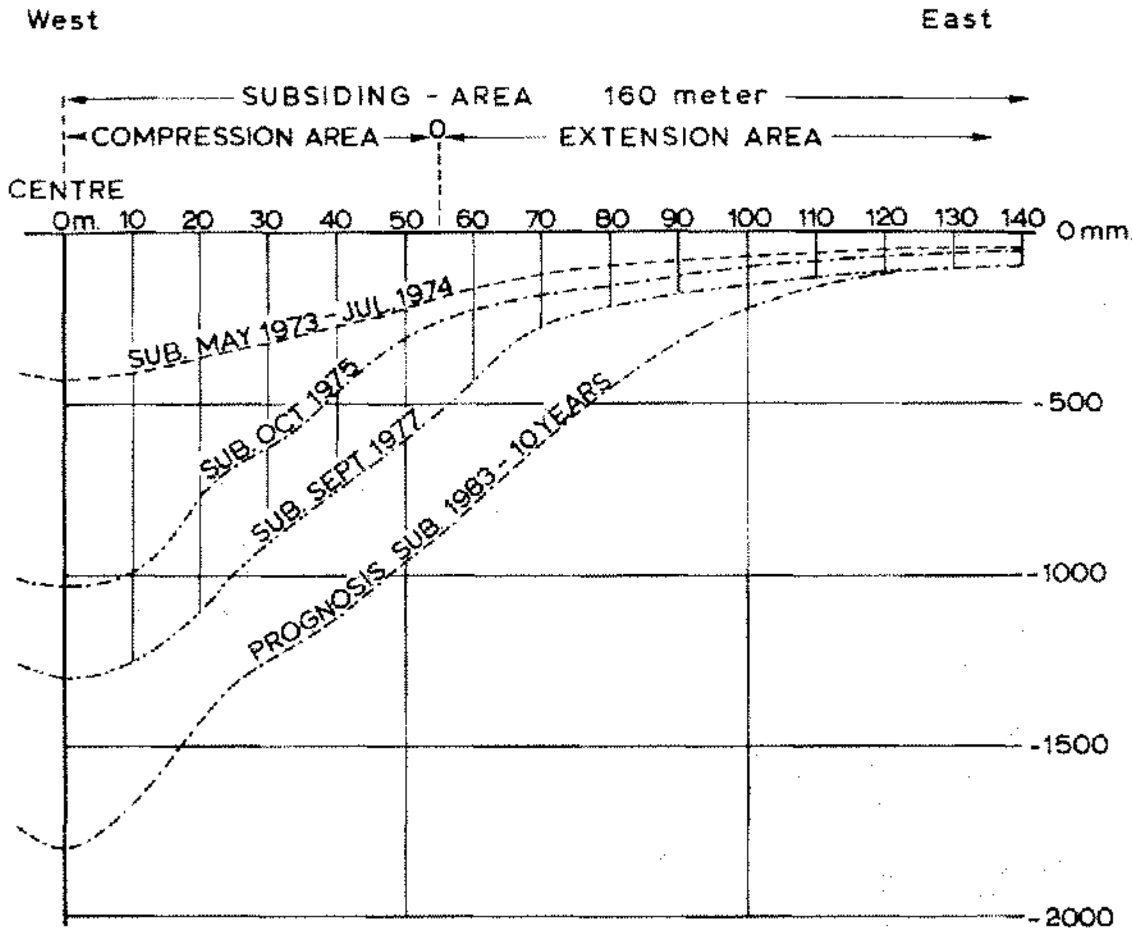

Figure 9. Actual measured and predicted subsidence in area 2 during the period 1973–1983.

were then given a tilt in the opposite direction. It is expected that the tanks will move downwards again and tilt back to horizontal position, or even more without maintenance to be done within the next five years. The same has been done with a small building with a stiff reinforced concrete foundation and brick walls.

Finally, Figure 11 shows a Casing-Collar-Log and a Gamma-Log of a suspect well. On the surface no subsidence has been measured up till now. Yet the expectation is that something will happen in the near future. This well is still accessible for logging and it is planned to make these logs every year. From this example it can be seen the original casing list set against a Casing-Collar-Log taken in 1976 and a 1974 Gamma-Log compared with the Gamma-Log of 1976. In both logs a vertical displacement increasing with depth can distinctly be noticed. At a depth of 250 meters a vertical displacement of about 2 meters can be read from the logs, whereas at a depth of 80 meters displacement is only a half a meter. These movements have already reached the unconsolidated clay and will probably soon be measurable at the surface. This kind of information is considered to be a first warning for possible movements at the surface.

TABLE 2
Tilt of the Purification Tanks in Minutes and Centimeters Till 1983

Tank (1)	Diameter (Meters) (2)	Distance To Center (Meters) (3)	Tilt (Minutes) (4)	Tilt (Centimeters) (5)
V 100	11.00	10–20	15.5′	4.9
V 101	22.40	5–30	19.3′	12.5
V 105	19.07	75–95	48.1′	26.7
V 112	14.25	30–40	41.3′	17.1
V 205	19.07	50–70	61.0′	33.8
V 219	10.90	50–60	61.9′	19.6
Cond.	10.90	30–40	41.3′	13.1
R 100	8.00	30–35	37.8′	8.8
R 103	8.00	40–50	55.0′	12.8
R 202	10.00	35–40	44.7′	13.0
R 203	10.00	60–70	60.2′	17.5
R 204	10.00	65–75	58.4′	17.0
S 100	18.30	35–55	54.1′	28.8
S 101	17.00	50–70	61.0′	30.2
S 200	22.00	35–60	55.7′	35.6
S 201	20.00	75–95	48.1′	28.0
S 301	20.00	70–90	53.3′	31.0

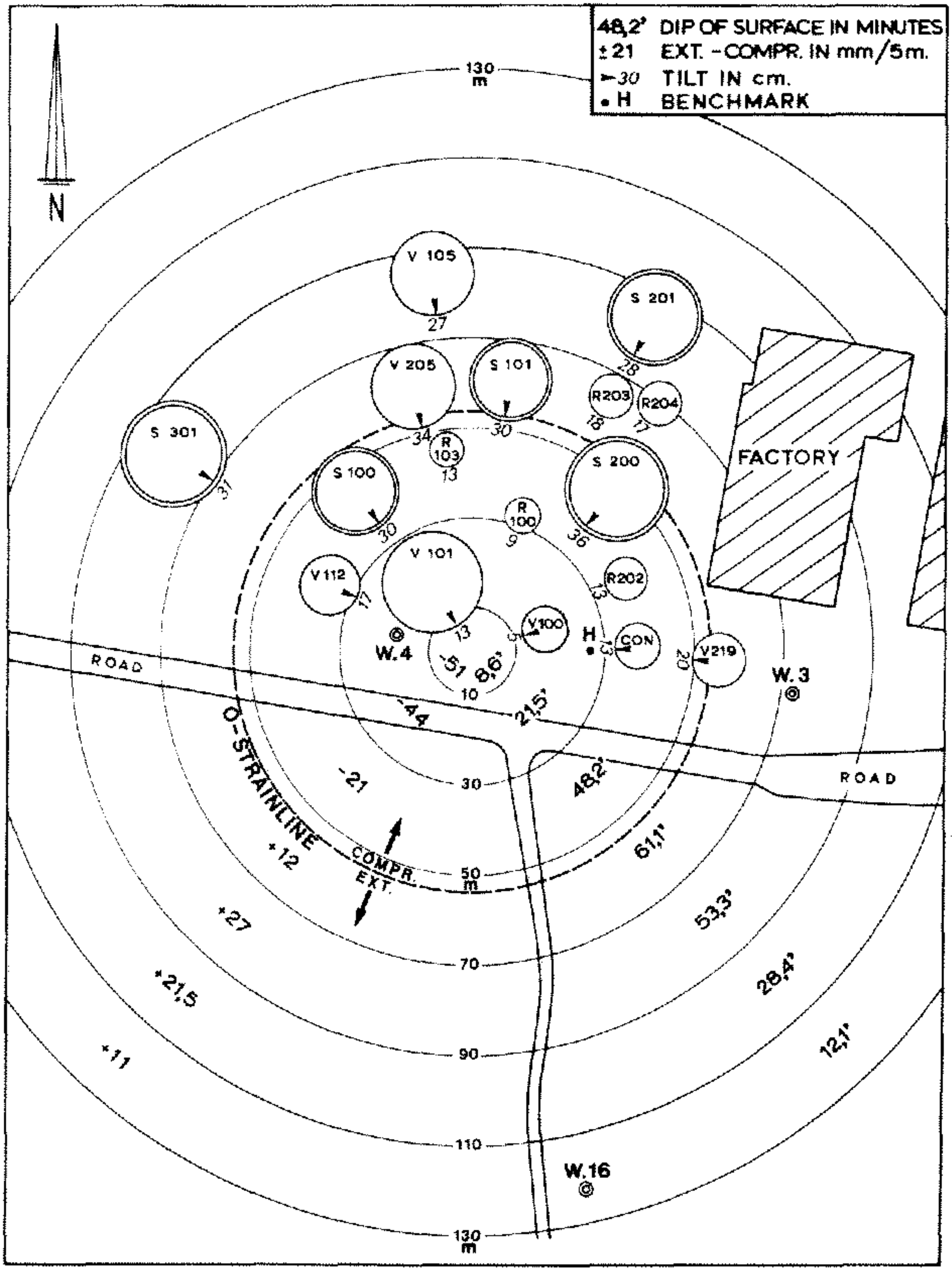

Figure 10. Predicted figures for tilt and strain at the surface for the 10 year period.

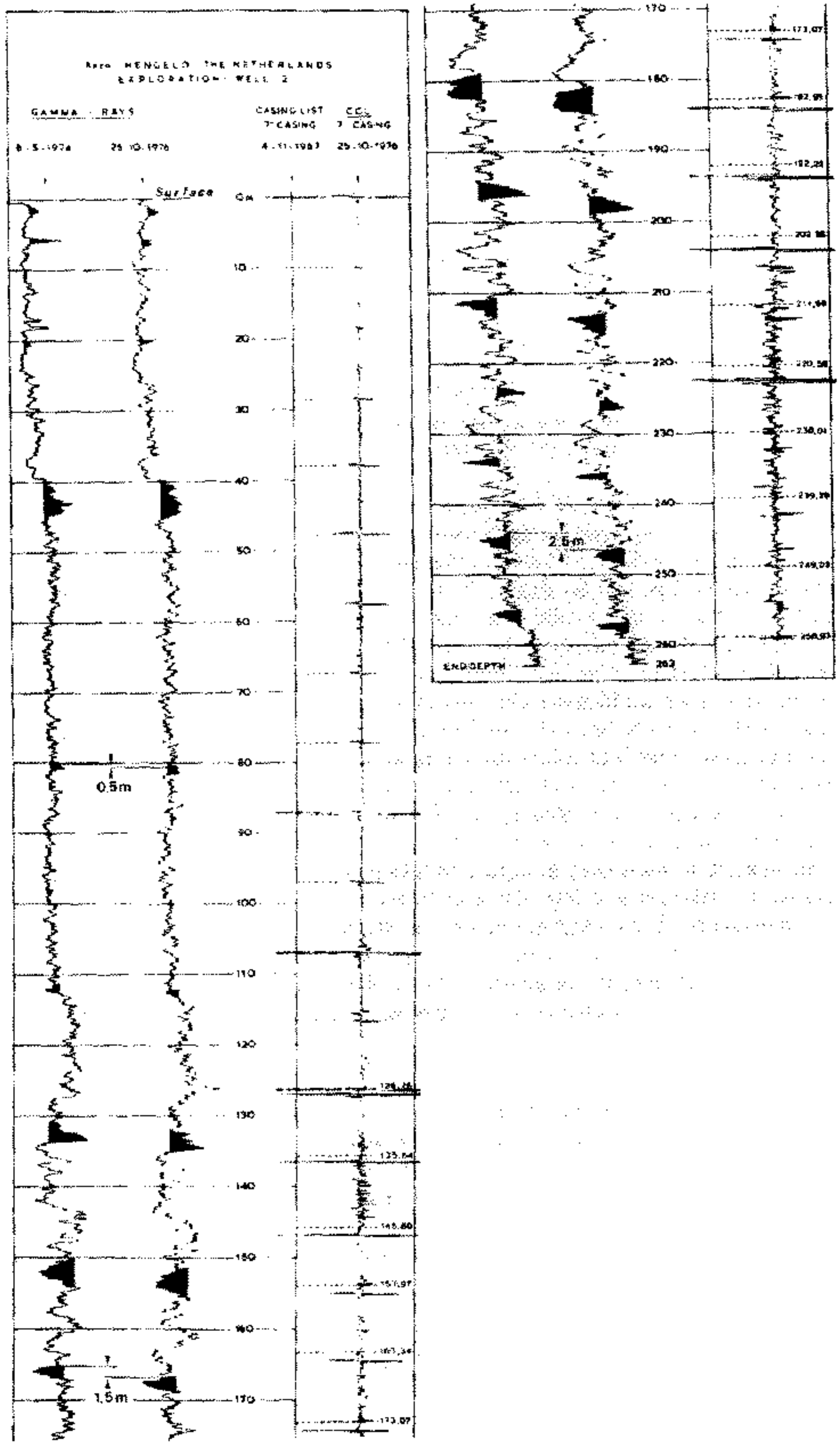

Figure 11. Vertical displacements increasing with depth due to caving of a cavity in a salt layer, measured by GR and CCL in the Hengelo field.