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To Jack Koenig with best wishes
Reinhard

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Gravity Investigations over a Salt Structure near Lübbecke, Northern Germany

Gravimetrische Untersuchungen über einer Salzstruktur in der Nähe von Lübbecke, Norddeutschland

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Summary: A detailed gravity survey was conducted parallel to the "Wiehengebirge" northwest of Minden in Northern Germany. The survey localized between Lübbecke and Levern a salt deposit, which is known as "Münder Mergel" salt of the Upper Jurassic. The salt deposit forms a cylindrical structure with an axis striking NWW. With a deep drill hole detailed interpretation was possible using the polygon method of TALWANI, WORZEL and LANDISMAN [1959]. The section shapes of salt bodies under eight profiles show asymmetrical figures of two salt units. Both increase in thickness strongly to the northeast, where the salt is interrupted by a fault zone. Here the strong gradient of the residual anomaly can only be explained by an increase of thickness and rise of the upper salt unit to about 50 m below the surface. This accounts for a number of sulfur and salt wells along the strike direction of the fault zone.

Zusammenfassung: Detaillierte gravimetrische Untersuchungen wurden parallel zum Wiehengebirge nordwestlich von Minden in Norddeutschland durchgeführt. Die Untersuchungen begrenzten zwischen Lübbecke und Levern eine Salzablagerung, die als Münder-Mergel-Salz im oberen Jura bekannt ist. Die Salzablagerung ist von zylindrischer Struktur, deren Achse in NWW-Richtung streicht. Unter Benutzung einer Tiefbohrung wurde eine detaillierte Interpretation unter Benutzung der „Polygon-Methode" von TALWANI, WORZEL und LANDISMAN [1959] durchgeführt. Die Querschnitte der Modellkörper unter den acht Profilen zeigen eine asymmetrische Form von zwei Salzstockwerken. Beide zeigen einen starken Mächtigkeitsanstieg nach Nordosten, wo das Salz von einer fast vertikalen Verwerfungszone abgeschnitten wird. Der hohe Gradient des lokalen Feldes läßt sich hier nur durch einen Mächtigkeitsanstieg und gleichzeitigen Aufstieg des oberen Salzstockwerkes bis zu etwa 50 m unterhalb der Erdoberfläche erklären. Davon zeugen eine Reihe von Schwefel- und Salzwasserquellen entlang der Streichrichtung der Verwerfungszone.

1. Introduction and Geological Background

The "Wiehengebirge" is the first major mountain range south of the Northern German flat land. Upper Jurassic strata, which are almost vertically bent, dip gently northward into the Lower Saxonian Basin. The Upper Jurassic layers are succeeded northward from the southern margin of the basin by Cretaceous and Tertiary rocks.

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A small anticlinal structure strikes parallel to the "Wiehengebirge" range at an average distance of approximately 7 to 8 km. Strata of the Upper Jurassic, developed as "Münder Mergel", and Lower Cretaceous, developed as Wealden, are slightly arched before they dip into the Lower Saxonian Basin. As a consequence of the desalination of the Upper Jurassic, the "Münder Mergel" occasionally appears as a salt facies along the anticlinal structure [BRINKMANN 1959, p. 185].

To support a geological survey which was conducted northwest of Minden between Lübbecke and Levern, corroborative geophysical investigations were made. Gravity measurements aided in localizing and estimating the thickness and shape of a salt deposit, which is a salt facies of the "Münder Mergel". Because salt has a lower density than most consolidated rock material, salt deposits can be associated with a mass deficit, which in such cases explains the often observed negative gravity anomaly.

The anticlinal structure between Lübbecke and Levern is known as the "Ellernburger Achse" [WORTMANN 1964]. It is on the southern flank of the "Schaumburg-Lippische Senke", which is a part of the major Lower Saxonian Basin. Tectonically the "Schaumburg-Lippische Senke" shows a succession of smaller local anticlines having a major strike direction from NWW to SEE.

2A. The Gravity Measurements

A total of 179 gravity points were measured in the area delinated by the topographic maps: "Blatt" Lübbecke (3617) and Levern (3616) (Fig. 1). The average distance between measuring points was 150 m. A coarse preliminary reduction of the data was made on the same day as the initial measurements. This practice facilitated the determination of intermediate gravity points whenever the interpolation of the anomaly between measuring points became doubtful. The gravity measurements were taken with a Worden Gravimeter "Prospector". Within one or two hours of measuring the required points, the gravity was repeatedly measured at a base point to correct for instrumental drift and tidal variation.

Elevations were measured with a RDS Wild. Point elevations were measured from benchmarks. The elevation points along the interstate channel "Mittellandkanal", which passes through the area, are periodically checked by the Water Ways Authority in Minden. This practice provides sufficient confidence in the recent accuracy of benchmarks because some swampy parts in the area of the measurements may have suffered subsidence.

Geological knowledge of the anticlinal structure referred to in the introduction suggests a cylindrical shape for the anomaly whose axis would be parallel to the "Wiehengebirge", thus, the number of gravity points were reduced by selecting several profiles normal to the axis.

In 1963 two profiles were measured at different angles to find the strike direction of the anomaly. They are profiles III (Hedem) and VI (Hedem-Hohenlüchte), which are near a bore hole whose coordinates are: R: 69420; H: 02200 (Fig. 2). In 1964 six

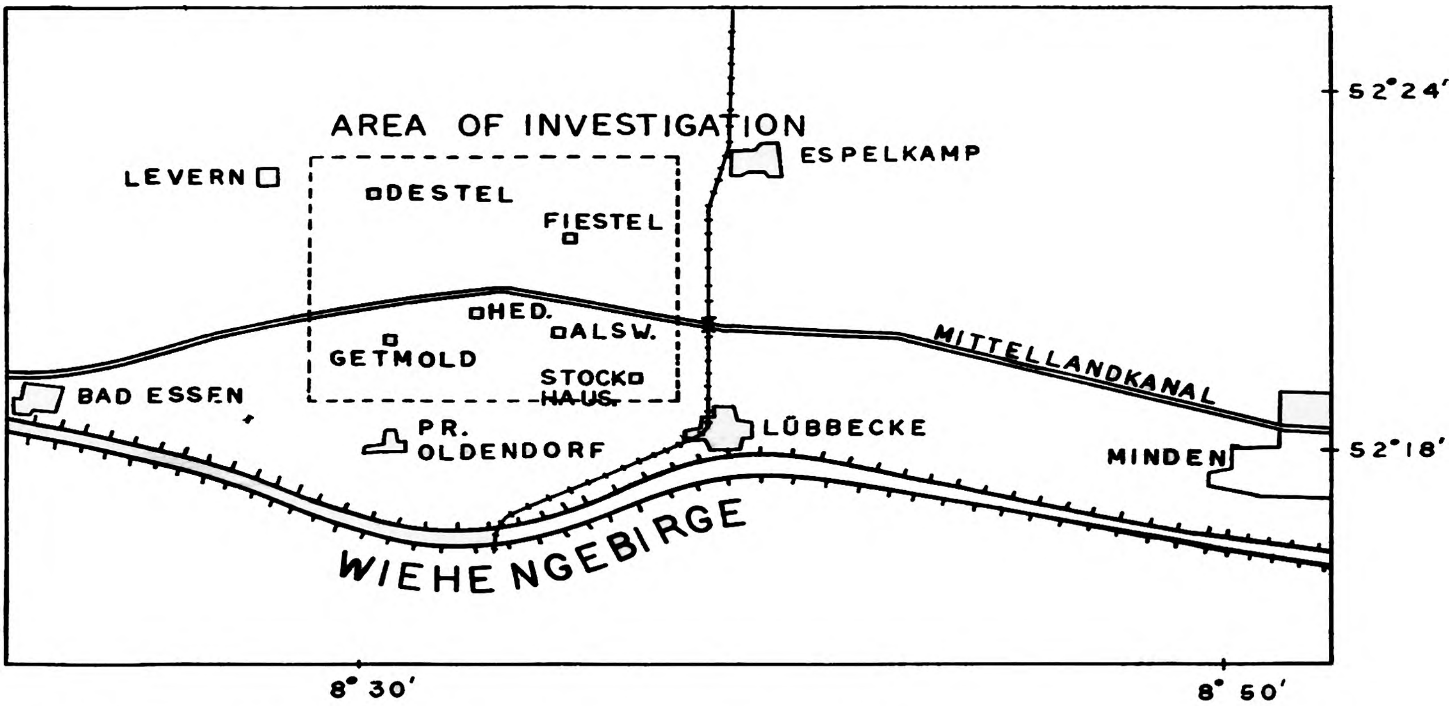

Fig. 1: Area of gravity investigations in Northern Germany.

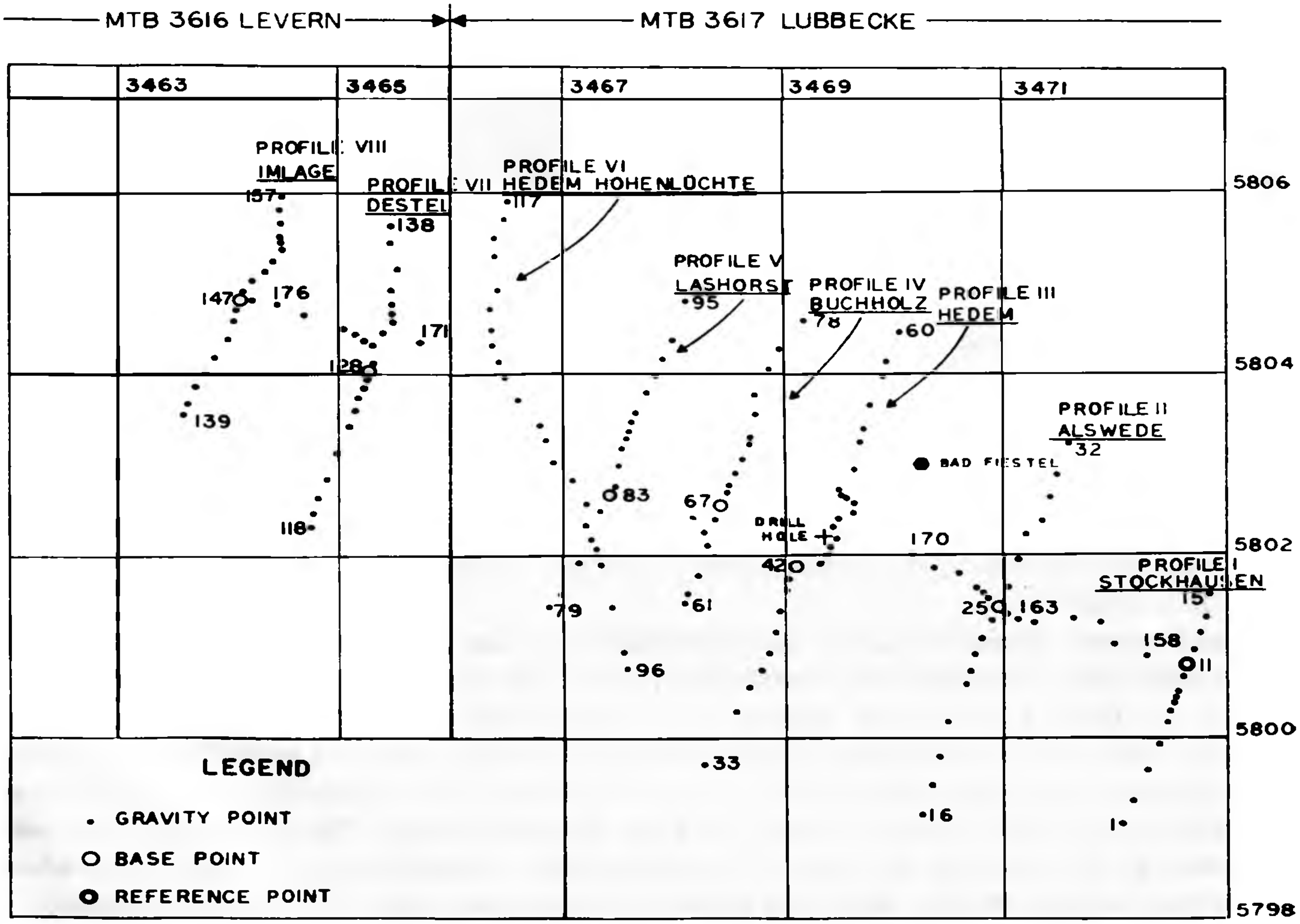

Fig. 2: Gravity points in the area of investigation.

more profiles were measured (I, II, IV, V, VII, and VIII). These were complemented by measurements taken between the profiles and parallel to the axis of the anomaly.

One particular base point was assigned to each profile. The profiles were connected with each other by these base points, for which geographical coordinates are given in Table I. For convenience, gravity point 11 on profile I (Stockhausen) was fixed at 1.0 mgal so that each gravity point would indicate a gravity anomaly relative to point 11 minus 1.0 mgal.

Table 1: Coordinates and Final Gravity Value of the Base Points

No.		Profile	R	H	$\Delta g''$ (mgal)
11	I	Stockhausen	34 72 660	58 00 790	1.00
25	II	Alswede	34 70 930	58 01 400	1.18
42	III	Hedem	34 69 140	58 01 870	1.55
67	IV	Buchholz	34 68 490	58 02 680	1.35
83	V	Lashorst	34 67 495	58 02 745	2.32
128	VII	Destel	34 65 380	58 04 450	3.21
147	VIII	Imlage	34 64 120	58 04 820	3.23

2B. Reduction of Gravity Measurements

A number of reductions of the measured data were necessary to yield the Bouguer Anomaly. It is given by the formula

$$\Delta\gamma'' = \Delta g_{\mathrm{M}} + \Delta g_{\mathrm{F.A.}} + \Delta g_{\mathrm{B.R.}} + \Delta g_{\mathrm{TOP}} + \Delta\gamma_0$$

where Δg_{M} is the Measured Gravity, $\Delta g_{\mathrm{B.R.}}$ is the Bouguer Reduction, $\Delta\gamma_0$ is the Latitude Reduction, $\Delta g_{\mathrm{F.A.}}$ is the Free Air Reduction, and Δg_{TOP} is the Topographic Reduction.

The *Measured Gravity* represents the difference between the scale reading and an arbitrarily assumed scale value multiplied by the instrumental scale factor. The scale values were corrected for instrumental drift and tidal variation.

The *Free Air Reduction* is applicable if the elevation of the measuring point is lowered or raised to a uniform reduction level. Its value (in mgals) is: $\Delta g_{\mathrm{F.A.}} = 0.3086 \cdot \Delta H$, where ΔH is the difference in height between the measuring point and the reduction level (in meters). If the latter is below the measuring point, ΔH is positive; otherwise, it is negative.

The *Bouguer Reduction* takes into consideration the gravitational attraction of the horizontal plate between the measuring point and the reduction level. Its value is: $\Delta g_{\mathrm{B.R.}} = -0.0419 \cdot \Delta\sigma' \cdot \Delta H$, where $\Delta\sigma'$ is the surface density. Its value has been adapted from the Gravity Map of North Rhine Westfalia with 1.9 gr/cm^3 (unpublished report of the Geological Survey of North Rhine Westfalia). Here the same convention for the sign of ΔH is used as for the Free Air Reduction. The reduction level was assumed at 60 m above sea level. It is known that reduction errors might arise when the actual surface density does not agree with the used value. This holds especially if there is a change of rock material. The only known possibility of an error in this case may be connected with small swamps. Because they generally are known not to be very deep in the area of investigation, their influence was neglected.

The *Topographic Reduction* was completely neglected because the area is flat, and the only topographic influence which could arise would be from the nearby "Wiehengebirge". By using the Hammer Charts [Hammer 1939] its influence on the nearest measuring point was calculated to be below 0.02 mgal.

The *Latitude Reduction* was derived from the International Gravity Formula. Its gradient is 0.78 mgal/km for the latitude $\Phi = 52° 24'$. Though this value depends on the latitude itself, it can be considered constant within the geographically limited area of the investigation.

3. The Bouguer Anomaly

The results of the measurements are shown in Fig. 3, which depicts contour lines of equal Bouguer gravity. On a first impression the map appears to present a standard

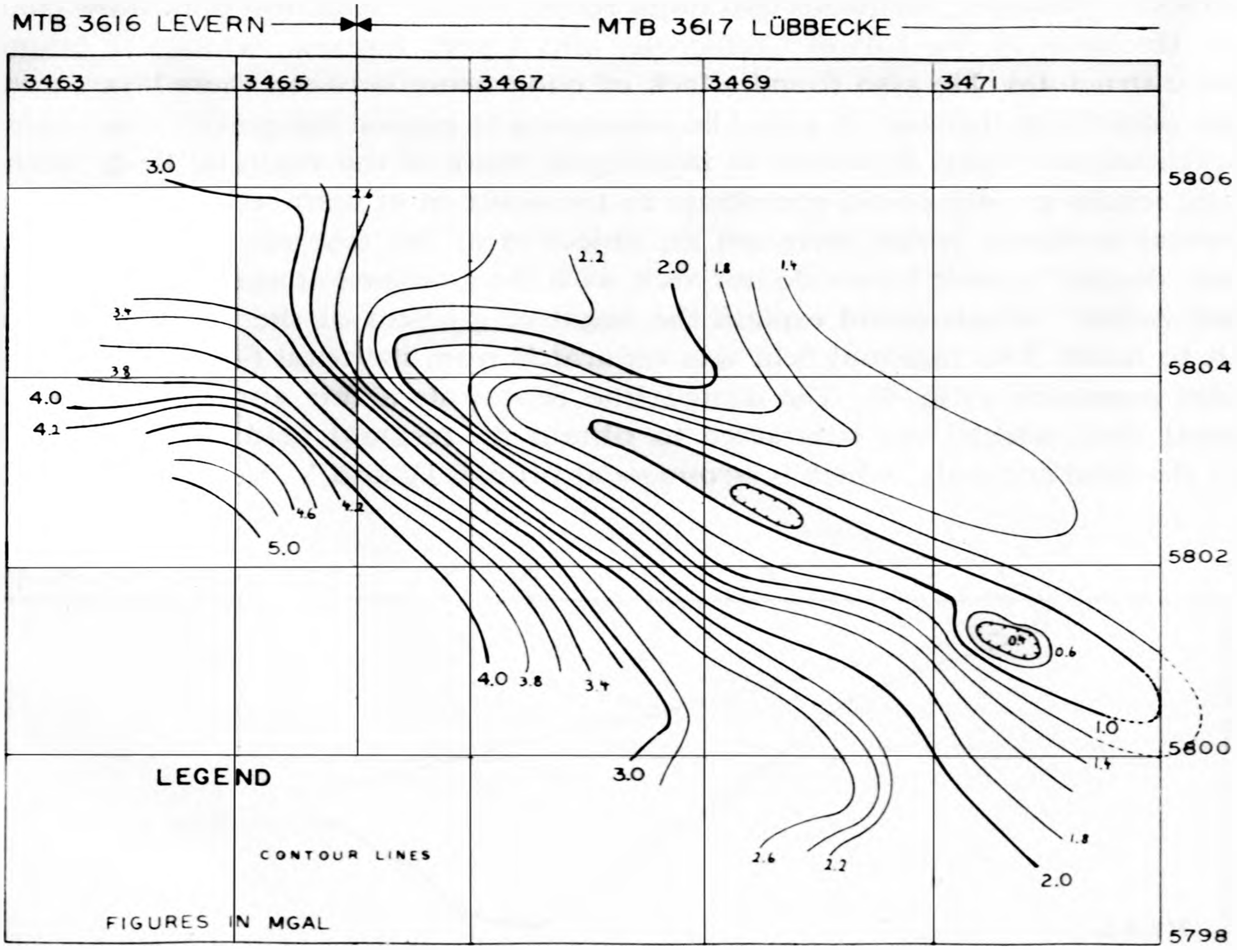

Fig. 3: Contour lines of the Bouguer Anomaly.

example of a regional and residual field and it does not require much skill to separate the residual field intuitively. The residual field can be recognized as the NWW-striking negative anomaly. The regional field decreases in northeast direction.

Though the separation of the residual field seems to be easy, some caution has to be applied. An analytical calculation of the regional field cannot be applied because there are not enough gravity points away from the residual field. The regional trend could be estimated along profiles II, III and V by taking the average value from equidistant points on a circle of 1.25 km radius. On all three profiles the gradient of the regional field was found to be almost equal at 1.1 mgal/km. This suggests that its source is rather deeply located compared with the source of the residual field. It appears reasonable to explain the regional field with the dip of the heavier Jurassic strata into the "Schaumburg-Lippische Senke". This seems to contradict depth contours of layers above the "Münder Mergel", which are shown by WORTMANN [1964] on the geologic-tectonic map of the Lower Cretaceous north of the "Wiehengebirge". The depth-contour lines are based on early refraction measurements of 1935 and indicate a rise of the "Münder Mergel" from south to north towards the "Ellernburger Sattel". WORTMANN, however, mentions that more recent seismic reflection data show changes of the thickness of the Lower Cretaceous and Upper Jurassic, which are bound to tectonic structures. He also found a lack of congruence between these layers and the deeper underlying Jurassic. It would be interesting to expand the gravity measurements in northeast-southwest direction to investigate more of the regional field. With the seismic results gravity could contribute to the solution of some of the more detailed tectonical problems which were not an objective of this research. It seems that the heavier deeper Jurassic layers do not arch with the anticlinal structure of the "Ellernburger Achse", which could explain the negative gradient of the regional field from south to north. The regional field was separated from the total field considering the profiles separately (Fig. 4). The dotted line represents a fair approximation of the regional field, which was subtracted to obtain the residual field. Profiles I to VIII cover the local anomaly, which is strongest at profiles IV and V. Each of the profiles I

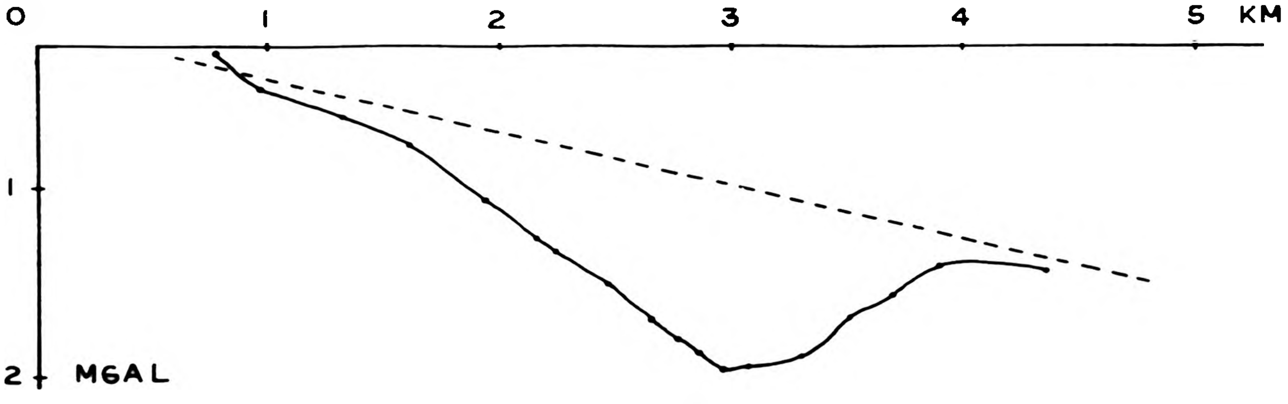

Fig. 4: Separation of the regional field (dotted line).

and VIII at the ends show only a small anomaly suggesting the limitation of the salt body. The salt itself very likely is not the only cause of the residual field. The harder rocks of the basement may contribute most certainly at the northeast flank of the salt body since there is reason to assume that the salt deposit is correlated to the tectonic structure of the Upper Jurassic. The following interpretation was carried out, however, under the simplified conception that the salt is the only cause of the residual field. This was decided because bore hole data on the Upper Jurassic were not available. With a contribution of the basement to the residual field the thickness of the salt deposit calculated from model curves will consequently be smaller.

4. A First Approximation Using a Direct Method of Interpretation

In the first approximation, the anomaly indicated a horizontally buried strip-like body of salt, which exhibited a negative density contrast with the surrounding rock material. The gravity anomaly of a strip-like body can be calculated with a simple expression [JUNG 1961, p. 222], but the graphic method known as the "Zweikreis-Verfahren" [JUNG 1961, p. 224] was preferred. For each profile the width, b, the depth, t, and the parameter, μ, was determined. The parameter, μ, is the product of $\Delta\sigma$, the density contrast and d, the thickness of the strip. The parameters are listed in Table II.

Table 2: Geometrical Parameters of a Horizontal Strip

Profile	b (m)	t (m)	μ (gr/cm^3)
I	924	170	13.50
II	1,790	215	21.90
III	1,470	220	35.20
IV	1,200	225	38.00
V	1,420	280	50.20
VII	1,550	290	18.90
VIII	1,100	225	8.25

There is still some uncertainty about the thickness, d, which can be solved as soon as an assumption about $\Delta\sigma$ is made.

5. The Determination of the Density Contrast

The rock material, which causes the anomaly, is not available, but the results from the drilling of "Bohrung Ellerburg I" in 1933 are available [FABIAN 1971], and these provide an indirect method for estimating the most probable value of $\Delta\sigma$ (unpublished report of the Geological Survey of North Rhine-Westfalia). Figure 5, presents a diagram of the drilling results and depicts the calcareous shale, anhydrite, and rock salt that were penetrated by the drill. The main part of the salt, which is only occasionally interrupted by thin layers of anhydrite, appears between 200 and 420 m. The anhydrite has a higher density than the calcareous shale. Another thinner salt deposit,

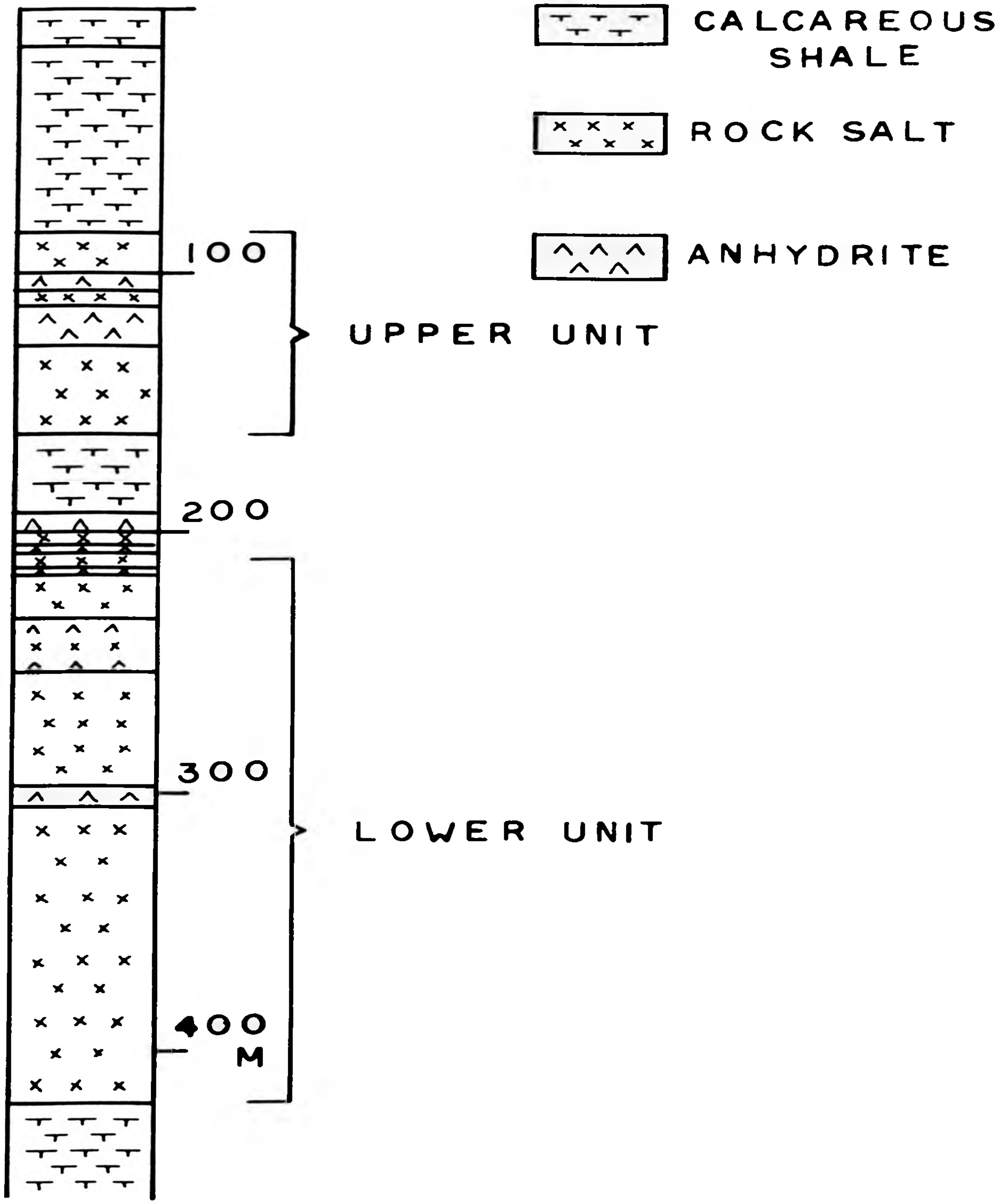

Fig. 5: Drilling result of the bore hole "Ellerburg 1".

which is more often interrupted by anhydrite, lies above the main body between 85 and 160 m. To evaluate the influence of the different rock material, a table of rock densities pertaining to the type of rock presented by the drilling results is taken from [Haalck 1953, p. 126f.].

Table 3: Rock Densities after Haalck

Rock Material	Density (gr/cm^3)	Average Density
anhydrite	2.92 – 2.98	2.96
rock salt	2.10 – 2.40	2.20
shale	1.80 – 2.60	2.20
calcareous shale	2.30 – 2.70	2.50

Table III shows that the denser anhydrite might well compensate for a negative density contrast caused by the salt. With an increase of the clay component of the shale, the density contrast between rock salt and the surrounding material becomes rather low. Thus the lower body of salt in having a higher proportion of salt to anhydrite compared with the upper one, most likely produces the bulk effect of the anomaly.

For all profiles the thickness, *d*, of a slab was calculated from Table II assuming different values of $\Delta\sigma$. The results are shown in Table IV.

Table 4: Calculation of *d* (m) Assuming Different Values for $\Delta\sigma$

Profile	$\Delta\sigma$ (gr/cm^3)					
	0.14	0.16	0.18	0.20	0.22	0.24
I	96	84	75	68	61	56
II	156	137	122	110	100	91
III	251	220	195	175	160	147
IV	271	238	211	190	172	158
V	359	314	279	251	228	209
VII	135	118	105	95	86	79
VIII	59	52	46	41	37	34

We compared *d* for the different values of $\Delta\sigma$ for profile IV with the drilling results. Assuming that the bulk of the anomaly is caused by the lower salt deposit between 200 and 420 m, the value $d = 211$ m of Table IV agrees with the drilling results, which implies a density contrast $\Delta\sigma = 0.18$ gr/cm^3. This value also fits the densities of Table III. It is assumed that the mean value for rock salt is 2.2 gr/cm^3 and that the surrounding calcareous shale has a density between shale (2.2 gr/cm^3) and calcareous shale (2.5 gr/cm^3). The term $\Delta\sigma = 0.18$ gr/cm^3 was accepted as the most probable density contrast for the approximate as well as detailed interpretation.

As a result of the approximate interpretation, the anomalies along each profile could be explained by a horizontal strip-like body whose geometrical parameters were taken from Table II and column 4 of Table IV.

6. Detailed Interpretation of the Local Anomaly

Because the local anomaly is cylindrical in character, a 2-dimensional model calculation is justified for its interpretation. The amount of calculation was considerably

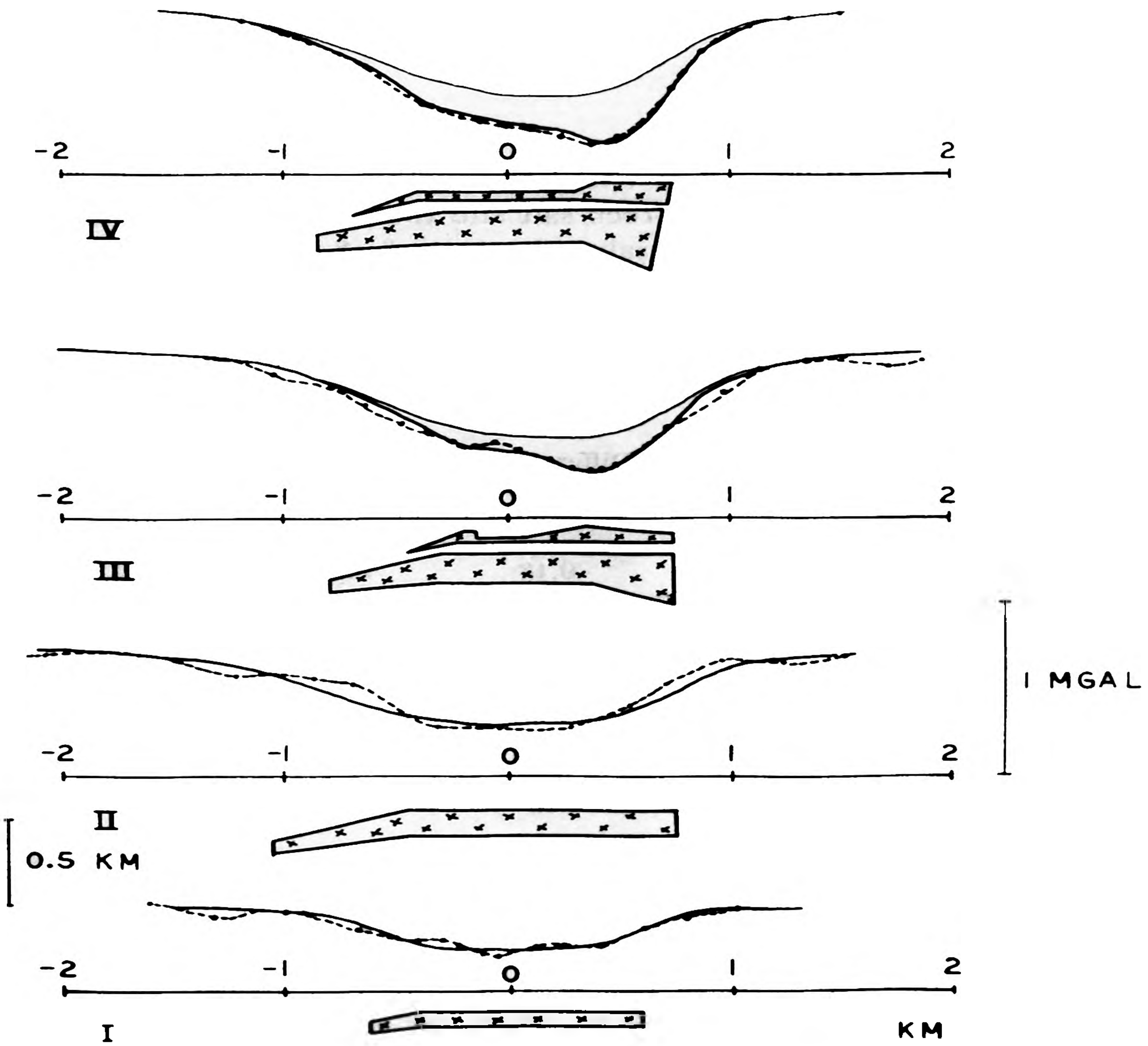

Fig. 6: Interpretation of gravity anomalies, profiles I to IV. Dotted line: measuring results. Heavy line: calculated gravity assuming the underlying salt body. Thin line: contribution to calculated gravity from the lower salt unit.

reduced by assuming that the mass distribution depended only on the square section described by the coordinates x and z which extend parallel to the y-axis to infinity. The "polygon method" [TALWANI, WORZEL, and LANDISMAN 1959] was applied with the aid of an IBM 360/50 computer. This method makes it possible to calculate a model for any section shape as long as the section can be approximated by a polygon. This can be achieved to any desired degree of approximation. It must be emphasized that an interpretation based on a method which allows for any polygonal shape of the model does not necessarily give a final solution for an indirect problem. Various mani-

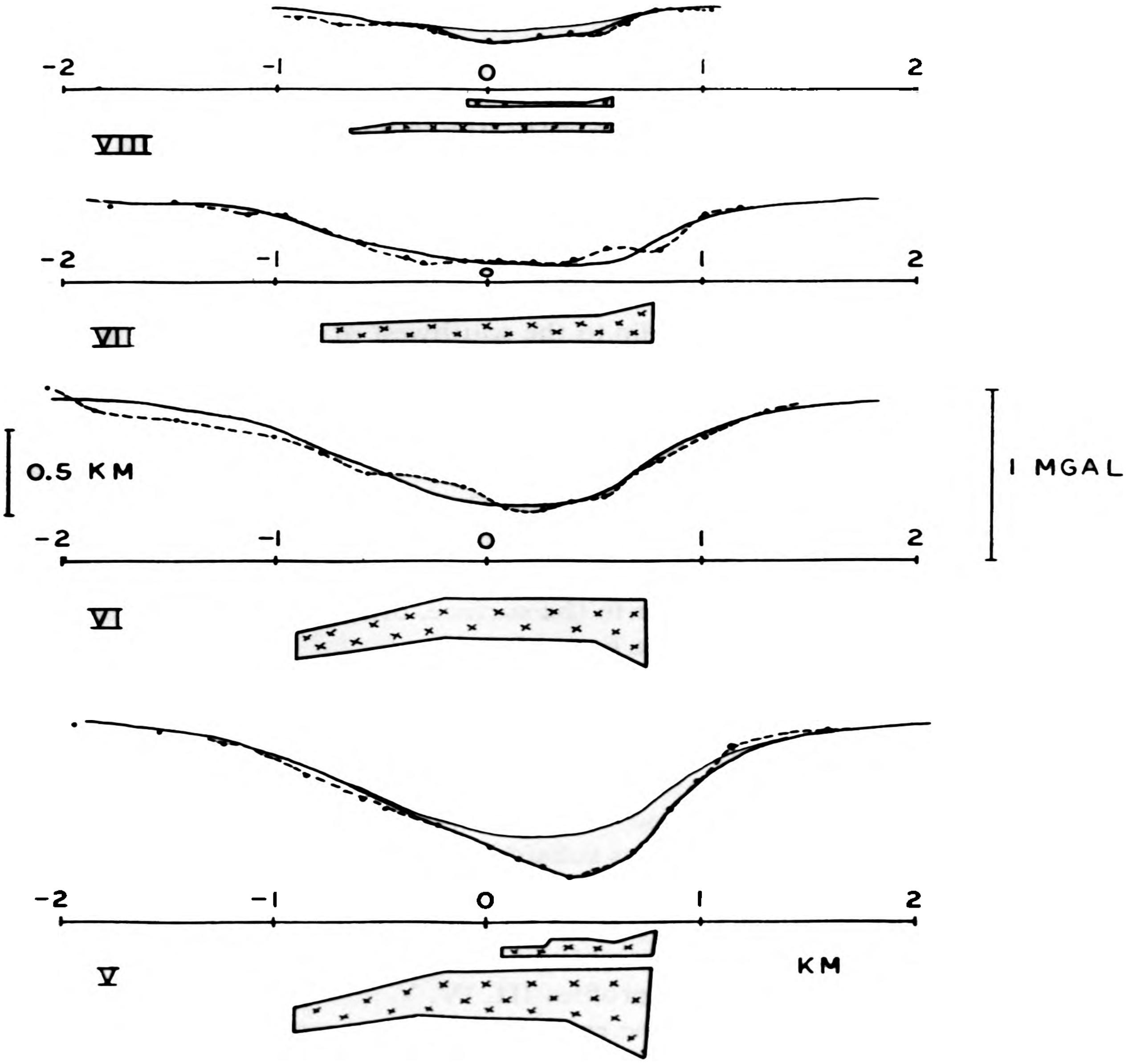

Fig. 7: Interpretation of gravity anomalies, profiles V to VIII. (legend see Fig. 6).

pulations of the polygon can lead to different models which will have the same gravity anomaly. Boundary conditions are needed to select the type of model most applicable to the case. Boundary conditions are other geophysical data and geological facts. The latter provide the only additional information available here, and the most important data are from the drilling results. Some less informative geological implications also have an indirect bearing on the rock salt distribution. The model to be derived can thus only be considered to be correct so long as it satisfies the anomaly and agrees with the available geological facts.

The strongest negative anomalies are along profiles IV and V. Both anomalies show a remarkable asymmetry. Consequently, the detailed shape of the mass distribution must deviate from the symmetrical, horizontal, striplike body, which was determined by the first approximation. While the slope is small on the southwest flank of the anomaly, it is steep on the northeast.

There are three possible shapes for the strip-like body that could account for such asymmetry: 1) The body has the form of a wedge. 2) It is a parallel strip dipping to the southwest. 3) The body increases considerably in thickness to the northeast. Model studies, each of which employed one of the three shapes, resulted in extreme dimensions in all three cases that were hard to accept from the standpoint of the known geology. A combination of all three aspects finally led to an acceptable solution. Because the salt forms the crest of an anticline, a dip to the southwest of 15° was assumed. Furthermore, it was assumed that the salt deposit in most of the profiles thins gradually to the southwest in order to satisfy the small slope on this side of the anomaly. On the northeast flank, the salt must be considerably thicker than towards the center of the profiles, where the thickness is known from the results of the drillhole near profile IV.

On the basis of the drillhole data, it was decided to assume the presence of two layers of salt; one above the other. It was also necessary to assume that the salt increases considerably in thickness towards the northeast flank, which terminates abruptly. Also the upper layer of salt must come near to the surface, otherwise, the steep slope on the southwest side of the anomaly cannot be explained.

While the greater part of the anomaly is caused by the deeper and larger salt deposit, smaller variations of the anomaly are most likely caused by the upper layer of salt, and there is much reason to believe that this layer has lateral density inhomogeneities which are responsible for the small variations in gravity. The drillhole data show a substantial amount of anhydrite, and the development of gypsum is likely to have caused a cap on the upper layer that has subsided through leaching. Some of the older surface swamps may owe their existence to this subsidence. The small variations of gravity over short distances were considered by adjustments in the model of the upper salt. Topography that allows for the leaching and an increase of the thickness towards the northeast margin, as exhibited in profiles III, IV, V, and VIII (Figs. 6 and 7) show, in the final stage of interpretation, the representative polygons used for the models. Though sharp corners cannot be expected in reality, any further approximation by replacing the corners with curved lines would not noticeably change the calculated anomaly.

In profile V the upper layer of salt was terminated to the southwest near the center of the anomaly. A steady decrease of the thickness to the southwest would also give an acceptable solution. Because of the steady slope of the southwest flank of the anomaly, it was felt that the laterally inhomogenious upper level might be absent here. Profile VIII shows a rather small anomaly. The steep slope of the northeast branch still requires rock salt near the surface, which also explains a sulfur spring near Imlage.

Profiles I, II, and III show a smaller degree of asymmetry. The salt deposit is thinner, and the contribution of the upper level was neglected. If at all, it apparently does not contribute appreciably to the anomaly.

7. Conclusion

The gravity survey along the eight profiles shows in connection with drillhole data a rock salt deposit which is about 15 km in length and averages 1.5 km in width. The

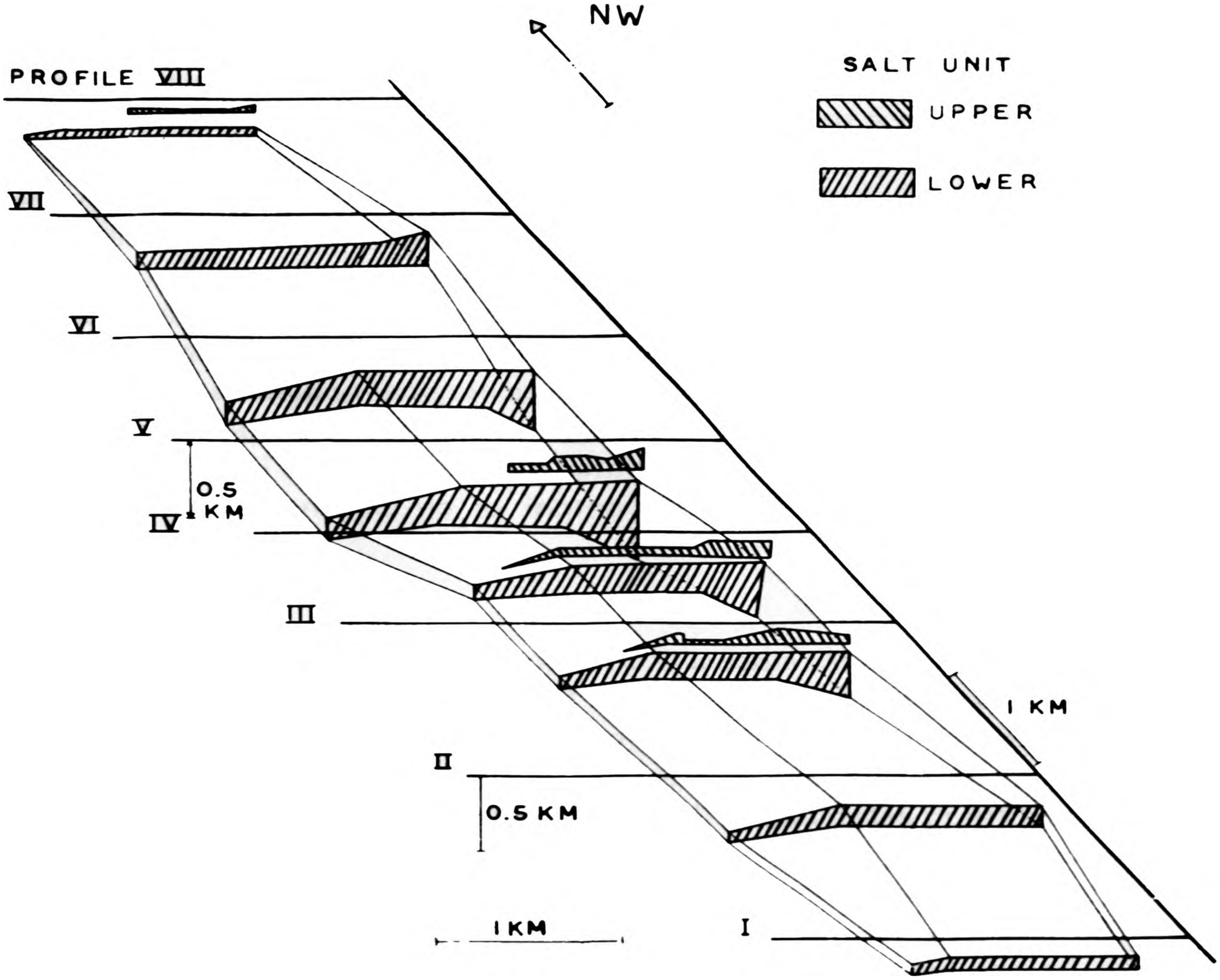

Fig. 8: Representation of the salt body as a result of the gravity investigations.

greatest thickness of the deposit is beneath profile V and is 0.5 km. Towards profile I in the southeast and profile VIII in the northwest, the thickness decreases gradually. In a first approximation, a horizontal strip-like body of salt with a density contrast of 0.18 gr/cm^3 and a different width, depth, and thickness under each profile explained the gravity anomaly.

A more detailed interpretation and consideration of the drilling results imposed two modifications on the strip-like model to the effect that the strongest anomalies under profile IV and V had to be derived from an asymmetrical mass distribution, and the model had to be considered as two salt layers; a large deep one which caused the major anomaly and a smaller overlying one which caused the small variations of the anomaly. Figure 8 shows a block diagram of the most likely distribution of the salt that can be derived from the gravity anomalies and which agrees with the geological facts.

Both salt layers thin to the southeast with a dip angle of 15°. To the northeast, the salt increases strongly in thickness and both layers terminate abruptly in an almost vertical fault plane. The upper salt layer near this plane reaches nearest to the surface. Where this plane intersects with the surface, a number of sulfur springs have been found and have been used for recreational purposes, such as at Bad Fiestel.

The strong increase of the thickness of the salt to the northeast terminating at the fault zone can be explained by a greater tectonic subsidence immediately south of the fault zone. This sense of movement along the fault zone is also supported by drillholes [Wortmann 1964, p. 340]. Also posttectonic stress most likely was blocked by the fault and caused the salt to yield up and downwards contributing to the abnormal thickness.

This present investigation shows that the detailed interpretative methods of a gravity survey can contribute substantially to the knowledge of geological subsurface conditions. Structural features, along which salt solutions are mobilized and brought near to the surface are of great importance for hydrogeological considerations. The knowledge of such zones is a prerequisite if natural salt water is needed for recreational purposes or if contamination of potable water by salt solutions is to be avoided. For more detailed questions about the salt content of circulating waters, geoelectrical investigations are recommended.

Acknowledgement

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