Seismic velocities in sedimentary rocks — indicators of subsidence and uplift?

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With 15 figures and 5 tables

Zusammenfassung

Für die Umgebung eines Salzstocks auf der Pompeckjschen Scholle werden mit Hilfe der seismischen Geschwindigkeiten die Beträge der scheinbaren Hebungen und Absenkungen ermittelt. Die Untersuchung der Sedimentationsverhältnisse im gleichen Gebiet ergibt jedoch keinen Hinweis auf tatsächliche Bewegungen in der geforderten Größenordnung. Die scheinbaren Hebungen lassen sich vielmehr als Folge der Druckbeanspruchung durch das Salz und den Einfluß des pleistozänen Inlandeises deuten.

Abstract

Seismic velocities from the environment of a saltdome on the Pompeckj-Swell were analysed in order to estimate the rates of subsidence and uplift. It is shown using geological data that no true movements of the demanded amount can be proved in the study area. The apparent uplifts estimated from velocity analysis can be interpreted as a result of the ice load during the Pleistocene together with compression caused by the salt.

Résumé

Les vitesses sismiques ont été analysées dans les environs d'un diapir situé sur le seuil de Pompeckj pour estimer l'ampleur des soulèvements et des affaissements apparents. L'étude des rapports sédimentaires ne montre aucun signe de mouvements réels dans la région étudiée. Les soulèvements apparents s'expliquent beaucoup mieux comme le résultat commun d'une déformation due à la calotte glaciaire du Pleistocène et à la compression par le sel.

Краткое содержание

С помощью сейсмических методов определили величины кажущегося поднятия и оседания пород, окружаёщих соляной шток глыбы Помпецкий. Однако исследования взаимоотношений осадконакопления в той же области не подтвердили наличие абсолютных движений значительного порядка. Кажущийся подъем можно рассматривать, как следствие давления соли и материкового льда в плейстоцене.

Introduction

The succesful interpretation of seismic reflecting profiles in locating hydrocarbon bearing structures depends strongly on an accurate knowledge of the seismic velocities. In shales and sandstones these are essentially a function of the porosity, pore contents, matrix nature, and temperature of the material (Hughes & Cross 1951, Hughes & Kelly 1952, Wyllie, Gregory & Gardner 1956, 1958). In carbonate rocks the shale-carbonate ratio plays the dominating role (Jankowsky 1970). Here dolomitization gives rise to local porosity which leads to a lower

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velocity. On the other hand a volume for volume replacement of calcite by dolomite tends to increase the velocity (Kisslinger 1953). Velocity increases during compaction can be interpreted as due to decreasing porosity with increasing pressure (Rubey 1927). The end process is a permanent structural change by recristallization (Hedberg 1936, von Engelhard 1960, Rieke & Chilingarian 1974).

Seismic velocities in sedimentary rocks are therefore an expression of the highest pressure level which the layer had to undergo during its tectonic history. A layer which lay at greater depth in its geological past and has been elevated will show a much higher velocity than expected from its present depth. Thus the analysis of seismic velocities is of great importance for the estimation of vertical tectonic movements (Philip et al. 1963, Jankowsky 1962, John 1975, 1978).

This paper is concerned with the critical comparison of subsidence and uplift rates estimated on the one hand with the aid of seismic velocity analysis and on the other hand by geological arguments. The environment of a saltdome with its peripheral sinks was chosen for investigation because its genesis is easy to reconstruct. The data used in this study come from the southern part of the Pompeckj-Swell which is distinguished by a nearly undisturbed base of Zechstein. The Jurassic and Lower Cretaceous sediments exist only in reduced thickness. During the Upper Cretaceous and Tertiary subsidence occurred in connection with the development of the Lower Saxonian Tectogene (Boigk 1968).

Because of the commercial value names and locations in the text are coded. I hope for the understanding of the reader.

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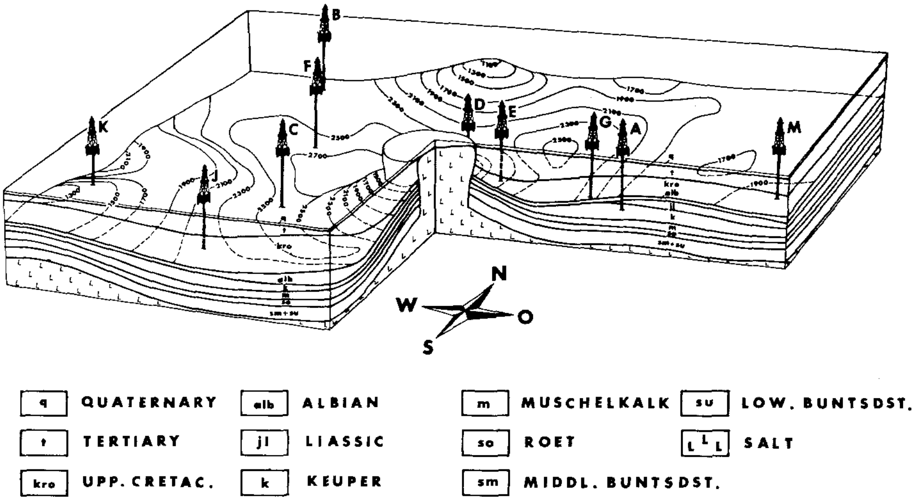

Fig. 1. Block diagram showing the structure of the area under study.

1. The structural situation

The depth contours of the base of the Upper Cretaceous and the position of the wells (capital letters) in the investigated area are shown in Figure 1. Two salt pillows which are seperated from the saltdome by peripheral sinks can be seen north and west of the diapir. The cross sections on the side of the block diagram show the reflection horizons corresponding to the most important stratigraphic horizons in this area. The existence of a salt pillow below the central diapir points toward still ongoing upward salt movement.

2. The estimation of subsidence and uplift rates with the aid of seismic velocity analysis

The relationship between seismic velocity in sediments and depth, geologic time and lithologic variations have been described by Faust (1951, 1953). He proposed the following formula:

$$v = a\,(T \cdot Z)^{1/6}$$

a = constant, T = geologic time, Z = depth, v = velocity
John (1956) estimated for the Swabian Molasse Basin (Fig. 2):

$$v = 400 \ln (400 + Z) + 0.4\,Z - 620$$

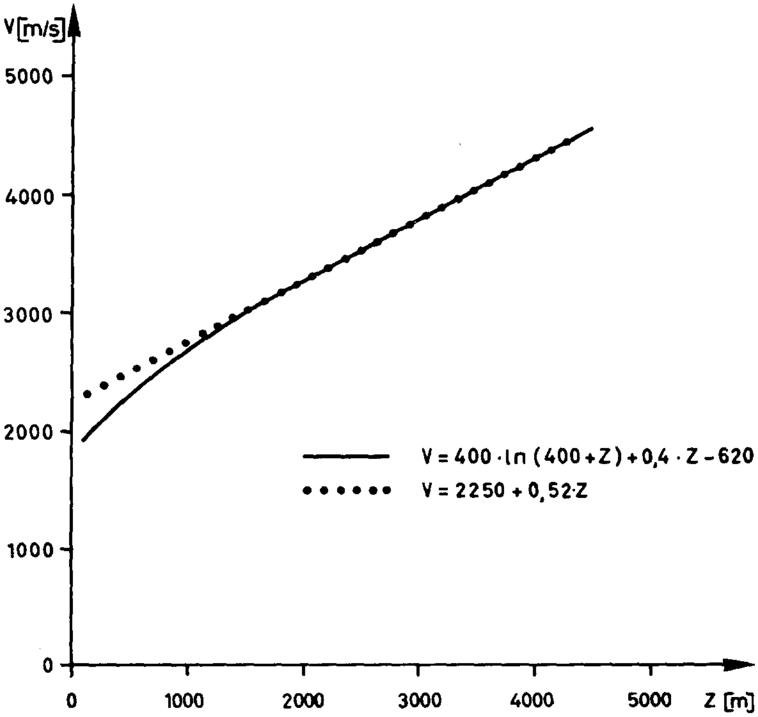

Fig. 2. Seismic velocity as a function of depth. Solid curve after John (1956).

At greater depths the velocity-depth relationship can be treated as linear (Fig. 2). Hence for the velocity analysis in this paper linear relations have been used similar to JOHN (1975, 1978). Table 1 gives the velocity-depth functions for the main reflecting horizons. The slopes have been determined by calculating the mean values of the velocity-depth gradients for each layer using several hundred wells in the Northwest German Basin. The smallest recorded velocities at each depth have been choosed as reference values for the determination of the initial values of the straight lines since they have the highest probability of beeing not influenced by uplift movements.

It is evident that for the younger layers the velocity increase with depth is more rapid. The high value for the Upper Cretaceous can be interpreted by taking into account the calcareous character of this horizon. The increase in the individual minimum velocities can be interpreted according to FAUST (1951) as due to the influence of the geologic time. The value for the Tertiary is not directly comparable because the velocity-depth function was estimated only for the lower section.

The velocity-depth relation for the Lower and Middle Buntsandstein is shown in Figure 3. The solid line represents the initial function as described above. All well-logs indicate greater velocities than should have been recorded bearing only depth in mind. Assuming that the velocity difference is caused by the vertical load during subsidence, the amount of the apparent uplift can be obtained from the diagram by drawing a vertical line from the velocity-depth point to the initial function. The apparent maximum depth of burial is then given by the point of intersection. These values are given for the wells A — M in Tables 2 and 3.

The most apparent uplifts for all investigated horizons occur at the flanks of the saltdome (Figs. 4—11). Minima for all the layers, except for the Tertiary, are found in the region of the rim syncline. For the Tertiary no peripheral sink is

Table 1. Velocity-depth functions for the main reflecting horizons.

Tertiary	v = 1295 m/s + 0.83 z
Upper Cretaceous	v = 850 m/s + 1.35 z
Lower Cretaceous	v = 1025 m/s + 0.85 z
Liassic	v = 1535 m/s + 0.58 z
Keuper	v = 1925 m/s + 0,48 z
Muschelkalk	v = 2230 m/s + 0.50 z
Roet	v = 2010 m/s + 0.51 z
Lower and Middle Buntsandstein	v = 2325 m/s + 0.51 z

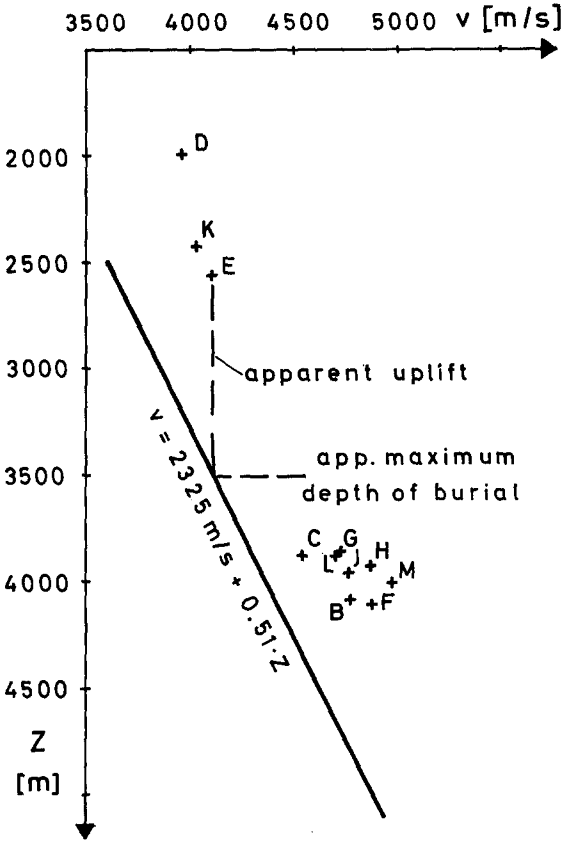

Fig. 3. Velocity-depth relation for the Lower and Middle Buntsandstein.

indicated in the spatial distribution of the apparent uplifts and only a small increase from 400 to 690 m towards the saltdome does exist (Fig. 11).

The mean values of apparent uplift for each horizon (Table 4) show, that a superficial interpretation as real movements will lead to difficulties. The average amount of uplift should increase with the age of the layer as every postsedimentational subsidence of a specific layer should contribute to a velocity increase. From lithological arguments however, it cannot be expected that all types of sediments are suited to investigate tectonic movements using a velocity analysis. Following John (1975) they should fulfil the following conditions:

— Homogeneity
— Evidence of little calcareous, salty and anhydritic portions
— Sufficient thickness, so as to reduce velocity determination inaccuracy to a minimum
— Deep enough depth of burial thereby making sure that the velocity increase is irreversible.

Additionally, the specific velocity-depth functions have to be taken into

Table 2. Apparent maximum depths of burial (m below sea level).

	A	B	C	D	E	F	G	H	J	K	L	M
Tertiary	1285	1455	2150	1640	1825	1790	1560	1535	1300	1060	1445	1370
Upper Cretaceous	2880	3530	3385	2500	2720	3665	3110	3145	3310	2655	3150	3065
Lower Cretaceous	3510	3715	3185	2055	2315	3255	3135	2945	3295	2760	3600	3420
Liassic	2945	3415					3035	3470				3590
Keuper		4945	4520	4365	3770	5235	4740	4930	4920	3480	4210	5040
Muschelkalk		5860	4875	3550	4585	5585	5450	5825	5150	3505	6220	5770
Roet		4670	4925	4525	3985	4705	4810	4645	4930	4070	4910	4735
Lower and Middle Buntsandstein		5040	4600	3525	3805	5255	4975	5305	5030	3430	4950	5435

Table 3. Apparent uplifts (m).

	A	B	C	D	E	F	G	H	J	K	L	M
Tertiary	460	400	560	690	610	505	515	555	565	415	520	525
Upper Cretaceous	1090	1050	870	1290	1050	1065	980	1035	1060	1220	1120	1120
Lower Cretaceous	1610	1040	530	745	545	560	890	710	635	1230	1030	990
Liassic	755	705					705	1090				995
Keuper		1670	1465	3015	1945	1925	1750	1875	1815	1725	1300	1915
Muschelkalk		2285	1530	2050	2545	1975	2155	2470	1730	1450	2965	2295
Roet		855	1320	2865	1730	875	1240	1080	1245	1760	1335	1035
Lower and Middle Buntsandstein		695	465	1210	925	890	825	1100	800	895	785	1150

account because, depending on the initial function and the average thicknesses of the layers a systematic error of for example 1 ms during well shooting would lead to non-negligible errors in the estimation of the apparent uplifts (Table 5). These arguments indicate that only Lower and Middle Buntsandstein and Tertiary seem to be suitable horizons for allowing tectonic interpretations of the velocity data in the investigated area.

3. The structural development of the saltdome and its vicinity

A basic assumption for the velocity analysis was that the apparent uplifts are a true document of vertical tectonic movements. This seems to be supported by the spatial distribution of these values (Figs. 4—11). From geological point of view the structural development of a saltdome is relatively easily followed. Analysis of the layer thicknesses allows the estimation of vertical movement. This provides criteria to test the basic assumption mentioned above.

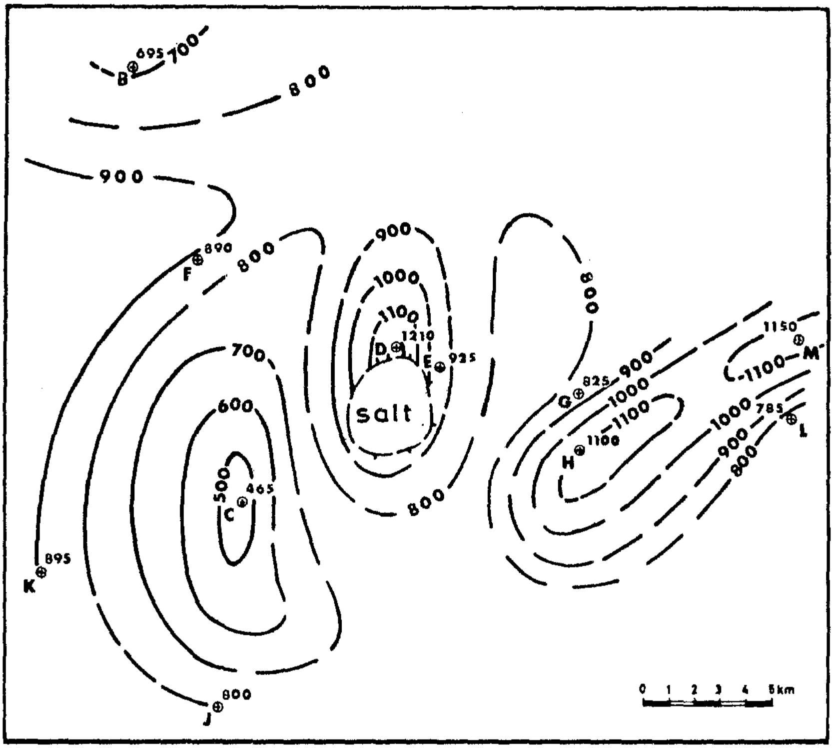

Fig. 4. Spatial distribution of the apparent uplifts for the Lower and Middle Buntsandstein.

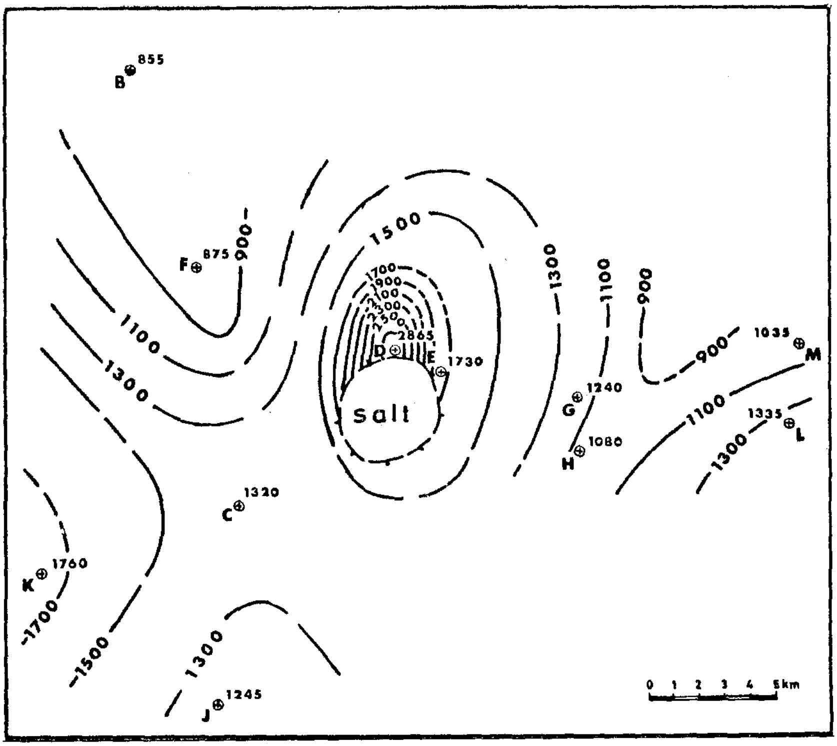

Fig. 5. Spatial distribution of the apparent uplifts for the Roet.

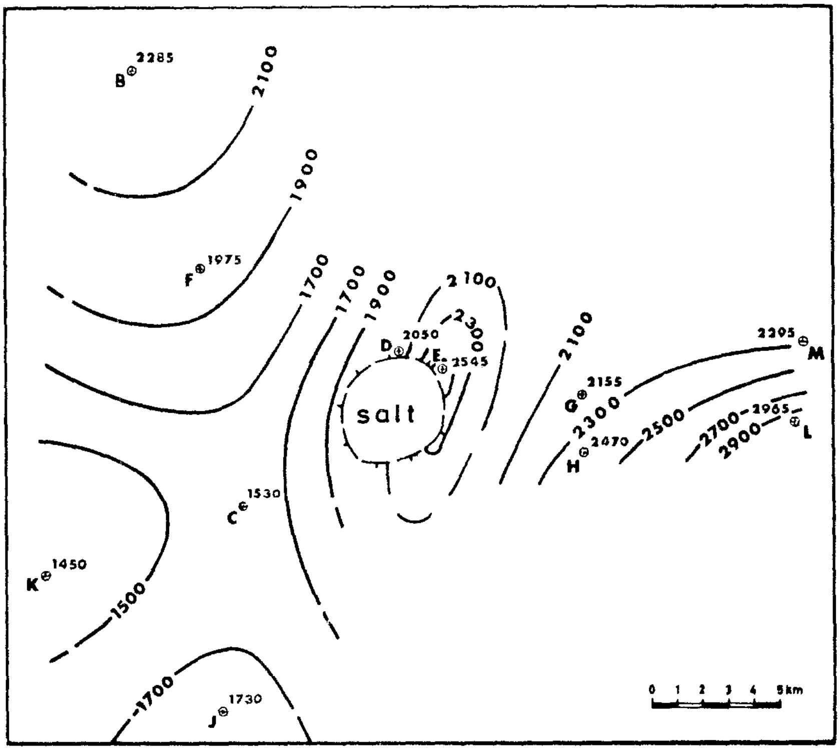

Fig. 6. Spatial distribution of the apparent uplifts for the Muschelkalk.

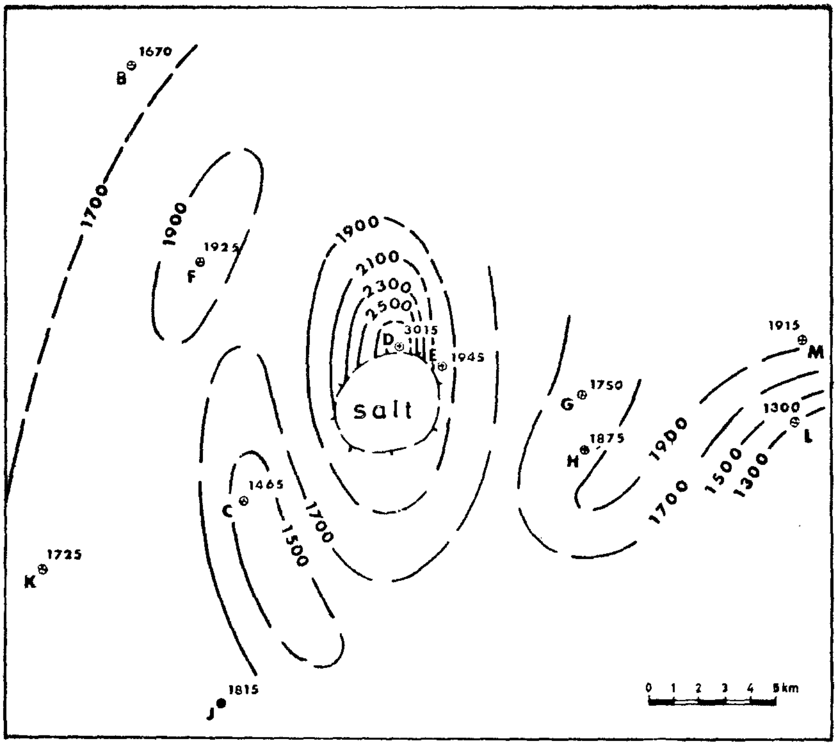

Fig. 7. Spatial distribution of the apparent uplifts for the Keuper.

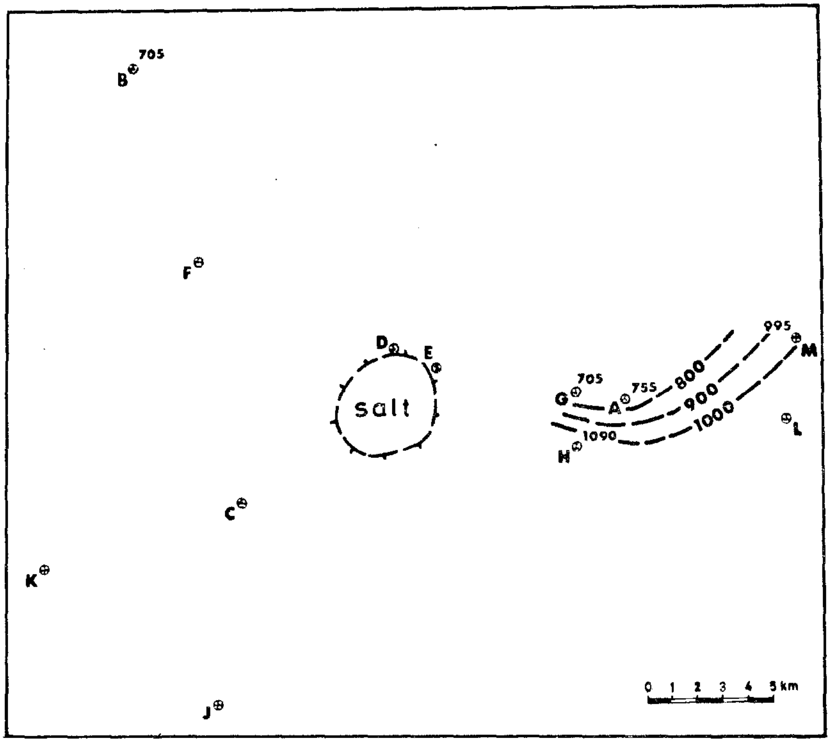

Fig. 8. Spatial distribution of the apparent uplifts for the Liassic.

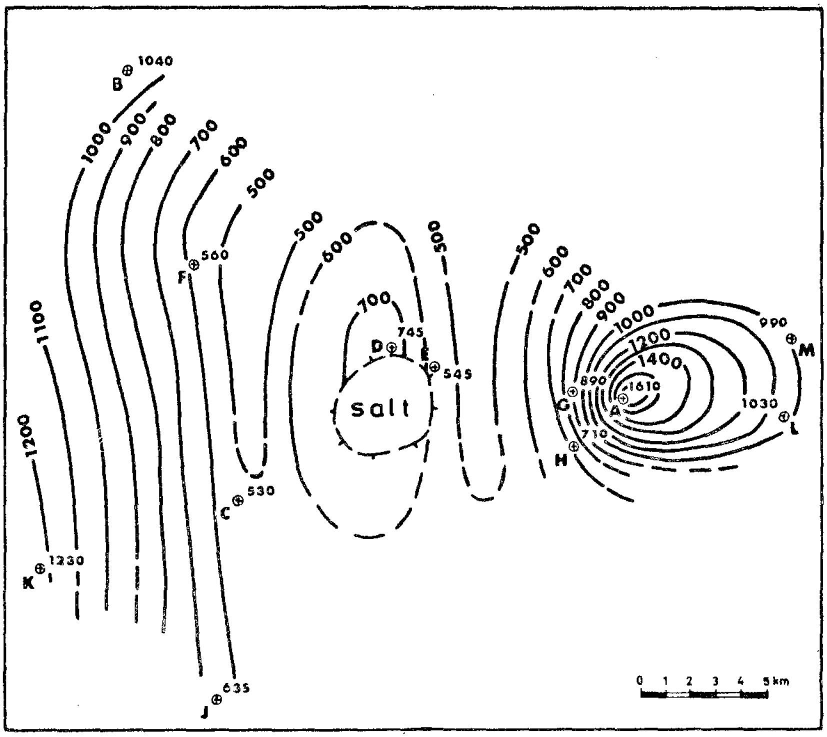

Fig. 9. Spatial distribution of the apparent uplifts for the Lower Cretaceous.

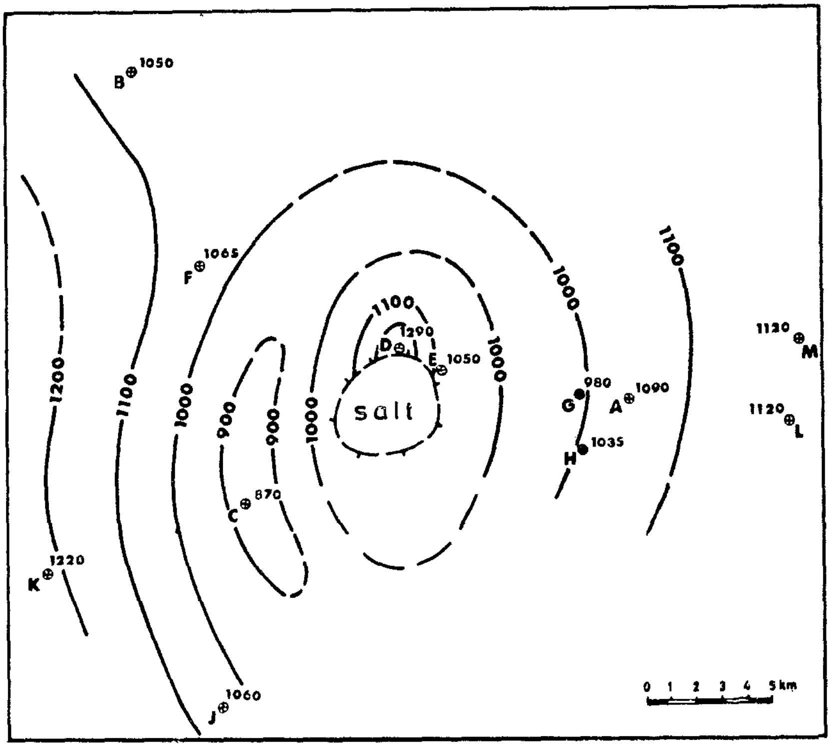

Fig. 10. Spatial distribution of the apparent uplifts for the Upper Cretaceous.

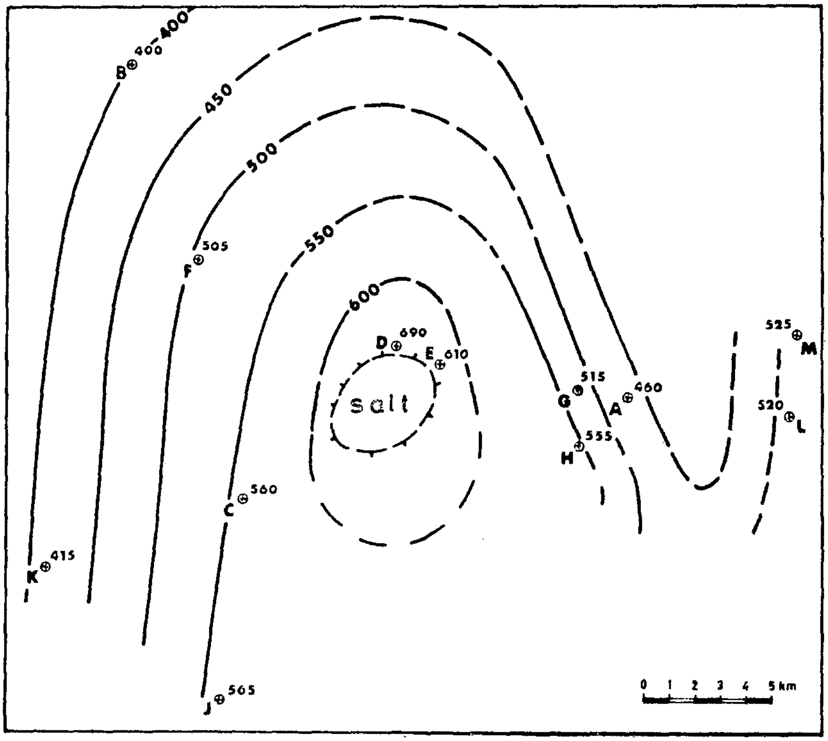

Fig. 11. Spatial distribution of the apparent uplifts for the Tertiary.

Table 4. Apparent uplift mean values.

Tertiary	$\bar{x} = 527 \pm 80$ m
Upper Cretaceous	$\bar{x} = 1079 \pm 107$ m
Lower Cretaceous	$\bar{x} = 876 \pm 325$ m
Liassic	$\bar{x} = 850 \pm 180$ m
Keuper	$\bar{x} = 1855 \pm 434$ m
Muschelkalk	$\bar{x} = 2132 \pm 453$ m
Roet	$\bar{x} = 1395 \pm 570$ m
Lower and Middle Buntsandstein	$\bar{x} = 885 \pm 214$ m

Table 5. Systematic errors in the estimation of the apparent uplifts (corresponding to 1 ms error in velocity estimation).

Tertiary	$\Delta x = \pm 6$ m
Upper Cretaceous	$\Delta x = \pm 14$ m
Lower Cretaceous	$\Delta x = \pm 70$ m
Liassic	$\Delta x = \pm 140$ m
Keuper	$\Delta x = \pm 73$ m
Muschelkalk	$\Delta x = \pm 152$ m
Roet	$\Delta x = \pm 140$ m
Lower and Middle Buntsandstein	$\Delta x = \pm 73$ m

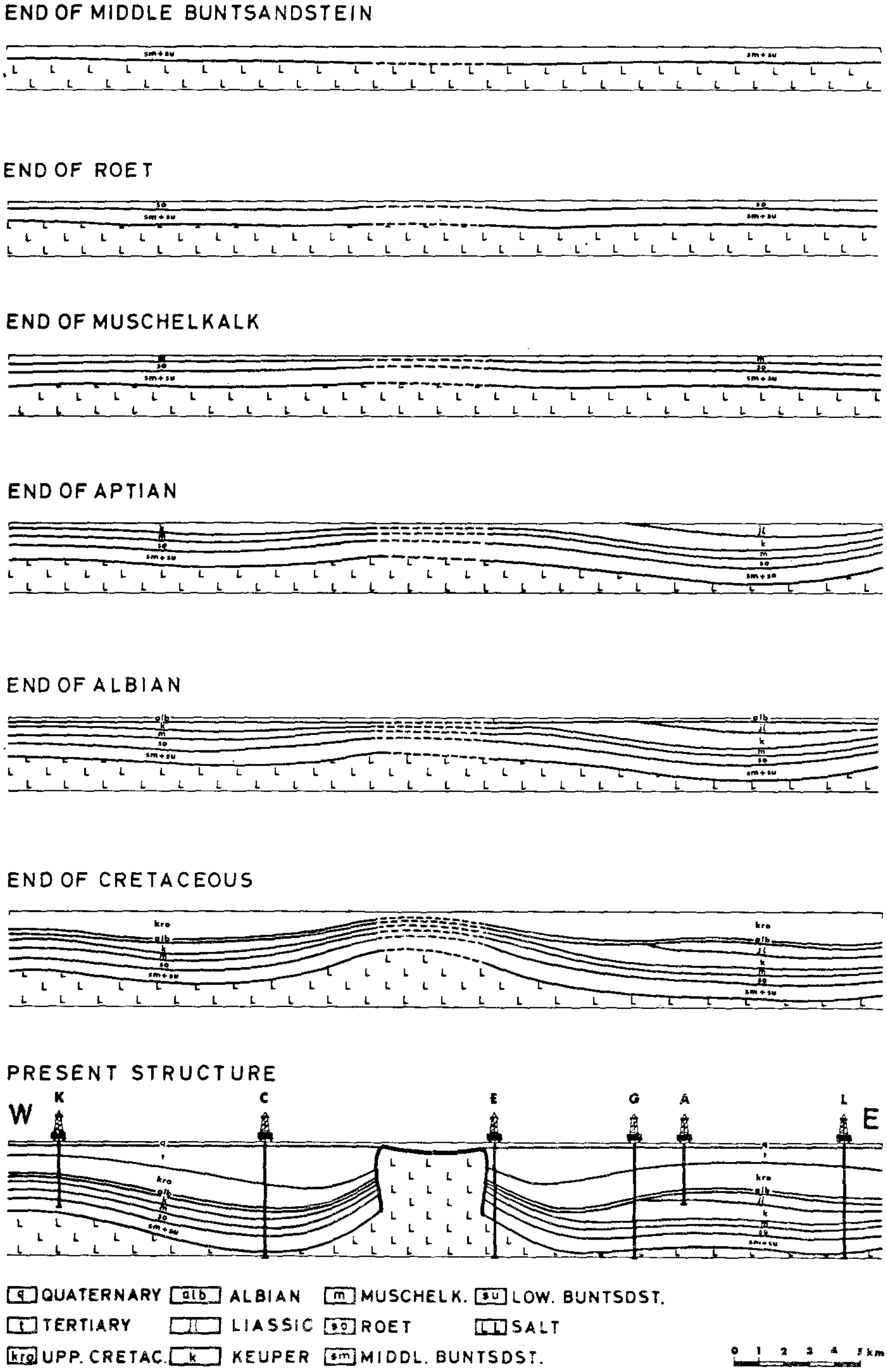

Fig. 12. Structural development of the saltdome.

Following Trusheim (1957) the development of a saltdome can be divided into two stages. During the pillow-stage, the salt begins to flow into the region of the later diapir. This is caused by primary instabilities inside of or above the salt. The diapir-stage begins with the intrusion of salt into the overlying layers. When an isostatic equilibrium is reached, the salt can flow horizontally and build the wellknown overhangs. Halokinesis can be halted by either underfeeding or by an increase in the thickness of the overlying sediments. The mass deficit in the vicinity of the dome caused by the salt flow is compensated by increasing sedimentation in the socalled rim synclines or peripheral sinks. Based on the two stages of diapir development the primary and secondary rim synclines can be distinguished. Primary rim synclines belong to the pillow phase. They show decreasing thicknesses into the direction of the pillow. Secondary rim synclines are the expression of the mass compensation during the diapir stage. Their thicknesses decrease with the distance away from the diapir. The development of the saltdome can be seen by backstripping of the sediments along a chosen cross-section (Fig. 12). The pillow stage started probably during the Muschelkalk and is marked for sure pre-albian. The salt flow started in the eastern part of the studied area where the liassic sediments were protected against pre-albian erosion. The diapir stage began during the Tertiary so that the accompanying rim syncline may be described as secondary after Trusheim (1957).

4. The estimation of subsidence and uplift rates from geological data

The sediment thickness gives a quantitative measure of the subsidence in the area. Subsidence diagrams as shown schematically in Figure 13 allow an estimation of the rate of vertical movement occurring during geological history. For the analysis of seismic velocities it is important to remember that if a layer is presently at its deepest position, the velocities will not document former subsidences which did not reach the present depth. Uplift is only expressed in the velocity if during subsidence the cumulative thickness exceeded the present one. For the horizontal section of the subsidence diagram no sediments are present, either because nothing has been sedimented or because sediments have been eroded.

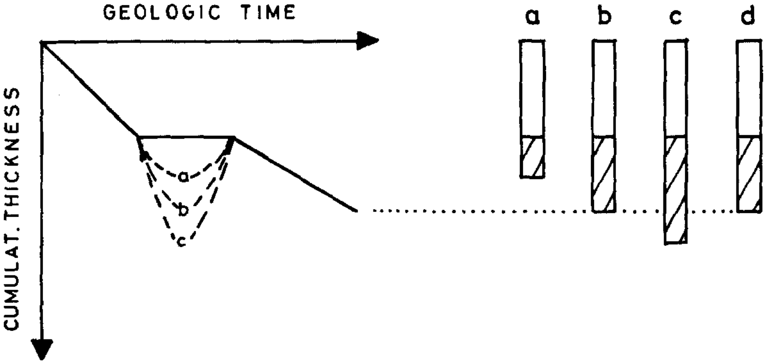

Fig. 13. Subsidence diagram and the corresponding cumulative thicknesses (columns a—d).

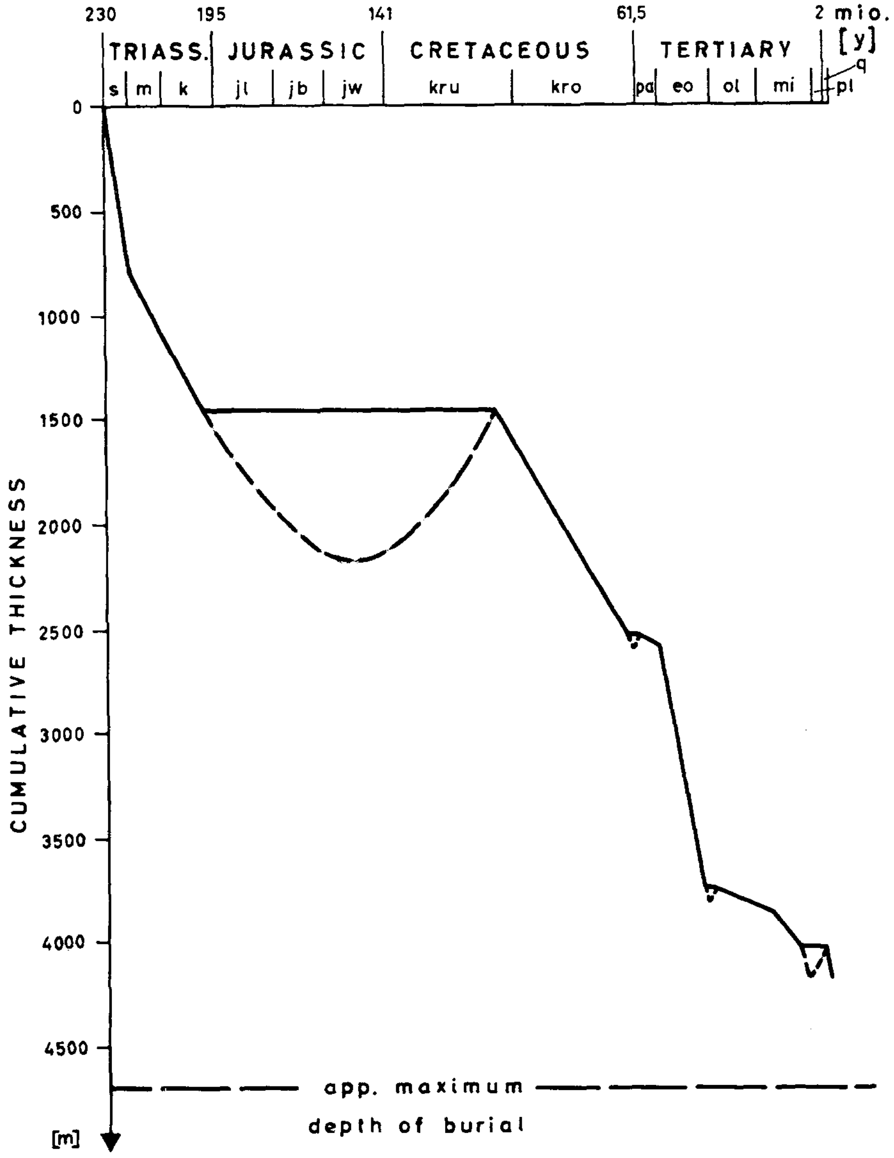

Fig. 14. Subsidence diagram for well C.

For the second case, three different possibilities of development for the time of the sedimentation gap are shown. The columns on the right of the picture show the related cumulative thicknesses. Column d shows the present thickness. Only the development corresponding to line c could be documented in the velocities. Figures 14 and 15 show the subsidence diagrams for the wells C and E together with the apparent maximum depths of the burial for the Lower and Middle Bunt-

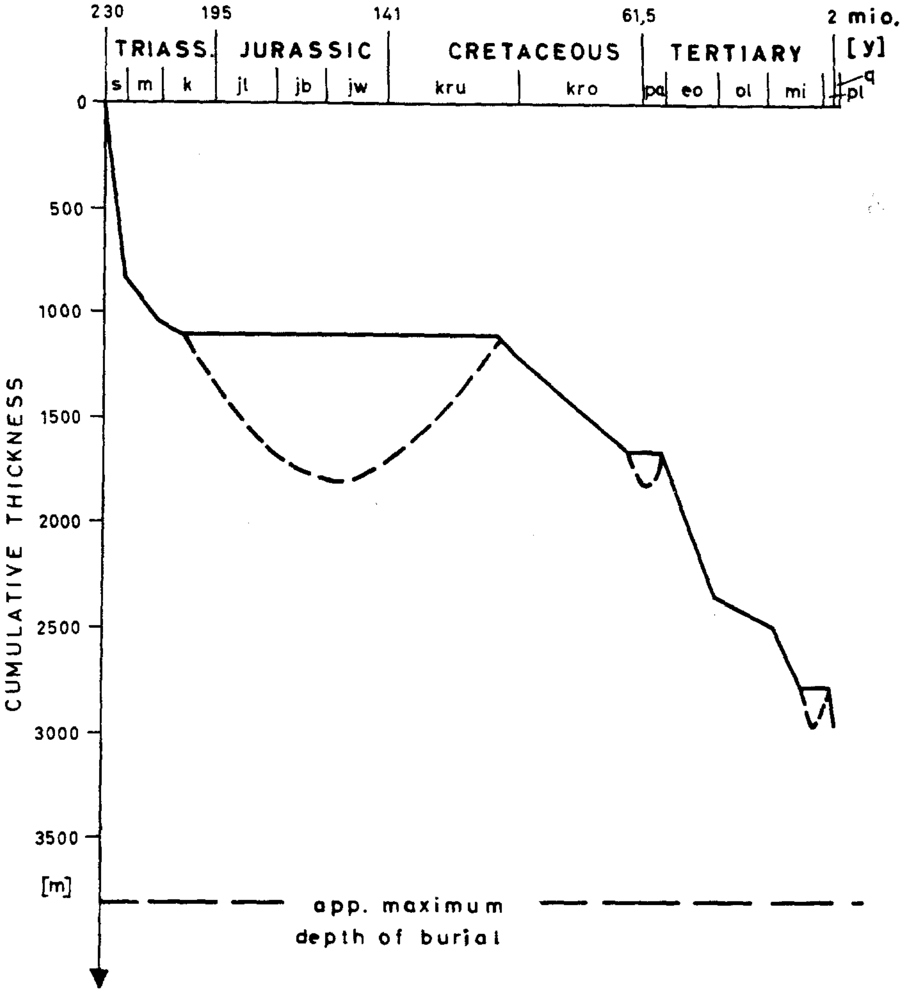

Fig. 15. Subsidence diagram for well E.

sandstein, estimated from the velocity data. The structural position can be seen from Figure 12. The interpretation of the estimated apparent uplifts as true tectonic movements demands that the maximum cumulative thickness reached at least once the so-called apparent maximum depth of burial. The sediments deposited during this time could have been eroded as a result of an uplift stage. Possible uplift stages as indicated from gaps in sedimentation are (Figs. 14 and 15):

— between Keuper and Albian
— between Maastrichtian and Danian
— between Upper Eocene and Middle Oligocene
— between Middle Miocene and Quaternary

The gap between Keuper and Albian as explanation for the estimated vertical movements demands desposition and erosion of at least 3200 m (well C) and 2500 m (well E) of Lower Jurassic sediments. Such values cannot be found anywhere in the region of the Pompeckj-Swell (Hoffmann 1949). The gaps between Maastrichtian and Danian and between Eocene and Oligocene can also be excluded in explaining the apparent maximum depths of burial as the demanded rates of sedimentation are unrealistically high.

During the time of the youngest gap, regression occured in the Northwest German Basin. During the Pliocene the coastline ran through the present Netherlands. Only the western part of the NW-German Basin lay under shallow water (BETTENSTAEDT 1949). On average 30 m of Upper Miocene deposits of the Langfeldian stage are to be expected for the studied area after HINSCH (1965). This could not explain several hundred meters of subsidence and uplift.

Even the differences of the apparent uplifts for the different wells exceed the amount of explainable tectonic movements. This means however, even if we take into account an inaccuracy in the determination of the initial values of the depth-velocity function the remaining apparent uplifts cannot be explained as due to true tectonic movements.

All the geological data reveal that the layers of the investigated area presently lie at their deepest positions. The halokinetic uplift in the environment of the saltdome occurred only as a negative phenomenon, that is a minor rate of subsidence. This is supported by the fact that no spatial variations in the amount of erosion of upper miocene and pliocene material occur. Stronger erosion in the regions of stronger uplift could be expected if true vertical movements had taken place.

5. Discussion and conclusions

The tectonic interpretation of the seismic velocities was based on the assumption that the deviations from the initial depth-velocity function are documents of tectonic movements. This seems to be supported by the spatial distributions of the so-called apparent uplifts. Uplifts of several hundred meters seemed to be possible from this point of view. The geological data however, show, that the layers of the investigated area are presently in their deepest positions. Subsidence and uplift rates which could have been documented in the seismic velocities can be excluded with high precision. The apparent uplifts have to be therefore due to other factors. These could be:

— lithological variations
— extra compaction due to glaciation during the Pleistocene
— compression in connection with the saltdome development (compaction halo).

It is difficult to explain fully the spatial distribution of the seismic velocities by only lithological variations. For example, for the Lower and Middle Buntsandstein no geological structure existed which could explain the velocities by facies differences (Fig. 12).

During the Pleistocene large areas of NW-Germany were under ice. The estimated thicknesses vary from 200—400 m (DÜCKER 1951, BERNHARD 1963).

It has been observed in the Molasse Basin that ice load could have led to seismic velocity increases by extra compaction (personal communication Hrubesch). On the other hand it would be expected that compaction due to ice load should have occured over the whole area to the same extent. The spatial distribution and the relation to the saltdome remains therefore still unexplained. Other effects have to be taken into account such as lateral compression during saltdome development. Reich (1945) and Lohr (1969) interpreted increases in seismic velocities from north to south in the vicinity of the Alps by lateral tectonic pressure. During salt intrusion, the initial horizontal stress in the salt will be much higher than the horizontal stress in the surrounding sediments. Outward movement of the salt brings about the compaction of the surrounding material (compaction halo) unless the stresses are equalized (Fyfe et al. 1978). During the pillow stage, extra compaction could be due to buoyancy forces inside of the growing diapir. This would explain the high apparent uplifts for the wells situated on top of one of the salt pillows compared to those situated in the peripheral sink. For the Tertiary however, only the dominating influence of the diapir-stage can be seen in the seismic velocities possibly together with the effect of the ice load during the Pleistocene.

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