GEOPHYSICAL STUDIES OF THE PAARUP SALT DOME, THE DANISH EMBAYMENT

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The Paarup salt dome in the Danish Embayment has been studied by seismic, gravimetric, magnetic, and electric methods. Reinterpretation of earlier models based solely on gravity studies is presented. The salt dome has intruded into the overburden to the region of the Tertiary/Cretaceous interface which is lifted and falls off away from the dome. The mushroom-shaped dome has a tilted upper surface found at a depth of about 150 m in the SW part of the profile down to about 270 m in the NE part. The heavy cap-rock has a wedge-like shape penetrating deep down into the salt masses, thus indicating that the upward flow of the salt dome has ceased.

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The Paarup salt dome is situated at the heart of Jutland, Denmark, north of the Ringkøbing-Fyn basement ridge and within the Danish Embayment which is part of an elongate sedimentary depression opening up towards the epicontinental North Sea basin (see fig. 1). The Paarup dome constitutes part of a line of salt domes extending parallel to the axes of both the Danish Embayment and the Ringkøbing-Fyn High. Like most of the salt domes in Denmark, (Ødum, 1960; Larsen, 1966; Sorgenfrei, 1966) the Paarup dome is hidden beneath Quarternary and Tertiary deposits, and only faint topographic expressions of the dome can be observed on the rather flat surface (Madirazza, 1968).

Recently Ramberg & Lind (1968) carried out a detailed gravimetric study of the Paarup dome and presented the general geology of the area. The present paper discusses the previously obtained interpretations in the light of the new geophysical data, especially seismic and resistivity data, obtained by the authors during 1968 and 1969.

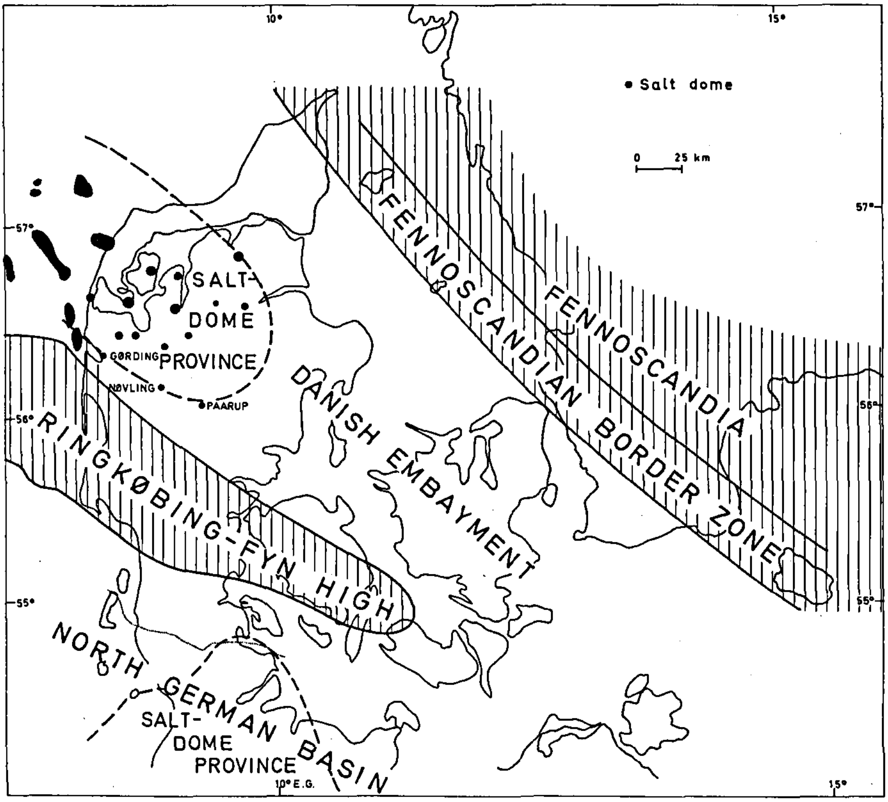

Fig. 1. Generalized structural map of Denmark. Location of the Paarup Salt dome is marked at the southern periphery of the Jutland dome province.

Seismic studies

Both refraction and reflection techniques were applied during the survey. The instruments used for the measurements consisted of the following units:

Amplifier:	El 40–42, Shell
Oscillograph:	AF – 25, August Fischer
Geophones:	HS-I, natural frequencies 14 c. p. s.

The seismic surveying was carried out along a line 4.0 km long. The charges varied between 2 kg to 25 kg T. N. T. Depth of charges varied between 3 m and 5 m. Each detector-spread covered a length of 500 m, and the records were taken on 24 channels. For the reflection shooting only center shots were used, while for the refraction shooting each of the shotpoints were recorded in a distance varying between 0 km up to 2.7 km by repeated shooting in each point, and by moving the cable the desired distance.

Interpretation

The depths to the different layers have been calculated by the method of Wyrobek (1956). The seismic cross section made at Paarup is shown in fig. 2. The location of the SW–NE running profile in relation to the gravity anomaly is marked on fig. 4.

The velocity of the seismic waves in the Quaternary and Tertiary deposits varies between 1600 m/s and 1800 m/s along the measured profile.

In the area from point 0 to 1300 along the profile a layer with velocity 3300 m/s – 3500 has been registered. This layer is likely Upper Cretaceous as the velocity corresponds very well to the velocity commonly obtained in Cretaceous rocks. In the area between 1300 m and 3100 m the velocity increases to 6000 m/s – 7500 m/s. This velocity most probably corresponds to the velocity in salt or cap-rock. The depth from the surface to the dome increases in the north-east direction and varies between 150 m and 270 m. The velocity of 3000 m/s which has been registered in the area between 1500 m and 1800 m, may correspond to a jointed or crushed zone in the salt dome. However, it is also conceivable that the dome forms a depression which is occupied by Cretaceous rocks in this area.

Along the NE part of the profile a velocity layer of 3200 m/s has been registered, which probably belongs to the Upper Cretaceous. In the discussion above the seismic velocity has been used to identify the different layers. The velocity 6500 m/s – 7000 m/s is very high (Clark, 1966) and is interpreted to be caused by a very dense cap-rock.

Generally the velocity in salt is around 4700 m/s, a figure normally found in the North Sea (Christian, 1969). This means that the cap-rock forms a high velocity layer, surrounded by layers with lower velocities. It is a known fact that relatively thin and shallow high velocity layers present considerable problems for seismic surveying. Such layers form a screen for the seismic waves and in both reflection and refraction surveying, it is therefore often difficult to obtain arrivals from the deeper layers. Observation from both model and field work shows that the propagation of energy of refracted waves abates very quickly along such layers if the layer thickness d and the wave-length λ fullfill the equation $\frac{d}{\lambda} < 0.2$. Poley & Nooteboom, 1966; Meissner & Meixner, 1969).

A study of the energy from the high velocity layer (cap-rock) does not show any rapid energy attenuation along the central area of the layer. It

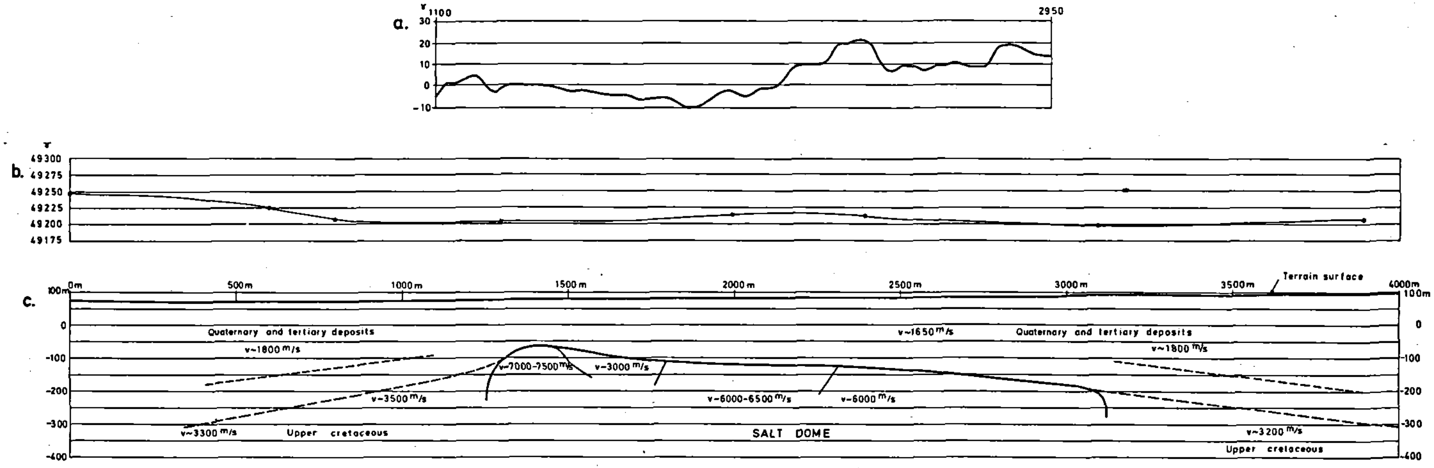

Fig. 2. Seismic cross section and magnetic profiles across the Paarup salt Dome. Profile *a* is a continuous profile while profile *b* is based on a scattered data. Location of the seismic and magnetic profiles is the same as for the gravimetric profile marked on fig. 4.

is therefore reasonable to assume $\frac{d}{\lambda} > 0.2$. From the records the frequency is determined to be approximately 20 c. p. s., giving a wave-length of approximately 300 m.

According to this average thickness of the layer is found to be $d > 0.2 \times 300\ m = 60\ m$, which is a lower limit of the thickness of cap-rock in the central area.

From the reflection measurements reflections were recorded from a number of layers in the Quaternary and Tertiary deposits. For most of the reflections it was difficult to make correlations to continuous horizons, but one continuous reflecting horizon was found at a level of about 100 m above the supposed Upper Cretaceous, as shown in the profile, fig. 2.

Resistivity measurements

Two resistivity soundings were made on top of the dome (centre of gravity high). The measurements were made with an instrument built at the Institute in Aarhus. The two soundings were made on the same spot, but perpendicular to each other, and with electrode configurations according to the Schlumberger technique (Kunetz, 1966). The results of the two soundings are identical, one of them is shown in fig. 3. The curve has been interpreted with master curves (Orellana & Mooney, 1966), the interpretation is presented in fig. 3. The rising curve at the end of the diagram corresponds to a resistant horizon, most probably cap rock or salt at a depth of 190 m below the surface. This type of curves over salt structures is a well known phenomenon (Gish. 1938; Migaux & Kunetz, 1955; Yungul, 1962). The result from the resistivity method fits the seismic results (see fig. 2) which gives a depth of 200 m below the surface at the point of maximum gravity.

Magnetic measurements

During the gravity survey in 1967 the magnetic total field was also measured at about the same observation points. In all about 90 stations were measured with an Elsec proton magnetometer having an accuracy of ± 1 gamma.

The measurements are reduced for daily variations with the help of continuous records from the Magnetic Observatory at Rude Skov. The result of the same profile as the gravity and seismic is shown in fig. 2. It is difficult from this result to see if there is an anomaly associated with the salt dome; it looks as if there could be a very small negative one.

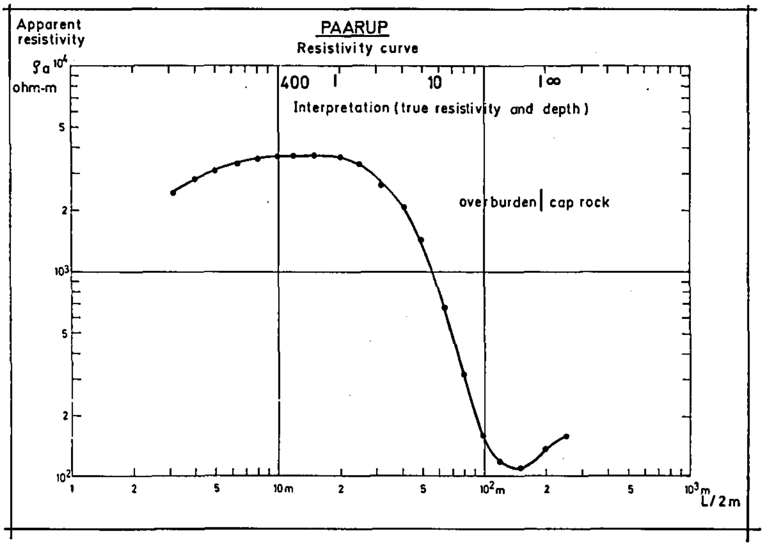

Fig. 3. Geoelectrical sounding at centre of the Paarup salt dome. Interpretation is shown at the top. L/2 is half distance of current electrodes and this scale is also used as depth scale.

In 1971 a continuous profile was measured approximately at the same site as the previous mentioned one. The measuring equipment consists of an Elsec proton magnetometer with a paper recorder mounted on a vehicle which can be pulled along tracks and roads. Distance (every 10 m) is measured and marked electronically on the magnetogram. The continuous profile is shown in fig. 2 and confirms that there is a small negative effect at least in the southern part, where the salt masses come closest to the surface.

Gravity studies

The gravimetric measurements were performed with a Worden Master gravity meter (No. 779). 89 new gravity stations were occupied in addition to the original measurements on professor Saxov's unpublished Bouguer anomaly map of central Jutland. For the corrections a Bouguer density of 2.0 g/cm^2 was used, tidal gravity corrections carried out, but no terrain corrections applied.

The obtained gravity field (fig. 3 in Ramberg & Lind, 1968) has been separated into a regional and a residual effect, the former being a part of the regional Silkeborg gravity high. The residual map (fig. 4) reveals a wide, sharp positive anomaly superimposed on an elongate gravity low. The resi-

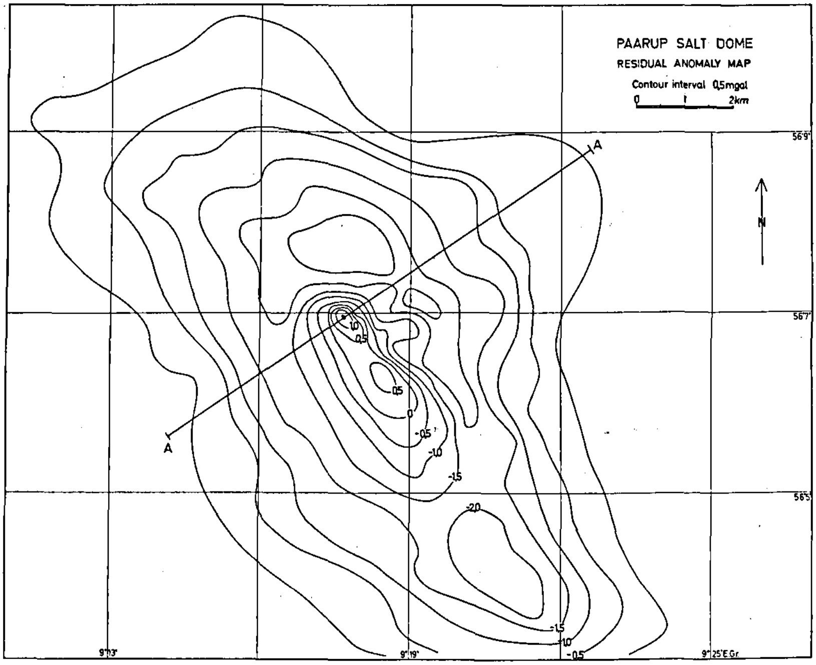

Fig. 4. Residual gravity anomaly map of the Paarup salt dome area. Seismic, magnetic and gravimetric profiles follow the line A – A. Resistivity measurements were made close to the maximum gravity anomaly.

dual low is part of a much longer negative anomaly with its longest axis parallel to the alignment of the salt domes Paarup, Nøvling, and Gørding (see Fig. 1).

The residual low is ascribed to the mass deficiency caused by the underlying salt dome. Judging from the shape of the residual gravity high the cause is necessarily found at a shallow depth, and the effect is probably due to a relatively thick cap-rock.

The preliminary interpretation in Ramberg & Lind (1968) was based on gravity data only, since other geophysical, or local geological data (except one well drilled in the Quaternary overburden) were lacking. Several models on the basis of various density contrasts were presented. The model having the least density contrast between salt and side rock is presented in fig. 5, together with an assumed stratigraphical column for the area investigated. The salt mirror was for the sake of simplicity defined by a horizontal plane at a depth of 450 m which was considered the maximum depth for the zone of circulating ground water. The cone-shaped cap-rock was placed at the top of the salt. Depending on the mineralogical composition of the cap-rock the

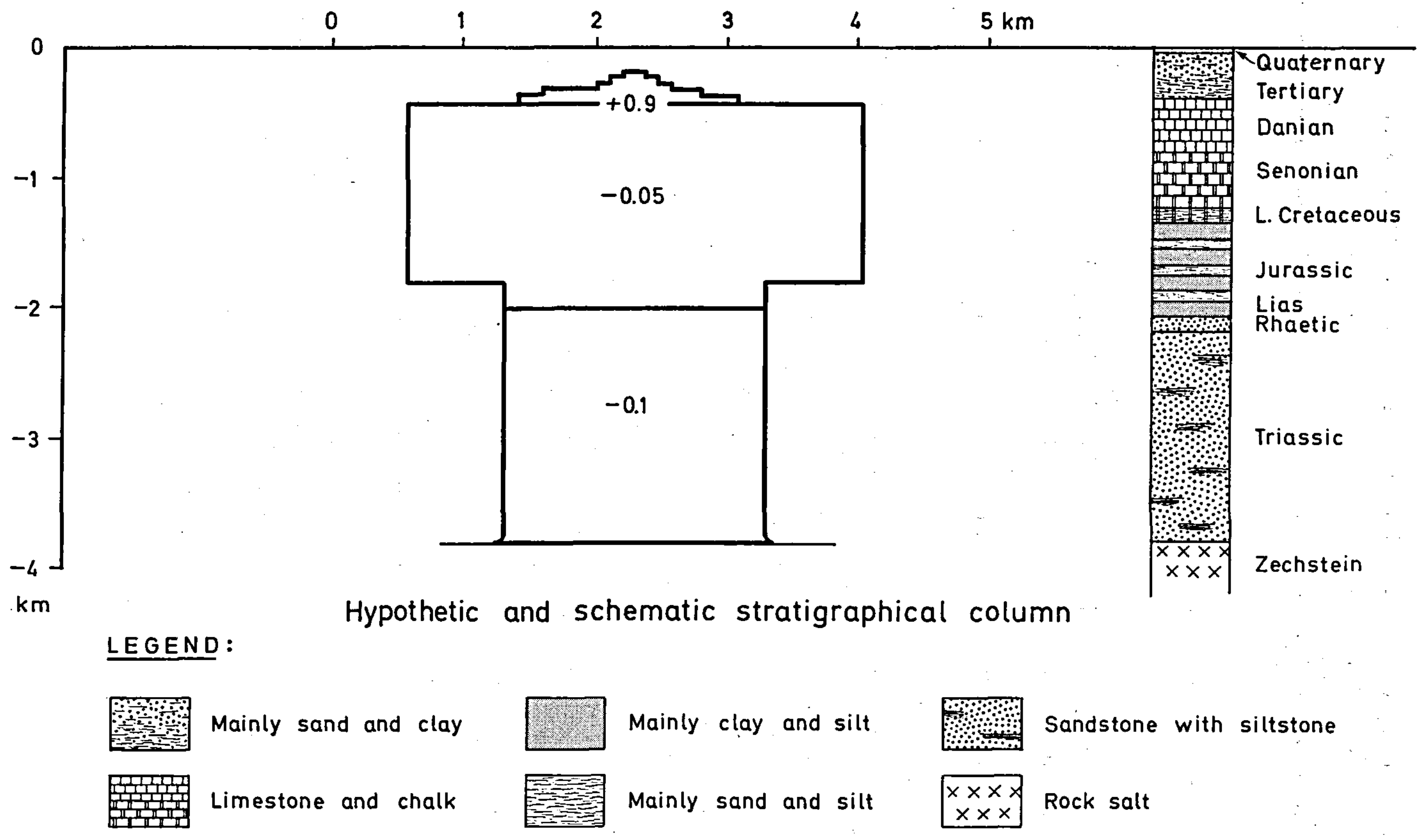

Fig. 5. Salt dome model presented in 1968, (figs 9c and 11 in Ramberg & Lind, 1968). Calculation is based on shown residual effect (fig. 4) and the density contrasts marked on the figure. Hypothetic stratigraphical column of the area is shown to the right.

depth to the top was calculated to 50 m, 125 m or 200 m below the surface using the minimum (+ 0.4 g/cm^3), mean (+ 0.7) or maximum (+ 0.9) density contrasts, respectively.

Interpretation of the geophysical data

The seismic and resistivity measurements have furnished valuable information that restricts the interpretation considerably. The depth to top of the dome is determined, and it is clear that the flat-toped dome forms a tilted plane which is most shallow (about 150 m) in the SW end of the profile (fig. 2). The cap-rock does not stand up like a pyramid; on the contrary, to fit the sharp gravity high the width of the cap-rock must rapidly be diminished downwards.

The P-velocities indicate the densities of the various lithologic units. Following the density/seismic velocity curve of Nafe & Drake (Talwani et al. 1959) the observed velocity range 16–1800 km/s in the Quaternary and Tertiary deposits may equal a mean density of 1.75 g/cm^3 which is 0.25 g/cm^3 less than assumed in the previous paper. Similarily the velocity range of 33–3500 km/s in the Cretaceous rocks equals about 2.3 g/cm^3 (the same as before). The velocity in the cap-rock is about 60–6500 km/s except in the SW end of the profile; this equals a density of about 2.85 g/cm^3 with local increases to about 3.2 g/cm^3 which is extremely high.

From the profile in fig. 2 Cretaceous beds are lifted so that the cap-rock is mainly surrounded by Cretaceous rocks and not so much by the Tertiary, thus giving rise to a density contrast of at least 0.9 g/cm^3 which is the maximum contrast used in the previous model computations. It is also clear that the density contrast between the rock salt (ϱ = 2.2–2.3 g/cm^3) and the Cretaceous is very little ($<$ 0.1 g/cm^3), but will increase within the more dense Triassic sandstones and siltstones at depths of about 2 km and downwards.

Thus by separating the residual field (fig. 4) into a rocksalt effect and a cap-rock effect in the manner described in Ramberg & Lind (1968), new gravity models can be calculated taking into consideration the information given above. For both cap-rock and rock-salt the calculations were performed by application of a Gier-Algol programme developed by Henkel (1969) for two-dimensional bodies making use of the formula according to Talwani et al. (1959). End correction was used following Nettleton's method (1940, p. 117).

For the cap-rock the + 0.9 g/cm^3 was chosen as the best density contrast. Its upper surface was fixed by the seismic interpretation and the lower was determined from the gravity anomaly, fig. 6. A still better fit between

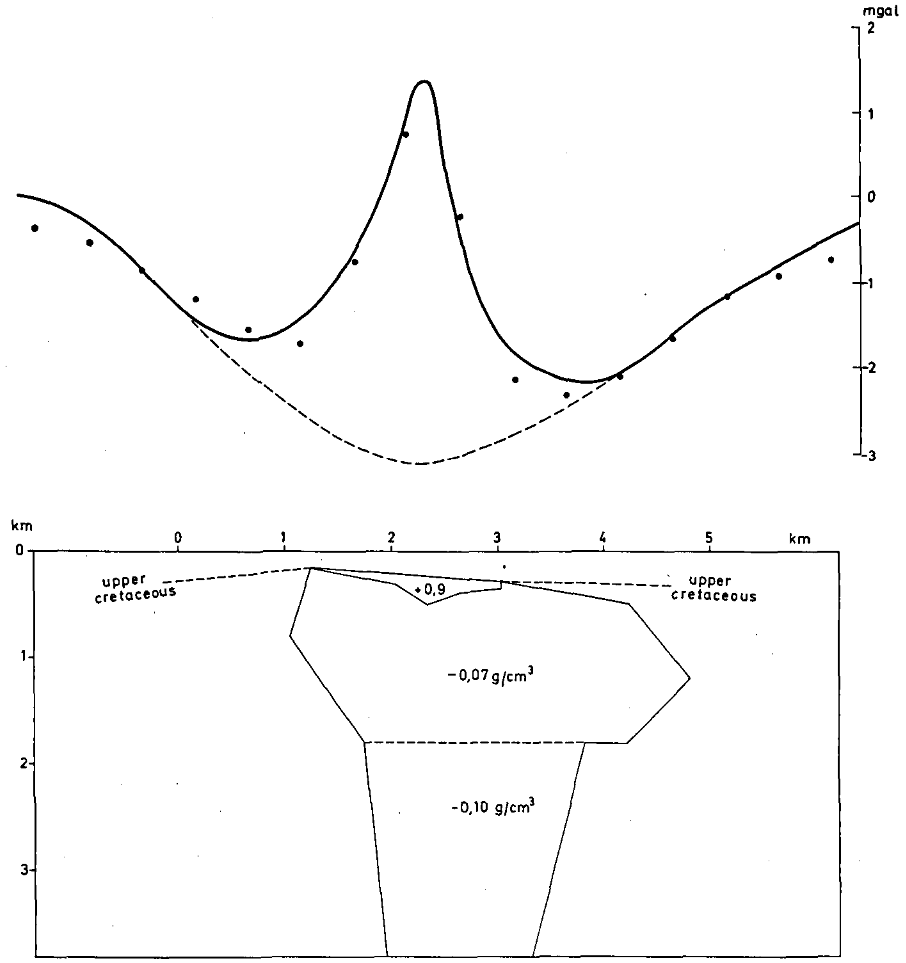

Fig. 6. Revised salt dome model. Calculation is based on the same residual effect as in fig. 5. The upper surface of the wedge shaped cap-rock was determined by the seismic data

observed and calculated anomaly will occur if the upper surface is assumed not to be perfectly flat, but that occasional bumps of cap rock material exist above the shown plane close to the center of the anomaly. Once the lower surface of the cap-rock is determined, the computations of the salt model can be done much more safely, fig. 6. Still the model does not offer any unique solution. Alternative model domes that satisfy the anomaly are possible, and small deviations in the real density contrast will make the models larger, while increased density contrasts will make smaller.

Concluding remarks

The combined geophysical methods removed many of the uncertainties that made the previous gravity interpretations ambiguous. When the stratigraphical parameters (depths and density variations) are known, the shape of lateral density variations, however, can be computed within small limits of error.

The geological implications of the geophysical models of cap-rock and salt (fig. 6) are that the salt masses have spread out in a wide upper half of the dome, and that the cap-rock is thickest in the middle of the dome and forms a relatively even upper surface. Such an enlargement close to the top is quite common in salt domes (Richter-Bernburg & Schott, 1959; Barton, 1946) and seems to be the case also for the Danish Gørding and Linde salt domes from where detailed seismic profiles have been published (Sorgenfrei, 1966). Horizontal spreading will occur when the rising salt masses hit rigid strata in the overburden. It may also result from subaquatic or sub-surface extrusion. The position of the salt mirror close to the Cretaceous/Tertiary interface beneath the dense Tertiary blue clays might support the first explanation in Paarup.

The inverted wedge shape of the cap-rock in Paarup seems a little different from the common flat lying "caps" of insoluble residue. The occurrence of a dense cap-rock on the top of the light rock salt is of course a gravitationally unstable situation which only can be maintained by the upward streaming of the salt. If the rise of the salt eventually ceases the cap-rock material will start a down-ward movement in the same way and by the same gravitational reasons that made the salt dome rise. Thus the shape of the cap-rock in Paarup might indicate that the buoyant movement of the salt masses has stopped some time ago, allowing the heavy residual masses to sink down into the rock salt.

The gravity low at Paarup is part of a more than 25 km long, elongate low in the direction of several known salt domes. The Paarup salt dome is probably a funnel-shaped protuberance arising from a regional salt wall running in the WSW–ESE direction which is characteristically found in the North German basin and probably also in the Norwegian Danish basin of the North Sea region.

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Dansk sammendrag

Seismiske, gravimetriske, magnetiske og elektriske metoder har været anvendt ved et studium af Paarup saltdomen. En ny tolkning præsenteres, og det konkluderes, at saltdomen har intruderet dæklagene op til grænsen mellem Kridt og Tertiær. Den pilzformede domes overflade ligger i den sydvestlige del i 150 m dybde og i den nordøstlige del i 270 m dybde. Cap rock-strukturerne antyder, at saltbevægelsen er ophørt.

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