Gravity and geological structure of the Fennoscandian Border-Zone in the southern Baltic Sea

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A new Bouguer anomaly map of the Baltic Sea surrounding the island of Bornholm, Denmark, shows unusually large positive and negative anomalies. These anomalies are interpretated geologically. Basement horsts or uplifts separated by sediment basins in between are demonstrated north and west of Bornholm. A 4–6 km deep part of the Danish-Polish sediment trough has been discovered south-west of the Fennoscandian Border Zone in the Baltic Sea.

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The boundary between the eastern Danish-Polish Trough and the Fennoscandian Precambrian Shield is a complicated block-faulted zone called the Fennoscandian Border Zone. In southernmost Sweden, the border zone takes the form of a belt of basement horsts with intervening subsided sediment blocks.

For a long time, the island of Bornholm in the southern Baltic Sea has been considered to be a horst forming a continuation of the border zone in the Baltic. A recent shallow marine seismic investigation around Bornholm has deliniated a number of down-faulted sediment blocks between the banks north and east of Bornholm (Larsen, in prep.). It was assumed that the banks were high-lying basement horsts, but positive evidences were lacking.

Bouguer gravity maps of Bornholm (Nørgaard 1939, Saxov 1945) and of southern Sweden (Wideland 1946) show that the basement horsts in the border zone caused marked positive Bouguer anomalies. The few published gravity measurements from the southern Baltic were too sparse (Honkasalo 1960) or too unreliable (Haalck 1935, Nørgaard 1939) to allow geological interpretation, but demonstrated a very variable gravity field around Bornholm.

The Danish Geodetic Institute conducts a systematic gravity surveying of the Danish waters, the results of which have been published in part (Andersen 1966). As part of this measuring program, gravity measurements were carried out, in 1972, in the Baltic Sea from Sjælland-Falster to Bornholm. An elaborate report comprising all measurements from the Danish waters will appear in the series of publications of the Geodetic Institute when a homogeneous surveying of all Danish interior waters has been accomplished. As the gravity information is of importance to the present geological interpretation, the preliminary results of the measurements around Bornholm will be given here. The aim of this paper is, furthermore, to elucidate some of the major geological structures in the light of the available seismic and gravimetric data. O. B. Andersen is responsible for the gravity measurements, S. W. Platou for the geophysical interpretation, and B. Larsen for the geological and seismic interpretations.

Gravity measurements

The measurements were recorded by a Graf-Askania seagravimeter on a gyro-controlled platform (Andersen 1966).

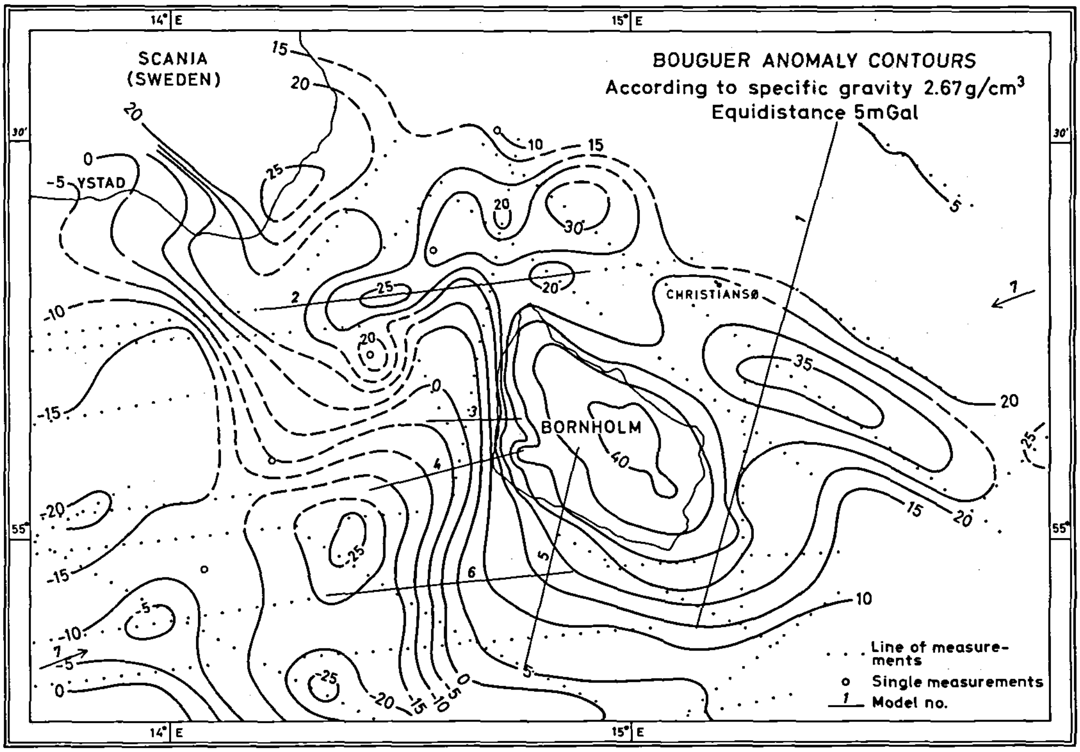

Fig. 1.

The gravimeter is basically a static instrument, modified for use under dynamic measuring conditions. As it is sensitive to all kinds of accelerations, the true gravity has to be determined by a measuring procedure which makes allowance for the enforced accelerations from the ship's motions.

The gravimeter was used in its automatic mode during the whole survey and continuous gravity records were obtained while the ship was sailing with steady course and speed along the measuring profiles.

The navigation was based on Decca-positions from either the Danish chain 7B or the Swedish chain 0A. Continuous depth profiles were recorded by normal echo-soundings to provide data for the Bouguer corrections.

All the data were reduced and controlled by a computer program (Andersen 1972) from which the final output was gravity anomalies for a sequence of measured points within each period of steady navigation.

The mean error of the individual gravity measurements is estimated at 2 mgal.

Gravity results

The Bouguer anomaly map (fig. 1) is based on gravity values approximately 2 km apart along the lines indicated. A few measurements of Honkasalo (1960) have been included. The Bouguer contours of Bornholm, according to Saxov (1945), are recalculated, using a density of 2.67 g/cm³ in the Bouguer correction, while those of Sweden are cited from Wideland (1946). At sea, the contour lines suffer from the relatively wide spacing of the anomaly determinations. Nevertheless, the results indicate a gravity anomaly pattern which is remarkably varied.

Bornholm appears clearly on the gravity map as a positive anomaly, and similar highs occur to the north and east of the island. Another pronounced trait is the steep gravity gradients south-east of Ystad and along the west coast of Bornholm, which separate the area of Scania-Bornholm from the area of low anomaly values towards south-west. A steep gravity gradient stretches in a south-easterly direction from Sweden through Christiansö.

The exact extent of this gradient is not known, but it exceeds 30 mgal at the eastern side of the map. The whole region, including Bornholm and Christiansö, is thus a major positive, south-east-trending anomaly upon which minor anomalies are superimposed. The uncertain northern gradient of this large anomaly makes it very difficult to separate the different minor anomalies.

Method of interpretation of the anomalies

The interpretation was carried out by means of an Algol computer program (Platou 1972), which calculates the effect of two-dimensional models composed of any number of submodels. It wâs made directly on the measured values without smoothing or interpretation and was carried out directly on the graphical display.

It is a general problem that the two-dimensional models imply infinite extension of the blocks perpendicular to the profile, but the geological structures causing the anomalies are seldom two-dimensional. In practice, 'infinite' means two to three times the width of the structure in the direction of the profile.

If this condition is not upheld, the interpreted structures will be narrower than the real structures and this causes the anomalies and the dip of fault planes to be somewhat affected. However, vertical distances (e. g. depths of graben structures) will not be affected.

Another general problem involved in interpretation is one of ambiguity. This arises because the same anomaly can result from different combinations of critical parameters.

The parameters which may be variated freely are the density contrast and the depth to the bottom of the basins as well as the positions of some of the faults. The effect of different density contrasts is mainly that it changes both the calculated depth to the bottom of the basins and the dip angle of the fault planes (cf. figs 5 and 6). Therefore, the broad structures obtained from the interpretation cannot be changed very much; but details such as complexity of boundary fault zones and the existence of local structures may well be added to the interpretation. However, to evaluate such details, far more measurements than available at present are required.

An important local problem is the often unfavourable distribution of measurements in relation to the geological structures of interest.

From the foregoing discussion it is clear that the choice of density contrast to be used in the geophysical interpretation is critical. The average density of the basement rocks is 2.67–2.70 g/ccm – a figure derived from an estimate of the volumes of the different rock types which comprise the basement at Bornholm (Platou, unpubl.). In the Bouguer corrections, a density of 2.67 g/ccm is used. A density of 2.2–2.25 g/ccm has been used for assumed Lower Mesozoic rocks near Bornholm. This value is based on several hundred density determinations on assumed similar sediments from Øresund (Geotechnical Institute 1964).

A density of 2.43–2.50 g/ccm was used for assumed Cretaceous limestone and Palaeozoic rocks (Saxov & Abrahamsen 1964).

The interpretations and the geology

The positions of the positive anomalies correspond fairly well with the areas which, on the basis of seismic and geological evidence have been considered as horsts (Larsen in prep.). Since Christiansö and northern Bornholm consist of basement rocks, it is very likely that other positive anomalies in the region may be attributed to the relatively high density of basement rocks in relation to the surrounding sediments.

A major positive anomaly straddles the whole of the Fennoscandian Border Zone around Bornholm. This regional anomaly extends across Scania (Wideland 1946) and, possibly, further northward (Åm 1973). A marked decrease in Bouguer anomaly is observed across the north-eastern border of the Border Zone in Scania, but only relatively insignificant sedimentary basins exist in this area. Thus, the cause of most of the gravity gradient has to be found at a deeper level. The same may, to some extent, be true of part of the anomaly around Bornholm. This is further discussed on p. 51.

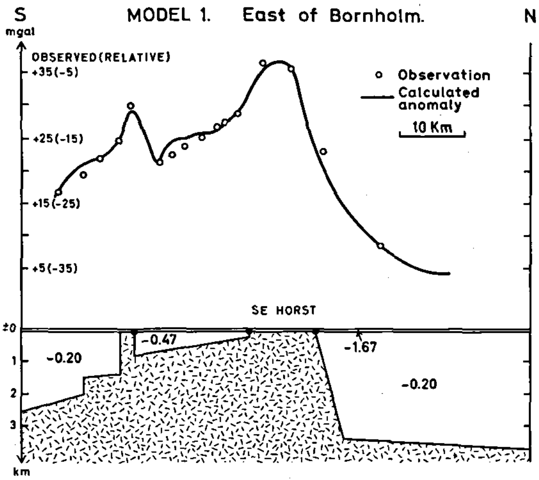

Fig. 2. Interpreted section across the south-east horst and the sedimentary basin east of Bornholm (cf. fig. 1). The marked corners are determined by seismic evidence. The estimated thickness of the sediments north of the south-east horst is probably too high due to regional gravity anomalies.

The South-east Bank

Model 1 (fig. 2) across the 35 mgal anomaly north-east of Bornholm tests whether the South-east Bank might be a basement horst. The section crosses a low bank – the South-east Bank. From seismic evidences (Larsen, in prep.) it is known that towards north and south the bank is surrounded by sediments of unknown thickness. No sediments have been detected inside the bank itself. From the gravity interpretation it appears that this bank represents a basement horst. The calculated boundary faults correspond well with those determined seismically. The curvature of the gravity anomaly requires that the top of the density contrast, i. e. the top of the basement, closely approaches the sea bottom. The displacement of the northern boundary fault has been estimated to be of the order of 2–3 km (figs 2 and 7). This estimate is probably too high due to a possible presence of a significant regional anomaly. The southern boundary is a gentle slope in the western part of the horst, but seems to change to a steep fault eastward. This is in accordance with the seismic evidences. The western boundary could be interpreted as a fault. If so, it must be of minor displacement.

The Hammervand horst and the Bornholm gat uplift

The unfavourable location of the few gravity measurements north of Bornholm does not allow geological interpretations.

A narrow uplift has been traced seismically from the north-western coast of Bornholm northwards, to the Davids bank (fig. 9). An interpretation of the sparse gravity data (Profile 2, fig. 3) confirms that the uplift at 55°19 N consists of relatively dense rocks – most probably basement. The basement is covered by a few hundred metres of sediments. The displacement of the boundary faults is of the order of 1 km. We propose to call this horst the 'Hammervand horst'.

A positive anomaly midway between Bornholm and the Swedish coast suggests the existence of a high-lying block of basement rocks. The extent of the anomaly coincides with a topographic elevation of the sea bottom (cf. Larsen & Kögler 1975). A fault has been observed along the eastern flank of the bank. The nature of the margins of this uplift towards the south and west is not known. We propose the name of 'Bornholm gat uplift' for the structure.

The Rønne fault

A prominent gradient in Bouguer anomaly straddles the west coast of Bornholm. It is caused by a major fault – the Rønne fault – which delimits the Bornholm horst towards the thick Jurassic sediments to the west (Gry 1960, 1969) and continues into the southern

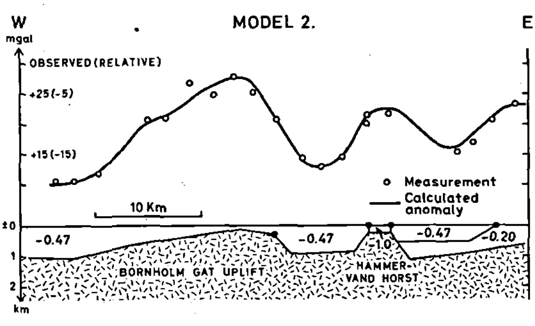

Fig. 3. Interpreted section across the sea between Bornholm and Scania (cf. fig. 1). The marked corners are determined by seismic evidence. The dip of the borders of the Hammervand horst is very uncertain due to a lack of measurements.

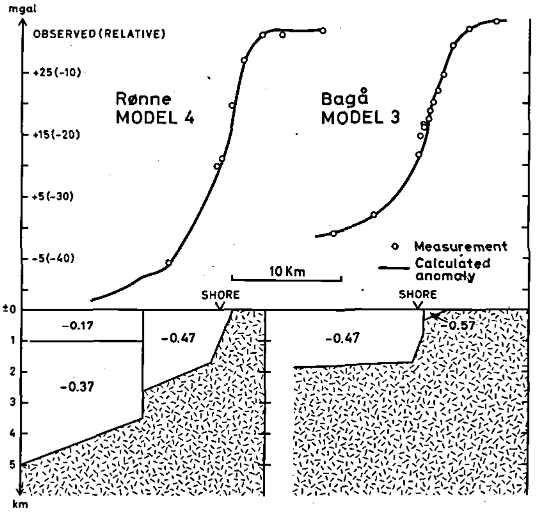

Fig. 4. Interpreted sections across the Rønne fault (cf. fig. 1).
Model 3: The triangular block to the east consists of Upper Jurassic clays and sand. The upper corners of the model have been determined geologically (Gry 1960).
Model 4: The outcrop of the eastern fault is determined geologically (Gry 1960). The other fault and the thickness of the –0.17 layer (Upper Cretaceous) is determined from seismic evidence. A simpler model is shown as part of Model 7, fig. 7.

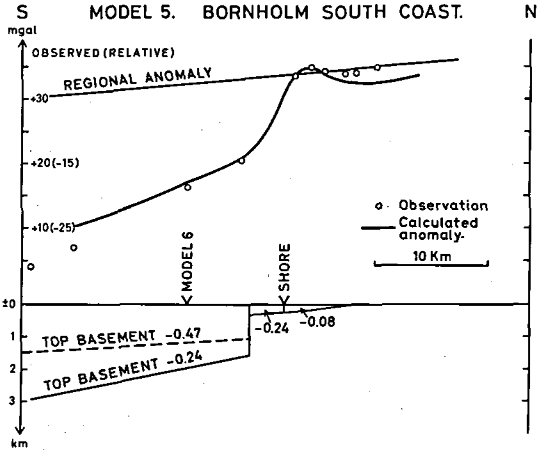

Fig. 5. Interpreted section across the south coast of Bornholm (cf. fig. 1). The northern triangular block consists according to Gry (1960), of Lower Cambrian sandstone and siltstone. The small block offshore represents a supposed extension of the Mesozoic sequence of southern Bornholm. A regional linear anomaly of 3 mgal/10 km has been subtracted before the interpretation was carried out.
In the southern block, – 0.24 was used for the calculated anomaly shown, the anomaly calculated with – 0.47 differs less than 1 mgal from the illustrated curve.

boundary fault of the Hammervand horst. The displacement of the fault was calculated in three sections (at Teglkaas, Bagå (Model 3) and Rønne (Model 4)) using a density contrast of – 0.47 g/ccm (figs 4 and 5). According to the calculation, the surface of the basement is displaced downwards between 1500 and 2000 m west of the fault. The fault plane dips steeper than 40°. The basement is thus covered by a 1–2 km thick series of sediments between the Rønne fault and the Bornholm gat uplift. The thickness decreases towards north.

The Rønne faults at southern Bornholm

The fault ramifies south of Rønne (Gry 1969) and the displacement at the eastern branch (the Rønne Boderne fault) is estimated to be more than 500 m (Münther 1973). The packing of isogals along the south coast of Bornholm possibly indicates that at least a major branch of the main fault follows the south coast close offshore. Model 5 (fig. 5) tests this assumption. According to the geological map (Gry 1969), the basement is covered by a faulted wedge of Lower Cambrian sediments which at Risebæk – the site of Model 5 (cf. fig. 1) attain an estimated thickness of 220 m close inshore. The Arnager Rev is an extension of the outcrops of the Upper Cretaceous formations at the shore and suggests that these formations continue to approx. 2 km from the shore at Risebæk.

It was necessary to subtract a linear regional gradient of 1.5 mgal/10 km from the Bouguer curve in the gravity profile before arriving at an interpretation which fulfills the geological preconditions. The interpretation indicates that a major fault is situated a few kilometres offshore. The displacement of the fault is calculated to 800 m, if a density contrast of – 0.47 between basement and Post Paleozoic sediments is used, and to 1300 m, if the contrast is reduced to –0.27. Therefore, the southern boundary fault of the Bornholm horst is situated within a few kilometres of the south coast of Bornholm.

Faults south of Bornholm

The marked gravity gradient of the west coast of Bornholm extends southwards to

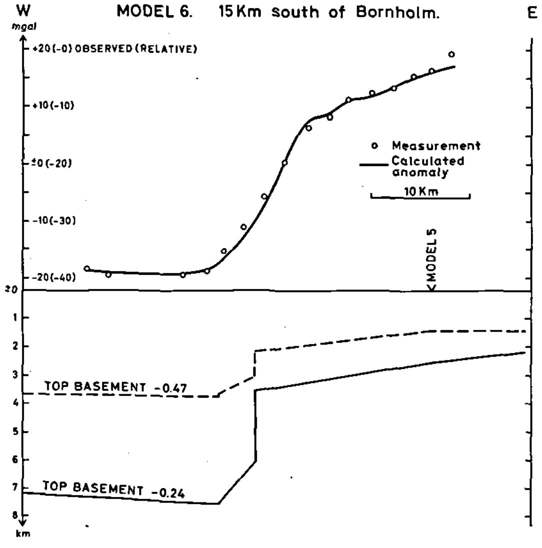

Fig. 6. Interpreted section of the gravity gradient 15 km south of Bornholm (cf. fig. 1). No seismic control. The illustrated calculated anomaly curve is based on a density contrast of – 0.24. The calculated curve for – 0.47 differs less than 1 mgal from the illustrated curve.

54°50N where it turns towards east. However, the maximum gradient – which often marks the position of a fault – is displaced from the Rønne fault some 7 km westward to 14°34E. A large fault has actually been detected at this position in a deep seismic section. This knowledge has been used in Model 4, fig. 4. The basement west of the fault is down-faulted. Considering the continuity of the gravity gradient, it is very likely that the strike of the fault or fault zone is nearly north-south until about 54°50N. It is possibly connected with the Koszalin fault (Dadlez 1974). The displacement of the fault at the top of the basement is estimated in Model 6, fig. 6, and Model 7, fig. 7, to between 1.7 and 4 km for density contrasts of – 0.47 and – 0.24, respectively. The deeper estimate appears to be more in accordance with the available seismic data.

The extension of the fault towards north is not known. A major north-west trending displacement of unknown type is evident from the steep gravity gradient south-east of southernmost Scania, Sweden. The displacement is on a direct line to the south-western fault of the Romele horst, which limits the Danish-Polish Trough in central Scania, but it is probably not a direct extension of this fault. The basement was encountered at a depth of only 719 m in a well in southernmost Scania (cf. fig. 9) (Skoglund in King 1973). This suggests that the displacement at basement level is not very large at the Fyledal fault (fig. 9) adjacent to the well. The gravity gradient across the fault decreases towards east which suggests that the fault fades away eastward. It is, thus, possible that the fault extends south of the Bornholm gat uplift and, very hypothetically, to Bagå at Bornholm.

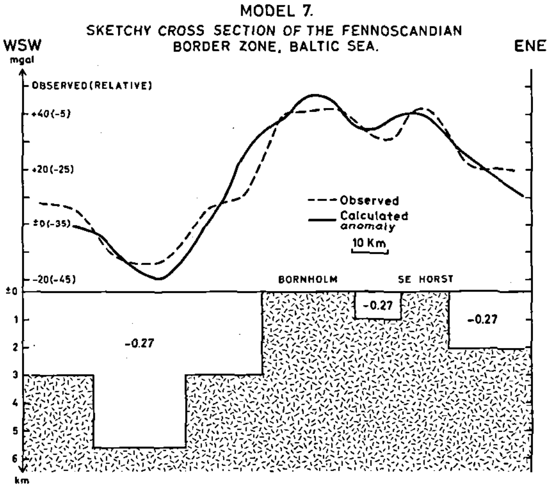

Fig. 7.

Discussion and regional conclusions

An outline of the fault pattern around Bornholm has been visualized in a rather tentative block diagram on fig. 8 and the map, fig. 9.

The most significant new result of the investigation is the discovery of a deep, sediment-filled basin marked by the row of gravity lows south west of the border zone. The basin contains a sedimentary section some 4–6 km thick. This deep part of the Danish-Polish Trough is only 15–20 km broad. It is probably the northernmost part of the thick Mesozoic sedimentary basin in Poland (Pozaryski 1962) which is now deformed in the Mid-Polish anticlinorium. Similarly narrow, deep parts of a sedimentary basin have been described south-west of the border zone in the Kattegat re-

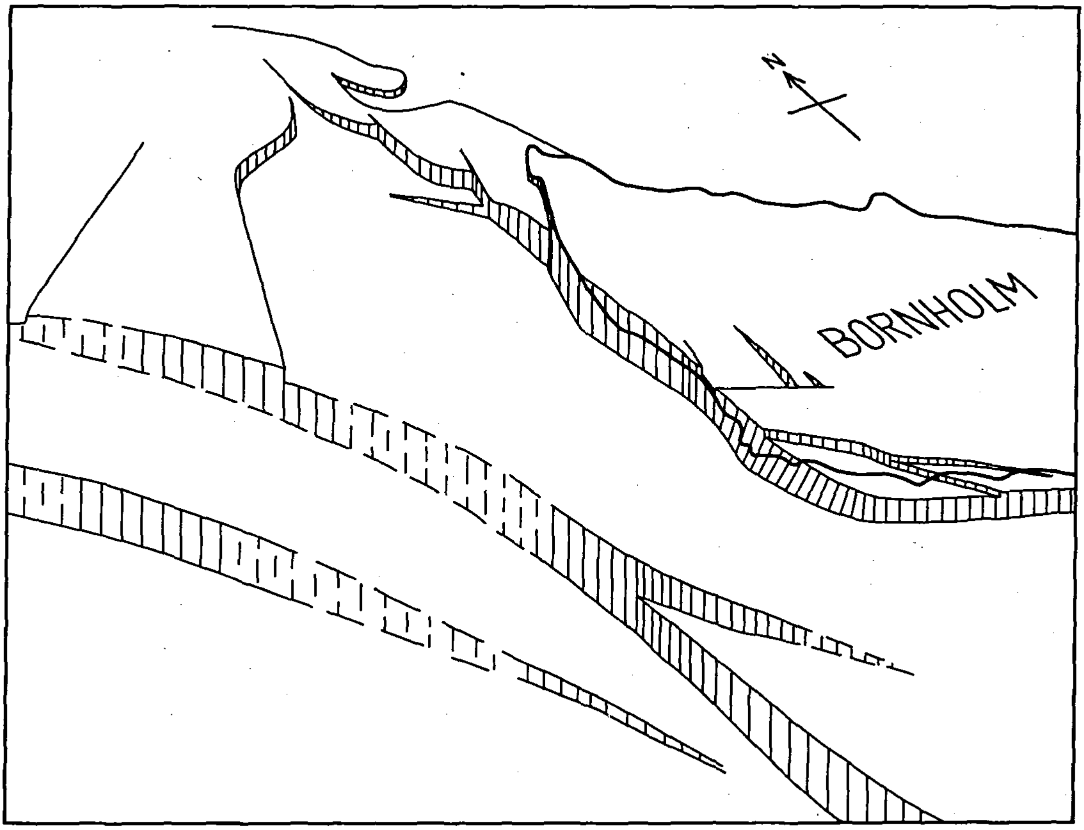

Fig. 8. Tentative block diagram of the surface of the basement in the surroundings of Bornholm.

gion by Stenestad (1972) and south of the Norwegian basement by Holtedal and Sellevoll (1971).

The proposed geological structures (Model 7, fig. 7) explain the variation in Bouguer anomaly across the border zone, but do not explain the absolute height of the anomaly. As noted above, the positive anomaly extends to Scania. Here part of the anomaly may be caused by deep-lying heavy material.

Volcanic necks – containing xenoliths of mantle material (Printzlau, pers. comm.) – occur in central Scania which, according to recent radiometric dating, have an age of Middle Jurassic to Middle Cretaceous (Printzlau & Larsen 1970). The direction of the contemporaneous dykes corresponds to the direction of the major faults of the border zone. This may suggest that the border zone, at least in central Scania, is a deep crustal structure.

The high positive anomaly over the basement of Bornholm indicates that the same may be true below the Baltic part of the border zone. If this is the case, the estimates of the displacement of the large faults towards the north (Model 1) and south of Bornholm (Models 4 and 6) are probably too high. However, based on the seismic evidence, we judge that the displacement of these faults can scarcely be reduced by more than a third of the estimated value. The existence of these structures is not in doubt.

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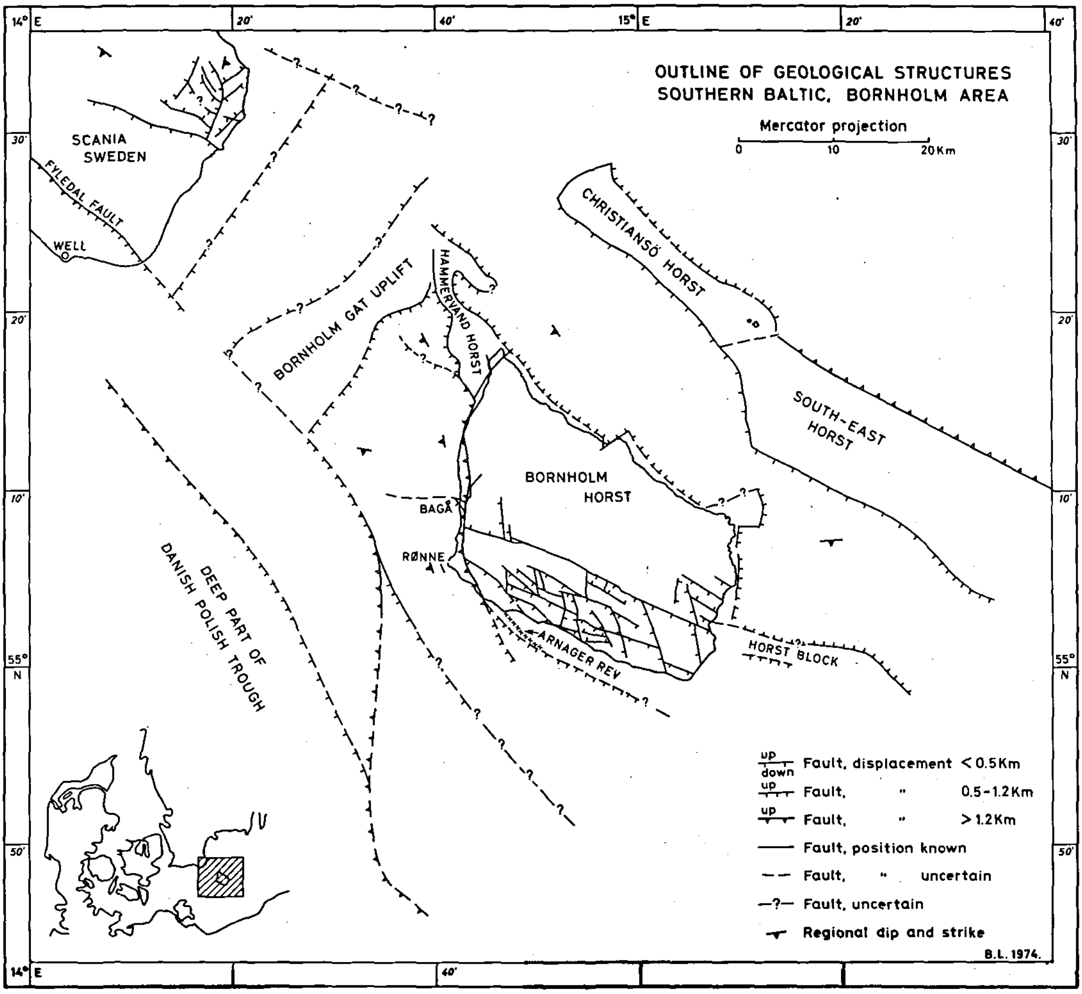

Fig. 9. Major geological structures in the Baltic around Bornholm. The indicated fault displacements are on the surface of the basement and do not necessarily continue through the whole sedimentary section.

Dansk sammendrag

Bornholm og de omgivende dele af Østersøen er karakteriseret af et usædvanligt varierende tyngdeforhold med store positive og negative Bougueranomalier. I afhandlingen søges disse tolket geologisk.

Tyngdekortet viser, at Sydøstbanken sydøst for Christiansø er underlejret af tungere materiale end de omgivende sedimenter. Den tolkes derfor som en højtliggende grundfjeldshorst (fig. 2). En anden grundfjeldshorst strækker sig fra Bornholms nordvestkyst til Davidsbanken (Hammervandshorsten – fig. 3).

En horstlignende forhøjning i grundfjeldets overflade (Bornholm gat uplift) adskiller to 1–2 km dybe sedimentområder mellem Bornholm og Skåne. Det østlige sedimentområde rummer bl. a. Vestbornholms jura-sedimenter. Det begrænses østpå af en stor forkastning, der forløber ca. 1 km inden for kysten. Ændringer i tyngdekraften over forkastningen tyder på, at grundfjeldet er nedsænket 1,5–2 km vest for forkastningen. Syd for Rønne deler den store forkastning sig og bevægelsen fordeles på flere trin. Bornholm horstens sydlige begrænsning formodes at være en forkastning, der forløber inden for nogle få kilometer fra sydkysten af øen.

Ca. 8 km sydvest for Rønne er der påvist endnu et 2–3 km højt trin i grundfjeldets overflade under et 2–3 km tykt sedimentdække. Denne forkastning kan følges ca. 30 km mod syd. Der er påvist strøg med en 4–6 km tyk sedimentserie lige sydvest for den Fennoskandiske Randzone. Det er usikkert, hvorvidt der i tyngdefeltets variation er tegn på dybereliggende strukturer.

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