The Submarine Morphology of the Baltic Cambro-Silurian Area

By

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ABSTRACT.—The extension and major morphology of the Cambro-Silurian escarpments, the *clints*, are outlined in the light of the deep boring on Gotska Sandön, the island ca. 40 km N of Gotland. The Ordovician and Silurian submarine clints and their connections with the supra-marine clints of Sweden and Estonia are shown in maps and profiles. Some remarks on Pre-glacial features in the landscape discussed are added.

Contents

Introduction

This study was begun in connection with the deep boring through the Ordovician and Cambrian strata of Gotska Sandön (THORSLUND 1958) in order to illustrate the situation of the core in the landscape of Palaeozoic rocks forming the floor of the greater part of the central Baltic. By this boring, in the summer of 1957, the bedrock surface of the Ordovician between Öland and Estonia was reached for the first time.

An attempt to construct isobaths with an equidistance of 10 metres on the nautical coast charts on the scale 1:200 000 gave unexpectedly good results as far as the Cambro-Silurian morphology is concerned. In this even landscape, levelled further by Quaternary deposits, there are very few cases where the contours can be drawn in alternative ways between the depth figures. The same charts, however, are almost useless for the construction of an approximately correct picture of the much dissected sea floors of Archaean rocks along the

Swedish mainland. A joint valley, for example, may occasionally be indicated only by one or a few depth figures which can exceed the neighbouring ones by 70–80 metres, and the result of an objective interpolation would, in the extreme case, be a narrow hole in the bottom instead of a fissure-shaped structure.

There is a general lack of detailed contoured charts of the parts of the Baltic concerned. Generally the equidistance of the contours on these maps (see *e.g.* GIERE 1938, LUNDQVIST 1957) increases with the depth so that it is impossible to compare floors near the coast with those of the open sea, which is obviously partly due to the fact that the sparser soundings made for the marine charts in the open sea do not encourage the construction of contours. Even if a contour is largely determined by the extent of the Cambro-Silurian clints (see the 100 m isobath in LUNDQVIST, *l.c.*, and in FROMM 1943, Fig. 5), the chart gives no information about the existence of an escarpment almost coincident with the contour in question.

There are, however, a few special maps illustrating the sea floor morphology of parts of the area treated here. WITTING's map of the Gulf of Finland 1910, with 20 m contours down to 100 m, includes the strip of Cambrian strata N of the Estonian clint. NILSSON (1913) interpolated a chart with 20 m contours on the current edition of the coast chart for the waters around Gotland, comprising parts of the clints, but obviously the depth records were not sufficient to illustrate the continuity of the Ordovician clint and the clint forming the edge of the Karlsö Shelf. FROMM (1943) used the primary echo-sounding charts of the Royal Hydrographic Survey (Kungliga Sjökarteverket) for a very detailed chart of the Archaean floors W, N, and NE of the Landsort Trench. Unfortunately this excellent chart does not reach the clints, but the accompanying paper contains the first empiric identifications of the submarine Ordovician clint (see below). Some months later NORDENSKJÖLD (1944a) published a contoured chart of northern Kalmarsund where the submarine parts of the clint of Öland are illustrated in 3 m contours.

The morphological connection between the Cambro-Silurian strata was shown in principle already by SCHMIDT (1881, Fig. 8, and 1891). His profile and map have been and are still reproduced and redrawn in numerous papers. At about the same time DAMES came to the same general view but interpreted the details in the Silurian stratigraphy in a different way (SCHMIDT 1891, p. 381 etc.). On SCHMIDT's map (1891) the limits of the Cambrian, Ordovician, and Silurian strata are drawn northwards in protracted arcs towards Åland, owing to the presence on Åland of boulders which later proved to come from the South Bothnian area. WIMAN (1901, Fig. 5) published a map which is a fairly independent variation of SCHMIDT's map, with the Upper Ordovician Porkuni (then Borkholm) beds striking along the coast of Gotland and touching the SE coast of Gotska Sandön. TAMMEKANN, in his monography on the Baltic clint (1940), published a map (*op. cit.*, Fig. 1) showing the clint arc from Öland to Estonia. A modern variation of this series of maps is that of SUJKOWSKI (1946), also sketching the limit of the Devonian in the Baltic. A map showing the Silurian clint connections between Ösel and Gotland—SCHMIDT's and his followers' maps showed the limit of the Silurian—was published by AALOE (1956).

The submarine Ordovician clint as a morphological feature was identified on sea charts by ELISABETH BÜCHTING (1918, p. 47). GIERE (1938, Fig. 4), guided only by the dip of the Subcambrian peneplain and on the knowledge of the Silurian-Devonian boundary in the Talsi (Talsen) area in Latvia, constructed a semischematic profile through the Palaeozoic of the Baltic. This profile is entirely corroborated by later investigations. The Ordovician clint is quite correctly identified as the escarpment of the "westgotländische Treppe", and GIERE (op. cit., p. 76) is the only author to mention the irregular shape of the clint which "zieht ... sich unregelmässig, in grösseren und kleineren Buchtungen, soweit das dünne Lotungsnetz erkennen lässt, auf die gotländische Sandinsel zu". On his morphological map, however, the Ordovician clint unites with the Silurian clint of Gotland near Gotska Sandön, and the geological character of this island is very vaguely discussed (op. cit., p. 8).

FROMM (1943, pp. 159–161, Fig. 7), uniting the Subcambrian peneplain with the Archaean surface in the cores of Visby and File Haidar and using the thickness of the Cambrian and Ordovician strata in the cores as reference surfaces, confirmed the earlier schematic profiles by detailed empiric data. A profile by GEJSLER (1956), based on the numerous borings perforating the Russian platform, shows the continuation of the Cambro-Silurian strata under the Devonian of Latvia.

There are, then, several authors treating or touching upon the problems concerning the clint morphology and the distribution of Palaeozoic rocks at the floor of the Baltic. The clints have been identified in profiles, but very little is known about the continuity of the clints and their extension on the map.

In the present study the illustrations are essentially based on the Swedish coast charts No:s 329, 330, and 331, issued in 1950, 1952, and 1955, respectively. The contour chart (Fig. 1) is constructed exclusively on these three modern charts. As Mercator's projection is used, the part of this chart falling within No. 329 has been redrawn graphically for the mean parallel 58° N used in No:s 330 and 331. The coast charts No. 24 (1903) and 332 (1945) and the Finnish chart No. 994 (1954) have been used for comparative purposes (in Figs. 2, 10, and 11; complete data for the charts on p. 33).

The interpolation of isobaths between as sparse sounding records as those on the coast charts gives a fairly generalized view of the bottom morphology. The primary sounding charts, which have not been used in this investigation, offer material for more detailed study of the clints as far as areas near the coast are concerned—the somewhat more detailed contours near the coasts in Fig. 1 are adopted directly from the nautical charts and are constructed on a greater sounding frequency. The deeper parts of the central Baltic, however, which are

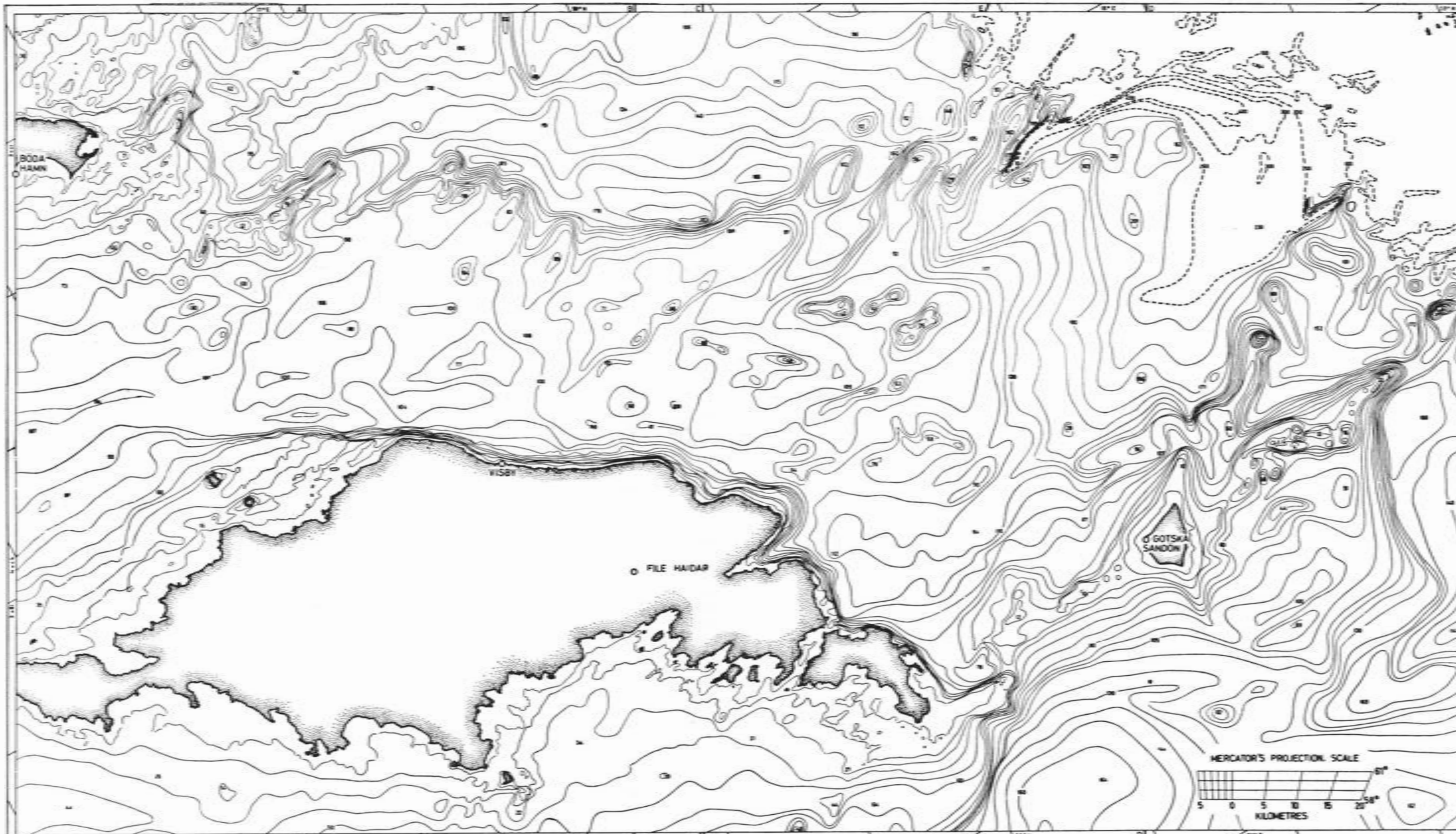

Fig. 1. Bathymetric chart showing the main morphological features in the western part of the Baltic. Scale 1 : 1 000000. Mercator's projection. Isobaths for every 10 m (between the Landsort Trench and the coast for every 100 m). Depth records to the nearest metre. Based on nautical charts Nos. 329, 330 and 331.

of critical interest in morphology but of little interest for navigation, need a special investigation by echo sounding before the view of the Baltic clint systems can become sufficiently complete.

The Ordovician clint complex

The term *clint* used in this study is originally a Danish and Swedish word (*klint*, synonymous with *klev*), signifying an escarpment, particularly in sedimentary rocks, without pointing out its morphogenesis (usually it comprises marine abrasion cliffs and fluviatile erosion scarps in Palaeozoic and Cretaceous rocks). The word was adopted already in Middle English and is recorded in its English form by BAULIG (1956). Unfortunately the word *clint* also occurs synonymously with *grike*, signifying a type of hollows formed by karst weathering. The literary German word *Glint* is widely used in German literature about Estonia and has also appeared in Swedish and English (e.g. TAMMEKANN 1940). It should be stressed that in the Baltic area its meaning is considerably more restricted than is stated by BAULIG (op. cit., p. 126: "tous ces mots"—Glint, klints, klint, and clint—"signifient simplement 'rocher'"). The corresponding Estonian word is *paekallas*; for the separate clint lobes and promontories the word *pank* (pl. nom. *pangad*) is used in western Estonia.

The "Ordovician clint complex" consists of an almost continuous, but indented and lobated clint arc from the western coast of Öland to the northern coast of Estonia (Fig. 2). Its basal part consists of Cambrian rocks, dominated by the Lower Cambrian sandstones, in the East Baltic area by sandstones and the "Blue Clays". Middle Cambrian, Upper Cambrian, and Lower Ordovician shales with subordinate sandstone and stinkstone beds form the basal part of the clint on the southern half of Öland, but the only important part of these shaly elements in the area treated here is the Middle Cambrian *Paradoxides oelandicus* shale, thinning out and disappearing between the bores of File Haidar and Gotska Sandön. In Estonia, again, the Lower Ordovician *Obolus* sandstone, *Dictyonema* shale, and Glauconite sandstone form an important component of the clint front. The hard crest layers of the clint, however, which primarily cause the steepness of the escarpment, consist of Lower and Middle Ordovician limestones. The limestone cover is usually fairly thin at the actual clint margin. In Estonia, where the clint margin is developed in the Uhaku, Lasnamägi, and Aseri beds (cf. GIERE 1932, ORVIKU 1940, and TAMMEKANN 1940), the limestone cover is usually about 10 m thick, often thinner, but seldom considerably thicker (cf. the profiles in TAMMEKANN 1940). The clint crest on Öland is developed exclusively in Lower Ordovician beds, from the *Raniceps* beds (BOHLIN 1955, Fig. 4) down to the lowermost parts of the *Limbata* limestone (REGNÉLL 1942, TJERNVIK 1956, pp. 145–147). The thickness of the limestone cover at the clint margin decreases in some places to a few metres.

The submarine clint is obviously developed in the same way. The thickness of the Cambrian in the profiles presented here must be extrapolated from the existing cores. The Böda Hamn core, with a thickness of the Cambrian of

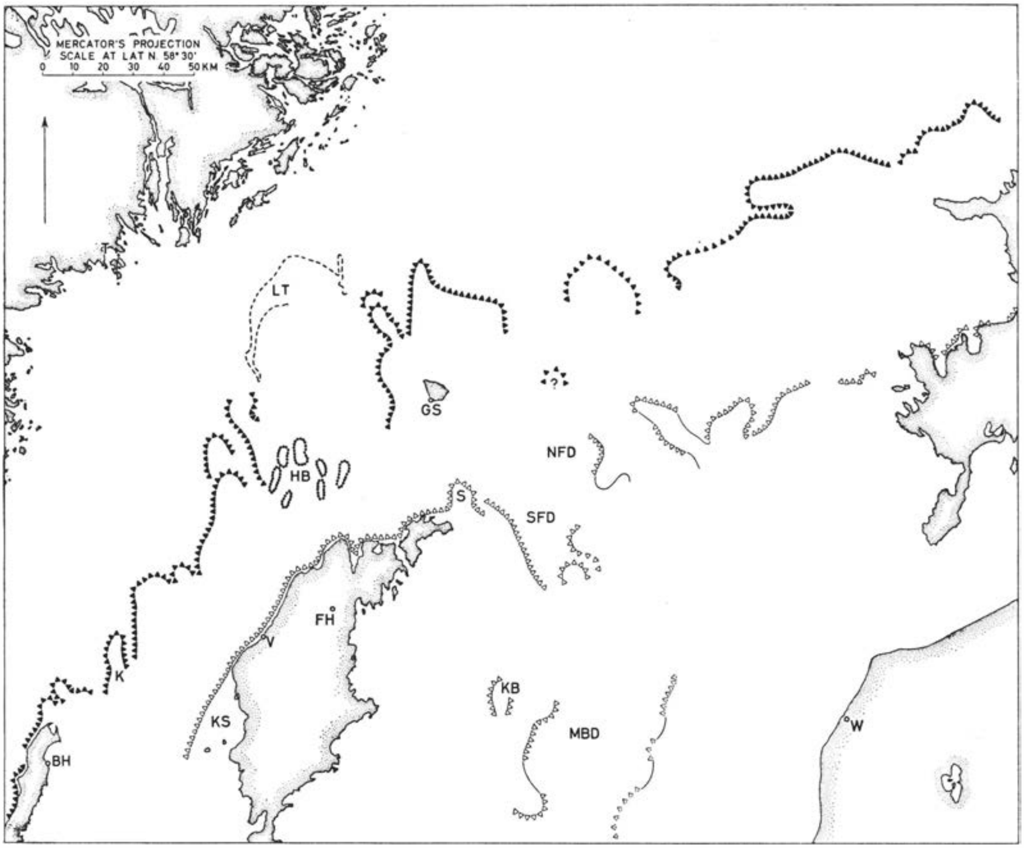

Fig. 2. The main features in the clint morphology of the Baltic.

Legend: Black triangles: The Ordovician clint complex. White triangles: The Silurian clint complex. Angles with dots: The Devonain slope towards the Middle Baltic Depression. Spaced signs indicate gentler slopes. BH: Böda Hamn. FH: File Haidar. GS: Gotska Sandön. HB: Hall Banks. K: Knoll's Bank. KB. Klint Bank. KS: Karlsö Shelf. LT: Landsort Trench. MBD: Middle Baltic Depression. NFD: Norther Fårö Depression. SFD: Southern Fårö Depression. S: Salvorev. T: Tvären. V: Visby. W: Ventspils (Windau).

123,2 m (WÆRN 1952) shows the conditions near the clint of northern Öland. In the Gotska Sandön core (THORSLUND 1958) the Cambrian is 72,5 m. Towards the centre of the Baltic it becomes thicker—141,7 m at Visby (HEDSTRÖM 1923) and 157,3 m at File Haidar (THORSLUND & WESTERGÅRD 1938). The Cambrian of Östergötland is 50,7 m thick (WESTERGÅRD 1940), but its palaeogeographic relations to the Baltic area are very little known. In the Tvären sequence (THORSLUND 1940) the Middle Ordovician lies directly on the Archaean.—Eastwards, along the coast of Estonia, the thickness increases (cf. the diagram of the Cambrian in southern Baltoscandia, Fig. 3 in WÆRN 1952).

In the profiles, therefore, the thickness of the Cambrian is presumed to decrease along the clint from northernmost Öland to Gotska Sandön. The reference level for the bottom of the Cambrian is the projection of the Subcambrian peneplain (RUDBERG 1954, Pl. 1) as exhibited in the sea bottoms of Precambrian rocks in front of the clint. This surface is well connected with the Archaean surface in the cores, but cannot, of course, be used infinitely (the Cambrian substratum further SE is mapped by GEJSLER 1956, Fig. 1; cf. Fig. 11 in this paper).

ÖLAND-LANDSORT TRENCH. The clint N of Öland forms two lobes separated by a narrow, 40 m deep valley. The southern lobe, bounded by the 30 m contour, is developed in Cambrian rocks and is evidently covered by glacifluvial deposits from the esker of Ängegärds udde. The other lobe, the Northern Bank of Öland (Ölands norra grund) has steeper features and is possibly also crowned by an esker ridge reaching 4,4 m. Here the clint bends eastwards, and gradually changes into a gentler slope until it regains its steeper forms in the Knoll's Bank area (K in Fig. 2). The clint of Knoll's Bank is about 85 m high. It is separated by a valley from the more continuous clint feature which reaches the region just south of the Landsort Trench (LT in Fig. 2). The valley in front of this clint is 150–200 m deep and the crest is at about 100 m below sea-level; only in one place is there a local elevation reaching 58 m. This part of the clint is locally broken by valley mouths. NW of Visby it runs practically straight for a stretch of 35 km before it is broken by 150–160 m deep valley, SW and W of which it forms two or possibly three outliers.

LANDSORT TRENCH AREA. About 13 km SE of the southern end of the Landsort Trench, immediately NE of the deep valley just mentioned, there is a ridge, evidently of Archaean rocks, projecting SE towards the Cambro-Ordovician clint. The upper surface of this ridge reaches about 100 m (93 and 105 m recorded in Fig. 1). It is bounded in SW by a joint valley (154 m in Fig. 1) merging into the front valley of the clint. In NE it is bounded by another joint valley (163 m), separated from the Landsort Trench by another, narrower ridge (119 m). A lobe of Cambro-Ordovician (56 m) seems to "ride" over the first-mentioned Archaean ridge. A separate hill on this ridge, probably Palaeozoic, reaches 75 m.

It is worth noting that the Tvären area (T), where the Middle Ordovician lies directly on the Archaean (Lower Ordovician is represented as pebbles in the basal conglomerate), is situated just in the direction of this ridge. Tvären is situated in the middle of a triangular Archaean block whose apex is near the southern end of the Landsort Trench. These features are very well illustrated in the chart by FROMM (1943, cf. the morphological map in Fig. 2 and the text, p. 144). Unfortunately it cannot be fully established whether the ridge discussed here continues into the triangular block or into a rib-shaped block extending towards the Landsort archipelago. As pointed out by FROMM (op. cit., p. 144) the Hävringe and Klemmingen-Sillen valleys limiting the very even triangular block both disappear in the squares D 12 and E 12 on FROMM's chart. (A comprehensive discussion of the age, origin and actualization in the recent relief of the joint morphology is found in RUDBERG 1954, pp. 36–48).

The conditions in this area have been discussed here in some detail as the sequence known from boulders from Tvären shows that the Cambrian and Lower Ordovician thin out and disappear in a smaller or larger area. The existence of the above mentioned ridge between the front valley of the clint and the Landsort Trench provide an indication that the Cambrian may thin out, primarily, or very likely by denudation in Ordovician time, over an elevation in the peneplain reaching the clint region. The material used in this study can hardly provide more than a suggestion, and the bottom topography of this part of the Baltic is so influenced by the evidently Tertiary disturbance forming the Landsort Trench (FROMM, op. cit., p. 157), that the ridge might well have an entirely different origin. Nor can it be excluded that the ridge might be a spur of Cambrian rocks uniting the Archaean landscape with the clint, though the joint valleys can be traced along its sides.

One of the profiles, Fig. 6, cuts the clint immediately SW of the ridge. The Cambrian is tentatively drawn after the same norms as in the other profiles.

LANDSORT TRENCH–GOTSKA SANDÖN. Between the southern end of the Landsort Trench and Gotska Sandön there is no marked clint feature. The bottom slopes gently down towards the inner margin of the trench. The contours form wide arcs towards the inner margin of the trench. The depth records are very sparse in this area, and the topography is definitely much more complicated than shown by the map. Whether the absence of a detectable clint should be put into connection with the Landsort Trench disturbance is impossible to judge from the present material, though it does not seem unlikely that a considerable area south of the trench should have subsided at the time of its formation. Theoretically there is a possibility, too, that the absence of a clint is due to the absence in this entire area of the easily eroded Cambrian strata.

HALL BANKS. South of the area last described there is a region of extensive hills here called the Hall Banks (HB in Fig. 2). The main summits of the outer hills reach 35, 41, and 42 m below sea level. The inner hills, nearer the coast of Gotland, reach 58, 63, 68, and 78 m. As shown in Fig. 6 the major part of the sequence of these hills, at least, consists of Upper Ordovician rocks; possibly they also contain Llandoverian elements. This is the region where the hard white and flint-carrying boulders of Porkuni limestone (Borkholmer Kalk, cf. WIMAN 1901) found on Gotland most likely have their origin.

GOTSKA SANDÖN AND KOPPARSTENARNA. West of Gotska Sandön the clint appears again, extending in N–S direction about 12 km from the island. It projects towards NW in a narrow lobe, the upper surface of which lies about 90 m over the surrounding sea floor; a hillock at the end of the lobe is over 40 m higher, reaching 27 m below sea-level. The crest of the lobe lies about 80 m below sea-level. Quaternary deposits have obviously no considerable thickness on this lobe. Another, very broad lobe projects with its western scarp northwards from the NW point of Gotska Sandön. N of Kopparstenarna the escarpment is sharply curved, forming a point, and then extends in a straight line ESE until it turns southwards after about 30 km, losing itself in a gentle slope.

The ridge from Kopparstenarna over Gotska Sandön and further south over Sandö Bank to Salvorev is a glaciofluvial deposit. In the Gotska Sandön core the bedrock was reached at a depth of 73 m, and the highest point of the dunes on the island lies 40 m higher than the boring-place. The Ordovician rocks form large surfaces at 70–80 m on both sides of the glaciofluvial ridge. Gotska Sandön is evidently situated where heavy marginal moraines have been deposited across the esker course—the sandy beaches on the eastern side of the island are suspended between the boulder caps in the esker and the rows of large blocks in Kyrkudden and Säludden. The contours round the island form sharp bends over the crest of a marked ridge disappearing about 10 km NW and about 15 km E of the island.

The esker ridge reaches 1 m below sea-level at Kopparstenarna. At Sandö Bank, 12 km S of Gotska Sandön, it reaches a minimum depth of 9,5 m (put down as 10 m on Fig. 1; a detail of the map is published in larger scale by THORSLUND 1958, Fig. 1).

As pointed out by FROMM (1943, p. 151) the notes concerning the bottom composition on the charts are not very helpful for the identification of the kind of deposit forming the bottom. A thin clay cover may, for example, conceal important deposits of coarser sediments. Records of "rock", "boulders", "stones", and possibly "sand" give somewhat more positive indications. It is evident that the Gotska Sandön esker continues from Salvorev (S in Fig. 2) southwards over the Klint Bank (KB). Northwards the continuation of the esker is not well discerned—"fine sand" is recorded in a very broad belt E of the southern archipelago of Stockholm.

Just north of the esker ridge of Kopparstenarna, in the right margin of Fig. 1, there is a high, isolated hill. FROMM's more detailed map (the squares K7 and K8) shows that it is developed as a dissected crag and that it is accompanied by another crag some km towards N. FROMM (op. cit., pp. 157 and 167) refers to them as the possible origin of the "Baltic porphyry" found particularly frequently on Gotska Sandön. Their very detailed morphology and sharp outline seem to indicate that they are not Palaeozoic outliers, and with this background it seems still more improbable that they have anything to do with the continuation of the Gotska Sandön esker.

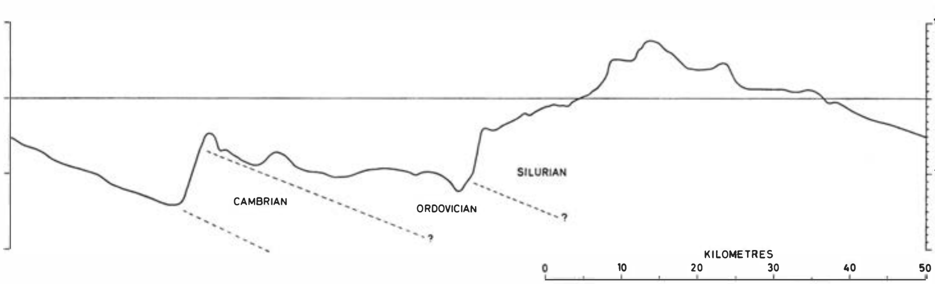

Fig. 3. Profile and schematic cross-section W 28°30′ N–E 28°30′ S between points A–A in the margin of Fig. 1, cutting the Ordovician clint at Knoll's Bank and the Silurian clint at the Karlsö Shelf.

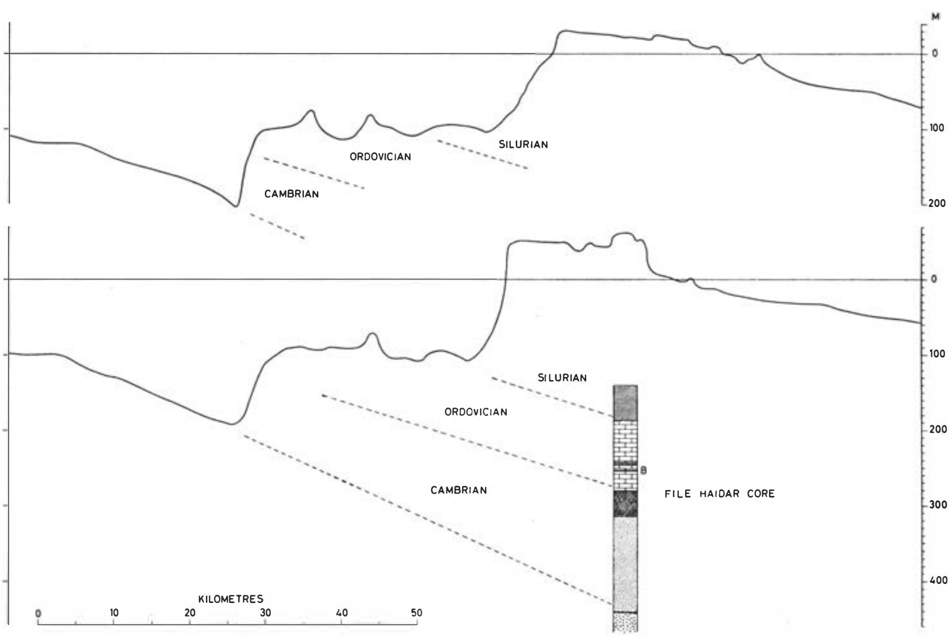

Fig. 4. Profiles in the same direction as Fig. 3. The lower profile, between poinst B–B in Fig. 1, passes through the File Haidar core and cuts the clints at right angles. The upper profile (C–C) cuts the Ordovician clint at the greatest depth of the front valley and the Silurian clint at Irevik. B = bentonite.

THE CENTRAL PART OF THE BALTIC. East of the Gotska Sandön lobe the distinct clint feature is interrupted by a valley which is blocked by a broad wall ("die Querschwelle des Kernteiles", GIERE 1938, p. 82). It lies in the continuation of the transversal ridge of Gotska Sandön and obviously consists more or less of glacial marginal deposits. Here the sparse soundings give a very uncertain picture of the morphology. A hill, with the question mark in Fig. 2, might indicate a more or less isolated lobe of Ordovician rocks. NE of this hill there is a large lobe, the slopes of which steepen on the NW and NE sides; the upper surface of the lobe lies at about 90 m and its base

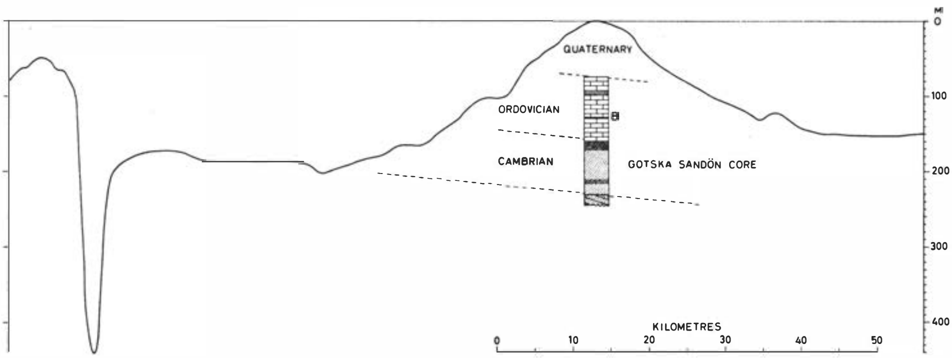

Fig. 5. Profile between points D–D in Fig. 1, parallel to the profiles in Figs. 3 and 4, cutting the southern end of the Landsort Trench and the Cambro-Ordovician sequence of Gotska Sandön.

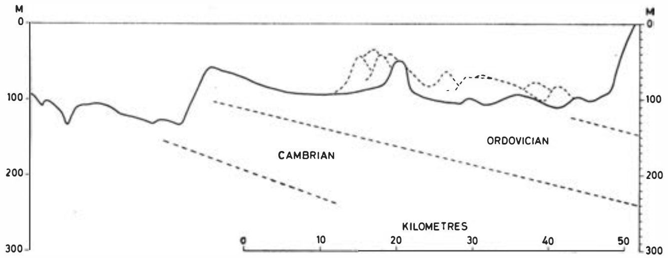

Fig. 6. Profile W 54° N–E 54° S between point E in the margin and the Silurian clint at Hall, Gotland, past the Hall Banks. The banks further NE are projected into the profile and are drawn with dashes.

between 160 and 200 m. It is separated from the coherent Estonian clint by a valley reching 144–146 m.

The ridge or wall of glacial deposits crossing the Gotska Sandön esker cannot with certainty be connected with any feature in Estonia. The continuation should probably be sought on or near Dagö (Hiiumaa). GIERE (1938, p. 110) also suggests glacial deposits as the cause of the complicated morphology of this part of the Baltic, south of the transversal ridge, but it is evident that the features pointed out by him are the clints in the Jaagarahu rocks (see below).

CENTRAL BALTIC–NW ESTONIA. Further east the clint can be traced fairly continuously on the sea bottom until it reaches the sea-level at Odensholm (Osmussaar) and the mainland near Paldiski (Baltischport). At 59° N, 21° W it curves sharply round a promontory with a hill reaching 53 m; N of this hill and in a narrow valley south of it the greatest depths are 178 m. This area was thoroughly mapped by echo-sounding before the last war, but the results were kept secret (cf. TAMMEKANN 1949, p. 444). They were studied, however, by ÖPIK, who used them in a lecture (the title mentioned in the proceedings of the Fourth Meeting of Estonian Natural Scientists; see ÖPIK 1940 in the references) but never had the opportunity of publishing them owing to the war.

The clint is obviously more dissected by transversal valleys (TAMMEKANN, l.c.) than shown in Fig. 3 which is based on the public nautical charts.

No features in the bottom morphology have been demonstrated which confirm ÖPIK's theory of a vast faulted area of Cambro-Ordovician rocks in the mouth of the Gulf of Finland (ÖPIK 1929, p. 10, Fig. 1, TAMMEKANN 1949, 445, Fig. 1). ÖPIK founded his view on the distribution of glacial boulders N of the outcrop of the corresponding strata in Estonia. This and the older theories of faults in front of the Estonian clint were rejected by GIERE (1938, p. 109), but TAMMEKANN (l. c.), for morphological reasons, extends the suggested fault area eastwards to the Suurupi (Surop) peninsula. He points to the fact that the lobes of a suggested Cambrian clint at the bottom of the Gulf of Finland cannot be traced W of Suurupi and that the greatest depths are found immediately N of the coast. These conditions, however, are quite normal for the parts of the clint complex described above. It is not impossible that the Cambrian rocks, the thickness of which increases considerably eastwards along the Estonian coast, form separate erosional features N of the main clint, but the borings at Kokskär and Wrangelsholm (Prangli), situated on one of the lobes, and at VSEGEI in Leningrad (profiles III and IV in GEJSLER 1956, cf. the review and references in GIERE 1938, p. 96) show that Quaternary deposits exceeding 100 m provide considerable sources of error in the morphological identification of the lobes and spurs outlined by TAMMEKANN (op cit., Fig. 1).

As pointed out earlier (GIERE 1938, p. 109, MARTINSSON 1956a, pp. 101–102) the fault theory of the origin of the "foreign boulders" at the mouth of the Gulf of Finland has very little foundation in facts. With the present knowledge about the submarine clint, the hypothesis that the boulders were transported from the clint area by differential movements during the last glaciation must also be abandoned (cf. MARTINSSON 1956a, pp. 96 and 102, 1956b, pp. 101–102). A thorough investigation of the composition of the South Bothnian drift in the easternmost parts of the distribution area is necessary for the further discussion of this problem.

The Silurian clint complex

The Silurian clint complex forms an arc of more or less lobed clints along the NW coast of Gotland and the north coast of Ösel (Saaremaa), continued over the sea bottom between these islands. In addition, there are steep slopes E of Gotland which are situated in Silurian strata.

GOTLAND. The westernmost part of this clint arc limits the shelf on which the Karlsö islands are situated (KS in Fig. 2). The entire NW coast of Gotland is determined by the clint which comprises almost the entire Silurian up to and including the Högklint limestone. There are a few indentations on this coast, at Lickershamn, Irevik, Kappelshamn, and Fårösund. One of them, Kappelshamn, is the mouth of a valley, filled by glacial deposits of unknown thickness, continuing over Lärbro to the Vägume Bay E of Slite. North of Kappelshamn it merges into the continuation of the front valley towards the Landsort Trech area. LINDSTRÖM (1888) believed this valley to be caused by faults. South of Lickershamn and Irevik there are less pronounced depressions with mires.

The larger part of the clint crest reaches between 40 and 50 m above sea-level; the bottom of the front valley lies at a depth of about 110 m, in one place reaching 120 m.

The clint curves sharply round Salvorev (S in Fig. 2). The thickness of the esker deposits in this area and the exact extent of the esker ridge are difficult to estimate. The sand masses form vast areas of dunes on Fårö Island. The sharp outline of Salvorev suggests that the Silurian strata lie near the surface. East of Salvorev the escarpment occupies the contours between 20 and 120 m, east of Fårö between 70 and 130 m, and east of the southern end of Fårösund the contours between 120 and 180 m converge into a separate scarp, outside the margin of Fig. 1. Altogether the clint extends from Salvorev about 50 km towards SE. The base is evidently situated in the lowermost Silurian rocks present in the area. The contours are finally sharply bent in a valley at long. E 10°48′ and then reach the margin of the chart used.

THE KLINT BANK AND THE MIDDLE BALTIC DEPRESSION. The Klint Bank (possibly Klint's Bank, KB in Fig. 2) is limited by slopes or escarpments in Silurian rocks. The crest of the bank reaches 26 m and the adjoining sea-floors 105–120 m. The bank obviously lies in the continuation of the Gotska Sandön esker, and glacial deposits may form parts of it. Probably the bank is developed in reef limestone. The steep slope limiting the Middle Baltic Depression (MBD) towards W is also developed in Silurian rocks, the eastern slope reaches up into the Devonian. The conditions in this part of the area are illustrated in a profile (Fig. 9).

CENTRAL BALTIC AND ÖSEL (SAAREMAA). Along the northern coast of Ösel clint lobes are developed in the Wenlockian Jaagarahu beds (AALOE 1956). They have an irregular continuation over the sea bottom to the Northern Fårö Depression (NFD). The depression is limited on the eastern side by a fairly steep slope. These clints lie higher in the sequence than the coast clint of Gotland, and comprise chiefly the Jaani and Jaagarahu beds which constitute the Wenlockian of Estonia. The clints of northern Ösel are of about the same size and dissected appearance as the inland clints of Gotland.

The distribution of Cambrian, Ordovician and Silurian rocks at the floor of the Baltic

The clints provide valuable features for the estimation of the horizontal distribution of Palaeozoic rocks at the sea floor. The boundaries between the systems are drawn in Fig. 10. Some remarks are added here on the construction and the exactness of the map.

CAMBRIAN. The Kalmarsund sandstone, regarded as Precambrian by ASKLUND (1927), is not differentiated on the map. The coherent belt of Cambrian is drawn according to the geological maps (MUNTHE & HEDSTRÖM 1904, HEDSTRÖM & WIMAN 1907), which are based on relatively few observations of Cambrian bedrock. Along the Swedish coast the Cambrian border is estimated to lie where the joint features of the Archaean lose themselves in the smoother floors of the front valley of the clint. The profiles published here and conditions known from the Kalmarsund area both suggest that the Cambrian cover at the sea floor is very thin, and it is probable that residual hills of different kinds on the Subcambrian peneplain reach through the surface as is known from Skallöarna (Skallaröarna) and Jungfrun in Kalmarsund.

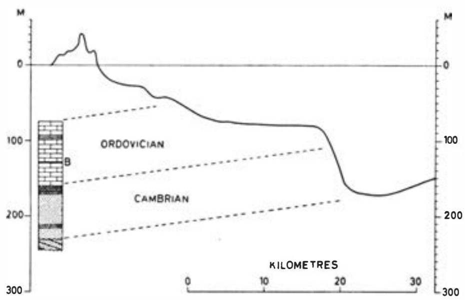

Fig. 7. Profile N 7° E–S 7° W between the Gotska Sandön core and point F in the margin of Fig. 1. B = bentonite.

At the ridge S of the Landsort Trench the Cambrian possibly occupies a narrower belt; this area, however, requires a special study as to the Cambrian-Archaean boundary (cf. p. 17). South of the Landsort Trench the details in the distribution of the systems are almost impossible to reconstruct, owing to the absence of a distinct clint. Around Gotska Sandön the Cambrian belt might be somewhat narrower than in the Kalmarsund area owing to the smaller thickness of the Cambrian sequence and the nearness of Archaean features in the bottom; the thickness of the sequence, and probably the width of the Cambrian belt, increase towards the Gulf of Finland where a rough limit can be drawn south of the more dissected bottoms along the coast of Finland.

In the Gotska Sandön core the Lower Cambrian rests with a conglomerate on a deeply weathered, presumably Precambrian sandstone (THORSLUND 1958). It is, of course, not known if this sandstone occupies any area outside the belt

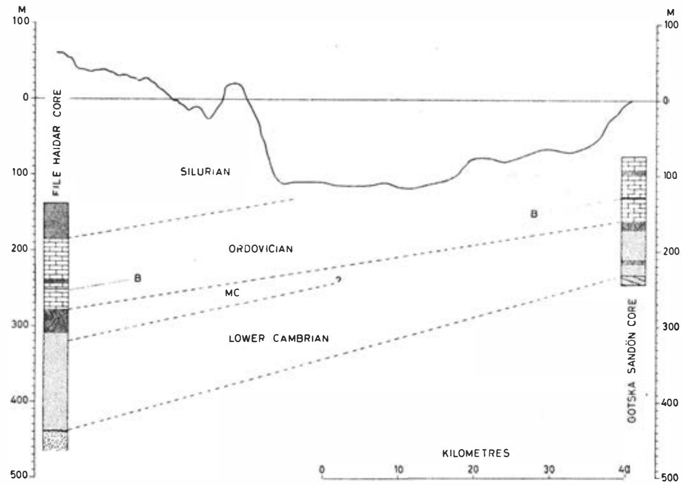

Fig. 8. Cross-section between the cores of File Haidar and Gotska Sandön. MC signifies the Middle Cambrian which thins out towards Gotska Sandön and disappears at an unknown line between this island and Gotland. B signifies the bentonite horizons in the Lower Chasmops beds, drawn, owing to the scale, as a single line.

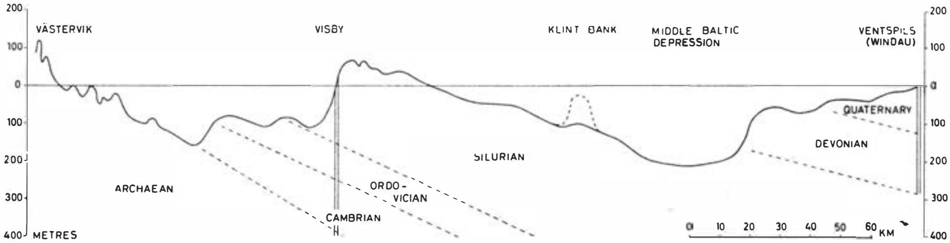

Fig. 9. Cross-section W 8° N–E 8° S from the Västervik region to the core of Ventspils (Windau) on the Latvian coast, cutting the Ordovician clint N of Knoll's Bank, the Silurian clint at the Visby core, the northern part of Klint Bank (the higher parts are projected into the figure by lines of dashes), and the Middle Baltic Depression.

of Cambrian rocks. Its thickness at Gotska Sandön and its age relationships to other Precambrian sandstones in Baltoscandia are still unknown.

The Cambrian has a large number of small outliers in the Archaean, mostly consisting only of joint fillings, "dikes". Cambro-Silurian outliers, including localities suggested by the distribution of boulders, are summarized in a map by Rudberg (1954, p.l 1). Fig. 10 in this paper comprises those dikes and the one larger outlier which are found as bedrock and are published (Gavelin 1904, Svenonius 1905, Wiman 1918, Lundquist 1920, Holmqvist 1920, Asklund 1923, von Eckermann 1928, Sundius 1928, Hjelmqvist 1939, and Nordenskjöld 1944a; in Finland according to Martinsson 1956b, Fig. 1). Nordenskjöld (1944a, p. 40) reports 146 dikes from the area investigated by him, but unfortunately they were not published before his death.

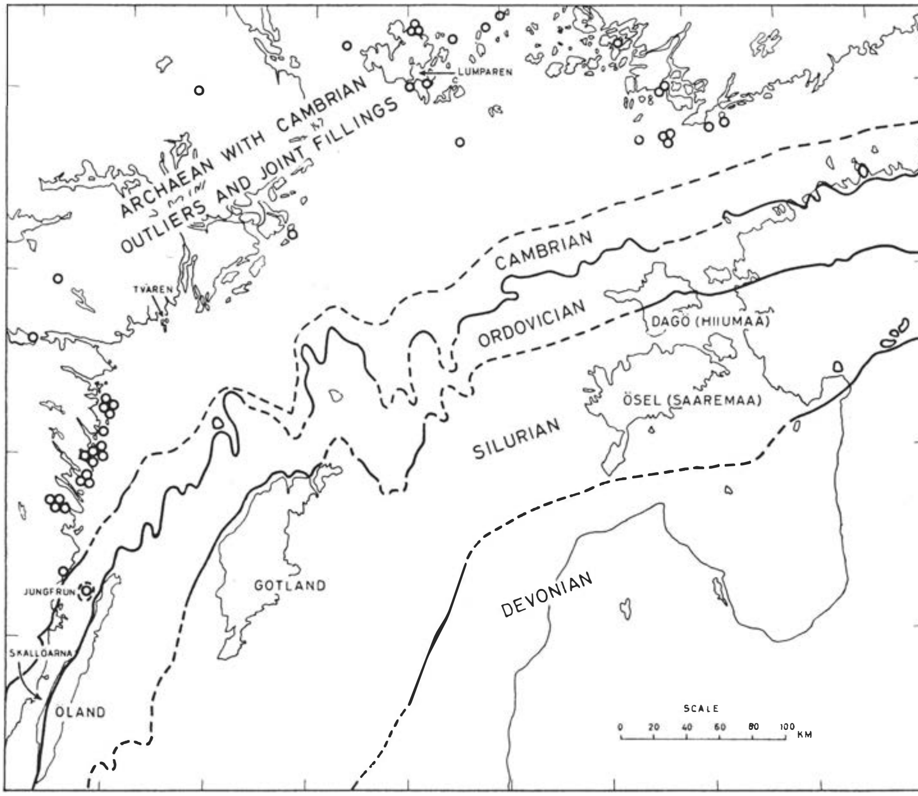

Fig. 10. The submarine distribution of Palaeozoic rocks at the floor of the Baltic. The lines of dashes indicate those parts of the boundaries which do not join morphological features and therefore are less well established. The rings indicate fissure fillings ("clastic dikes") in the strongly jointed Archaean rocks.

ORDOVICIAN. The Cambrian-Ordovician boundary can be traced very exactly as far as a distinct clint feature is present; in principle it almost coincides with the clint crest. In Estonia it is drawn according to JAANUSSON & MARTNA (1951).

In the central Baltic the conditions are more uncertain. It is evident that both the Cambrian-Ordovician and the Ordovician-Silurian boundaries have been moved southwards by erosion to considerable extent. The morphological background is discussed above (p. 15).

SILURIAN. As shown in the cross-sections, the Ordovician-Silurian boundary may be expected to run relatively near the coast of Gotland. The Hoburg Bank and, evidently, the Mid Sea Bank are Silurian, but it is impossible to draw the boundary exactly as there are no clint features south of the Karlsö shelf. The boundary curves round Salvorev at an unknown distance; the Silurian does not reach Gotska Sandön. It proceeds southwards round the Fårö depres-

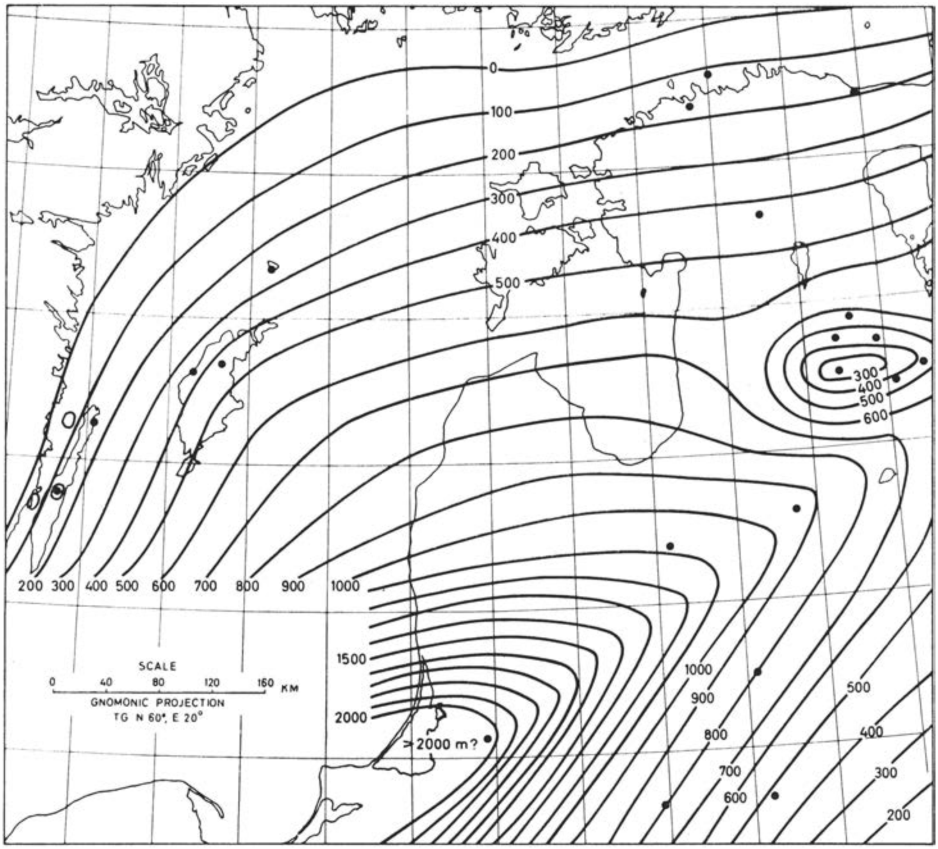

Fig. 11. The depth of the Palaeozoic substratum below the present sea-level as known from the existing deep borings. The parts east of the Baltic, slightly adjusted in accordance with the profiles, are adopted from GEJSLER 1956. The figure shows the gentle slope of the Subcambrian peneplain towards the very deep depression under Königsberg (Kaliningrad) and Tilsit (Sovetsk), where the Ludlovian sequence increases immensely and is overlain by Permian, Mezozoic and Kainozoic sediments. In the right hand margin the Lokno horst of Precambrian rocks locally protrudes through the entire Cambro-Silurian and is overlain by Devonian beds. As known from the Precambrian inliers and domes in the Kalmarsund region the Subcambrian peneplain is not so even as this diagrammatic picture might suggest.

The black dots indicate borings reaching or continuing into the Precambrian. The depths are in metres.

sions (SFD and NFD in Fig. 2) and, without any steep feature, further to Dagö (Hiiumaa). The boundary in Estonia is drawn according to JAANUSSON & MARTNA (1951).

It is doubtful whether there are any Silurian outliers in the area. The Hall Banks are touched by the projection plane of the Ordovician-Silurian boundary under Gotland, but it is not very probable that the erosion has left anything of the marly Llandoverian sediments on the summits of the hills of hard Upper Ordovician Limestone.

DEVONIAN. The Silurian-Devonian boundary, finally, is found in the eastern slope of the Middle Baltic Depression (cf. Fig. 9). It passes through the Irben Sound, probably somewhat nearer to Ösel than to the Latvian coast. The boundary in Estonia is drawn according to ORVIKU (1930) and JAANUSSON & MARTNA (1951).

Preglacial features in the Palaeozoic landscape

It is generally stated that very little is known about that great part of the history of the Baltic region which is marked by the sedimentological hiatus from the Silurian to the Holocene. The erosional work of the Pleistocene glaciers is regarded as so dominating a factor in the genesis of the landscape that its morphology immediately before the glaciations has been very little discussed. There are, however, conditions caused by the glaciations which are as important in this respect as the ice erosion: we do not know from what level the land warp under the ice masses started, although some guidance is given in the calculations of the remaining land upheaval (NISKANEN 1939, Appendix 2); we know very little about the distribution of land and sea during the interglacials; nor do we have a comprehensive view of the effects of fluvial erosion and marine abrasion in Late Quaternary time.

Modern aspects on the origin of the Baltic have been summarized by GIERE (1938), NORDENSKJÖLD (1944 b) and, especially, in FROMM's lucid outline (1943). The only special treatise on preglacial features in the Cambro-Silurian landscape is that by TAMMEKANN (1949).

For the entire Baltic GIERE completed the picture of the cuesta landscape outlined in Estonia originally by SCHMIDT (1881, Fig. 7). He does not discuss the drainage in detail but states that the rivers from the Bothnian area and the Gulf of Finland must have collected in the trough N of the central part of the Cambro-Ordovician clint. The origin of the cuesta landscape is dated to the Lower Devonian and its rejuvenation to the Tertiary; the Devonian extension of the clint is believed to coincide roughly with the flexure in the peneplain round the Cambro-Silurian area suggested by several authors; thus the Cambro-Silurian areas on the Swedish mainland and in the Bothnian sea were isolated from the coherent Cambro-Silurian of the Baltic. FROMM, referring to TROEDSSON (1927), regards the Cambro-Silurian as still having covered the central and northern parts of the Baltic in Mesozoic time forming a more or less peneplained surface in the continuation of the Fennoscandian block and across the Baltic. The origin of the cuesta landscape is attributed to a Tertiary upheaval of the marginal areas. NORDENSKJÖLD applies GIERE's view to the Kalmarsund region, where a preglacial valley is said to have been formed by subsequent fluviatile erosion in preglacial time. This valley was deepened by glacial erosion, and finally the clint of Öland was formed by marine abrasion. TAMMEKANN mapped and comprehensively described the Estonian cuesta landscape, also including the minor cuestas between the clint features treated here. His map (*op. cit.*, Fig. 1) includes the main preglacial valleys in the area; they form, however, an anastomosing network which does not reveal much about the drainage. The dating of the processes is about the same as GIERE's (GIERE's papers, however, are not quoted by TAMMEKANN 1940 and 1949).

TAMMEKANN differs from GIERE in stressing that the valleys causing the lobated morphology of the clint are preglacial (cf. TAMMEKANN 1926, p. 127). GIERE believes that the clint was moved by glacial erosion southwards from a line Tytärsaaret (Klein-Tütters, Gross-Tütters)—Lavansaari (Lövö)—Seitskär (Seitskaarto, Seiskari) to the clint along the Bay of Narva, and in his later paper (1949) TAMMEKANN postulates a considerable recession southwards of the clint owing to glacial erosion.

The main condition for the discussion of preglacial features in this morphology is an estimation of the influence of glacial erosion and the distribution of glacial deposits at the bottom. FROMM discusses both problems and concludes that both factors have very little influence on the major morphology; the selective glacial exaration, however, has played a considerable part in the joint-and-fault landscape discussed.

The Cambro-Silurian area treated here lies in the region characterized by dominant glacial erosion; to illustrate the contrast with the more peripheral accumulation region, the profiles in GEJSLER (1956) might again be quoted. It must generally be agreed that the glacial deposits in the erosion area cannot be expected to have any considerable influence in a map with 10 m contours such as Fig. 1, but the borings at e.g. Gotska Sandön, Kokskär (MICKWITZ 1907), and Rahumägi (KENTS 1938) show that there are considerable glacial deposits in the Gotska Sandön area and in front of the clint (as Dr. V. JAANUSSON has kindly informed the author there are several borings from the clint region showing the same conditions, some of them published by MICKWITZ and THOMSON in papers which are not accessible in Sweden). Obviously the morphology of the depressions in the Central Baltic is complicated by glacial deposits in a similar way. It is possible that a considerable part of these deposits derives from the large masses of unconsolidated or little consolidated Cambrian sediments in front of the clint.

FROMM suggests a preglacial erosion basis in his area at 90–100 m below the present sea-level owing to the fact that the joint valleys dissolve at about this depth. It is very probable, however, that these conditions mark the morphological boundary between the Archaean and the Cambrian landscape. Obviously a joint valley from the Valdemarsvik region is still traceable at 130 m.

The present investigation brings out some of the major features in the preglacial drainage, but it also points to some details which complicate the earlier and more abstract view of the Baltic cuesta landscape. The development of this landscape may be summarized as follows:

After the epeirogenetic movements which interrupted the sedimentation in the area at the end of the Silurian, the Palaeozoic strata formed a very shallow basin. The Middle Devonian transgression possibly resulted in a temporary covering of considerable areas of the Cambro-Silurian, but for the rest of the Palaeozoic and Mesozoic the strata were subject to river erosion. The considerable lapse of time and the absence of traceable disturbances makes it very probable that the erosion resulted in peneplanation. We do not know, however, to what extent this peneplain is preserved in the present relief, but it is incorrect, or a very wide generalization, to regard the surfaces cutting the strata of Öland, Gotland, and Estonia as parts of a common peneplain. In connection with the Tertiary uplift of the marginal areas a rejuvenation of the drainage system took place, and the main features in the present cuesta landscape were formed. The subsequent drainage system and the obsequent drainage across the cuesta margins can be traced to some extent.

The valley in front of the clint of Gotland has its origin (its highest point in the present morphology) south of Öland. It passes immediately W of the Southern Bank of Öland and then bends eastwards towards Gotland, obviously taking tributary valleys from the North Midsea Bank. It reaches the Silurian clint W of the Karlsö islands; the formation of the Karlsö Shelf is due to the fact that the erosion penetrated into the soft Llandoverian strata in this region. The valley descends from 50 m below sea-level south of Öland to almost 120 m W of Gotland, where it continues along the clint and loses itself towards the Landsort Trench E of the Hall Banks where two alternatives in the system of anastomosing valleys are possible. The bays on the northern coast of Gotland, especially Kappelshamn, apparently mark valleys in the obsequent drainage. In interpreting the direction of the subsequent drainage in front of the clints of Gotland and Öland we are greatly hampered by our limited knowledge of the Prequaternary height conditions in the region, but the drainage pattern described above suggests that the area was drained northwards round the clint of Kopparstenarna and then through the Fårö and Middle Baltic Depressions. For the general picture of the Central Baltic, however, one might quite as well presume the opposite direction (cf. the map in BRAUN 1923). The elevation of the area N of Gotland in relation to the thresholds S of Öland, which is necessary to turn the subsequent drainage southwards, and the corresponding effects on the entire drainage system are evident from any bathymetric chart of the Baltic. More than 200 m elevation would be necessary.

The latter consideration has yet more actuality when the direction of the drainage from the valley in front of the Ordovician clint is discussed. Under the present conditions this valley forms a closed basin with 203 m as greatest depth. The lowest thresholds are found on the ridge SW of the Landsort Trench and in the deep valley W of the Hall Banks, about 30 km N of Visby; both tresholds are about 105 m below sea-level. The valleys cutting the clint and causing its lobated appearance on the map suggest that the subsequent drainage entered the front valley in a more or less northerly direction. Theoretically it is possible to explain this in many ways (relatively greater subsidence of the area, passages hidden by glacial deposits or by the sparseness of depth records, disturbances in the northern part in connection with the origin of the Landsort Trench, etc.), but the empiric material is lacking.

As generally agreed, the drainage from almost the entire Baltic area passed east of Gotland towards the Danzig Depression. The front valley of the Ordovician clint in Estonia and valleys from the Ösel and Dagö region end in the system of depressions in the Central Baltic. The Bothnian Sea and Bothnian Gulf would, if compensation is made for the calculated remaining Postglacial upheaval of land, fit well into the drainage pattern. But for the explanation of the drainage E of Gotland it is necessary, again, to presume that the rate of subsidence of the Baltic increased considerably northwards, in addition to what is shown by the calculations of the remaining land upheaval.

Even if the drainage system of the cuesta landscape cannot be analysed, the structural background of the formation of the escarpments is evident. The Ordovician clint system is caused throughout its entire length by the erosion of the soft, mainly Cambrian, sandstone and clay strata, overlain by the Ordovician limestone which determines the retreat of the clint and causes the relative steepness of the feature. Corresponding to these strata in the Silurian clint of Gotland are the thick sequence of Llandoverian marls, which is eroded almost to its base, and the Högklint and younger limestones which overlie it. In the eastern part of the Baltic and in Estonia, harder carbonate rocks replace the major part of the Llandoverian marls. The main clint features are there situated higher up in the sequence, caused by the erosion of marls chiefly belonging to the Wenlockian Jaani beds, overlain by the Jaagarahu limestones, a large part of which consist of reefs which cause the dissected and lobated appearance of the clint. Owing to these conditions the Ordovician-Silurian boundary in this area lies far north of the main clint.

A quite different conception of the origin of the clint coast of Gotland was recently published by BEHRENS (1958, p. 175; cf. p. 170!) who states that this part of the clint has been formed by faults. This is utterly improbable, and there is hardly any room for a fault in the area, even if the maps and sections presented here are not detailed enough to establish the complete absence of important dislocations in the Cambro-Silurian part of the Baltic.

The clint is treated of above as a generally steep feature. It must be stressed, however, that the picture obtained in Fig. 1 and other contour charts is very diagrammatic, as the sparse depth records show only the number of contours which should be assembled in a more or less narrow zone. Experience from other cuesta landscapes and even from the supramarine clints in the Baltic area suggest that the clints constituted very prominent features in the Preglacial landscape. We know that glacial deposits play an important part in concealing the clint features in the northern Estonian landscape, and most certainly the same is the case concerning large parts of the submarine clints. On the other hand great caution is needed in all statements about the exarating activity of the glaciers in the front valleys and central depressions which is stressed in most of the earlier treatises on the subject. The activity of the recent marine abrasion, finally, which steepens the clint features, directly and by removing talus and glacial deposits in front of it, is of minor influence and is very little visible in the scale of the figures published here.

Conclusions

The present study was commenced as an orientation in the Preglacial landscape in the Palaeozoic rocks of the Baltic. The fairly rough marine chart material on which the profiles and the bathymetric chart are based does not provide the material for a correct identification of every detail of the clints or the sea floor between them, and essential features between the sparse depth records in the deeper parts of the sea may have escaped notice. The allowance for error in drawing the boundaries between the systems in the profiles is, however, large enough to secure the principal features in the distribution of the systems on the map. As a conclusion of the above discussion the following statements can be made:

1. The submarine Cambro-Ordovician clint is strongly indented and lobated and can be traced along the major part of its extent; is interrupted S of the Landsort Trench and NE of Gotska Sandön.
2. The submarine Silurian clint of Gotland forms a shelf on which the Karlsö islands are situated, joins the NW coastline of the island, curves sharply round Salvorev, and assumes a NW–SE direction E of Fårö. In the eastern part of the Baltic, the corresponding structure is a dissected clint feature situated higher up in the Silurian sequence, mainly in rocks of Wenlockian age.
3. Owing to the structural background of clint formation the Cambro-Ordovician boundary coincides in principle with the Cambro-Ordovician clint where this feature is developed. For the same reasons the Silurian is presumed to occupy a comparatively narrow zone in front of the clint of Gotland. In the eastern part of the Baltic the Silurian belt north of the clint is broader, owing to the greater resistance of the Llandoverian rocks in this area. The submarine Silurian-Devonian boundary can be traced for some distance in the eastern slope of the Middle Baltic Depression. The belt of Cambrian rocks is less well defined. A rough estimation of its width can be made from the conditions in the Kalmarsund region, the distance to the Cambrian joint fillings in the Archaean, the disappearance of the joint-determined valleys, and the relative thickness of the system in the clint.
4. The conception of the Baltic clints as the escarpments in a cuesta landscape is sustained. Some of the main features in the Preglacial subsequent and obsequent drainage are demonstrated, but it is pointed out that the drainage pattern and the general bathymetric conditions in the Baltic lead to partly contradictory conclusions as to the direction of the drainage. It is necessary, even for the conditions between Gotland and the mainland, to assume a Preglacial base level of erosion lying considerably deeper than 90–100 m below sea-level as presumed hitherto.

Conversely, it would contribute considerably to our knowledge of the Preglacial height conditions in the Baltic area if we could establish the direction of the subsequent drainage in front of the clints of Öland and Gotland by means of morphological analysis.

The present investigation points to a number of details which it is important to subject to further study. Some parts of the clints can already be illustrated in more detail with the existing sounding maps. The structural relationships of Archaean and Palaeozoic rocks and the depth conditions at the ridge SW of the Landsort Trench present a major problem. In the deeper parts of the sea it is almost impossible to give even an approximate picture of the steepness of the slopes or escarpments without special soundings, and in this connection the morphology and the distribution of glacial sediments in the chain of depressions in the middle of the Baltic are of cardinal importance for the understanding of the consequent drainage of the cuesta landscape.

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Palaeontological Institute of the University of Uppsala, April 17, 1958.

ADDENDUM. — During the printing of this paper Dr. T. N. ALICHOVA has kindly communicated the exact depth figure of the Silurian-Devonian boundary at Ventspils (Windau, cf. Fig. 9); it is 270.5 m (*fide* E. M. LJUTKEVIČ). I am also indebted to Dr. A. RÕÕMUSOKS for more detailed information about the nature of the break in the Lokno area.

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