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AN UNDULATION OF THE RATE OF SEDIMENTATION IN SOUTHERN GOTLAND

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SUMMARY

The silurian sediments of Gotland have been tilted ca. ½° about a SW-NE axis. Reconstruction of the original positions of the strata proves the existence of a N-S directed trough, which gradually moved towards the east, during the sedimentation. If one plots for a certain place the relation between time and rate of sedimentation, the resulting line shows an undulation (see fig. 5). In this way movements of some viscous matter, for instance magma, beneath the basement can occasionally be recorded by the sedimentation on top of the basement.

CONTENTS

I. INTRODUCTION

According to the detailed studies of Hede, the sequence of strata in southern Gotland can be divided into the following stratigraphical units:

Sundre Series
Hamra Series
Burgsvik Series
Eke Series
Hemse-series.

The Burgsvik Series, according to general opinion, is of Upper Ludlowian age. It correlates with the Upper Whitcliffe Flags in the type area of Great Britain (Hede, 1921; Säve-Söderbergh, 1941). At Grötlingbo a vertebrate-bearing sandstone layer is found approximately one metre below the oolitic limestone which usually forms the uppermost part of the Burgsvik Series (Spjeldnaes, 1950). Because most authors now draw the boundary between the Silurian and Devonian below the Ludlow Bone Bed, implying that the Upper Whitcliffe Flags are then the uppermost beds of the Silurian, the Burgsvik Oolite and the Hamra and Sundre Series on Gotland possibly belong to the basal Devonian (Downtonian).

Since it is essential for the interpretation given in chapter III that the transitions between the successive series really represent time boundaries these first will be considered in the next chapter.

II. THE STRATIGRAPHY OF SOUTHERN GOTLAND

a. *Upper Hemse and Eke Marls*

The Upper Hemse Series is characterized by marly shales which represent a good stratigraphic unit. It is terminated by the so-called Dayia Flags: a finely crystalline, thin-bedded limestone, very rich in *Dayia navicula* and *Strophomena impressa.* The whole thickness is less than 10 cm. In the field it is a very useful guide-layer, because of its wide occurrence and characteristic development.

The next-younger Eke Series begins in the east with a thin, even layer of phosphorite with

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glauconite, indicative of a discontinuity between the Eke Series and the Dayia-flags. Spjeldnaes (1950) here supposed a stratigraphic hiatus. This layer is covered by limestones, in which some reefs are found. The Upper Eke is formed by marly limestone.

In the west the Dayia Flags directly and conformably are overlain by Eke Marls, which here are somewhat fine-sandy and glimmer-containing. Limestones do not occur in the western part of the Eke area. No indication of a hiatus is found here. In consequence the break in the east, if present, is not of great importance.

The Eke Series reaches a thickness of about 10 metres in the east to about 14 metres in the west.

b. *Burgsvik Sandstone and Oolite*

Not only in the east but also in the west the Eke Series is overlain by Burgsvik Sandstone or Glay. The Burgsvik Series reaches in the west a thickness of about 50 metres, which is known by two deep-borings at Burgsvik and at Vamlingbo. Towards the east it thins out rather rapidly.

The Upper Burgsvik over its whole area shows a great number of characteristics which point to a deposition in one and the same shallow-water facies.

Near Burgsvik in the sandstone a fold-like structure occurs with a W-E directed axis. In the northern limb dips, up till 10° toward the north, occur; in the southern limb we see dips in the opposite direction. The breadth of this structure is more than 100 m.

Munthe (1910) supposed a later tectonical origin of this "folding". However I have found that the layer of oolite on top of the sandstone normally has a thickness of about 1,5 m, but wedges out to about 0,5 m at the top of this structure. Such a wedging out is a primary phenomenon, and in consequence it has not a tectonical origin. The oolite has been laid down on a surface already containing the structure.

The axis of this structure at Burgsvik has a W-E direction, parallel to the ripple marks at this place, described by Hadding (1929). Munthe reports another "fold" with a S-N directed axis, west of Fide, some kilometers to the north. Mechanically a case of two simultaneous folds with axes that are perpendicular to each other is impossible. A compression during orogenesis only has one direction at the same time and the same place. Moreover, in Gotland there are no indications for folding at all.

At Uddvide still another abnormal western dip occurs. In a quarry about 20 m east of this point the strata are horizontal; about 30 cm below the transition from sandstone to oolite a layer of clay occurred with a thickness of about 5 cm. About 60 m SSE of this place the top of the clay is situated 30 cm below the oolite too; its thickness at this place is 35 cm. At Uddvide the layers also wedge out towards the top, a structure that resembles that of Burgsvik.

These large primary dips, up till 10°, are found in the whole Burgsvik. The influence on these dips of a later tilt of ca. ½° about a NE directed axis can be neglected. All directions of strike occur, but a line can be drawn connecting all measurements (see fig. 1). Two directions, W-E and S-N dominate in this line.

In the south, at Valar, the direction is S-N; along the shore of Burgsviken the direction of strike bends towards the E. The so-called "folding" of Burgsvik occurs at the side where the line sharply turns back to a northward direction. The structures, west of Fide and Uddvide, have been mentioned already. ENE-strikes occur south of Grötlingbo; on Grötlingboudd the direction is to the east, with dips to the north as well as to the south. On the island Innerholmen yet another turning to a S-N direction takes place.

The explanation of these changes in strike of the Upper Burgsvik outcrop is found in the position of the coast at the time of sedimentation. During the whole Upper Silurian Gotland was under the influence of a mainly NE directed basin, and the present site of the island was at its margin.

During the Upper Burgsvik, after a regression, the sinuous coast was situated in southern Gotland. Broadly spoken it had a NNE direction.

The ripple marks ("oscillation ripples"), found at Valar by Manten (personal information) and at Burgsvik by Hadding (1929) in both cases are parallel to the reconstructed coastline.

As to the so-called "folding-structures" of Burgsvik and Fide the following remarks can be made. Large offshore bars parallel to the coast are a common phenomenon in front of sandy coasts. An analysis of many sections by Johnson and experiments by Timmermans (1935) proved the correctness of the theory of de Beaumont that waves erode a shallow sea-bottom and try to form an equilibrium in the shape of an offshore bar parallel to the waves. The waves are drawn parallel to the coastline by the slope of the sea-bottom; the maximal angle between axes of waves and a coastline is about 15° (Timmermans, 1935, p. 299). On dips we read that for instance the offshore bars at Long Beach (New Yersey) demonstrate common dips of 6°—8° (13° is possible too) (Timmermans, 1935, p. 298).

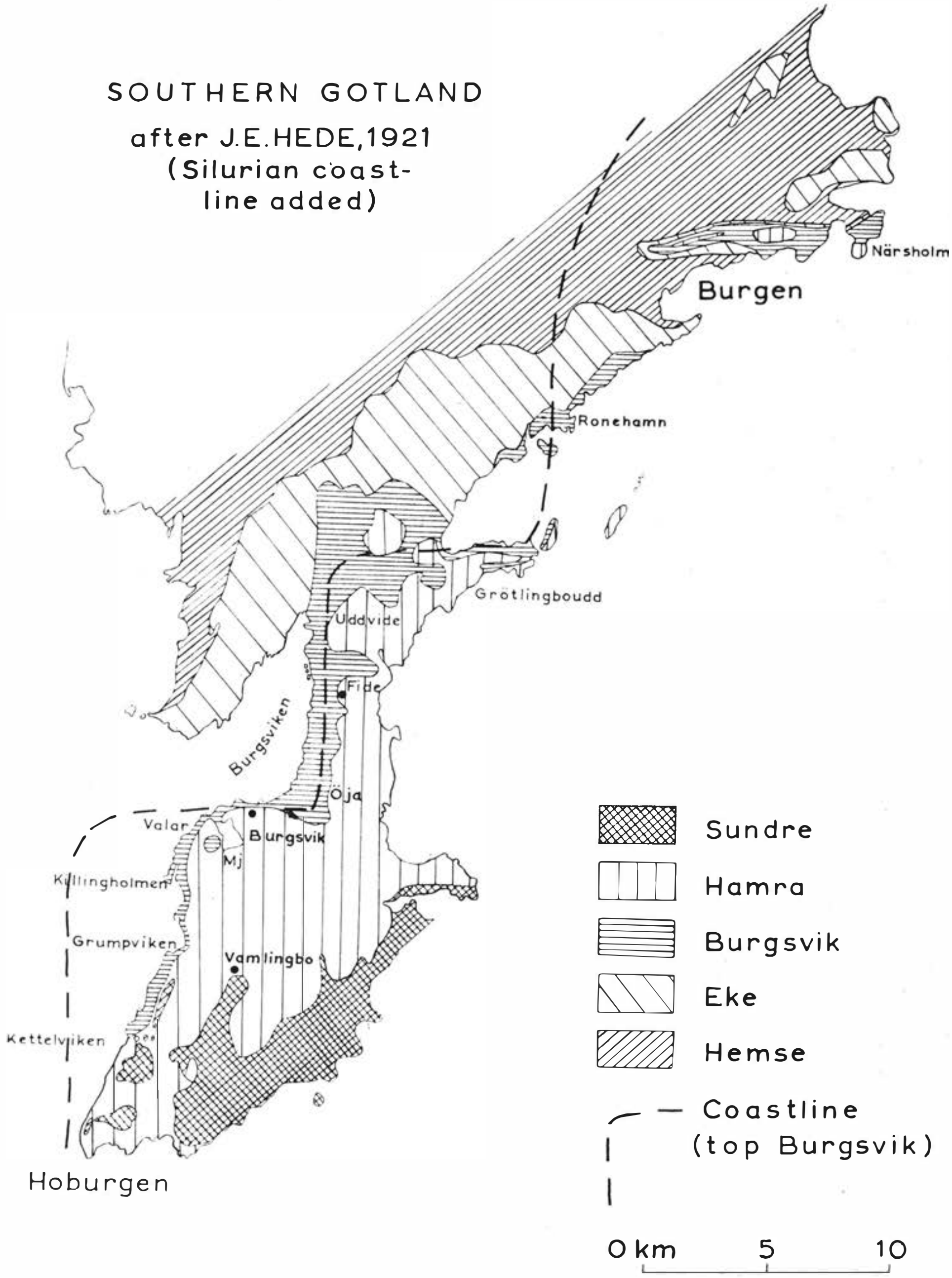

Fig. 1

In southern Gotland all circumstances to form offshore bars were present: a coast with shallow water, a flat seabottom, waves, and sandy material. It is therefore probable that the above mentioned "folding-structures" are silurian offshore bars, parallel to the coastline [2].

[2] The breadth of more than 100 m excludes the possibility of normal submarine bars and current ripples.

The course of the silirian coastline from Hoburgen to Valar in the south will be reconstructed in chapter III. Its position west of Burgen is unknown. The possible bending of its course towards the NE was deduced from the direction of a foreset-bedding in a crinoidal limestone at Burgen which had possibly a direction of slope perpendicular to the coast.

During the following transgression the coastline moved in a NW direction, that is in the direction of the Burgsvik land on account of the fact that the subsequent sediments are deep-water deposits (see II, c).

The shallow-water indications in the Upper Burgsvik can be summed up as follows:

(1) erosion channels (for instance at Hoburgen),
(2) cross-bedding (in sandstone at Hoburgen and in crinoidal limestones at Burgen),
(3) ripple marks,
(4) offshore bars, which alow the reconstruction of the Upper Burgsvik-coastline,
(5) formation of oolites,
(6) rounded pebbles of oolite in the sandstone and in the oolites,
(7) sorting of the partly rounded fossils at the transition from the sandstone to the oolite-deposit,
(8) clay as a "wad"-deposit,
(9) possible tidal channels,
(10) local shell accumulations,
(11) a high percentage of lamellibranchs with thick shells.

c. *Hamra and Sundre Limestones*

Everywhere the Hamra Series starts with the so-called Girvanella Limestone, more or less rich in *Girvanella* (*"Sphaerocodium"*). The Hamra Series reaches its greatest thickness in the east. The total thickness of these limestones can be assessed by direct obervations only in the SW, viz. at the steep cliffs of Hoburgen, where it reaches a thickness of about 20 to 25 metres. Here a great part of the series is built up by reefs. These Hamra reefs did not rise more than a few metres above the stratified sediments around it. Laterally extending reefs expanded over sediments which were deposited at about the same time. At some places the reef limestone interfingers with adjacent deposits. Thus it appears that at Hoburgen the total thickness of the Hamra Series is only a few metres thicker than at these places where no reefs occur. Without reefs its thickness should not have surpassed 20 m.

The Hamra Series is overlain by crystalline crinoidal limestone, forming the Sundre Series which shows a great impoverishment in fauna with regard to the Hamra Series.

d. *Dip of strata*

The series of strata in Gotland shows a general dip towards the SE. Hede (1921) already remarked that the silurian sediments as a whole have been tilled ca. 0°30′ about a SW-NE axis.

The mean dip of the layers in southern Gotland can be ascertained by means of their outcrops on the geoligical map and the deep-borings of Burgsvik and Vamlingbo. From the outcrops of the Eke Series to the outcrops of the Sundre Series, which normally strike toward the NE, the average dip is 0°23′ towards the SE.

III. THE UNDULATION OF THE RATE OF SEDIMENTATION IN TIME

a. *Possible explanations of the variations of the thickness of strata*

From the geological map and the borings it is evident that the Burgsvik and Hamra Series wedge out, the first in an eastward and the second in a westward direction. There are three fundamentally different possibilities to explain this curious fact.

(1) The Burgsvik Sandstone and Oolite and the Hamra Limestone wore all sedimented simultaneously, representing different facies of one and the same time-rock unit. The contacts of these different facies are not time boundaries.

(2) As the coast crossed southern Gotland during Upper Burgsvik time, with land at the westward side, a delta was formed with a primary dip towards the east. With the Hamra transgression all primary relief was levelled, so that in the west less Hamra Limestone were laid down. The contact then would be a time boundary.

(3) During the formation of the sandstone the basin descended strongest in the west near to the coastline of that time. In course of time this belt of maximal descent moved eastward, so that the sandstone is thinner there and covered by a thicker Hamra Limestone. The contact would then also represent a time boundary.

Possibility (1) was followed by van Hoepen (1910), but the transition certainly is a time boundary, as is proven in the preceding chapter. We also found that the Upper Burgsvik as a whole was horizontal during its deposition. In Grötlingboudd and Burgen-Närsholm the sea was shallow as it was at Hoburgen and Burgsvik.

Possibility (2), a delta, cannot be true, because of the indications for shallow water, found in all exposures of the Upper Burgsvik. Indeed at Grötlingboudd there was the same coastline as at Hoburgen.

It follows that the solution has to be found in possibility (3) as will be discussed in the following paragraphs.

b. *Reconstruction of the position of the strata before the tilt*

Figure 2 is an outline map of southern Gotland. On this map the contact between the Eke and Burgsvik Series and the contact between the

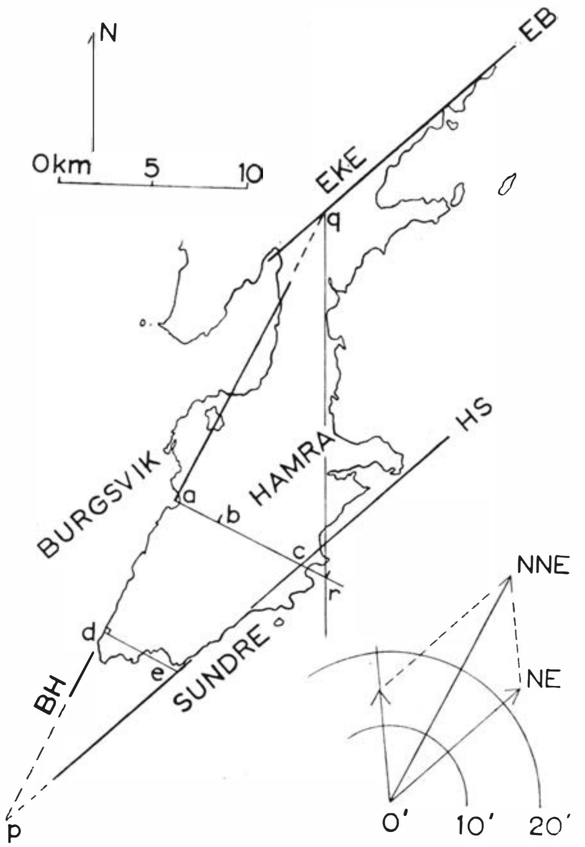

Fig. 2

Hamra and Sundre Series (in the next pages EB and HS) were drawn as the lines of intersection between these planes and sea level. The contact between the Burgsvik and Hamra Series (called BH) is also marked in this way, eliminating the large primary dips of the offshore bars.

The NE strike is the normal one on Gotland; it is due to the later tilt about a SW-NE axis. In general therefore the line of intersection of the contactplanes between the series of strata such as EB and HS with sealevel is striking SW-NE. The line of intersection between BH and the sea-level is approximately also straight. For this reason BH was probably a flat surface when it was tilted. If it was a curved surface at that time, *pq* (fig. 2) would be a curved line.

The total thickness of the Burgsvik and Hamra Series together amounts to about 90 metres. In the scheme (fig. 2) the Sundre sediments lie on the Burgsvik Series at *p,* where the Hamra Limestones wedged out completely. Likewise there is no Burgsvik Sandstone at *q,* where this sandstone wedges out. This construction agrees fairly well with the real facts (see III, c).

We are interested in the strike and dip of BH before the tilt of 23 minutes (see II, d). Qualitatively this position of BH is represented by block-diagram A (fig. 3), where BH is shaded. The later tilt and ersion till the present sea-level is shown in block-diagram B also by a shaded plane, which have to be imagined in a horizontal position. The lines in this new plain give the present situation on Gotland. It is evident that due to the tilt the angle α, the original angle between the strike of BH and the axis of tilt, is larger in A than than β in B, β being the present angle between the strike of BH and the axis of tilt. When a plane is tilted, the angle between its strike and the axis of tilt is diminished. In consequence, the present NNE direction is not the strike of BH before it was tilted.

Qualitatively we have now a clear picture of the structure and so we will try to reconstruct more exactly the position of BH before the strata were tilted. At first figure 2 will be controlled.

C o n s t r u c t i o n A. Because BH is a flat surface the wedging out of the Hamra Series towards the W is linear. This thinning out is given by the angle between *pq* and *pc.* This means that the ratio of the parallel lines *de* through Hoburgen and *abc* through Vamlingbo equals the wedging out. *ac* = 7,4 km and *de* = 4,4 km. The ratio *ac : de* = 1,7.

The boring at Vamlingbo was made at *b,* here the thickness of the limestone amouts to 40 m. At *d* (Hoburgen) Munthe gives 20—25 m (see I, c). The ratio *ac : de* = 1,7 is indeed equal to the thinning out: 40 : 22 = 1,8.

Schematically at *q* the Burgsvik Sandstone was taken as zero metres. At Burgen the thickness of the Lower Burgsvik amounts to about 5 m; in consequence in the east the Hamra Limestone does not ly conformably on the Eke Marls. However, this small deviation of the facts from

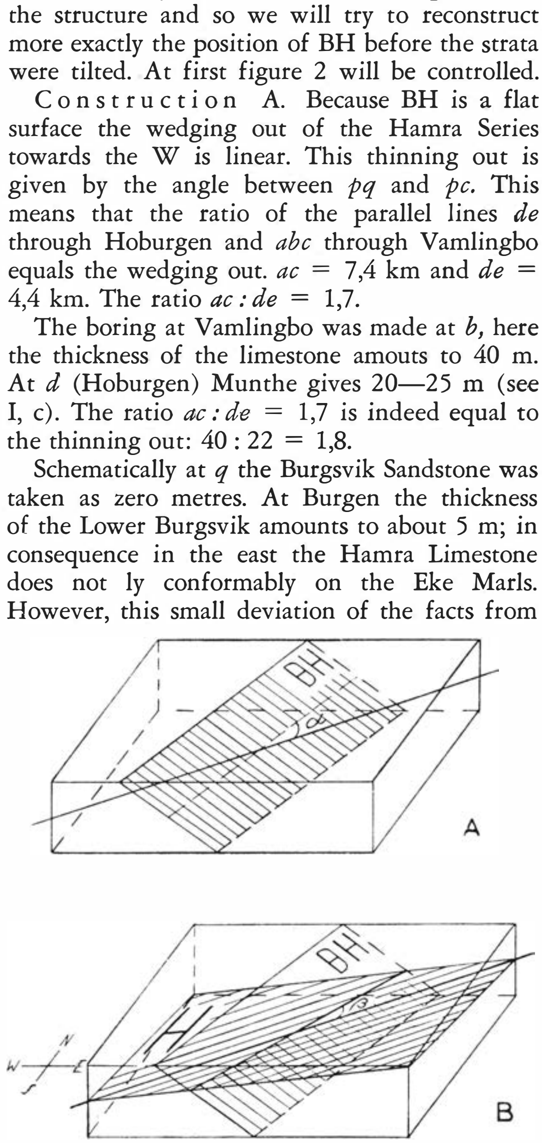

Fig. 3

the simplified map, on which no sandstone at all is assumed near *q*, is of no significance for the following construction.

C o n s t r u c t i o n B. ab = 2,5 km. The contact BH at *b* occurs 25 metres below sealevel. Therefore the present dip of BH is 0°34′ ESE. *ar* = 9 km; BH here will occur at $ar/ab \times 25$ m = 90 m below sealevel. Because *r* is situated near *pc*, the bottom of the Burgsvik (+ Hamra) Series is approximately 90 m below sealevel at this place. The construction shows that this 90 m entirely consists of Hamra Limestone. In consequence *r* is a point on the line where the Burgsvik Series has entirely wedged out. *q* was such a point too. The conclusion is, that the Burgsvik Series thins out in the W-E direction, perpendicular to *qr*. This wedging out of 90 m occurs over a distance of 17 km, that is the distance of *p* from *qr*.

This ratio is a first approximation, but the construction is influenced by three insufficiently exact data: (1) the relatively great dips of the strata in the synsedimentary offshore bars north of Grumpviken(*aq* on fig. 2), (2) the Burgsvik Sandstone does not wedge out entirely at *q*, (3) the constructed point *r* does not coincide exactly with *pc*. Therefore another construction will be given as a control.

C o n s t r u c t i o n C. For the following construction only the area south of the place Valar will be used, where no disturbing primary dips occur. The usual simple construction is that of the stereographic projection. But on Gotland the very small dips (fractions of one degree) exclude exact constructions in this way. For small angles a new method will be developed now, which can be used rapidly and very exactly.

Vector-analysis learns that two infinitesimal rotations about two different axes can be jointed to one rotation about a fixed axis. Axial vectors give the amount of rotation. If we see the system as a right-turning screw, such an axial vector has a fixed direction along the axis. In consequence the addition of infinitesimal rotations is like the addition of vectors [3].

Our problem is the following one. Before tilting the contact BH dipped x′ in a certain direction, this corresponds with a rotation of x′ about an unknown axis from a horizontal position. Next, a tilt of 23′ about a NE axis has to be added. The sum is 34′ about a NNE axis, that is the present dip at *b* according to the Vamlingbo drilling. Fig. 2 (right, lower corner) shows that the primary dip was 15′ E [4].

[3] The preceding is proved in many elementary books on physics and mathematics, for instance Sommerfeld (1949).

It appears from both constructions (B and C) that the primary strike of the contact BH was S-N.

C o n s t r u c t i o n D. There is a good check to this result, because — as we shall see in III, d — the silurian coastline must have had a course, by preference parallel to this S-N strike (see fig. 1).

The dip of BH is somewhat less certain than its strike before the tilt. The 0°15′ determined according method C seems quite probable. This corresponds to a wedging out of 90 m over a distance of 20 km. In method A we used a ratio of wedging out $ac : de$ = 1,7 or $ap : dp$ = 1,8. This ratio of wedging out has to be supplemented by a strike in order to obtain the value of the dip. If we take the strike N 7½° W of construction C (see fig. 2, right, lower corner) the 90 m Hamra will wedge out over 23 km. The result of method B was 90 m over a distance of 17 km. This disparity is not serious. Since we used more or less independent methods of construction the assumption of a dip of 90 m over a distance of 20 km seems to be a rather good mean value.

c. *Properties of the undulation of the rate of sedimentation in time*

In the section (fig. 4) the dates of Hoburgen, Vamlingbo, Burgsvik, and Burgen are projected along the original strike of BH on a W-E section, which gives their right position before the tilt of 0°23′. Fig. 6 is this W-E section, idealized according to principles which will be discussed in this paragraph. It appears from fig. 6 that abnormally thick strata were deposited at a certain time in a S-N belt with a width of 20 km. Thus we must conclude that there was a S-N directed trough, which gradually moved towards

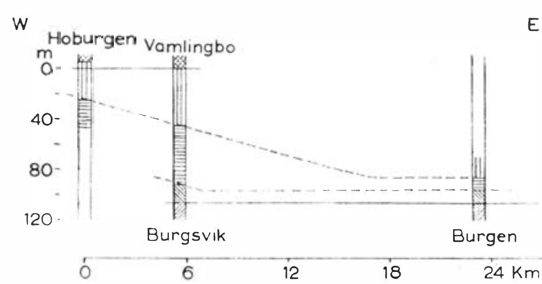

Fig. 4

[4] Very small rotations can be called infinitesimal. But probably in the tectonics on Gotland no pure rotations occurred but vertical movements. The tg and sin of an angle of 2° are still the same to four successive decimals. This means: for an angle of ½° it does not matter if there is a pure rotation about a NE axis or an incraesing subsidence in a SE direction with the same affect for the dip.

the east. The width of the trough is the same as the width of the thicker parts of the sedimentary sequence.

The borings of Vamlingbo and Burgsvik together give the whole profile from Hemse to Sundre Series. In diagram 5 the relation is shown between the rate of sedimentation and time at this place. For convenience all series are given the same length along the time-axis. The rate of sedimentation is called normal (n), when it does not differ from any other point of the basin, apart from those with an abnormal rate of sedimentation (a), which are situated in the local

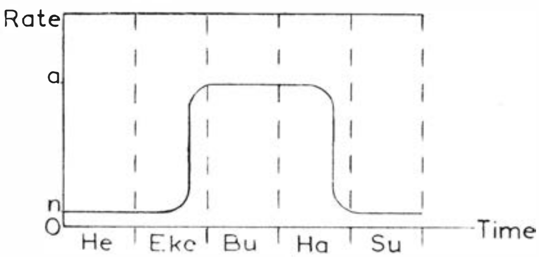

Fig. 5

trough. The ratio a : n = 10, on account of the fact that ca. 50 m sandstone and clay at Burgsvik probably correspond to ca. 5 m at Burgen.

The sideward movement of the trough is recorded by the differences in thickness of the strata and by the abnormal strikes of the outcrops on the geological map (fig. 1). At Vamlingbo-Burgsvik possibly an abnormal rate of sedimentation commenced during Upper Eke time because: (1) the thickness of the Eke Series is 14 m here, that is 4 m thicker than at Burgen, where evidently normal sedimentation occurred during Eke time (see the strike of EB in fig. 2), (2) at Näsudden, the peninsula NW of Burgsviken, the contacts between Hemse and Eke and between Eke and Burgsvik Series change from a NE to a NNE strike.

At Vamlingbo-Burgsvik a normal rate of sedimentation (n) returned during Upper Hamra time, because the outcrop assumes a normal NE direction. The rate of sedimentation apparently shows an undulation from Upper Eke to Upper Hamra.

Figure 6 schematically gives the structure of the cross-section if the rate of displacement of the trough is constant. The latter is an important value; it is given by cotg φ. The value of this rate of displacement is: km to one metre sediment, as unit of time; φ being the angle between the horizontal and the centres of the parts of maximal sedimentation of the successive series (fig. 6).

The strata in the trough, like the Upper Burgsvik in southern Gotland, were laid down horizontally. These strata obtained a dip α ($\alpha = 15'$, see III, c), because of the relatively greater subsidence of the basin to the east.

From fig. 6 the relation between φ, a : n, and α:

$$\operatorname{cotg} \varphi = \frac{a : n - \cos \alpha}{\sin \alpha}$$

can be derived by simple trigonometric methods. When α is small this relation means that

$$\operatorname{cotg} \varphi = \frac{a : n - 1}{\operatorname{tg} \alpha}$$

or the rate of displacement equals the ratio of increase of sedimentation less one, divided by the tangent of the dip of the strata which were laid down in the trough. As a result of this formula a rate of displacement of about 2 km/m sed. is found.

The formula is more exact than the argumentation given earlier in this paragraph, which said that during Upper Eke time the undulation arrived at Burgsvik combined with the fact that is

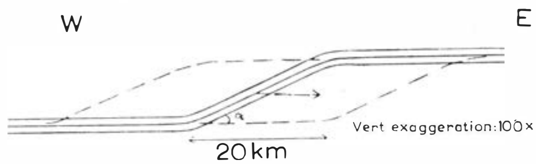

Fig. 6

arrived at Burgen during the Upper Burgsvik, because the Upper Burgsvik Series reaches the same thickness of about 7 m in Burgen and Vamlingbo-Burgsvik. In consequence the Upper Burgsvik Series has been laid down in the trough at both places. The component in the W-E direction of the horizontal distance between Burgsvik and Burgen is about 15 km and the normal sedimentation produced 5—15 m of sediments (see fig. 4). The rate of lateral displacement therefore is 1—3 km/m sed.

d. *On the origin of the sideward shifting undulation*

The development of the sedimentation in southern Gotland has been described as the result of an eastwards shifting trough of subsidence, combined with an abnormal thickness of sediments. Another possible method of description is that of a moving flexure. It is obvious that all

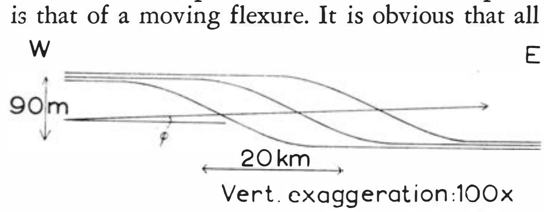

Fig. 7

points west of the trough had moved down 90 m with respect to the points east of it (fig. 7).

A coastline tries to be parallel to the axis of differential vertical movements, so that the principal NNE direction of the coast was resolved in two components: parallel to the trough (S-N direction) and perpendicular to it (W-E direction).

The hinge-zone along which movement took place moved toward the east. The layers were bent along this hinge-belt, which had a width of 20 km, and then straightened after it had passed them (fig. 7).

This Gotlandic example of a sidewards moving hinge-zone can be compared with an analogous phenomenon in NW-Germany. Sidewards movements of salt were studied by Trusheim in 1957. His „primäre Randsenken" are due to the squeezing out of salt towards a „Saltzkissen" (fig. 8; fig. 18 of Trusheim, 1957. Here we find a sidewards moving trough or hinge-belt too, but the dimensions are different, as is shown by the following table [5].

	Gotland	Gorleben	Ratio
Width of the trough	20 km	10 km	2 : 1
Thickness of the layer	90 m	2 m	1 : 20
Grade of the flexure = tg α	1 : 220	1 : 5	1 : 45
Increase in sedimentation = a : n	10		10 : 3
Rate of displacement = cotg φ	2 km/m sed.	10 m/m sed	40 : 1

The low regular grade of the flexure in southern Gotland pleads for a greater depth and lower viscosity of the material that probably flowed below Gotland during sedimentation. The difference in the rate of sidewards moving hinge-belt demonstrates a lower viscosity too.

This viscous matter, presumably magma, could not escape upwards, but on account of a basinward loadgradient it was squeezed out with a large horizontal component of flow direction. Perhaps this magma was intruded in connection with the Caledonian orogenesis.

The preceding pages aimed at demonstrating that movements of viscous subsurface matter (for instance magma) can be recorded by the sedimentation at the surface.

[5] To compare the rate of displacement = cotg φ in Gotland and Germany the absolute rates of subsidence of the several basins have to be known; at rough approximation the amount in Gotland is 500 m during 50 million years (Gotlandium) and in Germany 500 m during 10 million years (Rotliegendes, Trias, and Jura). In consequense the amount of 10 m/m sed. (rate of displacement) has to be multiplied by a factor 5, before comparison is possible.

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