MIDDLE AND UPPER ORDOVICIAN DISCONTINUITY SURFACES IN NORTHERN ESTONIA (ZONALITY BASED ON THEIR IMPREGNATION TYPE)

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The Ordovician section in Estonia shows a great variety of impregnation types and number of discontinuity surfaces (DS). The most distinct changes take place in the interval B_{II}-D_I (especially in its middle part - C_Ib-C_{II}). This paper is mainly based on the data derived from about 150 drill cores investigated by the author. In addition about 50 core descriptions, made mainly by the geologists of the Geological Survey of Estonia K. Suuroja, A. Haas, Anne and Ain Põldvere, have been used. A certain zonality based on the impregnation type of the DSs has been noticed (from north to south): 1 - pyritic, 2 - pyritic and phosphatic mixed, 3 - phosphatic. In some intervals southward of the pyritic zone a nonimpregnated one has been observed. In interval C_Ib-C_{II} the zone boundaries migrate gradually southward. In the Tatruse Formation the shift in opposite direction has been noticed. As shown for the best internally stratified interval (C_Ib-C_{II}) the pyritic DSs occur on certain beds and are of the greatest extent. The phosphatic DSs are less extensive and are not so closely connected with a definite level. Several regularities have been established between the impregnation type of the DSs and their number, character of the surrounding rocks and the relative thickness of the corresponding stratigraphic unit.
In the author's opinion the DSs are of submarine origin. The phosphate is supposed to be derived by upwellings. The changes in impregnation types are suggested to dependend on different hydrochemical conditions in various parts of the basin.

Key words: discontinuity surface (DS), Ordovician, impregnation type, zonality, northern Estonia.
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INTRODUCTION

The Ordovician section in Estonia shows a great variety of impregnation types and number of discontinuity surfaces (further abbreviated DS). The most distinct changes in both above-mentioned characteristics take place in interval B_{II}-D_I, especially in its middle part (C_Ib-C_{II}) and F_IaP-F_Ib (Põlma, 1982; Saadre,1993). In the study area these intervals are dominated by the pyritic and phosphatic DSs. Along with them goethitic DSs occur in B_{III}-C_Ia (in places they can be met in the peripheral part of the zone also in C_Ib, F_Ia and F_Ib), nonimpregnated DSs in C_Ic and C_{II} (in spots in F_Ia as well). In F_Ia some DSs are covered with a glauconitic lamina. Also a well-developed lateral zonation of DSs can be followed there.

This report is largely based on the material derived from more than 15O drill cores described by the author (concerning mainly the Lower and Middle Ordovician). In addition, about 5O core-descriptions from northern and central Estonia, made by the geologists of the Estonian Geological Survey K.Suuroja, A.Haas, Anne and Ain Põldvere, and the descriptions of mapping drill cores from southern Estonia by K.Kajak, E.Kirs, L.Põlma etc. have been used.

In the distribution schemes the types of impregnation, number of DSs and outcrops are shown. The data obtained for northern Estonia are presented only partly. The number of DSs (as shown before, Saadre, 1993) could not be considered as absolute. Nevertheless, they are important for comprehension of this phenomenon.

The vertical and lateral distribution of the DSs is greatly dependent on their impregnation type. The most suitable interval for such investigations is C_Ib-C_{II} due to its very detailed inner stratification (Männil, Bauert, 1984, Männil, Saadre, 1987), that enables to follow every DS. In the whole interval the best observable and of the greatest extent are the DSs with pyritic impregnation. For example, in the Väo Formation there occur several well traceable pyritic DSs (e.g. "doubledisc", "sixfolddisc", etc.,Orviku, 194O), that can be distinguished in the outcrops and cores around Tallinn within the radius of tens of a kilometer. In the Uhaku and Kukruse stages, the pyritic as well as nonimpregnated DSs occur generally on very definite levels, mainly on the upper boundaries of the kukersite beds and/or seams (H, K_1, K_2, M, O, P, I, II, III, IV, VI) or within the limits of the succeeding pure limestone beds (C/D, H/K, L/M, C/D). The extent of these DSs is relatively great. In eastern Estonia they can be followed for 2O to 4O km in the north-south Tapa - Järva-Jaani profile (Männil, Bauert, 1984; Männil, Saadre, 1987). Some of them (III, K_2) can be observed throughout northern Estonia (Bauert, 199O). More rarely pyritic DSs occur at the lower boundaries of the kukersite beds (M, P, I,) or inside them (M, O, P, I, VII), particularly in their northern, outwedging parts. In this area several (up to three) DSs are found in some kukersite beds. Southward their number decreases rapidly to one. Further to the south, the remained DSs of other types have a great extent (some of them more than 2O km). In the Pärtliorg Member of the Uhaku Stage, the DSs are of a smaller extent.

ZONALITY

As a rule, the pyritic DSs disappear in the southward direction or are replaced by nonimpregnated ones on the same level. The latter are fixed only in interval C_IcP-C_{II}P, mostly in the eastern part of Estonia. In the Maidla Member these DSs can also be found in north-western Estonia. Their north-south extent is smaller than that of the pyritic ones, but some of them reach for more than 10 km. Further to the south, the phosphatic DSs appear in the sequence. Unfortunately, the inner stratification of C_Ic-C_{II} outside the kukersite distribution area is much coarser. Therefore in most cases it is not possible to prove the correspondence of a phosphatic DS from this area to a certain pyritic DS from a more northern section. Yet, different numbers of DSs of the both types show clearly that most of the phosphatic DSs do not have their pyritic counterparts.

Analogous, but notably more comprehensive is the lateral substitution of the impregnation type if the DSs are grouped by units (stages, formations, members). Since the lines of the exchange of impregnation types of DSs do not coincide on different levels (Fig. 1), a mixed zone is formed where both the pyritic and phosphatic DSs occur. In some cases its width is so small that it cannot be fixed in the cores investigated.

The most widespread is t h e p y r i t i c z o n e extending throughout the Ordovician (B_{III}-F_{II}). However, the position and width of the zone, as well as the number of DSs in it vary considerably in different stages. For example, both in the Kunda and Aseri stages, the zone is located in the farthest northwestern Estonia (mainly on Hiiumaa Island) (Saadre, 1992; Fig 4). In the Väo Formation it is missing, but presumably has existed north of the contemporary erosion line. At the base of the Kõrgekallas Formation, in the Koljala Member, it occurs only in the northern part of Hiiumaa Island (Fig. 2). In the Pärtliorg Member, it has widened to the northwestern part of Estonian mainland. Starting from the Erra Member, the pyritic zone forms a west-east strip ranging through the whole northern Estonia. Further, up to the Peetri Member (incl.), this strip widens gradually southward. In the Tatruse Formation it is shifted back to the north again (Fig. 3). In the Jõhvi Stage the withdrawal continues, the zone is observable only in northwestern and northeastern Estonia. In the intervening area the DSs are completely missing. In the Keila, Oandu and Rakvere stages only pyritic DSs occur on the Estonian territory (Saadre, 1992, Fig. 5).

Along with the pyritic DSs, some nonimpregnated ones also occur in this zone. (C_Ic, C_{II}, F_Ia). On several levels (C_{II}K, C_{II}M), nonimpregnated DSs form an independent zone between the pyritic and phosphatic zones.

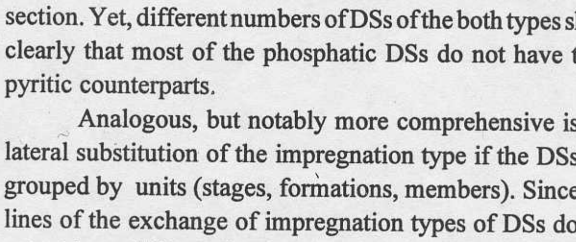

Fig. 1. General scheme of the zones.
1 - pyritic DS, 2 - phosphatic DS.

T h e m i x e d z o n e, represented by pyritic, as well as phosphatic DSs, is distributed in several intervals (B_{III}, C_Ib, C_IcK, C_IcP, C_{II}P, F_IaP, F_Ib) between the pyritic and phosphatic zones. Depending on the interval, its width is very variable. The zone is widest in the Kunda, Vormsi and Nabala stages (Saadre, 1992, Fig. 4, 5), where the purely phosphatic zone is entirely missing. It is comparatively wide also in the Kõrgekallas Formation. In other cases the zone is very narrow. In some intervals (C_{II}K, C_{II}M, C_{III}*tt*) it has not been registered at all.

T h e p h o s p h a t i c z o n e has usually the largest (C_Ib-C_Ib *vä*, C_IcK, C_IcE, C_{II}K; in eastern Estonia also in C_{II}M and C_{III}*tt*, in western Estonia in C_Ia) lateral distribution. Compared to the aforedescribed zones, the maximum number of DSs is, as a rule, higher in the phosphatic zones (Table 1). By way of exception (C_IcE; C_{II}P), in northeastern Estonia the nonimpregnated DSs are found side by side with the phosphatic ones.

T h e m i g r a t i o n o f t h e z o n a l b o u n d a r i e s. Beginning from the Lasnamägi Stage up to the Peetri Member of the Kukruse Stage, a gradual but constant south- or southeastward migration of the zonal boundaries is registered, especially in eastern Estonia. As mentioned above, in the Tatruse Formation, the northern

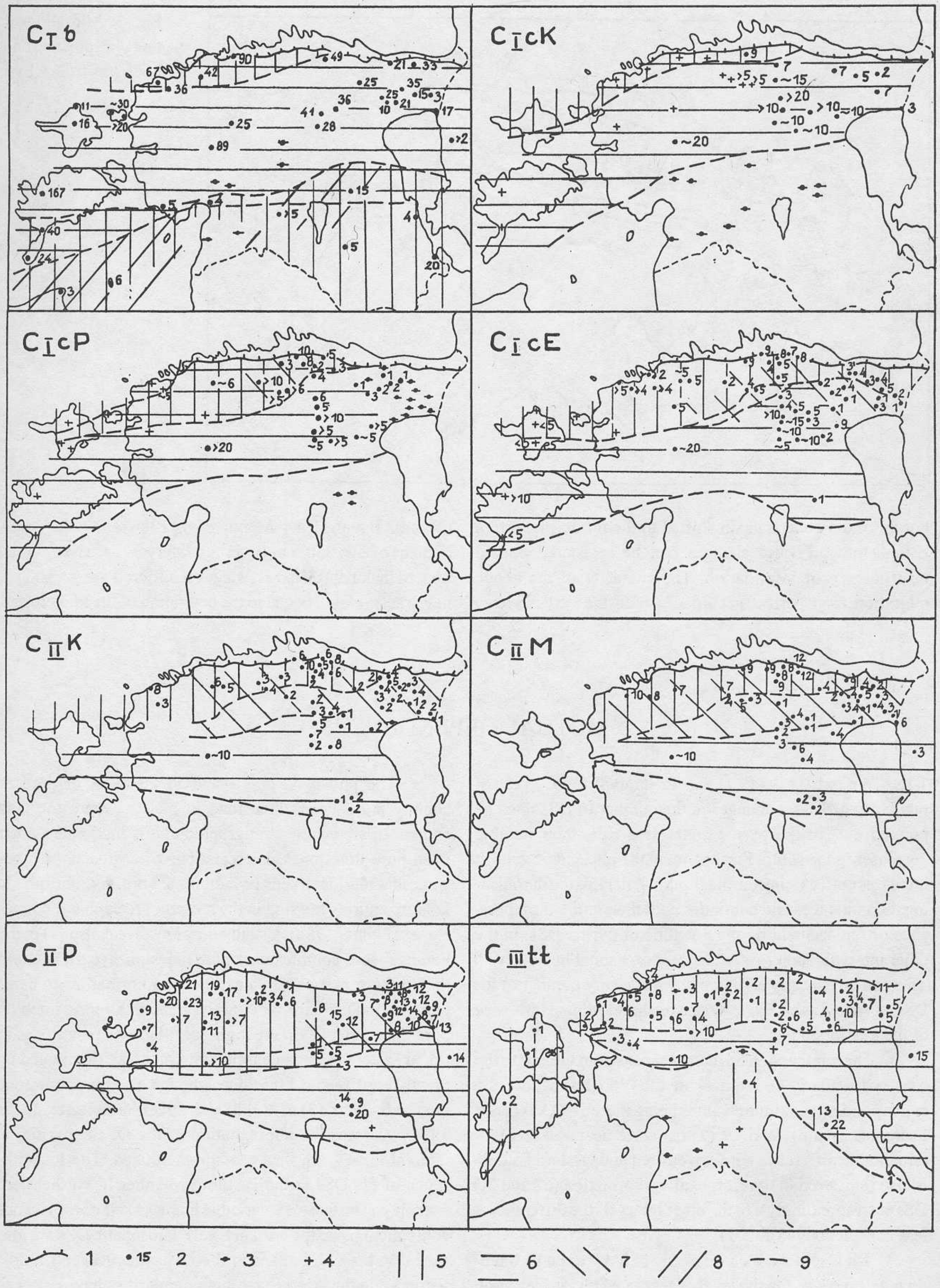

Fig. 2. Spatial distribution of DSs in north and middle Estonia.
1 - erosion line, 2 - borehole, outcrop, the number of DSs, 3 - borehole, where DSs are missing, 4 - borehole, where the number of DSs is not fixed, 5-8 - DSs impregnation type: 5 - pyritic, 6 - phosphatic, 7 - nonimpregnated, 8 - goethitic, 9 - boundary of the DSs impregnation zone.

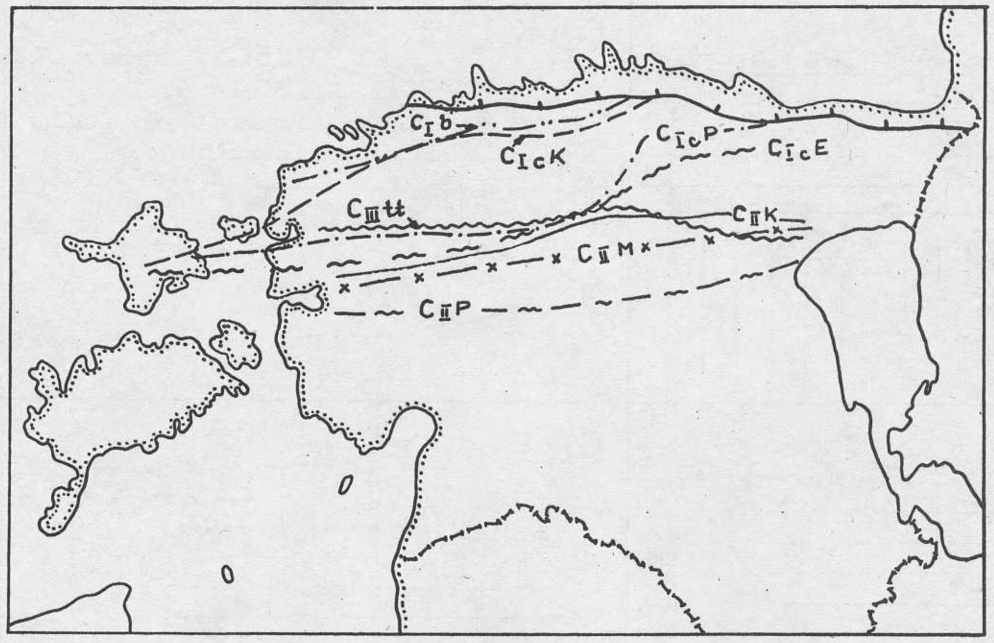

Fig. 3. Migration of the phosphatic zone boundary from $C_I b$ *vä* to $C_{III}T$.

border of the zone is again shifted to the north. In western Estonia not all these changes can be registered due to insufficiency of information. The character of the above migration is in perfect accordance with the earlier views (Männil, Bauert, 1984; Männil et al., 1986) about the development of the Baltic basin in the interval discussed: in the upper Uhaku and Kukruse stages it suffered a regression, a new transgression began in the beginning of the Idavere age.

MUTUAL DEPENDENCES

T h e n u m b e r o f D S s. In interval $C_I c$-C_{II} certain regularity of lateral changes in the number of DSs must be pointed out. In the pyritic zone, as a rule, their number decreases to the south. Further on, in the phosphatic zone, it increases until gaining the maximum. After this the diminishing recommences and continues until their entire disappearance or replacement by the goethitic or pyritic DSs. In the other intervals such evident tendencies cannot be observed. This can be partially explained by the scanty number of the DSs, in some cases (B_{III}, $C_I a$) also by the additional influence of the goethitic DSs.

The number of DSs increases also from the east to the west, particularly (~3 times) in the Väo Formation, the corresponding maximum values being there 167 (Viki core, Saaremaa Island) and 49 (Tursa core, near Rakvere). A remarkable difference between eastern and western Estonia is also registered in the Kõrgekallas Formation (62 and 3O DSs correspondingly). In the other intervals the difference is less conspicuous (Table 1).

T h e c o n n e c t i o n w i t h t h e s u r r o u n d i n g r o c k s. On the level of separate DSs, as well as on a more generalized level (grouped by members, formations or stages), distinct relations between the lithology of the rocks and the impregnation type of the DSs have been established (Põlma, 1982; Saadre, 1992).

The phospatic DSs occur in the beds of pure or slightly argillaceous limestone in places, where the clay content of a concrete stratigraphic unit is moderate - apart from pure limestones, intercalations of argillaceous limestone and marl interbeds or laminas are present. Phosphatic DSs are entirely missing in the red-coloured aphanitic limestones (Põlma, 1982). Usually they are absent also (1) in the homogeneous complexes of pure limestones (e.g. $C_I c$, C_{II} in the northern part of Hiiumaa; the Väo Formation contains phosphatic DSs only very rarely in an area represented by pure limestone; (2) in the high - argillaceous facies (e.g. in $C_I c$ in eastern Estonia near the outcrop area), dominated by greatly argillaceous limestones, though also pure limestone interbeds occur; (3) in the kukersite distribution area. In the all above cases the impregnation of the DSs is pyritic, in interval $C_I c$-C_{II}, in places, nonimpregnated. The local absence of the DSs in the Pärtliorg Member in northeastern Estonia can be due to remarkable increase in the argillaceous component (over the critical level). Phosphatic DSs are also absent in the oolitic beds in the Lasnamägi Stage (middle Estonia). In the Aseri Stage such regularities have not been observed.

T h e r e l a t i o n s b e t w e e n t h e t y p e o f i m p r e g n a t i o n a n d t h e t h i c k n e s s o f a s t r a t o n. As a rule, the distribution of various impreg-

Table 1

Vertical variation of maximum number of DSs and character of the zones

Stage, Formation, Member		Max. number of DSs										Width of the DSs zones (km)				Pace of migration of the zones (km)
		Western Estonia					Eastern Estonia									
		Σ	P	Ph	N	G	Σ	P	Ph	N	G	P	M	N	Ph	
Vormsi St.	F_I b	7	7	3	-	-	7	4	4	-	2	0-10	15-45	-	-	
Nabala St. Paekna Fm.	F_I *apk*	20	17	12	2	2	6	5	4	-	-	0-30	30-60	-	-	
Jõhvi St.	D_I	10	8	1	-	-	5	2	2	5	-	0-20	-	-	0-20	0-20 N
Idavere St. Tatruse Fm.	C_{III} *tt*	10	10	10	-	-	22	10	22	2	-	15-60	-	-	10-75	10 N
Peetri Mb.	C_{II} P	23	21	6	-	-	20	11	20	6	-	20-50	5-10	(20)	20-40	15 S
Maidla Mb.	C_{II} M	10	7	10	7	-	12	12	3	3	-	5-30	-	0-20	20-50	0-10 S
Kiviõli Mb.	C_{II} K	>10	8	>10	4	-	10	8	6	4	-	0-30	-	0-20	20-50	0-15 S
Kukruse St.	C_{II}	39	35	33	5	-	25	13	25	14	-	15-35	5-20	(10-45)	10-45	0-15 S
Erra Mb.	C_I cE	~20	>5	~20	2	-	15	8	~15	2	-	5-35	0-10	(30)	20-60	0-10 S
Pärtliorg Mb.	C_I cP	>20	6	>20	2	-	>10	4	>10	1	-	15+	0-30	(15)	20-50	10-20 S
Koljala Mb.	C_I cK											15+	0-10	-	45-60	
Uhaku St.	C_I c	62	-	64	-	-	36	-	38	-	-	0-15	10-40	(30)	15-40	
Lasnamägi St.	C_I b	167	-	-	-	-	49	-	-	-	-	-	0-15	-	~60	
Aseri St.	C_I a	8	2	7	1	4	20	-	-	-	20	0-15+	0-20	-	0-60	
Kunda St.	B_{III}	50	9	46	-	20	45	4	45	-	20	0-30+	0-15	-	20-40	
Volhov St.		>40	2	6	1	>40	60	-	-	1	>50	-	-	-	-	

nation types is not dependent on the thickness of the corresponding stratigraphic unit. An exception is interval C_Ib-C_{II} in eastern Estonia. Here the phosphatic DSs occur mainly in the southern area, where the corresponding units have evenly small thicknesses. In western Estonia, on the contrary, in the distribution area of the phosphatic DSs, there is a remarkable southward increase in the thickness of the studied stratons.

DISCUSSION AND CONCLUSIONS

From the material presented above, several problems arise which will not be discussed here in detail, solving of them stays out of the limits of this paper:

1. submarine or subaereal origin of the DSs studied;

2. the source of the phosphate occurring in the impregnation rims of DSs;

3. the cause of lateral changes in the impregnation types of DSs.

1. The author supports the opinion that DSs are mostly of submarine origin (Orviku, 1940; 1961; Gekker, 1960; Lindström, 1963; Einasto, 1954; Põlma, 1982, etc). Only a few of them with a very intensive pyritic impregnation and deep carvings can be of subaereal genesis. H. Bauert (1989) has considered them to be of microkarst origin.

2. Phosphatic compounds, greatly varying in content both vertically and laterally, are wide-spread in the sediments of the Ordovician Baltoscandian Basin. In the eastern Baltic region phosphate occurs mainly in two intervals: A_{II}-D_I and F_Ia-F_Ib (Põlma, 1982). The richest in phosphate is the Pakerort Stage in northern Estonia, where in places tremendous reserves of shelly phosphorites are distributed (the content of P_2O_5 being up to 15-25%). They are represented by quartzose sandstones containing diverse fragments or complete phosphatic shells of inarticulate brachiopods. The brachiopod valves consist of fluor-carbonate-apatite (=francolite) with an admixture of clay matter and fine scattered pyrite. The P content (>1 % P_2O_5) is high also in the Arenigian-Llanvirnian boundary beds in some regions of Sweden (Lindström, Wortisch, 1983).

In the post-Tremadocian Ordovician, the content of phosphate is many times smaller. Phosphate occurs there mainly in ooids, organic detritus, rounded grains and clasts and impregnation rims of DSs (Jaanusson, 1960; Põlma, 1982; Nordlund, 1989). In the eastern Baltic region, a gradual decrease in P content can be observed from the Pakerort Stage up to the Jõhvi Stage. Up to the Uhaku Stage this tendency has been proved by means of spectro-chemical analyses (Kiipli et al., 1984), higher it can be observed visually on the basis of diminishing intensity of the impregnation of DSs and their number.

From the southern East Baltic there are no exact data available about the content of phosphate. Nevertheless, by visual estimations also there the content of P in rocks is imperceptible.

The origin of phosphate has not been proved unambiguously yet, therefore opinions on this differ. M. Lindström and W. Vortisch (1983) suppose phosphate of the abovementioned Swedish occurrences to be of coastal upwelling origin. L. Põlma (1982) and U. Nordlund (1989) deny entirely the possibility of coastal upwelling in the Baltic Ordovician Basin, motivating such a standpoint with shallowness of the basin and its extremely low relief (Jaanusson, 1984). By L. Põlma phosphorus has flown in from the surrounding peneplaned mainland, during the transgressive stages of the basin (Põlma, 1985, an unpublished manuscript). U. Nordlund (1989) reckons the nutrient content in the basin not to be enhanced and the organic productivity not to exceed normal.

Proceeding from the following considerations, not trying to prove unambiguously any of the abovementioned opinions, the author of this paper tends to prefer the upwelling model.

The phosphate impregnating DSs could be considered as having derived from the normal (regarding to phosphorus-bearing nutrients) marine environment. However, this model seems not to account for the rich phosphate content in the Tremadocian and Arenigian. Also, very high content of organic material on several levels (accumulations of the thick kukersite layers in intervals B_{III} and C_Ic-C_{II} and of the organic rich "black shale" seams in A_{II}, A_{III}, D_{III} and F_Ib)(Põlma, 1982).

According to Baturin (1983), recent upwelling zones evidently include such criteria as accumulation of organic-rich sediments of a variable composition, high contents of organic matter, occurrence of pyrite-glauconite-phosphate associations among calcium carbonate and silica. Most of these criteria can be followed in the sediments of the Baltoscandian Basin. By some authors (Parrish, Ziegler, 1983), the existence of coastal upwelling is likely if already 1-2 criteria are fulfilled.

3. The lateral changes of the impregnation types must have been caused by the alteration of the hydrochemical conditions in different facies. The impregnating minerals - francolite and pyrite - were evidently precipitated from the interstitial water after the decay of buried organic material. A significant fact is that on some levels between the pyritic and phosphatic DSs there is a zone of DSs without any impregnation.

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