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Micromorphological investigation of soils formed on carbonate moraines in the taiga belt

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Development of soils on carbonate rocks is mainly defined by the carbonate influence. In the taiga zone, however, this influence is not permanent, since rocks are subjected to discarbonation. The rate of soils development on carbonate rocks is determined by the amount of carbonates in these rocks and by their leaching rate. In cold climate of the forest zone the dissolving of carbonates is particularly intensive.

On carbonate moraines in the taiga belt different soils are formed: typical soddy-calcareous soil, soddy-calcareous leached soil, soddy-calcareous podzolized soil and if the profile leaching is severe, podzolic and soddy-podzolic soils are formed. As moraine discarbonation proceeds a gradual change of soddy-calcareous soils into podzolic ones occurs [3]. There are many problems to be solved in the development of this process.

It is known, that the soil processes are revealed first of all in the microstructure peculiarities of individual genetic horizons, as well as in the composition and form of soil plasma separation. In this connection the main objective of the present paper was to discover variations in the microstructure of carbonate soils as leaching of carbonates proceeds. In order to solve this problem it was also important to study the influence of carbonate fragments in the profile of taiga soils. For this purpose problems of weathering of carbonate fragments in different genetic horizons of soddy-calcareous soils have been considered. For the interpretation of data of micromorphological analysis the results of other investigation methods have been used.

Two soil series have been studied. One series of soil profiles was selected in the northern taiga on a thin carbonate moraine loam underlain by coal limestones and dolomites at various depths (Arkhangelsk region). The climatic features are as follows: mean annual air temperature is about 0°C; duration of the period with the temperature above +5°C is 145 days; July is the warmest month (+16°C); January is the coldest month (−13°C). Mean annual precipitation is about 500 mm.

The second series of soils was studied in the sub-zone of the southern taiga and coniferous and in broad-leaved forests on a carbonate moraine loam, underlain by Devonian argillaceous dolomitic limestones (Novgorod region). Main climatic features are as follows: mean annual temperature is +4°C; mean temperature in January is −8°C; mean temperature in July is +17.5°C. The duration of the period with temperature above 5°C is 176 days. Mean annual precipitation is about 550 mm.

Table 1. General soil characteristic on carbonate moraines

Soil	Region	Section No.	Horizon	Depth (cm)	Salt pH	Humus %	Absorbed Ca+Mg for 100g of soil mg-equiv.	Fraction <0.001 mm, %	$\frac{C_{h.a.}}{C_{f.a.}}$
Soddy-calcareous typical	Arkhangelsk	41	A_1	0-10	6.60	8.91	47.5	13.7	0.99
	Novgorod	2	A_1	0-10	7.20	11.03	—	44.7	0.91
			A(B)	19-30	7.31	4.77	—	37.8	—
Soddy-calcareous leached	Arkhangelsk	29	A_1	0-10	6.28	8.75	36.4	24.5	0.84
			AB	10-21	6.41	4.25	35.4	29.5	—
	Novgorod	1	A_1	0-10	6.37	2.76	16.3	20.2	0.92
			B_1	37-45	6.03	0.61	20.0	40.9	—
				55-65	6.51	0.44	33.1	52.1	—
			B_2	65-70	6.98	0.92	—	—	0.20
			BC	90-100	7.00	—	—	26.4	0.29
Soddy-calcareous podzolized	Arkhangelsk	28	A_1	0-9	5.89	4.92	28.2	14.2	0.66
			A_2B	9-17	5.89	2.74	26.9	17.6	0.34
			B	17-20	6.29	2.03	50.5	63.2	0.14
			BC	30-40	6.60	2.61	—	37.4	0.25
Highly podzolized	Arkhangelsk	31	A_0	0-4	5.17	68.03[a]	46.0	—	—
			A_1A_2	4-8	4.11	6.06	13.4	13.6	0.65
			A_2	8-14	3.92	1.94	6.5	6.2	—
			B_1	14-21	4.32	1.24	6.0	14.3	0.18
			B_2	25-30	4.66	0.90	14.9	23.9	—
			BC	45-50	5.06	0.81	22.0	26.5	—
Soddy-highly-podzolized	Novgorod	102	A_0	0-5	5.15	54.68[a]	36.2	—	—
			A_1	5-15	4.06	5.92	7.4	12.5	0.82
			A_2	20-30	4.02	0.83	4.2	12.4	0.44
			B_1	43-55	3.59	0.43	7.4	37.1	0.05
			B_2	64-73	4.55	0.33	14.2	30.8	—
			C	100-110	7.30	—	29.5	26.9	—

[a] Losses at heating.

On a highly carbonate moraine at the availability of carbonates from the surface soddy-calcareous typical soils are developed with the following structure of the profile: A_1 — AC — C — D.

The presence of carbonates in the humus horizon results in a complete base saturation, which causes neutral or weakly alkaline reaction (Table 1). A complete aggregation of the soil mass is typical of these soils. The structure of microaggregates resembles those of chernozem, which is especially evident in southern samples of the studied (soddy-calcareous) soils. A proper microaggregation of the latter is due to a relatively high concentration of argillaceous particles and a peculiar humus nature. Finely dispersed humus matters are properly connected with an argillaceous soil mass and form isotropic microaggregates. In the composition of the organic matter of these soils the ratio $C_{h.a.}:C_{f.a.}$ is close to 1 and humic acids connected with Ca are prevailing among humic acids. Thus, at the availability of carbonates in the humus horizon the general nature of humification of plant residues contributes to the accumulation of a considerable amount of humus in the soil. As discarbonation of the humus horizon proceeds, the weathering of the mineral mass is intensified. The products of weathering and soil formation, however, are fixed in situ, so the motion of matters along the profile is not observed, except dissolving and leaching of carbonates themselves. The "discarbonation" is especially severe in bioclimatic conditions of the northern taiga where one-way carbonate migration down the profile prevails.

Chemical and mineralogical composition of the argillaceous fraction of soddy-calcareous typical soils testifies a weak rate of weathering of argillaceous minerals where the following minerals are present: hydrous mica, chlorite, kaolinite and nonregulated mixed-schistous formations showing a stadial transformation of hydrous mica and chlorite into vermiculite.

After the removal of carbonates from the upper horizon soddy-calcareous leached soils with the following structure of the profile A_1 — B — C — D are formed on moraines. The base saturation is still high, but the reaction is neutral, as leaching proceeds, the reaction becomes weakly acidic. The mineral mass weathering tends to increase, it is especially evident at the end of the phase of carbonates leaching, when in the upper horizon there is a sufficient amount of minerals with a poor resistance to weathering, unprotected by carbonates against the effect of weathering agents. In this case the oxidation of siliceous Fe results in the separation of free iron. Therewith a considerable portion of Fe in combination with organic acids is fixed in situ causing the browning of the soil profile. Iron hydroxides tend to concentrate in the argillaceous fraction, encourage its ferrugination and form various independent microseparations (Table 2).

Table 2. Chemical characteristic of argillaceous fractions of soils on carbonate moraines

Section No.	% for Heated Sample								
	gross chemical composition					non-silicate oxides			
	SiO_2	Al_2O_3	Fe_2O_3	MgO	K_2O	SiO_2	Al_2O_3	Fe_2O_3 according to Tamm	Fe_2O_3 according to Jackson
41	50.47	23.86	13.07	4.09	3.86	6.67	5.54	5.07	7.07
2	52.43	25.12	12.07	2.33	4.29	7.97	4.04	2.71	5.82
	52.16	28.95	11.81	2.75	4.03	6.06	3.95	1.97	3.21
29	51.90	24.65	12.89	3.68	2.33	5.86	4.94	5.35	10.71
	51.07	24.78	14.13	3.82	2.17	3.63	4.13	4.37	8.11
1	52.62	26.51	12.03	1.84	4.40	5.04	2.48	1.49	5.81
	51.64	28.15	13.52	2.09	4.40	6.35	3.59	1.01	5.83
	51.09	28.11	12.87	2.07	3.91	8.62	4.16	0.42	5.33
	50.88	27.78	12.06	2.48	4.35	—	—	0.68	3.04
28	58.89	26.40	8.23	3.04	2.15	5.87	4.97	4.90	6.08
	55.42	29.67	9.40	3.39	1.37	4.35	5.32	4.61	6.35
	53.60	23.06	14.10	3.51	1.46	6.03	5.15	4.28	6.52
	55.31	22.60	13.60	3.23	2.63	7.77	3.17	4.60	6.03
31	59.38	24.52	9.72	3.72	2.16	9.77	3.48	3.31	4.59
	57.60	24.02	11.44	3.77	2.80	7.71	2.89	4.48	5.49
	53.77	27.22	13.07	3.76	1.97	5.40	5.81	5.73	6.35
	53.10	24.77	14.31	4.68	1.95	3.35	4.30	5.27	6.42
	55.36	23.18	13.39	4.33	2.94	4.89	2.00	5.05	5.35
102	61.19	27.29	6.11	1.94	2.65	6.79	2.83	1.48	2.69
	59.26	23.95	9.86	2.43	2.86	4.99	3.61	2.38	4.52
	60.81	22.84	10.05	2.73	3.27	5.41	3.20	2.11	3.11
	57.13	24.61	10.26	2.82	3.44	5.72	2.76	1.35	4.00
	57.20	24.19	10.60	2.89	3.60	5.54	2.37	1.46	4.06

The carbonate leaching breaks the ratio between clay and humus (due to the decrease of the amount and change of the nature of humus). The dispersion of components of the soil absorbing complex occurs and the initial features of their redistribution are observed at the existing washing-type of the hydrological regime. At the first stage the transference of the finely dispersed mass does not go beyond the limits of microplots. The occurring variations are expressed in the soil microstructure: microaggregates become coarser and of a more simple structure; individual microeluvial areas washed from the finely dispersed soil fraction are formed. In the lower part of the profile weakly expressed features of the illuvial horizon are developed, characterized by the accumulation of the redistributed, from the top, highly ferruginous finely dispersed mass and its separation in the form of clots under coagulating influence of carbonates. The clay is dark brown, slightly transparent, enriched by iron hydroxides and humus, and often contains silty material. Such a heterogeneity of the structure results in a poorly expressed anisotropy.

Carbonate particles play an important role in the redistribution and deposition of finely dispersed mass of soil. Certain conditions for deposition of matters from solutions are created around these particles. In this case a metasomatic substitution of carbonates by the illuviated argillaceous and ferroginous matters often occurs.

As discarbonation of the upper part of the profile proceeds, the matters migration becomes more evident, resulting in the differentiation of soil into horizons. The differentiation of the profile is the greatest in case of soddy-calcareous podzolized soils when eluvial whitish stains appear under the humus horizon and a developed argillaceous illuvial horizon of red-brown colour and nutty structure is formed. The soil profile has the following structure: A_1 — A_2B — B — C — D. At this stage of development of soddy-calcareous soils the composition of organic matters is especially changed. Concurrent with the increased amount of fulvic acids the portion of participation of mobile humus fraction tends to increase which is especially typical of northern taiga soils. The mentioned variations in the humus composition cause greater dispersion of finely dispersed mass. The simplification of the microstructure of the humus horizon is evident, more eluvial microplots are formed, composed almost entirely of fragmentals, and at last, a macromorphologically expressed bleached horizon is formed, which is characterized by a further development upward and downward. The separation of argillaceous clots with evident traces of decay may be probably considered as former carbonation of upper horizons. The mentioned forms of clay separation, inherited from earlier phases of soil development may be regarded as relict forms (Fig. 1).

At this stage of soil development horizon B is illuvial. This is the most argillaceous horizon in the whole soil profile. The study of its microstructure proved the availability of different separation of tongues of highly ferruginous (and thus poorly anisotropic) clay, which envelopes aggregates, grains of minerals and is separated in hollows in the form of clots under the coagulating effect of carbonate (Figs. 2, 3). The appearance of a clearly developed argillaceous illuvial horizon at this stage of soils development is connected with the fact that carbonate leaching and soils browning resulted in the accumulation of a sufficient amount of mineral and organic colloids, which become mobile at a certain stage of soil development and are dislocated into lower horizons at a high washing of the profile.

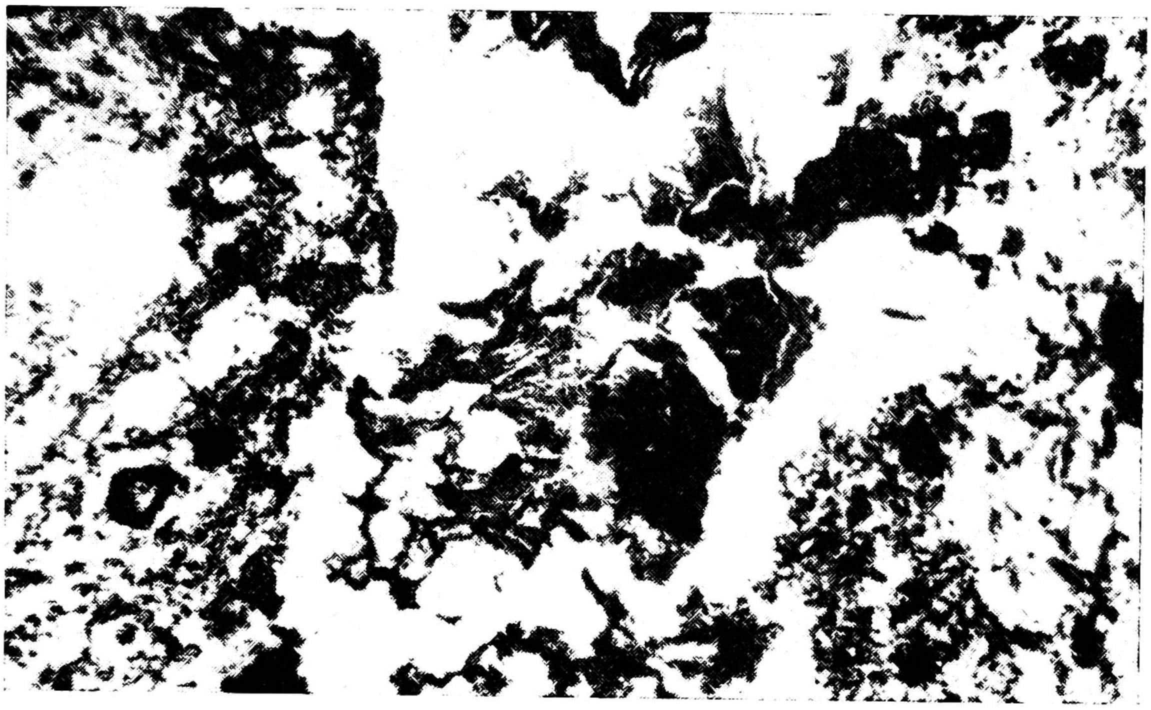

Fig. 1. Relict argillaceous clots in horizon A_1A_2 of soddy-calcareous podzolized soil. Magnif. ×85, Ni II.

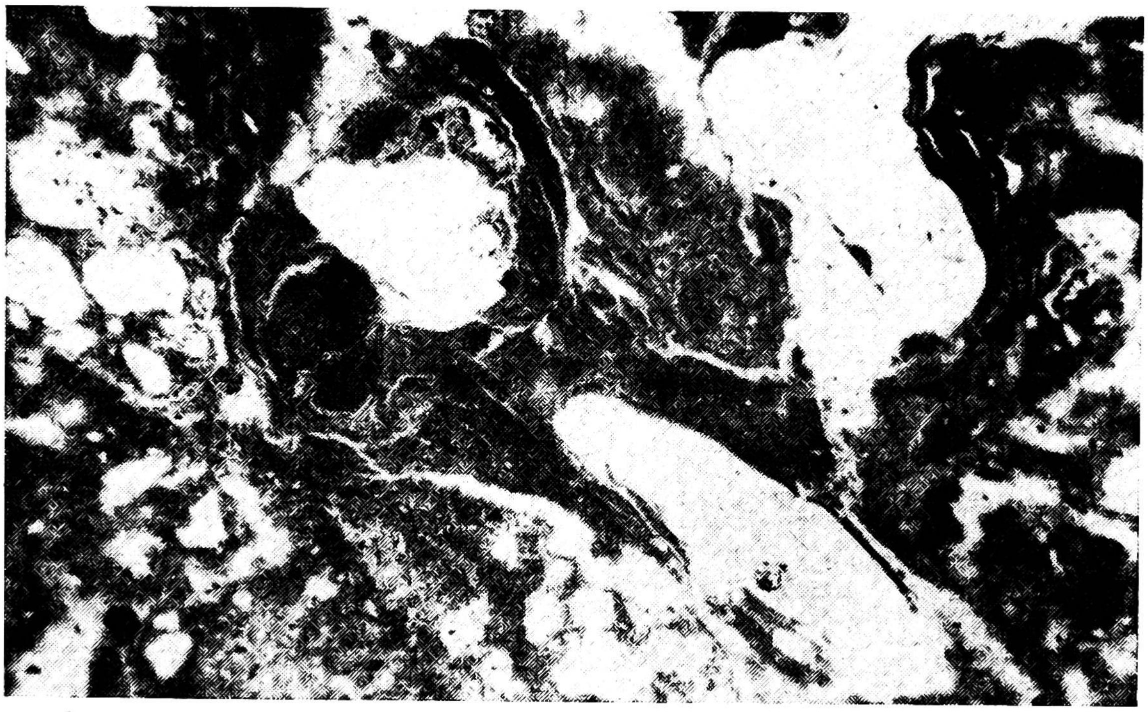

Fig. 2. Argillaceous tongues in horizon B of soddy-calcareous podzolized soil. Magnif. ×90, Ni II.

The intense lessivage occurs due to a shallow underlying of soils by crumbling parent carbonate rock or a highly detrital horizon of the moraine. These particularly conditions encourage an additional drainage and an appreciable motion of the finely dispersed mass along the profile. The formation of the illuvial horizon is affected by the parent carbonate rock, as its location at the surface serves as a sharp geochemical bar where all the matters transferred by soil solutions are deposited.

In soddy-calcareous podzolized soils all phases of a gradual change of carbonate fragments are observed. The investigation of microstructure of carbonate particles with a different rate of weathering, as well as the

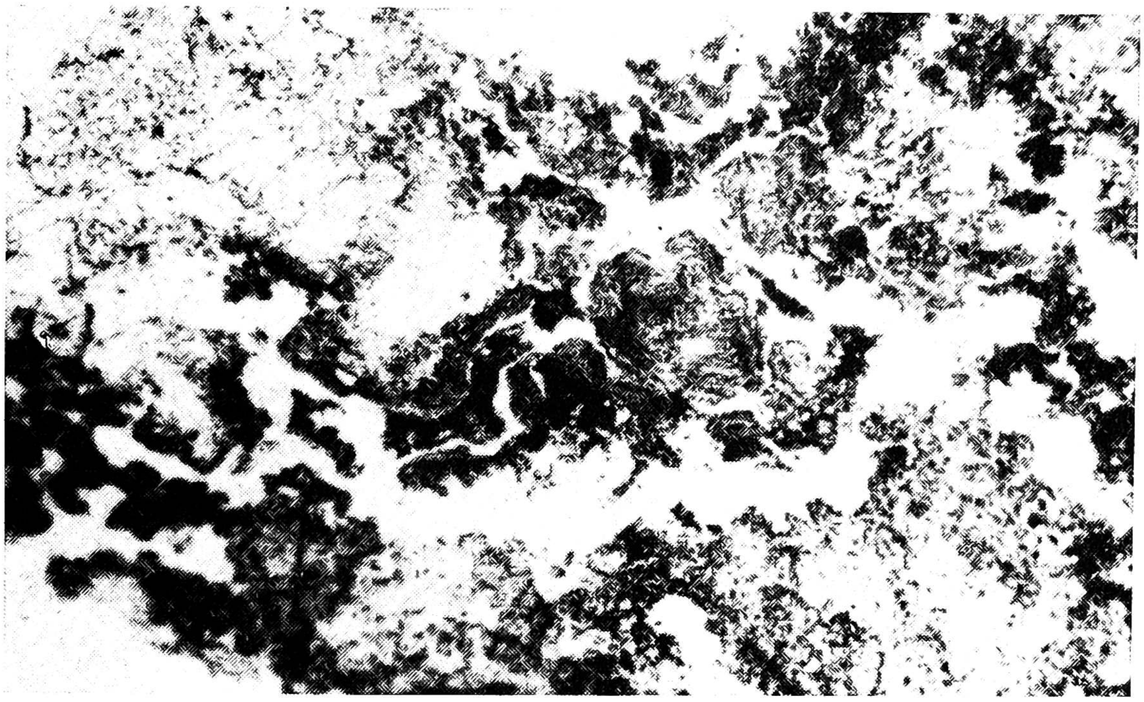

Fig. 3. Separation of the illuviated clay in the limestone fragment under weathering effect. Magnif. ×100, Ni II.

experiments on the leaching of carbonates under laboratory conditions proved the following. At the weathering of fragments of carbonate rocks the dissolving and leaching of carbonates occur, as well as eluviation of finely dispersed non-soluble impurities. As the development of the mentioned processes proceeds, the metasomatic substitution of carbonate fragments by argillaceous and ferroginous materials occurs, illuviated by soil solutions (Figs. 4, 5). The rate of the metasomatic clayization depends on the local soil conditions and is mostly expressed in the illuvial horizons of the studied soils [1].

Variations, occurring in soils at the leaching of carbonates, are also revealed in chemical and mineralogical composition of their argillaceous

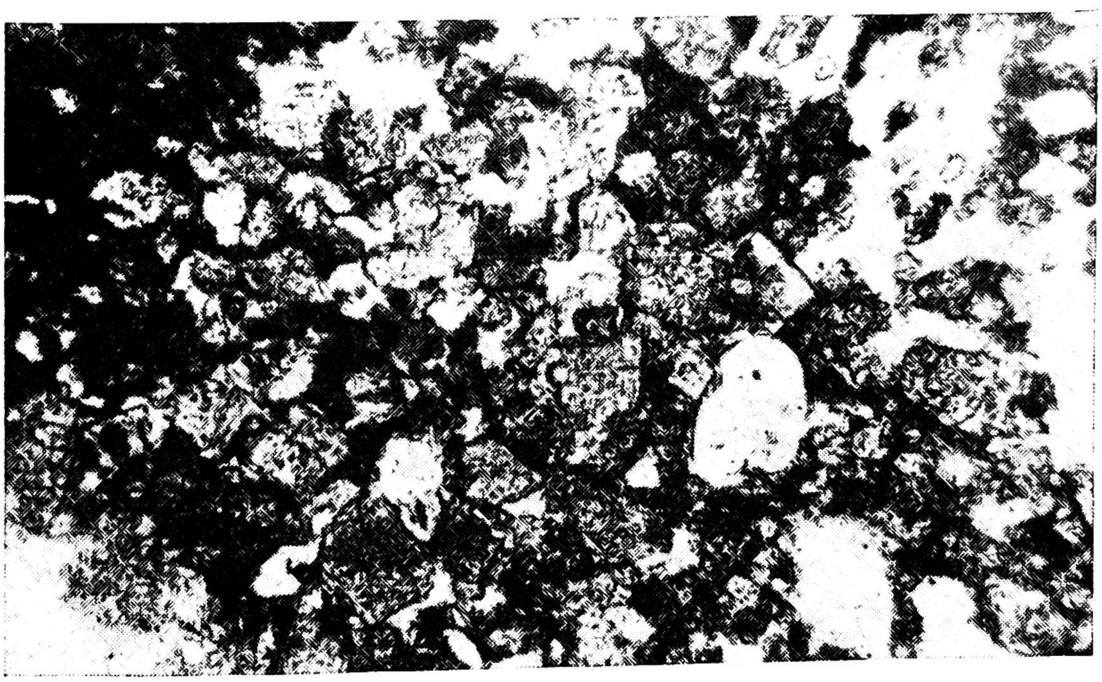

Fig. 4. Substitution of a dolomite fragment by an argillaceousferroginous matter. Magnif. ×90, Ni II.

fractions. In upper horizons of soddy-calcareous leached and podzolized soils a stadial transformation of argillaceous minerals occurs. It is revealed by the transition of hydrous mica through mixed-schistous argillaceous formations mainly into vermiculite and partially into montmorillonite, as well as by a poor chloritization of products of weathering in upper horizons. Chloritized minerals mainly comprise minerals with a widening grid, if inter-stratum spaces are partially blocked by hydroxide Al (or Fe). Argillaceous fractions of upper horizons of the mentioned soils are characterized by a high percentage of non-silicate oxides, especially amorphous forms of Fe, it testifies a poor resistance of weathering of mineral fragments and separation of Fe (browning). Finely dispersed mass of northern taiga soils is particularly enriched by non-silicate oxides

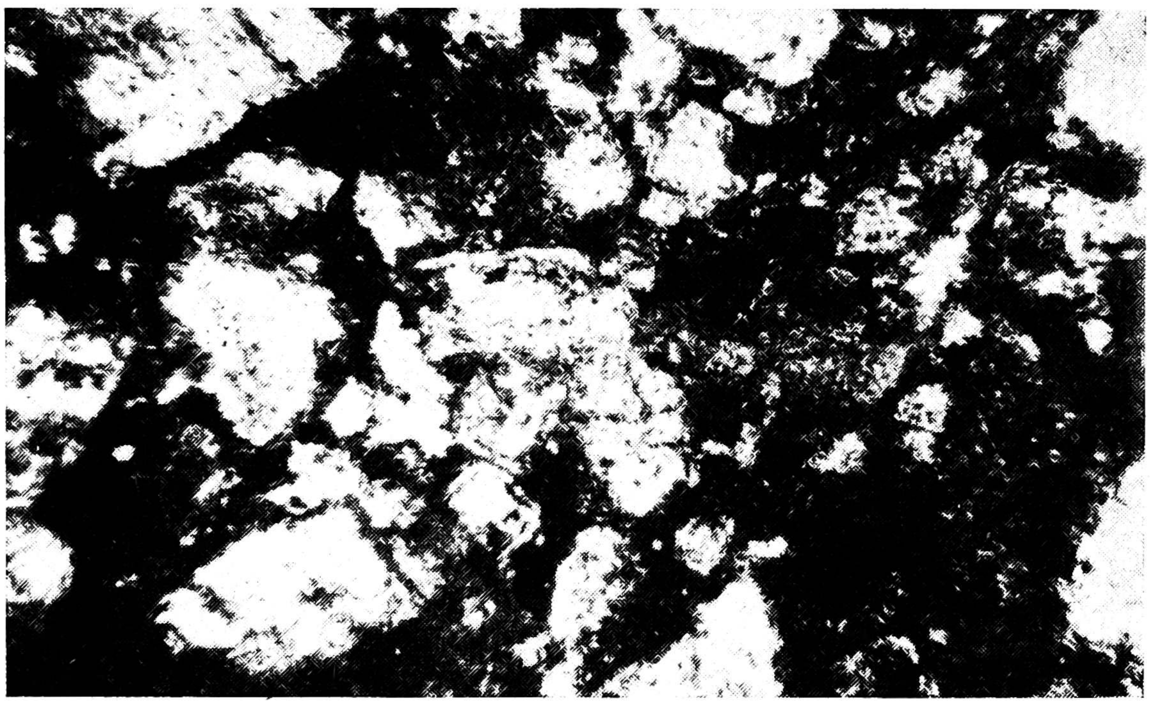

Fig. 5. Dissolving of dolomite crystals and clayization of the whole carbonate fragment. Magnif. ×200, Ni X.

(amorphous Fe_2O_3 in general) (Table 2). The redistribution of an argillaceous fraction along the profile occurring in the soil results in the change of the composition of its components in different genetic horizons. The most finely dispersed minerals, i.e. vermiculite and montmorillonite are subjected to transference. It results in a relative accumulation of less dispersed minerals in the upper soil (hydrous mica, kaolinite, quartz, partially mixed-schistous formations). In the illuvial horizon finely dispersed products of weathering and soil formation are concentrated, i.e. vermiculite and montmorillonite. Sometimes the argillaceous fraction of horizon B is almost monomineral, just as in the case of soddy-calcareous podzolized soil of the northern taiga, where vermiculite prevails. It should be noted, that the argillaceous fraction of horizon B, as well as of humus horizon, is highly enriched by non-silicate oxides where the portion of crystallized forms in comparison with amorphous ones tends to increase.

The accumulation of crystallized non-silicate oxides in the argillaceous structure of horizon B testifies their dislocation together with argillaceous particles in the form of envelops on the surface of argillaceous minerals. It makes the whole illuvial horizon red-brown at a high accumulation of clay dislocated from above.

In soils with a clearly expressed whitish eluvial horizon and considerable leaching of carbonates new qualitative features are displayed. In the upper part of the profile of such soils the reaction is acidic (Table 1), soil absorbing complex has a poor base saturation, $H^{\cdot}$ and $Al^{\cdot\cdot\cdot}$ prevail. The organic matters composition hardly differs from that of the composition of zonal podzolic soils developed on non-carbonate rocks. In the upper part of the profile the major portion of the humus composition is due to fulvic acids, which is especially typical of northern taiga soils. In soils of the southern part of the forest zone the amount of humic acids tends to increase though the ratio $C_{h.a.}:C_{f.a.}$ is less than 1. The acidic nature of humus causes great variations in the upper soil horizons, developed on leached carbonate moraines. The components of the soil absorbing complex are highly dispersed, it results in almost a complete lack of microaggreation particularly in northern soils. Mineral soil mass is subjected to a severe decay. Field spars dim, individual areas of the field spar in crossed nicols become isotropic, this is probably the result of substitution by opal-alophane matter [4]. All the coloured minerals are bleached. Products of weathering are dissolved under the influence of an acidic organic matter and migrate into lower horizons. This process results in the lack of staining envelopes on the surface of grains of mineral and argillaceous fragments, in literature it is considered as so-called "bleaching weathering" [2]. This is proved by the exhaustion of non-silicate oxides in the argillaceous fraction of the upper horizons. The clay is characterized by a high percentage of kaolinite, quartz and hydrous mica with a different rate of hydration. Three-stratum minerals in the upper horizons of soddy-podzolic and podzolic soils, developed on a carbonate moraine are subjected to a greater chloritization than those of soddy-calcareous podzolized soils up to their transformation into secondary chlorites, which is particularly characteristic for the soils in the south of the forest zone. The presence of secondary chlorites testifies great changes and considerable weathering of argillaceous minerals [5].

Illuvial horizons of the mentioned soils are very peculiar, it is proved by their extension and different features of their upper and lower parts. Since humus and podzolic horizons are greatly weathered and are in a relative balance with the environments, the top of the illuvial horizon is subjected to the effect of weathering agents. Considerable variations of the mineral mass are proved by the acidic reaction, a high percentage of amorphous compounds in the argillaceous fraction, mixed-schistous structure of argillaceous minerals and the availability of chloritized components. Thus, the top of the illuvial horizon comprises the zone of decay and eluviation. The traces of the mentioned process in the form of micro-eluvial stains are seen through a microscope at the study of soils. The argillaceous tongues are less ferruginized and more finely dispersed and more homogeneous than in the illuvial horizon of soddy-calcareous podzolized soils.

In the lower part of horizon B of the studied soils there are no evident features of any decay. The reaction is less acidic, the base saturation tends to increase. The argillaceous fraction contains a considerable amount of vermiculite and montmorillonite. A high percentage of non-silicate oxides is characteristic, the portion of crystallized forms tends to increase. This is a common feature of clay in horizon B of soddy-calcareous podzolized and podzolic soils, formed on a carbonate moraine. This similarity is displayed, however, not only in the character, but also in the forms of clay separation. The separation of ferruginous slightly transparent clots of clay is observed, sometimes they are mobile and tend to redistribution in the horizon, it is probably connected with the influence of contemporary soil formation processes (Fig. 6).

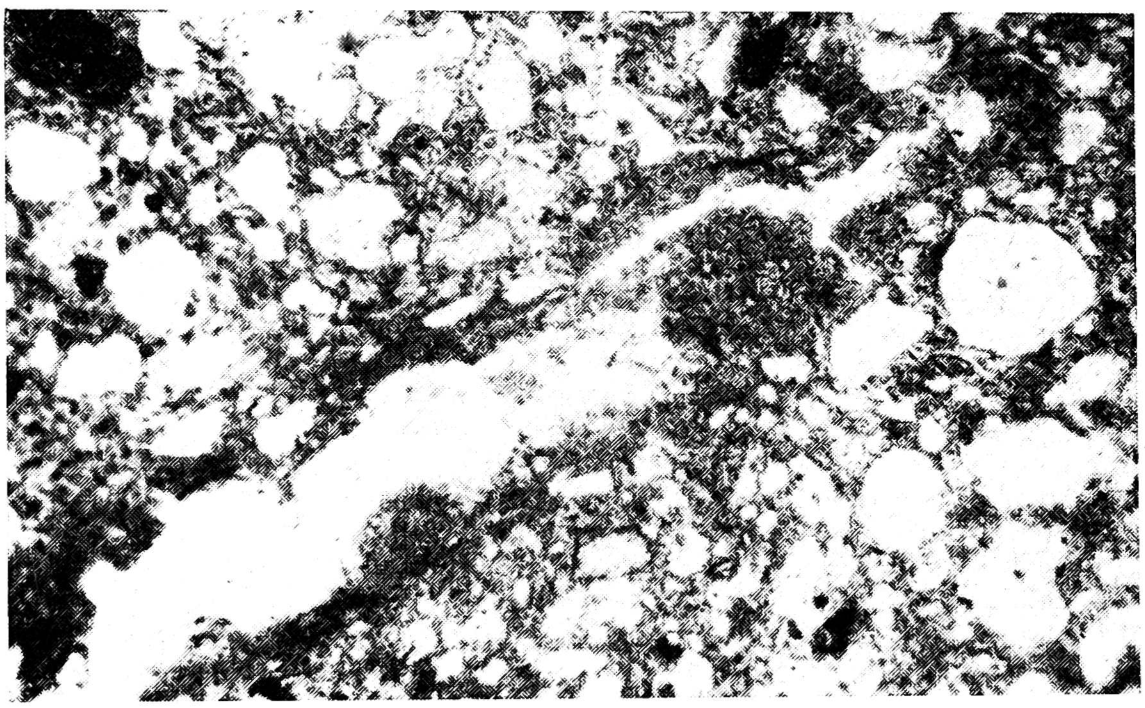

Fig. 6. Clots at clay separation and their transformation in horizon BC of highly podzolized soil. Magnif. ×100, Ni II.

Thus, a considerable leaching of carbonates and formation of a clearly expressed bleached horizon in the upper part of the profile result in the development of soils, similar to zonal podzolic soils on non-carbonate rocks. This similarity is revealed however, only in the character of horizon A_1, A_2 and in the upper part of horizon B. The degree of podzolization is less expressed. Such features as acidity and base saturation are poorer revealed, and eliminated at the depth of 50-70 cm. In the lower part of horizon B the influence of the rock carbonation is clearly felt. The protective role of carbonates tends to decrease under bioclimatic conditions of the northern taiga. Under the canopy podzolic soils are developed on a carbonate moraine at the location of carbonates 40-50 cm deep. In southern taiga part of the forest zone carbonates affect on the soil formation, and their motion upward due to soil cultivation hinders and even stops podzolization.

CONCLUSION

Soil formation on carbonate moraines in the forest zone comprises a complex combination of alternating or simultaneous processes in different genetic horizons, namely: leaching of carbonates, browning, lessivage, podzolization.

As development of soddy-calcareous soils proceeds, regular changes of their microstructure occur. Therewith a combination of features and properties both of contemporary and ancient processes is observed, occurring at less leaching rate of carbonates.

The weathering of fragments of carbonate rocks in forest soils is accompanied by leaching of carbonates, eluviation of finely dispersed non-soluble impurity, and by metasomatic substitution of carbonate particles by argillaceous-ferroginous matter illuviated by soil solutions.

Variations, occurring in soils, are reflected in the composition of the argillaceous fraction. The stadial transformation of argillaceous minerals into vermiculite and montmorillonite is observed through mixed-schistous formations, as well as the chloritization of weathering products up to appearance of secondary chlorites.

SUMMARY

The microstructure and properties of soils developed on carbonate moraines under bioclimatic conditions of the sub-zone of the northern taiga and coniferous-broad-leaved forests have been studied. The leaching of carbonates from the profile causes the transformation of soddy-calcareous soils into podzolic ones. The mentioned transformation is accompanied by the alternation of different processes, namely: leaching of carbonates, browning, lessivage, podzolization. As the development of soddy-calcareous soils proceeds, regular changes of soil microstructure are observed. Therewith a combination of features both of contemporary and ancient processes, occurred at less bleaching of carbonates. The weathering of carbonate fragments occurs, it is accompanied by carbonates leaching and metasomatic substitution of carbonate particles by argillaceous-ferroginous matter, illuviated by soil solutions. Soil variations are reflected in the composition of the argillaceous fraction. The stadial transformation of argillaceous minerals into vermiculite and montmorillonite

is observed through mixed-schistous formations, as well as chloritization of weathering products up to appearance of secondary chlorites.

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