Thermokarst transformation of soil cover on cryolithozone flat territories

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Evolution of a biosphere of the Earth and modern climatic conditions have caused a wide spread on a planet of a zone of a long-term frozen ground. On the main evolutionary events on the Earth the glacial ages played a huge role (Fig. 1), covering occurrence of free oxygen in an atmosphere, causing on development of climatic zones, a coming out of plants and animals on continents. In Silurian age as the result of interaction between lithosphere and biosphere arises pedosphere and becomes the powerful factor of evolution on land (Vernadsky, 1940; Kovda, 1973, 1991; John, 1982; Sokolov, 1993). After the formation, by a rule of a feedback, podosphere renders strong influence on the current functioning of biosphere and becomes the specific, difficultly constructed, structural regulator and redistributor of basic streams of substance and the energy, working in system of biosphere - geosphere (Targuljan, 1992). During evolution the soil cover began to represent a self-regulating, a structurally functional subsystem of biosphere of the land, carrying out global functions in regulating atmospheric, hydrospheric, litospheric, biospheric and anthropospheric processes (Dobrovolsky and Nikitin, 1990).

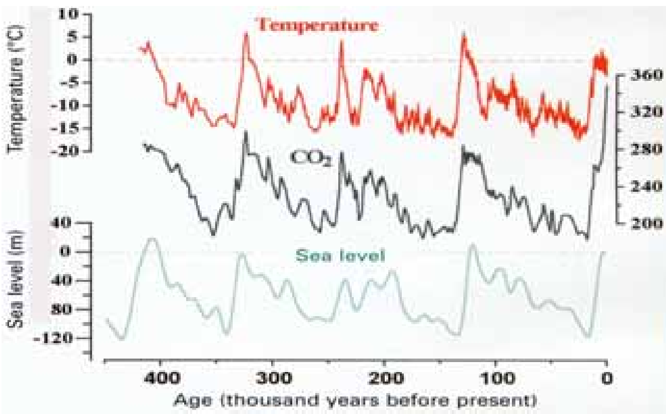

Fig. 1. Fluctuations of temperature, contents of CO_2 and a sea level on the Earth for last 450 thousand years (the periods of downturn of temperature coincide with glacial ages).

On modern structure of a biodiversity and functioning of a life on the Earth the leading part belongs to Quarternary period. In Pleistocene an intensified cold snap in the average and high latitudes, caused numerous occurrence of large continental glaciations and their approach to average latitudes (Fig. 2). Global changes of natural and climatic conditions have led to freezing of rocks on depth of hundreds, and even thousands meters, forming thus a zone of permafrost grounds (Velichko, 1973; Andrews, 1982; Budiko, 1984). Fluctuations of a climate

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have played an essential role in formation of soil forming layers and a soil cover of large territories.

Fig. 2. Pleistocene glaciations in territory of the former USSR (on Markov, 1961 and Popov, 1961). White spots - integumentary glaciers, a dotted line - southern border of cryolithozone

Nowadays permafrost grounds occupy on the Earth the area more than 35 million sq. km. On Northern hemisphere the area of cryolithozone is estimated in 22.35 million sq. km, including 6.64 million sq. km of continuous permafrost and 14.71 million sq. km. of discontinuous permafrost (Fig. 3). The area of permafrost grounds of Russia makes more than 10 million sq. km and covers about 60 % of territory (Kudryavtsev et al., 1978; Brown and Grave, 1981).

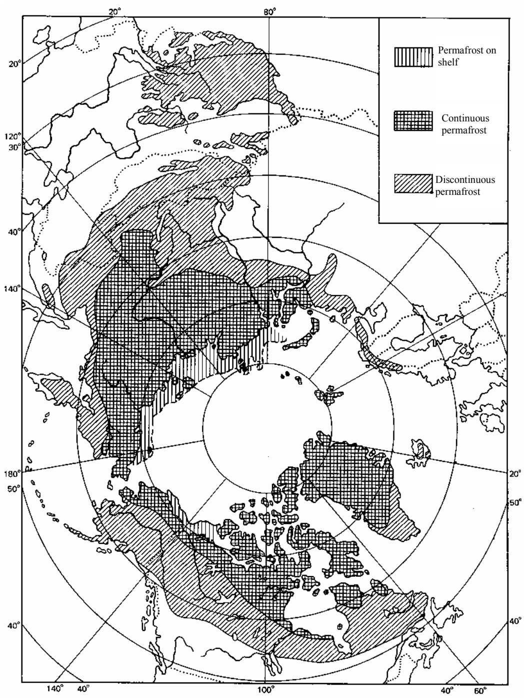

Fig. 3. The cryolithozone of Northern hemisphere (Washburn, 1979).

In flat territories of permafrost zone the ice complex is widely advanced. On plains of the Central Yakutia the capacity of reformed ice wedges makes 40-60 m, the underground ice occupies there up to 40-50 % from volume of an ice complex.

On lowlands of northern latitudes the Arctic type of an ice complex (edoma) is distributed. The volumetric contents of ice in it makes up to 90 %.

Fig. 4. Outputs of an ice complex
(at the left - in the Central Yakutia, on the right - on Seaside lowland)

Fluctuations of thermal conditions during Holocene has led to the partial degradation of underground ice. On Seaside plains the thermokarst process leads to approach of the sea (Fig. 5), and on continental plains leads to the formation of alases (Fig. 6). In both cases of degradation of an ice complex there is a thermokarst transformation of a soil cover.

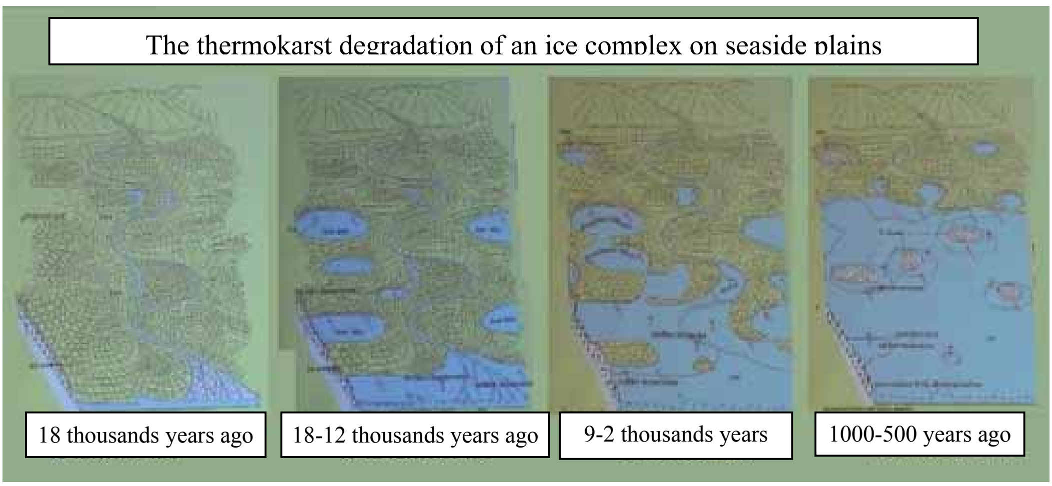

Fig. 5. The thermokarst degradation of Seaside plains in Alleroed and Holocene
(Hubberten, Romanovskii, 2005).

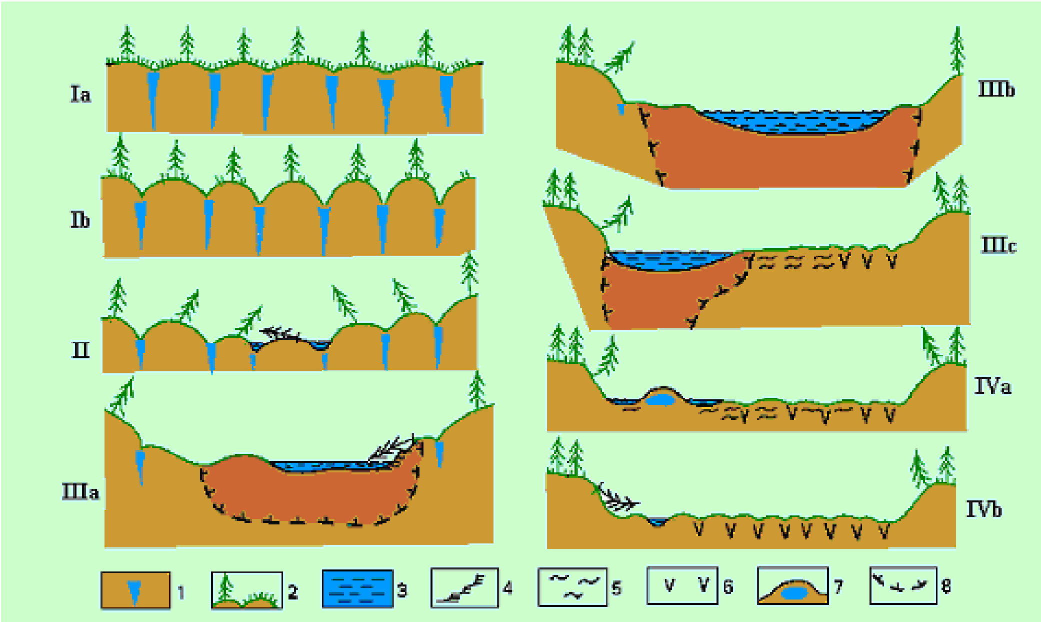

Fig. 6. The thermokarst formation of alases. Symbols: 1 - syngenetic ice veins; 2 - a tree-grassy cover; 3 - water; 4 - landslips; 5 - alas deposits; 6 - epigenetic ice veins; 7 - swelling knoll; 8 - a roof of a permafrost grounds.

Nowadays about 20 - 30 % of all area of the territory of Central Yakutia is occupied by alases (Fig. 7). In circumpolar regions of Eurasia and Northern America within the limits of a zone of northern taiga, forest-tundras and tundras, the thermokarst occupies the huge area. For example, only about 25 % of territory of Yana-Indigirka and Kolyma lowlands represent plain with an ice complex. Other part of lowland is advanced by thermokarst and activity of superficial waters of big and small rivers.

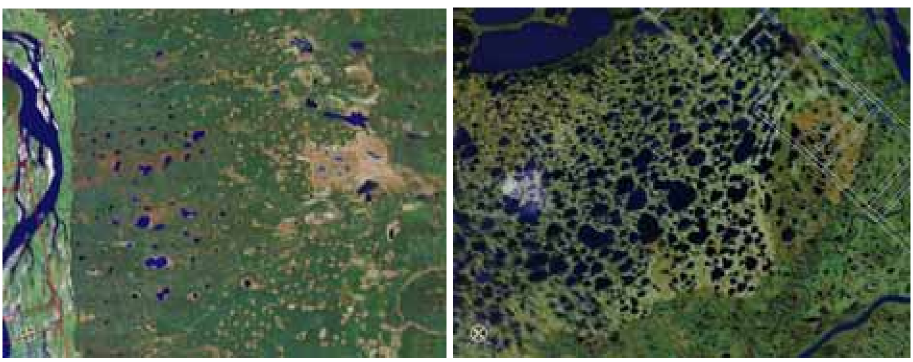

Fig. 7. Thermokarst disturbance of territories
(at the left - the Central Yakutia, on the right - the Kolyma lowland)

Development of thermokarst and formation of alases began during epoch of warming on a boundary of Pleistocene and Holocene about 12.8-16.0 thousand years ago (Kaplina and Lozhkin, 1978; Romanovskii et al., 1999; Andreev, 2000).

The thermokarst degradation of an ice complex of flat territories of cryolithozone results transformation of a soil cover. The process of transformation of a soil cover at thermokarst we shall consider by the example of a soil cover of the Central Yakutia.

The zonal type of soils on untouched by thermokarst plain is a permafrost pale-yellow ground, formed under light coniferous taiga (Fig. 8). Grounds thaw for a summer on depth of 1.0-1.3 m. The morphological structure of a profile differs by weak differentiation on genetic horizons A-B-C. The humus-accumulative horizon A is thin (up to 3-5 cm), the content of humus can be up to 3-4 %. Frequently allocate horizon A_2. Below lies horizon B which is subdivided into 2 layers: top is tightened and enriched with one-and-a-half oxides and bottom is carbonate horizon. On depth of 0.9-1.2 m lie parent grounds (C).

The thermokarst is a long-term process, as its driving motives are primary and residual lakes. The beginning of thermokarst is characterized by occurrence of primary lakes on a surface of a plain. While long-term thawing of icy grounds the depth of a reservoir gradually increases and under lake the thawing bowl is formed. In result of thermal abrasion processing of coast the size of lake increases, the layer of ground deposits accumulates. Cyclicity of climatic conditions causes constant fluctuations of water level in alases. Even at rather short century cycle (during all time of existence of alases there can be up to 120-170) alases can once as much as possible be flooded and be dried up. Within century rhythms short-term cycles operate (Bruckner, Hale and 11-years solar activity) during which the degree of humidifying, hence, the natural shape of alases is undergone with appreciable changes. With an each cycle of flood the area of alas extends, and alas become deeper until stocks of underground ice will not run low (Fig. 9).

Fig. 8. A structure of zonal permafrost pale-yellow soil

The formation of alases, their functioning and dynamics in aggregate composing evolution of all natural shape of large territories of cryolithozone, are considered as an integrated **alas process** (Desyatkin, 1984, 1990; Desyatkin and Sotnikova, 1982; Desyatkin and Romanov, 1989).

The alas process is a driving motive of a thermokarst sedimentogenesis and it promotes the regeneration of grounds of an ice complex. In alases does not remain grounds of an ice complex, they are entirely replaced with deposits of a water origin. Alas deposit is a combination of very different on mechanical structure synlithogenic deposits (sand, sandy loams, loams, etc.) and organic lake formations (silt, peat, sapropel) which are formed in the closed hollows. These deposits as soil-forming grounds, differ from soil-forming grounds of an ice complex on mechanical, chemical, mineralogical, cryogenic and organic structure (Desyatkin, 1984, 1990, 1992).

The alas process determines the features of soils formation in thermokarst hollows, causing existence of two stages of soil formation: hydromorphic and xeromorphic. Within these stages, and also at their transition into each other, the functioning of alases promotes soils to pass the phases of independent development: lake, marsh, meadow and steppe (Desyatkin, 1984, 1990).

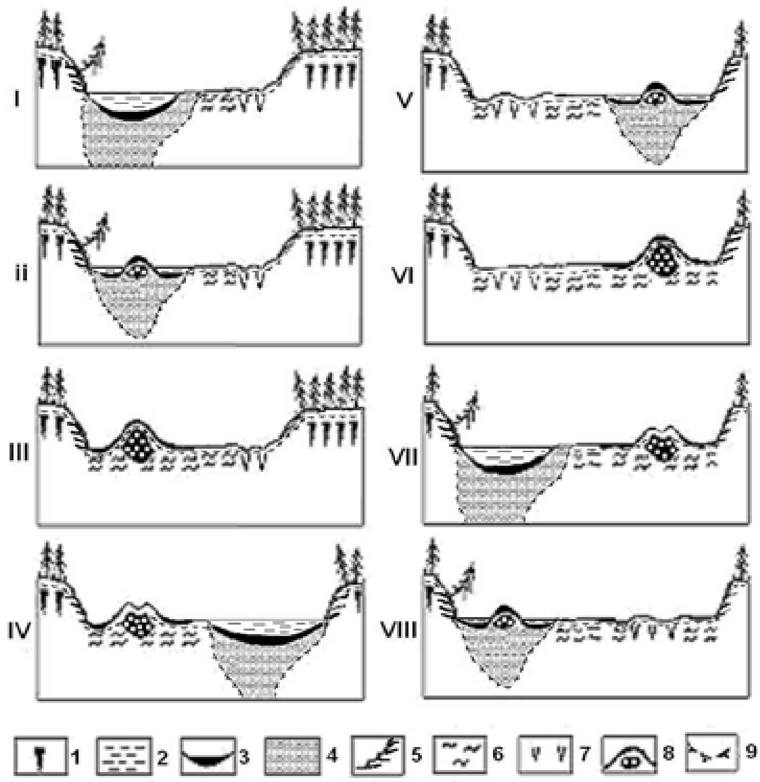

Fig. 9. The circuit of gradual expansion of thermokarst hollows and permanent processing of soil forming grounds while alas process. Symbols: 1 - syngenetic ice veins; 2 - lake; 3 - ground biogenic deposits; 4 - under-lake talik ; 5 - landslips; 6 - alas deposits; 7 - epigenetic ice veins; 8 - swelling knoll; 9 - a roof of a permafrost grounds. I-VIII - stages of thermokarst alas formation.

The hydromorphic stage corresponds to a lake phase of development and by virtue of the big differences is subdivided on two semi-stages, first of which corresponds to a deep state of lakes, and the second corresponds to a drying up state. First half of a lake phase is characterized be intensive thermal abrasion and thermal denudation processing of coast of lakes and expansion by such way of the area of thermokarst hollows. The expansion of thermokarst hollows is accompanied by formation of mineral layer at the bottom of reservoirs due to accumulation of terrigenous deposits from boards of alas. With an approach of the second semi-stage of development of lake, the accumulation of sapropels begins. Hydrochemical and hydrobiological parameters of alas lakes testify to high degree of throphic content (Desyatkin and et al., 2000). The biomass consisting of plankton and benthos, which is produced during the warm period of year, during winter time in part drops out in ground deposits of lakes and promotes accumulation of organic and biogenic-mineral deposits (sapropels). The maximal capacities of biogenic deposits in lakes with a stable water regime reach up to 4,5-6,0 meters (Gavriliev et al., 1983; Bakulina et al., 2000). Thus while passing a lake phase of development the morphological structure of soils "accrues" on two layers: bottom is mineral, top is biogenic (Fig. 10).

At a finishing stage of the second semi-phase of lake development of alas soil formations on shallow sites and swamped soils of alases, the processes of gleyization are accompanied by lake deposit accumulation and peat accumulation. In this interval of soils development the accumulation of ground deposits continues, which promotes weighting of mechanical structure of a superficial soil layer, and predetermines its saturation by carbonates. Saturation by carbonates occurs due to accumulation of fine cockleshells and authigenic carbonate minerals (Desyatkin, 1983, 1990). In structure of lake deposits of a coastal strip the high share is occupied with incompletely decomposed vegetative leavings. Peat accumulation goes under the circuit of accumulation of low-lying peatbogs. The grassy plants (hygrophytes) are the basic peat-forming sources.

At thermokarst formation of alases occurs syngenetic salinization of an active layer (Desyatkin, 1984, 1992). It is caused by washing away of a part of water-soluble substances of an ice complex grounds while thermokarst into the waters of primary lakes with their subsequent accumulation at drying lakes in an active layer of alases. Even at washing away of a minimum quantity of salts from high-capacity thickness of an ice complex (till 40-60 m) and thawing of great volume of ice with the subsequent accumulation of water-soluble salts in thin (1-2,5 m) active layer, the syngenetic salinization of alas soils is inevitable.

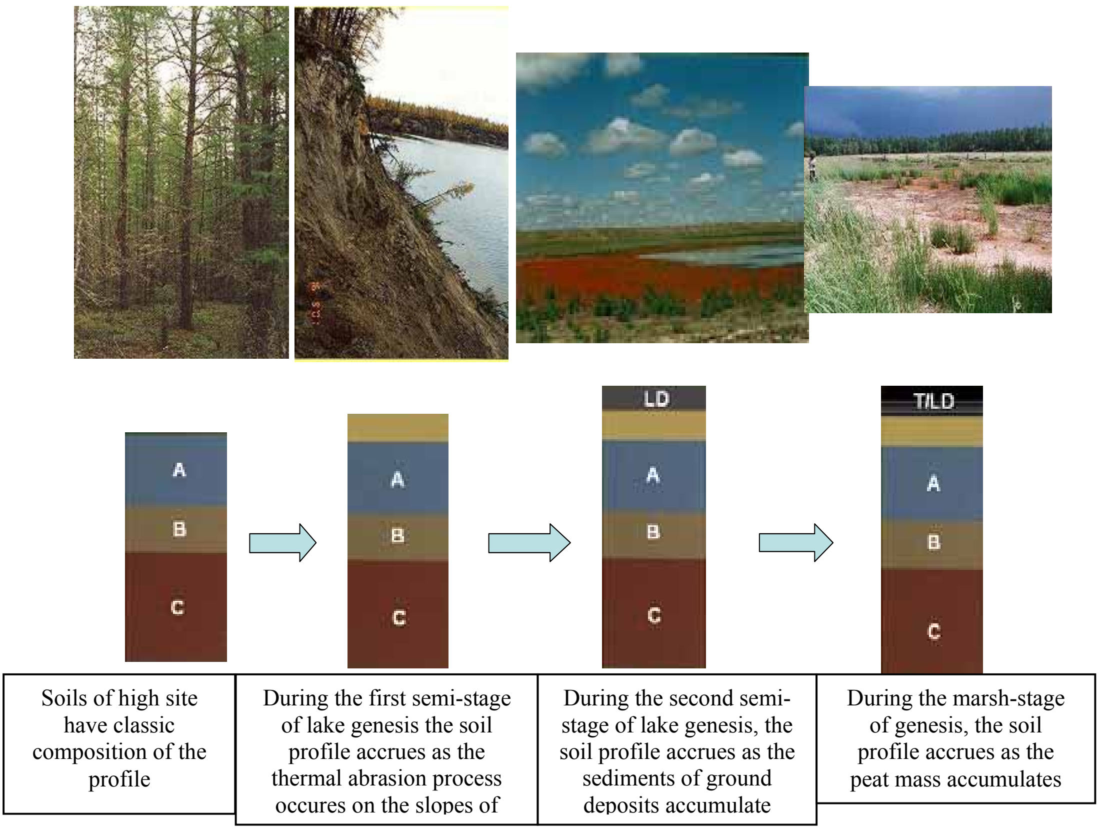

Fig. 10. The influence of one cycle of alas process on a composition of soil structure.

The quality of primary salinization of soils is defined by structure of water-soluble substances of an ice complex, and the degree of salinization has direct correlation connection with the contents of salts and volume of transformed thicknesses by thermokarst. The further destiny of a saved up by thermokarst in an active layer of alases of mobile compunds is determined by geochemical conditions of hollows. In result of thermokarst sedimentation of grounds of an ice complex in alas deposits is formed a number of authigenic secondary minerals (The structure ..., 1979; Pewe and Journaux, 1983). These are: calcite, manganese calcite, dolomite, hydroxides of iron, magnetite, melnikovite, pyrite, vivianite. Formation of minerals while thermokarst sedimentation promotes accumulation in structure of soil-forming grounds a plenty of sodium salts (especially as soda) and to formation hydrocarbonate-sodium, less often chloride-hydrocarbonate-sodium structure of alas lakes waters.

Under influence of alas process the content and structure of organic substance in alas's soils undergo changes (Desyatkin, 1981, 1984, 1990). Zonal permafrost pale-yellow soils are related to soils with low-humus content (Table 1). The content of humus in alas soils sharply grows (Desyatkin, 1981, 1984; Matsuura et al., 1994a, 1994b, 1995). This process is promoted by the presence of allochthones layers of lake and phytogenous biogenic substance in the structure of soil-forming grounds, and also promoted by the active procession of turf and humus-accumulative processes of soil formation under meadow vegetation after lake deposits reach ground surface. The combined lake-soil accumulation of organic substances in soils results the increase of humus content. Humus-accumulative horizons of alas soils contain up to 7-10 and more % of humus, and the ground, tested in the recent development a lake phase, contain superficial humus or peat horizons.

Table 1. Stocks of carbon and nitrogen in soils of model alas

Section	Vegetative cover	Site	Capacity of an active layer	Substratum	C, kg/m^2	N, kg/m^2
AS-1	Larch forest	High site	96 cm	Fall	1.79	0.04
				Humus	4.67	0.47
				Carbonates	2.01	-
AS-2	Larch forest	Slope	66 cm	Fall	1.16	0.03
				Humus	3.92	0.27
				Carbonates	0.0	-
AS-5	Motley grass meadow	Edge of forest	90 cm	Fall	3.26	0.28
				Humus	36.53	3.17
				Carbonates	2.25	-
AS-4	Wet meadow	The bottom belt of alas	80 cm	Fall	0.39	0.02
				Humus	65.19	5.39
				Carbonates	6.79	-
AS-6	Real meadow	The middle belt of alas	137 cm	Fall	0.32	0,02
				Humus	30.21	2.39
				Carbonates	4.0	-
AS-3	Steppe meadow	The upper belt of alas	260 cm	Fall	0.12	0.01
				Humus	16.26	1.79
				Carbonates	15.7	-

The formation of soil-forming grounds in alases is complicated with the dynamic processes of a relief of the bottom of hollows (the swelling and the slump process) which during the separate water-plentiful periods cause migration of lakes and by that during long evolutionary development of alas landscapes cause gradual processing of deposits on all area of hollows (Fig. 11). As a result of influence of the permanent alas process during repeated cyclic change of hydromorphic and xeromorphic stages, the expansion of thermokarst hollows takes place, there is a formation of a multilayered soil-forming grounds in alases. At drying of lakes the ground deposits reach surface and become a substratum for formation of alas soils. The heterogeneous lamination of alas deposits promotes infringement of a classical structure of a soil's profile (i.e. the ranked change from top to down of horizons A-B-C), formed on them, and also leads to the occurrence in the profile of alas of soils not only superficial horizons, but also buried two-three biogenic horizons of lake and marsh genesis (Fig. 10).

Such horizons are designated by index LD which designates the first letters of English word ***Lakustrine deposits***, in translation meaning «lake deposits». The horizon is frequently submitted by peated sapropelic deposits, less often by corbonated layers with weighted granulometric structure which emerged as a result of siltization of buried at present soil surface in benthic conditions at passage of a lake phase of development. The quantity of LD horizons thus shows how many cycles of metamorphic developments the soil has passed. The capacity of LD horizons gives the representation about duration of phases of lake and marsh development.

Lake or hydromorphic stage	Marsh or hygromorphic stage	Meadow or semi-hydromorphic stage	Steppe or xeromorphic stage
The regenerative conditions, accumulation of lake biogenic deposits (sapropel), accumulation of carbonates as fine cockleshells and minerals, weighting of mechanical structure owing to the siltization, formation and accumulation of authigenic minerals of iron oxide	The prevalence of regenerative conditions, peat accumulation, gleyization, accumulation of easily soluble salts, formation and accumulation of authigenic minerals of iron oxide	Oxidizing conditions, humus and salts accumulation in turf horizon, variable oxidation-reduction conditions and gleyization of the bottom half of soil profile	Oxidizing conditions, the increase of humus accumulation intensity, desalination with the amplification of saturation of a soil absorbing complex by ions of sodium (solonetz process) of the top half of soil profile

Fig. 11. The scheme of polycyclic soil formation in alases.

At approach of xerophilic stage of alas soil-formation as heterogeneous deposits exit on a surface, the alas soils begin to develop on these heterogenous deposits. Distinctions of hydrothermal conditions of a different alas ecosystems cause development of the certain types of vegetation, formation and decomposition of organic mass. The organic mass has influence with the degree of expressiveness and an orientation of elementary soil processes on concrete parts of alases and in aggregate leads to the formation of various types of soils during period of xerophilic stage of soil formation. In this stage of development the evolution of alas soils can include a marsh, meadow and steppe phase (Fig. 11).

CONCLUSION

1. During Holocene there was an active thermokarst degradation of a cryolithozone's soil cover with an ice complex.
2. On a disturbed by thermokarst territories the huge influence in soil formation rendered by alas process.
3. In alases are formed soils with a complicated structure with the participation of buried and superficial horizons of lake-marsh genesis and with the big stocks of carbon.
4. In conditions of a global climate changes the probability of thermokarst transformations of zonal soils into the intrazonal (alas type) grows.

REFERENCES

Andreev AA (2000) The history of vegetation and a climate of the Central Yakutia in Holocene and late Ice age. *The materials of international conference «Lakes of cold regions », Part 4. - Yakutsk, the Yakut state university*, 15-29.

Andrews J (1982) A modern glacial age: Cainozoic age, *Winter of our planet, Moscow: Mir*, 220-281.

Bakulina NT, Spektor VB, Novikov NI, Kurchatova AN, Spektor VV (2000) The cut of ground deposits of Small Chabyda lake. *The materials of internation conference «Lakes of cold regions », Part 4. - Yakutsk, the Yakut state university*, 29-41.

Brown G, Garve NA (1981) The disturbane of surface and its protection at development of the North. - *Novosibirsk: Science*, 88.

Budiko MI (1984) The evolution of biosphere, *Leningrad: Gidrometeoizdat*, 488.

Desyatkin RV (1981) The content and structure of humus in soils of Lena-Amga interfluve - *Vesti: Leningrad University*. **6**, 75-82.

Desyatkin RV, Romanov VI (1982) Soils of a valley of average watercourse of Amga river. 120 p. *Yakutsk.*

Desyatkin RV, Sotnikova IS (1982) About alas type of soil-formation. *Vesti: Leningrad university,* **24,** 105-108.

Desyatkin RV (1983) The influence of thermokarst lakes on structure and characteristics of alas soils, *Questions of rational use and protection of natural resources of polytypic lakes of cryolithozone - Yakutsk*, 58-63.

Desyatkin RV (1984) The soils of Lena-Amga interfluve. *Yakutsk: Yakut Branch RAS*, 168.

Desyatkin RV (1990) The specificity of soil formation in alases. *Pochvovedniye* **12**, 5-15.

Desyatkin RV (1992) The syngenetic salinization of soils at thermokarst alas-formation. *Pochvovedniye* **7**, 106-113.

Desyatkin RV, Desyatkin AR (2000) The hydrochemical and the hydrobiological characteristic of lakes of differently aged alases during the droughty period of natural rhythms, *Materials of international conference «Lakes of cold regions», Part 4. - Yakutsk, the Yakut state university,* p. 52-66.

Dobrovolsky GV, Nikitin ED (1990) Functions of soils in biosphere and ecosystems. *Moscow: Science*. p. 260.

Gavriljev KA, Dmitriev AI, Ivanov KP (1983) The sapropelic resources of lakes of the Central Yakutia. *Questions of rational use and protection of natural resources of polytypic lakes of cryolithozone - Yakutsk.,* p. 47-58.

Hubberten HW, Romanovskii NN (2005) The evolution of permafrost during the last climatic cycle in the Laptev Sea Region, Russia. *First CliC International Science Conference – Beijing, April,* p. 103.

John B (1982) The Earth and cold intervals of its history. *Winters of our planet, Moscow: Mir,* p. 13-37.

Karplina TN, Lozhkin AV (1978) The age of alas deposits of Yakutia's seaside lowland: a radiocarbon substantiation. *Note of Academy of Sciences, USSR,* **2**, 69-76.

Katasonov EM, Ivanov MS, etc. (1979) The structure and absolute geochronology of alas deposits of the Central Yakutia, *Novosibirsk: Science, p. 95.*

Kovda VA (1973) The basis of the doctrine about soils. vol. 2., *Moscow: Science,* p.467.

Kovda BA (1991) Alive substance, biosphere and a soil cover. *Pochvovedniye* **6**. 5-14.

Kudrjavtsev VA, Kondratjeva KA, Romanovskii NN (1978) The zonal and regional laws of formation of cryolithozone in the USSR. *Works of Ш International conference on permafrost studies. 1978. Edmonton, Albert, Canada. vol. 1, Ottawa:* p. 419-426.

Markov, KK (1961). Sur les phenomenes periglaciaires du Pieistocene dans le territoire de I`USSR: *Biuletyn Peryglacjalny* **10**, 75-85.

Matsuura Y, Ohta S, Sanada M, Desyatkin RV (1994) Carbon and nitrogen storage in soil developed on two different toposeguences of the Lena River terrain. *Proceeding of Second Simposium...,- Tsukuba,* p. 177-182.

Matsuura Y, Ohta S, Sanada M, Desyatkin RV (1994) Carbon and nitrogen storage in soils deveioped on two different toposeguences of the Lena River terrain. *Interum Report of Joint Research Project "Carbon Storage and Carbon Dioxide Budget in Forest Ecosystems" - Sapporo,* p. 72-78.

Matsuura Y, Ohta S, Desyatkin RV, Yefremov D (1995) Carbon and nitrogen storage in soils of forest-tundra, forest and alas in Sakha. *Proceedings of the Symposium on Joint Permafrost Stydy between Japan and Russia in 1992-1994. - Yakutsk,* p. 40-45.

Pewe Troy J, Journaux Andre (1983) Origin and Character of leosslike silt in Unglaciated South—Central Yakutiya, Siberia, USSR, *Geol. Sur. Prefess Pap.,* **1262**. 46.

Popov, AI (1961). Cartes des formations periglaciaires actuelles et Pieistocenes en territoire de I`USSR: *Biuletyn Peryglacjalny* **10**, 87-96.

Romanovskij NN, Holodov AL, Gavrilov AV, Tumskoj VE, Hubberten GV, Кassens X (1999) The capacity of frozen thicknesses on east part of a shelf of the Laptev sea. *Cryosphere of the Earth, vol. III* **2,** 22-32.

Targuljan VO (1992) Pedosphere as a superficial planetary environment. *Pochvovedniye* **2**, 27-40.

Velichko AA (1973) The natural process in Pleistocene. *Moscow: Science,* p. 256.

Vernadsky VI (1940) The biogeochemical sketches. 1922-1932. *Moscow - Leningrad: publishing house Academy of Sciences of the USSR,* p. 250.

Washburn, AL (1979) Geocryology. In: *A survey of periglacial processes and environments.* p.384.