Consistency of Iksinskoe bog dynamics with extreme the Holocene climate events

Preis Yu.I., Krutikov V.A., Polishchuk V.Yu.

Institute of Monitoring of Climatic and Ecological Systems SB RAS, Russia, Tomsk

Assessment of the consistency of changes in the functional state of mires and climate is necessary to develop their forecasts for the coming centuries. This is especially important for the West-Siberian region. However, to date, opinions on the response of this region's bogs to the Holocene climate change are ambiguous and sometimes contradictory.

Bogs of different natural and climatic zones and even separate parts of the same bog massif have different sensitivity and even the opposite response to specific climatic events. In the Holocene permafrost in mineral soils and peat deposits was repeatedly formed. We have found that different response of the bogs with presence or absence of permafrost in the cooling periods of the Holocene are connected. However, to date, the influence of paleo-cryogenic processes on the dynamics of bogs outside the cryolithic zone has rarely been taken into account. Repeated paleochriogenic processes have caused peat accumulation stops. Lack of taking into account the influence of these processes leads to incorrect data on reconstructions of functional state of bogs and paleoclimate. The existing spatial and temporal models of bogs are based on the opinion about their mainly endogenous development and continuous course of bog formation process (Neushtadt, 1987; Lapshina et al., 2000; Borren et al., 2006).

In numerous peat cores of the forest zone of Western Siberia, we found a wide spread climatogenic type of bog formation process, which differs from the autogenic one primarily by meso- and oligotrophic paludification of carbonate soils and repeated cryogenic stoppages of peat accumulation (fig. 1). The main paleostratigraphic boundaries in peat deposits are dated. These paleostratigraphic boundaries are indicators of focal changes in the bog functional state under the Holocene climate. However, the degree and scale of influence of these events on the origin and development of climatogenic bogs have not been sufficiently studied.

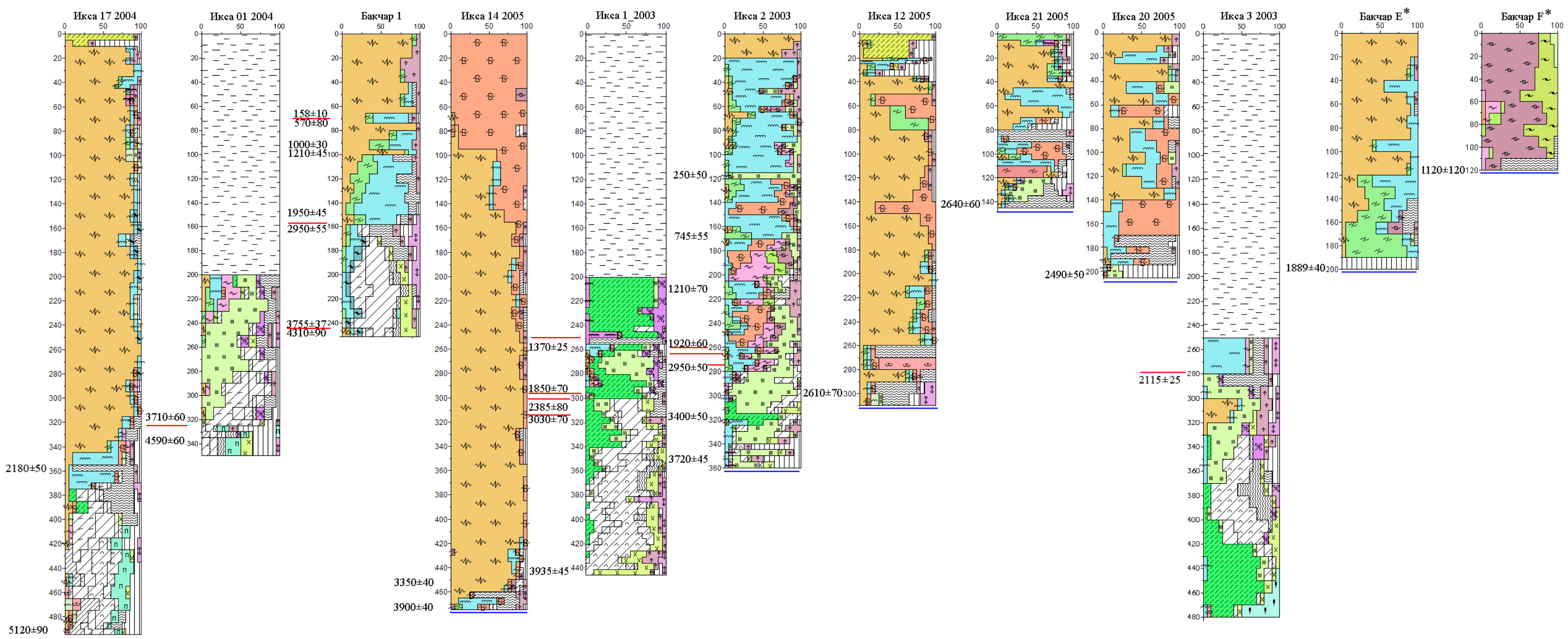

Fig. 1. Peat cores of Iksinskoe and Bakcharskoe bogs

The aim of the work is to create a spatio-temporal model of paludification and vegetation succession of the climatogenic massif to reveal the influence of extreme Holocene climate events on these processes.

The object of study is the **oligotrophic Iksinskoe bog**.

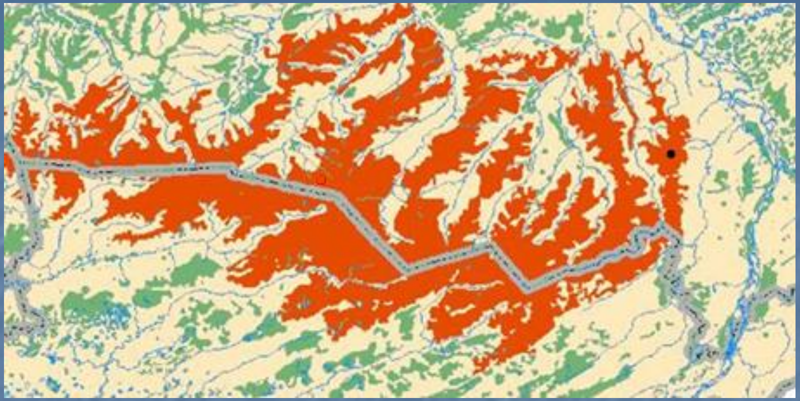

Fig. 2. The Great Vasyugan Bog

The Iksinskoe bog is located in southern taiga of the Western Siberia (56°54′ – 56°59′ N, 82°21′ – 83°22′ E). It is the northeastern spur of the Great Vasyugan Bog. It occupies the section of asymmetric watershed of the rivers Shegarka and Iksa. The watershed has complex and significant meso- and microrelief differentiation of the surface. Here, sublatitudinal mineral ridges and local elevations, cannels of ancient streams are represented.

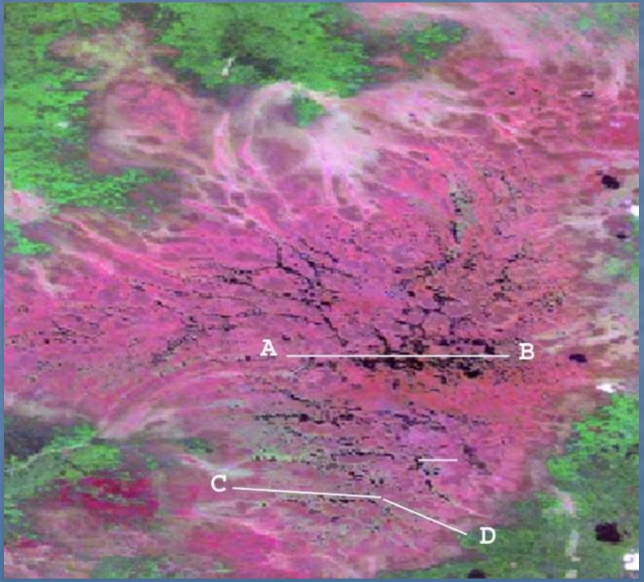

Fig. 3. The Iksinskoe Bog

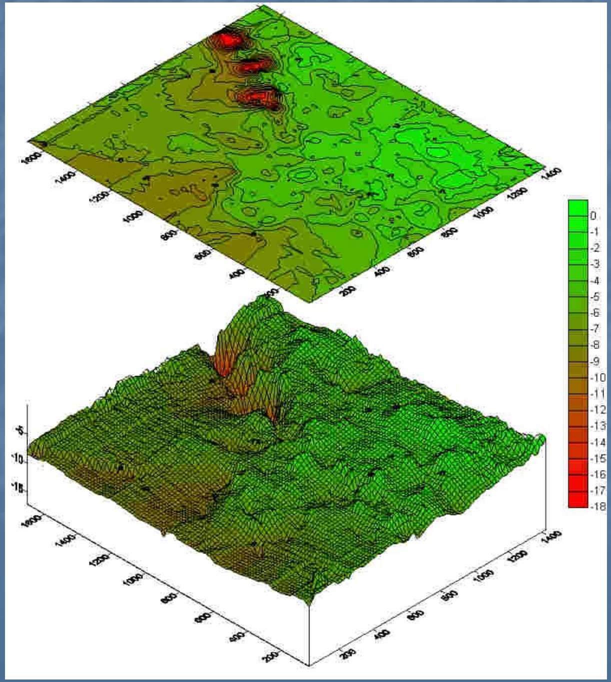

Fig. 4. The relief of the rivers Shegarka and Iksa watershed section

The watershed surface numerous shallow depressions of thermocarst and suffosion origin are presented.

The mineral bottom of the Iksinskoe bog is composed of loess-like carbonate loams and clays.

The Iksinskoe bog is not connected with groundwater and therefore its development was completely dependent on climatic conditions.

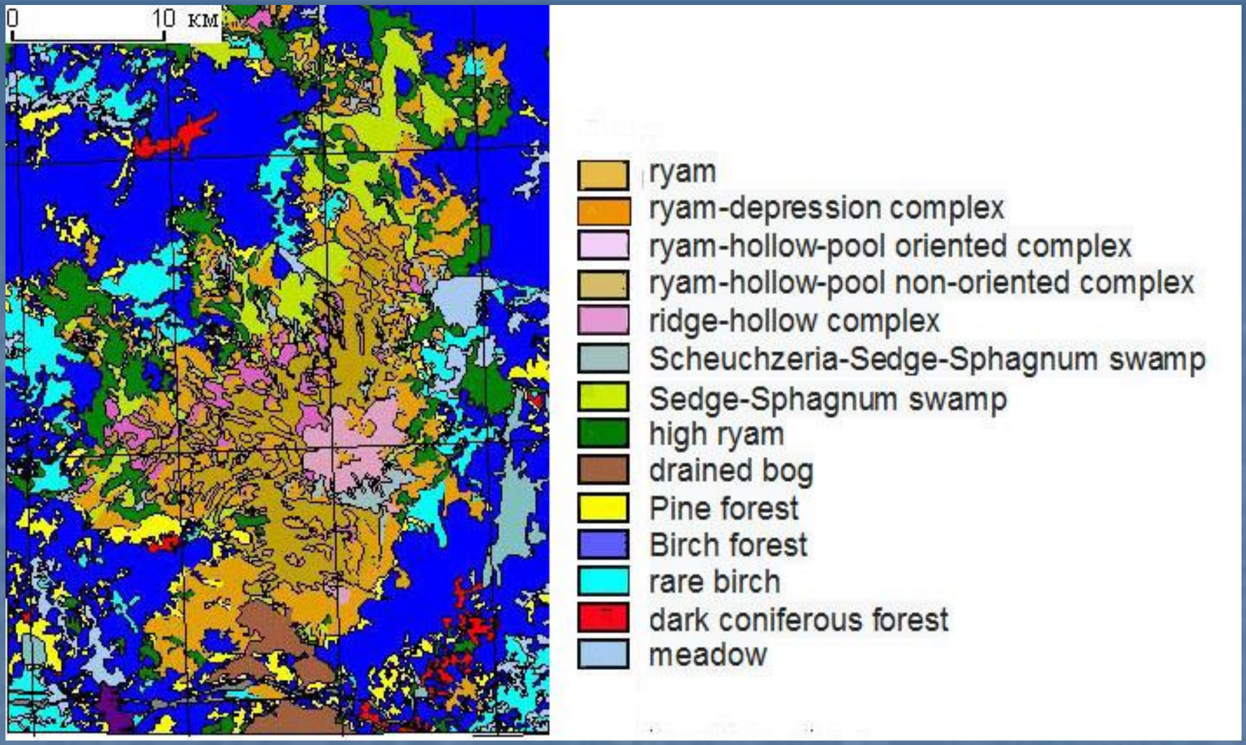

Fig. 5. Microlandscapes map of the Iksinskoe bog

The Iksinskoe bog is a complex mire system. It consists of numerous convex forested uplands and heavily watered swamps and hollows of runoff with ridges and pools.

In the northern half of this mire system, the eccentric bog massif with a highly pool-free apex plateau and radial slope structure made of alternating strips of low ryams and heavily watered troughs of runoff with ridges and pools is represented. It resembles a typical bog massif of the Narym type, which is in the late stage of development. However, apex plateau is not the genetic center of the bog massif. It is timed to the flattened top of the highest section of the interfluves. Peat deposits are less thick (2.3-4.5 m) than on the adjacent slopes (up to 5.6 m).

The southern part of the bog is elongated from south to north. Here an eccentric bog massif with predominantly sublatitudinal microlandscapes structure is represented. The main background is formed by *Carex-Scheuchzeria-Sphagnum* swamps with pools and rare ridges. This background is disturbed by numerous hollows of runoff with pools and chains of low ryams islands.

The internal bog hydrographic network of deep (up to 2.5-3.0 m) pools was formed at early eutrophic and mesotrophic stages of its development. Less deep pools were formed at the oligotrophic stage.

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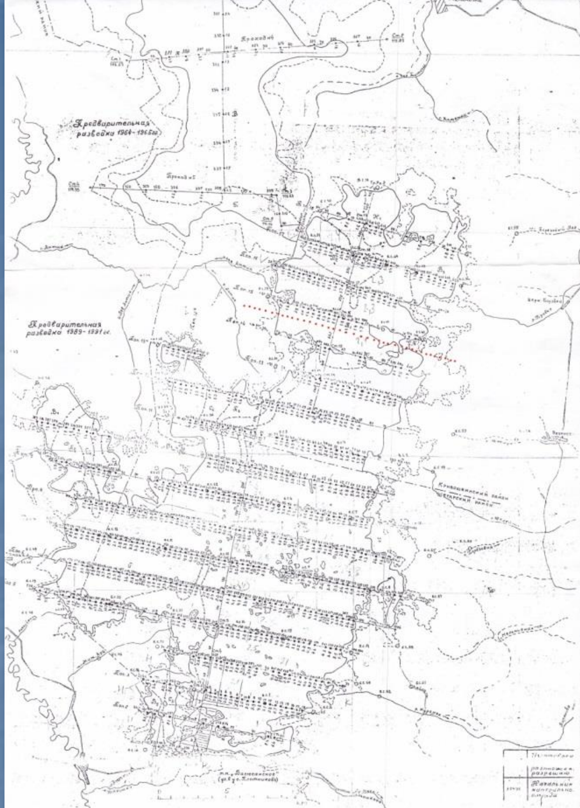


Fig. 6. Plan of the Site № 6 of the Vasyuganskoye peat deposit

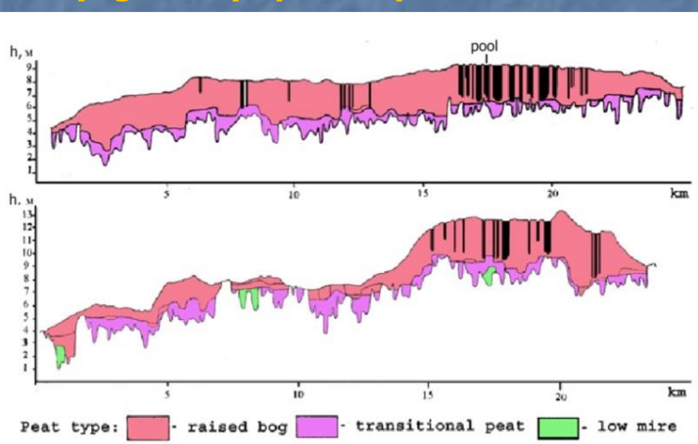


Fig. 7. Stratigraphic profiles across cross sections No. 5 and 7

Spatial-temporal model of the Iksinskoe bog on the data of preliminary geological exploration of the Site № 6 of peat deposit the Vasyuganskoe is based. The plan of this deposit (M: 1:100000) was linked to the space image. Geographical coordinates of its 14 profiles and 441 peat sampling points have been determined. For the model of the mineral bottom relief, the surface and depth markings of the peat deposit at the sampling points were taken. Layer-by-layer (after 25 cm) values of plant macrofossil composition and general technical properties of peat have been used. Paleophytocoenoses by plant macrofossil composition of peat layers have been reconstructed.

For chrono-slices of the bog paleosurfaces spatial-temporal models of age of paleostratigraphic boundaries of peat cores-analogues were taken. 29 dated peat cores of Iksinskoe and neighboring Bakcharskoe bogs obtained by the authors and taken from (Khotinskii, 1977; Lapshina et al., 2000; Golovatskaya, 2013) are taken as analogues. When selecting an analogue, the location of the peat sampling points within the bog massif, on an element of meso- and microrelief was taken into account. The search for paleostratigraphic boundaries in peat deposits of the sampling points on the basis of layer-by-layer values of botanical composition, degree of decomposition (*R*), ash content (*A*), and natural moisture content (*W*nat.) of peat was carried out.

The layer-by-layer and total cumulative mass indices of organic matter in peat were used to determine their age.

To calculate the cumulative mass of organic matter of peat for each of 10560 samples of sampling points, the "Tables for determining the outputs of air-dry peat in tons at a relative humidity of 40%" were used. According to these tables, taking into account the type, R and Wnat, peat density the layer-by-layer cumulative masses at a relative humidity of 40% were determined and calculated. Then the obtained values were recalculated for organic matter of absolutely dry peat.

The values of the cumulative mass and the rate of peat organic matter accumulation for the layers of different types of peat between the paleostratigraphic boundaries of the peat cut-analogous were obtained. These values were used for the most reasonable determination of the age of the layers of the peat deposit at the sampling points.

Processing of data on the dynamics of the Iksinskoe bog in the geoinformation system ArcGIS 10 was carried out. Tools for 3D modeling of the bog surface for different periods of its development have been applied. Interpolation of paleophytocoenosis data for the creation of time-space model chrono-slices of the Iksinskoe bog paleosurfaces was performed.

On the basis of comparative analysis of data obtained for chrono-slices, on the core-analogues and reconstructions of paleoclimate of the forest zone of Western Siberia [Volkova et al., 2002], the following was established.

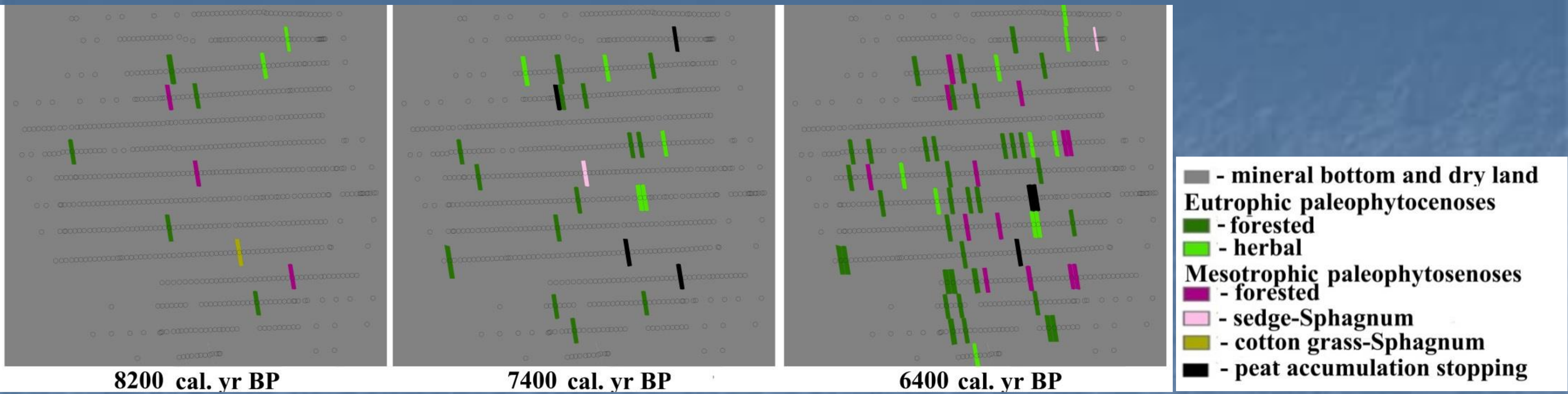


Fig. 8. The chrono-slices of the Iksinskoe bog paleosurfaces of spatial-temporal model

The first sporadic paludification hearths appeared about **8000 cal. yr BP**. This was the beginning of warming after global cooling about 8200 cal. yr BP (**Bond event 5**) (Bond et al., 2001). The degradation of permafrost was most likely favorable for paludification. Melt water in the closed depressions of the slopes of the watershed plateau and of the channels of ancient streams accumulated. The type of paludification depends on the physical (melted/frozen) state of the soil. In place of sparse forests, eutrophic or mesotrophic grass communities were formed from sediments, horsetail, watch and reed. Sometimes small lakes were stuck by herbal-moth communities with Sphagnum teres. Peat accumulation was short-lived. After complete degradation of permafrost for a long time, up to 7400 and even 5900 cal. yr BP it stopped.

About **7400-7200 cal. yr BP**, in the wettest period of the Atlantic Holocene optimum, new hearths of eutrophic paludification appeared. In the deepest depressions of the channels of ancient streams, the watershed plateau and its northern slope, shallow lakes appeared. These lakes started to overgrow with sedges, Typha, horsetails and bog beans, sometimes with an admixture of reeds.

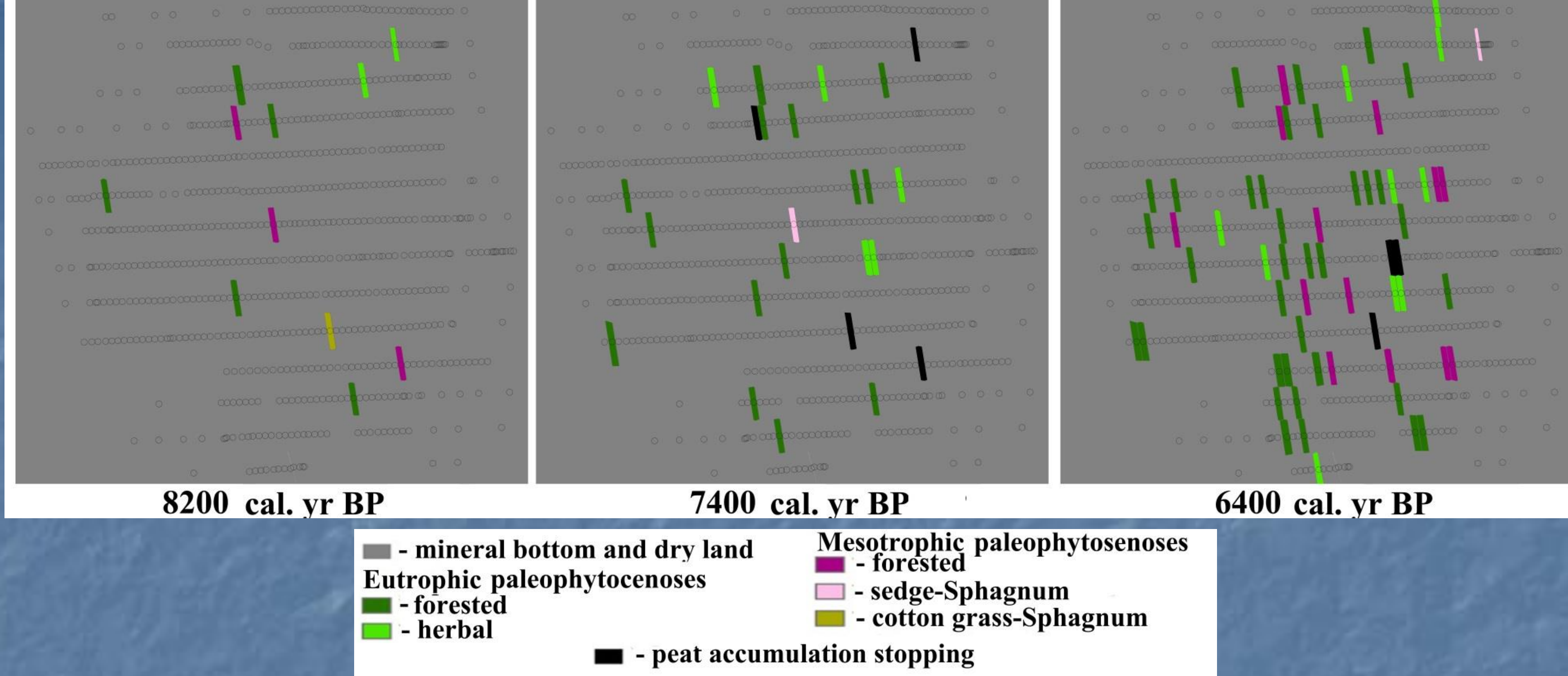
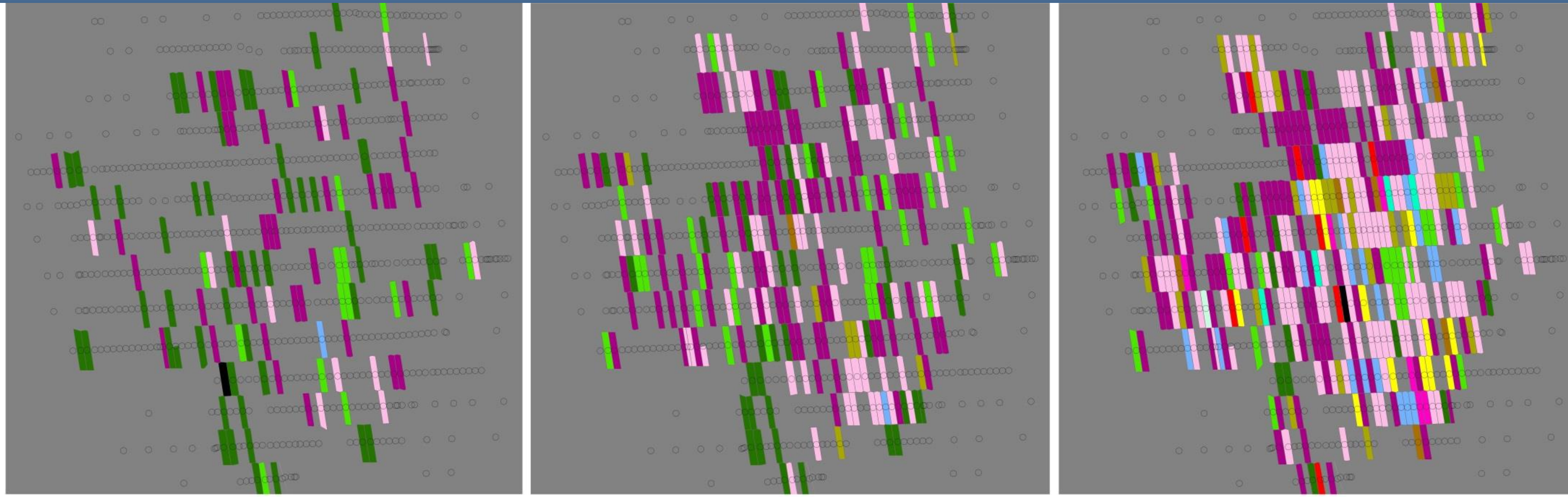


Fig. 9. The chrono-slices of the Iksinskoe bog paleosurfaces of spatial-temporal model

By **6400 cal. yr BP**, in the warm humid climate practically on the whole area of the future bog, the number of new hearths of paludification forests in deep closed depressions increased. In some meridionally oriented channels of ancient streams, the merging of isolated hearths occurred. Eutrophic weakly forested and open grass communities with dominant sedges prevailed. The hearths of mesotrophic paludification appeared. Most likely, it is the result of long seasonal thawing of soils during short-term coolings. At some sites the peat accumulation has resumed. However, in the depressions of the highest flat part of the watershed, peat accumulation stoped. The total area of paludification about 14% of the modern area of the peat deposit in boundary of the industrial depth was.



5900 cal. yr BP | 4850-4700 cal. yr BP | 3950 cal. yr BP

Fig. 10. The chrono-slices of the Iksinskoe bog paleosurfaces of spatial-temporal model

- mineral bottom and dry land

Eutrophic modern and paleophytocenoses
- forested
- herbal

Mesotrophic modern and paleophytosenoses
- forested
- sedge-Sphagnum
- cotton grass-Sphagnum
- Scheuchzeria-Sphagnum swamp

Oligotrophic modern and paleophytocenoses
- high ryam
- cotton grass-Sphagnum
- ryam
- mosaic Sphagnum swamp
- Spheuchzeria-Sphagnum swamp
- pool
- peat accumulation stopping

By **5900 cal. yr BP**, the number of hearths of mesotrophic, mostly afforested, herbal communities had significantly increased. The main number of hearths appeared in depressions of the most elevated mesorelief elements. This was most likely facilitated by the widespread long-term thawing of seasonal frost here under the conditions of the beginning of global cooling about 5900 cal. years ago (**Bond Event 4**). By this time, the hearths in many of the channels of ancient streams have merged. The total area of paludification has doubled and made up 26%.

By **4850-4700 cal. yr BP**, under conditions of new cooling, the area of paludification has doubled and made up 53%. The hearths of mesotrophic paludification of forests in the depressions of sublatitudinal mineral ridges and their slopes, as well as on the periphery of the future bog massive appeared. In general, mesotrophic communities prevailed (about 69%). In many sites, eutrophic communities have changed into mesotrophic ones. Cotton grass has appeared and even dominated in these hearths. This indicates that the surface has dried up locally. The transgressions of sphagnum mosses from long-term thawing seasonal frost and permafrost most likely contributed to the formation of waterproofing. In some areas, palsa were formed and peat accumulation stopped. 14C-dating of peat cores-analogs and catastrophic oligotrophization of vegetation at the sampling points in the subsequent warm period confirm this.

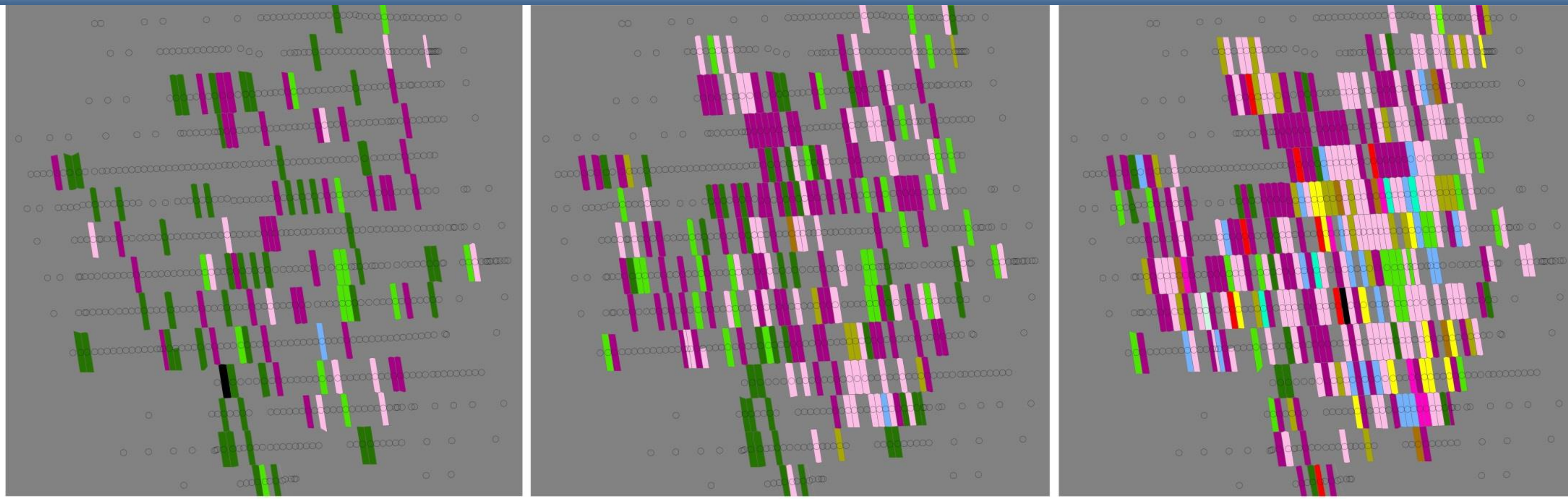


Fig. 11. The chrono-slices of the Iksinskoe bog paleosurfaces of spatial-temporal model

- mineral bottom and dry land

Eutrophic modern and paleophytocenoses
- forested
- herbal

Mesotrophic modern and paleophytosenoses
- forested
- sedge-Sphagnum
- cotton grass-Sphagnum
- Scheuchzeria-Sphagnum swamp

Oligotrophic modern and paleophytocenoses
- high ryam
- cotton grass-Sphagnum
- ryam
- mosaic Sphagnum swamp
- Spheuchzeria-Sphagnum swamp
- pool
- peat accumulation stopping

In the depressions at the foot of the watershed plateau about **4300 cal. yr BP**, the paludification of hearths through oligotrophic cotton grass-*Sphagnum* communities took place. In some of them, peat accumulation was short-lived. At the main area of the bogs, peat accumulation continued. In the subsequent period of some climate mitigation, paludification intensified.

By **3950 cal. yr BP**, by the subboreal Holocene optimum the area of the bog had reached 78%. The mire water level increased. The area of mesotrophic seadge- and cotton grass-Sphagnum communities, as well as the area of *Sheuchzeria-Sphagnum* swamps almost doubled. The hearths of oligotrophic cotton grass-*Sphagnum* communities, *Sheuchzeria-Sphagnum* swamps, tall and low ryams appeared (about 9%). New hearths of paludification appeared mainly in the eastern part of the mire on the highest elements of mesorelief. This effect of permafrost in mineral soils on their appearance is confirmed. The appearance of cotton grass-*Sphagnum* communities also confirms the presence of permafrost hearths in the preceding coolling. At the foot and on the slopes of the watershed plateau, new hollows runoff began to form. Mire water level increase with peat growth in conditions of relatively humid climate, as well as water inflow from the degraded permafrost hearths contributed to progressive paludification. During the formation of top water over these permafrost hearths, oligotrophic paludification took place.

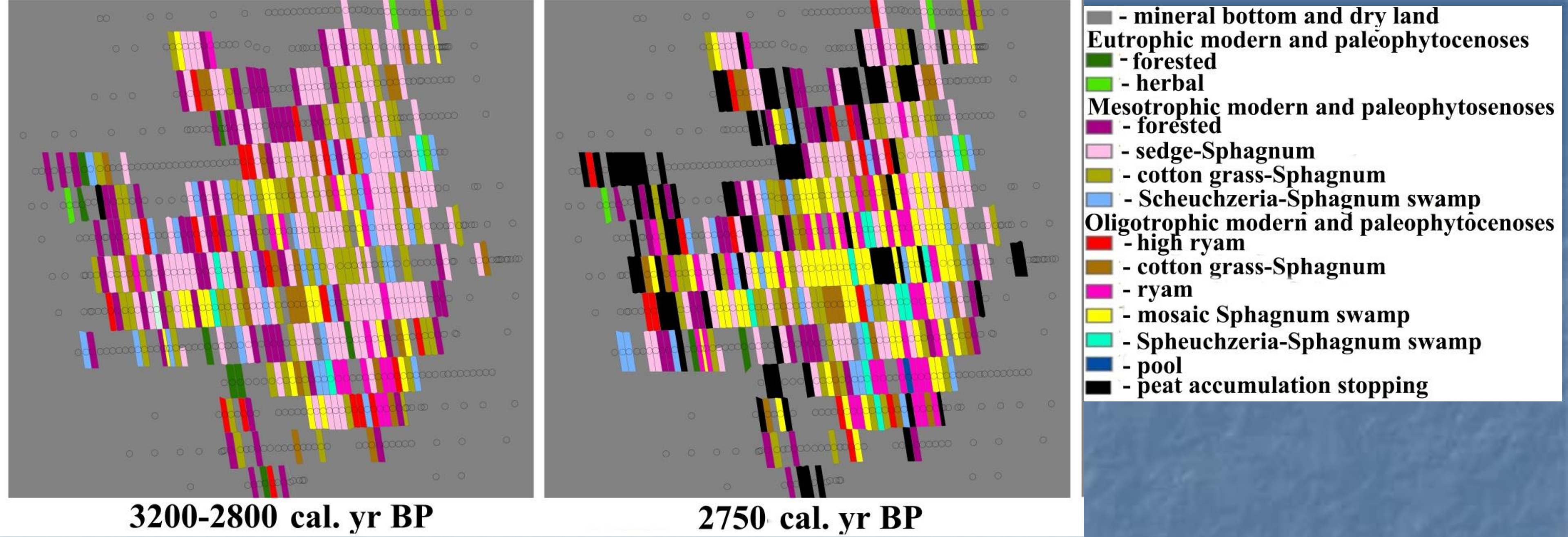


Fig. 32. Модель of the Iksinskoe bog Модель

Fig. 12. The chrono-slices of the Iksinskoe bog paleosurfaces of spatial-temporal model

By **3200-2800 cal. yr BP** the area of the mire increased to 90%. Under conditions of aridization of first warm and then cold climate the area of mesotrophic and oligotrophic cotton grass-*Sphagnum* communities reached 21.5%. The number of hearths of tall ryams has increased. Some herbal communities have become afforested. Significant drying of the mire surface occurred. Global dry cooling about 2800 cal. yr BP (**Bond Event 3**) caused deep freezing of peat deposits and palsa formation. In a large area of the mire, peat accumulation stopped up to 2450 or 1900 cal. yr BP. These cryogenic processes were most active in the areas with shallow peat deposit of the mire periphery. They also took place on high mesorelief elements, including the depressions of the central plateau. The 14C-datas of core-analogs confirm the presence of these processes. The low values of the organic cumulative mass of the peat layer of the sampling points above the paleostratigraphic boundary corresponding to this age, are also confirmed. Peat accumulation continued in the rest of the mire area. Especially active peat growth at the foothills of the central plateau and other highest mesorelief elements took place. Here, a continuous moss cover of *S. fuscum* was formed.

About **2750 cal. yr BP** warming began. The mire area by oligotrophic and mesotrophic paludification of margins and mineral islands inside the mire massif reached up to 96%. Oligotrophic ryams, cottongrass- and *Sheuchzeria-Sphagnum* communities occupied 34% of the area. Mire water levels in the central part of the mire has increased. New hollows runoff with oligotrophic mosaic swamps with *Sphagnum magellanicum* and *Sheuchzeria-Sphagnum* swamps began to form. The beginning of degradation of the permafrost hearths has caused it. However, still a significant mire area in the permafrost state remained.

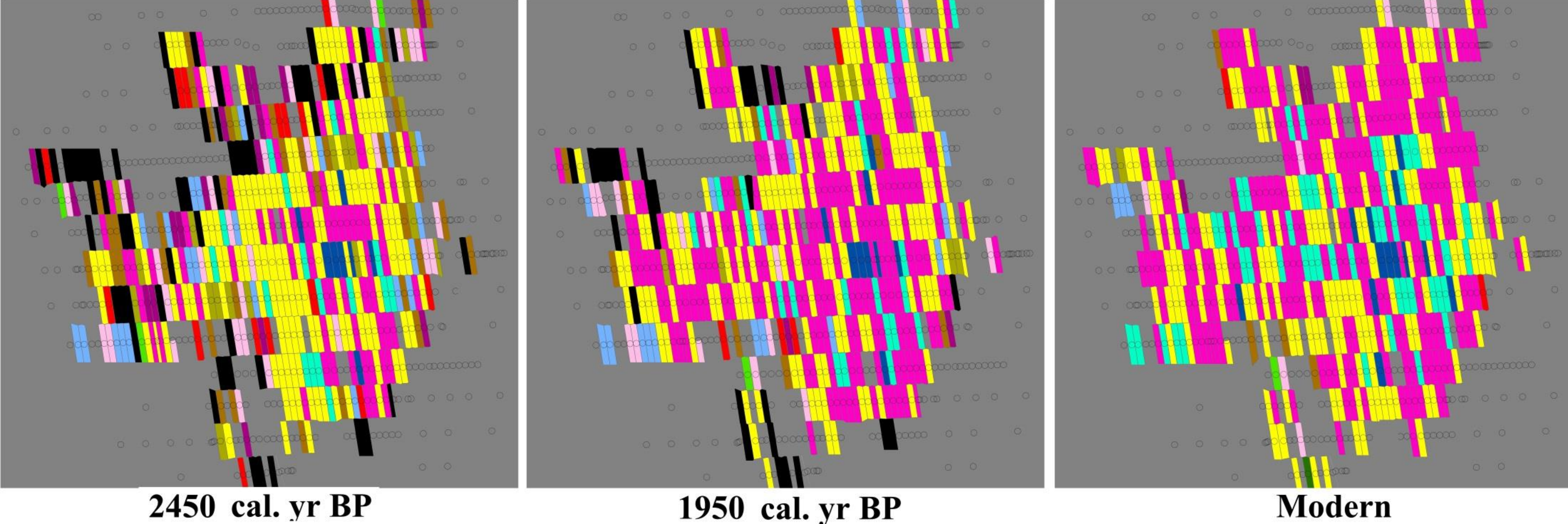


Fig. 13. The chrono-slices of the Iksinskoe bog paleosurfaces of spatial-temporal model

By **2450 cal. yr BP** , more than half of the area (65%) of the mire was already occupied by oligotrophic communities. The process of permafrost degradation continued in the warm climate. Mire water levels have risen. This was a period of maximum spread of the swamp communities. The main part of the mire were occupied by mosaic swamps with separate islands of low ryams. The main area of the mire was occupied by *Sheuchzeria-Sphagnum* swamps. Sublatitudinal mineral ridges were flooded and hollow runoff formed on them. Primary lakes and secondary pools were formed as a result of flooding mineral islands and depressions of the central plateau.

1900 cal. yr BP , oligotrophic communities already occupied almost the entire mire area. This was promoted by active peat accumulation in the warm climate. On the periphery of the mire some hearths of permafrost are still preserved or new hearths were formated in dry cooling about 2000 cal. yr BP. In the chrono-slice of this period, the area of the swamp communities decreased significantly due to the increase in the area of the low ryams islands. This was a period of active formation of the surface hydrological system of runoff from the bog. The radial structure of slopes of the central plateau from alternating bands of ryams and heavily waterlogged swamps and ridge-hollow-lake complexes of hollows runoff in place of the ancient channels of water flow and submerged mineral ridges were formed at this time.

In the last two chrono-slices, the *Scheuchzeria-Sphagnum* and mosaic swamps are well reflected. However, the areas of low ryam hearths are considerably overestimated in comparison with the data of space images interpretation and our field studies. This is due to the fact that during geological exploration in summer on the most watered areas sampling of peat was possible only on high hummocks and ridges with *S. fuscum*.

Thus, it was found that the Iksinskoe bog was formed mainly in the subboreal period, under the conditions of directed cooling of the Holocene climate. Widespread distribution of permafrost during the cooling, which caused autochthonous mesotrophic and oligotrophic paludification of carbonate soils of elevated relief, and high watering of the entire territory with the degradation of permafrost in the periods of subsequent warming, the active development of paludification on different elements of meso- and microrelief were favorable. This resulted in the formation of a vast swamp system occupying almost the entire considered section of the watershed under frequent climate changes. The dynamics of paludification and succession of plant communities were maximally affected by extreme events of Holocene climate, especially global dry cooling of about 5900, 4850-4700, 3200-2800 cal. yr BP.

Thanks for attention!