

Investigating the peat deposits of the Great Vasyugan Mire margin using ground-penetrating radar

A A Sinyutkina

Scientific Department, Siberian Research Institute of Agriculture and Peat, Siberian Federal Scientific Centre of Agro-Biotechnologies, 3 Gagarina st., Tomsk 634050, Russian Federation

Abstract. The objectives of this study are to discuss some algorithms for the interpretation of GPR data in conditions of wetlands, estimate the peat layer thickness, and assess the surface transformation due to peat accumulation in the Great Vasyugan Mire. The study area is located in the southeastern part of the West Siberian plain (Middle Ob River watershed) and consists of typical Western Siberia pine-shrub-sphagnum, pine-shrub sedge-sphagnum ombrotrophic mires and swamp forest with birch, aspen, Siberian cedar, and spruce. Four separate georadar complexes corresponding to snow, fibric peat, hemic and sapric peat, and mineral subsoil were revealed with a 250 MHz antenna. An isolated area of peatland in depression within the swamp forest is identified. At the same time, a distribution of peat accumulation processes outside the original depressions was observed. The study has shown surface leveling where the surface slope decreases from 5 to 0.1 % in the process of peat accumulation within the border of the swamp and mire. An inversion of the surface slopes is observed in areas corresponding to intensive accumulation of sphagnum peat within the pine-shrub-sphagnum bog.

1. Introduction

Peat has a high proportion of soil carbon due to a relatively high carbon density of organic-rich soil. Therefore, it has become increasingly important to measure and model soil carbon storage and change in peat stocks to facilitate the management of carbon change over time in the context of climate-change mitigation activities [1, 2]. The Great Vasyugan Mire plays a key role in the global carbon cycle, the formation of hydrochemical and hydrological regimes in the West Siberian Plain, and significantly affects regional and global climate processes. This makes it important to study the state and dynamics, especially the mire marginal parts in the zone of interaction with adjacent landscapes characterized by high variability in the parameters of the abiotic environment and the vegetation [3]. The ambiguity of the paludification trend estimates within the mires marginal parts determines the need to obtain new data on the current carbon stocks here.

The carbon storage of peatland is determined by the peat volume, specific stratigraphy, and the peat properties, such as the bulk density and organic matter content. Within the peat deposits, the bulk density and carbon content differ between the peat types and degree of decomposition [2]. The traditional methods of peat investigation and inventory with manual peat coring are slow, labor intensive, and costly. The study of peatland stratigraphy by coring can be supported by geophysical techniques, such as the ground penetrating radar (GPR). The GPR can be used to provide information on the depth and volume of peat deposits at a level of details to information obtained with manual techniques [2, 4]. Compared with traditional methods, the GPR is a more efficient tool for estimating



the peat thickness and properties, characterizing the sub-surface topography of the peat and mineral subsoil interface. The GPR can be used to distinguish layers having differences in the bulk density, degree of decomposition, and volumetric water content [5-7], to integrate hydrological and geophysical studies of the morphology and stratigraphy [8], to investigate the relationship between the mire genesis and bedrock setting and the chronology of peat deposition [9].

Until now, only few geophysical studies have been reported focusing on West Siberian mires [10, 11]. These authors draw attention to the georadar sounding possibility to isolate boundaries that are well interpretable (for example, between the peat and the mire mineral bottom), but, in addition, a number of boundaries difficult for interpretation exist. This determines the need to improve the GPR data processing methods. The objectives of this study are to discuss the algorithms for interpretation of GPR data in conditions of wetlands, to show robust estimates of the peat layer thickness, and to assess the surface transformation as a result of the peat accumulation process within the north-eastern part of the Great Vasyugan Mire. In this paper we use sensed GPR data to estimate the peat thickness and properties validated with a limited number of ground peat depth measurements.

2. Study sites

The study area is located within the southeast West Siberian plain in the interfluvium of the Bakchar River and the Iksha River (Middle Ob River watershed). The territory belongs biogeographically to the south taiga zone. The quaternary deposits are represented by fluviolacustrine loams and clays. The thickness of the quaternary deposits on the interfluvium of the Bakchar River and the Iksha River reaches 40-60 m [12]. The climate is continental with long, cold winters and short, hot summers; the average annual temperature is 0.23°C. The annual amount of precipitation is 473 mm according to the meteorological station near the Bakchar village. The average annual evapotranspiration reaches 332 mm. Positive atmospheric water balances, flat relief, and weak drainability by rivers allows the formation and sustainable evolution of mires [13]. Large mire massifs are widely distributed within the study area. Change of the mire microlandscapes comes from the swamp forest in the margins to the ridge-hollows and ridge-pool complex in the center. A GPR survey was conducted in the north-eastern part of the Great Vasyugan Mire (Bakchar Bog) in Tomsk region of Russia (N56°58' E82°36'). The study area includes typical Western Siberia pine-shrub-sphagnum, pine-shrub sedge-sphagnum ombrotrophic mires, and swamp forest with birch, aspen, Siberian cedar, and spruce in the margin part of the mire (Figure 1). The vegetation of the pine-shrub-sphagnum mire is dominated by *Pinus silvestris*, *Chamaedaphne calyculata*, *Ledum palustre*, and *Sphagnum fuscum*. The pine-shrub sedge-sphagnum mire is occupied by *Pinus silvestris*, *Betula pubescens*, *Pinus sibirica*, *Ledum palustre*, *Chamaedaphne calyculata*, *Carex rostrata*, *Eriophorum vaginatum*, and *Sphagnum angustifolium*. The ombrotrophic mire is surrounded by a swamp forest dominated by *Pinus sibirica*, *Betula pubescens*, *Picea obovata*, *Populus tremula*, *Rosa acicularis*, *Ledum palustre*, *Carex cespitosa*, *Calla palustris*, *Menyanthes trifoliata*, *Sphagnum angustifolium*, and *Bryidae*. The swamp forest and mire are characterized by uneven terrain with moss hummock, tussocks, and depressions.

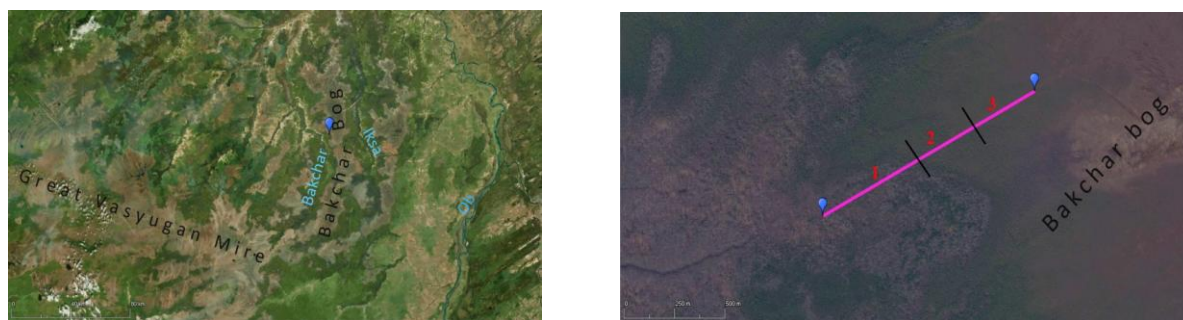


Figure 1. Study area: part of the Bakchar Bog (north-eastern part of the Great Vasyugan Mire):

- 1 – Swamp forest with birch, aspen, Siberian cedar, and spruce, 2 – Pine-shrub sedge- sphagnum ombrotrophic mire, 3 – Pine-shrub-sphagnum ombrotrophic mire.

3. Methods

3.1. GPR survey

The GPR is a geophysical method using a transmitting antenna to generate a high-frequency electromagnetic (EM) wave which penetrates the subsurface and returns to the receiving antenna as a sequence of reflections from stratigraphic interfaces. The success of layer detecting depends on the dielectric contrast between the various layers [2]. Strong GPR reflections occur at the contact between peat and bedrock [9, 14], peat and organic-rich lake sediments [8]. A significant contrast between peat and the underlying mineral soil will likely occur due to markedly different physical characteristics of organic versus inorganic sediments. Changes in the type and the degree of decomposition in peat may also cause GPR reflections [8]. The velocity of electromagnetic wave is controlled by the relative dielectric permittivity. This is a geophysical property that is strongly dependent on water content and organic matter content [6]. EM wave data allow conversion of a time record of reflections to an estimated depth [15]. The information from borehole is one of the methods to calculate the depth scale. Radar stratigraphic interpretation is based on the definition of sedimentary radar facies that result from the distribution and configuration of radar reflection [16].

The GPR surveys, which covered a total distance of 1.3 kilometers, were conducted in March 2017. The winter season was chosen because the GPR antenna and the displacement sensor cannot be moved in the snowless period due to the intense microrelief of swamp forest and mire. We employed a GPR system “OKO-2” (“Logical systems”, Russia) with 250 MHz shielded antenna and displacement sensor. Depending on the ground studied, the antenna may have a penetration depth of up to 8 m and a vertical resolution of 0.25 m. However, the depth of penetration is limited by the peat moisture and reflection losses from a material with large reflection coefficients, such as clay and, in fact, it was 2 m within the study area. Measurements were collected with a step size of 50 mm and a receiver set at a 100 ns time window. We placed marks as vertical lines on radiograms every 50-100 m during the GPR surveys to collected peat core and to binding high-altitude data in summer. The step size between the marks was determined by the peat deposits heterogeneity. The marks, the beginning and end of the GPR transect were located with GPS (accuracy: 5 m).

3.2. Field study

Field data were collected in June 2017 to validate the GPR data, the depth and properties of the peat deposits. A leveling survey was carried out with automatic level in steps of 50-100 m along the GPR profiles to binding high-altitude data. Peat cores were collected manually using a Russian peat corer with a 50 cm sample chamber. The sample cores were sliced at irregular intervals (by peat class) down to the core base. A total of 16 cores were drilled in peat every 50 m in the pine-shrub sedge-sphagnum bog and every 100 m in the swamp forest and the pine-shrub-sphagnum bog along the GPR transect. The peat materials were classified using scale of decomposition and guidance for peat class determination by visual observation [17, 18]. Visual examinations of peat were done by squeezing the undisturbed peat sample in hand. Visual observation of the peat decomposition is based on the determination of the plastic property, the plant remains content, the quantity and color of the squeeze water. The peat sample is classified as belonging to one of the decomposition categories (Table 1).

Table 1. Description of peat decomposition categories [17, 19].

Decomposition categories	Description
I Mostly undecomposed peat	Peat is not extruded between the fingers; plant remains are visible and easily identifiable; peat releases a lot of clear or yellowish water when squeezed.
II Intermediate in the degree of	Peat is not extruded between the fingers;

decomposition	plant remains are visible; peat releases a small of brown water when squeezed.
III Highly decomposed peat	Peat is extruded between the fingers; the structure of the plant remains is quite indistinct; the water, if any is released, is very dark and almost pasty

Peat class was determined by the composition of visible plant remains, color and degree of decomposition of peat sample. A total of 5 classes of peat were determined within the study site (Table 2).

Table 2. Description of peat class within the study site [17].

Peat class	Visible plant remains	Color	Decomposition categories
Wood	Reddish remains of pine bark	Dark brown	III 40-55 %
Wood-grass	Reddish remains of pine bark and black roots of cotton grass	Dark brown	II, III 30-60 %
Wood-moss	Reddish remains of pine bark and sphagnum remains	Dark brown	II 25-50 %
Grass-moss	Sphagnum remains and cotton grass fibers	Light brown	I, II 15-40 %
Moss	Easily identifiable sphagnum remains	Yellow, light brown	I 5-30 %

3.3. Data processing

The data processing was carried out with the GeoScan32 V.2.6 software (Logical Systems, 2016) and had the following main steps:

1. Background signal removal by applying average subtraction. Subtracting the mean is an effective method for removing a constant component of the GPR signal to subtract a forward signal that does not carry useful information.
2. Using the gain function to compensate for the signal decay. We used an exponential curve with a coefficient of amplification 100 to gain the signal within the GPR transect.
3. Zeroing of the depth scale in accordance with the peat surface. The surface of the peat deposit is determined by an increase in the amplitude of the signal during the transition to another medium.
4. Identification of the reflector depth representing the peat and mineral subsoil (clay) interface and interface between the classes of peat.
5. Determination of the dielectric permittivity and depth of peat layers. The dielectric permittivity was determined at a specific point using the known true depth of the interface between the peat deposits and the mineral subsoil and genetic layer of peat with data from the core samples.
6. Import of the altitude data of the leveling survey to marks of the GPR traces.

4. Results and discussion

4.1. GPR data interpretation

Four separate georadar complexes with a characteristic wave field distribution are confidently distinguished on the radargram obtained with the 250 MHz antenna. Georadar complexes correspond to layers of snow; sphagnum and grass-sphagnum fibric peat; hemic and sapric peat; mineral subsoil (clay and clay loam). Radargrams from the pine-shrub-sphagnum ombrotrophic mire are shown in Figure 2, for example.

The first complex corresponds to the snow cover layer. Elongated parallel in-phase axes, low-amplitude oscillations of the direct signal, and a gradual decrease in the amplitude from the lower part

of the layer characterized the GPR complex. The upper boundary of the second georadar complex corresponds to the mire surface. It stands out quite confidently along the boundary between the axes of the white and black phase and a sharp increase in the signal amplitude. Almost complete attenuation of the signal at its lower boundary is observed within the georadar complex.

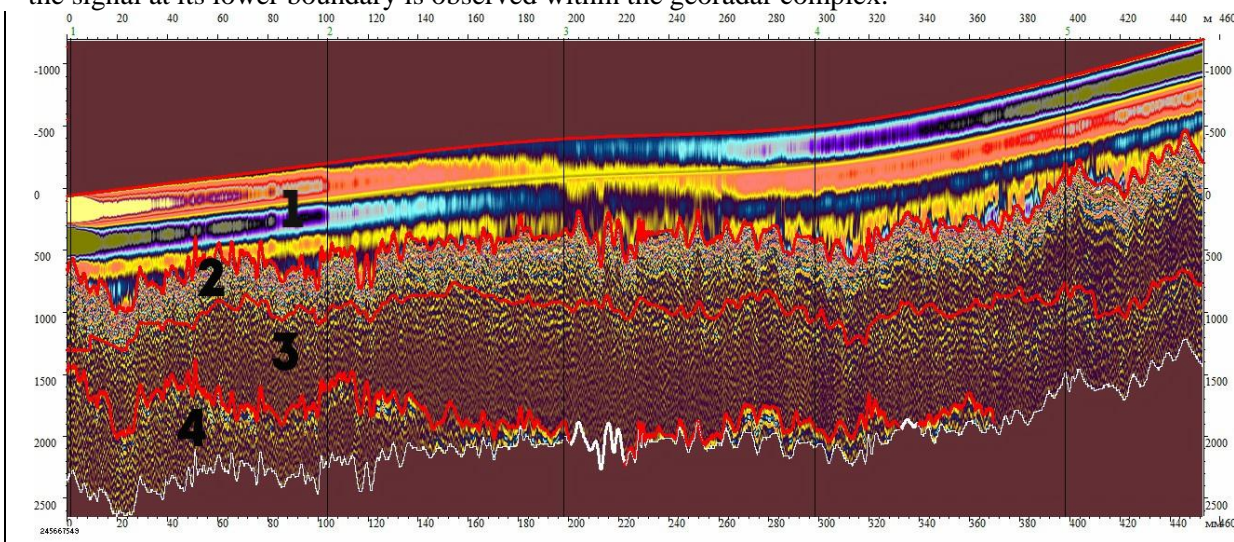


Figure 2. Georadar complex boundary.

Layers: 1 – Snow; 2 – Fibric peat; 3 – Hemic and sapric peat; 4 – Mineral subsoil

The second georadar complex corresponds to the layer of sphagnum and grass-sphagnum mostly undecomposed peat (fibric) in accordance with the data of manual study of peat deposits. The boundary between the second and third georadar complexes is not clear and not expressed throughout the radargram due to a gradual change in the properties of the peat. The complex is distinguished by a slight increase in the signal amplitude in the transition to a denser layer of intermediate and highly decomposed peat (hemic and sapric peat layers). The fourth georadar complex corresponds to the deposits of the mire mineral bottom built on this site with clays and loams. We note differences in the clarity of the peat deposit and the mineral subsoil boundaries between the swamp forest in the marginal part of the mire and the pine-shrub-sphagnum bog. The lower boundary of the peat deposit is more clear within the mire part of the profile due to large differences in the values of the dielectric permeability of the layers between the intermediate in the degree of decomposition of the peat layer and clay. The peat deposit boundaries within the swamp forest are less clear in comparison with the mire area due to a high degree of peat decomposition and smaller differences in the dielectric permittivity of the layers. The boundary is distinguished by a sharp increase in the signal amplitude and a change in the pattern of the commonality axes on the radargram. In addition, we used the tool "Hilbert transform" to visualize the change of the amplitudes in the absence of clear reflecting boundaries within the sections of the profile that are difficult to interpret. We found out that the selection of the boundaries between the GPR complexes for a given configuration of the GPR system in terms of freezing the top layer is possible at a peat deposit depth of more than 0.25–0.30 m.

4.2. Peat stratigraphy and form of mineral bottom

4.2.1. Swamp with birch, aspen, Siberian cedar, and spruce. Stratigraphic profiles of the Bakchar bog marginal part are shown in Figure 3. The profile begins within the site with mineral soil of heavy granulometric composition (core 1). The next three cores are characterized by the presence of wood intermediate and highly decomposed peat deposit with a depth of 0.80-1.20 m. Further along the profile the peat deposit depth decreases up to 0.15 m (cores 5-8). Highly decomposed wood peat is presented. The degree of peat decomposition exceeds 50 %. We found the site long about 300 m with peat deposits of more than 0.30 m within the swamp forest. The average depth of the peat deposits is

0.90 m, and the maximum value is 1.30 m within the considered layer. The surface of the mineral bottom is not flat. Two depressions of the mineral bottom allocated with surface slope reaching 1-1.5 %. The depressions are filled with peat. The surface was leveled to 0.1 % due to the peat accumulation in depressions.

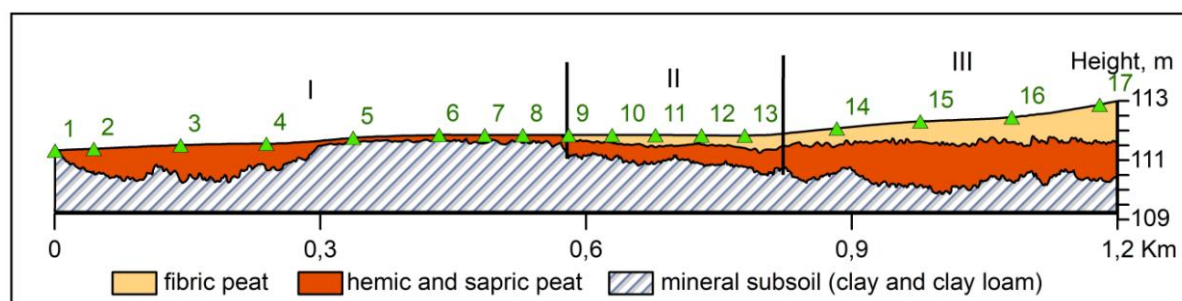


Figure 3. Stratigraphic profile of Bakchar bog marginal part. 1-17 – manual peat cores.

I – Swamp forest with birch, aspen, Siberian cedar, and spruce, II – Pine-shrub sedge-sphagnum ombrotrophic mire, III – Pine-shrub-sphagnum ombrotrophic mire.

4.2.2. Pine-shrub sedge-sphagnum ombrotrophic mire. The border of the swamp forest and the pine-shrub sedge-sphagnum ombrotrophic mire is located at a distance of 600 m from the profile beginning (Figure 3). The thickness of the peat deposit near the border sharply increases from 0.30 to 0.75 m (core 9). Further along the profile the peat deposit depth gradually increases up to 1 m within the pine-shrub sedge-sphagnum mire. Moss and grass-moss mostly undecomposed peat form the upper peat layer. Wood-grass and wood highly decomposed peats are present in the lower layer of the peat deposit (cores 10-13). The average depth of the peat deposits is 0.84 m, and the maximum value is 1.10 m within the mire site under study. The mineral bottom slope in the border part reaches 5%. The surface of the mineral bottom is almost flat with elevation changes of 0.20-0.30 m within the pine-shrub sedge-sphagnum mire.

4.2.3. Pine-shrub-sphagnum ombrotrophic mire. The border of the pine-shrub sedge-sphagnum ombrotrophic mire and the pine-shrub-sphagnum ombrotrophic mire is located at a distance of 800 m from the profile beginning (Figure 3). The thickness of the peat deposit gradually increases from 1.20 to 2.40 m (cores 14-17) within the mire site under study. The upper layer is composed by the moss mostly undecomposed peat (5-10 %). The peat decomposition increases to 30-40 % (intermediate in the degree of decomposition) in the lower peat layer. Grass-moss and wood moss peats are prevailed. The deposits of the mire the mineral bottom are characterized by a heavy granulometric composition. The mineral bottom is almost flat, and has no pronounced slope towards the mire central part. It is characterized by the presence of small depressions to a 0.40-0.50 cm depth. Inversion of the surface slopes is observed due to intensive accumulation of sphagnum peat.

4.3. The relief influence on the paludification

A complex of external factors including the geomorphologic conditions of the territories adjacent to the mire determines the paludification trend. The relief is one of the leading factors in the formation of spatial differentiation of the earth surface. Particularly, the role of the relief is manifested in the wetlands due to its influence on the features of the surface runoff and the drainage conditions of the territory. The territory under study refers to the zone of moderately progressing paludification. The waterlogging processes are most active at the periphery of the mires, especially in the flat relief conditions [20]. The mires transgression process has intensified in the past 500 years, and the current climate warming has not caused the termination of the mire formation process due to flooding of the adjacent territories [21].

We used georadar survey and surface leveling data to calculate the morphometric parameters of the mire mineral bottom as an indicator of the initial conditions for the territory waterlogging. The surface profiles and the mineral bottom of the mire and the adjacent swamp forest were obtained as a result of the study. The studies have shown a significant transformation of the surface as a result of the process of peat accumulation. The values of the mineral bottom slopes and surface slope are shown in Table 3.

Table 3. Mire mineral bottom and surface slope of marginal part of Bakchar bog.

Site	Mineral bottom slope, %	Surface slope, %
Swamp forest	1-1.5	0.1
Border of swamp forest and mire	5	flat surface
Pine-shrub sedge-sphagnum ombrotrophic mire	0.4	flat surface
Pine-shrub-sphagnum ombrotrophic mire	0.02	0.17

Inversion of the surface slopes and a change of the surface runoff direction occurred within the mire part of the profile. The water flow was directed from the marginal part to the mire center during the initial stages of peat formation. At present, the water flow is carried out to the territory adjacent to the mire. This leads to their excessive moisture and, as a consequence, the appearance of a wood peat layer within the forest. The most surface leveling occurs within the swamp forest and the border of the mire and swamp forest due to the accumulation of peat, which enhances the process of hydromorphic transformation of the territories adjacent to the mire.

5. Conclusions

Thus, four georadar complexes were identified, corresponding to media with different values of the dielectric permittivity as a result of the survey data layer-by-layer interpretation using a 250 MHz antenna. The georadar complexes correspond to layers of snow; sphagnum and grass-sphagnum fibric peat; hemic and sapric peat; mineral subsoil (clay and clay loam). The boundaries of selected layers with e data of contact measurements were compared. A profile of the structure of the peat deposit and the mire mineral bottom was constructed. High accuracy of the data obtained with the use of a georadar confirmed by the convergence with the data of contact measurements was revealed. As a result of the study, it was concluded that GPR methods can be used in conjunction with contact measurements to estimate the thickness of the peat deposit and its genetic layers.

New data have been obtained about the peat deposit structure and the form of the mineral bottom within a marginal part of the Bakchar Bog as a result of georadar research, contact measurements, and level survey of the mire surface. Depressions of the mineral bottom likely to be paludification center were identified. The surface was leveled in the process of peat accumulation. Inversion of the surface slopes was observed in areas corresponding to intensive accumulation of sphagnum peat. An isolated area of the mire in the mineral bottom depression within the swamp forest was identified. At the same time, a distribution of the peat accumulation processes outside the original depressions was observed.

Acknowledgments

This study was funded by RFBR, research project no. 18-35-00387.

References

- [1] Keaney A, McKinley J, Graham C, Robinson M and Ruffell A 2013 Spatial statistics to estimate peat thickness using airborne radiometric data *Spatial Statistics*. **5** 3-24
- [2] Walter J, Hamann G, Lück E, Klingenfuss C and Zeitz J 2016 Stratigraphy and soil properties of fens: Geophysical case studies from northeastern Germany *Catena* **142** 112-25

- [3] *Research of Natural and Climatic Processes on the Great Vasyugan Mire* 2012 ed M V Kabanov (Novosibirsk: Publishing House of the Siberian Branch of the Russian Academy of Sciences) p 243
- [4] Ulriksen P 1980 Investigation of peat thickness with radar *Proc. of 6th Int. Peat Congress, (Duluth, Minnesota)* p 126-29
- [5] Worsfold R D, Parashar S K and Perrot T 1986 Depth profiling of peat deposits with impulse radar *Can. Geotech. J.* **23** (2) 142-45
- [6] Daniels D J 2004 *Ground Penetrating Radar. second ed.* (London: The Institution of Electrical Engineers) p 796
- [7] Theimer B D, Nobes D C and Warner B G 1994 A study of the geoelectrical properties of peatlands and their influence on groundpenetrating radar surveying *Geophys. Prosp* **42** 179-209
- [8] Comas X, Slaterra L and Reeve A 2004 Geophysical evidence for peat basin morphology and stratigraphic controls on vegetation observed in a Northern Peatland *Journal of Hydrology* **295** 173-84
- [9] Campos J R R, Silva A C, Slater L, Nanni M R, Vidal-Torrado P 2016 Stratigraphic control and chronology of peat bog deposition in the Serra do Espinhaço Meridional, Brazil *Catena* **143** 167-73
- [10] Orlov T V, Sadkov S A, Zverev A V, Viktorov A S, Kalashnikov A Yu, Zarov E A and Filippov I V 2016 The use of georadar and remote methods and mathematical modeling in the study of peat deposits for solving geoecological problems *Proc. Conf. Sergeevsky readings. Engineering geology and geoecology. Fundamental and applied problems (Moscow)* (Moccow: RUDN) p 679-683
- [11] Karpov D V and Semenov S P 2012 Georadiolocation measurements in wetlands *Bulletin of Ugra State University* **3** (26) 66-70
- [12] Richter G D 1963 *Relief and geological structure Western Siberia* (Moscow: Publishing House of the USSR Academy of Sciences) pp 22-68
- [13] Evseeva N S, Sinyutkina A A and Kharanzhevskaya Yu A *et al* 2012 *Landscape of the mires in Tomsk Region* (Tomsk: Publishing house of NTL) p 400
- [14] Jol H M, Smith D G 1995 Ground penetrating radar surveys for oilfield pipelines in Canada *J. of Applied Geophysics* **34** 109-23
- [15] Gómez-Ortiz D, Martín-Crespo T, Martín-Velázquez S, Martínez-Pagán P, Higuera H and Manzano M 2010 Application of ground penetrating radar (GPR) to delineate clay layers in wetlands. A case study in the Soto Grande and Soto Chico watercourses, Doñana (SW Spain) *J. of Applied Geophysics* **72** 107-13
- [16] Jakobsen P R and Overgaard T 2002 Georadar facies and glaciotectionic structures in ice marginal deposits, northwest Zealand, Denmark *Quaternary Science Reviews* **21** 917-27
- [17] Tyuremnov S N 1976 *Peatlands* (Moscow: Nedra) p 488
- [18] von Post L 1922 The Swedish Revolution of the Geological Survey, and some of its findings *The Swedish Mosque Society Association's Journal* **1** 1-27
- [19] Huat B K K 2004 Organic and peat soils engineering *University Putra Malaysia Press, Serdang* pp 146-50
- [20] Liss O L, Abramova L I, Avetov N A, Berezina N A, Inisheva L I, Kurnishkova T V, Slyka Z A, Tolpysheva T Yu and Shvedchikova N K 2001 *Bog System of Western Siberia and their Environmental Significance (Tula:Grif and K)* p 584
- [21] Syso A I and Peregon A M 2009 The features of peat-accumulation process at the southern slope of the Great Vasyugan Bog *Contemporary Problems of Ecology* **2** (2) 124-27