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FORMATION OF RELIEF IN THE REGIONS OF ICE COMPLEX DEPOSITS DISTRIBUTION: REMOTE SENSING AND GIS STUDIES IN THE KOLYMA LOWLAND TUNDRA

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The study of the relief of the Kolyma lowland tundra using remote sensing data and GIS technologies with subsequent construction of a map of Quaternary deposits cover based on Landsat images has been presented. It has been established that the Ice Complex deposits forming positive relief forms (yedomas) occupy 16 % of the Kolyma lowland tundra area. These data are in sharp contrast with earlier estimations of the 1:1 000 000 geological map of Quaternary deposits that shows the Ice Complex deposits cover 40 % of its area. The map of vertical dissection of the relief yielded by this study provides insights into the Ice Complex thickness and extent in the area. The morphological types of the yedoma have been identified, and main regularities of relief evolution in the Holocene summarized. Eight types of land relief have been established and characterized on the basis of the ratios between specific areas occupied by the Ice Complex deposits and by thermokarst lakes.

Ice Complex, thermokarst, relief, Holocene, satellite images, GIS studies, Kolyma lowland

INTRODUCTION

Late Pleistocene ice complex (IC) deposits in the Yakutian coastal lowlands areas are represented by extremely ice-rich silty sediments with thick polygonal ice wedges. The IC deposits form positive forms of the relief, the yedoma uplands. These are also common in the lowlands of Central Yakutia and to a lesser extent in the areas of the Taimyr Peninsula and Chukotka [*Tomirdiaro, 1980; Grosse et al., 2013*]. The research into such areas has been gaining importance in recent years due to the growing concern about the climate-change-driven impact on the permafrost dynamics [*Zolnikov et al., 2004; Grigoriev et al., 2009; Romanovsky et al., 2010; Konishchev, 2011*], and in view of determining the organic matter content and predicting greenhouse gas emissions in case of permafrost degradation [*Gubin and Veremeeva, 2010; Grosse et al., 2013; Shmelev et al., 2013; Strauss et al., 2013*]. Thus, the mean annual air temperature observed in the vicinity of Chersky settlement increased from −12 to −9 °C, while the ground temperature at a depth of 15 m warmed up from −10.5 to −9 °C over the period from 1970 to 2010 [*Romanovsky et al., 2010*].

Changes in the extent and number of thermokarst lakes which are typical for the areas of IC distribution can be viewed as critical indicators of landscapes' response to climate changes [*Kravtsova and Bystrova, 2009; Veremeeva and Gubin, 2009; Kravtsov and Tarasenko, 2011; Tarasenko et al., 2013*]. Given that the remote sensing data have encompassed only the last 50 years, it is questionable whether the observed trends actually represent landscape-scale responses to recent climate changes. A better knowledge of the evolution of thermokarst processes in the Holocene can be useful for understanding the modern dynamics of the thermokarst lakes areas. Quaternary deposits and relief of the Yakutian coastal lowlands have been intensively studied since the late 1950s [*Baranova, 1957; Katasonov and Biske, 1959*].

Quaternary deposits in most parts of the area are shown only on a 1:1 000 000 map [*State... Map..., 2000a*] and 1:200 000 geological maps cover the sites with outcrops of bedrock. The use of multispectral satellite imagery allowed to refine the area extent of different types of Quaternary deposits and analyze the patterns of their distribution. This kind of studies have been given only to small areas of the Lena-Anabar lowland [*Grosse et al., 2006*] and the Lena Delta [*Grosse et al., 2005; Morgenstern et al., 2011, 2013*].

The aim of this study is to identify the relief formation patterns in the areas of the IC deposits distribution in the Holocene.

Characteristics of the geological structure and relief forms of the Kolyma Lowland tundra zone

The relief studies were conducted in the tundra zone of the Kolyma lowland within the Alazeya-Kolyma thermokarst-lake landscape province subsumed into a group of tundra provinces within the continuous permafrost zone [*Fedorov, 1991*]. In the east, the investigation site is delimited by the Khallerchin tundra composed of sandy deposits [*Spector, 1980*], and by a chain of rocky ridges of the Suor-Uyata ridge and the left bank area of the Alazeya river in the west (Fig. 1). The southern boundary of the tundra is delineated using Landsat 5 TM and 7 ETM+ satellite imagery with a 30 m resolution based on the spectral differences for forested and non-forested areas (Fig. 1).

The tundra area extent within the Kolyma lowland, excluding the Khallerchin tundra, is 45,000 km^2. The area being confined to the persistently subsiding area since the Oligocene–Neopleistocene time, this favored the accumulation of loose sediment with a thickness reaching 500 m [*Arkhangelov, 1977; Balandin, 1980*]. The sequence stratigraphy of the unconsolidated sedimentary cover is underpinned by the study of key outcrops in the middle and lower reaches of the Bolshaya Chukochya river, the Kon'kovaya river valley, and the middle reaches of the Alazeya river [*Sher, 1971; Arkhangelov, 1977; Arkhangelov et al., 1979; Kaplina, 1981; Kaplina et al., 1981; Resolutions..., 1987*], and by drilled borehole data [*Rivkina et al., 2006*].

The uppermost part of the sequence is represented primarily by the late Pleistocene IC and alas deposits formed due to IC deposits thawing during the Holocene. The Ice Complex is the syngenetically frozen sediments with thickness up to 40–50 m, mostly aleurite in composition, penetrated by large polygonal ice wedges, very ice-rich with ice content ranging from 65 to 90 % [*Romanovskii, 1961; Sher, 1971; Arkhangelov, 1977; Tomirdiaro, 1980; Schirrmeister et al., 2010*]. The synonym of the term Ice Complex in the english literature is the Yedoma deposits which means both the geological suite and geomorphological feature. The paleopedological studies showed that the IC deposits were subject to reworking during the synlithogenic soil formation [*Gubin, 1994, 2002*].

Affected by the late Pleistocene climate warming, the ice-rich IC deposits underwent thermokarst, thermodenudation and thermal erosion processes, which resulted in their significant reworking and subsequent formation of the alas complex [*Romanovskii, 1961; Plakht, 1985; Schirrmeister et al., 2002; Kaplina, 2009; Morgenstern et al., 2013*]. The radiocarbon data revealed that both the formation of thermokarst lakes and thawing of IC deposits (the so-called a surge of thermokarst) occurred within a short time period, ca. 13–12 ka BP [*Kaplina, 2009*]. In most of the study area, the alas relief had already been formed ca. 11–10 ka BP [*Kaplina and Lozhkin, 1979; Kaplina, 2009*]. The hydrologic system evolved concurrently with the emergence and further spread of thermokarst lakes, which became its integrated part [*Lakhtina and Koreysha, 1978; Plakht, 1985*].

The relief of the study area is a lowland plain. The ground surface heights gradually reduce from 70–90 m in the south of the Kolyma lowland tundra down to 5–10 m on the coast of the East Siberian Sea. There have been distinguished several elevation levels of relief characterized by neotectonic activity with different rates and directionality. These largely controlled the degree of late Pleistocene plains reworking by thermokarst and thermal erosion processes in the Holocene, the character of limnicity, the types of river valleys, etc. [*Baranova, 1957; Katasonov and Biske, 1959; Lakhtina and Koreysha, 1978; Patyk-Kara et al., 1982; Kaplina et al., 1986; State... Map..., 2000b*].

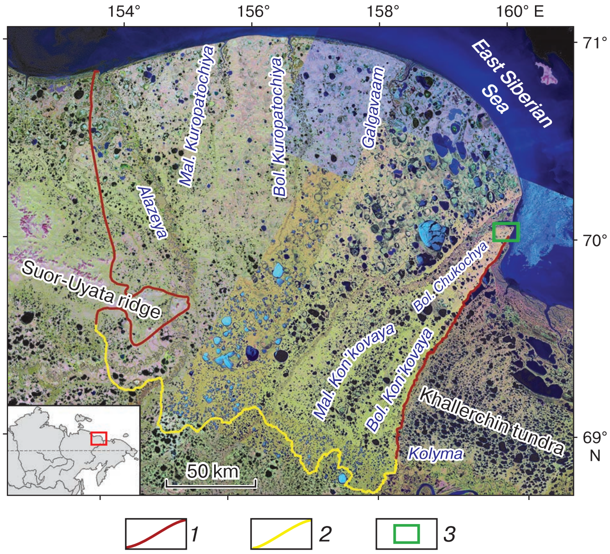

Fig. 1. Study area.

1 – tundra zone of the Kolyma lowland; *2* – southern boundary of tundra; *3* – field study site.

Applications of satellite images and GIS technologies

Construction of the Quaternary deposits distribution map. The relief of the IC distribution regions is strongly marked by thermokarst- and thermoerosion-induced dissection. The elevation of the yedoma surfaces over the alas bottoms is 20–25 m. Given that the level of detail of the available topographic maps is not sufficient for such analysis, the mapping of the Quaternary deposits area should be done using satellite imagery with medium and high-resolution, as well as 1:100 000- and 1:200 000-scaled topographic maps.

The widely developing cryogenic processes have led to emergence of drained surfaces within the alases and bogged surfaces on yedoma uplands. Thus the application of automatic classification of land cover features by using satellite imagery was difficult to use and the digitizing of the Quaternary deposits boundaries was done manually.

The ground truthing of satellite images was carried out by the authors in the lower reaches of the Bolshaya Chukochya river in August 2009. The mapping of Quaternary deposits of the Kolyma lowland tundra zone was done using Landsat TM 5 and 7 ETM+ satellite images of the summer period:

1) Landsat – 5, 27.07.09 (LT51080112009208GLC00);
2) Landsat – 5, 20.08.10 (LT51110102010232MGR00);
3) Landsat – 5, 12.08.09 (LT51080102009224GLC00);
4) Landsat – 7, 04.07.01 (LE71090112001185EDC00);
5) Landsat – 7, 03.08.01 (LE71110112001215EDC00).

Processing level of images is L1T (with radiometric and geometric correction, and orthorectified using a digital elevation model (DEM), and a set of ground-controlled points). Positional accuracy of the satellite images corresponds to 1:200 000–1:500 000 scale [*Tucker et al., 2004*], and a projection WGS 1984 UTM zone 57N were used.

In interpretations of satellite imagery, the applied option consisted in color synthesis from shortwave infrared, near infrared and red zones (RGB 543). The yedoma surface was allocated due to a less granular combination of shades of green, yellow and pink colors on more drained areas characterized by subshrub-green moss tundra (Fig. 2).

Wetlands are differentiated by grainier surface pattern and by predominance of darker pink and purple shades. Therefore, for mapping of Quaternary deposits areas the spectral characteristics of satellite images reflected specific features of the vegetation cover, the underlying surface, and morphological features of the relief were used. The elevation data of the 1:200 000 topographic maps and resultant DEM covering most of the study area, and the boundaries of Quaternary deposits at the 1:1 000 000 map were also taken into account [*State... Map..., 2000a*]. The working scale of the mapping is 1:30 000, which allowed to allocate the alluvial deposits within the yedoma uplands in the river valleys with a width greater than 50 m. The mapping of alluvial deposits in alases was done for the largest permanent watercourses with a width over 100 m. The mapped Quaternary deposits are represented by six types: ice complex, alas complex, alluvial, alluvial-marine, marine, and bedrocks outcrops.

Identification of relief types and their characterization. The authors have developed a novel technique for relief surfaces analysis on the basis of mapping and monitoring heterogeneous landscapes with the use of remote sensing data [*Zolnikov et al., 2010, 2011*]. The peculiarities of thermokarst processes development in the Holocene in the areas of IC distribution represent such parameters as yedomas uplands fraction and limnicity (thermokarst lake fraction), the relief dissection depth, and yedoma surfaces.

The maps of the yedoma and thermokarst lake fractions were constructed. The lakes areas were allocated by the automatizied classification of the Landsat images using the spectral angle mapper (SAM) approach.

The density grids (sliding window radius: 5 km; grid spacing: 30 m) served as a basis for constructing maps of yedoma fraction and limnicity. The obtained values were divided into three classes, with the thresholds for these classes derived from analysis of statistical distribution of density characteristics (sudden drops in values on density plots). For the yedoma fraction map the following classes were established: 0–5, 5–28 and greater than 28 % (Fig. 3, *a*). This indicator represents the ratio of the area occupied by the yedoma uplands to the entire study area.

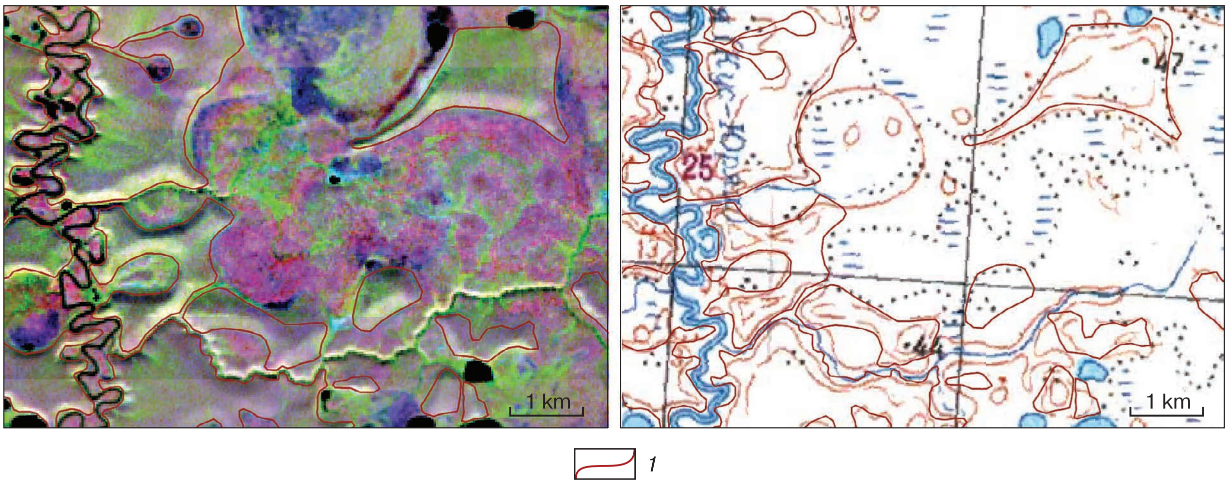

Fig. 2. Differentiation of yedoma surface using Landsat satellite imagery and topographic map at 1:200 000 scale.

1 – boundaries of yedoma uplands formed by IC deposits.

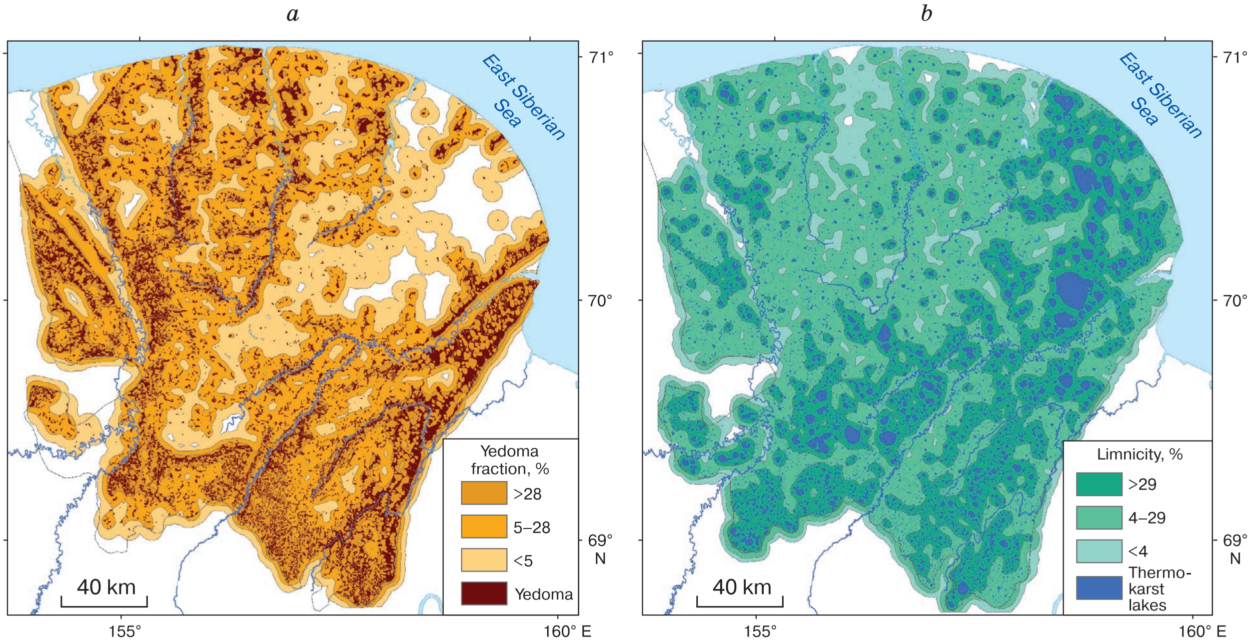

Fig. 3. Maps of yedoma fraction (*a*) and limnicity (*b*).

The limnicity-related density grid includes the following classes: 0–4, 4–29 and greater than 29 % (Fig. 3, *b*). The intersection of density grids for yedoma uplands and lakes of these classes prompted nine types of the yedoma fraction to thermokarst lake fraction ratios (Table 1).

Based on the areal extent of the dominant class or a combination of classes, there have been established eight types of relief. The analysis of the relief types distribution was compared with DEM and with the map of average surfaces slopes derived from DEM. The map of the relief dissection depths was constructed on the basis of difference of absolute elevations of the yedoma surface and the heights of thermokarst lakes water levels and alases bottoms, with the data obtained from the topographic map at 1:200 000 scale.

The pre-processing of the satellite imagery and SAM classification for deriving the lake areas were performed with the ENVI 4.8 software. Mapping the Quaternary deposits distribution area, construction of the yedoma fraction and limnicity map, and subsequent layer overlapping operations were done using the ArcGIS 9.3 software.

Table 1. **Classes resulted from the intersection of density grids for yedomas and thermokarst lakes (Fig. 5)**

Yedoma fraction	Limnicity		
	High (>29 %)	Medium (4–29 %)	Low (<4 %)
High (>28 %)			
Medium (5–28 %)			
Low (<5 %)			

Distribution of Quaternary deposits in the Kolyma lowland tundra zone

A map of Quaternary deposits areas in the tundra zone of the Kolyma lowland was compiled using the Landsat satellite imagery (Fig. 4). It has been established that the late Pleistocene yedoma uplands are preserved only on 16 % of the territory, whereas alases cover 72 % (Table 2, Fig. 4, *a*). The comparison of the Quaternary deposits area allocated by the authors on the basis of the satellite imagery interpretation, and the data from the 1:1 000 000 geological map has revealed the 2.5-times overestimation of the IC deposits extent area on the 1:1 000 000 scale (Table 2, Fig. 4, *a*).

In other regions of the coastal lowlands of Yakutia, the IC deposits cover 15 % on the Buor-Khaya Peninsula [*Günther et al., 2013*], and 42 % on the Shirokostan Peninsula [*Tarasenko et al., 2013*] within the Yana-Indigirka lowland, 22 % on the Lena-Anabar lowland [*Grosse et al., 2006*], about 50 % on the Bykovsky Peninsula [*Grosse et al., 2005*], and 34 % in the Lena River delta region [*Morgenstern et al., 2011*], relative to the total area. Therefore, most of the IC deposits within the Yakutian coastal lowlands appear to be greatly reworked by thermokarst.

The limnicity in the area of the Kolyma lowland tundra zone averages 13.5 %. In other regions within the IC deposits distribution, the lakes occupy: 14.4 %

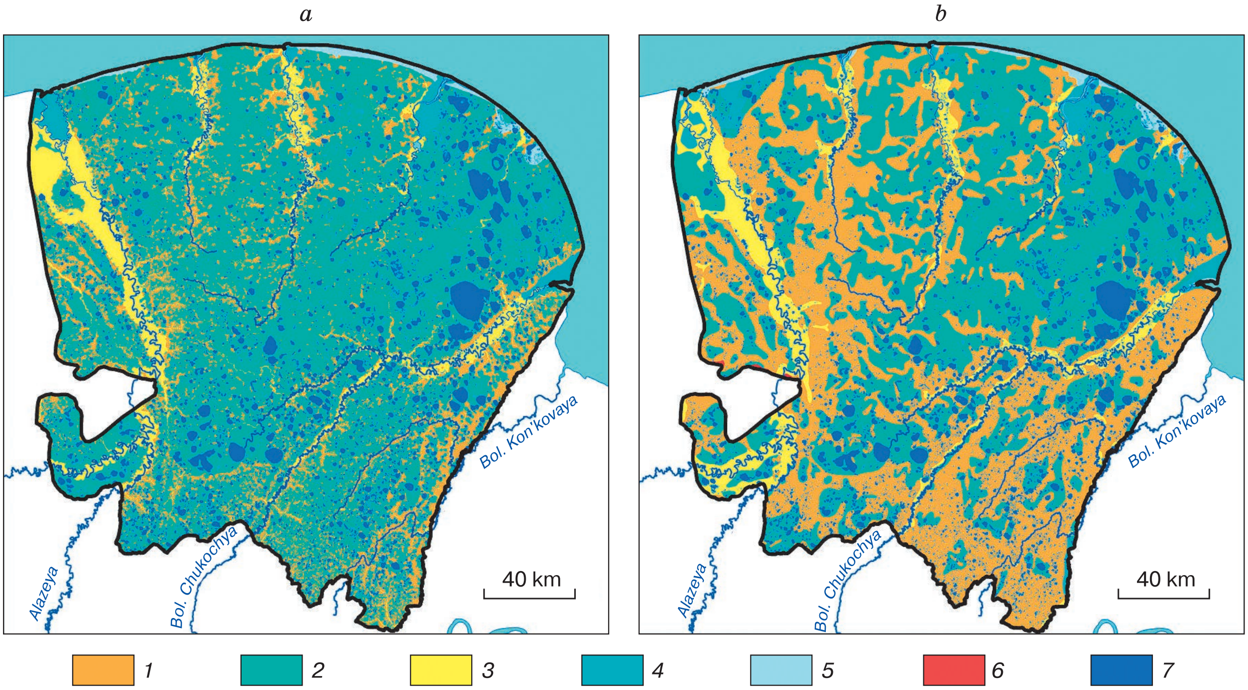

Fig. 4. Comparison of the identified Quaternary deposits using Landsat images (*a*) and the information from the 1:1 000 000 map of Quaternary deposits (*b*) [*State… Map…, 2000a*].

1 – ice complex deposits; *2* – alas complex deposits; *3* – alluvial deposits; *4* – alluvial-marine deposits; *5* – marine deposits; *6* – outcrops of bedrocks; *7* – thermokarst lakes.

of the entire area of Bykovsky Peninsula [*Grosse et al., 2005*], 9–15 % in the northern part of the Anabar-Olenek interfluve area [*Romanenko, 1997; Grosse et al., 2006*], and 13.3 % in the Lena Delta region [*Morgenstern et al., 2011*]. The vast majority of lakes have been drained by now, and lakes are found mostly in the previously formed alases. Close values of limnicity in different regions of the Yakutian coastal lowlands indicate similarity in the conditions, which affected the hydrologic system development.

Analysis of the IC deposits and hydrologic system distribution patterns revealed that the most significant area of yedoma uplands preserved in the valleys of large rivers and their tributaries, and in the areas adjacent to the escarps with a 20–30 m difference in the relief elevations (Fig. 4, *a*). These are the lower reaches of the Alazeya rv., the Alazeya and Bolshaya Chukochya rv. intefluve area in their middle reaches, the right bank of the lower reaches of Bolshaya Chukochya and interfluve area of the Malaya Kon'kovaya and Bolshaya Kon'kovaya rivers. The greatest degree of thermokarst reworking of the IC deposits is characteristic of the lower geomorphological levels of the interfluves of the Bolshaya Chukochya, Galgavaam and Bolshaya Kuropatochya, as well as the Bolshaya Chukochya and Alazeya in their middle stream (Fig. 4, *a*). Most of these areas are occupied by the coalesced thermokarst-lake depressions with sporadic remnants of yedoma surface.

Table 2. **Areas of Quaternary deposits allocated using Landsat satellite imagery and the Quaternary deposits map at a scale of 1:1 000 000**

Type of Quaternary deposits	Area of deposits according to Landsat data		Area of deposits according to the 1:1 000 000 map	
	km^2	%	km^2	%
Ice Complex	6923	16	17 976	40
Alas Complex	32 175	72	21 138	48
Alluvial	4151	9	3742	8
Alluvial-marine	680	2	1089	2
Marine	476	1	431	1
Outcrops of bedrocks	0	0	32	0
Total area	44 406	100	44 406	100

Characterization of relief and thermokarst development patterns in the Holocene

We established eight types of relief based on the yedoma fraction to limnicity ratio (Fig. 5, Table 3). Alases are dominant in all types but their area and the degree of lake fraction differ.

High limnicity is common in southern part of the area, which roughly coincides with the boundaries of the subzone of southern tundra. Areas with high yedoma fraction (over 28 %) are indicative of high or medium limnicity (more than 29 and 4–29 %, respectively). Such areas in the lower Alazeya and Bol. Chukochya river basins are characterized by terracing shores of lake depressions, and by the presence of thermokarst mounds (baydzherakhs) on the yedoma shores of most lakes. This suggests a gradual displacement of the lakes and is attributed to the area experiencing tectonic uplift during the Holocene [*Gerasimov, 1970*].

Areas with high to medium yedoma fraction (over 28 and 5–28 %, respectively) occupy a greater half of the Kolyma lowland tundra. Also significant area is covered by alas plains where yedoma uplands occupy less than 5 %, whereas lakes – more than 29 % of the total area (Fig. 5). The alas plains with low yedoma fraction and low to medium limnicity were allocated. The drained lakes on such sites may indicate the tectonic uplift in these areas, which took place simultaneously with the diminishing erosion base level after the Early Holocene transgression [*State... Map..., 2000a,b*].

The regions with low yedoma fraction are typical for the areas with low absolute elevations, but also can exist in the higher geomorphological levels, for example in the upper reaches of the Malaya Kuropatochya and Bolshaya Kuropatochya rivers (Fig. 6, *a*). *T.N. Kaplina et al.* [*1986*] have concluded that the best preserved yedoma uplands correpond to the elevated sites. However, as it follows from the compared IC distribution patterns and DEM results, that it is not always the case.

The comparison of relief types distribution map and DEM-derived average surface slopes map revealed that the degree of the yedoma uplands preservation correlates well with the value of the mean slope angles of the surface. Thus, areas with great yedoma fraction are characterized by the highest average slopes values of 4–6° (Fig. 6, *b*), which is consistent with elevated areas, including those currently tectonically active [*State... Map..., 2000b*].

Given that the depth of the relief dissection is largely controlled by the IC deposits thickness [*Kaplina et al., 1986*], this indicator can be used to measure modern IC deposits thickness, taking into account that thickness of the preserved IC deposits occurring below the alas complex is 2 m [*Shmelev et al., 2013*]. The average depth of the relief dissection, according to the constructed map, reaches 20–25 m, which is consistent with the literature data [*Arkhan-*

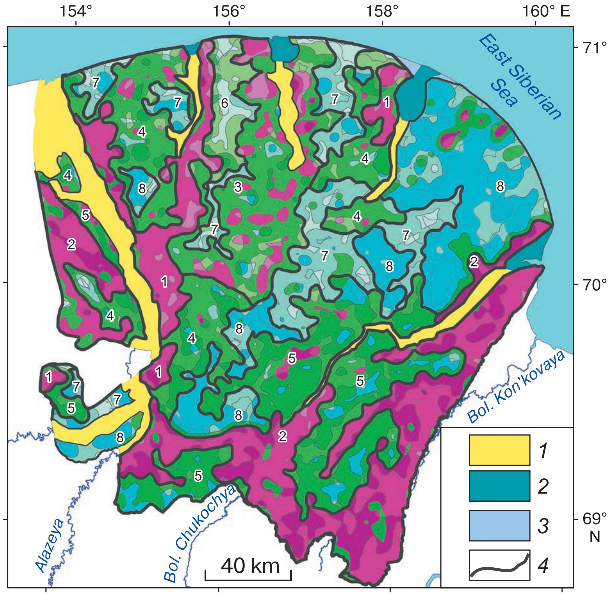

Fig. 5. Relief types based on yedoma to lake areas ratio as derived from the intersection of yedomas and lakes density plots (cf. Table 1, Fig. 3):

1 – high yedoma fraction, medium limnicity; 2 – a combination of high yedoma fraction and medium limnicity; 3 – a combination of high yedoma fraction and limnicity, and medium yedoma fraction and limnicity; 4 – medium yedoma fraction, medium limnicity; 5 – medium yedoma fraction, high limnicity; 6 – medium and low yedoma fraction, low limnicity; 7 – low yedoma fraction, medium limnicity; 8 – low yedoma fraction, high limnicity. Boundaries for river valleys (*1*), deltas (*2*) and marshes (*3*) taken from the 1:1 000 000 map of Quaternary deposits [*State... Map..., 2000a*]; *4* – boundaries of relief types.

Table 3. **Characterization of relief types on the basis of predominant combination of yedoma fraction and limnicity**

No.	Type of relief	Specific area, %	Absolute elevation, m	Average surface slopes, degrees	Relief dissection depths, m	Yedoma morphotype
1	High yedoma fraction, medium limnicity	7	20–50	5–6	20–40	Massive-island, massive
2	High yedoma fraction, high to medium limnicity	20	30–60	5–6	20–50	Massive, hilly-outlier
3	A combination of sites with high yedoma fraction and limnicity, and medium yedoma fraction and limnicity	9	10–30	3–5	20–40	Sparce massive outlier
4	Medium yedoma fraction, medium limnicity	7	10–35	2–3	10–30	Sparse massive-island, island
5	Medium yedoma fraction, high limnicity	19	20–50	2–4	10–40	Island
6	Medium to low yedoma fraction, low limnicity	2	10–30	0–2	10–20	»
7	Low yedoma fraction, medium limnicity	11	10–25	1–2	10–30	»
8	Low yedoma fraction, high limnicity	17	0–20	0–1	10–40	»

gelov et al., 1979; Kaplina et al., 1981]. *T.N. Kaplina et al.* [*1986*] have highlighted that the depths of yedoma uplands dissection by alases tend to become shallower with decreasing a.s.l. marks, which they attribute to the IC thinning as the surface elevation decreases. However, the IC deposits spatial distribution pattern confirms the point of view about their "covering" character [*Tomirdiaro, 1980*].

Thus, areas with a maximum depth dissection of the relief are confined to depressions where the yedoma uplands are preserved as remnants (Fig. 6, *a*, *c*), whereas the depths of thermokarst–induced dissection decreases in more elevated areas, which indicates that the IC deposits thickness was originally lower there. The IC deposits almost completely thawed in the interfluve area between the Galgavaam and Bol-

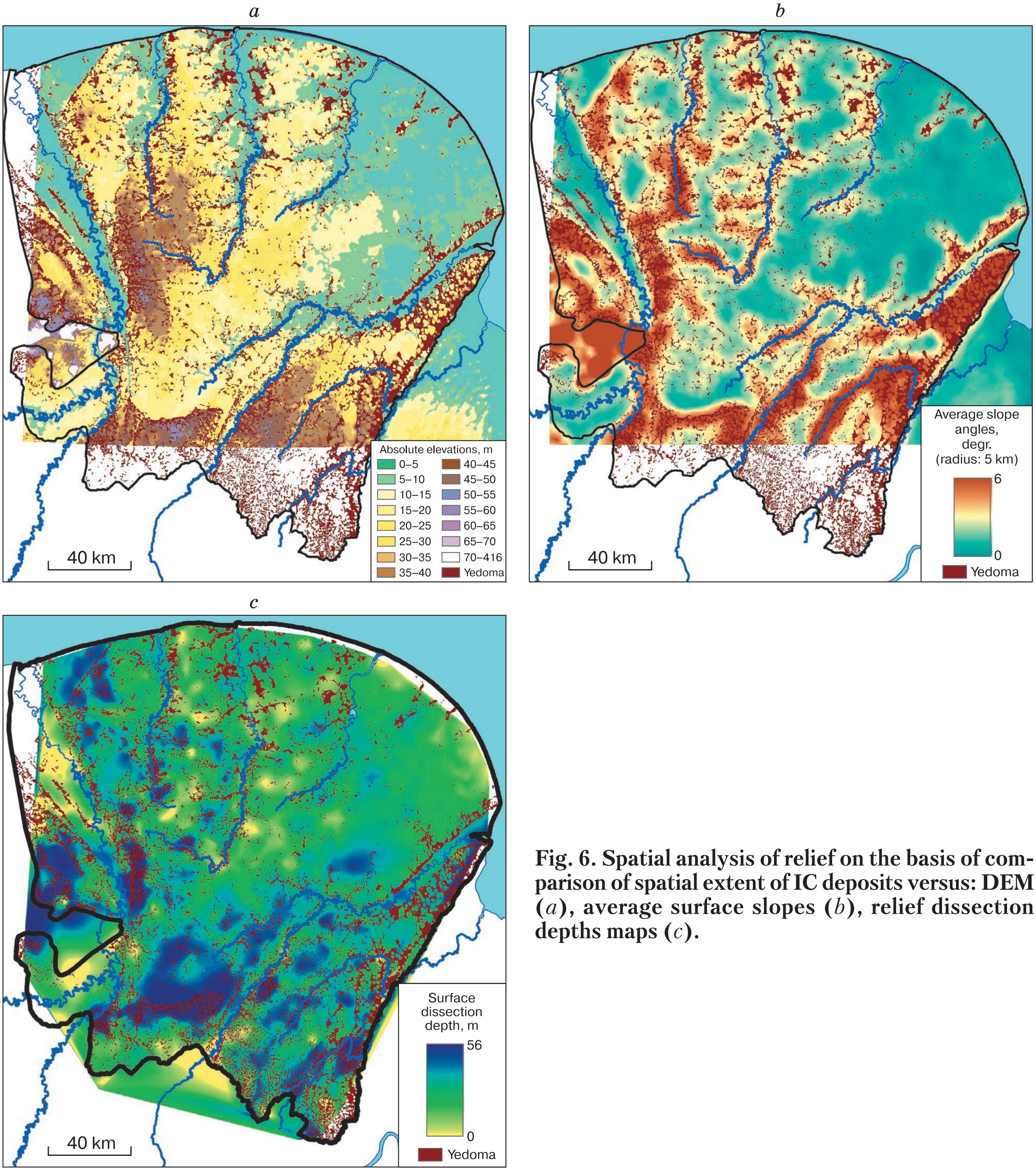

Fig. 6. Spatial analysis of relief on the basis of comparison of spatial extent of IC deposits versus: DEM (*a*), average surface slopes (*b*), relief dissection depths maps (*c*).

shaya Chukochya and the relief appears dissected slightly there, to a depth of 0–15 m.

The morphology of yedoma surface is an important indicator of the relief development features in the Holocene. In this work, five morphological types of yedoma uplands have been identified (Fig. 7). Areas with high yedoma fraction encompass the following types: massive, massive-island and hilly-outlier. The massive and massive-island types of yedoma uplands are characteristic for areas with the highest values of average surface slopes (4–6°) and correspond to the area currently experiencing the tectonic uplift (Fig. 8).

The hilly–oulier morphotype is commonly spread in the southern tundra zone, the same yedoma morphotype is typical for the adjacent taiga zone. In the early Holocene (ca. 9.5–8.0 ka BP), the tree line advanced as far as the contemporary coastline [*Lozhkin et al., 1975; Kaplina, 2009*], whereas in the middle to late Holocene it may have existed within the areas of the modern southern tundra subzone. Therefore, the boundaries of the hilly-outliers morphotype may indicate with high probability the position of the northernmost limit of the tree line in the middle and late Holocene (Fig. 8). The areas with medium yedoma fraction are characterized by sparse massive-island yedoma morphotype, which corresponds to the areas with the average values of surface slopes (2–4°). The island yedoma morphotype is common on flat areas with low yedoma fraction and medium to high limnicity.

Therefore, the identified relief types of the yedoma fraction and limnicity ratio are characterized by different absolute elevation heights, average surface slopes, depths of the relief dissection, and yedoma uplands morphotypes (Table 3), thus representing the relief formation pattern in the Holocene.

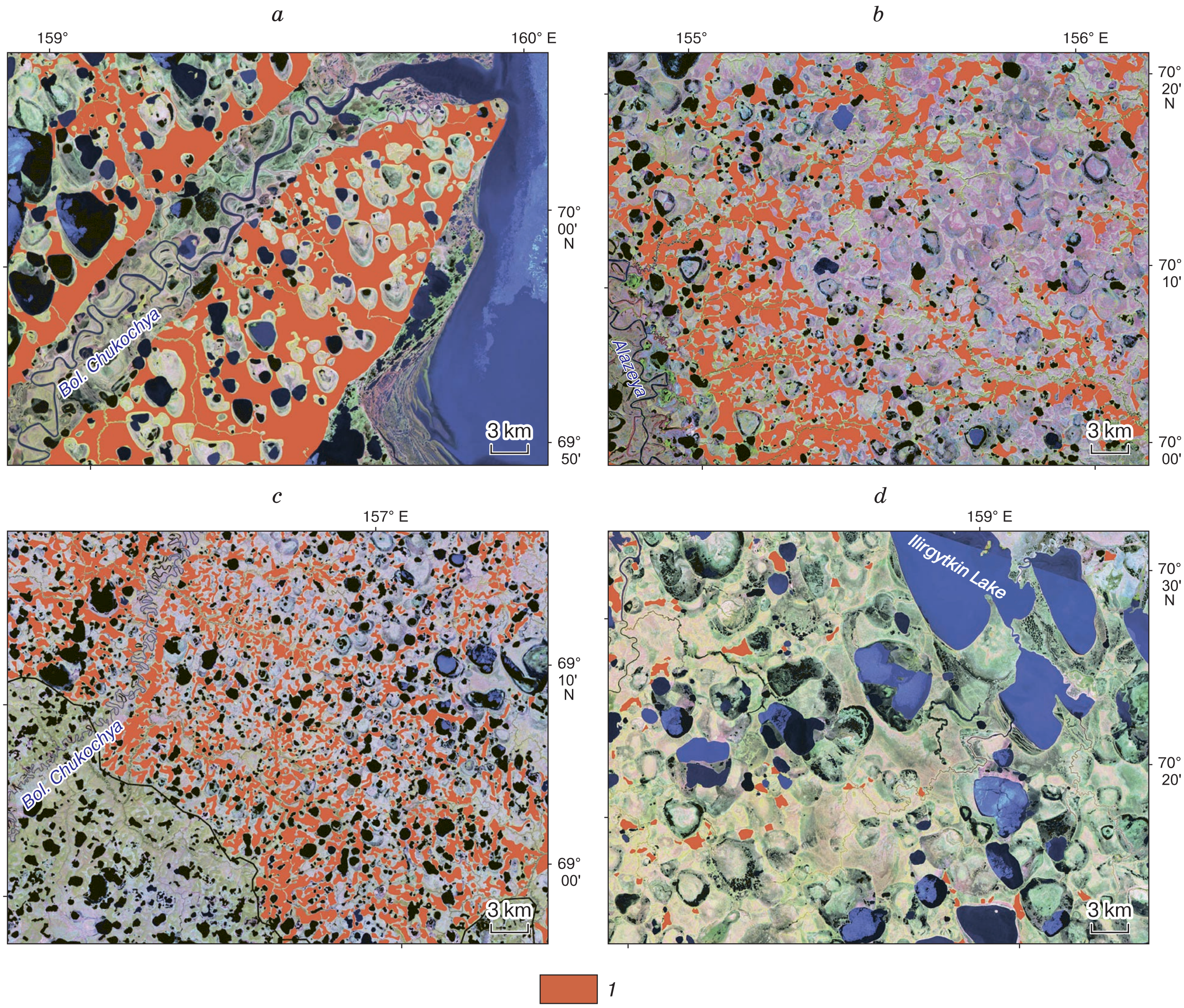

Fig. 7. Morphological types of yedomas:

a – massive, *b* – massive-island and sparse massive-island, *c* – hilly-outlier, *d* – island. *1* – yedoma surface.

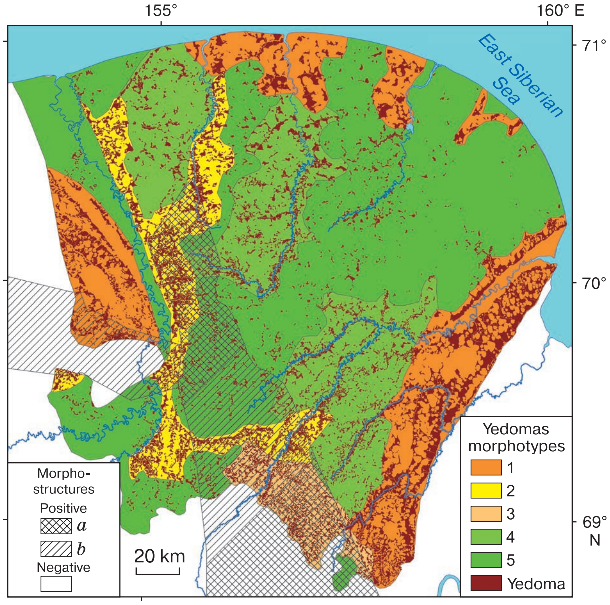

Fig. 8. Distribution of morphological types of yedomas and morphostructures (landforms) [*State… Map…, 2000b*].

Morphotypes of yedomas: 1 – massive, 2 – massive-island, 3 – hilly-outlier, 4 – sparse massive-island, 5 – island. Morphostructures: positive (*a* – presently experiencing active uplifting, *b* – retarded) and negative.

CONCLUSIONS

The use of the Landsat satellite imagery for mapping Quaternary deposits in the areas of the IC occurrence and novel technique developed by the authors on the basis of GIS technologies allowed detailed estimations of area extents for different types of Quaternary deposits and a comprehensive terrain surface analysis.

For the first time, a Quaternary deposits map was constructed for the tundra zone of the Kolyma lowland using the Landsat satellite imagery. It was established that yedoma uplands formed by the IC deposits were greatly reworked by thermokarst and thermoerosion in the Holocene and preserved only within 16 % of the territory, with alases covering 72 %. Comparison with the data derived from the 1:1 000 000 geological map has shown that the area extent of the IC deposits is overestimated by 2.5 times on the map. It has been revealed that the largest sites with the preserved yedoma are attributed to areas presently experiencing tectonic uplifting and characterized by the following least favorable conditions for thermokarst processes: the highest values of average surface slopes (4–6°), relative excess in absolute elevations, and a developed hydrologic system.

Average limnicity in the Kolyma tundra zone is found to be 13.5 %. Most lakes formed in early Holocene and exist in already formed alases. By now the larger part of them has been drained. Close values for limnicity in different regions on the coastal lowlands of Yakutia attest to the similar conditions that control the development of hydrologic system.

The identified eight types of the relief based on the ratio between yedoma fraction and limnicity reflect characteristic features of the relief development in the Holocene, with each type provided a detailed characterization. Alases appear dominant in all the types of relief, however, indicators of their specific areas and the degree of limnicity differ. Alas plains with low lake fraction and low yedoma fraction indicate that the tectonic uplift event was taking place against the background of reducing erosion base after the Early Holocene transgression. Given that low yedoma fraction and high limnicity areas which are typical for sites with low absolute elevation heights were encountered at higher geomorphological levels as well, this goes against the opinion that the best preserved yedoma uplands correspond to the most elevated sites [*Kaplina et al., 1986*].

The average depths of the relief dissection are found to be 20–25 m. The areas with maximum depths of relief dissection are confined to the depressions where yedoma uplands are preserved as the remnants. In the areas marked by higher elevation heights, the depth of relief dissection tends to be shallower, implying that the IC deposits thickness may have been originally lower. Thus, the inference made by *T.N. Kaplina et al.* [*1986*] about the decreasing trend in depths of yedoma surfaces dissection by alases with decreasing absolute elevation marks is not always true.

The following five morphological types of yedoma uplands have been established: the massive and massive-island correspond to areas with high average surface slope and areas presently experiencing tectonical uplift; the hilly-outliers morphotype commonly spread in the south of the study area, are likely to indicate the position of the treeline in the middle and late Holocene; the island yedoma morphotype corresponds to sites with the lowest geomorphological levels.

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