Predictive Mapping of Glacial and Fluvioglacial Landforms in the Nadym River Basin (North of West Siberia) With TanDEM-X DEM

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Abstract—**Remote mapping of glacier and fluvioglacial landforms has been extensively used globally. It is supported by a range of mid-scale spatial datasets (space imaging and digital terrain models) available to the research community. Such studies are very important for the northern regions of West Siberia since the existence and scale of the Pleistocene glaciation there is still debated. Here, we use digital terrain models, multispectral images, and historical survey materials for the Nadym river basin to reveal sustainable local signs of such landforms as kames, kame (terminal) moraines, moraine and kame hilly areas, linear ridges, ancient discharge valleys, eskers, and wind-scoured basins at the fluvioglacial deposits. The mapping of the identified features showed an abundance and a great variety of glacial and fluvioglacial landforms on most of the area under consideration. Verification against the historical data confirmed the validity of identifying kames, terminal moraines, and kame hilly areas with their geology typical for the region. The results point to the primary contribution of the Pleistocene glaciation to the formation of medium and large geomorphological landforms. The proposed mid-scale geomorphological mapping strategy is also applicable to other regions of the northern part of West Siberia.**

Index Terms—**Digital terrain models, glacial landforms, glaciation, remote sensing (RS), West Siberia.**

I. Introduction

ASSUMPTIONS about the signs of large glaciations in the northern part of the West Siberian Plain appeared in the first half of the 20th century. [1]–[3]. Nowadays it is assumed that most of this territory did not have any glaciation in the Sartanian (MIS2) and Zyrian (MIS4) ages [4], [5]. However, the ideas about the abundance of landforms associated with the Taz (MIS6) and Samarovo (MIS8) glaciations are still valid [6], [7]. Some researchers reject the existence of glaciations and associate the landform formation to the north of the Siberian Uvaly with the Pleistocene marine transgressions only [8].

The history of the Nadym River studies clearly shows that a distinct division into "glacialists" and "marinists" occurred as early as the 1950s as large-scale surveys of the territory began [9]–[12]. The geology maps and geotechnical surveys also follow these different approaches. Quite often, drastically different maps coexist for the same territory [7], [13]–[16]. It results in considerable difficulties with geotechnical, construction activities, and applied soil, geobotanical, and geocryological research.

One of the research-backed and most widely used approaches to identification and mapping of glacial and aqueoglacial landform is aerial and space imaging [7]. The existing approaches need to be upgraded as new digital remote sensing (RS) acquisition and digital terrain/elevation models (DEM/DTM) are introduced. To date, significant international experience has been gained using advanced RS methods, including lidar, radar, and multispectral approaches for fluvioglacial landform mapping [17]–[22].

For the north of West Siberia, despite some overview studies [23], [24], most geomorphological maps are based on aerial surveys taken in the 1950–1980s [9]–[14]. It is difficult to verify such maps since the initial aerial survey materials are either confidential or lost. It should also be noted that high-res DTMs (ArcticDEM, AW3D, AsterGDEM2, and TanDEM-X DEM) of the artctic territories became available only 5–7 years ago. With the availability of such DTMs and open access to RS data (e.g., Landsat-8, Sentinel-2) the existing approaches to geomorphological interpretation [25] should be adapted to match the conditions of the West Siberia north. The terrain should be re-surveyed.

The article objective is predictive mapping of the glacial and fluvioglacial landforms in the Nadym river basin with the publicly available multispectral mid- and high-resolution RS/DTM data by identifying sustainable and verifiable remotely sensed morphological features of the glaciations in the north of West Siberia.

A distinct feature of this study is using the TanDEM-X DEM. The model based on radar surveying better represents the terrain irregularities in the context of sparse northern taiga vegetation. It is significant since the glacial and aqueoglacial landforms associated with the Taz glaciation (MIS6) are poorly preserved and strongly eroded for more than 120 000 years. Both visual interpretation (still a valuable mapping tool) and morphometric analysis tools are used for interpreting the TanDEM-X DEM.

Manuscript received June 30, 2020; revised March 10, 2021; accepted April 21, 2021. Date of publication May 4, 2021; date of current version June 9, 2021. This work was supported by RFBR and the Yamal-Nenets Autonomous District under Project 19-45-890008.

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Digital Object Identifier 10.1109/JSTARS.2021.3077474

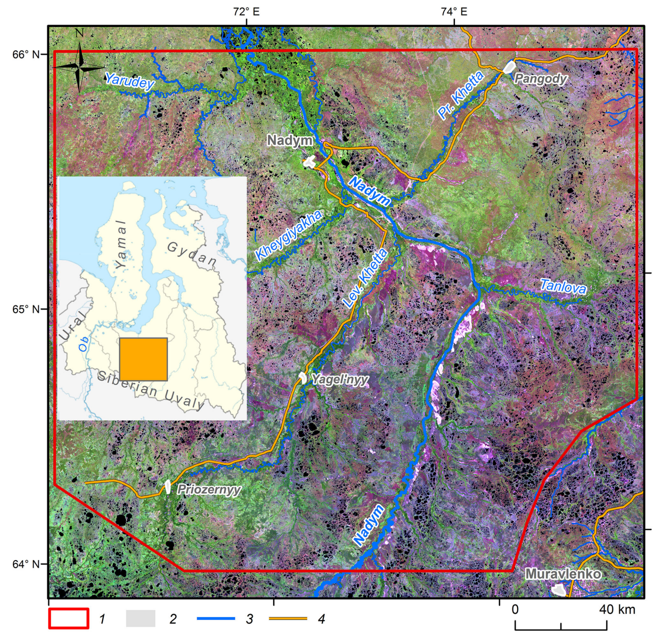

Fig. 1. Overview map. 1: Region of interest. 2: Settlements. 3: Rivers. 4: Roads. Background image: Landsat 7, 2000.

II. Territory and Research Data

We studied the Nadym river basin (lower and middle course) and all its major inflowing streams Kheigiyaha, Yarudei, Right and Left Khetta rivers) (see Fig. 1.) The area is more or less accessible since there are large rivers and roads. The area hosts large oil&gas fields (Medvezhie, Yamsoveiskoe, and Yarudeiskoe), many main pipelines (Nadym-Punga, Urengoi-Pomary-Uzhgorod, etc.), the Northern Latitudinal Railway is under construction to connect Salekhard–Nadym–Novy Urengoy.

At the Kheigiyaha (Longyugan) mouth, there is a permanent research station run by Tyumen River University. Since 2016 the University has become a hub for survey expeditions studying the most prominent geomorphological areas with various landforms. The detailed survey results are then verified at the hub.

The site is at the boundary between northern taiga and forest-tundra natural area (Nadym, Poluy, and Nadym-Pur provinces.) The terrain features include flat-lying lake and bog clusters with frost hummocks, valleys and benches, and forest uplands with a dense erosional pattern. The region features all the geomorphological levels conventionally defined in the north of West Siberia [26], [27]. The absolute elevations are in the range of 10 m (Nadym River waterline at its lower course) to 120–130 m a.s.l. (some hills and ridges in the eastern part of the Poluy upland.

The key data selection criteria for the remote geomorphological analysis were their high accuracy and raw data availability for the entire Nadym river basin. The primary DTM was the TanDEM-X DEM (DLR). The RS multispectral data provider is Sentinel-2 (ESA). The TanDEM-X DEM is a product of global interferometry sensing by two German radar satellites: TerraSAR-X and TanDEM-X. The optimized concurrent observation technology enabled the high resolution (∼12 m) and accuracy (relative: 2 m and absolute: 4 m) of the resulting DTM [28]. For most of the region under investigation, we obtained a “core” grade product with 12 and 26 m resolution through a research project by the German Aerospace Center (DLR). The Sentinel-2 data spectral range expands from light blue to near IR with 10 to 60 m resolution (swath width: 290 km) [29].

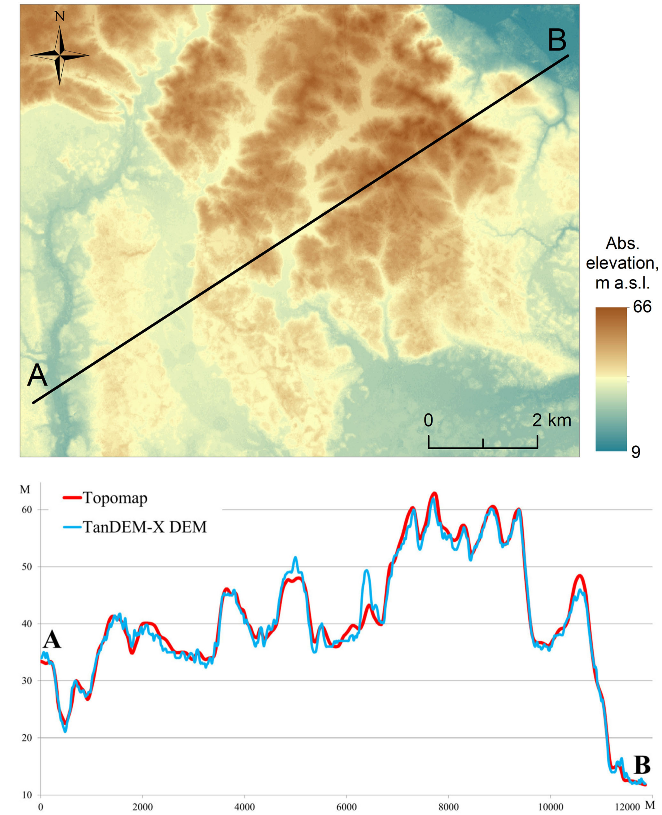

Fig. 2. Elevation profiles of the topographic map (1:25000 scale) and the TanDEM-X DEM.

To assess the TanDEM-X DEM suitability for remote terrain mapping of the studied region with its relatively low elevation differences and forest areas, the elevation profiles for a test area covering 10 to 65 m elevation ranges and with over 90% covered by forest (the dissected plain to the north off the Kheigiyaha River) were compared (see Fig. 2.) The reference elevations were taken from a 1:25000 scale topographic map (1 cm on the map equals 250 m on the ground) with a 2.5 m depression contour spacing.

The comparison showed that the absolute elevations provided by the TanDEM-X DEM are about 16 m lower than the elevations indicated relative to the Baltic elevation system datum. As the mismatch of the two height systems was corrected, the standard deviation of the elevations reported by TanDEM-X and a 1:25 000 scale topographic map was 1.38 m, and the correlation of the elevations was 0.993. The min outlying elevation value is 3.7 m and the max one is 7.7 m. The residual sum of squares is 33.6. If we compare the profiles visually, we see that the TanDEM-X DEM correctly represents the terrain irregularities and the elevation differences except for the uplands up to 8 m at the dense forest patches and depressions to 3–4 m in the valleys and shallows. So, the TanDEM-X DEM provides valid elevations for the depression contours indicated on a 1:25000 scale topographic map and is suitable for mid-scale geomorphological mapping of the northern taiga area in West Siberia.

The raw data preprocessing comprised of the following.

1) Composing a six-channel (visible, near and mid-IR channels) Sentinel-2 mosaic (10 m resolution) using the cloudless swaths taken on June 18 and July 7, 2016.
2) Composing a single 26 m resolution mosaic from the available TanDEM-X DEM tiles and correcting the systematic error relative to the Baltic elevation system.
3) Converting all the spatial data to a unified coordinate system (UTM, zone 42N).

The Nadym river basin areas presented in the National Geology Institute and the National Oil Geology Survey Institute 1953–1957 geology and geomorphology survey reports were used as references [9]–[12]. The reports contain detailed features of the landforms discovered through the field surveys including their geology and distribution (linked to the waypoints, map sheets, and major natural features.) The reports also include detailed geological and geomorphological maps, survey paths, and aerial some photographs as semitransparent pages with various types of the glacial and fluvioglacial landforms indicated. Each map sheet and an aerial photograph was digitized (converted to a digital photo.) The raster images were enhanced (gamma, contrast correction, sharpness enhancement). Then the images were referenced to the coordinate system and the Sentinel-2 data.

Surface topology maps were used as references. Georeferenced raster maps were downloaded from the National Geology Institute map portal.[1] The other map was obtained through an online service.[2]

All the RS data were compiled into a single GIS project in ArcGIS. The maps were analyzed manually since a formal description of the existing landforms was quite challenging. In most cases, expert evaluation although time-consuming provides better results as compared to morphometry and automated analysis [25], [30]. For further enhancement, the images were color shaded (Sun elevation: 45° and azimuth: 45°) and the histogram was adaptively adjusted to match the visible range.

III. Classification of Remotely Identified Glacial and Fluvioglacial Landform Features

The glacial and fluvioglacial landforms of the Nadym River basin were categorized in 1953–1957 with a geological and geomorphological survey that included both field and remote (aerial photography) data [9]–[12]. Kame hills and kame hilly areas, terminal moraines and esker-like linear ridges, drainage valleys, and wind-scoured basins associated with sandur plains. The morphology typical for drumlins and drumlinoids was not found. Matching old reports, maps, and aerial photos with the contemporary RS and DSM data revealed the most prominent features of the glacial and fluvioglacial terrain in the studied territory. They are described as follows.

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[2]Online. [Available]: https://vsegei.ru/ru/info/quaternary-2500/

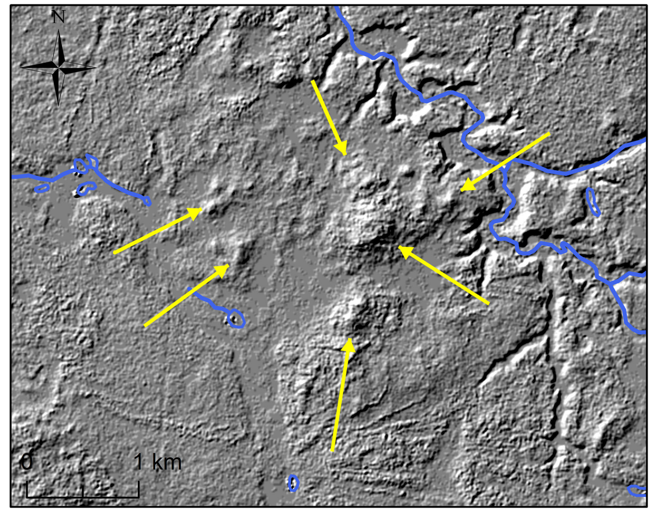

Fig. 3. Kame hills (indicated by arrows), right-bank tributary of the Bolshoi Khulmyogan river, Nadym and Poluy watershed (TanDEM-X DEM, 2018).

1) The survey identified typical kames at the watershed of the Kheigiyaha and Left Khetta, Kheigiyaha and Poluy, Tanlova, and right Khetta rivers, and others [9]–[12]. In terms of morphology, they are irregularly or even chaotically located hills and ridges with their relative elevation not exceeding 10 to 20 m (see Fig. 3.) The hills are plateau-shaped, the slopes are gentle and arching. The slope steepness varies. The hills and ridges are distinctive in the DSM against the flatten territory. They are often separated by arheic kettles and shallows. The hills are on the highest parts of the watersheds and are often combined into clusters or even bent chains running from NE to SW or E to W. On the multispectral images, the highest hill areas have sparse vegetation. Note that the large frost mounds (also turf-mineral polygenic mounds) have similar features that are also found in the swamped watersheds. The key differentiator between the kames and the frost mounds is that the mounds are associated with drained lakes or low river terraces; in most cases, their boundaries are distinctively shown on the DSM. Besides, the frost mounds are isolated and are not combined into chains or ridges.
2) The moraine and kame hilly areas are local uplands of eroded and poorly preserved glacial accumulative formations (kame hills and ridges) [11]. They are also associated with the watersheds and high terraces, have rather sustainable boundaries indicated on the DSM, and are distinctive on the flat lacustrine-alluvial plain due to the relative elevation difference and strong vertical and horizontal breakdown. Individual kames and kame moraines in various states of preservation and manifestation can also be found there. A distinct feature of such hill areas in the Right Khetta and Kheigiyaha basins is small (up to 8–10 m high and up to 30–40 m in diameter) “stone hillocks” (locally used name) or hills. As a result of deflation, gravel and various boulders up to 0.5–0.6 m are accumulated on top of such hills. The hill area boundaries are poorly expressed in the multispectral images.

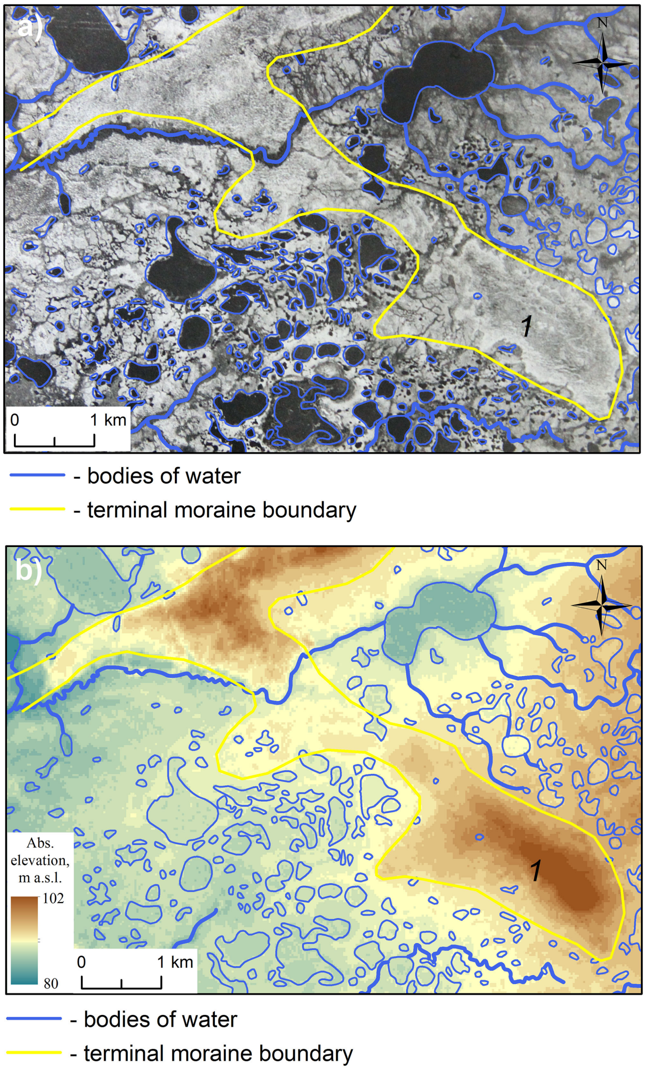

Fig. 4. Terminal (kame) moraine (1), headwater of the right tributary of the Kharayakha River, watershed of the Nadym and Pur rivers. (a). Aerial photography, 1953. (b). TanDEM-X DEM, 2016.

3) The survey identified terminal (kame) moraines in the upper headwaters of the Nadym and Left Khetta rivers [see Fig. 4(a)] [10], [11]. They are also mostly associated with watersheds and are narrow, with winding elevations (relative elevation up to 5–7 m, sometimes to 10 m.) The terminal moraines may have different quality and range from high linear uplands with steep straight slopes to subtle ridges extending to 10–12 km. Since the morphology is different, DSM with different resolutions is to be used to identify the terminal moraines. High resolution (2–10 m) is better for identifying small local marginal moraine formations, while mid-resolution (25 to 30 m) are better for larger, poorly preserved landforms [see Fig. 4(b)] The key features are the length and orientation: the moraine 2-D pattern is often a regular interconnected structure reflecting the glaciation extent and the stages of its degradation. The moraine ridges with pine and lichenaceous sparse forest on the multispectral images often mark the natural boundaries of the large forests and bogs. We can note that in the mid-course of the Nadym river the terminal moraines are restricted. Mosts of the marginal formations are to the south, in the center of the Siberian Uvaly [14], [31].
4) One of the most prominent landforms in glaciation areas is linear ridges. In this case, the surveys identified parallel linear ridges often accompanied by freeze-thaw processes and not connected to the present hydrographic network [9]. They are easy to identify on the DSM and the multispectral images. As opposed to the terminal moraine ridges, the linear ridges are smaller and shorter while their direction is more pronounced (almost no bends.) For instance, on the left bank of the Yangyu River such ridges 1–2 km wide are 18–20 km long in the longitudinal direction. The watershed of the Kheigiyaha and Left Khetta rivers the linear ridges are NE oriented and consist of two areas 0.8 and 1.5 km wide each [10]. When ridges are poorly expressed, an additional indicator is a linear structure of the multispectral image caused by the similar orientation of the river valleys, chains of small lakes, forest and bog boundaries. We can propose that the ridges are formed through glaciation and erosion similar to the formation of drumlinoids while the classical drumlins in the area under consideration are not presented in the records and are not identified in contemporary RS data.
5) The eskers are linear uphill areas 2 to 5 m high and 3 to 5 km long with sparse pine forest surrounded by swampy plains. The survey identified these in the watershed of the Kheigiyaha and Poluy rivers [10]. The location of the eskers is not associated with the existing river network, but in some cases, the endpoints can be associated with Moraine and kame hill areas. Still, the eskers are often continued as the remains of the ancient discharge valleys. The multispectral RS images are the major data source to identify eskers. A combination with near and mid-IR channels helps identify the esker areas with space coniferous forests within the lake and swamp clusters, and even more so as the seasons are changed (April and May.) Often the esker surface has some bulges. It points to sandy deposits.
6) The drainage valleys for glacial meltwater with well-preserved slopes and linear chains of lake basins are widely found fluvioglacial landforms in the Nadym river basin, and even more so in its mid-course [11]. The drainage valleys are dozens of kilometers long and often intersect the modern river valleys at right angles so they are easy to identify on the DSM and the satellite imagery. The valley-like depressions are twisted similar to smooth river meanders. Nowadays they are swamped and turned into lakes (see Fig. 5.) Merging and splitting, they form a typical pattern of the hydrographic network. The valleys are often associated with expected drainwater sources mostly located in glacial accumulative formations on the watersheds; with this in mind, the flow direction can be identified in many cases. The valleys often terminate with chains of lakes perfectly visible in satellite images. The linear and arc-shaped valleys in the linear ridge areas alternating with relatively large ridges can be

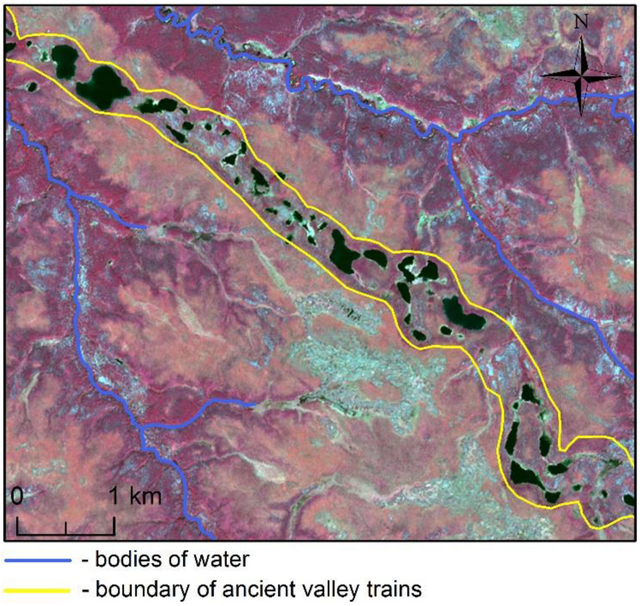

Fig. 5. Ancient valley trains. Interfluve area between the left tributaries of the Khadyta river, the watershed of the right Khetta and Tanlova rivers (Sentinel-2, 2016).

categorized as a separate subtype. As to the individual chains of lake basins, they can be easily identified within the swamped lacustrine-alluvial plains on both the DSM and the multispectral images. The orientation of individual basins and their clusters coincides with the direction of the ancient drainage valleys, with almost no correlation with the present river network. The identification showed that the ancient drainage valleys and the lake basin chains match a logical and cohesive concept of their development.

7) Aeolian sands are a sustainable paragenetic indicator of glacial and fluvioglacial deposits [21], [32], [33]. Within the area under consideration, the aeolian terrain is associated with a range of geomorphological levels: Moraine and kame hilly areas at the watersheds (part of the sandur plains are wind-borne) (see Fig. 6), esker surfaces on the fluvioglacial (lacustrine-alluvial) plain, and the flatten terraces of the major modern rivers partly consisting of outwash fluvioglacial deposits (marking the major glacial spillways) [11], [12], [32]. The wind-scoured sand (deflation basins) mostly do not exceed 1 km^2. Sometimes, as adjacent basins are jointed, large sand areas up to 30 km^2 can be formed. Exposed sand is identified with bright spectral features of sand surfaces highly contrast against dark forest and swamp areas. Sandy surface patterns (parabolic and regular dunes, barchans, accumulative levees, and hills) are also easy to identify on detailed DSMs.

IV. Remote Mapping Results

The above listed RS indicators were used for mapping the glacial and fluvioglacial landforms at a 55 117 km^2 site with its boundaries at the watersheds of the Nadym River and its tributaries. The summarized mapping results are given in Table I and Fig. 7.

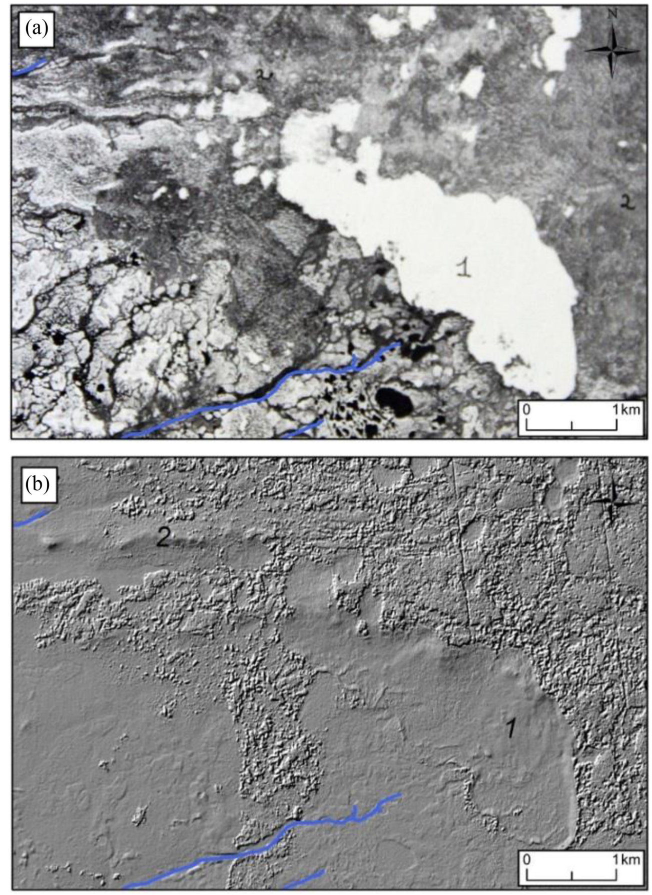

Fig. 6. Aeolian sands (1) and kame ridges (2) near the headwater of the right tributary of the Kharlova River, watershed of the Nadym, and Left Khetta rivers. (a). Aerial photography, 1953. (b). TanDEM-X DEM, 2018.

TABLE I
Remote Mapping of the Glacial and Fluvioglacial Landforms in the Nadym River Basin (Middle and Lower Course)

Landforms	Number of identified features	Total area/length
Kames and kame-like hills	157	-
Moraine kame hilly areas	27	1,552 km^2
Terminal moraines	122	851.3 km
Linear ridges	16	157.2 km
Eskers	20	75.7 km
Valley trains	103	1411.3 km
Chains of lakes	21	169.1 km
Aeolian sands	1,290 (over 1 ha)	230.5 km^2

As the resulting map (see Fig. 7) shows two clear regularities with the distribution of the supposed glacial and fluvioglacial landforms within the area under consideration of the following.

1) All the identified landforms are to the south off the Yarudei and Right Khetta rivers. In the Interfluve area between the Yarudei and Kheigiyaha (Longyugan) only individual landforms are found while in the southern and western parts there is a max variety and density of landforms (watershed between the Tanlova and Right Khetta rivers; left bank of the Nadym River in the middle course);

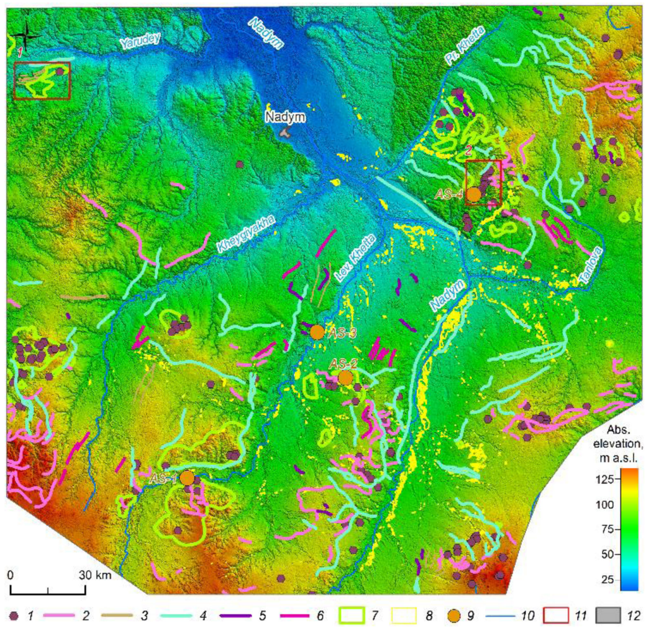

Fig. 7. Identification of the glacial and fluvioglacial landforms in the mid-course of the Nadym River (background image: TanDEM-X DEM, resolution: 26 m). 1. Kames and kame-like hills. 2: Terminal moraines. 3: Linear ridge landforms. 4: Valley trains. 5: Eskers. 6: Lake chains. 7: Moraine and kame hilly areas. 8: Aeolian sands. 9: Quaternary deposit sites available in the records [9], [11], [12]. 10: Water drains. 11: Concentrated ridges and kames (for details refer Fig. 8 and 9). 12: Settlements.

2) All the identified landforms are found at 40 m a.s.l. and up. The landform density is much higher at the watershed sites above 70–75 m a.s.l.

The kame hill distribution is representative of the total landform distribution over elevations. Out of 157 local landforms, 145 (92%) are above 75 m a.s.l., whereas 53 (34%) are identified in a narrow range of 95–104 m a.s.l. Below 75 m a.s.l. there are only individual large landforms poorly differentiated morphologically

The largest moraine and kame hill areas (up to 450 km^2) are identified in the middle course of the Left Khetta and at the watershed of the Tanlova and Right Khetta rivers. They are rather pronounced against the background of lacustrine-boggy plains, have individual kame hills, and a dense erosion network.

The network of long (over 850 km) terminal (kame-like) moraines marking the final positions of the glaciation can be identified. The network extends in various trendings (EW, NW, etc.) It may indicate there was no single direction of the glacier movement. The moraines as mentioned above are mostly associated with the watersheds and are often accompanied by other glacial landforms (kame hills, drainage valleys, etc.) Frequently they are crossed by ancient valley trains. Most probably the kame hill chains at the Tanlova and Right Khetta rivers watershed are erosion remnants of the marginal moraine formation. In terms of morphology, they are in between individual kames and kame moraines.

Other individual landforms are eskers and linear ridges (total length about 190 km.) A possible reason for the poor condition of the eskers is their sand composition vulnerable to rapid erosion and loss of the specific shape. The linear ridge landforms also show obvious signs of erosion (washing-outs, subsidences). It most cases they form a distinctive linear terrain texture. The ridges to the west of the studied region in the Poluy River basin are more pronounced, but their genesis is not clearly defined and is to be investigated further.

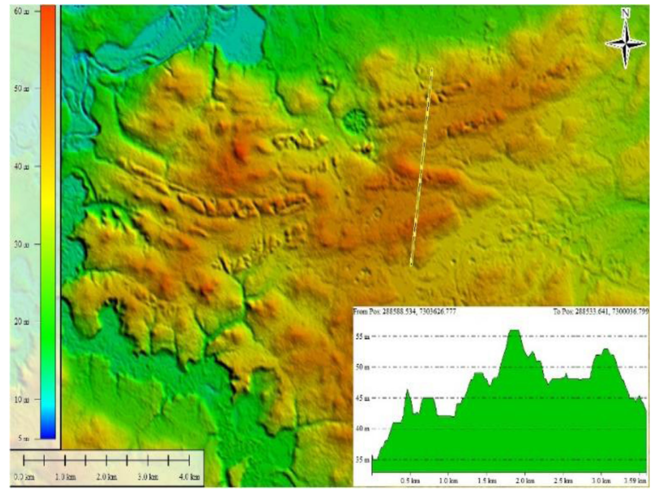

Fig. 8. Example: A site with linear ridges. TanDEM-X DEM, 26 m.

The valley trains and shallows are over 1400 km long. The valleys are well-pronounced in the southern and eastern parts of the region. They virtually do not exist below 40 m a.s.l. There is almost no match between the valley network and the existing water streams that can be located either parallel and close to the ancient valleys or cross them at right angles. The ancient drainage valleys and shallows are often associated with marginal formations. The good condition of the valleys is one of the major indicators showing there was no marine transgression in the middle course of the Nadym River since the last glaciation in this area. The lake chains in the south are NE oriented. They may identify the traces of glacier-induced erosion in the areas of its max speed of movement.

A specific feature of the region is a wide-spread occurrence of aeolian sands (especially at the first and second terraces of the Nadym river.) Although intense aeolian terrain formation occurred in the late Pleistocene and the drought periods of the Holocene [5], [34], [35], that is later than the last glaciation, the exposed sand sites at the mid and low geomorphological levels with sufficient accuracy indicate the fluvioglacial deposit accumulation areas in both modern and ancient drainage valleys [32]. At the high levels, the flatten, well-drained dry sandur plains next to the terminal moraine ridges are wind-driven.

For clarity, to sites with typical glacial landforms are marked on the map (see Fig. 7) as follows.

1) A site with prevailing linear ridges on the right bank of the Yarudei river (a left tributary of the Nadym River) close to the Nadym-Salekhard road highway construction (see Fig. 8). There are four well-preserved long and bent ridges up to 55 m high (the relative elevation difference is 10–12 m.) To the south, there is a site with hilly, probably

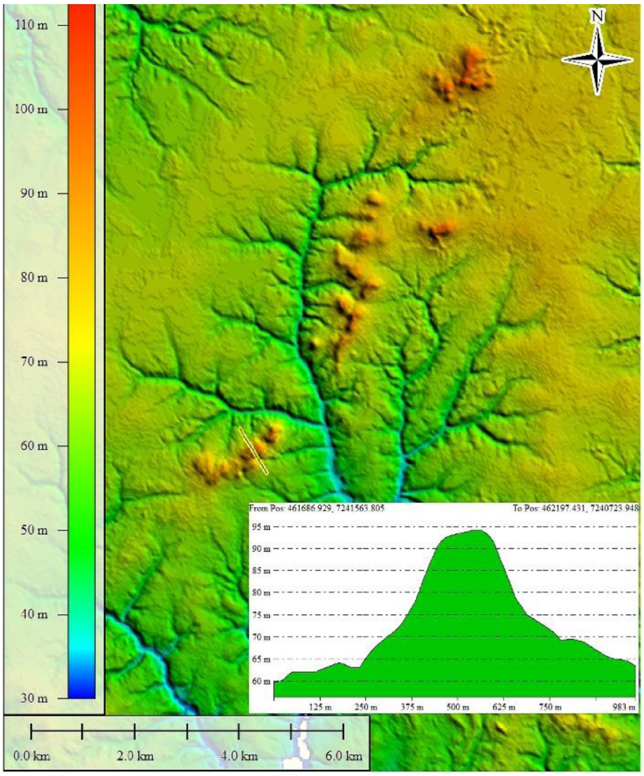

Fig. 9. Example: A site with kame landforms. TanDEM-X DEM, 26 m.

kame, terrain. The ridges are accompanied by thermokarst and erosion landforms.

2) A site with a cluster of kame hills on the right bank of the Nadym River, to the south off the main pipeline path (see Fig. 9.) The absolute elevation of the kames can be as high as over 100 m (relative elevation difference up to 30 m.) The kames are relatively well-preserved but some hills are destroyed by the river erosion network.

V. Morphometric Analysis

Morphometric properties are not commonly used for glacial landforms analysis. They are mostly applied when the identified landforms are to be verified and studied in detail (e.g., to determine the number and orientation of the drumlins) [25]. In this article, we used the SAGA GIS software package to obtain several morphometric properties that indicate the terrain irregularity in the area under consideration as follows.

1) *Relative Slope Positions*: The cell slope and its relative position between the valley bottom and spine is estimated as its height relative to the height of the valley towards which the drain is oriented, and the height of the spine from which the drain flows [36].
2) *Wind Exposition Index*: A dimensionless index indicating the areas in wind shadows (the index is less than 1) and the areas exposed to wind erosion (the index is over 1) [37], [38].
3) *Topographic Position Index* (TPI): An index that compares the target cell elevation with the mean elevation of the surrounding cells in the area (its shape and size are adjustable). Positive PTI values indicate a local uphill over the surrounding area, while negative values indicate a depression [39]–[41].

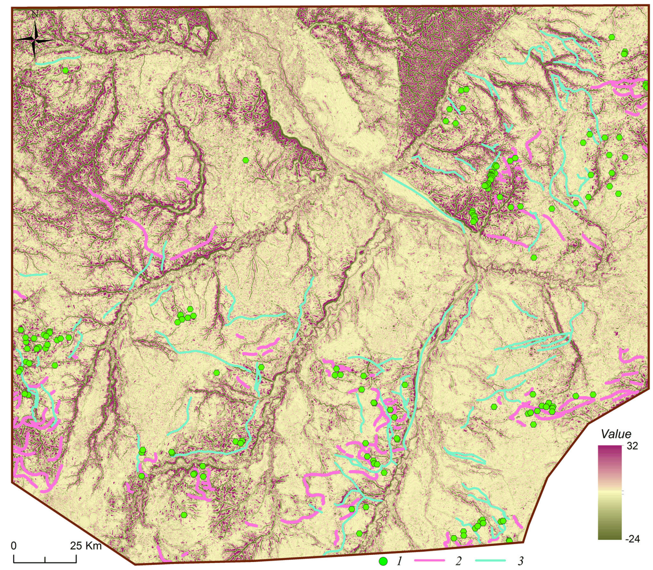

Fig. 10. TPI, vicinity area size: 1000. Legend: 1: kames and kame-like hills; 2: terminal moraines; 3: valley trains.

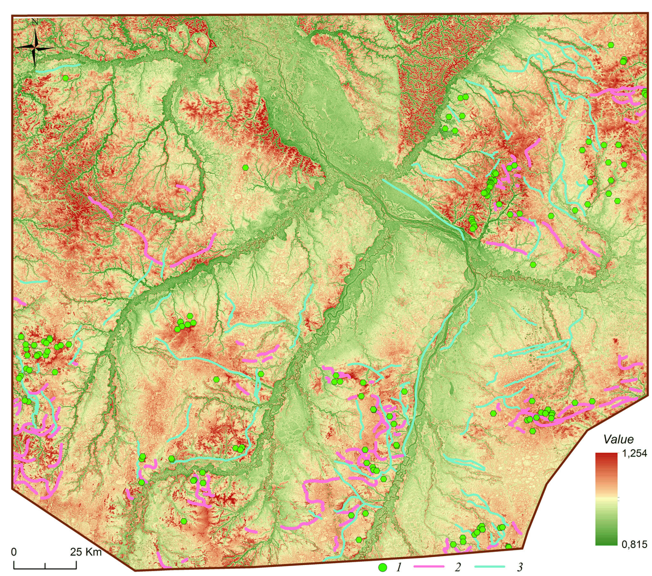

Fig. 11. Wind exposition. Legend. 1: Kames and kame-like hills. 2: Terminal moraines. 3: Valley trains.

The results (see Figs. 10–13) are as follows.

1) The Nadym river valley in its lower course up to the Left Khetta river mouth has an unusually wide and virtually flat river bed. Besides, on the right bank below the Right Khetta river mouth, an erosion bench of a marine terrace is identified in all the images. This feature well matches the conclusion about the absence of glacial topography at the lower geomorphological level.
2) In the northern part on the right bank of the Right Khetta river, in the upper headwaters of the Yarudei River and on the left bank of the Nadym river below the Kheigiyaha

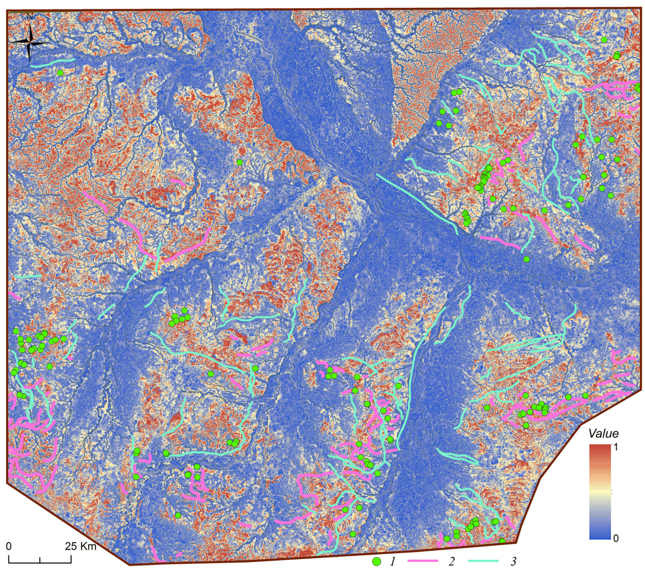

Fig. 12. Relative slope position. Legend: 1: Kames and kame-like hills. 2: Terminal moraines. 3: Valley trains.

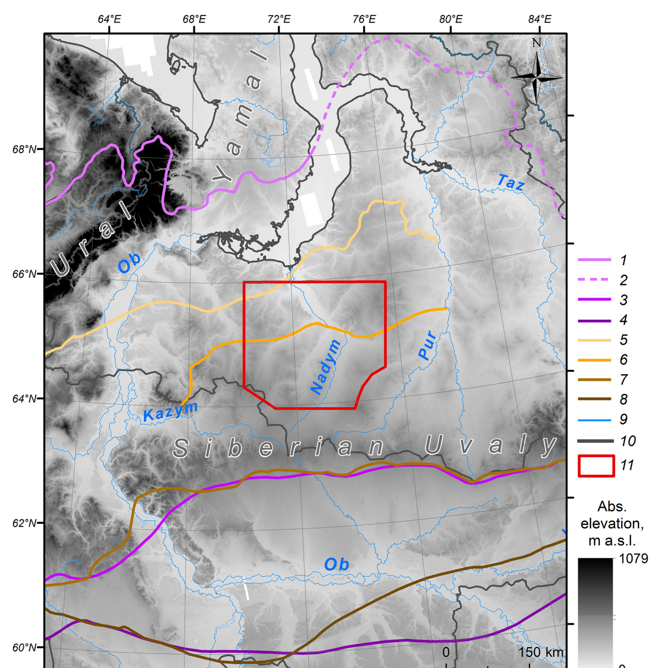

Fig. 13. Glaciation boundaries in the north of West Siberia. 1: Zyrian [23]. 2: Zyrian (probable) [23]. 3: Taz [23]. 4: Samarovo (max) [23]. 5: Zyrian [14], [34]. 6: Taz (second stage) [14], [34]. 7: Taz [14], [34]. 8: Samarovo [14], [34]. 9: Bodies of water. 10: Administrative boudaries. 11: Surveyed site boundaries (background image: TanDEM-X DEM 90).

river mouth the TPI (see Fig. 10) clearly shows high, dissected plains made of marine deposits [14], [15].

3) The valleys of the Kheigiyaha, Left Khetta, Nadym, Right Khetta, and Tanlova have pronounced terraces mostly formed along one of the banks. Kheigiyaha, Left Khetta, and Tanlova rivers have wider mid-course valleys (see Figs. 11 and 12). It may indicate that the existing water streams follow the previously formed shallows

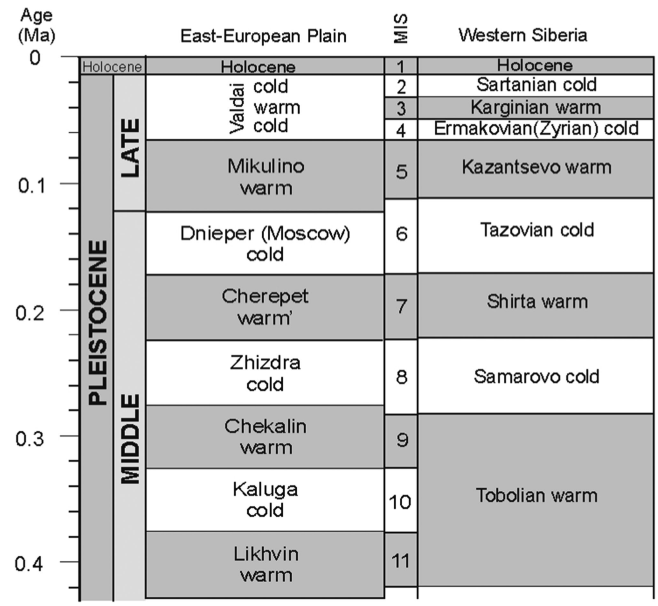

Fig. 14. Palaeoenvironmental event successions on the East European Plain (adapted from [42]; [43] and in West Siberia [44]).

4) The watersheds of the Kheigiyaha and Left Khetta, Left Khetta and Nadym, Right Khetta and Tanlova have generally flattened surfaces (see Fig. 10) but differ from the terrace formations of these rivers in the slope length and various exposures (see Figs. 11 and 12.) The watersheds have distinctive local uplands (hills and ridges) that often form regular 2-D patterns.
5) In some cases, the images show a linear pattern (headwaters of the Kheigiyaha river, left bank of the Tanlova River) (see Fig. 11) that can be interpreted as glaciation traces. Then, two possible glacial lobes are identified: at the north, in the Kheigiyaha River basin, and at the east (NE) in the Tanlova River basin.

Since the indicators are closely converged, the morphometric properties cannot serve as an independent data source for mapping. In most cases, landform categorization requires additional analysis of the original DEM that can be represented in several color and shade variations.

VI. Discussion and Verification of Results

A contemporary view is that the north of West Siberia was affected by several glaciations: Zyrian (MIS4), Taz (MIS6) and Samarovo (MIS8.) The low-level areas (up to 40–45 m a.s.l.) could have been affected by multiple marine transgressions in Kazantsevo (MIS5) and Karginsky (MIS3) epochs. Fig. 13 shows the extreme positions of the glaciations. The timeline of West Siberian glaciations and interglacial periods versus East European ones are shown in Fig. 14. Some researchers identify some stages of Taz (MIS6) and probably Zyryanka (MIS4) glaciations directly within the studied area.

The key indicator of the glacial genesis for the Quaternary rocks in the north of West Siberia is the presence of fragmentary material: semirounded angulated pebbles; gravel; and large boulders with glacial striae carried over by the glacier from the areas beyond the west Siberian plain [45], [46]. The glacial deposits in the studied area are unscreened coarse sand with a lot of coarse gravel, and moraine-like lumpy clay formations, clay loam and clay sand with gravel and large boulders. The boulders and pebble consist of quartz, opal, malmrock, quartz porphyries, amphibolites, granitoids, gneisses, trachytes, etc. [9]–[11]. It is noted that attempts to identify the exact location of the bed-rock crops with geology markers failed. The fluvioglacial deposits consist of cross-bedded, well-washed gray sand with a homogeneous chemical composition (the share of SiO_2 is 94% to 97%) with some gravel and pebble [9]–[11].

The historical survey records [9]–[15] were used to verify the landform identification including absolute dating of various deposits. The verification sites are shown in Fig. 7.

Specific sections demonstrating the ratio of the above-listed deposit types were studied in the middle course of the Left Khetta River. The sections are 20–25 m deep and reveal the structure of the largest moraine-kame hill area in the region. For instance, at point AS-1 (see Fig. 7) starting from 2.5 m depth a 20 m thick formation of dense lumpy clay loam interbedded with micaceous sand (interbed width up to 25 cm) [11]. The clay loam is reddish-brown, with small mica flakes, small angulated fragments, including granite boulders up to 25 cm in diameter. The right side of the section (upstream, revealed by stripping) shows a layer of light-grey fine sand. At 15 m depth, it is followed by gravel and pebble interbed layer. The talus is covered with loamy rock debris. There is an accumulation of gravel and pebble on the slope.

A large kame moraine was found at the watershed of the Nadym and Left Khetta rivers (see AS2, Fig. 7) [11]. It extends in the NS direction and is 25–30 m above the surrounding plain. The top of the ridge is concave and consists of individual summits separated by saddles. There is an accumulation of pebble and gravel on the ridge. Well-washed coarse pebble and gravel sand are found down to 1.2 m.

In the lower course of the Left Khetta River at the intersection between the river, two esker-like ridges, and a small kame hill area well No. 18 (seeAS3, Fig. 7) at 1.8 m depth reached a gravel and pebble layer 17.6 m thick [11]. The pebble size range is from 0.5 to 3–4 cm. The pebbles are poorly smoothed and mostly consist of quartz and malmrock.

Moraine ridges are quite common in the headwaters of the Bolshoi Khukhu River (a right tributary of the Nadym River.) The directions of the ridges are NW and NE. Their length is up to 6–7 km while the relative elevation is from 15 to 60 m [9], [12]. In terms of morphology, the ridges comprise of smoothed summits separated by small saddles. All the ridges have steep slopes. The top layer of the ridges down to 1–2 m consists of moraine loam soil with abundant pebbles. The pebbles are poorly smoothed. Their diameter does not exceed 2–4 cm. The petrographic composition in one of the uncoverings (see AS4, Fig. 7): silicon, clay shale, arkose sandstone, breccia of clay-siliceous rocks, limonized rock [9]. Manual drilling of some small hills [12], [47] showed that they are composed of frozen ice-bearing loam and clay deposits. The total ice content estimated visually is at least 30%. Well, no. 10 [12] can be used as an example. At 1.4 to 10.7 m depth, the clay is light grey and yellowish, light, porous, interbedded with aleurite. The bedding is convolute and horizontal. Under the clay mass, there is a layer of poorly screened grey clay fine sand containing gravel quartz grains and silicon pebbles. It should be noted that only small knobs up to 6–8 m high were drilled. Most of the highest hills were not studied by drilling.

The genesis of the linear ridge landforms is still unclear. As Andreev reported [47] it contains up to 30 %–40% of frozen ice-bearing clay. On one hand, the small ridges can be associated with fractures in the glacier [9]. On the other hand, there is a hypothesis that tectonic and permafrost factors play a major role (the ridges are associated with the clay component of the subjacent positive structure) [47].

As to the aeolian terrain, the reports specify [11] that at the watersheds it is associated with kame uplands, ridges, sandur plains, and other accumulative landforms produced by the fluvioglacial streams as the glaciation degraded. In the Nadym River valley, the second terrace deposits exposed to wind consist of sand carried over from the watersheds. Their primary genesis is fluvioglacial. In the lowest part, a gravel cover is often formed over the exposed sand.

The independent field survey results of the large Nadym River basin [9]–[11], [14] are in good agreement with the mapping results. Generally, they support the glacial and aqueoglacial genesis of the identified landforms. It may indicate that we found generic indicators for the territory of interest that can be used in other areas of the West Siberia north part. The results will be used for future field surveys at the key areas to study the formation of the glacial and aqueoglacial landforms and to estimate their age.

Presently, as DSM/DEM raw data become more available, remote mapping of glacial landforms turns into a common method used across the world [17], [21], [48], [49]. Canada and US geological surveys [50] regularly develop glacial maps based on DSM/DEM data. A detailed glacial map of the British Isles and the surrounding continental shelf (BRITICE-2) was updated with the new spatial data. Now it is available for analysis in digital form [18]. Remotely identified features of most glacial landforms in various natural conditions are described in great detail, confirmed by field studies. When RS/DTM data are available for the research community, the mapping results can be discussed in detail by the advocates of different theories.

For the article, we should note that the glacial terrain formation theory is confirmed in most of the Nadym river basin under consideration. The watershed areas above 70 m asl have the highest density of well-preserved glacial signs (Baltic height system.) The identified glacial and fluvioglacial landforms are arranged in regular associations. It is an important sign for the landform genesis studies [51]. The primary restriction of the resulting dataset is the low automation of the mapping procedure. The morphometric features often do not express the intrinsic properties that can be found visually. Visual interpretation also explains any possible deviations between the object boundaries. They can also be affected by DTM visualization settings. The presented geomorphological mapping methods apply to at least all the northern regions of west Siberia for making and updating the geological maps. We assume that the objective RS and DTM data complemented by recent field survey data will eventually end the discussion between the "glacialists" and "marinists."

VII. Conclusion

The article of the lower and middle course of the Nadym river showed that using publicly available RS data and DEM it is possible to map glacial and fluvioglacial landforms on large areas. Today's mid- and high-resolution DEMs, such as TanDEM-X provide the elevation accuracy comparable to a 1:25 000 scale topographic map accuracy but they better represent individual landforms even in forest-covered northern taiga areas.

Sustainable and reliable indicators are the key to geomorphological mapping. With this study, we verified, increased accuracy, and extended the indicators found through field surveys by comparing the aerial photo fragments with modern RS data. The presented indicators, references, and identification methods apply to detailed remote studies in other northern regions of West Siberia and updating of the national geological maps. Since the indicators are closely converged, the morphometric properties can serve as a supplemental data source only.

The mapping produced two clear regularities in the glacial and fluvioglacial landform distribution in the Nadym river basin.

1) All the identified landforms are to the south off the Yarudei and Right Khetta river centerlines. In the interfluve area between the Yarudei and Kheigiyaha (Longyugan) only individual landforms are found while in the southern and western parts there is a max variety and density of landforms.
2) All the identified landforms are found above 40 m a.s.l. (except for the exposed sand in the re-deposited fluvioglacial sand in the Nadym River valley). The landforms density increases greatly at the watersheds above 70 m a.s.l.

The depositional landforms (kame hills and ridges, moraine and kame hill areas, and terminal moraine formations) are composed mainly of unscreened coarse sand with an abundance of pebble, as well as moraine-like layers of lumpy clays, clay loams and clay sand with gravel and large boulders. The records show that the glacial terrain was formed no later than the Taz glaciation (MIS6). This conclusion shall be verified by advanced dating methods in the course of future field surveys.

Generally, our results support the glacial terrain formation theory in most of the Nadym River basin under consideration. The density and preservation quality of the surface glacier signs increase with the absolute height. Generally, the results were produced from publicly available raw RS data so they can be independently verified and further refined. Besides, the high mapping accuracy of each feature makes it possible to plan the field survey paths for additional studies of the geology of the most controversial landforms. It will gradually improve the quality and reliability of the resulting geological maps.

Acknowledgment

The author would like to thank DLR and the TerraSAR-X research team for providing the digital elevation models (proposal ID–DEM_GEOL1378).

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