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UAV-based photogrammetry: Assessing the application potential and effectiveness for archaeological monitoring and surveying in the research on the 'valley of the kings' (Tuva, Russia)

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ABSTRACT

The article offers an evaluation of the adequacy and effectiveness of using UAV-based photogrammetry for updating the planigraphy of well-studied archaeological sites and discovering new ones. The study is based on the data collected in the 'Valley of the Kings' in the Republic of Tyva (otherwise called Tuva, Russia). Data analysis using GIS software found 1000 archaeological objects and other, possibly archaeological objects. UAV-based digital photogrammetry has proved informative and effective in our study. In addition to the previously known archaeological objects, it enabled us to detect numerous new archaeological objects, which had been missed in the earlier investigations carried out on the ground. However, this survey technology has been found to have a significant number of limitations as to its applicability in the search for archaeological objects, and it is concluded that UAVs cannot replace archaeological investigations on the ground, particularly as regards identification of objects.

1. Introduction

Aerial photography has earned a solid reputation in archaeology as a method offering a distinctive perspective on cultural heritage. Specific crop, soil or shadow marks identified via airborne imagery enable new archaeological objects, invisible on the ground, to be discovered from the air.

In archaeology, aerial photography was first used in the late 19th century and became widespread in the 20th century. Further improvement and increased accessibility of unmanned aerial vehicles (UAV) as well as the arrival and proliferation of digital photography led to aerial photography being ever more utilised by archaeologists, with a number of detailed scientific review articles on this technology having already been published in the field (e.g. Adamopoulos and Rinaudo, 2020; Agapiou and Lysandrou, 2015; Bewley, 2003; 1999; Campana, 2017; Deng et al., 2010; Luo et al., 2019; Nex and Remondino, 2014; Nikolakopoulos et al., 2017; Verhoeven, 2017). Previously, photography helped to visually identify crop, soil or shadow marks; later on, enhanced computational capacities enabled automatic digital photogrammetry and, as a consequence, relief surveys of archaeological sites' entire area with high-resolution data on relief features (Daponte et al., 2017; Gruszczyński et al., 2017; Kršák et al., 2016). Digital elevation models (DEM) produced as a result of such photography (which is significantly cheaper than laser scanning (LiDAR)) have allowed to use different tools to analyse the earth's surface relief characteristics and to search for, document and study archaeological objects (see, e.g., Dubbini et al., 2016; Greco, 2018; Hamilton, 2017; Howland et al., 2018; Kreij et al., 2018; Pierdicca, 2018; Themistocleous et al., 2014; Torres et al., 2014, among others). Undoubtedly, the use of aerophotogrammetry can be considerably limited depending on specific natural and weather conditions. This technology can be taken most advantage of on low vegetation terrains such as tundra, steppes, and deserts. Also, the potential appears to be significant of its application in remote, hard-to-reach areas (e.g., in the mountains) for preliminary archaeological surveying.

The current availability of aerophotogrammetry has raised the issue of whether it can be effectively utilised to update the planigraphy of well-studied archaeological sites and discover new ones. Based on the data collected in the 'Valley of the Kings' in the Republic of Tyva (otherwise called Tuva, Russia), the article offers an evaluation of the adequacy and effectiveness of using UAV-based photogrammetry for these purposes.

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2. Geographical and archaeological description of the ‘valley of the kings’ (Tuva, Russia)

The ‘Valley of the Kings’ is the unofficial name of the territory in the western part of the Turan-Uyuk intermountain basin (Republic of Tyva), which has a significant number of burial mounds. The basin is part of the Western Sayan mountain system and is found between the Kurtushibinskii mountain range in the north and the Uyuk mountain range in the south (Fig. 1). The Uyuk River, which is the right tributary of the Bii-Khem River (Big Yenisei), runs through the Valley, cutting it into two parts; the Uyuk River has a large area of marshy floodplain. The bottom of the basin is estimated at 800–900 m above mean sea level; the peaks of the surrounding mountains reach up to 2000 to 2300 m above sea level. In the central part of the basin, there are some isolated hills, their height reaching around 1100 to 1250 m above mean sea level, and a marshy depression with two big and several smaller salt lakes called White Lakes.

The vegetation found here is of the kind characteristic of steppes and meadows. Most of the territory had been plowed and used for agriculture. The northern hillsides of the mountain ranges are covered with forests. High vegetation is also found in the marshy floodplains in the central part of the basin (Maskaev et al., 1985, pp. 218–221).

A distinctive feature of the basin is multiple burial mounds dated primarily to the early nomad era, found along the left bank of the Uyuk River in the western part of the basin. This part of the basin was named ‘Valley of the Kings’ after these easily distinguishable ancient structures. The mounds form a narrow line stretching across 19 km from southwest to northeast, along the southern slopes of the Kurtushibinskii range. In the literature, the Valley of the Kings is generally divided into three burial fields – Chinge-Tei, Kek-Ton, and Arzhan. Under the isolated mountain of Kosh-Pei in the centre of the Valley, there is another burial field also bearing the name Kosh-Pei (Belikova, 2014, pp. 265–269; Chugunov, 2009; Semenov, 2010; Chugunov, 2011). The Kosh-Pei burial mounds extend from south to north, perpendicular to the other mounds. In addition to the burial fields of the Scythian era, other archaeological objects have been found in the Valley, including nomad campsites, deer stones, stelae with Old Turkic runiform inscriptions, Balbals, and small medieval mounds.

The first archaeological investigations in the Valley were conducted by Aleksandr V. Adrianov in 1916 (Belikova, 2014, pp. 222–269, 497–523). In 1929, Sergei A. Teploukhov carried out his research in the valley of the Uyuk River (Poltoratskaia, 1966). The large-scale field research on documentation of the archaeological sites in Tuva, including the Turan-Uyuk basin, was done by the State Museum of the Tuva People’s Republic under the leadership of Nikolai M. Bogatyrev in 1941 and 1942, and under the leadership of Daniil B. Danzyn-oola from 1943 to 1945 (Liundup, 2014). After Tuva became part of the USSR, extensive agricultural development of local lands started, entailing damage to or destruction of cultural heritage objects—for example, small mounds (of 15–20 m in diameter) were levelled (Dorgu and Liundup, 2016). Also, it is possible that during the Soviet period local stone mounds would be dismantled to be used by the population as building material (Lundup and Dorgu, 2019, p. 76).

Archaeological excavations in the valley of the Uyuk River continued in the 1970s and were associated with the building of irrigation systems and roads in the region. Archaeological investigations took place near the village of Tarlag, conducted by Anatolii M. Mandel’shtam (Chugunov et al., 2017, p. 16). In 1989 and 1991, under the leadership of Vladimir A. Semenov and Marina E. Kilunovskaia, several burial mounds were excavated on the Kosh-Pei burial site (Semenov, 1992). Near the village of Arzhan, two small burial mounds were studied by Leonid S.

Fig. 1. Turan-Uyuk intermountain basin.

Marsadolov (2002). All of these mounds, small- or average-sized, had already been looted in ancient times, yet a significant amount of gold jewelry was nonetheless found in some of them.

Out of the many burial mounds in the Valley of the Kings, some are of particular interest—those of 70–100 m in diameter and 2–4 m high. These round 'platforms', made chiefly of stones, are generally surrounded by multiple additional structures in the form of circular alignments of stones and piled stones. The Valley of the Kings became well-known after two of such burial-memorial complexes had been excavated, namely, Arzhan-1, studied in the early 1970s, and Arzhan-2, studied in the early 21st century (Griaznov, 1980; Chugunov et al., 2010, 2017). The material, which the excavations of these sites allowed to obtain, is of great scientific value for the study of archaeological issues reaching beyond this region. It contributes to the analysis of fundamental issues in Scythology, that is, the genesis and spread of Scythian-type cultures in Eurasia, the formation of animal-style art, and development of weapons and horse equipment in the Scythian era. In addition to the large number of finds, radiocarbon dates were produced for some organic samples taken from the sites (Chugunov et al., 2005; Zaitseva et al., 2004; Alekseev et al., 2005), which enabled these complexes to be dated with great precision. All this allows considering the research carried out in the Tuva Valley of the Kings as exemplary and relevant for the cultural and chronological analysis of vast territories within the so-called Eurasian steppe belt.

It is unsurprising that the results of previous excavations in the Valley have attracted many archaeologists' attention. Since 2018, annual expeditions headed by Konstantin V. Chugunov have been conducted by the State Hermitage Museum to investigate another burial-memorial complex here—Chinge-Tei I (Chugunov, 2019, 2018, 2017, 2011, p. 359). In 2008 and 2009, the study on the Kosh-Pei burial mounds took place, supervised by Vladimir A. Semenov (2010). During it, in 2009, Aleksei G. Akulov carried out a large-scale mapping of the Valley's parts featuring most burial mounds. In this article we draw on his work and compare the survey results produced by him in the traditional manner, on the ground, with those obtained by us via UAV-executed aerial photography.

In 2012 and 2013, rescue excavations were performed in the Valley as part of the building of the Kuragino-Kyzyl railway line (Semenov et al., 2015, p. 730, 2014). From 2012 to 2015, during the expedition led by Dmitrii V. Rukavishnikov and Irina V. Rukavishnikova of the Institute of Archaeology (Russian Academy of Sciences), airborne imagery was collected on the burial sites of Arzhan, Chinge-Tei, Kek-Ton, and on the burial mound of Tunnug-I, whereby an air balloon was used to update the sites' planigraphy and obtain information on the design features of some of the structures (Rukavishnikov et al., 2017; Rukavishnikova and Rukavishnikov, 2013). From 2013 to 2015, Rukavishnikov and Rukavishnikova also studied the burial mound Arzhan-5, which had been substantially destroyed in the 1960s (Rukavishnikova and Gladchenkov, 2016). Since 2017, a project has been implemented, headed by Timur R. Sadykov, Gino Caspari, and Egor K. Blokhin, to excavate the Tunnug-I burial mound (Caspari et al., 2018; Sadykov et al., 2019). Under the supervision of Gino Caspari, based on satellite imagery data (Caspari, 2020), the Valley's largest burial mounds have been detected, mapped and assessed as to their current state and the potential explored of using synthetic-aperture radar (SAR) data to search for archaeological objects (Caspari et al., 2020).

3. Materials and methods

3.1. The area surveyed

During the fieldwork in 2016 and 2017, researchers from Tomsk State University (Zaitceva et al., 2017) photographed the Valley from the air, using an unmanned aerial vehicle (UAV) to further process the collected photogrammetry imagery and build 3D models of local archaeological sites. The survey area included the burial sites of Chinge-Tei, Kek-Ton, Kosh-Pei, and Arzhan. In the south, the survey area approached the floodplain of the Uyuk River and the marshland near White Lakes. The territory of and surrounding the mountain Kosh-Pei was included in the survey area as a separate site. In the southwest, the survey area reached the floodplain of the Tarlag River. In the northwest, it covered the nearest foothills of the Kurtushibinskii range, including the mountains: Ulug-Dag, Chinge-Kyr, Ulug-Khadylyg (partially), Kashkyl, and Chinzhash. Only in the northeast was the survey area not limited by any natural objects: it stretched across 2 km off the furthest of the Arzhan group's burial mounds—Arzhan-2. Overall, the survey area made up a rectangular of 22.7 by 6.9 km, with an additional rectangular piece of the Kosh-Pei territory of 5.5. by 6.7 km; the total area surveyed thus equated to around 195 km^2 (Fig. 2).

3.2. Data collection

In our study, we used the unmanned aerial vehicle *Geoscan 201* equipped with the *Sony DSC-RX1* camera. The survey was performed at the maximum height of approximately 300 m above the highest point on the ground along the lines of flight. Given the specific characteristics of the camera (35 mm Full Frame CMOS sensor (35.8 × 23.8 mm), 6000 × 4000 resolution, and 35 mm focal length (Sony, 2020)) and the height at which the UAV was flown, photographs were obtained with the spatial resolution (GSD – ground sample distance) of 5–8 cm per pixel (for most of the area—of around 6 cm per pixel), taking into account elevation differences (He et al., 2012). The photographs were taken with at least 50% of side overlap and 70% of forward overlap, which resulted in 150-to-160-m distances between the lines of flight. The survey took place in August, which is not the most suitable period for doing aerial photography in the region due to high vegetation at this time of year.

According to the *Geoscan* specification (Geoscan, 2020) and the flight parameters, an area of around 19 km^2 was covered per flight, with a total of 2000 acquired photographs. During the 10 flights executed, surveyed was the overall area of around 195 km^2, with 20,500 photographs obtained as a result (Fig. 3). Each photograph's centre coordinates were located via an onboard GNSS receiver. Additionally, we had marked the whole of the survey area with 42 ground control points (GCPs) (Fig. 3), and these were georeferenced using dual-frequency dual-system GNSS receivers *Topcon Hiper+*. The data from the GNSS receivers were processed and the GCP coordinates established using *Topcon Tools* software. All the coordinates were calculated using the method of precise point positioning (PPP) and IGS Network data (Heroux and Kouba, 2001; IGS_Network, 2020).

Photogrammetric processing was done in *Agisoft Photoscan Pro* software (v.1.4.0). First, the cameras were associated with the geographic coordinates, whereby camera orientation angles were not used. Then, with the reference preselection function activated, all of the 20,500 photographs were compared and aligned. Further, reference marks were placed on the images of the GCPs, and camera alignment was optimised. Thus, the georeferencing was specified for the entire survey area. To optimise further calculations, the area was divided into squares of around 1 km^2 each, with a one-percent overlap, using the corresponding 'split in chunks' script (Agisoft, 2017). Further processing of each of the acquired chunks was done automatically in the batch process: building dense cloud, building digital elevation model (DEM), building orthomosaic, exporting DEM, and exporting orthomosaic.

As a result, two sets of data were produced (DEM and orthomosaic) for the whole of the surveyed area with the spatial resolution of 5–8 cm per pixel. The data were divided into fragments of 1 km^2 each.

3.3. Data analysis

Two separate sets of data were analysed in the study. The first dataset included data on the area coinciding with the area mapped by Aleksei G. Akulov in his survey on the ground (Akulov, 2009). Akulov mapped the Valley's burial mounds using a GNSS receiver in 2009. He documented

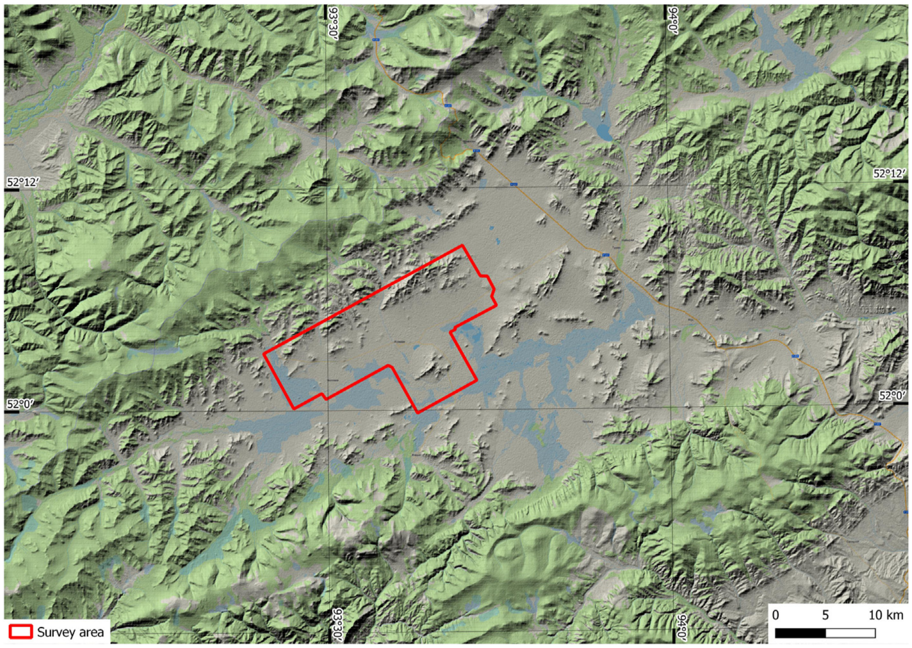

Fig. 2. Survey area in the Turan-Uyuk intermountain basin.

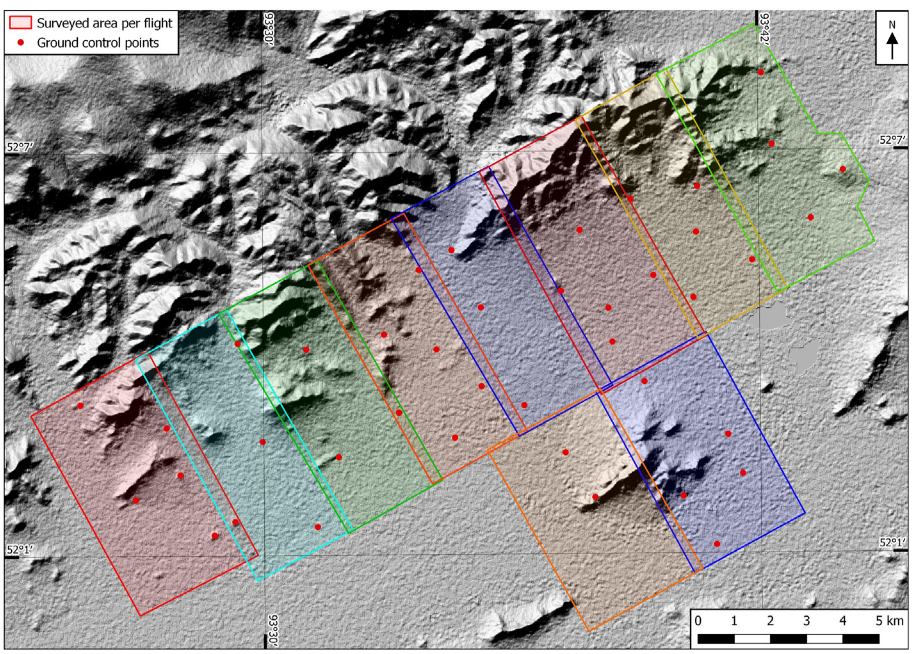

Fig. 3. Areas surveyed per flight, featuring ground control points.

all of the 4 burial fields of Chinge-Tei, Kek-Ton, Kosh-Pei, and Arzhan, and his 4 area plans (hereinafter referred to as 'control area plans') cover all of the main chains of burial mounds along with their adjacent territory, which makes up an area of 33 km^2 in total. This area covered by the 4 area plans of Akulov and hereinafter referred to in our study as a whole—control area—was used to compare our UAV data with Akulov's data obtained on the ground (Fig. 6) and thus evaluate how precise and effective UAVs can be in surveying archaeological objects. The second dataset included data on the peripheral parts of the survey area and was studied to assess the potential of aerial photogrammetry for detecting previously unknown archaeological objects.

The data were analysed in *Quantum GIS* software (Quantum_GIS, 2020). Specifically, three layers were processed: a) orthophoto, b) (DEM-based) hillshade, and c) DEM. A visual search for any objects was carried out manually. For a general examination of the territory, the orthophoto and hillshade layers were used. When a more detailed analysis of objects or parts of the area was needed, the DEM was additionally used; in more complex cases, elevation profiles were generated based on the DEM, using the *Profile Tool* plugin (Jurgiel et al., 2012)) (Fig. 4).

The first dataset featured data on the Valley's most dense clusters of burial mounds, that is, several chains of burial mounds stretching as a thin line across 20 km, parallel to the Kurtushibinskii range. These mounds are located on flat terrain in-between the foothills of the Kurtushibinskii range in the north and the floodplain of the Uyuk River in the south. Despite the fact that most of this territory had been utilised for agricultural purposes, the majority of these mounds had not been

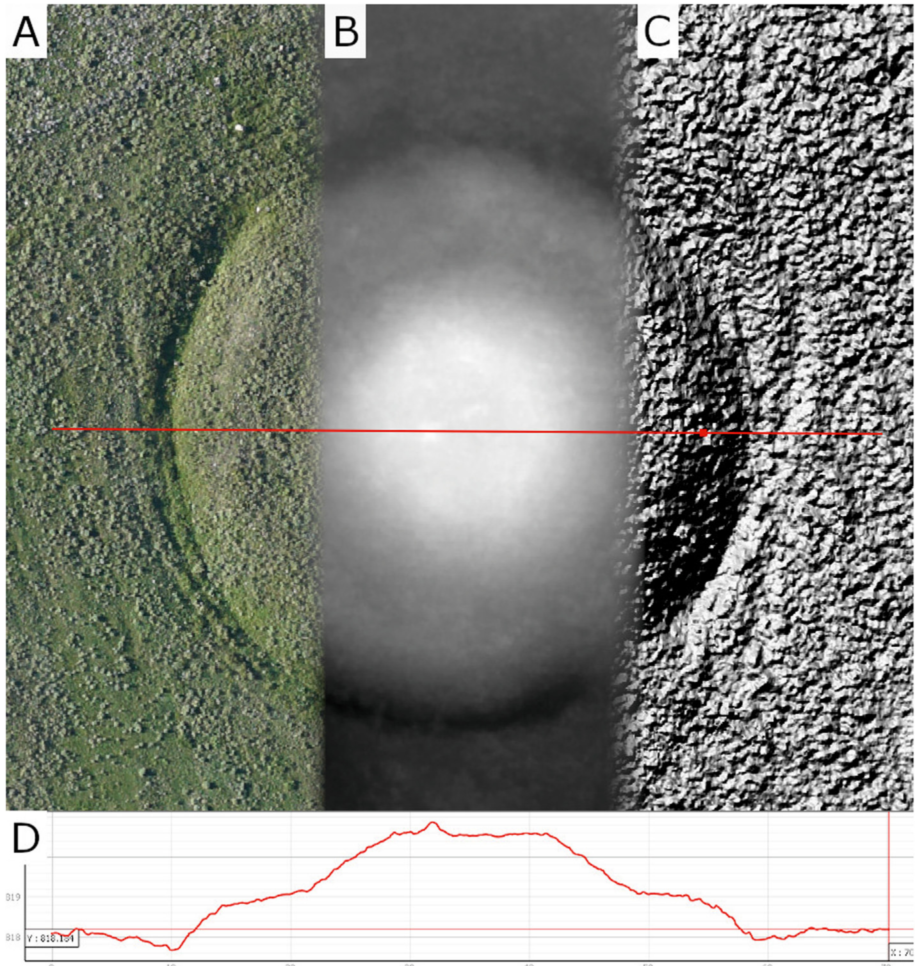

Fig. 4. Layers of data and analysis tools used. A – orthophoto, B – DEM, C – hillshade, D – elevation profile (Profile Tool).

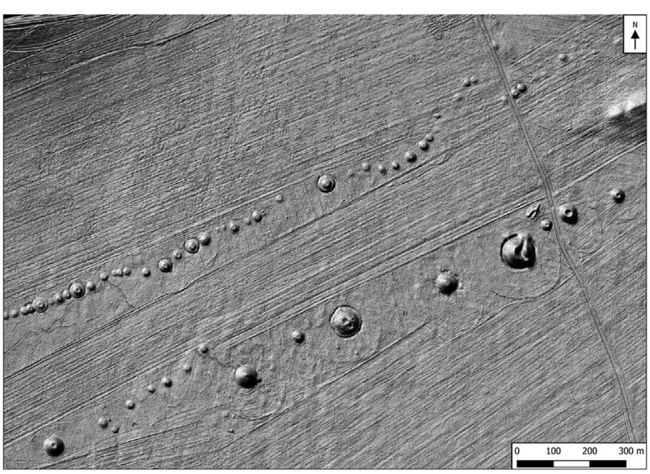

Fig. 5. Fragment of the Chinge-Tei group of burial mounds.

affected by plowing. This was due to the mounds' close proximity to one another, the large size of some of them, as well as the type of stones contained in some of the mounds.

The hillshade layer is most suitable for identifying objects on flat surfaces; in it, all elevation differences are clearly visible, and the majority of archaeological objects that stand out on the earth's surface, particularly the ones as big as burial mounds, can be easily detected. Where objects did not stand out, or there were any other doubts regarding them, the DEM layer was used to analyse the specific part of the territory and elevation profiles were built. The orthophoto layer was used to search for objects not standing out against the earth's surface, as well as to establish the presence of stone material in damaged objects.

The second dataset features data on the territory peripheral with respect to the clusters of the mounds and was used to search for new archaeological objects. It covers the foothills in the north and northeast; in the south and southwest, it covers large parts of the floodplains of the rivers Uyuk and Tarlag and is extended in the central part opposite the village of Arzhan to include the mountain Kosh-Pei and the adjacent territory—162 km^2 in total. Depending on the morphology, vegetation, and degree of anthropogenic impact, different methods of analysis are required to identify new archaeological objects. Therefore, analysing these territories separately was deemed most productive.

The flatland here was investigated in the same way as for the first dataset: the hillshade layer was analysed first, with the orthophoto and DEM layers complementing the analysis. This search method was applied to most of the area, including the floodplains, the Valley's flatland areas used for agriculture, the mountains and hills' flat slopes, as well as other flat territories within the survey area (foothills and marshy territories).

In terms of analysis of steep slopes and mountain peaks, neither the hillshade layer nor the DEM can give the results as informative as the ones obtained for flat territories. When any given part of the area is analysed separately, it can be seen that big elevation differences visually overshadow smaller ones, which makes search for objects impossible or difficult to apply. Yet, in our study, for the parts of the area with slow topsoil formation and low vegetation, we were able to visually distinguish in the orthophoto layer clusters of stones not covered with

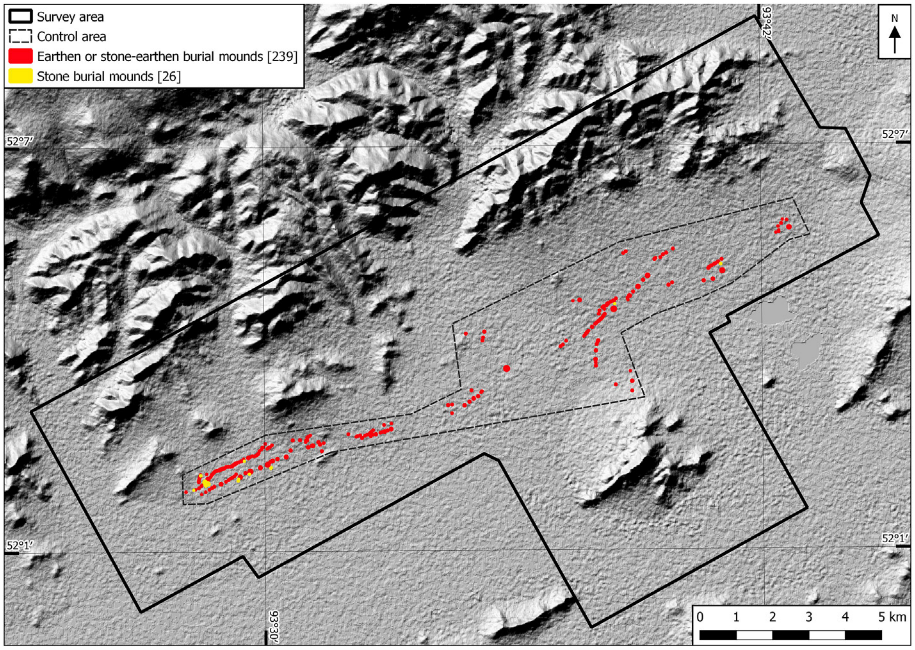

Fig. 6. Archaeological objects previously mapped by Akulov, identified by Geoscan 201.

vegetation or circular alignments of stones; and we measured the relative height of any object identified, using DEM-based profiles.

4. Results

4.1. Comparing the UAV-collected data with the control area plans

We compared our aerial photogrammetric data with Akulov's data obtained on the same area via archaeological survey on the ground. According to the UAV-data, two types of archaeological objects can be identified based on the area's morphological characteristics: a) earthen or stone-earthen burial mounds (these are large objects, usually of over 10 m in diameter) and b) stone burial mounds (usually of less than 15 m in diameter). The control area plans do feature these types of objects as well.

4.1.1. Previously known archaeological objects identified via aerial photogrammetry

The UAV-based data clearly demonstrate the presence of the two types of mounds: a) earthen or stone-earthen mounds and b) small stone mounds.

The first type includes large mounds which comprise the Valley's major clusters of mounds (Fig. 5). Overall, the data revealed 239 such objects. The identified chains of burial mounds are primarily made up of mounds of 15–50 m in diameter, 1–4 m high. Additionally, 15 particularly large burial mounds can be seen here, which vary from 50 to 100 m in diameter and are 3.5–7 m high. In the data, we could also clearly see the remains of the Valley's largest mounds studied before – Arzhan-1 and Arzhan-2, of 120 m in diameter and 3–4 m high and of 80 m in diameter and around 2 m high, respectively (Griaznov, 1980, p. 5; Chugunov, 2009). According to the previous excavations in the area, all of these monuments date back to the early nomad era—between the 9th and the 2nd centuries BC (Savinov, 2002, pp. 119–121, 135–136; Alekseev et al., 2005, pp. 67–68, 74–90; Semenov, 2010; Chugunov, 2013; Belikova, 2014, pp. 232–235, 256–260; Rukavishnikova, 2017; Mannai-Ool, 1970, pp. 9–13). These mounds are mostly earthen; some of them are stone-earthen or are covered with stones (Semenov, 2010). As the previous research on the monuments has shown (Chugunov et al., 2017, pp. 12–24), the largest burial-memorial complexes were erected mainly from stones, using clay. All of these mounds are clearly visible on the earth's surface and had been previously mapped; they are also easily distinguishable in our visual data. All of the 239 objects previously mapped were compared with the ones in our UAV-based data (Fig. 6).

The second type of objects identified consists of stone burial mounds—26 of them, as seen in the processed data. Most of them do not exceed 15 m in diameter and are up to 0.8 m high (Fig. 7). Similar previously studied objects were dated primarily to the Early Middle Ages (5th to 11th centuries) (Belikova, 2014, pp. 222–232, 235–256, 260–265; Kyzlasov, 1960, pp. 51–57), yet their external morphology allows us to suggest that such structures may date to even earlier periods (Kilunovskaia, 2016; Mannai-Ool, 1970, pp. 13–21).

These objects are located outside of the chains of mounds and are found either on their own or in small groups. Some of them are situated near the larger mounds. The objects found in close proximity to the major groups of burial mounds had not been affected by plowing and had already been mapped. Of the distinctly prominent objects found in our data, we identified all of the 26 stone burial mounds mapped in the control area (Fig. 6).

4.1.2. Previously known archaeological objects not identified via aerial photogrammetry

Small objects not standing out against the earth's surface, such as circular alignments of stones, are either difficult to distinguish or completely invisible in the UAV-acquired imagery. The majority of such circular alignments of stones are found in large groups (with tens of objects in each), and constitute the periphery of the burial-memorial complexes. These are schematically drawn on one of the control area plans in varying numbers from a few to a few hundred—all accompanying 65 separate burial mounds of different size. The diameter of the circular alignments of stones varies from 1 to 8.5 m, and due to the surrounding vegetation, most of them are hardly seen in the images. Similarly, the orthophoto layer allows us to identify only some of these alignments.

Another object present on one of the control area plans but not found in the UAV data is an enclosure with Balbals. Although some of its elements are visible in the orthophoto layer, such an object could easily be missed in data analysis.

Other objects marked by Akulov such as separate stones, the remains of other structures and piled stones were not identified via aerial photogrammetry.

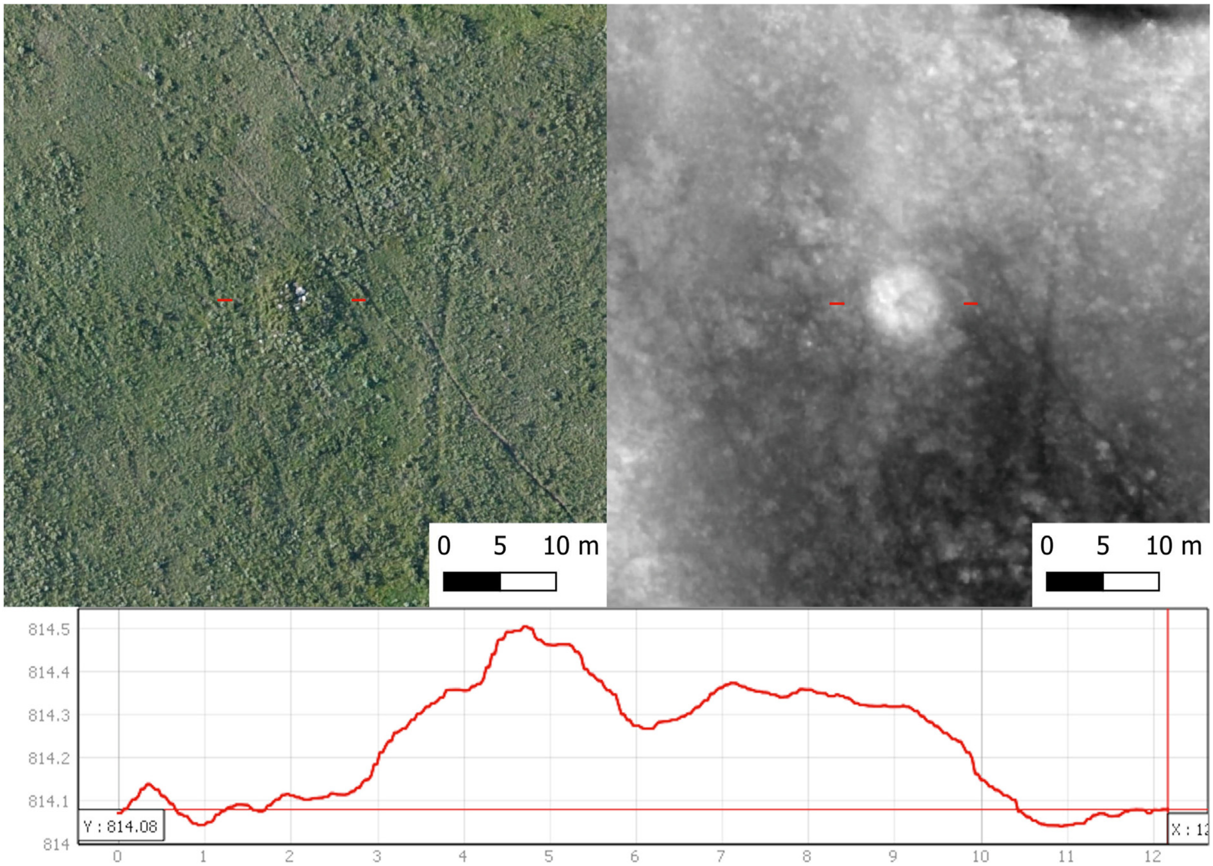

Fig. 7. Small-sized stone burial mound.

4.1.3. *Previously unknown archaeological objects identified via aerial photogrammetry*

In addition to the objects mapped by Akulov, we found 93 new burial mounds and 96 anomalies which may be archaeological objects.

Some of the mounds belonging to the first group of objects identified (that is, large earthen and stone-earthen burial mounds) turned out to have been plowed. These were relatively small structures located at the edges of the chains of mounds or standing apart from the burial mound groups. These had been levelled during plowing. Now low-lying, without clear-cut features and structurally similar to the surrounding territory,

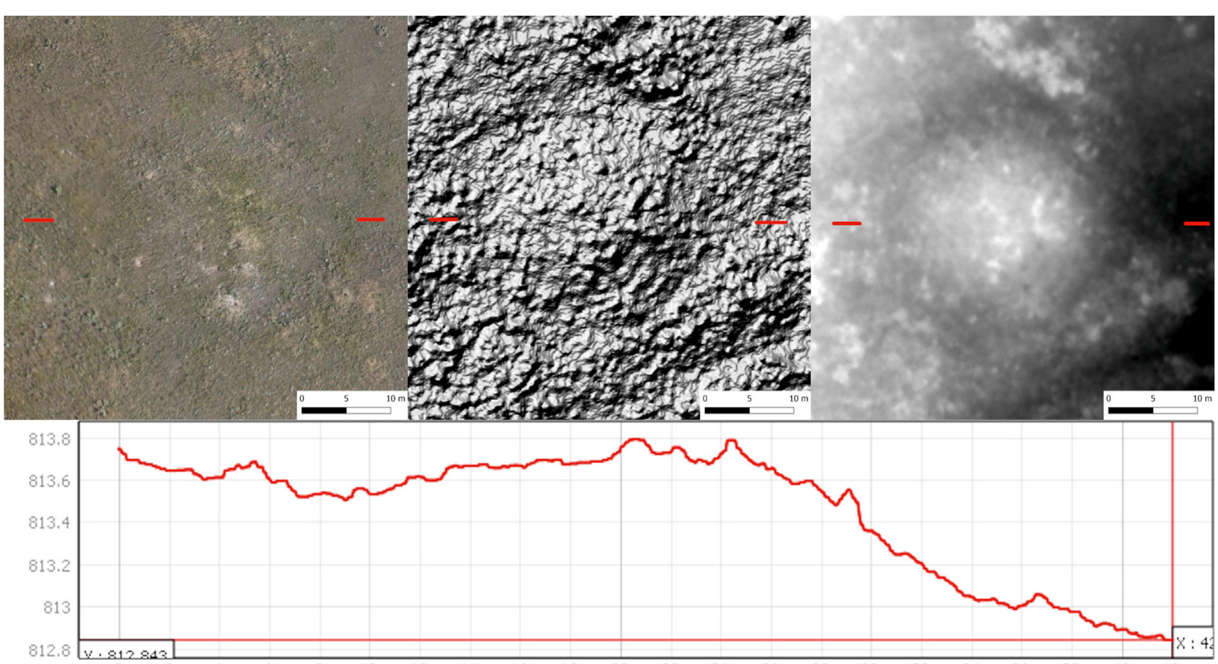

Fig. 8. Plowed burial mound.

these mounds have become indistinguishable as such on the ground; yet, the hillshade layer did reveal them. Generally, these are small structures of 10–30 m in diameter, up to 0.5 m high, not displaying sharp elevation differences (Fig. 8). In total, we identified 65 such new objects within the surveyed area. In addition, 43 anomalies of a similar kind, yet of less distinguishable shape or height, were discovered (Fig. 9). These objects can be either archaeological or natural. To classify them as archaeological requires excavation or geophysical investigations.

The results for the second type of objects (small stone burial mounds) were different. Being separate and small-sized structures, most of them had been plowed. However, the stones comprising them did leave some anomalies indicative of the mounds' presence in the plowed territory. Specifically, we identified some lenticular formations, formed as a result of the plow skirting around the central stone structure of 5–15 m in diameter. The central part of the majority of these objects is elevated at 0.3 m maximum, whereas for some of them it does not stand out against the earth's surface at all, but the orthophoto layer shows these stone clusters clearly (Fig. 10). In total, 28 such objects, with clear, distinctive features, were identified within the surveyed area (Fig. 9). The archaeological origin of 47 more anomalies found appears doubtful: most of these were identified by similar lenticular traces, but neither the surface relief nor the orthophoto layer revealed any distinct features in the centre of them. Similarly, these anomalies need to be further investigated on the ground.

4.2. Results of the search for cultural heritage objects in the survey area's periphery

A separate line of our research included looking for possible, new archaeological objects in the peripheral parts of the survey area, away from the major clusters of burial mounds. In total, 341 archaeological objects and 205 anomalies that may be archaeological objects were found within the area of 162 km^2. Different methods were used to study the area depending on specific natural and morphological factors: floodplain, marshland, agricultural land, other flat territories, hills, or mountains (Fig. 11).

Here, the survey area covered large parts of the Uyuk and Tarlag floodplains—the area of 31 km^2 overall. Although found in the Uyuk River floodplain (in that part of it which does not fall within our survey area) is one of the Valley's largest burial mounds—Tunnug I (Griaznov, 1980, p. 5; Caspari et al., 2018; Sadykov et al., 2019) and one could expect to find some other burial mounds in the floodplain area as well, our data on the area revealed no large object, showing only small-sized anomalies here (Fig. 11). The total number of these anomalies is 31, and these are mostly low elevations of rounded shape, of 8–16 m in diameter. Their distinctive features are either the maximum height of 0.2 m or contrasting types of vegetation. The majority also feature stones.

The area of the flat marshland between the floodplain of the Uyuk River and agricultural lands equated to 22 km^2; here we found 9 stone burial mounds and 6 unknown anomalies (Fig. 11).

Both the floodplain and the marshland's surfaces are highly eroded by water flows, and multiple elevations formed as a result of that complicated our search for archaeological objects. Also, due to generally abundant local vegetation, any search results for this area depend on the time of surveying. Our survey was conducted when the vegetation was already high and dense, which limited the search in this territory. Most objects that might have been otherwise well distinguishable could hardly be spotted here at this time of year (Fig. 12).

The largest area surveyed—that of 51 km^2—was the area that had been previously plowed. It features both flatland (excluding floodplains and marshland) and gentle slopes of mountains. As in the case of the first dataset (Section 4.1 of this article), with the data on the part of the survey area once plowed, here we searched for objects, also relying on surface relief anomalies. Overall, we found 83 earthen or stone-earthen burial mounds, 43 stone burial mounds, as well as 64 anomalies that may be archaeological objects (Fig. 11).

Other parts of flatland are found on mountain slopes, either too narrow or too steep to be plowed, yet gentle enough to be analysed using the hillshade layer. The area these parts make up (9 km^2, in total) also features several 'islands' left unploughed thanks to the nearby clusters of burial mounds. Here, we discovered 23 large earthen or stone-earthen burial mounds—some grouped in chains of 4, 5, and 7, and 7 more – as separate burial mounds. Steeper, unploughed slopes revealed better preserved and easy-to-detect stone burial mounds whose total number equated to 36 (Fig. 11). In addition, a new type of objects was discovered in this territory, that is, stone circles of 5–30 m in diameter. Although they do not stand out on the earth's surface, they are still visible in the orthophoto layer, possibly, thanks to slow topsoil formation and no plowing done here. The resolution of the orthophoto is such that it allows

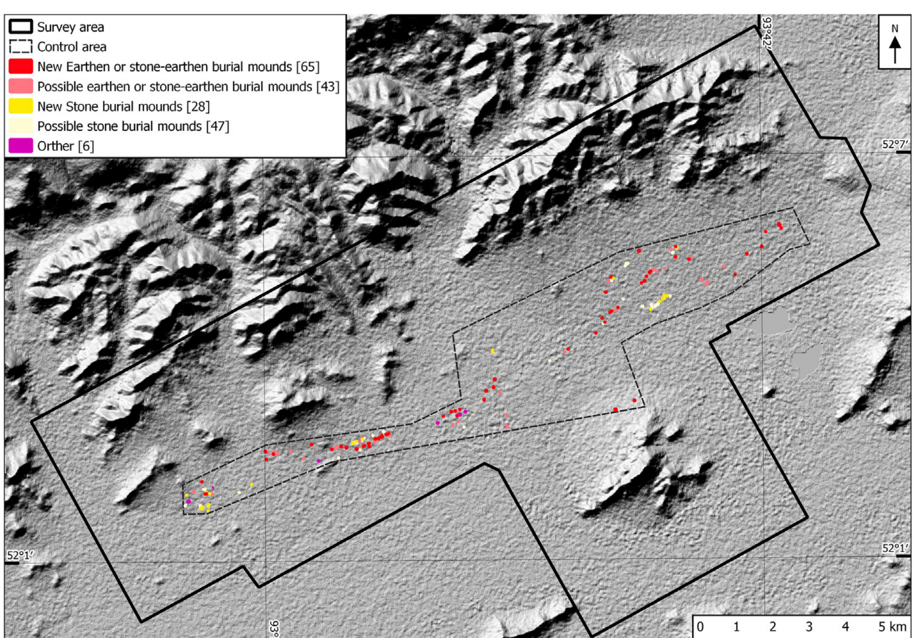

Fig. 9. New archaeological objects and anomalies of unknown origin identified.

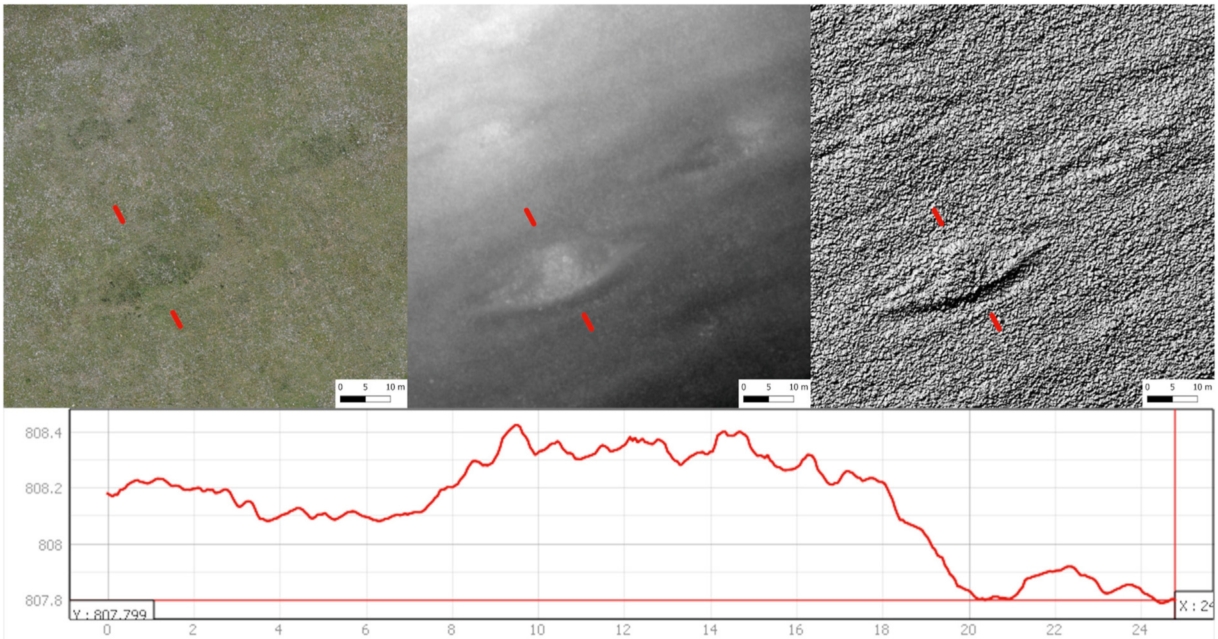

Fig. 10. Lenticular formations in the plowed territory.

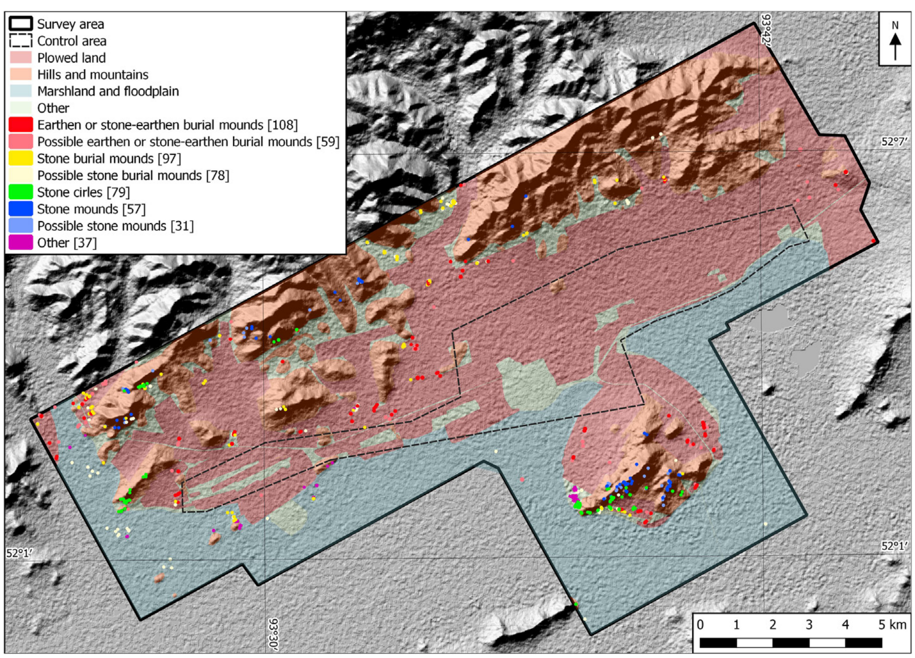

Fig. 11. Types of landscape and archaeological objects detected.

us to see stones of 0.2–0.5 m in size, placed to create the stone circles (Fig. 13). In total, 22 such circles were found in groups, located on the southern slope of the mountain Kosh-Pei. In addition, 55 anomalies were detected that may be archaeological objects (Fig. 11). Among them, there is a type of anomalies found on the same slope, in close proximity to the groups of stone circles—it is a group of 22 sub-rectangular objects with dimensions varying from 10 to 20 m. These objects do not stand out against the terrain relief, yet they are distinguishable thanks to the colour of vegetation that covers them. They cannot be definitively said to be of archaeological value prior to visual examination on the ground, therefore we classified them as anomalies of unknown origin.

We also surveyed the mountainous territory which includes mountain peaks, steep slopes, and hills—the total area of 49 km^2. Within it, 10 small stone burial mounds were found: these are low elevations not fully covered with vegetation, with their stone material clearly visible. Two more separate large earthen or stone-earthen burial mounds were detected on the hilltops. The diameter and the height of one of them are 20 m and 0.6 m, respectively; the other one is 40 m in diameter and 1 m high.

The orthophoto layer for this mountainous territory clearly shows stone circles of 3–30 m in diameter. Some of these are elevated at 0.3–0.4 m but most are not elevated. The stone circles are found as two large clusters—of 23 objects on the southern and south-western slopes of the mountain Kosh-Pei (the 22 stone circles referred to above are found in the same place but on the flatter surface) and of 21 objects on the slopes and peaks of the mountain Chinge-Tag. 13 more objects were found

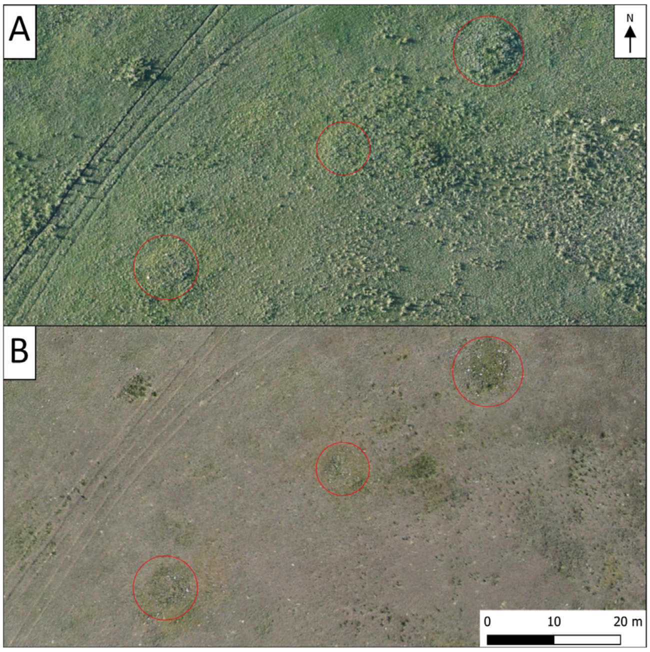

Fig. 12. Stone burial mounds. A – high vegetation. B – low vegetation.

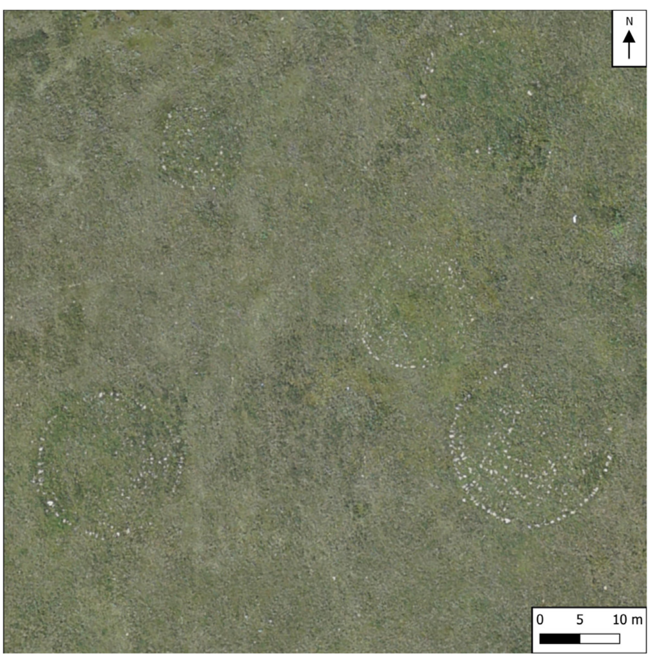

Fig. 13. Stone circles.

scattered or in small groups on the slopes of the Kurtushibinskii range. Thus, 57 objects were detected here, overall.

The mountainous territory features one more type of objects—clusters of stones of rounded shape (stone mounds), not fully covered by vegetation. These are easily distinguishable against the surrounding, evenly sparse vegetation. Some of them are elevated at up to 1.5 m (the height of the majority ranges from 0.2 to 0.5 m), whereas some rise only insignificantly. Their diameter varies from 5 to 10 m (Fig. 14). In total, 57 such objects were detected (Fig. 11). Nearly all of them are located on the peaks and ridges of the highest mountains. Some of these objects can be hypothesised to be the same kind of stone burial mounds as the ones found in the flatland parts of the survey area, though not covered by vegetation; some can be hypothesised to be memorial complexes without high-elevated mounds; some can be hypothesised not to be associated with burial-memorial practices and be instead complexes of ritual and religious value—*ovaa* (*oboo* in Mongolian) (Diakonova, 1977, pp. 185–195). The UAV-collected data do not allow for precise classification of these objects.

In the mountainous territory, we also detected 49 anomalies of unknown origin (Fig. 11). Such anomalies are distinguishable in the orthophoto layer as clusters of stones or changes in vegetation; however, other features of theirs such as shape, height and boundaries are not so pronounced. These can be hypothesised to be either of anthropogenic or natural origin, and visual examination is needed to classify them.

4.3. Summary

The UAV-based photogrammetric survey in the Tuva Valley of the Kings allowed us to collect data on the major local burial fields and most of the territory surrounding them. We also investigated an additional area of the mountain of Kosh-Pei. The overall area surveyed in this study is 195 km^2. After the photogrammetric processing of the data, we built a digital elevation model (DEM) and an orthophoto of high resolution (5–8 cm per pixel). Detailed analysis of the data revealed 699 cultural heritage objects with distinct morphological characteristics, according to which we classified these objects into four groups: a) large earthen or stone-earthen burial mounds (412 in total, most of them over 10 m in diameter), b) small stone burial mounds (151 in total, most of them under 15 m in diameter), c) stone circles (79 in total), and d) stone mounds in the mountains (57 in total). This classification should be seen as preliminary, done based not on the actual structure of the objects but rather on their features as manifested in the visual data. In addition, 301 anomalies of unknown origin were found that may be archaeological or natural objects or objects of contemporary anthropogenic origin (Table 1, Fig. 15).

The shapefile containing the data on the objects detected in this study is given as the article's supplementary material.

Different types of landscape require different investigation methods. Objects similar in their structure can look differently depending on a given landscape, and this is primarily due to specific features of ground cover and surrounding vegetation. All objects that stand out on the earth's surface are clearly distinguishable on flatlands, although small and low objects covered by vegetation can still be hard to detect. Also, on mountain slopes and peaks, due to sharp elevation differences, objects that stand out can still be less noticeable. Limited ground cover and low vegetation enable detecting piled stones even if these do not have pronounced relief features. Consequently, it appears optimal to conduct UAV-based investigations at the time of year when ground cover is minimal. This should enable detecting as many objects as possible, be them small yet standing out against the land surface or 'flattened'. Small-sized objects are hard to detect: in our survey, we were able to find only 8 objects and 23 anomalies with the maximum diameter of less than 5 m.

In the flatland parts of the control area, nearly all of the objects not associated with significant elevation differences are covered by vegetation and not visible in the photographs. Small objects, even where these are distinguishable in the photographs, are not always identifiable; therefore, we did not classify these as archaeological objects. We hypothesise that within the entire survey area we did not detect the majority of the objects known to be in the area which are small-sized or do not stand out against the surrounding territory, and using UAVs and digital photogrammetry in archaeological surveys of such objects under similar natural and climatic conditions appears to be ineffective.

However, we did detect all of the large objects with pronounced features previously known to be in the area, as well as some new ones. The majority of new objects are plowed burial mounds, characterised by being elevated at 0.3–1 m, having the significantly large diameter of 10–35 m and not featuring clear-cut boundaries. On the ground, such objects may be taken for natural relief elevations or may not be noticed at all.

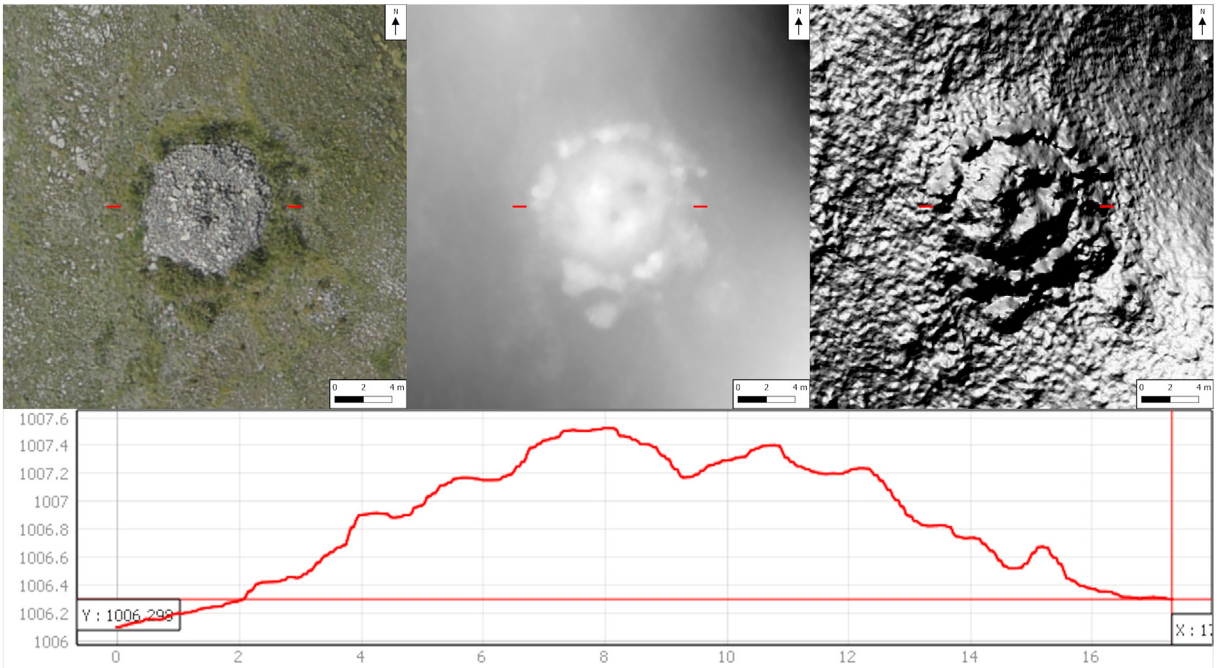

Fig. 14. One of the stone mounds found in the mountains.

Table 1
UAV-detected archaeological objects, compared with the objects on the control area plans.

	Control area		New objects in the area's periphery	Total
	Previously known objects	Previously unknown objects		
Earthen and stone-earthen burial mounds	239	65	108	412
Stone burial mounds	26	28	97	151
Stone circles	–	–	79	79
Stone mounds	–	–	57	57
Archaeological objects identified in total	**265**	**93**	**341**	**699**
Possible earthen and stone-earthen burial mounds	–	43	59	102
Possible stone burial mounds	-	47	78	125
Possible stone mounds	-	–	31	31
Other	-	6	37	43
Other (possibly archaeological) objects detected in total	**-**	**96**	**205**	**301**

In 2019, one of the substantially plowed burial mounds not present on the control area plans but detected in our UAV-based survey—an earthen burial mound—was examined by the South Siberian expedition of the State Hermitage Museum, jointly with a group of archaeologists led by Łukasz Oleszczak from the Jagiellonian University (Kraków, Poland) (Zdzieblowski, 2019). This earthen burial mound is moated and contains several graves of the early Scythian period. The data obtained on it as well as its position in the chain of similar mounds in close proximity to the burial-memorial complex of Chinge-Tei allow us to suggest that this mound is part of this complex's periphery.

In our study, large objects that stand out against the earth's surface were well visible across the entire survey area; such objects can easily be detected and mapped using UAVs and digital photogrammetry.

5. Discussion

UAV-based digital photogrammetry has a significant number of limitations as to its applicability in the search for archaeological objects. First, the productive use of this technology depends on the type of landscape and vegetation found in a given survey area. UAV-based investigations cannot be conducted in territories covered with coniferous forests, and it is only in some cases that UAVs can be reasonably deployed in territories with deciduous forests—at the time of year when trees and shrubs have no leaves. Forest canopy and undergrowth density would need to be such that would allow seeing the earth's surface well. Also, archaeological objects would need to stand out against the earth's surface and be sufficiently large, as the earth's surface points photographed by the UAV would be fewer, thus negatively affecting the resultant model's resolution. UAV and digital photogrammetry data appear to be most informative when collected in territories with low vegetation (steppes, tundra, etc.). Yet, even in such landscapes, it is preferable that survey is conducted when vegetation is the lowest, as this should better enable a more detailed analysis of the surface relief and help detect small-sized archaeological objects.

This said, UAVs cannot replace archaeological investigations on the ground, particularly as regards identification of objects. From the air, it is not always possible to see small-sized structures or low objects without clear-cut boundaries. UAV-executed surveys need to be complemented by visual examination of archaeological objects on the ground so that different types of data can be collected and cross-checked. It should be noted, though, that large-sized objects without clear-cut boundaries can sometimes be hardly recognised as such on the ground; to prevent researchers from missing such objects on the ground, surveying an area of interest via UAVs is recommended. In addition, as our study has shown, new objects can still be found even on well-studied archaeological sites. UAV-based photogrammetric survey can help identify small objects found in groups, when these cannot be easily recognised as such on the ground.

In addition, aerophotogrammetry can accelerate topographic investigations, increase precision and produce more detailed data, while the spread and affordability of UAVs helped make collecting aerial photography data less labourious and costly. Overall, UAVs can be

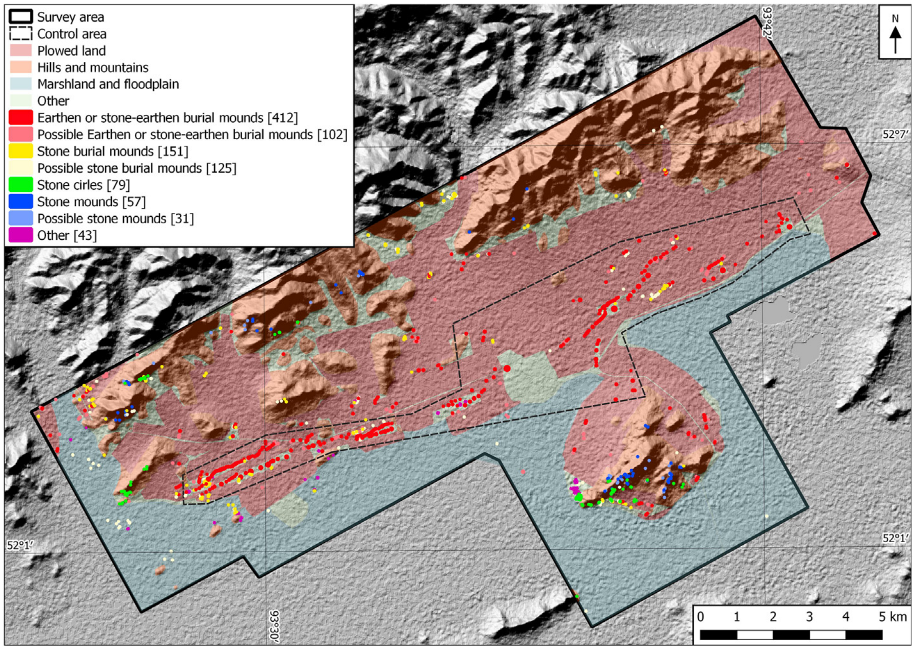

Fig. 15. Objects identified within the survey area and preliminarily classified.

recommended for use in archaeological investigations as an additional tool, or even the primary means of topographic survey, provided all the necessary conditions are met.

Another way to search for archaeological objects is to analyse satellite imagery. The survey area in this study has already been researched from such an angle by Gino Caspari (2020). Via satellite surveying, Caspari detected 716 burial mounds on the northern terrace of the Uyuk River (and west of the Tarlag River). His data on 234 objects of over 20 m in diameter (provided in the article by Caspari (2020) as supplementary material and used in this study of ours) were compared with our data, including on objects of unknown origin (only on those that are also found in Caspari's data (6 in total)).

According to Caspari's data, there are 189 objects of over 20 m in diameter within our survey area. Of these we did not detect 22 objects; we checked them and established that 4 of these objects classified by Caspari as burial mounds are in fact natural elevations in the landscape, 6 are the result of twentieth-century anthropogenic changes, and 6 more are the result of local changes in vegetation; the origin of 6 other objects could not be determined. Further, our measurements of the objects' diameter also turned out to be different from Caspari's: of the 167 objects found in both his and our datasets, 39 are of less than 20 m in diameter, according to our data, whereas in Caspari's data these have the diameter of over 20 m. Additionally, our dataset features 88 objects not present in Caspari's data: he had probably found those as well but, for his research purposes, excluded many of them that are less than 20 m in diameter. Thus, due to the selective character of Caspari's dataset, comparative quantitative analysis using these data would be unreliable, and so we did not conduct it in this study.

In sum, using satellite imagery appears to be effective enough in terms of detecting large burial mounds (of over 20 m in diameter). In Caspari's survey, it allowed acquiring good quality data, with only 11.6% of the results being false-positive and no work required on the ground (interestingly, Caspari's dataset features 5 objects that had not been mapped by Akulov in his survey of the area on the ground). However, we could not assess the quality of the results of search for archaeological objects on the basis of the satellite imagery due to the above-mentioned discrepancies in the data.

6. Conclusion

UAV-based digital photogrammetry has proved informative and effective in our study. In addition to the previously known archaeological objects that this technology enabled us to detect, we discovered a multitude of new archaeological objects which had been missed in the earlier investigations carried out on the ground. Yet, the application of this method is limited in many respects and requires a number of conditions to be met for it to produce reliable results. UAV-based digital photogrammetry appears to be hardly effective for the purposes of rescue archaeology, as UAV imagery may not reflect small-sized or low objects, and without traditional field research the risk of destruction of such objects cannot be eliminated. UAV data are not sufficient to draw conclusions as to the absence of archaeological objects in an area. However, where archaeological objects are not threatened by destruction, UAV-executed surveys can be recommended for the purposes of examining vast areas and identifying places of archaeological interest for further, more targeted research on the ground. This is particularly relevant for impassable terrains or inaccessible areas, for example, in the mountains. It should also be noted that if cheaper light multi-rotor UAVs are suitable for investigation of small areas, surveys of large areas require more expensive unmanned aircraft. When only large objects need to be examined, satellite surveying appears most suitable. Yet, further research on the ground would be warranted to confirm the origin of surveyed objects in any case.

CRediT authorship contribution statement

Mikhail V. Vavulin: Methodology, Software, Formal analysis, Resources, Writing - original draft, Funding acquisition, Visualization. **Konstantin V. Chugunov:** Investigation, Writing - review & editing. **Olga V. Zaitceva:** Investigation, Conceptualization, Writing - review & editing, Supervision, Project administration. **Evgeny V. Vodyasov:** Investigation, Writing - review & editing. **Andrei A. Pushkarev:** Investigation, Validation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.daach.2021.e00172.

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