Geomorphological processes and landforms of glacier forelands in the upper Aktru River basin (Gornyi Altai), Russia: evidence for rapid recent retreat and paraglacial adjustment

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Abstract

The glaciers in the Aktru River basin of Gornyi Altai, Russia currently represent some of the fastest receding glaciers in the world. Formation of the morainic complexes closest to the contemporary glaciers in the Aktru River basin took place during the 17th - 18th centuries with recession commencing at the end of the 18th century. Coupled with this glacial retreat, earth surface processes and vegetation succession are responding to shape the glacier forelands. This article presents the first geomorphological maps for the upper reaches of the Aktru River basin and focuses on the geomorphological landforms that occur in the rapidly changing glacier forelands. Geomorphological mapping is difficult in steep mountainous regions and, thus, mapping was completed using satellite imagery, field mapping and observations coupled with highresolution aerial photography obtained from Unmanned Aerial Vehicles (UAVs). Critical steps of the procedure used to process UAV imagery and difficulties encountered in this mountainous terrain are noted. The acquired spatial data enable the mapping and classification of small-scale transient geomorphological features such as talus, glacial and glaciofluvial landforms. Their dynamics provide insights into supraglacial and subglacial processes of the glaciers of the Aktru River basin and subsequent paraglacial adjustment. The presented highresolution spatial data, which can also be obtained at high temporal resolutions in the future, can act as a reference frame for geomorphologists and ecologists studying the temporal evolution of glacier forelands of the Aktru River basin during paraglacial adjustment and subsequent colonisation and stabilisation by biota.

Keywords: Geomorphology; Glacier Forelands; Unmanned Aerial Vehicle; Aktru; Altai; Russia

Introduction

The Altai Mountains of Central Asia comprise several NW-SE orientated ranges with elevations up to 4500 m above sea level (a.s.l.). Blomdin et al. (2016) present a cross-border regional geomorphological map of glacial erosional and depositional landforms as a framework to develop glacial reconstructions of the Altai Mountains. However, owing to important spatial variations in the timing and number of events recorded by glacial landforms across the Altai Mountains, Blomdin et al. (2018) call for additional mapping, dating, and modelling studies in individual mountains ranges and massifs to elucidate these patterns. Most of the geomorphological research in the Aktru River basin of Gornyi Altai, Russia has been devoted to mapping and monitoring the glaciers and documenting morainic deposits for palaeo-climatic reconstructions (e.g. Tronov 1925; Dushkin 1965; Narozhniy 2001; Agatova et al. 2012; Galakhov et al. 2013). In the early Holocene, from at least 10.4 ka (Nazarov et al. 2012), the glaciers in the Russian Altai Mountains, including the Aktru River basin, were probably smaller than they are at present (Solomina et al. 2015). Solomina et al. (2015) also indicate that the first evidence for glacial advances in the Russian Altai dates to 4.9-4.2 ka (the most extensive Holocene advance) with some advances at 3.7-3.3 ka, however, constraining the dates of both advances (4.9-4.2 ka and 3.7-3.3 ka) remains difficult (Agatova et al. 2012). The advances at 2.3-1.7 ka and in the 13th, 15th-16th, and 17th-19th centuries CE are more accurately dated due to extensive wood macrofossil collections in the glacier forelands (see Agatova et al. 2012). According to the alpine chronology presented by Chernykh et al. (2013), the so-called Aktru stage corresponds to the ‘Little Ice Age’. Research carried out in the upper Aktru River basin (North-Chuisky ridge) indicates that the Maliy Aktru glacier moraines correspond to two alpine stages; that is, the Fernau advance 1500–1800 (AS2) and the preceding Fernau advance 1200–1300 (AS1) (Chernykh et al. 2013). The Fernau stage moraine is associated with the outer terminal moraine complex with the radiocarbon dating of organic residues found in these moraines, clearly demonstrating their chronological separation (Galakhov et al. 2008), as had been previously suggested by Dushkin (1965) and Ivanovsky et al. (1982). The most recent glacial retreat appears to have commenced at the start of the 19th century (Agatova et al. 2012; Solomina et al. 2015) and has accelerated since the early 1950s when systematic measurements began (Galakhov et al. 2013). Present-day glaciers only occupy the highest mountains of the Altai and are sensitive indicators of both regional and local climate (Blomdin et al. 2016), with Narozhniy and Zemtsov (2011) suggesting that the glaciers in the Aktru River basin currently represent some of the fastest receding glaciers in the world.

The recent rapid recession of the glaciers in the Aktru River basin documented by Narozhniy and Zemtsov (2011) has produced several landforms during deglaciation that can provide a crucial source of information regarding the extent, character and behaviour of former glaciers. In particular, these erosional and depositional landforms are a valuable record of palaeo-glaciological characteristics including the spatial and temporal evolution of ice flow configurations, meltwater drainage patterns, basal thermal regimes, internal dynamics and ice-marginal recession (Sutherland et al. 2019). Landform identification and interpretation can be performed through geomorphological mapping, which is a well-established method for examining earth surface processes and landscape evolution in a range of environmental contexts (Chandler et al. 2018). In particular, geomorphological mapping provides essential data for palaeo-climatic and palaeo-glaciological reconstructions as well as process-oriented studies (Chandler et al. 2018). In the case of the former, geomorphological mapping can provide a framework for establishing glacial chronologies when coupled with data from dating programmes. However, palaeo-climatic reconstructions rely, crucially, on accurate landform identification and interpretation in terms of process-form regimes before dating programmes are initiated (Sutherland et al. 2019). The need for more geomorphological studies of deglaciating glacier forelands has also been highlighted (e.g. Carrivick and Heckmann 2017). Furthermore, geomorphological mapping is integral to understanding processes and landform evolution present in proglacial systems (Carrivick and Heckmann 2017). Thus, the main aim of this paper is to create detailed geomorphological maps of the glacier forelands in the Aktru River basin and accurately identify and assess the process-origins of the contemporary and relict glacial, talus, glaciofluvial and fluvial landforms assemblages to provide a geomorphological framework for establishing glacial chronologies. These geomorphological maps will enable targeted and efficient field campaigns and a better understanding of past glacier-climate interactions (Sutherland et al. 2019). However, geomorphological mapping is difficult and dangerous in steep mountainous terrains and geomorphological features in glacier forelands are typically relatively small and transient (Knight and Harrison 2018), making them difficult to map and document at high spatial and temporal resolutions. Thus, this paper also discusses the effectiveness of using Unmanned Aerial Vehicles (UAVs) to supplement traditional field surveys to map and categorise contemporary geomorphological features within rapidly changing landscapes of remote mountainous regions.

1 Geographical Setting

The Aktru River basin (50°06'03'' N, 87°40'14'' E) belongs to the Aktru – Chuya – Katun' – Ob' river system (Savichev and Paromov 2013), which flows northwest through Siberia (Figure 1). The North Chuya range, which includes the Aktru River basin, is part of a tectonic block formed by faulting during Cenozoic and Paleozoic-Mesozoic eras (Novikov 2004). Predominantly, the tectonic structures have a common north-western extension with steep incidence angles of 70°–80°. Geologically, this region is composed of strongly dislocated sericite-chlorite schists with an admixture of quartzite and other rocks of the Devonian age. In addition to the Middle Devonian deposits, Upper Silurian marine deposits of the Chuya Formation, in the form of grey-green sandstones interbedded with green, lilac and greylilac shales, occur in the valley (Petkevich 1972). Climatic conditions in the upper reaches of the Aktru River basin are characterized by a mean annual air temperature of -5.2°C with a maximum average air temperature of 9.7°C in July and minimum average air temperature of -21.6°C in January (Galakhov et al. 1987). The average annual precipitation in the upper reaches of the Aktru River basin is 890 mm (Sevastyanov and Shantykova 2001).

The Aktru River basin is a narrow glacial valley, 700-800 meters wide. Steep valley sides are dominated by talus (scree) slopes, which adjoin (sometimes vertical) rocky ledges and reach 15-50 meters in width. The rapid rate of glacier retreat has exposed expansive glacier forelands, which are dynamic environments to monitor glacial, glaciofluvial and fluvial processes. A floodplain of various widths is distinguished in the relief of the main valley floor, from several meters in the upper reaches to hundreds of meters in the middle section. The rapid rate of glacier retreat has also influenced meltwater loss and sediment yield, which affect river dynamics in the Aktru River basin (see Savichev and Paromov 2013; Vershinin et al. 2014), with implications for ecosystems downstream. The erosion of this recently exposed terrain by the action of both well-defined streams and ephemeral streams, where the channel often shifts, has implications for soil pedogenesis, sediment yield and vegetation colonisation (e.g. Davydov and Timoshok 2010), as well as local landscape development and ecosystem functioning of glacier-fed rivers downstream. The fluvial complex of landforms lower in the Aktru River basin includes a floodplain associated with first and second order stream channels (braided streams) (Figure 1). Near the base of the Aktru River basin, the river forms transient channels that transport glacial and talus sediments. These functional types of channel subsystems (erosion, transportation and deposition) are characterized by different types of channel form and process (see Chalov 2008). The foreland of the Maliy (Small) Aktru glacier erodes and transports sediment and exhibits a floodplain with braided channels. Moreover, the braided channels observed here indicate high rates of meltwater discharge and comprise a large volume of sediment entering the channel. The fluvial system located in the middle reaches of the valley near the Aktru Research Station is characterized by a single-channel and narrow floodplain. The depositional subsystem (outwash plain or valley sandur) has a scattered channel system divided into 2-3 channels and multiple anabranched patterns.

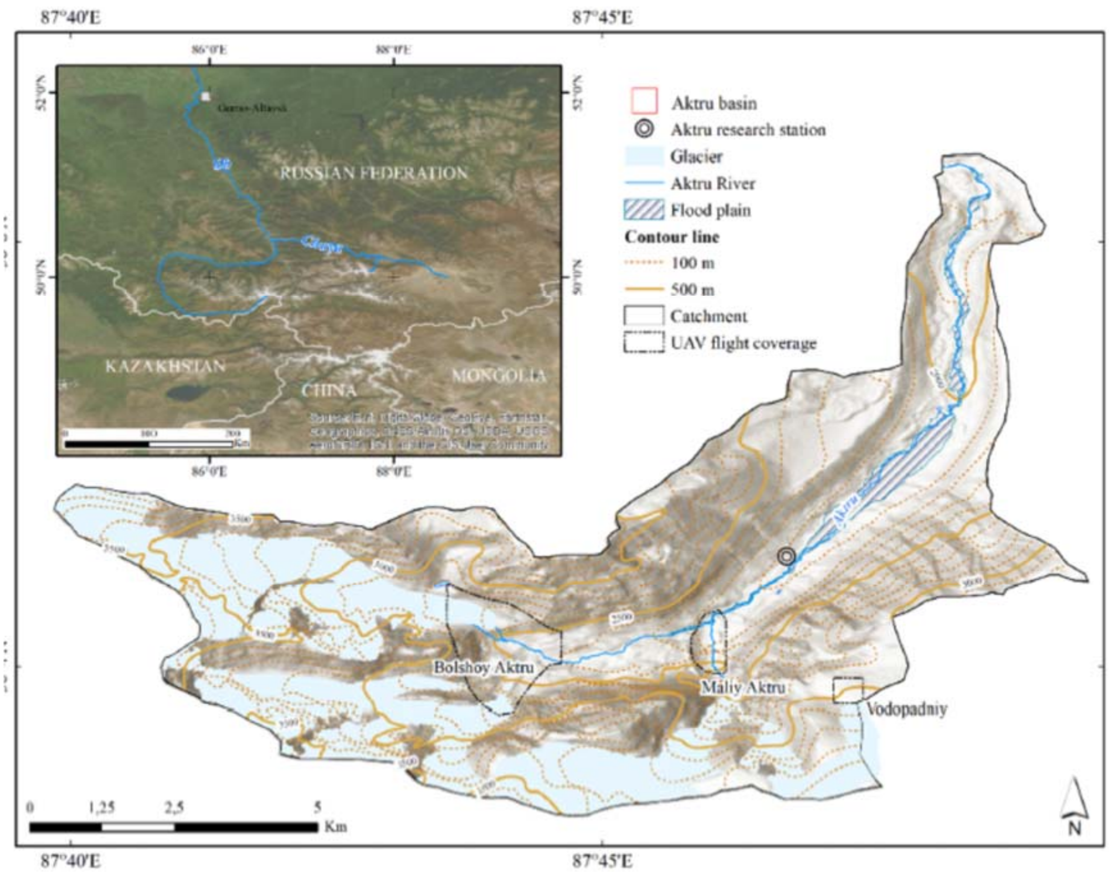

Figure 1 Location and topography of the Aktru River basin, Russia with the spatial extent of the surveys using an unmanned aerial vehicle indicated.

Narozhniy and Zemtsov (2011) state that in the northwest reaches of the Altai Mountains of Gornyi Altai, Russia (49°30' N, 88°45' E), most glaciers show signs of rapid retreat due to climate change that significantly affects the ecosystems of glacier-fed rivers downstream. Blomdin et al. (2016) note that the limited extent of contemporary glaciers in the eastern Russian and Mongolian Altai is the result of decreasing precipitation and increasing equilibrium line altitudes (ELAs) from west to east (Tronov 1949; Dolgushin and Osipova 1989; Lehmkuhl et al. 2004). Currently, glaciers in the Altai region are typically distributed between 2100 and 4500 m a.s.l. with an average glacier ELA of 2800 m a.s.l. (Aizen 2011). At the start of the 21st Century, there were about 1,030 glaciers recorded in Altai region, with a total area of 805 km^2 and volume of 42.5 km^3 (Narozhnyj and Nikitin 2003). By 2008, because of degradation, the total number of glaciers had decreased to 953 comprising an area of 724 km^2 and volume of 38 km3. The Aktru River basin comprises several glaciers, which have receded drastically in recent years (see Narozhniy and Zemtsov 2011). Previously, some glaciers covered extensive areas within the Aktru River basin but have receded into smaller individual valley glaciers. For example, the Bolshoy Aktru glacier has exhibited downwasting and receded into two separate glaciers, now known as the Leviy (Left) and Praviy (Right) Aktru glaciers (Agatova et al. 2012). The average rate of glacier recession in the Aktru River basin has been calculated at 4 m/y between 1850-2008 (Narozhniy and Zemtsov 2011). Based on the work of Narozhniy (2001), Ganyushkin et al. (2018) state that, in terms of a general retreat, the Praviy (Right) Aktru glacier stabilised or even advanced in 1936, 1940, 1969, and 1993, whereas the Maliy Aktru glacier may have stabilised or advanced in 1911, 1936, 1960, 1979, and 1993. The recently deglaciated terrains also contain small-scale transient geomorphological features that could provide insights into subglacial or submarginal processes (Ely et al. 2017). These areas are also subjected to pedogenesis which, according to Davydoy and Timoshok (2010), takes 300-500 years and culminates in the formation of podburs and cryozems. These glacier forelands are also subjected to rapid change from erosion and colonisation (Gatti et al. 2018) through various feedback mechanisms (see Eichel et al. 2016; Eichel et al. 2018).

2 Methodology

Manconi et al. (2019) demonstrate that UAVs are an effective alternative to traditional field mapping and/or standard airborne surveys in steep terrains. Difficult terrain and unpredictable weather conditions (strong wind, rain, temperature fluctuations, etc.) in mountainous areas often make it difficult to perform traditional geomorphological mapping surveys and present a set of obstacles for the use of large professional, typically fixed-wing, UAVs. Therefore, the multi-rotor DJI Mavic Pro was selected to perform aerial surveys of the study areas. The advantages of this UAV are the relatively low cost, ease of use, high flight speed, limited space requirements for take-off and landing and the ability to get high spatial and temporal resolution imagery. Mapping and morphological analysis of the depositional (positive) and erosional (negative) talus, glacial, glaciofluvial and fluvial relief forms in the glacier forelands of the Aktru River basin was conducted using Digital Surface Models (DSMs) and hillshade data to depict relief. Geomorphological maps were developed from satellite imagery and aerial imagery, acquired using a UAV, as well as from traditional field mapping. Chandler et al. (2018) state that geomorphological mapping, which uses a combination of field mapping and remotely-sensed data interpretation or several remote sensing methods, provides a holistic approach to mapping, wherein the advantages of each method/dataset can be combined to produce an accurate map with robust interpretations. The geomorphological mapping presented here follows a reductionist, thematic approach to focus primarily on glacial, periglacial and mass movement features in and adjacent to the glaciers and glacier forelands of the Aktru River basin (see Chandler et al. 2018). The orthophotos, DSMs and hillshade imagery derived from the aerial surveys formed the basis for mapping the various glacier forelands. Subsequently, landforms in these areas (indicated with a black outline on Figure 1) are mapped at the highest resolution. Areas outside the aerial surveys were mapped using satellite imagery from ESRI's Living Atlas World Imagery layer (resolution 1 m – 2.5 m). All landforms were mapped using orthophotos and hillshade data at a constant scale of 1:250 whereas landforms mapped using satellite images mapped at a constant scale of 1:1000 respectively. Data obtained in the field (GNSS points and photographs) were used to validate mapped landforms. For ease of reference, mapped landforms were subsequently categorised into geomorphic features and surficial units (see Evans et al. 2016; Chandler at al. 2018).

The flight plan for the aerial surveys was created in the Drone Deploy mobile application. Photogrammetric processing of the imagery was done using the Agisoft Photoscan software package. The surveys focused on three key sites within the Aktru River basin:
1. Glacier foreland and lower ablation surface of the Maliy Aktru glacier (0.317 km2);
2. Glacier foreland and lower ablation surface of the Bolshoy Aktru glacier (Levyi and Pravyi Aktru) (1.169 km2);
3. Glacier foreland and lower ablation surface of the Vodopadniy glacier (0.312 km2).

All studied glaciers belong to the World Glacier Monitoring Service (WGMS) "reference" glaciers, which represents one of the internationally coordinated glacier monitoring networks (WGMS 2015). The attributes of aerial surveys and post-processing parameters are shown in Table 1.

Table 1 The parameters of aerial surveys and properties of the processing of aerial images.

Studied areas	Relative flight altitude at the starting point (m)	Number of sections (chunks)	Number of images	Spatial resolution of orthophoto / DSM (cm per pixel)
Glacier foreland of the Maliy (Small) Aktru glacier	50	1	138	5/17
Glacier foreland of the Bolshoy (Big) Aktru glacier	75	1	347	10/30
Glacier foreland of the Vodopadniy glacier	50	2	302	5/10

In addition to mapping the landforms in and adjacent to the glaciers and forelands of the Aktru River basin, the glacier fronts previously demarcated by glaciologists and geomorphologists (i.e. V. Sapozhnikov, M. Tronov, and A. Rudoy) were also mapped. To complement the data produced from aerial surveys (i.e. DSMs and orthophotos), field mapping was conducted in July 2018 and July 2019 using a hand-held GPS to map landforms. Correct landform identification and interpretation of process-origin using a multiple-hypothesis approach is an imperative step in complex open systems (Schumm 1998), because any landform attributed to specific processes may only be so in origin, growth, or maintenance, or it may be so throughout its development (Thorn 1992). Moreover, correct landform identification and interpretation of process-origin is a crucial step prior to any palaeo-climatic reconstruction being developed, irrespective of the dating technique applied (Hedding et al. 2018). Thus, similar to the work of Sutherland et al. (2019), interpretations and subsequent landform classifications were based upon known process-form relationships in the recently deglaciated terrains. Field mapping in July 2018 and 2019, following the methodology of Hedding (2008), coupled with spatial data (DSMs, hillshade and orthophotos) of the terrain generated from the UAV images satellite imagery enabled the identification of talus, glacial and glaciofluvial relief forms. Symbols in the resultant geomorphological maps were adapted from Hendrickx et al. (2015) and Kneisel et al. (1998) and moraines were classified according to the descriptions presented by Schomacker (2011).

Figure 2 Photographic evidence of retreat of the Maliy Aktru glacier between 1959 (A; Photo: M.V. Tronov) and 2018 (B; Photo: D.W. Hedding).

3 Results

The glaciers in the Aktru River basin have receded drastically since observations began in the 1950s (Figure 2), with the average annual rate of glacier recession of the Maliy Aktru glacier estimated at 12.4 m/y (1952-2017). However, recently, the rate of recession of some glaciers within the Aktru River basin has shown signs of acceleration. For example, the Maliy Aktru glacier retreated an average of 5 m/y (1952-1993), between 1993-1999 it was 11 m/y, between 1999-2013 it was 27 m/y and finally new remote sensing data presented here shows that between 2013-2017 it was a staggering 43 m/y (Figure 3). This rapid and expansive retreat of the glaciers in the Aktru River basin has generated vast glacier forelands. These glacier forelands of the Aktru River basin are highly dynamic paraglacial environments that exhibit extensive glaciofluvial networks. Figure 2 depicts the mapped glacier front markers of the Maliy Aktru glacier, which clearly illustrate that glacier retreat is accelerating. The main geomorphological features in the foreland of the Maliy Aktru glacier, based on the interpretation of high-resolution DSMs, hillshade imagery, orthophotos and field observations, are mapped in Figure 3. The periglacial and paraglacial complex of the Maliy Aktru glacier enters the main Aktru valley from the left (looking upslope). It includes extensive talus (scree) slopes, an assemblage of moraines as well as a glaciofluvial and proluvial complex of glacier forelands (see Figure 3 of the Maliy Aktru glacier foreland with outlines). The assemblage of moraine deposits consists of two lateral moraines, two terminal moraines, several fragments of recessional moraine and ground moraine. The middle and lower section of the left lateral moraine abuts against the distal slope of the terminal moraine of the former Bolshoy Aktru glacier, dated to the Historical stage (Shnitnikov 1963; Okishev 1982, 2011; Agatova et al. 2012). Many gullies and rills are present on the inner slope of the left lateral moraine (Figure 4A) and are similar to those observed by Eichel et al. (2018). Glaciofluvial erosion has separated the left lateral moraine from the terminal moraine of the Maliy Aktru glacier. The terminal moraine of the Maliy

Aktru is arc-shaped, 40 to 60 m wide and 310 m long with a relative height of between 4 and 6 m. The western section of the terminal moraine tapers away near the Aktru River. The right lateral moraine of the Maliy Aktru runs along the rocky valley side for its entire length. This lateral moraine receives a large amount of rockfall material from the upper slopes and, in some places, is over-ridden by talus. Two gullies from the valley slopes to the east cut through the right lateral moraine. Mass wasting of the moraine detritus is visible at the foot of moraines in various locations with some boulders reaching 9 m (a-axis). At the intersection between the right lateral and terminal moraine, a complicated relief has developed through proluvial processes. Evidence for needle ice activity in sediments is also observed in this area.

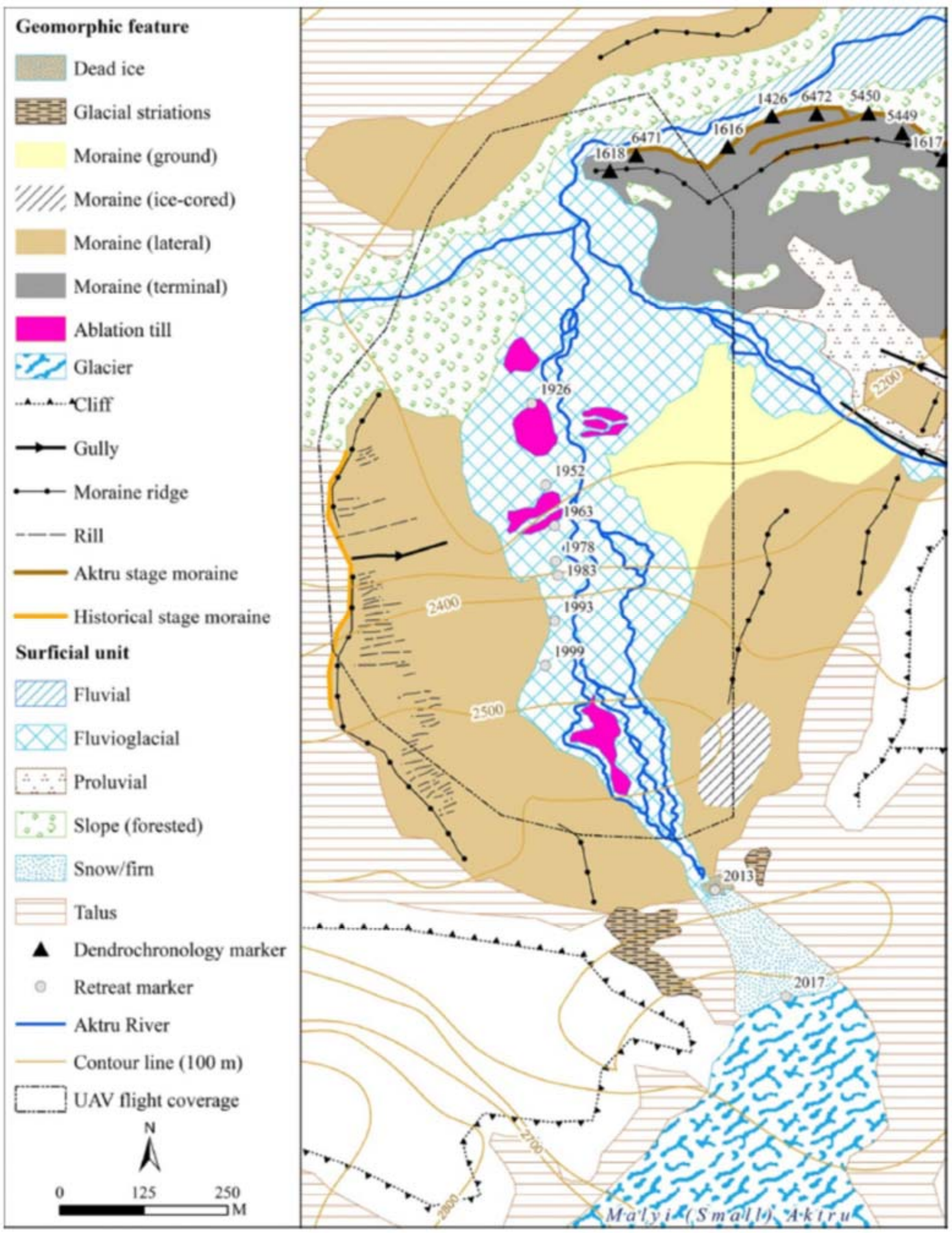

Figure 3 Geomorphological map of the foreland of the Maliy Aktru glacier.

Longitudinally, the glacier foreland is divided into three sections:
1. The upslope area exhibits active glaciofluvial erosion of moraine and talus deposits. Glaciofluvial action is reflected through the microrelief across the entire valley bottom, which is flatter than the surrounding moraines and talus slopes. The clastic material is poorly sorted.
2. Areas of partial degradation are present at the bases of moraines and proluvial cones. Near the river channels, the large clasts (a-axis > 0.5 m) are stable and do not constitute a part of sediment transport. Within modern channels, the surface is dominated by pebble- to boulder-sized material (a-axis < 0.5 m).
3. The lower section is characterized by preferential redeposition, which leads to the development of braided glaciofluvial streams. The confluence of the streams from the Maliy and former Bolshoy Aktru glaciers represents the boundary between the glaciofluvial and fluvial systems. The most intense erosion occurs here.

Just downslope of the current position of the tongue of the Maliy Aktru glacier, glacially-moulded surfaces and debris-covered dead ice are present. Further down valley, remnants of recessional moraines are visible, which might be linked to the pauses and/or advances mentioned by Ganyushkin et al. (2018). The glacier foreland is characterised by a complex ridge-hollow and knob-and-basin topography resulting from glaciofluvial erosion of unconsolidated debris and downslope movement of talus and moraine material. The glaciofluvial complex comprises two kame-hill channel networks and it changes both down and across the valley. In cross-section, it is possible to distinguish the areas of modern riverbed formation (the lightest areas with distinct bands of riverbed meanders) and areas bearing traces of melt-water flow that currently lie outside the zone of glaciofluvial channel flows.

The moraine complex of the former Bolshoy Aktru glacier comprises a terminal moraine with three arc-shaped bars as well as lateral, medial and ground moraines (Figure 4B and 5). The most recent frontal (terminal) moraine of the former Bolshoy Aktru glacier is dated to the late 20th century (Okishev and Narozhniy 2001). The lateral moraine is identified owing to its position on the valley side and linear form. The medial moraine is dominated by ablation till and has an uneven topography. The ground moraine is mostly covered by a thick layer of debris and glaciofluvial deposits. During fieldwork, its composition was partially observed within a deep incision in the glaciofluvial and moraine deposits of the Bolshoy Aktru basin. The absence of the moraines flanking and immediately downslope of the Leviy and Praviy Aktru glaciers can be explained by the recent rapid retreat as the Bolshoy Aktru glacier separated into the Leviy and Praviy Aktru glaciers. At the tongue of the Praviy Aktru glacier, moraine formations include lateral and medial moraines adjacent to the lower part of the Praviy Aktru glacier tongue. Further downslope from the Praviy Aktru glacier, a large area of debris-covered dead ice is present.

At the tongue of the Leviy Aktru glacier, a lateral moraine is located only on the left side, but it can be traced along the entire length of the glacier from the front of the tongue to the accumulation zone. The left lateral moraine has a height of 20 to 60 m at the glacier tongue and shallow debris slides expose an ice core. On the right side of the Leviy Aktru glacier, a well-marked lateral moraine is located along the mid- to upper section of the glacier, with a pronival rampart (see Hedding 2016) perched above the poorly-developed lateral moraine in an alcove of the cliffface near the glacier tongue. Just downslope of the Leviy Aktru glacier front, in the vicinity of the rôche moutonnée typically referred to as “sheep rock”, fragments of a frontal moraine, comprising mainly clastic material creating an uneven micro-topography, are observed. This frontal moraine has a total length of approximately 130 m and exhibits as a chain of arcuate ridges with heights from 3 to 11 m and widths between 19 and 22 m, as well as several smaller isometric hills, filling the area between the edge of the glacier and channel of the glaciofluvial stream. In the future, as the Leviy Aktru glacier retreats these deposits will become the frontal moraine. Evidence of needle ice activity is also found in this area. The glaciofluvial complex of landforms also occurs on the surface of the Leviy Aktru glacier, whereby channels exploit small cracks on the glacier surface.

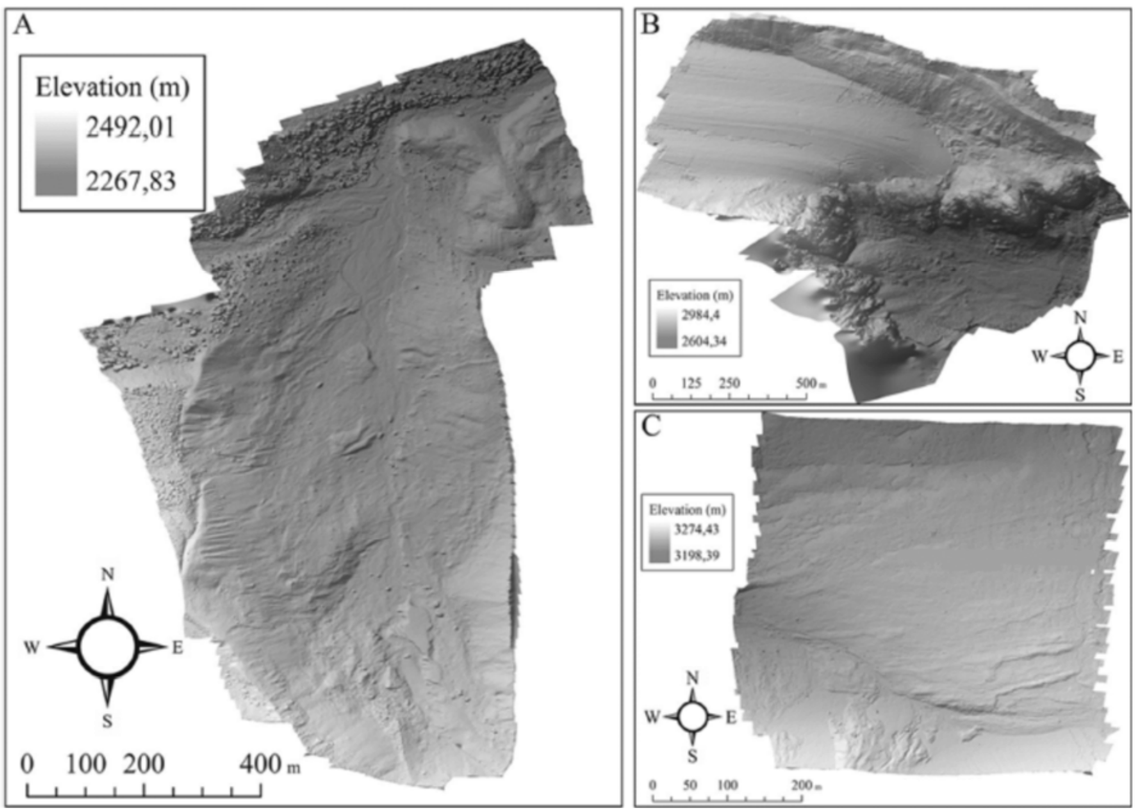

Figure 4 Digital Surface Models (DSMs) draped over hillshade imagery to depict relief in the surveyed sections of the Aktru River basin using an Unmanned Aerial Vehicle. A) DSM and hillshade imagery of Maliy Aktru glacier tongue and forelands; B) DSM and hillshade imagery of Bolshoy Aktru glacier tongue and forelands; C) DSM and hillshade imagery of Vodopadniy glacier tongue and forelands.

The Vodopadniy glacier system comprises a small cirque glacier which is 0.8 km2 in area (Figure 6). It encompasses a corrie depression that is elongated in a northerly direction, the glacier foreland consists of ground and recessional moraines, a glaciofluvial complex of landforms and surrounding rocky talus slopes. The fan-shaped moraine complex extends to the north of the glacier tongue and exhibits a hummocky relief (Figure 4C). This microrelief is formed by a set of largely parallel arcuate ridges, which run mainly from west to east. These rather pronounced relief forms represent remnants of the ground and recessional moraine. Near the glacier tongue (at a distance of 92 m) are five clearly defined arcuate moraines, marking the historical position of the frontal part of the glacier. The recessional moraines are limited in lateral extent (west to east), and the troughs between the ridges have been deepened by streams from melt-out water. The frontal moraine and the set of slightly arcuate ridges representing recessional moraines control the flow of melt and rainwater. These two meltwater streams erode and transport material from the ground moraine surface. As a result of this erosion, the glacial deposits are transferred into the glaciofluvial streams and transported downstream into the Aktru River basin. The foreland of the Vodopadniy glacier exhibits the only clearly identifiable forms of solifluction lobes and patterned ground (Rudoy 2004), which encompass sorted stripes on steeper surfaces and nets on surfaces with shallower gradients. The forms of patterned ground in the foreland of Vodopadniy glacier represent the best examples in the Aktru River basin. However, the distribution of the patterned ground is highly sporadic and most likely linked to the presence of fines to facilitate sorting. In addition, the size of the patterned ground is small (up to 0.3 m), which make them too small to map in Figure 6.

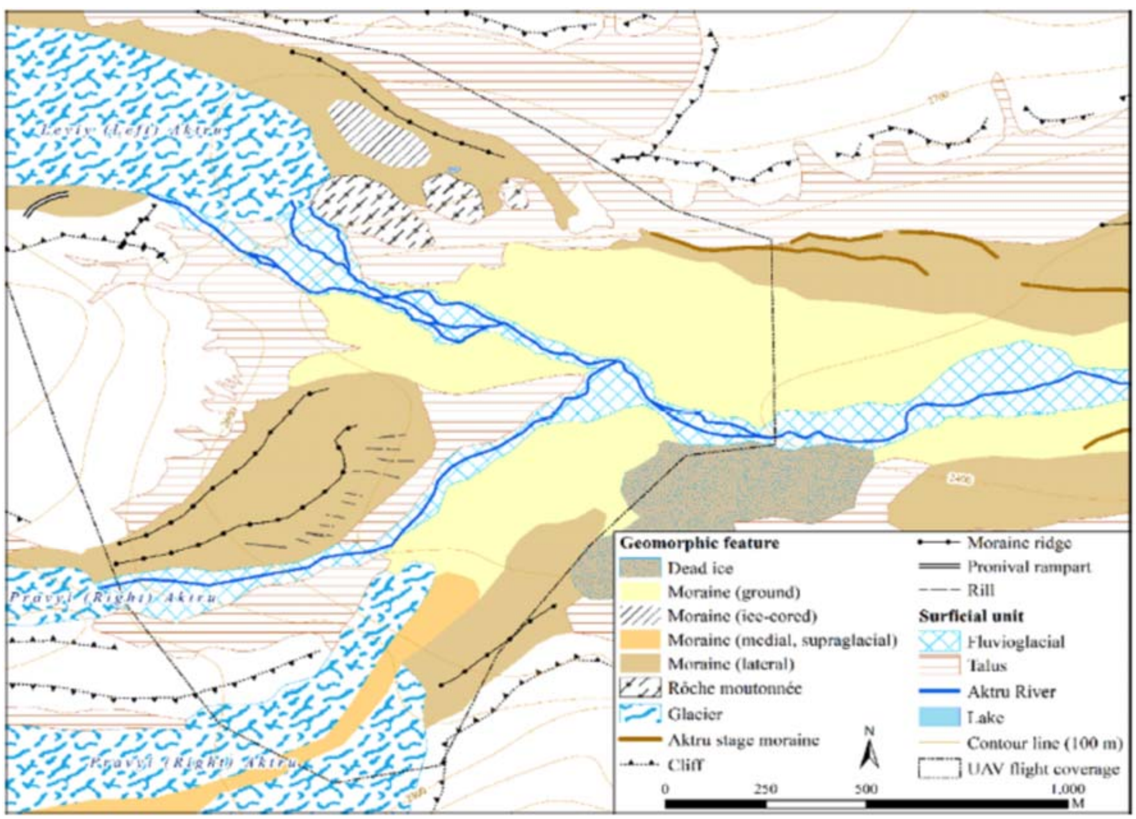

Figure 5 Geomorphological map of the foreland of the Bolshoy Aktru glacier.

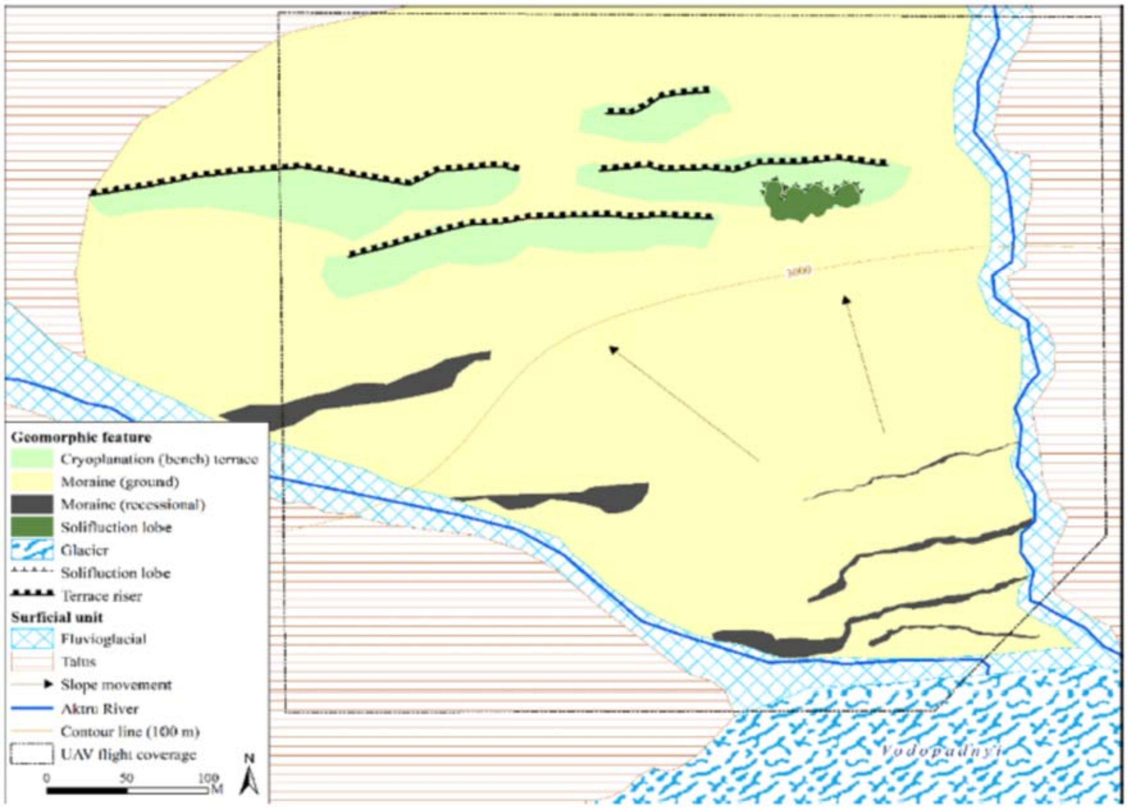

Figure 6 Geomorphological map of the glacier foreland of the Vodopadniy Aktru glacier.

4 Discussion

The recent rapid rate of glacial retreat presented here exceed the values presented by Narozhniy and Zemtsov (2011) and makes a case for intensive monitoring, through glacier mass balance measurements, to be re-instituted for these glaciers to better understand contemporary glacier dynamics. Specifically, the observed rapid rate of glacial retreat should be assessed within the context of climate change in this region of the Altai Mountains to identify any possible local differences to regional studies (see Blomdin et al. 2016; Blomdin et al. 2018). Increased monitoring of the glaciers and associated rivers should also expand on the work of Savichev and Paromov (2013) and Vershinin et al. (2014) to focus on water discharge and sediment yield, which will generate several downstream impacts over time if the rapid rate of glacial retreat continues. For example, increased water discharge in the Aktru River associated with increased melt-out may benefit downstream users in the short term but once the glaciers have melted away, water discharge will decrease dramatically and cause drastic impacts on water use and ecosystem functioning downstream.

The presented geomorphological maps of the forelands of the Aktru glaciers detail a highly dynamic environment following recent rapid glacial retreat. These maps provide a valuable framework that can be used by future studies to assess landscape evolution over time. Glaciofluvial processes on active glacier forelands often make these environments unfavourable for preservation of (small) landforms (Chandler et al. 2018). Thus, the transient nature of landforms during paraglacial landscape evolution require repeated studies in order to understand landscape dynamics which, in this case, will impact melt-water loss and sediment yield over time (Knight and Harrison 2018). Paraglacial geomorphological adjustment and subsequent colonisation and stabilisation by biota are evident in the Aktru River basin (Figure 7). Gatti et al. (2018) describe the plant α-and β-diversity along the incremental distance from the glacier forefront which they indicate confirms the three main stages of vegetation succession. Paraglacial adjustment and vegetation succession are affected by feedback mechanisms, which control landscape development in terms of stability over time (Eichel et al. 2016). Recently, Eichel et al. (2019) applied a deep learning approach using high-resolution spatial data from UAVs coupled with environmental and vegetation plot surveys to link geomorphic and ecologic properties to the glacial chronology to identify ecosystem engineer species. Once a glacial chronology for the Aktru River basin is constructed for the Holocene, a similar approach could be applied to supplement the work of Gatti et al. (2018).

Figure 7 Vegetation succession moving from left (south) to right (north) along the left lateral moraine of the Maliy Aktru glacier (Photo: D.W. Hedding).

Several types of moraines are identified in the upper Aktru River basin (Figures 3-5). Absolute (e.g. cosmogenic nuclide dating and 14C) and relative-age (e.g. Schmidt Hammer rebound) dating of the moraines in Aktru River basin should be conducted and will enable a more complete reconstruction of the glacial chronology for the Aktru River basin during the Holocene. This glacial chronology would be extremely useful to better understand glacial landscape responses to climate change over time and this information could supplement regional information for northern Asia, specifically the Altai Mountains (see Blomdin et al. 2016), which exhibits a continental climate (Solomina et al. 2015). However, similar to the reconstruction of glaciers everywhere, the deglacial record of the Aktru River basin hinges on chronologies based on the correct identification of landform process-origin using a hypothetico-deductive method (see Hedding et al. 2018) coupled with dating techniques.

It is also pertinent to highlight that the Aktru River basin is affected by seismic activity, with the most recent being in 2003 when the region was impacted by a 7.3 moment magnitude earthquake with a maximum Mercalli intensity of X (Extreme) (Ovsuchenko et al. 2004). The impacts of such co-seismic activity can complicate landform interpretation with respect to separating origin from formative processes (see Hedding et al. 2018). For example, co-seismic activity can alter debris supply onto the surface of glaciers changing albedo and debris cover and co-seismic or mass movement events can cause 'interruptions' or 'pulses', which can influence geomorphic processes by affecting debris supply from slopes (Cotton 1945). In addition, the presented geomorphological maps and high-resolution spatial data provide valuable insights from an applied perspective, whereby this data should be used to generate hazard-risk maps of the Aktru River basin. The Aktru River basin is an extremely popular tourist destination but is affected by seismic activity and prone to mass wasting such as rockfalls and mudslides (see Fuzella et al. 2018). As such, hazard-risk maps of the valley will improve the safety of tourists by identifying areas of high hazard risks.

5 Conclusions

Some mountainous regions, particularly those in Russia, have limited topographic data and high-resolution satellite imagery. This paper demonstrates the potential of using high-resolution stereo aerial photography and Digital Surface Models (DSMs) derived from UAVs in the geomorphological mapping and analysis of the Aktru glacial basin; particularly the rapidly changing glacier forelands. The DSMs coupled with field mapping and interpretation of satellite imagery was used to construct the first geomorphological maps for the upper reaches of the Aktru River basin and to obtain information about the morphology of individual landforms and their landscape assemblages. The geomorphological maps provide a better understanding of the contemporary rate of glacier fluctuations in the Aktru River basin and responses of glacier forelands, which is critical to assess the potential impacts on meltwater loss and sediment yield that will, in turn, affect downstream ecological functioning and hydrology. In particular, the mapped locations of glacial landforms (i.e. moraines) in the Aktru River basin will aid future studies that assess the palaeo-climatic during the Holocene. On a shorter timescale, the Aktru glaciers appear to be maintaining their rapid rates of retreat of 12.4 m/y (1952-2017) with extreme recent rates of retreat of 43 m/y (2013-2017), making them some of the fastest retreating glaciers in the world, exposing large tracts of freshly deglaciated terrains. Monitoring of the Aktru glaciers terminated in 2008 but, given the information on accelerated retreat presented here, it is hoped that monitoring will recommence in the near future and provide glacier mass balance data for the WGMS and importantly provide data for regional assessments of glacier mass balance in the context of climate change. Finally, the described glacier forelands are characterized by rapid change and, as such, the presented high-resolution geomorphological maps will act as a reference frame for geomorphologists and ecologists studying the temporal evolution of glacier forelands during paraglacial adjustment and subsequent colonisation and stabilisation by biota.

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