**Supplementary Material**

**Preliminary paleoenvironmental analysis and luminescence dating of upper Middle Pleistocene permafrost deposits of the Ulakhan Sular Formation, Adycha River, east Siberia**

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**Supplementary text 1: Study area**

The study area contains two key Pleistocene cryostratigraphic sequences from the Yana Uplands: the Batagay megaslump and Ulakhan Sular, the latter located ~43 km east–northeast of the slump, along the eastern bank of the Adycha River (Fig. 2a). To set the regional context, we summarize the study area in terms of its terrain and bedrock geology, Cenozoic geology, climate and permafrost, and vegetation and soils. Further details obtained by regional geological mapping at 1:200,000 scale are given by Vdovina (2002a, 2002b) and Vdovina and Skuba (2013a, 2013b).

# *Terrain and bedrock*

The terrain consists mainly of poorly dissected, flattish watersheds and gentle (5–10°) convex slopes at elevations of ~250–600 m above sea level (asl) inset by the two major valleys of the rivers Yana and Adycha (Fig. 2). Both valleys are linked to a network of tributary valleys and streams that drain into them. Up to four terraces above the modern floodplain occupy the valley network. Low mountains rise above this terrain, principally Mount Ynnakh–Haya (1622 m asl) developed on a dome-like granite massif. This massif hosts upland (cryoplanation) terraces and pillar-like tors (kisilyakhs).

Five terrain units are pertinent to the present study: the Verkhoyansk depression, the Yana–Adycha plateau (informal name), the Nizhneadychanska (or Tuostakhskaya) depression, the Sililyakh plain and the Tabalakh depression (Fig. 2). The Verkhoyansk depression is located in the western part of the study area and is occupied by the River Yana, which flows close to the town of Batagay. The Yana–Adycha plateau rises to elevations of ~250–350 m asl and represents the higher ground between the Yana and Adycha rivers. The plateau is widely underlain by folded Triassic sandstones, siltstone and mudstones, locally intruded by Early Cretaceous granites, and numerous igneous dykes. Some rocks have been weakly metamorphosed by contact metamorphism. Valleys on the plateau run mainly westward into the Yana basin and eastward into the Adycha basin. Incipient erosional hollows are common, and many hillslopes contain gullies, for example near the Batagay megaslump (Murton et al., 2023). Much of this upland area is thought to have undergone steady uplift throughout the Cenozoic. The Nizhneadychanska depression contains the Adycha River, a right-bank tributary of the River Yana, which it joins to the north of the study area. Erosion on the outer bend of a large meander of the Adycha River has created a major stratigraphic section at Ulakhan Sular. The Sililyakh plain rises to elevations of ~200–420 m asl to the east of the Nizhneadychanska depression. Ravines incise the western edge of the plain. Farther east, the Tabalakh depression is inset in the Sililyakh plain.

*Cenozoic geology*

Throughout the late Cenozoic, most of the Yana Uplands were unglaciated (Batchelor et al., 2019) and belonged to the western region of western Beringia (Fig. 1a). In the absence of glacial disturbance, the uplands and basins in the study area contain a wide variety of unconsolidated nonglacial deposits (Fig. 2a–b), the thickness of which ranges from 0.5–3.0 m on watersheds and steep slopes, through 3–20 m on gentle slopes to maxima of 50–185 m in the valleys and intra-mountain depressions. According to Vdovina and Skuba (2013a, 2013b), the deposits accumulated during the Miocene, Pliocene, Pleistocene, and Holocene (Fig. 2). Pliocene deposits are distinguished on the geological map in Fig. 2a (as per Vdovina and Skuba, 2013a) but grouped together with Miocene deposits as ‘loose, pre-Quaternary formations’ in the geological cross-section in Fig. 2c (as per Vdovina and Skuba, 2002a).

*Miocene*

Miocene deposits up to 93.6 m thick have a limited spatial distribution and are mostly buried in the bottoms of intra-montane troughs or ancient river valleys. **Lower Miocene formations** represent weathering profiles 11–32 m thick developed on Triassic sedimentary rocks and Early Cretaceous contact hornblende rocks. Exposures of the weathering profiles at the surface are limited to the left side of the Adycha River. Overlying the weathering crust or resting directly on bedrock, but not exposed at the surface, are alluvial–slope deposits of the **Magyar Formation**. Usually 3–10 m thick (maximum 30 m), these deposits commonly consist of rock fragments with clay infills between them, though rounded pebbles occur in ancient thalwegs. Spore–pollen spectra from the formation point to dark spruce, *Picea* sp., and juniper, *Juniperus* sp., forests with patches of birch, *Betula* spp., and broad-leaved species. The overlying alluvial deposits of the **Malyshov Formation**, also not exposed, are up to 34 m thick and consist of pebbly gravel, pebbly sand and pebbly loam. Spore–pollen spectra from them suggest the presence of dark coniferous forests with patches of deciduous and broad-leaved trees associated with moderately warm and humid conditions.

*Pliocene*

Pliocene deposits of the Ust-Nelgehinski and Tabalakh formations crop out extensively beneath the Ulakhan Sular plateau to the east of the Ulakhan Sular river bluffs (Fig. 2a). The **Ust-Nelgehinski Formation (aN2*un*)** is dominantly sandy gravel and pebbly sand up to ~30 m thick that infills the middle parts of inter-montane depressions and the main parts of piedmont alluvial plains. It is interpreted as alluvial in origin. Spore–pollen assemblages from it record coniferous forest of pine–larch, *Pinus* sp. and *Larix gmelinii*, or mixed forest, with unforested areas. The overlying **Tabalakh Formation (LaN2*tb*)** is mostly sand and fine sand ≤95 m thick that form the upper part of sedimentary sequences infilling inter-montane troughs. The formation has been attributed to lacustrine and alluvial deposition. Palynological data from the Tabalakh Formation differ from older deposits through their almost complete lack of tree pollen and from younger deposits in the absence of *Pinus pumila* (dwarf stone pine) and *Selaginella sibirica* (Siberian spikemoss). This formation was potentially a major source of sand for younger deposits in the region.

*Pleistocene*

The **lacustrine deposits (LII3–4)** consist of silt and sandy loam with some gravel and plant remains, and interlayers and lenses of ice and peat. The deposits attain thicknesses up to 40 m and occur at elevations of ~200–250 m asl on the eastern and western flanks of the Yana–Adycha plateau and within the Tabalakh depression (Fig. 2a and c). Spore–pollen spectra within the deposits are mainly green mosses, sedges, wormwood, *Artemisia* sp., and mixed grass, suggesting that exceptionally cold and relatively dry conditions existed when one or more extensive lakes formed. According to Vdovina and Skuba (2013a, 2013b) the age of the deposits is assigned to steps 3–4 of the Middle Neopleistocene, i.e., to MIS 9 (~337–279 ka) and MIS 8 (~279–243 ka). However, according to the geological cross-section shown in Fig. 2c, this high, elevated lacustrine unit has been deeply incised by the paleo-Adycha River, such that the lacustrine deposits must be older than the Adycha Formation and overlying Ulakhan Sular Formation. Thus we discuss the lacustrine deposits before the Adycha Formation and consider the lacustrine deposits to be the oldest identified Pleistocene deposits in the study area.

The oldest Pleistocene deposits identified by Vdovina and Skuba (2013a, 2013b) in the study area have been designated as the **Adycha Formation (aE–I*ad*)**. The Adycha Formationcomprises sandy loam to loamy sand 6–30 m thick, contains abundant pebbles derived from the surrounding Mesozoic uplands, and is embedded in Neogene strata or overlies bedrock. Remains of large vertebrate fauna within the Adycha Formation include *Equus caballus*, *Bison priscus*, and *Castor fiber*, and small vertebrate fauna include *Lepus* sp., *Lemmus obensis*, and *Microtus* sp. (summarized in Kaplina et al., 1983; Grigoriev et al., 2017). Spore and pollen analysis has suggested development of a light coniferous forest with a mix of *Picea* sp. and *Betula* shrubs (Kaplina et al., 1983). The Adycha Formation crops out at Ulakhan Sular, and also in the headwaters of the Batagay River and in the valley of the Arsenopiritovyy River. The formation is interpreted as alluvial in origin. Its age has been assigned to the Eopleistocene to lower Neopleistocene, i.e., between a maximum age of 2.58 or 1.8 Ma and a minimum age of ~429 ka (end of MIS 12) (Vdovina and Skuba, 2013b). Sediments from this formation have a normal polarity and have been correlated with the Brunhes Chron (0.78–0 Ma) (Minyuk and Ivanov, 2011). Sher et al. (2011) suggested that the upper part of the formation may be of late Middle Pleistocene age. An electron spin resonance (ESR) age of 360 ± 17 ka (MIS 11–10) has been obtained from bivalve shells ~1 m above river level (arl) within ‘unit 2’ of it (Nikolskiy, 2010; Lee et al., 2015). A second ESR age of 212 ± 10 ka from bivalves shells ~5 m arl in ‘unit 3’ (Nikolskiy, 2010) has been attributed to MIS 7–6 (Nikolskiy, P.A., personal communication, 2019), though we cannot discount the possibility that this is from the base of the Ulakhan Sular Formation.

Middle Neopleistocene (i.e., MIS 11–6: ~429–132 ka) deposits in the study area are identified as the Ulakhan Sular Formation and lacustrine deposits. The **Ulakhan Sular Formation (aII1–2*us*)**,≤43 m thick, comprises mainly sands with lenses of gravel and abundant remains of vegetation. Soil-like bodies occur within it, including initial paleo-Fluvisols 3–7 cm thick, with well-preserved pervasive grass and sedge root remnants and redoximorphic features (Supplementary Fig. 1). Bones of large vertebrates from the Ulakhan Sular Formation include *Mammuthus primigenius*, *Bison priscus*, *Rangifer tarandus*, and *Equus caballus* (summarized in Kaplina et al., 1983; Grigoriev et al., 2017). Spores and pollen from it are dominantly green mosses and grasses, with subsidiary amounts of *Artemisia* sp. and shrub *Betula*; the spectra are consistent with tundra–steppe vegetation and areas of shrub–steppe vegetation associated with a cold, dry climate (Kaplina et al., 1983). The Ulakhan Sular Formation crops out in the fourth terrace above the modern floodplain, the terrace surface having a relative elevation of about 45–55 m above the floodplain. The formation occurs principally around Ulakhan Sular, as well as in the valley of the Asar-Jungkure River, and in two areas several kilometers southwest of Batagay (Fig. 2a). It has been interpreted as alluvial in origin, likely deposited by the ancestral rivers Adycha, Yana and Asar-Jungkure, based on its spatial distribution shown in Fig. 2a. Its age—inferred from its stratigraphic position directly above the Adycha Formation and by the finds of Middle Pleistocene fauna (mammoth, cave lion, and wolf) in sediment cones along the base of the sections—has proved contentious. Suggested ages range from steps 1–2 of the middle link of the Neopleistocene (Vdovina and Skuba, 2013b) to the Kazantsev interglacial (MIS 5) and, near the top of the sequence, possibly Zyrian (MIS 4: ~72–58 ka) of the Late Pleistocene (reviewed in Kaplina et al., 1983). The former are equivalent to the interval of time spanning the Holsteinian and Fuhne stages of the Middle Pleistocene of northwest Europe (Zastrozhnov et al., 2018), i.e., MIS 11 (~429–365 ka) and MIS 10 (~365–337 ka), respectively. Kaplina et al. (1983), however, concluded that the bulk of the sequence is of Middle Pleistocene age, possibly with Late Pleistocene deposits at the top, similar to Sher et al. (2011), who assigned the Ulakhan Sular Formation to the latest Middle Pleistocene to early Late Pleistocene. A canid skull with close affinities to a Paleolithic dog morphotype has provided a calibrated 14C age of ~17,200 BP (Germonpré et al., 2017). Unfortunately the skull from Ulakhan Sular was found without stratigraphic context.



Supplementary Figure 1. Initial paleo-Fluvisol with well-preserved pervasive root remnants within the Ulakhan Sular Formation. Photograph by Aleksei Lupachev.

The upper Neopleistocene (i.e., MIS 5–1: ~132–11.7 ka) is represented in the study area by two units of alluvial deposits and one of lacustrine deposits. **Alluvial deposits of the third terrace** **above the floodplain (a3III1–2)**, with a relative elevation of 30–35 m, occur along valleys near Ese-Khayya, the Batagay River, and southwest of Betenkes. The deposits consist of gravel overlain by sand and sandy loam up to 32 m thick. Spores, pollen, and vertebrate remains within them suggest deposition of gravel coincided with *Larix* forest and sparse *Picea* areas before climate cooling and drying led to tundra–steppe vegetation (Kaplina et al., 1983). The age of the unit has been assigned to steps 1–2 of the upper Neopleistocene, i.e., approximately MIS 5–3. **Alluvial deposits of the second terrace** **above the floodplain (a2III3–4)**, with a relative elevation of 12–15 m, are dominantly sandy in the Yana basin and sandy to pebbly in the Aydcha basin. The unit is up to 15 m thick. Spore–pollen spectra suggest a tundra–steppe vegetation associated with a cold climate (Kaplina et al., 1983). The age of the unit has been assigned to steps 3–2 of the Upper Neopleistocene, i.e., ~MIS 4–3. **Lacustrine deposits** **(LIII4)** up to 10 m thick consist of loams and sandy loams with intercalated peat. The deposits form a low lacustrine plain and underlie some thermokarst depressions. Their age has been tentatively assigned to step 4 of the upper Neopleistocene, i.e., ~MIS 2, based on geomorphological features.

*The last glacial–interglacial transition*

Stratigraphically, the last glacial–interglacial transition is represented by upper Neopleistocene–Holocene alluvial, slopewash (‘deluvial’ in Russian terminology), and solifluction deposits. **Alluvial deposits (a1III-H)** up to 12 m thick consist predominantly of sand and loam, pebbly near the base and peaty near the top. The deposits occur widely within the first terrace above the modern floodplain in second-order river valleys. Pollen and spores of green mosses, shrub birch, and alder dominate the spectra (Kaplina et al., 1983). **Deluvial–solifluctional deposits** **(dsIII-H)** commonly 5–10 m thick (≤30 m) of sandy loam and some angular rock debris widely mantle hillslopes to the west of the Adycha River valley. The deposits transition downslope into alluvial deposits of the first terrace above the floodplain, and have therefore been assigned a similar age to it.

*Holocene*

Holocene deposits are widespread in the study area, both in valleys and on hillslopes. Some deposits are subdivided into lower and upper parts, though others are undivided in terms of their age assignment. **Alluvial deposits of the high floodplain (aH1)** occur in the main part of the Yana and Adycha river valleys—e.g., near the settlements of Batagay and Betenkes (Fig. 2a)—and in second-order valleys that drain granitoid massifs. Up to 12 m thick, the sediments consist of loams and sandy loams, and less commonly gravel, and often contain abundant plant remains or peat lenses. Spore and pollen spectra from the deposits are dominated by green mosses, *Alnus alnobetula* and *B. nana*, and smaller amounts of sedges, dwarf *Pinus pumila* and *L. gmelinii*, a palynological assemblage similar to present-day conditions (Kaplina et al., 1983). **Alluvial sands and gravels (aH2) of channel facies and low floodplains** of the Yana and Adycha rivers are up to 8 m thick. The palynological assemblage within them reflects the present-day vegetation: sparse *Larix* forest with alpine tundra and *Betula* groves in river valleys. **Lacustrine and bog** **(l,plH2)** **deposits** comprise loams with abundant plant remains, including peat, and are particularly common on the wide floodplains of the Yana and Adycha rivers and on old lacustrine deposits. Higher and/or steeper terrain on watersheds, plateaus, and hillslopes are underlain by a variety of slope deposits, usually no more than a few to several meters thick, of sand, sandy loam or gravel. These are attributed to **eluvial (eH)** (i.e., material remaining after erosion and degradation; Miller and Juilleret, 2020), slopewash (**deluvial: dH**), and downslope creep of dry material **(desertion: drH** in Russian terminology;see Harris et al., 2018) and **solifluction (sH)**. Finally, some **technogenic deposits (tH2)** of silt, sand, and gravel represent human activities; examples include mine tailings near Batagay and Ese-Khayya.

## *Vegetation and soils*

*Present day*

The present-day vegetation in valleys and lower hillslopes is commonly open woodlands dominated by *L. gmelinii* with an undergrowth of *Betula nana subsp. exilis* and *B. divaricata* and a ground cover of lichen–green moss. Upland areas tend to be covered by thickets of *P. pumila*, abundant wild rosemary (*Ledum palustre*), rare graminoids, mountain tundra species or vegetation-free stony debris.

Soils of the forested watersheds and gentle hillslopes are commonly Histic Spodic Cryosols (Arenic) (IUSS Working Group WRB, 2022) beneath open woodlands of *Larix* spp. (Supplementary Fig. 2a). These soils have a well-developed peaty-humus uppermost horizon (~10 cm thick) underlain by a slightly bleached, sandy mineral horizon with an ooid (“caviar-like”) postcryogenic soil structure. Middle mineral soil horizons bear poorly expressed redoximorphic features and signs of migration of humic substances. Lowermost suprapermafrost horizons are oversaturated and structureless. Materials underlying the upper permafrost layer commonly have a massive or microlenticular cryostructure, with the ice-rich transition layer (Shur et al., 2005) well expressed in relatively moister conditions of relief microdepressions. Underdeveloped stony Leptosols with evidence of cryogenic sorting characterize rubbly mountain areas. Underdeveloped sandy Arenosols and permafrost-affected Fluvisols underlie small river valleys. Nearly all natural soil profiles (excluding Fluvisols) contain features of wild fires (charcoal) and phytoturbations after windfalls. Naturally (or in rare cases anthropogenically) disturbed areas are occupied with pioneer vegetation – mainly rosebay (*Epilobium angustifolium*), different species of *Artemisia sp.*, and abundant graminoids.



Supplementary Figure 2. Modern soil and aeolian sand-sheet deposits in the Batagay–Betenkes region. (a) Histic Spodic Cryosol (Arenic) beneath open woodland of larch near Batagay megaslump. The soil profile is morphologically similar to those dug at Ulakhan Sular. (b) Recently deposited sand on a sparsely vegetated surface. Field of view ~1 m across. (c) Sand-rich mossy organic layer beneath active sand sheet (note freshly deposited sand on green leaves). Gloves for scale. (b) and (c) are located ~60 m inland of the bluff top near section 4 at Ulakhan Sular. Photograph (a) by Aleksei Lupachev, (b) and (c) by Julian Murton.

Although vegetation on the terrace surface above the Ulakhan Sular outcrop can be broadly described as *L. gmelinii* taiga, our local vegetation survey revealed significant difference in undergrowth and composition of ground cover plants along a transect from the bluff edge of the terrace inland for more than ~150 m. Near the terrace edge, the plant cover can be characterized as an open *L. gmelinii* forest with *Salix* undergrowth. The sparse groundcover vegetation was represented by several *Carex* species, and the moss cover was completely buried by a layer of sand up to 5 cm thick, the sand actively blown by wind from the outcrop itself. Farther inland (60 m) into the larch forest, the sand cover thinned, giving opportunity for a greater number of plants to establish in the undergrowth: wild rose (*Rosa canina*), willow (*Salix* sp.), grasses (*Poa* species and *Deschampsia caespitosa*) and sedges (*Carex*), round-leaved wintergreen (*Pyrola rotundifolia*), bearberry (*Arctous alpina*), *Senecio* sp., and dwarf birch (*B. nana*). A test soil pit revealed a frost table at 90 cm depth. The upper 30 cm of the active layer was composed of alternating bands of mosses and sand, the latter probably washed down the profile due to rain and/or snowmelt. Such recent sand–plant cover alternation might be an example of a process that resulted in horizontal alternating bedding (HAB) in the stratigraphy of Ulakhan Sular deposits. Mineralized soil composed the deeper 60 cm of an active layer. At a distance of ~150 m from the terrace edge, aeolian sand transport does not affect the vegetation cover. Here, closed-canopy larch taiga with well-developed moss cover (*Sphagnum*) and wood horsetail (*Equisetum silvaticum*), bilberry (*Vaccinium uliginosum*), and cranberry (*Vaccinium vitis-idaea*) was established. According to the soil test pit, the frost table was at a depth of 50 cm in sand, with a sand-free organic layer comprising the upper 25 cm.

Noteworthy is extrazonal vegetation (not typical for taiga forest) also present near the Ulakhan Sular outcrop, particularly on south-facing slopes of gullies, terraces, and hills. About 1 km from the bluff, we observed steppe patches with thyme (*Thymus* spp.), wind flower (*Pulsatilla* spp.), sage (*Salvia* spp.), silver speedwell (*Veronica incana*), mugworts (*Artemisia* spp.), rockfoils (*Saxifraga* spp.), junegrass (*Koeleria* spp.), lousewort (*Pedicularis* spp.), fescue (*Festuca* spp.), and cinquefoils (*Potentilla* spp.).

*Paleovegetation*

Palaeobotanical investigations of the Ulakhan Sular bluff began in the 1970s with the palynological work of Tomskaya and Goncharova (Biske, 1978). The lower sand unit (0–1 m arl) revealed pollen typical for coniferous forests with small-leaved undergrowth and dense grass cover. In the samples from the overlying unit (1–8 m arl) pollen of light coniferous pine–larch woodlands with spruce and birch shrubs was present (Tomskaya and Savvinova, 1971). The upper unit of the Ulakhan Sular Formation (> 8 m arl) was deposited along with high densities of Bryales spores, spores of shrub alder (*Alnaster*) and dwarf birch (*B. nana*) as well as mugworts (*Artemisia* sp.), Caryophyllaceae, and Chenopodiaceae.

Plant macrofossil remains were recovered and analyzed by Dorofeev and Nikitin from the lower part of the Ulakhan Sular bluff (from river level up to 8 m arl). According to the summary of Doforofeev and Nikitin’s work provided in Kaplina et al. (1983), the typical river valley vegetation was alder and willow thickets in a larch taiga zone. Hill tops and slopes were occupied by wood sorrel (*Oxyria digyna*), buttercup (*Ranunculus hyperboreus*), cloudberry (*Rubus chamaemorus*), crowberry (*Empetrum nigrum*), and mesoxerophilic plants like knotweed (*Polygonum* sp.), sorrel (*Rumex* sp.), saltbush (*Atriplex* sp.), and bugseed (*Corispermum* sp.). The presence of wetland and aquatic plants—a wide variety of bur-reed (*Sparganium* sp.), water-plantains (Alismataceae), pondweeds (*Potamogeton* sp.), water lily (*Nuphar* sp.), sedges (Cyperaceae), coontails (*Ceratophyllum* sp.), water-crowfoot (*Ranunculus* sp.), water milfoil (*Myriophyllum* sp.), and bogbean (*Menyanthes trifolia*)—also suggested accumulation of sediments in the river bed.

Kaplina et al. (1983) reported six distinct palynocomplexes or pollen assemblages (labelled I to VI) for the Ulakhan Sular Formation. Their sequence can be described as an alternation of woodland and open vegetation, where pollen assemblages with odd numbers have a prominent amount of woodland vegetation, and those with even numbers are dominated by open vegetation types and a low amount of woodland pollen. Pollen assemblage I came from the lower part of Kaplina’s section III (corresponding to our sections 1 and 3; Fig. 3) of the bluff, covering the first 2 m arl. Low pollen and spore concentrations were typical for the samples. Kaplina et al. proposed that open larch woodlands with undergrowth represented by *Betula* sp., *Salix* sp., *Alnaster*, and *P. pumila* were present at the river valley, whereas watersheds were occupied by steppe vegetation such as *Artemisia*, Caryophillaceae, Amaranthaceae, green mosses, and spike mosses (*Selaginella* sp.).

Pollen assemblages II–VI were sampled at Kaplina et al.’s section II (corresponding to our section 4; Fig. 3). Pollen assemblage II extended 0–5.5 m arl. Palynological samples revealed a high concentration of pollen characteristic of steppe vegetation with *Artemisia*, Caryophyllaceae, Poaceae, and spores of green mosses and *Selaginella rupestris*, suggesting the presence of open ground, meadow and steppe vegetation in the region. The low аmount of tree and shrub pollen—with several counts of *P. pumila*, *Salix*, shrub *Betula* spp., and single grains of *Larix* and *Betula*—suggests that patches of woodland vegetation were sustained along the river valley.

Pollen assemblage III extended 5.5–12 m arl. The pollen diagram shows a high concentration of woodland genera and a lower concentration and diversity of grasses, although *Artemisia* pollen counts still remain prominent. Such an assemblage indicates well-established *Larix* forests resembling modern northern taiga type, while south-facing slopes were occupied by steppe vegetation and barren ground.

Pollen assemblage IV is reconstructed on the basis of samples from 13 to 47 m arl. The pollen diagram is similar to palynocomplex II: a low concentration of woodland vegetation, and a high concentration of grasses, *Artemisia*, Amaranthaceae, Caryophyllaceae, and Asteraceae.

Pollen assemblage V extended from 47 to 52 m arl and was dated to ≥43,000 years ago (MSU-570). The results delivered from these samples resemble pollen assemblage III: a high amount of *Larix* pollen, and a prominent concentration of *Carex* pollen and *Selaginella* sp., representing woodlands with open ground patches.

Pollen assemblage VI extended 52–60 m arl and is similar to palynocomplex IV, with high concentrations of *Artmesia*, Caryophyllaceae, Asteraceae, and *Selaginella*, indicating open ground and steppe vegetation.

**Supplementary text 2: Methods**

***Mineralogy: Sample preparation and procedure of QEMSCAN® analysis***

Eight samples of sand grains were prepared for QEMSCAN® analysis. For each sample, 5 g of dry material were placed into 30 mm diameter sample moulds with enough Epofix resin to produce a 1.5-cm-thick block. The moulds were then placed in a Struers Citovac for four 5-minute vacuum cycles to remove any trapped air before transfer to a pressure vessel. The moulds were allowed to harden in the pressure vessel and the resulting hardened blocks were then removed from the moulds. A Tegrasystem machine was used to grind and polish the blocks using four progressively finer grinding discs to obtain an even and polished surface. The polished blocks were then carbon-coated ready for QEMSCAN® analysis.

The QUANTA 650F Scanning Electron Microscope used for the QEMSCAN® analysis was fitted with two energy dispersive spectrometer detectors (EDSs), a back-scattered electron detector (BSE), a microprocessor, and electronic processing unit. Acquisition and processing of raw data were undertaken simultaneously by the system and results transferred directly to the iExplorer software once analysis had ended to enable user investigation of mineral and textural features.

Samples were analyzed in QEMSCAN® by user selection of an analysis area split into fields to form a grid. Each field was split further into measurement points, with the number of points per field and distance between points determined by the scanning resolution. Lowering the scanning resolution increases the number of data points measured and the time needed to complete an analysis. For this analysis, the polished blocks were each divided into 1.0 mm x 1.0 mm fields and analyzed with a 15 keV electron beam and 10 nA sample current. The samples were analyzed at a 25 μm scanning resolution over the entire surface of each block. Initially, primary and secondary backscattered electrons were measured, with brightness indicating sample density, and the surface detections being equated to atomic weight. A back-scatter cut-off was then used to distinguish the rock fragments from the mounting medium and these particles were further analyzed with X-rays collected by the EDS detectors to obtain a mineralogical map of each sample. The given measurement settings enabled approximately 600,000 mineral measurements to be taken per sample across the surface of each polished block.

***Luminescence dating***

### *Sample preparation*

All samples were prepared and measured in the Luminescence Dating Laboratory at the University of Gloucestershire. Equivalent dose (De) preparation was conducted under controlled lighting conditions provided by Encapsulite RB-10 (red) filters, to preserve the luminescence signal retained by mineral grains. Sediments situated at the end of the cylinders and exposed to sunlight during sampling were removed and discarded. The remaining sediments were extracted and treated with HCl (10%) and H2O2 (15%) to remove carbonates and organics, respectively. Samples were dry sieved to isolate the modal fine sand fraction (125–180 µm), from which K-feldspar grains were then extracted using heavy-liquid (sodium polytungstate) separations at 2.53 and 2.58 g.cm-3. To isolate the quartz fraction, minerals >2.58 g.cm-3 were treated with 40% HF for 60 minutes to etch the outer 10–15 µm of quartz grains affected by alpha radiation and to remove any residing low-density minerals. The remaining material was rinsed with HCl (10%) to remove acid-soluble fluorides, then dried and resieved. A further heavy-liquid separation at 2.68 g/cm3 was conducted on the quartz fraction to remove heavy minerals. Initial De analysis highlighted significant feldspar contamination within quartz isolates, an issue previously highlighted in the region (Murton et al.,2022). To remove contaminants, samples with sufficient material underwent digestion in 35% H2SiF6 for two weeks. Multi-grain aliquots of quartz (6 mm) and K-feldspar (2 mm) were then mounted on stainless-steel cups and aluminium discs, respectively, for De determination. Note that differences in substrate and aliquot size relate to analytical equipment and limited mass of K-feldspars. Bulk subsamples for lithogenic dose rate (Dr) assessment were dried and homogenized using a mill. For each sample 50 g of material were sealed in a polystyrene pot with a polyethylene lid and stored for 3 weeks prior to measurement for radon retention.

### *Measurement*

Quartz De measurements were conducted on a Lexsyg Smart luminescence detection system (Richter et al., 2015) using a single-aliquot regenerative-dose protocol (Murray and Wintle, 2000, 2003). The quartz signal was stimulated for 50 s at *~*125°C (105°C substrate temperature) using blue laser diodes fronted by 3 mm Schott GG420 and HC448/20 filters, conveying a peak wavelength of 445 ± 3 nm at 30 mW.cm-2 to the measurement position. Photon emissions from quartz were separated from stimulation photons by 2.5 mm Hoya U-340 and 1 mm NG4 glass filters, and a Delta BP 365/50 interference filter, then detected by a Hamamatsu H7360-02 bi-alkaline cathode photomultiplier. Aliquot irradiation was conducted using a 1.85 GBq 90Sr/90Y β source delivering 0.11 Gy.s-1. Preheat temperatures were selected using dose recovery experiments with a range of substrate temperatures (140 to 240°C); optimum preheats were those that produced given-to-recovered dose ratios consistent with unity. To detect feldspar contamination using post-IR OSL ratios (Duller, 2003), aliquots were also given an IR stimulation using IR laser diodes filtered by 3 mm RG 715 and conveying a peak wavelength of 850 ± 3 nm at 200 mW.cm-2.

K-Feldspar measurements were conducted on a Risø TL-DA-15 reader (Markey et al., 1997; Bøtter-Jensen et al., 1999) with an updated DA-20 controller. Optical stimulation was provided by IR diodes (Telefunken TSHA 6203) conveying a peak wavelength of 875 ± 80 nm at 40 mW.cm-2. Irradiation was conducted using a 1.48 GBq 90Sr/90Y β source delivering 0.07 Gy.s-1. An adapted MET-pIR-IRSL protocol (Li et al., 2014) was used for K-feldspar De assessment, with aliquots preheated to 300°C for 60 s, after which they were stimulated for 100 s at 50°C then 200°C to remove the signals most likely to be affected by anomalous fading. A pIRIR signal was then measured for 100 s at 250°C (pIRIR250). Photons arising from K-feldspar simulation were filtered by 2 mm Schott BG-39 and 3 mm Schott BG-3 glass then detected by an EMI 9235QA photomultiplier fitted with a blue–green sensitive bi-alkaline photocathode. Dose recovery experiments were conducted on 3 aliquots of each sample to assess the ability of each signal (IR50, pIRIR200 and pIRIR250) to recover a known laboratory dose.

To monitor sensitivity changes during measurement, quartz and feldspar aliquots were given 30 Gy test doses, against which natural and regenerative doses were standardized to produce dose response curves (DRCs). DRCs were fitted with a single saturating exponential function in Analyst (Duller, 2015) using the initial 0.25 and 5 s of stimulation for signal integration and final 5 and 10 s for background subtraction for quartz and K-feldspar, respectively. To assess the reproducibility of both OSL and IR/pIRIR signals across the dose range, all aliquots were given a replicate low and high regenerative dose to produce repeated dose ratios.

Anomalous fading and bleaching tests were conducted on the K-feldspar fraction of one sample (GL17111). Fading measurements followed a similar procedure to Auclair et al. (2003) but incorporated measurements for each K-feldspar pIRIR signal. To minimize the influence of initial sensitivity change upon fading calculations, each aliquot was subjected to the first cycle of the adapted MET-pIR-IRSL protocol. Aliquots were then bleached for 4 h in a Hönle SOL2 solar simulator to minimise any residual, optically sensitive signals. Each aliquot was then given a 480 Gy dose and preheated at 300°C for 60 s before storage. Lx/Tx values were obtained for three aliquots per storage interval (62, 421, 771 and 1418 hrs) and *g*-values were calculated using the R Luminescence package (Kreutzer et al., 2012). Bleaching tests were conducted upon two sets of aliquots from GL17111 to assess the potential size of residual doses. One set of aliquots was naturally dosed (unmeasured); the other had been measured, bleached and given a laboratory dose of 480 Gy. Aliquots were placed in the solar simulator for durations ranging from 30 s to 4 hrs and residual doses were then measured using the K-feldspar measurement protocol.

Concentrations of K, Th and U within sediments were estimated using a laboratory-based Ortec GEM-S high-purity Ge coaxial detector spectrometer system, calibrated with certified reference materials supplied by CANMET. Estimates of radionuclide concentration were converted into external lithogenic Dr values (Adamiec and Aitken, 1998) using DRAC (Durcan et al., 2015), accounting for Dr modulation forced by grain size (Mejdahl, 1979) and gravimetric moisture content (Zimmerman, 1971). Gravimetric water content (22.6%) was assumed to be representative of the burial period, however, the effects of in-situ ice content upon Dr is unknown and cannot be accounted for. A K content of 12.5% (Huntley and Baril, 1997) was used to account for lithogenic radiation internal to K-feldspar grains. Cosmogenic Dr values were calculated using sample depth, geographic position, and matrix density (Prescott and Hutton, 1994). Luminescence ages are reported as thousands of years (ka) before the time of sampling (2017).

**Supplementary text 3: Results**

## *Adycha Formation*

The Adycha Formation exposed at the base of section 2 was at least 3 m thick, sand-rich and texturally variable (Table 1; Supplementary Table 2). The particle size varied from silt, through fine to medium sand to pebbly sand or sandy gravel. The colour varied from brown to orange brown, grey and dark grey. Sedimentary structures included well-laminated to cross-stratified sand with foresets dipping towards the northwest to massive units of silt, pebbly sand or sandy gravel. Pebbles observed were up to 4 cm in maximum dimension and rounded to subangular. Wood fragments up to 15 cm diameter and a few meters long were abundant. They had rounded ends. Pore ice cemented the formation, and a sand wedge and sand vein descended into it from the overlying Ulakhan Sular Formation (Fig. 6a).

Sample A17-K-06—from ~3 m arl (~3 m below the contact between the Adycha and Ulakhan Sular formations, ~4.5m below A17-S2-OSL1)—provides very sparse plant macrofossil data: only several sedge nutlets. Sedges have a broad ecological tolerance and if not identified to species level, cannot be characteristic. However, this sample provided several elytra of beetles *Dicheirotrichus mannerheimii* and *Ceutorhynchus* sp., both were also found in the presumably Holocene sample A17-K-05. *Dicheirotrichus mannerheimii* Sahlb. occupies well-drained sites with diverse grasses and herbs and inhabits the taiga zone as well as steppe patches within it (Sher and Kuzmina, 2013). Genera of *Ceutorhynchus* feed on plants of Brassicaceae (*Draba* sp.) and Asteraceae families that inhabit mostly woodlands (Korotyaev, 2020).

**Supplementary Table 1.** Stratigraphy and sedimentology of section 1 (67°42’12.6”N; 135°43’44.2”E), Ulakhan Sular.

|  |  |  |
| --- | --- | --- |
| **Unit and thickness (m)** | **Description** | **Interpretation** |
|  | **Sedimentology** | **Ground ice and cryogenic structures** | **Organic material** |  |
| Ulakhan Sular Formation (≥20) | ~30–35 m above river level (arl): well-stratified sand, horizontal to subhorizontal strata few mm to 10s cm thick (not examined in detail) | Ice wedges in and adjacent to wood-rich organic body; several cm to few 10s of cm wide, ≤ few m high (Fig. 6e) | Prominent lens of black, wood-rich organic body ~15 m wide, ≤5 m thick; irregular lower contact with relief ~2–3 m (Fig. 5g). Abundant woody material ≤ at least 10 cm diameter, ≤ few meters long | Erosive base to woody organic body (similar to woody debris lenses at Batagay megaslump; Murton et al., 2017, 2022) |
| ~15–20 m arl: well-stratified fine–medium sand with (1) horizontal–subhorizontal, planar parallel laminated (Supplementary Fig. 3); (2) trough cross sets ~0.5–1.5 m thick, some with well-developed, concave-up basal erosion surfaces (Fig. 5a and Supplementary Fig. 3); (3) tabular cross sets (Supplementary Fig. 3); or (4) reactivation surfaces in one cross set. Numerous truncation surfaces (horizontal, subhorizontal or concave-up). Possible trough cross-lamination.  | Pore-ice cemented | Few occurrences of isolated or clumped in situ roots.Sand is largely free of in situ rootlets (in contrast to HAB, which contains abundant in situ rootlets) | Channel-belt deposits of sandy braided river:(1) upper flow regime plane bed (flood deposits);(2) large, sinuous-crested, subaqueous dunes;(3) bars; (4) stage change during bar migration (Collinson, 1970; Cant and Walker, 1978; Sambrook Smith et al., 2006; Ashworth et al., 2011) |



**Supplementary Figure 3**. Stream channel deposits comprising a large tabular cross set at least 1.5 m thick (deposited at the margins of a migrating bar), horizontal planar parallel lamination (upper flow regime plane bed deposits), and a trough cross set (subaqueous, sinuous-crested dune deposits), ~15–20 m arl, section 1, Ulakhan Sular Formation. Photograph by Julian Murton.

**Supplementary Table 2.** Stratigraphy and sedimentology of section 2 (67°41’14.5”N; 135°44’02.6”E), Ulakhan Sular.

|  |  |  |
| --- | --- | --- |
| **Unit and thickness (m)** | **Description** | **Interpretation** |
|  | **Sedimentology** | **Ground ice & cryogenic structures** | **Organic material** |  |
| 3. Un-named unit overlying Ulakhan Sular Formation (~2) | Uppermost 2 m (top S2 in Fig. 5h): sand, silty sand and silt; horizontal parallel stratification, strata few mm to 2 cm thick |  | Black cryoturbated organic layer; white mollusc remains ≤ few millimeters long (cf. *Pisidium* spp.) abundant in dark grey silt to silty sand, dark brown organic layers and grey sand | Pond or small-lake deposits |
| 2. Ulakhan Sular Formation (≥20) | 6 to at least 45 m arl:Horizontal alternating bedding (HAB): grey fine sand and dark grey silty sand, well stratified. Horizontal–subhorizontal, planar to gently undulating to wavy strata, 0.5 to several centimeters thick (Figs. 5c–d, 6a–c) | Multiple sand wedges, at different stratigraphic levels, few centimeters to 30 cm wide, at least several meters high (some chimney-like; Fig. 6c), spaced ~5–7 m laterally apart, with well-developed vertical sand laminae; sand veins at 6.3 m arl | In situ roots and rhizomes, some woody, abundant | Aeolian sand-sheet facies (cf. Schwan, 1986, 1988)Primary sand veins and syngenetic sand wedges (cf. chimney-like sand wedges in aeolian sand-sheet deposits of Kittigazuit Formation; Murton and Bateman, 2007) |
| Basal 30 cm or more of light grey fine sand with subcritical climbing-ripple cross lamination and trough cross lamination (Fig. 5b) |  |  | Subaqueous current ripples and climbing ripples (fluvial) (Ashley et al., 1982) |
| Lower contact: sharp, planar horizontal with darker grey sand of Ulakhan Sular Formation overlying yellowish–light grey sand of Adycha Formation |  |  | Basal erosion surface |
| 1. Adycha Formation (>3) | 4–6 m arl: Variable particle size: sand, silt, pebbly sand to sandy gravel. Fine–medium sand, brown to orange brown, uncohesive, well laminated, cross set with foresets dipping towards northwest. Dark grey silt, massive, cohesive and involuted. Dark grey pebbly sand to sandy gravel, clast–matrix-supported, pebbles ≤4 cm, rounded to subangular. Erosional surfaces within the formation | Pore-ice cemented.Sand vein extends down from overlying formation.Sand wedge at least 2 m high, ≤15 cm wide, with well-developed vertical laminae, some branching downwards | Abundant wood fragments ≤15 cm diameter, ≤ few meters long, with rounded ends in pebbly sand to sandy gravel. Large vertebrate bones on beach, possibly derived from Adycha Formation | Fluvial depositPrimary sand wedge and sand vein |

**Supplementary Table 3.** Stratigraphy and sedimentology of section 3 (67°41’41.2”N; 135°44’25.7”E), Ulakhan Sular.

|  |  |  |
| --- | --- | --- |
| **Unit and thickness (m)** | **Description** | **Interpretation** |
|  | **Sedimentology** | **Ground ice and cryogenic structures** | **Organic material** |  |
| Ulakhan Sular Formation (≥20) | ~20 m arl: horizontally stratified sand | Composite sand–ice wedge, ≤15 cm wide, >1.5 m high, comprising alternating sand veins and ice veins; few sand veins extend below icy part of wedge (Fig. 6d) |  | Composite wedge of primary infilling |
| ~15 m arl: grey, humic, medium sand, massive. Some stratified fine sand and silty sand, with planar parallel lamination to cross stratified. Sedimentology cf. section 1. No evidence of horizontal alternating bedding |  | Brown organic layers to lenses, few millimeters to 3 cm thick, horizontal to subhorizontal, laterally continuous for at least 2 m to discontinuous lenses several centimeters wide (Fig. 5f). In situ roots, delicate, abundant in sand. Brown fibrous organic mat in dark grey icy silty sand above other examples | Channel-belt deposits of sandy braided river. Multiple stacked palaeosols attributed to warm climate similar to that at presentPossible stratigraphically higher equivalents to thick peaty paleosols identified by Kaplina et al. (1983) |

**Supplementary Table 4.** Stratigraphy and sedimentology of section 4 (67°41’34.0”N; 135°44’27.8”E), Ulakhan Sular.

|  |  |  |
| --- | --- | --- |
| **Unit and thickness (m)** | **Description** | **Interpretation** |
|  | **Sedimentology** | **Ground ice and cryogenic structures** | **Organic material** |  |
| Ulakhan Sular Formation (≥20) | ~20 m arl: pinstripe lamination: planar parallel lamination, with laminae several millimeters to 1 cm thick, gently dipping | Sand wedges ≤7 m high, with chimney-like structureComposite sand–ice wedge ≤15 cm thick, at least 4 m high, containing ice veins and sand veins | Fine root mats, brown, fibrous, adjacent to chimney-like sand wedge, ~35 m arl | Aeolian sand-sheet depositsSyngenetic sand wedges of primary infilling (cf. Murton and Bateman, 2007)Composite wedge of primary infillingAeolian wind ripples (pinstripe lamination cf. Bateman and Murton, 2006) |

**Supplementary Table 5.** Stable isotope (δ18O, δD and d excess) minimum, mean and maximum values, standard deviations as well as slopes and intercept in the δ18O–δD diagram for ice and composite wedges as well as pore ice, respectively.

|  |  |  |
| --- | --- | --- |
|  | **Ulakhan Sular exposure** | **Holocene river bank Adycha River** |
| **Ice wedge/type of water** | **A17-IW1 (composite wedge)** | **A17-IW2 (composite wedge)** | **Pore ice** | **A17-IW3** |
| Width (m) | 0.15 | 0.15 | n/a | 0.3 |
| Samples (n) | 3 | 3 | 2 | 10 |
| δ18O min (‰) | –32.02 | –31.65 | –27.99 | –30.4 |
| δ18O mean (‰) | –31.9 | –31.57 | –24.9 | –28.98 |
| δ18O max (‰) | –31.75 | –31.47 | –21.82 | –28.15 |
| δ18O sd (‰) | 0.14 | 0.09 | 4.36 | 0.74 |
| δD min (‰) | –258.8 | –236.6 | –208.8 | –236.6 |
| δD mean (‰) | –257.5 | –234.5 | –189.1 | –226.3 |
| δD max (‰) | –256.1 | –232 | –169.5 | –220.5 |
| δD sd (‰) | 1.4 | 2.4 | 27.8 | 5.2 |
| D min (‰) | –2.7 | 16.6 | 5.1 | 4.4 |
| D mean (‰) | –2.3 | 18 | 10.1 | 5.5 |
| D max (‰) | –2 | 19.8 | 15.1 | 7.3 |
| D sd (‰) | 0.4 | 1.6 | 7.1 | 0.9 |
| Slope | 9.65 | 25.74 | 6.37 | 7.01 |
| Intercept | 50.31 | 578.1 | –30.43 | –23.25 |
| R2 | 0.96 | 1 | 1 | 0.99 |

**Supplementary Table 6.** Bulk mineralogy of eight sediment samples, determined by QEMSCAN®, from Ulakhan Sular Formation (Sed-1 to Sed-7) and overlying deposits (Sed-8). Units % volume.

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
|  | **Sed-1** | **Sed-2** | **Sed-3** | **Sed-4.1** | **Sed-4.2** | **Sed-6** | **Sed-7** | **Sed-8** |
| **Quartz** | 47.56 | 47.85 | 46.70 | 51.28 | 46.57 | 43.86 | 44.23 | 39.50 |
| **K-feldspar** | 7.66 | 7.70 | 6.83 | 6.60 | 7.52 | 6.10 | 7.58 | 3.86 |
| **Plagioclase feldspar** | 18.83 | 18.95 | 19.28 | 18.03 | 19.97 | 18.84 | 19.08 | 19.59 |
| **Biotite** | 1.07 | 1.19 | 1.11 | 1.17 | 1.10 | 1.67 | 1.24 | 1.17 |
| **Muscovite** | 3.08 | 2.95 | 3.26 | 3.46 | 3.09 | 3.69 | 3.73 | 3.35 |
| **Chlorite** | 4.31 | 4.40 | 4.61 | 4.72 | 4.37 | 5.02 | 4.81 | 6.09 |
| **Illite** | 7.92 | 7.70 | 8.00 | 6.89 | 8.00 | 9.58 | 7.97 | 13.24 |
| **Glauconite** | 0.06 | 0.07 | 0.05 | 0.06 | 0.06 | 0.12 | 0.05 | 0.13 |
| **Smectite** | 2.00 | 1.95 | 1.87 | 1.64 | 1.90 | 1.75 | 2.57 | 1.26 |
| **Kaolinite** | 2.62 | 2.67 | 2.79 | 2.76 | 2.74 | 3.16 | 2.72 | 6.56 |
| **Calcite** | 0.45 | 0.44 | 0.50 | 0.09 | 0.35 | 1.06 | 1.25 | 1.76 |
| **Ferroan calcite** | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| **Dolomite** | 0.43 | 0.51 | 0.77 | 0.17 | 0.45 | 1.07 | 1.08 | 0.80 |
| **Ferroan dolomite** | 0.01 | 0.03 | 0.03 | 0.01 | 0.03 | 0.09 | 0.03 | 0.09 |
| **Ankerite** | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| **Siderite** | 0.73 | 0.77 | 0.79 | 0.69 | 0.89 | 0.76 | 0.76 | 0.28 |
| **Gypsum / anhydrite** | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.03 | 0.01 | 0.04 |
| **Pyrite** | 0.01 | 0.00 | 0.01 | 0.01 | 0.00 | 0.01 | 0.00 | 0.00 |
| **Heavy minerals** | 0.81 | 0.74 | 0.96 | 0.69 | 0.82 | 0.91 | 1.07 | 1.17 |
| **Pores** | 2.26 | 1.87 | 2.21 | 1.56 | 1.90 | 2.04 | 1.57 | 0.76 |
| **Others** | 0.19 | 0.21 | 0.22 | 0.18 | 0.22 | 0.26 | 0.24 | 0.36 |
| **Total (%)** | 100.00 | 100.00 | 100.00 | 100.00 | 100.00 | 100.00 | 100.00 | 100.00 |

**Supplementary Table 7.** Heavy minerals of eight sediment samples, determined by QEMSCAN®, from Ulakhan Sular Formation (Sed-1 to Sed-7) and overlying deposits (Sed-8). Units % volume.

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
|  | **Sed-1** | **Sed-2** | **Sed-3** | **Sed-4.1** | **Sed-4.2** | **Sed-6** | **Sed-7** | **Sed-8** |
| **Epidote** | 0.03 | 0.02 | 0.04 | 0.03 | 0.04 | 0.04 | 0.07 | 0.03 |
| **Amphibole** | 0.18 | 0.12 | 0.17 | 0.06 | 0.14 | 0.14 | 0.26 | 0.13 |
| **Titanite** | 0.05 | 0.04 | 0.06 | 0.05 | 0.05 | 0.04 | 0.06 | 0.04 |
| **Rutile** | 0.06 | 0.08 | 0.08 | 0.09 | 0.08 | 0.08 | 0.06 | 0.12 |
| **Apatite** | 0.27 | 0.24 | 0.31 | 0.28 | 0.27 | 0.32 | 0.32 | 0.49 |
| **Zircon** | 0.01 | 0.01 | 0.02 | 0.01 | 0.01 | 0.02 | 0.01 | 0.01 |
| **Monazite** | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| **Ilmenite** | 0.04 | 0.03 | 0.05 | 0.04 | 0.03 | 0.04 | 0.05 | 0.03 |
| **Chromite** | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| **Magnetite** | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| **Olivine** | 0.05 | 0.06 | 0.08 | 0.05 | 0.07 | 0.09 | 0.06 | 0.17 |
| **Serpentine** | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| **Pyroxene** | 0.05 | 0.06 | 0.06 | 0.02 | 0.05 | 0.06 | 0.09 | 0.06 |
| **Garnet** | 0.02 | 0.02 | 0.02 | 0.01 | 0.02 | 0.03 | 0.03 | 0.03 |
| **Spinel** | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| **Tourmaline** | 0.04 | 0.05 | 0.05 | 0.04 | 0.04 | 0.05 | 0.04 | 0.04 |
| **Kyanite** | 0.00 | 0.00 | 0.00 | 0.00 | 0.01 | 0.00 | 0.00 | 0.00 |
| **Pyrrhotite** | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| **Others & Pores** | 99.19 | 99.26 | 99.04 | 99.31 | 99.18 | 99.09 | 98.93 | 98.83 |
| **TOTAL** | 100.00 | 100.00 | 100.00 | 100.00 | 100.00 | 100.00 | 100.00 | 100.00 |

**Supplementary Table 8.** An overview of identified plant and invertebrate macrofossils found within samples from Holocene riverbank alluvium and from deposits above, below and within the Ulakhan Sular Formation.

|  |  |  |
| --- | --- | --- |
| **Taxon** | **Element** | **Sample name** |
| A17-K-03(Holocene riverbank alluvium ~2 m bgs) | A17-K-05(un-named silty unit above Ulakhan Sular Formation, 1.7 m bgs, section 2) | A17-K-06(Adycha Formation ~3 m below upper contact, section 2) | A17-K-07(composite sample of Ulakhan Sular Formation, section 2) |
| **Trees, shrubs and forest vegetation** |
| *Betula* sp. | catkin scale |   | + |   |   |
| *Betula* sp. | nutlet | + | + |   |   |
| *Larix gmelinii* | needle | + | + |   |   |
| *Larix gmelinii* | cone |   | + |   |   |
| *Larix gmelinii* | seed |   | + |   |   |
| *Rubus idaeus* | pyrene |   | + |   |   |
| *Moehringia laterifolia* | seed |   | + |   |   |
| *Carex* sect Digitatae | nutlet |   | + |   |   |
| **Aquatic plants** |
| *Potamogeton* cf. *filiformis* | fruit |   | + |   |   |
| *Potamogeton* scf. *vaginatus* | fruit |   | + |   |   |
| *Potamogeton* sp. | fruit |   | + |   |   |
| **Riparian plants** |
| *Chenopodium* cf. *rubrum* | seed |   | + |   |   |
| **Other** |
| *Carex* sp. | nutlet | + | + | + |   |
| *Carex* sp. | utricle |   | + |   |   |
| Bryophyta |   | + |   |   |   |
| non-identified | rootlet |   |   |   | + |
| non-identified | wood fragment |   |   | + |   |
| **Planktonic crustaceans** |
| Daphniidae |   |   | + |   |   |
| **Invertebrates** |
| *Pterostichus* (*Cryobius*) sp. | elytron |   | + |   |   |
| *Pterostichus* (*Lenapterus*) *vermiculosus* Men. | elytron |   | + |   |   |
| *Dicheirotrichus mannerheimii* Sahlb. | elytron |   | + | + |   |
| *Ceutorhynchus* sp.  | elytron |   | + | + |   |
| *Pterostichus* (*Cryobius*) *ventricosus* Esch. | elytron |   | + |   |   |

bgs = below ground surface.

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