

Sediment provenance of late Quaternary morainic, fluvial and loess-like deposits in the southwestern Verkhoyansk Mountains (eastern Siberia) and implications for regional palaeoenvironmental reconstructions

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A provenance analysis of late Quaternary deposits from tributaries of the Aldan and Lena rivers in Central Yakutia (eastern Siberia) was carried out using analysis of heavy minerals and clay mineralogy. Cluster analysis revealed one assemblage that is characterized by relatively high proportions of amphibole, orthopyroxene and garnet as well as pedogenic clay minerals, reflecting a sediment provenance from the wide catchment area of the Lena and Aldan rivers. In contrast, the three other clusters are dominated by stable heavy minerals with varying amounts of clinopyroxene, apatite and garnet, as well as high percentages of illite and chlorite that are indicative of source rocks of the Verkhoyansk Mountains. Glacial moraines reveal the local mountain source signal that is overprinted by the Lena-Aldan signal in the oldest moraines by reworking processes. Alluvial sediments in the Verkhoyansk Foreland show a clear Lena source signal through intervals of the middle and late Pleistocene, related to a stream course closer to the mountains at that time. Loess-like cover sediments are characterized by the dominant Lena provenance with increasing proportions of local mountain sources towards the mountain valleys. Aeolian sands in an alluvial terrace section at the mountain margin covering the time between 30 ka and 10 ka BP reflect temporarily dominant inputs of aeolian materials from the Lena Plains. Copyright © 2007 John Wiley & Sons, Ltd.

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1. INTRODUCTION

The Verkhoyansk Mountains of Central Yakutia (eastern Siberia) are situated in one of the world's extreme continental settings around the 'cold pole' of the northern hemisphere. Strong seasonal climate gradients and long-lasting periglacial conditions since about 2.5 Myr have given rise to widespread and deep-reaching permafrost (Velichko and Nechaev 2005). During the Quaternary glacial–interglacial climate cycles, cryogenic processes, fluvial and aeolian activity, and lake formation sculptured the Yakutian landscape. Local glaciations affected the Verkhoyansk Mountains and its foreland (e.g. Rusanov *et al.* 1967; Kind *et al.* 1971; Kind 1975; Kolpakov 1979; Péwé and Journaux 1983; Zamoruyev 2004).

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The present paper focuses on sedimentological provenance studies of morainic, fluvial and loess-like sediments exposed along the tributaries of the Lena and Aldan rivers at the southwestern margin of the Verkhoyansk Mountains, whose regional glaciation history and permafrost palaeoenvironment is being investigated by a joint Russian–German research project (Stauch *et al.* 2005, 2007; Popp *et al.* 2006).

By using clay mineralogy and heavy-mineral analyses, the purpose of the study is to outline the mineralogical inventory of the different genetic sediment types and to discuss their origin in terms of palaeoenvironmental changes. The basis of our interpretations is provided by the mineralogical composition of recent fluvial sands that are presumed to reflect the average detrital source signals in the respective modern sedimentary catchment areas. Mineral assemblages from glacial tills and glaciofluvial outwash sediments of morainic arcs were investigated to constrain the palaeo-catchment areas of former glaciers in the Verkhoyansk Mountains and are tested for their potential as a stratigraphic tool for the correlation of distinct morainic stages observed between the studied river outcrops. Furthermore, detrital source signals in aquatic deposits of ancient river terraces that interfinger with glacial deposits are helpful in giving insights into postulated displacements of the course of the River Lena in the past (e.g. Kolpakov 1986; Grigoriev *et al.* 1989; Alekseev and Drouchits 2004).

2. REGIONAL GEOLOGY

The area of study stretches from the Verkhoyansk Mountains across the southwestern Verkhoyansk Foreland to the Lena and Aldan rivers in Central Yakutia (Figure 1). Field work took place in 2002 and 2003 along the Tumara River (64°N/130°E), a tributary of the Aldan, and along the Dyanushka River (65°N/126°E), a tributary of the Lena (Figure 1). Both rivers originate in the Verkhoyansk Mountains and pass through the glacially and periglacially formed foreland. The area is situated in the continuous permafrost zone, climatically characterized by a strong seasonal temperature gradient. Mean January and July temperatures of −41°C and +19°C, respectively, and a low mean annual precipitation of around 250 mm for the meteorological station in Yakutsk (Agriculture Atlas of the Republic Sakha (Yakutia) 1989) characterize the cold continental climate, promoting physical weathering processes.

2.1. Pre-Quaternary geology

Yakutia lies at the boundary of two major geotectonic provinces with diverse stratigraphic and lithological successions that influence the mineralogical inventory of modern river sediments in the area (Behrends *et al.* 1999; Peregovich *et al.* 1999): the Siberian Platform to the west and the Verkhoyansk-Kolymian Orogen to the east.

Crystalline basement rocks of the Siberian Platform are exposed on the Anabar Massif in the northwestern part of Yakutia and on the Aldan Shield in southeastern Yakutia (Figure 2). The Aldan Shield represents the headwater region of the Aldan River and comprises Archaean metamorphic rocks with schist, gneiss, granulite, gabbro, amphibolite and metabasalt (Chain and Koronovskii 1995). The Lena River originates in the southern margin of the Siberian Platform, around Lake Baikal, where crystalline rocks of the Trans-Baikal-Highlands comprise Proterozoic metamorphic rocks of greenschist facies and amphibolite facies, clastic-carbonate sedimentary units, and granitoids (Dolginow and Kropatschjow 1994). In western Yakutia, flood-basalt successions form the upper parts of the Siberian Platform, uplifted during the Palaeozoic–Mesozoic transition. The Riphean to Cenozoic sedimentary cover rocks of the eastern margin of the Siberian Platform form the Yakutian lowland basin along the middle and lower courses of the Aldan and Lena rivers, reaching a maximum thickness of up to 15 km in the Vilyuy Basin (Chain and Koronovskii 1995).

The Verkhoyansk Mountains on the eastern margins of the Aldan and Lena rivers are the topographic expression of the approximately 200-km-wide Verkhoyansk fold-and-thrust belt (Figure 2). It resulted from the collision of the North Asia Craton with the Kolyma–Omolon Microcontinent along the eastern margin of the Siberian Platform in Mesozoic times (Parfenov 1991; Oxman 2003). The lower stratigraphic units of the mountain belt are primarily composed of Riphean and Palaeozoic clastic and carbonate rocks with inclusions of basic and intermediary tuffs

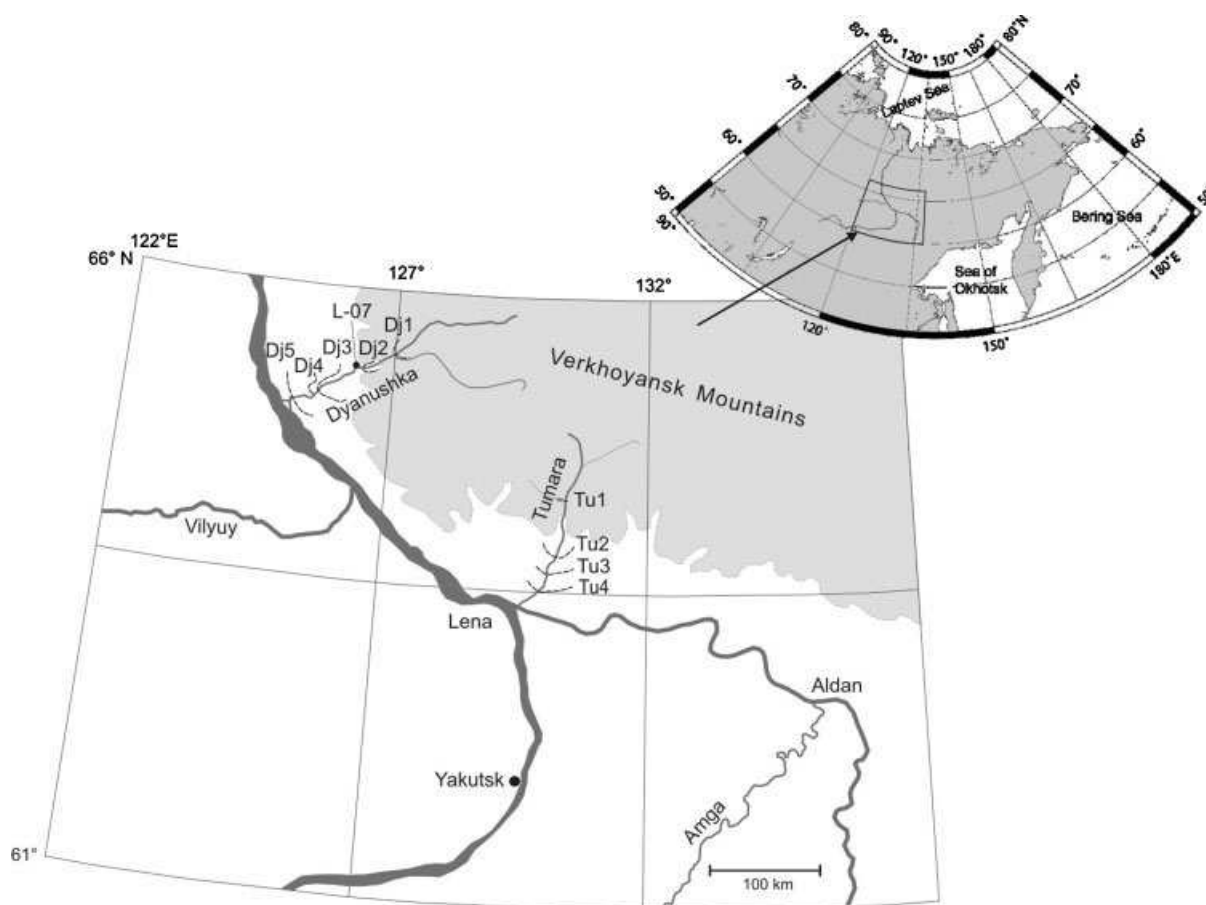


Figure 1. Map of the study area in Central Yakutia, NE Siberia. The dotted lines delineate the terminal-moraine stages along the Tumara and Dyanushka rivers, according to Stauch *et al.* (2007).

and dykes. These units are overlain by continental to shallow-marine sandstones, siltstones and shales of Carboniferous to middle Jurassic age that are exposed along the Tumara and Dyanushka rivers (Parfenov 1991; Chain and Koronovskii 1995). Granitoid intrusions occur in the eastern part of the Verkhoyansk fold-and-thrust belt and farther east within other geotectonic provinces of the Verkhoyansk-Kolymian Orogen (Oxman 2003). To the west and southwest, the Verkhoyansk fold-and-thrust belt is bordered by the Priverkhoyansk Foredeep, a molasse basin that was filled with Cretaceous coal-bearing deposits, which were partly deformed and folded in the course of orogenesis of the Verkhoyansk Mountains (Parfenov 1991).

Between the late Cretaceous and the Miocene, the area was subject to denudation and the formation of weathering crusts in the mountain areas as well as in the Lena–Aldan lowlands, where these processes prevailed during the Palaeogene (Rusanov *et al.* 1967; Chain and Koronovskii 1995). By the end of the Palaeogene, the Aldan Basin developed as an intra-continental tectonic depression along the lower Aldan River on the Priverkhoyansk Foredeep (Figure 2) and was filled with several hundred metres of coal-bearing sands of Neogene age (Katasonov and Soloviev 1969; Baranova 1979; Grigoriev *et al.* 1989).

2.2. Quaternary geology of the Verkhoyansk Foreland

By the end of the Neogene, the Verkhoyansk Foreland, which includes the Priverkhoyansk Foredeep, was a plain of several tens of kilometres width. Periodic uplift along the foothills of the Verkhoyansk Mountains increased the

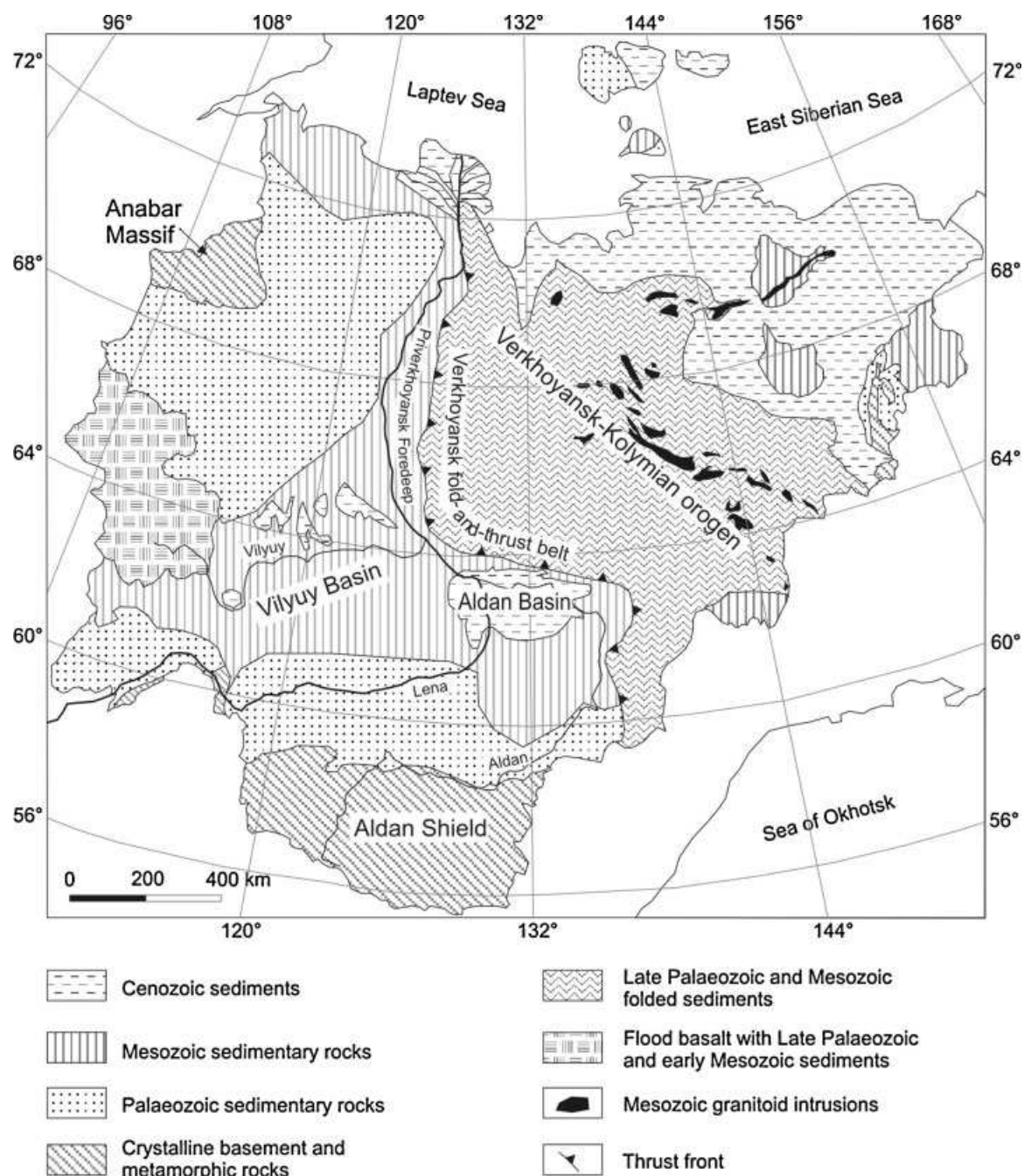


Figure 2. Generalized geological map of the Sakha Republic (Yakutia) (after Sedenko *et al.* 2001).

erosional gradients between the mountains and the river basins of the Lena and Aldan rivers (Kolpakov 1984). At the same time, a cooling trend heralded the onset of the Pleistocene cold-continental climate. At least since the beginning of the middle Pleistocene, continuous and deep-reaching permafrost has been widespread in Yakutia (Fradkina *et al.* 2005).

Table 1. Classification of different terrace levels in Central Yakutia, according to the Russian literature (citation see text)

Terrace level (above modern river level)	Stratigraphy
80–200 m	Early Pleistocene–Neogene
40–80 m	Middle Pleistocene
15–25 m	Holocene–late Pleistocene

During the Pleistocene, numerous fluvial terraces have developed in the Verkhoyansk Foreland along the Lena and Aldan rivers and their tributaries (Table 1) (Alekseev 1961; Rusanov *et al.* 1967; Solovyev 1973; Péwé and Journaux 1983). The older terraces usually comprise a pre-Quaternary basement that is covered by coarse alluvial sediments. The alluvial sediments of the middle terraces are in places intercalated with glacial sediments derived from the Verkhoyansk Mountains. The late Pleistocene terraces include re-deposited morainic material between fluvial sands and gravel. Fluvial sediments of Holocene age make up the lowest terrace levels. The petrographic composition of the distinct alluvial sediments in the Verkhoyansk Foreland suggests that the Lena flowed eastward of the present course, about 50 km closer to the Verkhoyansk Mountains during the middle and late Pleistocene (Kind 1975; Grigoriev *et al.* 1989; Alekseev and Drouchits 2004).

During the Quaternary, the Verkhoyansk Mountains were affected by several glaciations, as documented by well-preserved morainic arcs and till deposits in the Verkhoyansk Foreland (Katasonov 1963; Kind *et al.* 1971; Kind 1975; Kolpakov 1979). According to the latter authors, glacier advances occurred in the middle Pleistocene and repeatedly during the early to late Weichselian (Table 2).

Most terraces and glacial deposits are covered by loess-like sediments with variable thickness between 0.5 and 30 m (Katasonov 1963; Péwé and Journaux 1983). The origin of this so-called mantle loam has been a matter of debate for a long time, involving weathering, fluvial and lacustrine hypotheses. Péwé and Journaux (1983) and Kolpakov (1986), however, concluded that the silty deposits are primarily of aeolian origin, but in many places were modified by secondary slope processes, such as gelifluction and frost creep. Sediments may include high amounts of intergranular ground ice due to migration of moisture into the ground towards the permafrost table. Massive ground ice also occurs in the sediments that has formed by repeated cracking of the ground and filling the thermal-contraction cracks with snowmelt during spring (Mackay 1983; Romanovskii 1985). During the Pleistocene, these processes resulted in the simultaneous accumulation of ice-rich sediments with large polygonal ice-wedge systems (Ice Complex or Yedomas), which are widely distributed in the lowlands of Yakutia (e.g. Gavrilova *et al.* 2003).

3. MATERIALS AND METHODS

3.1. Outcrop

Samples were taken from outcrops along the riverbanks of the Tumara and Dyanushka rivers, as well as from modern Lena River sediments. Four sediment types have been differentiated, comprising: (1) modern fluvial sands

Table 2. Exposed glacial deposits along Tumara (Tu) and Dyanushka (Dj) rivers (numbered from the youngest to the oldest), the related prevalent Russian stratigraphy and the newly obtained infrared stimulated luminescence dating results (citation see text)

Moraines	Russian stratigraphy	New age constraints
Tu1/Dj1	Sartan (Late Weichselian, MIS 2)	>50 ka
Tu2/Dj2	Sartan (Late Weichselian, MIS 2)	No results
Tu3/Dj3	Sartan (Late Weichselian, MIS 2)	~87 ka
Tu4/Dj4	Zhigansk (middle Weichselian, MIS 3)	≥100 ka
—/Dj5	Not exposed	~135–140 ka

that are representative source indicators for the different catchment areas, (2) fluvial sand and gravel of river terraces ranging in age from Neogene to early Holocene, (3) loess-like sediments and (4) morainic deposits. In this study, we deal with a total number of 83 samples, containing 12 samples of modern fluvial sands, 21 samples of morainic deposits, 36 samples of older river terraces (26 belong to the profile L-07) and 14 samples of loess-like deposits. The specifications of the studied samples are compiled in Table 3.

Sampling of medium- and fine-grained fluvial sands has been performed on sand bars along the river courses. Older fluvial sediments were sampled from terraces at different elevations above the river level. A geological map of the area (Prokopyev *et al.* 1994) shows middle and late Pleistocene terraces cropping out along the rivers. The middle Pleistocene terraces were sampled at the lower river courses of the Tumara and Dyanushka rivers (up to 50 m above the river level). The late Pleistocene terraces comprise terrace levels of global Last Glacial Maximum (gLGM) age (10–20 m altitude above the modern valley floor) and a late glacial to early Holocene age (approximately up to 15 m in altitude) at the middle and lower courses of the Dyanushka River (Katasonov 1963; Rusanov *et al.* 1967; Katasonov and Solovyev 1969; Grigoriev *et al.* 1989). The late glacial to early Holocene terrace was sampled in detail, comprising an 8-m-thick sand profile (L-07) with marked colour changes in front of the mountain margin from a steep bank at Dyanushka River (Figure 1).

Morainic deposits comprise both glacial diamictons and glaciofluvial outwash sands and gravels, which were sampled along riverbanks and in thermokarst pits at locations shown in Figure 1. Samples were taken from the sand-to clay-sized matrix of the sediments.

Loess-like sediments were sampled in the immediate vicinity of the morainic deposits from fresh outcrops and dug holes, avoiding sections that were strongly modified by soil-forming processes.

3.2. Laboratory

After disaggregation and removal of organic matter of bulk samples in 10% hydrogen peroxide solution, wet-sieving at 63 μm was performed in order to separate silt and clay from sand and gravel. Further grain-size separations were achieved by Stokes' law settling procedure in 'Atterberg' tubes (silt and clay) and dry-sieving in whole Phi-steps with 'Sonic shifter' (sand and gravel). In this paper, the grain-size data are only discussed as far as they are needed for the interpretation of sediment provenance.

Heavy-mineral analysis was conducted on the very fine sand fraction (63–125 μm). Sample preparation and analysis followed standard procedures outlined in relevant laboratory manuals (Boenigk 1983; Mange and Maurer 1991). The heavy minerals were obtained by density separation in a centrifuge, dispersed in sodium metatungstate solution (density of 2.89 g cm^{-3}). For optical identification under a polarization microscope, the heavy fraction was mounted with Meltmount (refraction index = 1.68). Per sample, we tried to count at least 100 translucent grains, which was not always achieved owing to a predominance of weathered grains. We are aware that this relatively low number of grains may be of low statistical confidence. However, empirical studies have revealed that the statistical error produced by counting only 100 grains still ranges below the compositional variability of natural samples from distinct geological sections (Boenigk 1983). Approximately one-third of the studied samples present less than 100 counts, the average grain number of two-thirds of the samples amounts to 150. The counting results are expressed as frequency grain percentages (Figures 3–6).

The clay fraction was analysed with an X-ray diffraction machine (Philips PW, 1830). Step scan measurements were run with Co K_{α} radiation (40 kV, 40 mA) from 2 to 18° 2θ in a 0.02° $2\theta/\text{s}$ mode for air-dried samples. Additionally, glycolated samples were analysed from 2 to 40° 2θ in 0.02° $2\theta/\text{s}$ and 0.005° $2\theta/\text{s}$ mode in order to differentiate between expandable clay minerals (mainly smectite), chlorite and the kaolinite-chlorite double peak. The semi-quantitative evaluation of the X-ray diffractograms followed techniques adopted from marine studies, which are explained in detail elsewhere (see e.g. Biscaye 1965; Ehrmann *et al.* 1992; Petschick *et al.* 1996; Kuhn and Diekmann 2002). Mineral proportions are calculated from weighted peak areas and the relative abundance of the clay-mineral groups in the clay fraction is summed to 100% using standard weighting factors (Biscaye 1965): the 17-Å peak area $\times$ 1 for smectite, 10-Å peak area $\times$ 4 for illite and 7-Å peak area $\times$ 2 for kaolinite and chlorite

Table 3. Specifications of the studied samples

Geological unit/sediment type	Sample no.	Formation	Age	Age ^a	Coordinates Northing/Easting
According to the geological map					
Modern fluvial sands					
Tumara River	Di-02/07/19_02	Recent fluvial sand	—	—	64°35'N/130°38'E
Tumara River	Di-02/07/21-04	Recent fluvial sand	—	—	64°26'N/130°43'E
Tumara River	Di-02/07/25-01	Recent fluvial sand	—	—	64°21'N/130°26'E
Tumara River	Di-02/07/26_02	Recent fluvial sand	—	—	64°07'N/130°23'E
Dyanushka River	Di-03/08/17-01	Recent fluvial sand	—	—	65°31'N/127°06'E
Dyanushka River	Di-03/08/19-03	Recent fluvial sand	—	—	65°27'N/126°58'E
Dyanushka River	Di-03/08/19-04	Recent fluvial sand	—	—	65°27'N/126°58'E
Dyanushka River	Di-03/09/05-01	Recent fluvial sand	—	—	65°01'N/125°06'E
Lena River	Di-02/07/14_01	Recent fluvial sand	—	—	62°02'N/129°44'E
Lena River	Di-03/09/07-03	Recent fluvial sand	—	—	64°60'N/124°58'E
Lena River	Di-03/09/07-04	Recent fluvial sand	—	—	64°60'N/124°58'E
Aldan River	Di-02/08/07_01	Recent fluvial sand	—	—	63°27'N/129°35'E
Morainic deposits					
Diamicton Tu1	Di-02/07/25_02	Sartansk horizon	28–18 ka BP	>53 ka BP	64°19'N/130°24'E
Glaciofluvial outwash Tu2	TUM-M1-W_Graukies_O	Segemdin Stadial (Sartan)	~15 ka BP*	—	63°51'N/130°18'E
Diamicton Tu3	Di-02/07/31_01	Lower Sartan Stadials	~26~19 ka BP*	~87 ka BP	63°49'N/130°17'E
Diamicton Tu3	Di-02/07/31_02	Lower Sartan Stadials	~26~19 ka BP*	~87 ka BP	63°49'N/130°17'E
Diamicton Tu3	Di-02/07/31_07	Lower Sartan Stadials	~26~19 ka BP*	~87 ka BP	63°49'N/130°17'E
Diamicton Tu3	Di-02/08/01_02	Lower Sartan Stadials	~26~19 ka BP*	~87 ka BP	63°47'N/130°10'E
Glaciofluvial outwash Tu3	Di-02/07/31_04	Lower Sartan Stadials	~26~19 ka BP*	≤87 ka BP	63°49'N/130°17'E
Diamicton Tu4	Di-02/08/03_01	Zhigansk Stadial	33–30 ka BP*	>100 ka BP	63°42'N/130°10'E
Diamicton Tu4	Di-02/08/03_03	Zhigansk Stadial	33–30 ka BP*	>100 ka BP	63°42'N/130°10'E
Diamicton Dj1	Di-03/08/19-01	Sartan horizon	28–18 ka BP	>40 ka BP	65°27'N/126°58'E
Diamicton Dj1	Di-03/08/19-02	Sartan horizon	28–18 ka BP	>40 ka BP	65°27'N/126°58'E
Diamicton Dj2	Di-03/08/23-03	Sartan horizon	28–18 ka BP	—	65°20'N/126°28'E
Diamicton Dj2	Di-03/08/24-03	Sartan horizon	28–18 ka BP	—	65°21'N/126°16'E
Diamicton Dj3	Di-03/08/30-07	Lower Sartan Stadials	~26~19 ka BP*	<92 ka BP	65°09'N/125°33'E
Diamicton Dj4	Di-03/08/30-12	Zhigansk Stadial	33–30 ka BP*	>100 ka BP	65°05'N/125°30'E
Diamicton Dj4	Di-03/08/30-13	Zhigansk Stadial	33–30 ka BP*	>100 ka BP	65°05'N/125°30'E
Diamicton Dj4	Di-03/08/30-14	Zhigansk Stadial	33–30 ka BP*	>100 ka BP	65°05'N/125°30'E
Diamicton Dj5	Di-03/09/04-05	Samarov horizon	Middle Pleistocene	140–135 ka BP	65°01'N/125°06'E
Diamicton Dj5	Di-03/09/04-06	Samarov horizon	Middle Pleistocene	140–135 ka BP	65°01'N/125°06'E
Diamicton Dj5	Di-03/09/04-04	Samarov horizon	Middle Pleistocene	140–135 ka BP	65°01'N/125°06'E
Diamicton Dj5	Di-03/09/04-03	Samarov horizon	Middle Pleistocene	140–135 ka BP	65°01'N/125°06'E
Terrace deposits					
Pleistocene sand on Neogene	Di-02/08/04_09	Tustakh facies	Upper Eopleistocene	>100 ka BP	63°37'N/129°58'E
Pleistocene gravel on Neogene	Di-02/08/04_05	Tustakh facies	Upper Eopleistocene	>100 ka BP	63°37'N/129°58'E

(Continues)

Table 3. (Continued)

Geological unit/sediment type	Sample no.	Formation	Age	Age ^a	Coordinates Northing/Easting
			According to the geological map		
Neogene sand	Di-02/08/04_01	Mamontovy Khayata horizon	Middle Miocene	—	63°37'N/129°58'E
Pleistocene sand Stau1	Di-03/08/22-07	Sartan horizon	28–18 ka BP	≥17 ka BP#	65°21'N/126°37'E
Loess-like silt	L07-1/0-10	Sartan horizon-early holocene	11–9 ka BP	—	65°20'N/126°14'E
Loess-like silt	L07-1/40-45	Sartan horizon-early holocene	11–9 ka BP	—	65°20'N/126°14'E
Loess-like silt	L07-1/95-100	Sartan horizon-early holocene	11–9 ka BP	—	65°20'N/126°14'E
Fluvial sand	L07-1/155-160	Sartan horizon-early holocene	11–9 ka BP	~11 ka BP#	65°20'N/126°14'E
Fluvial sand	L07-1/170-175	Sartan horizon-early holocene	11–9 ka BP	~13 ka BP#	65°20'N/126°14'E
Fluvial sand	L07-1/200-205	Sartan horizon-early holocene	11–9 ka BP	—	65°20'N/126°14'E
Fluvial sand	L07-1/225-230	Sartan horizon-early holocene	11–9 ka BP	—	65°20'N/126°14'E
Fluvial sand	L07-1/270-275	Sartan horizon-early holocene	11–9 ka BP	—	65°20'N/126°14'E
Fluvial sand	L07-1/320-325	Sartan horizon-early holocene	11–9 ka BP	—	65°20'N/126°14'E
Fluvial sand	L07-1/340-345	Sartan horizon-early holocene	11–9 ka BP	—	65°20'N/126°14'E
Fluvial sand	L07-1/355-360	Sartan horizon-early holocene	11–9 ka BP	~10.7 ka BP#	65°20'N/126°14'E
Fluvial sand	L07-1/385-390	Sartan horizon-early holocene	11–9 ka BP	—	65°20'N/126°14'E
Fluvial sand	L07-1/430-435	Sartan horizon-early holocene	11–9 ka BP	—	65°20'N/126°14'E
Fluvial sand	L07-1/465-470	Sartan horizon-early holocene	11–9 ka BP	—	65°20'N/126°14'E
Fluvial sand	L07-1/510-515	Sartan horizon-early holocene	11–9 ka BP	—	65°20'N/126°14'E
Fluvial sand	L07-1/525-535	Sartan horizon-early holocene	11–9 ka BP	~44 ka BP#	65°20'N/126°14'E
Fluvial sand	L07-1/535-545	Sartan horizon-early holocene	11–9 ka BP	—	65°20'N/126°14'E
Fluvial sand	L07-1/545-555	Sartan horizon-early holocene	11–9 ka BP	—	65°20'N/126°14'E
Fluvial sand	L07-1/555-560	Sartan horizon-early holocene	11–9 ka BP	—	65°20'N/126°14'E
Fluvial sand	L07-1/575-580	Sartan horizon-early holocene	11–9 ka BP	~14 ka BP#	65°20'N/126°14'E
Fluvial sand	L07-1/610-615	Sartan horizon-early holocene	11–9 ka BP	—	65°20'N/126°14'E
Fluvial sand	L07-1/650-655	Sartan horizon-early holocene	11–9 ka BP	—	65°20'N/126°14'E
Fluvial sand	L07-1/700-705	Sartan horizon-early holocene	11–9 ka BP	—	65°20'N/126°14'E
Fluvial sand	L07-1/740-745	Sartan horizon-early holocene	11–9 ka BP	—	65°20'N/126°14'E
Fluvial sand	L07-1/780-785	Sartan horizon-early holocene	11–9 ka BP	~37 ka BP	65°20'N/126°14'E
Fluvial sand	L07-1/800-810	Sartan horizon-early holocene	11–9 ka BP	~9.5 ka BP#	65°20'N/126°14'E
Fluvial sand	L09-1/265-270	Segemdin Stadial (Sartan)	~15 ka BP*	<14 ka BP#	65°10'N/125°42'E
Fluvial sand	L09-1/165-170	Segemdin Stadial (Sartan)	~15 ka BP*	<14 ka BP#	65°10'N/125°42'E
Sand, silty L12	Di-03/09/01_02	Sartan horizon-early holocene	11–9 ka BP	—	65°03'N/125°27'E
Gravel, sandy L14	Di-03/09/04_20	Tobol H., Bestyakhskier facies	Middle Pleistocene	>100 ka BP	65°01'N/125°06'E
Sand, silty L14	Di-03/09/04_23	Tobol H., Bestyakhskier facies	Middle Pleistocene	>100 ka BP	65°01'N/125°06'E
Sand L14	Di-03/09/04_26	Tobol H., Bestyakhskier facies	Middle Pleistocene	>100 ka BP	65°01'N/125°06'E
Loess-like deposits					
Silt, sandy Tu1	Di-02/07/23_02/045	Sartan horizon	28–18 ka BP	12–9 ka BP	64°20'N/130°24'E
Silt, sandy Tu2	Tum-M1-W-1.0	Segemdin Stadial (Sartan)	~15 ka BP*	~19 ka BP	63°51'N/130°18'E
Silt, sandy Tu2	Tum-M1-W-9.2	Segemdin Stadial (Sartan)	~15 ka BP*	~27 ka BP	63°51'N/130°18'E

Table 3. (Continued)

Geological unit/sediment type	Sample no.	Formation	Age	Age ^a	Coordinates Northing/Easting
			According to the geological map		
Silt on Neogene	P III 100	Muruktin–Kargin horizon	49–32 ka BP	50–9 ka BP	63°37'N/129°58'E
Silt Dj1	Di-03/08/19-07	Sartan horizon	28–18 ka BP	11 ka BP	65°27'N/126°58'E
Silt Dj1	Di-03/08/19-08	Sartan horizon	28–18 ka BP	11 ka BP	65°27'N/126°58'E
Silt Dj1	Di-03/08/19-09	Sartan horizon	28–18 ka BP	11 ka BP	65°27'N/126°58'E
Silt Dj2	Di-03/08/23-04	Sartan horizon	28–18 ka BP	10 ka BP	65°20'N/126°28'E
Silt Dj2	Di-03/08/23-05	Sartan horizon	28–18 ka BP	10 ka BP	65°20'N/126°28'E
Silt Dj3	Di-03/08/30-09	Above lower Sartan Stadials	<19 ka BP	~27 ka BP	65°08'N/125°33'E
Silt Dj4	Di-03/08/31-03	Above Zhigansk Stadial	<30 ka BP	32–13 ka BP	65°04'N/125°31'E
Silt Dj4	Di-03/08/31-04	Above Zhigansk Stadial	<30 ka BP	32–13 ka BP	65°04'N/125°31'E
Silt Dj5	Di-03/09/03-01	Muruktin–Kargin horizon	49–32 ka BP	—	65°01'N/125°06'E
Silt Dj5	Di-03/09/03-05	Muruktin–Kargin horizon	49–32 ka BP	—	65°01'N/125°06'E

Information on the geological formation and age assignments are adopted from the geological map and after Kind (1975), the latter marked by the *symbol.

^aThe second age column presents newly obtained age data according to Stauch *et al.* (2007) and radiocarbon dating results (this study), marked by the #symbol.

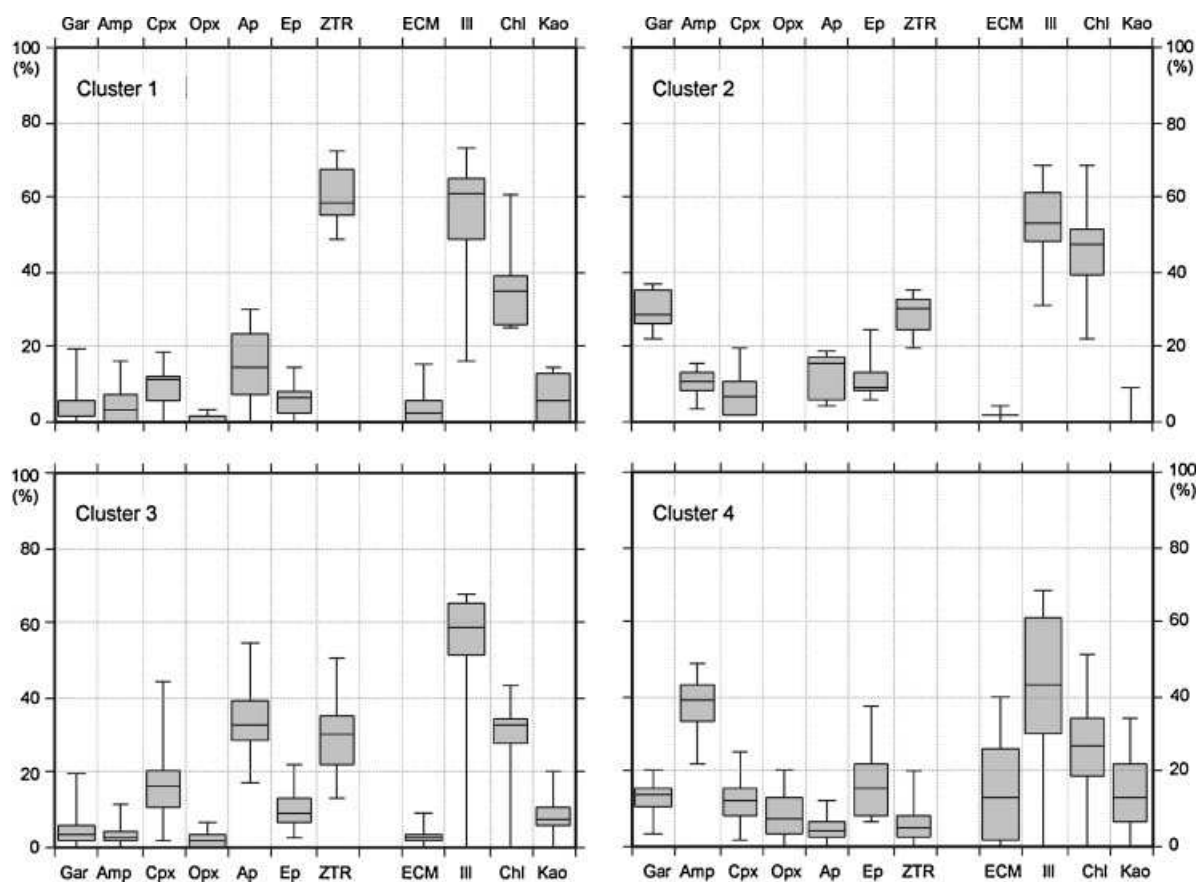


Figure 3. Compositional variations of heavy-mineral assemblages as inferred from the cluster analysis in comparison with the respective clay-mineral composition. The boxes enclose 50% of the data with the median value of the mineral displayed as a line. The top and the bottom of the box mark the limit of $\pm 25\%$ of the mineral population. The extending lines mark the minimum and maximum values of the populations. gar = garnet; amp = amphibole; cpx = clinopyroxene; opx = orthopyroxene; ap = apatite; ep = epidote; ZTR = zircon + tourmaline + rutile; KAST = kyanite + andalusite + staurolite + titanite; ECM = expandable clay minerals; ill = illite; chl = chlorite; kao = kaolinite.

subdivided in proportion to the relative areas of their 3.57-Å and 3.54-Å peaks, respectively. Relative analytical precision is 6–9% for major clay components and 8–14% for minor clay components (Ehrmann *et al.* 1992).

4. RESULTS

4.1. Heavy-mineral assemblages

Heavy-mineral grains appear in typical shapes, as described in petrographic manuals (Boenigk 1983; Mange and Maurer 1991). Fluvial and glacial samples from the Verkhoysansk Mountain area, however, contain a lot of oxidized and weathered grains that are hard to identify.

We carried out a conventional joining cluster analysis to define heavy-mineral assemblages (Swan and Sandilands 1995). A similarity matrix based on Euclidian distance calculations and Ward's linkage method was

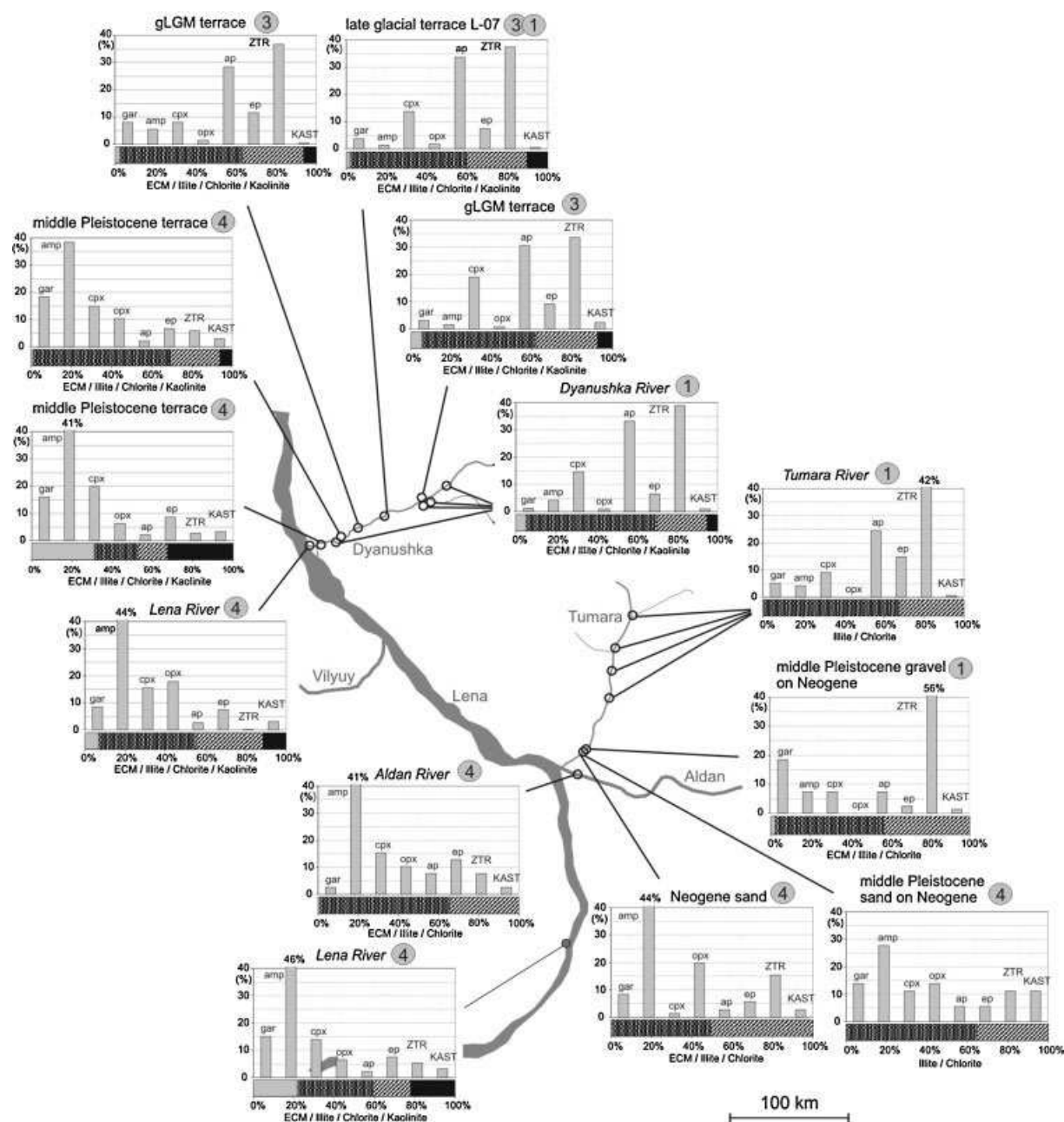


Figure 4. Provenance signature (heavy minerals and clay mineralogy) of modern fluvial sands of Lena, Aldan, Tumara and Dyanushka rivers and Quaternary alluvial as well as Neogene sediments. The circles indicate the sample position and the numbers above the diagrams refer to the respective heavy-mineral cluster of the sample. gar = garnet; amp = amphibole; cpx = clinopyroxene; opx = orthopyroxene; ap = apatite; ep = epidote; ZTR = zircon + tourmaline + rutile; KAST = kyanite + andalusite + staurolite + titanite; ECM = expandable clay minerals.

applied for sample clustering, following routines of the commercial 'STATISTICA' software. The cluster analysis was used to obtain specific associations and key species of the observed heavy-mineral spectra. Only unaltered translucent heavy minerals were used for this statistical approach. The results show that the heavy-mineral inventory of the various sediment types can be pooled to distinct assemblages, even though the genesis of the

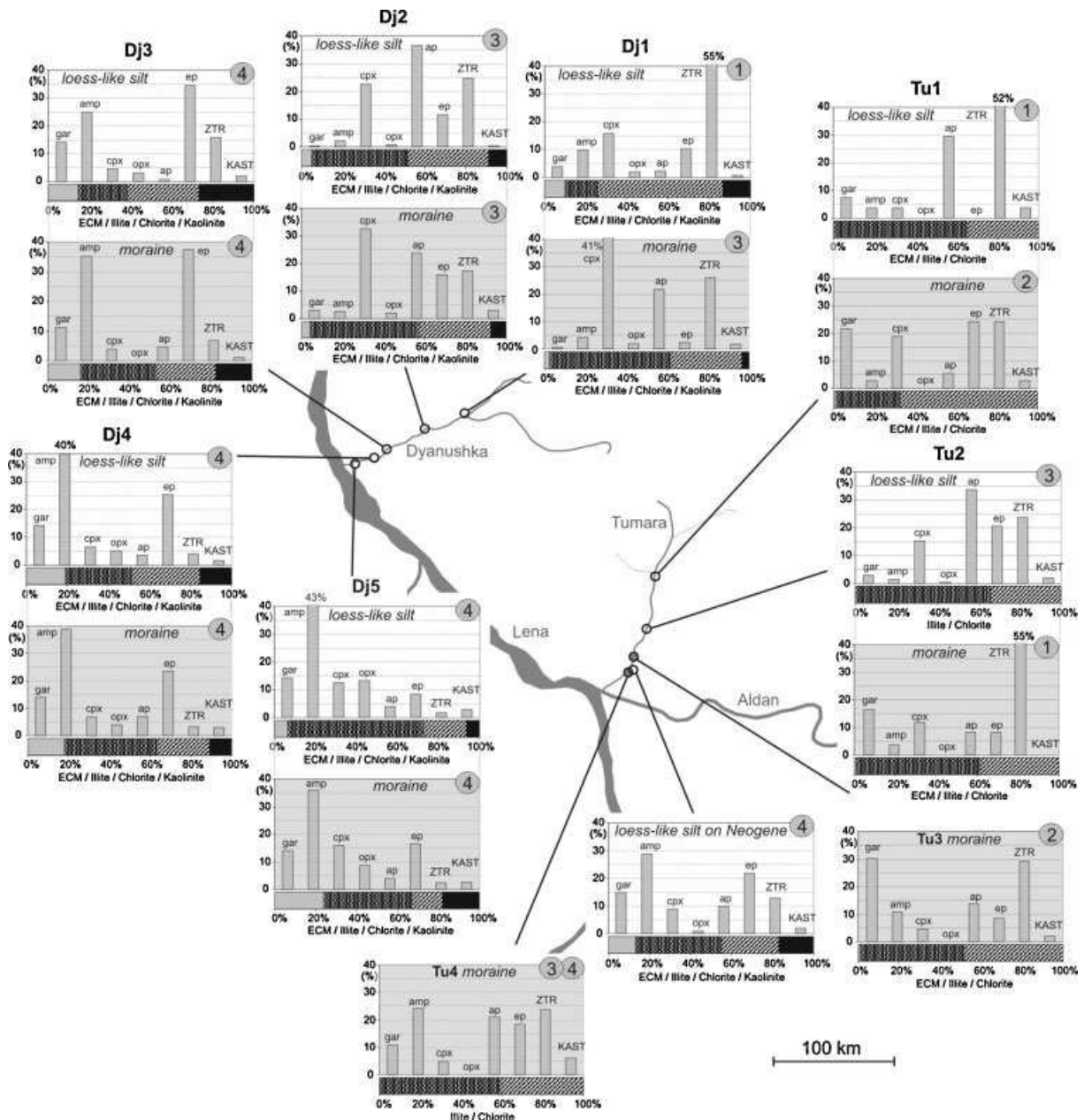


Figure 5. Provenance signature (heavy minerals and clay mineralogy) of morainic deposits (grey shaded diagrams) and loess-like sediments along Tumara and Dyanushka rivers. The circles indicate the sample position of both the morainic and the loess-like sediments, with the exception of the 'Tu3' and 'Tu4' moraines and 'loess-like silt on Neogene', which are displayed in single diagrams. The reference to the respective cluster is given by the encircled number in the diagrams. The abbreviations for the mineral names are valid as used in Figure 4.

sediments is different. Four different clusters can be distinguished (Figure 3). In the following description of the clusters, we refer to mean heavy-mineral percentages.

Cluster 1: This cluster is clearly dominated by the stable heavy minerals zircon, tourmaline and rutile (ZTR, ~60%), followed by apatite (~15%) and clinopyroxene (~9%). The assemblage comprises modern fluvial sands of

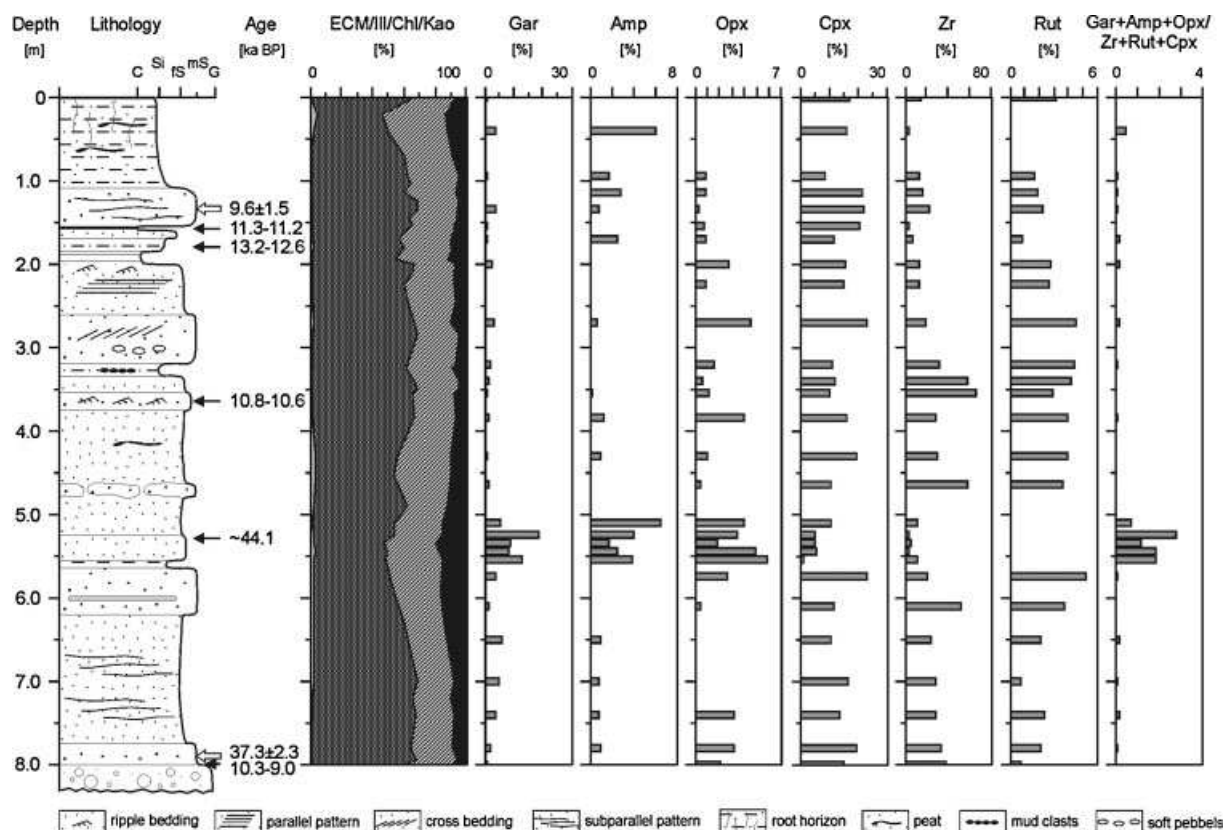


Figure 6. Mineralogical composition of the sand sequence L-07 at Dyanushka River close to the mountain margin. The indicated ages were obtained from radiocarbon dating (black arrows) and infrared stimulated luminescence (IRSL, white arrows). Note the appearance of the increased proportions of garnet, amphibole and orthopyroxene between 5.1 and 5.6 m depth, which is assigned to the yellowish sand layer. The abbreviations for mineral names are valid as used in Figure 4 with the exception of zr = zircon; rut = rutile. Lithological abbreviations, which are used: C = clay; Si = silt; fS = fine sand; mS = medium sand; G = gravel.

the Tumara and Dyanushka rivers as well as four samples from the L-07 sand sequence. Furthermore, loess-like deposits at the Tu1 and Dj1 moraines, morainic deposits of the Tu2 moraine and Pleistocene gravel from the lower reaches of the Tumara River are also related to this cluster.

Cluster 2: This assemblage differs from the previous cluster by a high percentage of garnet (~29%) and a lower amount of stable heavy minerals (ZTR, ~28%). With the exception of a higher amount of amphibole (~10%), the remaining heavy minerals occur in similar abundance as in Cluster 1. Only morainic deposits of the Tu1 and Tu3 moraines characterize the assemblage.

Cluster 3: The key minerals of this cluster are apatite (~34%), ZTR (~30%) and clinopyroxene (~17%), associated with epidote (~10%). Modern fluvial sand samples from the Tumara and Dyanushka rivers are included. Other related sediment types are morainic deposits of the Tu4, Dj1 and Dj2 moraines, loess-like deposits of the Tu2 and Dj2 moraines, as well as almost the complete sample set from the L-07 sand profile. Some samples of this sequence as well as morainic deposits of the Dj1 and Dj2-moraine, loess-like deposits at Dj2-moraine and a modern sand sample of the Dyanushka River present a high percentage of clinopyroxene (29–40%).

Cluster 4: In contrast to the previous clusters, this assemblage is defined by high amounts of hornblende (~38%) and the frequent presence of orthopyroxene (~8%) as well as low proportions of apatite (~5%) and stable heavy minerals (~6%). Another key mineral is garnet (~13%). Cluster 4 is shared by various sediment types, comprising

modern Lena sands, the old morainic deposits along the Tumara and Dyanushka rivers (Tu4, Dj3–Dj5), as well as Neogene and younger overlying fluvial and loess-like sediments from the lower reaches of the Tumara River.

4.2. Clay mineralogy

The clay mineral spectrum of the studied sediments is mostly dominated by illite (25–60%) and chlorite (20–50%) with low amounts of kaolinite (<20%) and expandable clay minerals (<25%). In comparison with the inferred heavy-mineral clusters, the increased amounts of kaolinite and expandable clay minerals are generally associated with the sediment types of Cluster 4, whereas the sediment types of the other clusters are barren or only include trace amounts of both clay minerals and cannot be clearly distinguished in terms of clay mineralogy. However, the absence of kaolinite and expandable clay minerals in most deposits along the middle and upper reaches of the Tumara River indicate a rough regional differentiation of clay-mineral provinces, whereas ubiquitous amounts of both appear along the Dyanushka River. The highest amounts of the two clay minerals always appear in sediments of the Verkhoyansk Foreland situated close to the Lena River.

5. DATA INTERPRETATION AND DISCUSSION

The interpretation of heavy-mineral assemblages and the clay mineralogy of the Quaternary fluvial, glacial and aeolian sediments in the Verkhoyansk Mountains and its foreland indicate their provenance from two different geological provinces. The sediments basically comprise mixtures of detrital material derived from the local sources of the Verkhoyansk Mountain range and supra-regional material, which originates from the vast catchment area of the Aldan and Lena rivers and shows signs of multiple recycling. In the following sections, we will explain the mineralogical source indicators and discuss the provenance signals of the different genetic sediment types in respect to palaeoenvironmental conditions.

5.1. Sediment provenance

5.1.1. Verkhoyansk area

Dominant sediment supply from the Verkhoyansk Mountains is indicated by the heavy-mineral assemblages of clusters 1–3 and by the dominance of illite and chlorite clay minerals (Figure 3). High concentrations of the stable heavy minerals zircon, rutile and tourmaline are considered as recycled components of the Siberian craton that were re-deposited and mechanically enriched at the former continental margin of the craton during the Palaeozoic to Mesozoic. Today, these deposits comprise the highly indurated sandstone and shale sequences of the Verkhoyansk Mountains.

The high percentages of apatite in Cluster 3 may point to source signals from either magmatic intrusions (granitoids), which are locally present in the Dyanushka hinterland, or more likely from apatite-bearing calcareous concretions, which are frequently hosted in Triassic sedimentary rocks. The latter possibility can also explain the appearance of carbonate particles in the deposits of the Dj1 moraine.

Clinopyroxene can be related to the presence of volcanic dykes and porphyrites, intercalated in some stratigraphic units of the Verkhoyansk Mountains. The high abundance of garnet in Cluster 2 is most likely related to sediment provenance from garnet-rich Jurassic rocks that are widely distributed along the mountain margin at Tumara River (Kossovskaya *et al.* 1960). The chlorite- and illite-dominated clay-mineral composition of Quaternary sediments derived from the Verkhoyansk Mountain range is consistent with the high diagenetic consolidation of the exposed clastic series. The presence of small amounts of kaolinite and expandable clay minerals in some Quaternary sediments of the Dyanushka area points to the local erosion of Tertiary soil remnants in the hinterland (Rusanov *et al.* 1967; Chain and Koronovskii 1995).

5.1.2. *Lena–Aldan catchment area*

Sediment supply from the large catchment area of the Aldan and Lena rivers is indicated by the heavy-mineral assemblage of Cluster 4 with high amounts of amphibole (green hornblende), pyroxene and garnet as well as relatively high abundances of kaolinite and expandable clay minerals (Figures 3 and 4). The Precambrian crystalline rocks of the Aldan Shield and the Trans-Baikal-Highlands are considered as primary source rocks of the heavy-mineral inventory of the Aldan and Lena rivers. The metamorphic source areas also account for epidote in the Lena and Aldan sediments. Sediments from the Aldan River can be distinguished from the Lena River by virtue of higher proportions of orthopyroxene and different geochemical compositions of amphibole and garnet (Hoops 1999). The second largest tributary farther downstream, the Vilyuy River, provides abundant pyroxene to the Lena River (Hoops 1999).

A distinctive feature of the sediments derived from the Lena and Aldan sources are increased proportions of kaolinite and expandable clay minerals. Since the Quaternary, palaeoclimatic conditions have not been favourable for the genesis of pedogenic clay minerals, the increased amounts of kaolinite and expandable clay minerals in modern river sands and terrace deposits point to the intermittent storage and recycling of late Mesozoic and Cenozoic sediments in the Central Yakutian denudation–accumulation plains. In particular, the coal-bearing clastic series and Neogene ‘Red Sands’ are often associated with kaolinite and expandable clay minerals, which may be reworked in Quaternary sediments (Alekseev *et al.* 1990).

5.2. *Source signals of the morainic deposits*

The mineralogical composition of morainic deposits along the Tumara and Dyanushka rivers is heterogeneous in space and time (Figure 5). Along the Tumara River, the moraines (Tu1–Tu4) are primarily composed of heavy-mineral assemblages of clusters 1 and 2 and are almost barren of kaolinite and expandable clay minerals, being consistent with dominant glacial sediment supply from the Verkhoyansk Mountains. In comparison with modern fluvial sands of the Tumara River, however, the moraines of the Tumara area generally include increased portions of garnet. The enrichment of garnet may be both the result of glacial erosion of underlying garnet-bearing Cenozoic sediments of Lena–Aldan origin in the Verkhoyansk Foreland and a secondary feature, explained by selective transport processes and multiple sediment recycling of glacial sediments, which has been observed frequently (Gravenor 1979; Diekmann and Wopfner 1996; Diekmann and Kuhn 1999). In the study area, multiple recycling actually is indicated by the presence of abundant rounded and striated glacial clasts in the morainic sediments.

However, invoking simple erosion and reworking of the underlying Cenozoic sediments is not sustainable because of the minor amounts of amphibole and orthopyroxene in the moraines Tu1–Tu3 (Figure 5). Moreover, the fact that garnet is less dominant in the Dyanushka than in the Tumara moraines argues against garnet enrichment. It is more likely that the enrichment of garnet in the Tumara moraines was related to the glacial erosion of nearby Upper Jurassic rocks cropping out widely in the low hills along the mountain margin (Kossovskaya *et al.* 1960), whereas the garnet signal in modern river sands of Tumara is only evident in a sample in the immediate vicinity of the Jurassic outcrops.

Generally, the mineralogical composition of the morainic deposits along the Dyanushka River is less uniform than of those along the Tumara River. The Dj1 and Dj2 moraines, which are situated within the Verkhoyansk Mountains, clearly document sediment provenance from the adjacent mountains, as indicated by clay mineralogy and the heavy-mineral assemblages of Cluster 3. In contrast, the morainic deposits and basal tills of the foreland (Dj3–Dj5) exhibit mineralogical source signals of a Lena–Aldan provenance with abundant hornblende, orthopyroxene and kaolinite, which are very likely reworked from older underlying sediments.

In summary, an important finding is that the mineral composition does not allow a correlation of the morainic deposits of distinct glacial stages between the Dyanushka and Tumara areas, as defined by Stauch *et al.* (2005).

5.3. Source signals of the loess-like deposits

Loess-like deposits along the studied rivers exhibit spatial differences in sediment provenance (Figure 5). In the younger moraines of the Tumara and Dyanushka areas (Dj1, Dj2, Tu1, Tu2), the heavy-mineral assemblages of clusters 1 and 3, and low concentrations of kaolinite and expandable clay minerals are consistent with nearby sediment sources from the mountain areas. Closer to the Aldan and Lena rivers, loess-like sediments mantling the older moraines and the Lena terraces show increased percentages of Lena–Aldan indicator minerals, such as hornblende, garnet and significant proportions of orthopyroxene as well as kaolinite and expandable clay minerals. Given a dominant aeolian origin of the Weichselian loess-like sediments (Péwé and Journaux 1983), the marked differences in sediment provenance possibly point to local sediment sources and short-distance transport of fine-grained (possibly wind-blown) components.

The deposition of loess-like sediments took place during a time of stronger aridity and sparser vegetation cover than today, as revealed by a pollen record of a loess sequence at the lower Tumara River (Müller *et al.* 2004). At that site, a steppe-like environment with shrubby tundra communities existed between 50 and 30 ¹⁴C ka BP, while the most severe climate conditions and the lowest vegetation covers are documented for the gLGM. Exposed fluvial accumulation plains with sand and silt surfaces are considered as major targets for aeolian deflation. According to our provenance data, the braided Lena River has been the main source for wind-blown material in the Verkhoyansk Foreland. In the Verkhoyansk Mountains, the tributaries of the Lena River form braided-river systems with additional deflation plains. The provenance signals in loess-like sediments in the mountain area along the Tumara and Dyanushka rivers point to the mixing of subordinate wind-blown material from the Lena River with silty materials from mostly local sources in the mountain valleys. Local periglacial slope processes, which may modify the primary aeolian sediment texture have no significant impact on the provenance signature of the loess-like material.

5.4. Source signals of alluvial terrace deposits

In the study area, the oldest and most widely distributed terrace level is the 50-m high middle Pleistocene terrace (Rusanov *et al.* 1967). Along the Tumara River, this middle Pleistocene level extends from the mountain margin to the sub-recent alluvial plain of the Aldan Valley and is covered by morainic deposits (Katasonov 1963). At the lower reaches of the Tumara River, its base comprises Neogene sands covered by interfingering sand and gravel successions of early to middle Pleistocene age. The terrace sands reveal a distinct Aldan source signal with high amounts of hornblende and orthopyroxene, whereas the gravel possibly represent glaciofluvial outwash deposits, as they show mineralogical affinities to mountain sources (Figure 4).

At the Dyanushka River, the middle Pleistocene terrace is exposed along the lower riverbanks. Close to the Lena valley, the terrace sands interlock with basal tills of the Dj5 moraine stage, dated to 140 and 135 ka BP (Stauch *et al.* 2007). Between the Dj5 and the Dj3 moraines, yellowish fluvial sands in different elevations crop out, likely related to the middle Pleistocene, or in the case of the accumulation on the Dj4 moraine, to an early Weichselian terrace level. The heavy-mineral assemblage of Cluster 4 clearly points to a Lena origin of these yellowish fluvial sands, implying a stream course closer to the mountains. A long-term displacement of the Lena–Aldan course away from the mountains to the recent pathways was already described by some Russian studies (Kolpakov 1986; Grigoriev *et al.* 1989; Alekseev and Drouchits 2004). The reason for the displacement, however, is not fully understood, but tectonic movements and climatic causes might have played a major role. According to the new dating results of morainic deposits in the Verkhoyansk Foreland (Table 2) (Stauch *et al.* 2005, 2007), the latest fluvial sedimentation of the Lena River farther east of its recent pathway is indicated for the early late Pleistocene.

The late Weichselian terrace levels of gLGM and late glacial age in the foreland, which are exposed along the lower and middle Dyanushka River, reveal a mountain source influence (high amounts of stable heavy minerals).

5.4.1. Indicators of environmental change in alluvial sediments

In the late glacial to early Holocene terrace, which is exposed at the Dyanushka profile L-07 (Figure 6), a yellowish sand layer seems to represent a short-term event of environmental change that caused an enhanced sediment supply

of Lena origin. Temporarily damming events of the Lena River caused by progressing glaciers are supposed to have taken place during the middle Pleistocene glaciations (Kolpakov 1986; Grigoriev *et al.* 1989; Alekseev and Drouchits 2004). A similar process might have taken place during late glacial times in northern Yakutia, as revealed by a freshwater event recorded in marine sediments of the Laptev Sea (Spielhagen *et al.* 2005). The latter authors postulate that an outstanding anomaly in a foraminiferal stable oxygen isotope record around 13 cal-ka BP gives evidence of a rapid outburst of large amounts of fresh water, which likely were linked with an ice-dammed lake in the hinterland of the Lena Valley.

With regard to such a damming event, the late glacial sediment sequence of profile L-07 was studied in detail. Underlain by coarse gravel, the terrace succession is dominated by dark greyish, fluvial sands with varying proportions of silt and clay, topped by loess-like sediments with intercalated peat horizons (Figure 6). Throughout the succession, sediment provenance from the adjacent Verkhoyansk Mountains prevailed, as documented by the heavy-mineral assemblages of clusters 1 and 3 as well as by dominant illite and chlorite amounts in the clay fraction. Between 5.1 and 5.6 m profile depth, however, the yellow coloured sand layer shows increased percentages of garnet, hornblende and orthopyroxene as well as kaolinite (Figure 6) indicating a distinct signal of increased Lena sediment influence in this stratum.

The age of the terrace deposits, late glacial to early Holocene according to geological maps of the area, is confirmed by the new dating results, embracing the timing of the fresh-water event in the Laptev Sea. However, the exact age for the yellowish sand layer is hard to ascertain, because of contradictory results from infrared stimulated luminescence (IRSL) dating (Stauch *et al.* 2007) and ^{14}C ages that do not reveal a coherent age-depth relationship (Figure 6). We feel certain about the dating at the silt-sand transition at 1.1 m profile depth, determined as the Pleistocene–Holocene transition around 10 ka by both radiocarbon and IRSL technique. The onset of sand accumulation at 8.0 m depth, however, is marked by two different ages. The IRSL dating results in an age around 37 ka while the radiocarbon dating gives an age of 10–9 ka, which seems to be questionable in comparison with the youngest sand layers. The old radiocarbon age of around 44 ka in the middle part of the profile has to be considered as a result of re-deposited organic material in comparison with the other obtained dating results. Taking into account the increased reliability of the IRSL data from the bottom (8.0 m, 37.3 ± 2.3 ka BP) and the top of the sand succession (1.1 m, 9.6 ± 1.5 ka BP), an average sedimentation rate of about 25 cm/1000 years would account for that interval. This time-frame would place the base of the yellowish sand layer at around 27 ka BP, too old to be consistent with the Laptev Sea event, even when assuming a high variability of sedimentation rates that usually characterize fluvial systems. Besides, the new IRSL age constraints of glacial deposits give evidence that the study area was not affected by extensive glaciations during the last 50 000 years (Table 2) (Stauch *et al.* 2005, 2007).

In addition to the uncertainty of age determinations, sedimentological features do not support the existence of a dammed-up lake basin in the study area. Likewise, there are no indications of a proximal lacustrine shore facies, which should exhibit coarse transgressive beach deposits (Mangerud *et al.* 2001), or signs of laminated proglacial lacustrine sediments (Houmark-Nielsen *et al.* 2001). Furthermore, no aquatic organisms were found in the yellowish sand layer. Another strong argument against a large lake is the absence of any lacustrine sediments on terraces downstream from the Dyanushka River. To date, a thick succession of lacustrine laminates of uncertain age was only found along the Menkere River, 300 km north of the Dyanushka River (e.g. Kind 1975; Kolpakov 1986).

Most likely, the yellowish sand layer documents increased aeolian input of sand-sized sediments from barren fluvial deposits of the ancient Lena Valley. This is indicated by the provenance signal with increased proportions of amphibole, which is consistent with source signals of loess-like cover sediments along the Dyanushka River, revealing a still given influence of Cluster-4 mineral assemblages towards the Verkhoyansk Mountains. In addition to mineralogical evidence, the presence of frosted quartz grains and specific grain-size characteristics support the interpretation of an aeolian input. In comparison with wind-drifted Lena sand and sand-rich loess-like sediments overlying the sand sequence, the yellowish sands of the L-07 profile also show a significant maximum in the fine sand fraction, which is not revealed by both fluvial Lena sands and the grey sands of profile L-07 (Figure 7). When trusting an age of roughly 27 ka BP for the yellowish sand layer, this stratum would be placed into a period of strong aridity in Central Yakutia (Müller *et al.* 2004). According to IRSL dating of loess-like sediments, two major accumulation stages of aeolian sedimentation occurred in the study area between 33 and 24 ka and between 13 and

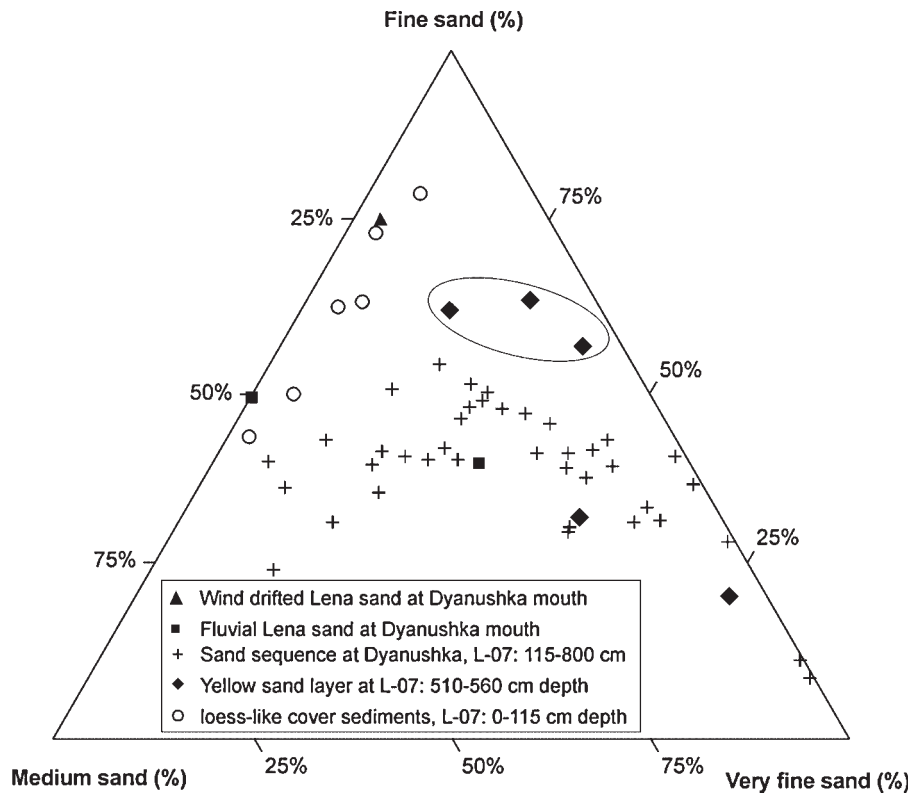


Figure 7. Ternary diagram of very fine sand, fine sand and medium sand concentration of the sample set L-07 in comparison with wind-drifted material of modern Lena sand and the loess-like covering material of L-07. Three of five data points from the yellowish sand layer (encircled) show an enrichment in fine sand, which is also typical for loess-like sediments and wind-drifted Lena sand.

9 ka BP (Stauch *et al.* 2007). The wind-blown sand can be related to the older dry stage, while the cover sediments of the L-07 profile possibly represent the younger dry stage, which may be associated with the cold and dry climate conditions of the Younger Dryas (Werner *et al.* 2005).

6. CONCLUSIONS

Provenance analysis of Quaternary sediments is a useful tool to gain insights into palaeoenvironmental changes in the Central Yakutian Verkhoyansk Mountain area and its foreland, related to glacial, fluvial and aeolian processes. The interpretation of source signals is straightforward, because two end members basically determine the source signals that can be easily deciphered by heavy-mineral signals and clay mineralogy. Local sediment sources from the mountainous hinterland can be clearly differentiated from sediments derived from the vast catchment area of the Lena and Aldan rivers. In summary, our study revealed the following findings:

- The provenance signals in morainic deposits of the stages (Tu1–Tu3, Dj1, Dj2) reflect source-rock geology in the Verkhoyansk Mountains and provide evidence for extensions of the former glacial catchment areas. Consistent with far-reaching advances to the Verkhoyansk Foreland, the old moraines (Tu4, Dj3–Dj5) include eroded

materials of the Lena Basin. The spatial correlation of distinct morainic stages is not possible by petrographic means, as shown by variable provenance signals in respective moraines exposed along the Dyanushka and Tumara rivers. A reason for this might be different distances of glacier advance in respect to the mountain margin.

- Provenance of loess-like sediments is basically related to deflation plains of braided river systems. Thus, aeolian sediments in the foreland are characterized by a Lena–Aldan source signal, whereas mixing and local provenance increases towards the mountains.
- In the Verkhoyansk Foreland, alluvial sediments of various terraces reveal a clear Lena source signal since at least the end of the middle Pleistocene and during intervals of the late Pleistocene that relates to a stream course closer to the Verkhoyansk Mountains. Fluvial sediments of the middle to late Weichselian terrace section exposed along the Dyanushka River at the Verkhoyansk Mountain margin reveal a local mountain source signals. A yellowish sand layer in the succession of L-07 at the Dyanushka River points to a Lena influence that might be related to a late Weichselian increased mountainward aeolian sand supply from the Lena Basin, consistent with a regional dry period between 30 and 24 ka BP.

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