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The genesis of Yedoma Ice Complex permafrost – grain-size endmember modeling analysis from Siberia and Alaska

Lutz Schirrmeister et al.

Correspondence to: Lutz Schirrmeister (lutz.schirrmeister@awi.de)

Supplementary material

Table S1: Overview of current hypotheses about the formation of Yedoma deposits during the last ~120 years of research.

Origin	Reference
(1) Fluvial, alluvial and proluvial	
Fluvial and alluvial sediments of meandering rivers **Floodplain sediments** **Proluvial slope sediments**	Katasonov (1975) Popov (1953, 1969) Romanovsky (1958) Slagoda (1991, 1993, 2004) Vtyurin et al.(1957)
(2) Aeolian	
Cryogenic-aeolian ("loess ice") loess and retransported loess	Murton et al. (2015, 2017) Péwé (1955, 1975) Péwé and Journaux (1983) Tomirdiaro (1982, 1996) Tomirdiaro et al. (1984) Tomirdiaro and Chernen'kiy (1987) Walter et al. (2007)
(3) Lacustrine and palustrine	
Sediments of river deltas and swamps dammed by a shelf ice sheet	Nagaoka (1994) Nagaoka et al. (1995)
(4) Glacial and proglacial	
Buried remnants of glaciers **Proglacial deposits in basins dammed by a shelf glacier**	Grosswald (1983, 1998) Toll (1895) Vollosowitch (1914)
(5) Marine-estuarine-lagoon	
Near-shore marine and lagoon deposits	Bol'shiyanov et al. (2013)
(6) Polygenetic	
Polygenetic deposits as products of fluvial, lacustrine, palustrine, slope, aeolian transport	Konishchev (1987) Sher (1997) Schirrmeister et al. (2011, 2013)
(7) Nival -polygenetic	
Nival-polygenetic deposits as products of aeolian, fluvial, solifluction transport from melting extensive perennial snow patches in non-glaciated Siberia	Galabala (1997) Kunitsky (1989), Kunitsky et al. (2002)

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Table S2: Study sites, coordinates, geological and geomorphological characteristics, and corresponding site-specific publications.

Loc. No.	Location	Elevation (m asl)	Age (kyr)	°N	°E	bedrock/ parent rock	Distance to mountains, rivers, past glacier border lines (Kaufmann et al., 2004; Archipov et al., 1986, 1988; Ehlers et al., 2011)
Alaska							
1	Colville River (Grosse et al., 2015)	250 120	45 - 13	69.03 69.30	-155.44 -152.32	Cretaceous sedimentary bedrock in the rolling foothills of the Brooks Range	80 km N of Brooks Range, at the Colville River, 78 km and 94 km N of the Laurentian Ice Sheet
2	Itkillik River (Kanevskiy et al., 2016; Lapointe et al., 2017; Strauss et al., 2012b)	85	>47.5 - 14	69.57	-150.87	Cretaceous sedimentary bedrock in the rolling foothills of the Brooks Range	135 km N of Brooks Range, at the Itkillik River, 91 km N of the Laurentian Ice Sheet
3	Seward Peninsula (Kitluk River) (unpublished data)	~ 30	----	66.55	-164.45	Loess-like deposits from the floodplains of the palaeo river (Péwé, 1975); local late Quaternary massive tephra layers and lava fields	150 km SW of the Brooks Range, 3 km S of the Chukchi Sea coast, 269 km W of the Laurentian Ice Sheet
4	Vault Creek tunnel (Schirrmeister et al., 2016a)	200	50 - 20	65.03	-147.71	Weathered schistose bedrock of the Precambrian or Lower Paleozoic “Birch-Creek schist”	270 km S of the Brooks Range, 27 km N of the Tanana River, between the Brooks (260 km) and Alaska range ice sheets (107 km)
Western Laptev Sea							
5	Cape Mamontov Klyk (Schirrmeister et al., 2004, 2008; Winterfeld et al., 2011)	30	46 - 9.5	73.61	117.18	Mesozoic sandstone and siltstone of the Pronchishchev Range	40 km N of the Pronshishchev Range, Laptev Sea coast, ca. 477 km SE of the Eurasian ice border (60 ka BP), 487 km NW of the Verkhoyansk Glacier
Lena Delta							

6	Ebe Basyn Sise Island (Nagym) (Schirrmeister et al., 2001, 2003)	25	>56.8 - 43	72.88	123.32	Mesozoic sandstone and slate of the Chekanovsky Ridge	20 km N of the Chekanovsky Ridge, Olenyek Channel, Lena delta, ca. 679 km SE of the Eurasian ice border (60 ka BP), 302 km NW of the Verkhoyansk Glacier
7	Khardang Sise Island (Schirrmeister et al., 2007)	20	30 - 20	72.95	124.21	Mesozoic sandstone and slate of the Chekanovsky Ridge	65 km N of the Chekanovsky Ridge, Olenyek Channel, Lena Delta, 696 km SE of the Eurasian ice border (60 ka BP), 298 km NW of the Verkhoyansk Glacier
8	Kurungnakh Sise Island (Schirrmeister et al., 2001, 2003, 2011a; Schwamborn et al., 2002; Wetterich et al., 2008)	35	50 - 32	72.33	126.30	Mesozoic sandstone and slate of the Chekanovsky Ridge	15 km N of the Chekanovsky Ridge, Olenyek Channel, Lena Delta, 794 km SE of the Eurasian ice border (60 ka BP), 218 km NW of the Verkhoyansk Glacier
Central and Eastern Laptev Sea							
9	Bykovsky Peninsula, (Mamontovy Khayata) (Grosse et al., 2007; Schirrmeister et al., 2002a,b; Siegert et al., 1999, 2002; Sher et al., 2000, 2005)	40	57 - 12	71.78	129.43	Permocarbon sandstone and slate of the Kharaulakh Mountain	40 km E of the Kharaulakh Ridge, at the Laptev Sea coast, 914 km SE of the Eurasian ice border (60 ka BP), 121 km NNE of the Verkhoyansk Glacier
10	Muostakh Island (Grigoriev et al., 2003; Schirrmeister et al., 2011b)	20	39 - 20	71.60	129.99	Permocarbon sandstone and slate of the Kharaulakh Mountain	40 km E of the Kharaulakh Ridge, at the Laptev Sea coast, 942 km SE of the Eurasian ice border (60 ka BP), 103 km NNE of the Verkhoyansk Glacier

11	Buor Khaya Peninsula (Schirrmeister et al., 2017; Strauss et al., 2011, 2015)	35	54 - 11	71.42	132.11	Permocarbon sandstone and slate of the Kharaulakh Mountains	100 km E of the Kharaulakh Ridge, at the Laptev Sea coast, 1010 km SE of the Eurasian ice border (60 ka BP), 123 km NE of the Verkhoyansk Glacier
New Siberian Archipelago and the Dmitry Laptev Strait							
12	Stolbovoy Island (Schirrmeister et al., 2011b)	30	>51 – 36.6	74.06	136.08	Cretaceous sandstone, siltstone	at the Laptev Sea coast, 938 km E of the Eurasian ice border (60 ka BP), 434 km NNE of the Verkhoyansk Glacier
13	Bel'kovskiy Island (Schirrmeister et al., 2011b)	15	54 - 40	75.37	135.59	Devonian siltstone, mudstone, sandstone, limestone	at the Laptev Sea coast, 853 km E of the Eurasian ice border (60 ka BP), 714 km NNW of the Chersky Range Glaciation, 554 km N of the Verkhoyansk Glacier
14	Northern Kotelny Island (Cape Anisii) (Schirrmeister et al., 2011b)	20	28	76.17	139.01	Silurian limestone, siltstone	at the Laptev Sea coast, 887 km ESE of the Eurasian ice border (60 ka BP), 800 km NNW of the Chersky Range Glaciation, 677 km N of the Verkhoyansk Glacier
15	Southwestern Kotelny Island (Komurganakh River mouth) (Schirrmeister et al., 2011b)	20	46 - 35	74.74	138.38	Devonian siltstone, mudstone, sandstone, limestone	at the Laptev Sea coast (Sannikov Strait), 962 km ESE of the Eurasian ice border (60 ka BP), 641 km NNW of the Chersky Range Glaciation, 535 km N of the Verkhoyansk Glacier

16	Maly Lyakhovsky Island (Schirrmeister et al., 2011b)	15	38 - 28	74.25	140.35	Jurassic siltstone, mudstone, sandstone	at the Laptev Sea coast (Sannikov Strait), 1040 km SE of the Eurasian ice border (60 ka BP), 594 km N of the Chersky Range Glaciation, 563 km NNE of the Verkhoyansk Glacier
17	Bol'shoy Lyakhovsky Island (Zimov'e River) (Schirrmeister et al., 2000; Andreev et al., 2004, 2009; Wetterich et al., 2011b, 2014; Schwamborn and Wetterich, 2015)	35	54 - 22	73.30	141.5	Permian to Triassic siltstone, sandstone, mudstone, Early Cretaceous granite	at the Laptev Sea coast (Dmitrii Laptev Strait), 1127 km SE of the Eurasian ice border (60 ka BP), 502 km N of the Chersky Range Glaciation, 505 km NNE of the Verkhoyansk Glacier
18	Oyogos Yar coast (Boike et al., 2008; Grigoriev et al., 2003; Opel et al., 2017; Schirrmeister et al., 2011b)	30	48 - 32	72.68	143.53	Neogene silt, sand, gravel	at the Laptev Sea coast (Dmitrii Laptev Strait), 1223 km SE of the Eurasian ice border (60 ka BP), 467 km NNE of the Chersky Range Glaciation, 529 km NE of the Verkhoyansk Glacier
Yakutian inland							
19	Duvanny Yar (Kolyma lowland) (Strauss et al., 2012a; Wetterich et al., 2011a)	50	47 - 22	68.63	159.14		at the Kolyma River, 120 km W of the Belaya Strelka Mountains, 315 m west of the Anyou Range Glaciation
20	Kytalyk (Indigirka lowland) (Schirrmeister et al., 2012)	30	31 - 16	70.84	147.45		at the Berelekh River, 410 km NE of the Chersky Range Glaciation,
21	Batagay Mega-slump (Ashastina et al., 2017; Kunitsky et al., 2013; Murton et al., 2017)	300	>51 - 26	67.58	134.76	Tertiary terrigenous siltstone, mudstone, has undergone low-grade metamorphism	10 km SE of the Yana River, 200 km E of the Verkhoyansk Glacier, 105 km W of the Chersky Range Glaciation

22	Tabaga (Central Yakutia) (unpublished data)	160	32 - 20	61.66	130.94	40 km SE of the Lena River, 226 km S of the Verkhoyansk Glacier
23	Yukechi (Central Yakutia) (unpublished data)	200	>49 - 22	61.76	130.47	on the Abalakh terrace, 60 km SE of the Lena River, 219 km S of the Verkhoyansk Glacier
Non Yedoma (as reference)						
	Pokhodsk polygon cores (Schirrmeister et al., 2016b, 2018)	8	2 - 3	69.1	160.9	
	Pokhodsk polygon bottom (Schirrmeister et al., 2016b)	7	modern	69.1	160.9	
	Kytalyk polygon cores (Schirrmeister et al., 2018)	5	2 - 3	70.8	147.5	
	Kytalyk polygon bottom (de Klerk et al., in prep., Schirrmeister et al., 2012, 2016b)	4	modern	70.8	147.5	
	Kolyma+Berelekh flood plains (Schirrmeister et al., 2016b)	5	modern	69.1 70.8	161.0 147.5	

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Figs. S3 Examples of Yedoma locations across Beringia.

Fig. S3.1 (a) The Alaskan Yedoma from the Colville site (Alaskan North Slope), (b) from the Vault Creek tunnel (Fairbanks), and (c) from the Seward Peninsula (Kitluk River).

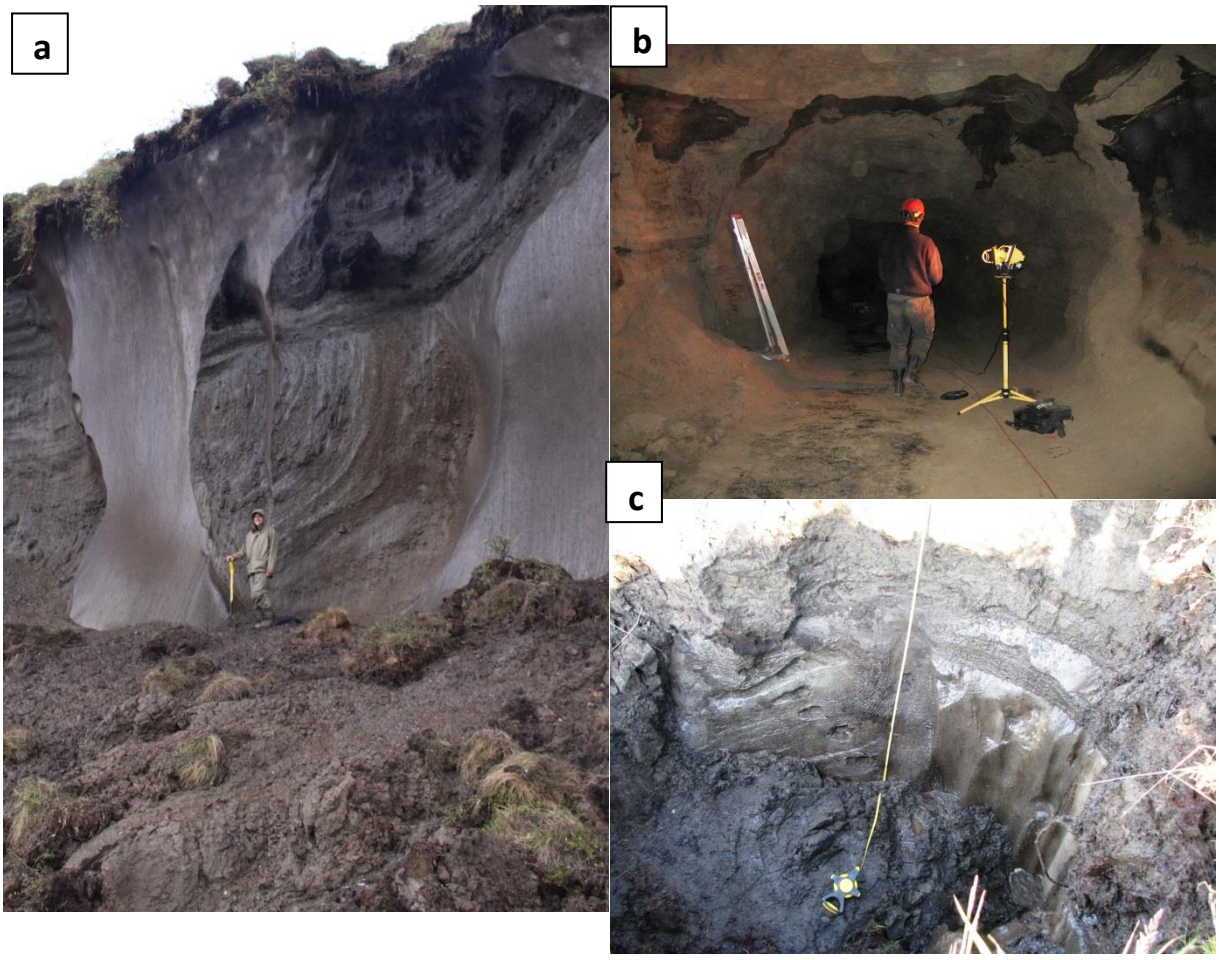


Fig. S3.2 The Yedoma from the Laptev Sea coast and the Lena Delta (a) Cap Mamontov Klyk (western Laptev Sea), (b) Kurungnakh Island (Lena Delta), (c) Ebe Basyn Sise Island (Lena Delta), (d) Muostakh Island (Central Laptev Sea), (e) Bykovsky Peninsula, and (f) Buor Khaya Peninsula.

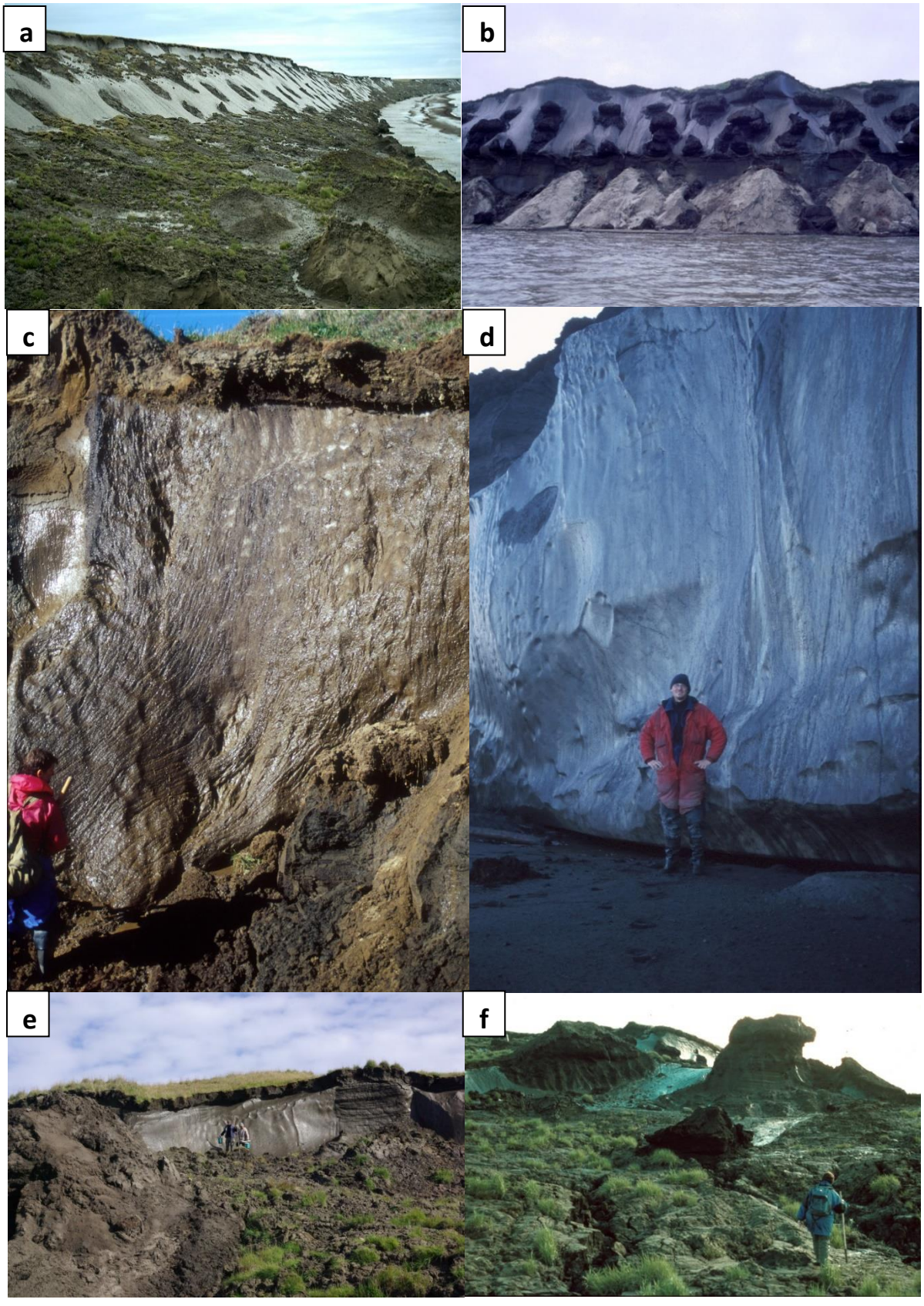


Fig. S3.3 The Yedoma from the Yakutian inland (a) Kytalyk near the Berelekh River (Indigirka Lowland), (b) Batagay Mega-slump (Yana Highland), and (c) Tabaga (Central Yakutia).

Figs. S4 End-member modeling from all the 17 studied Yedoma sites and the non-Yedoma ice-wedge polygon sites

Fig. S4.1 End-member modeling results from the Alaskan Yedoma sites.

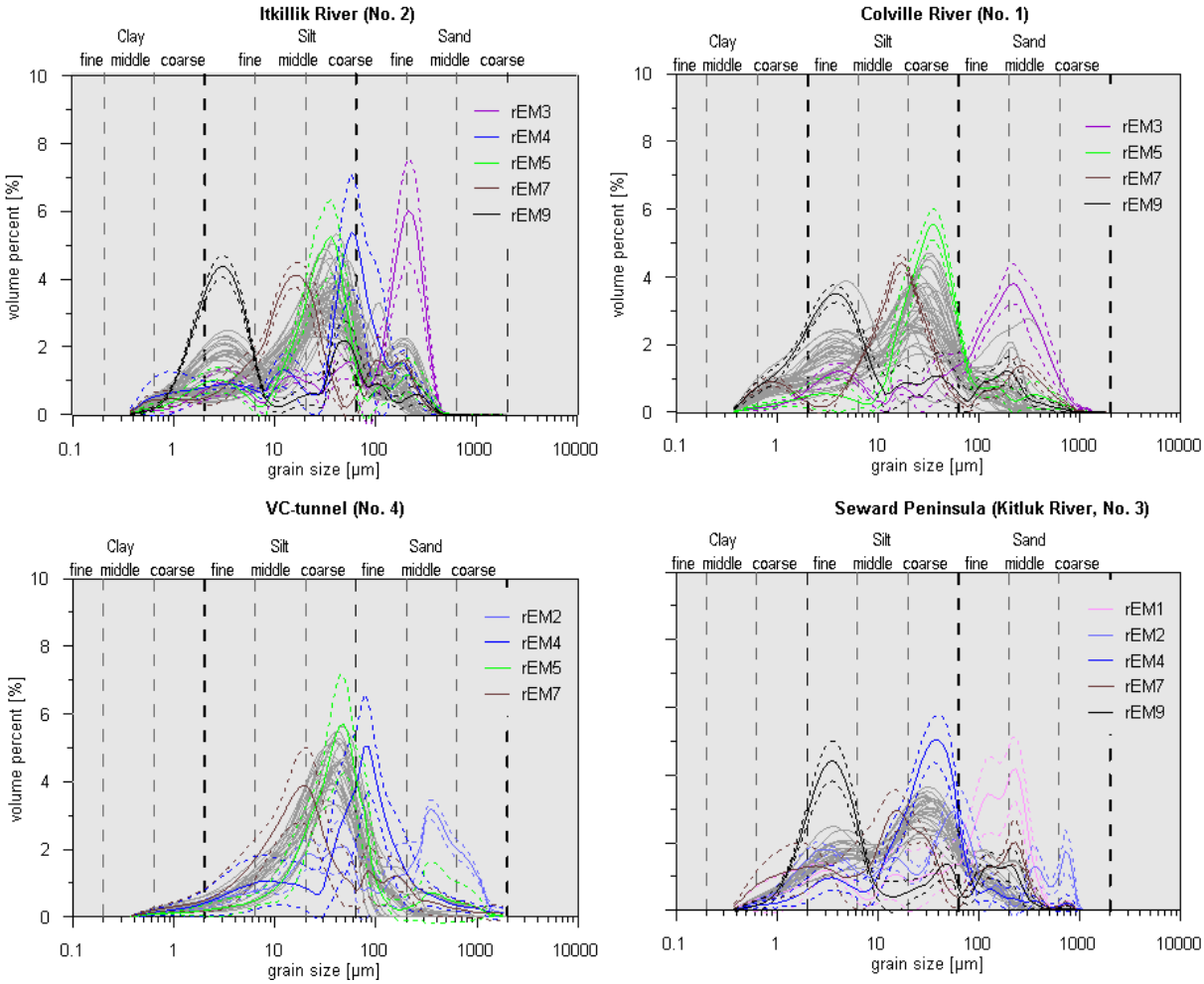


Fig. S4.2 Endmember modeling results from the Yedoma sites of the Laptev Sea coast and the Lena Delta.

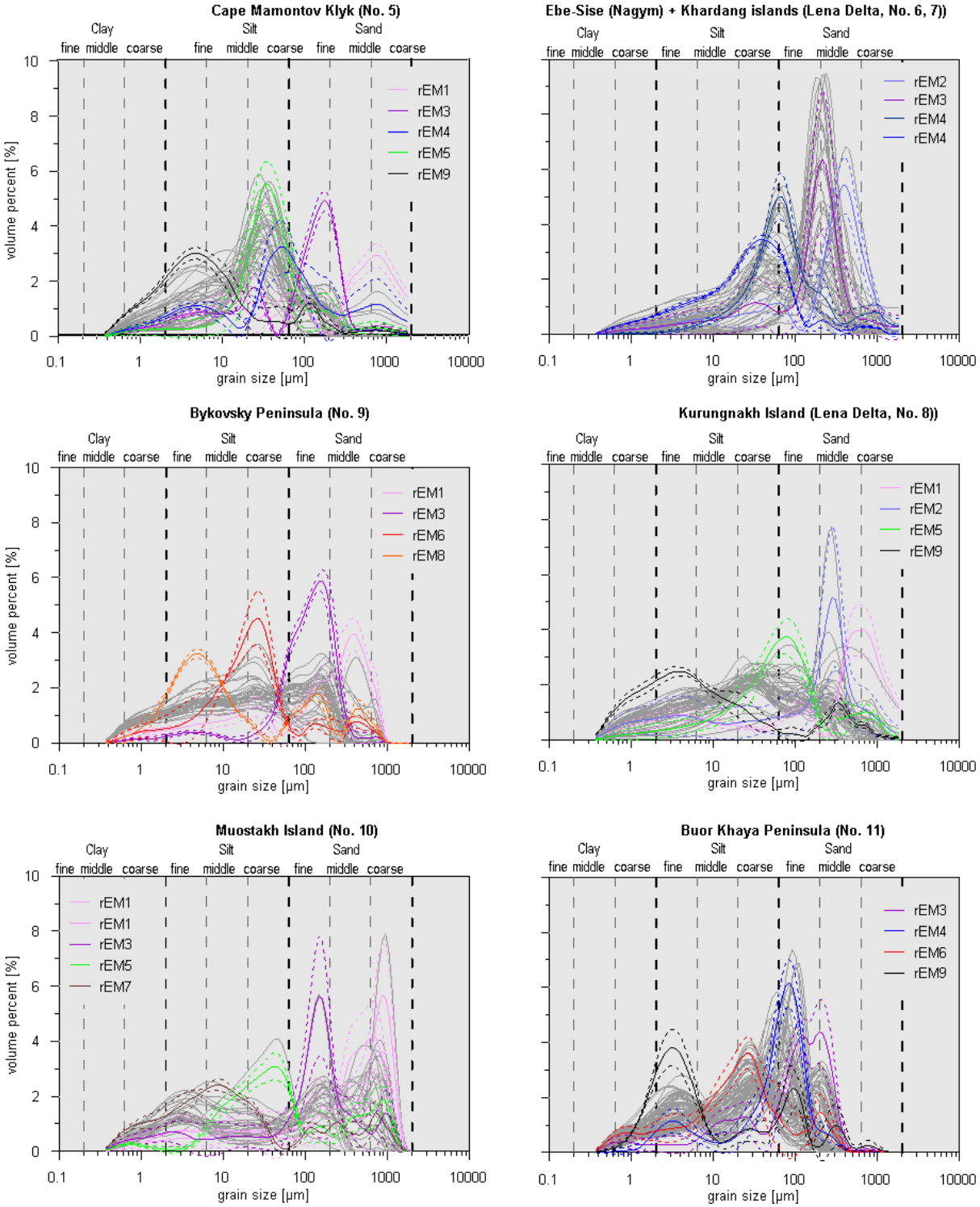


Fig. S4.3 Endmember modeling results from the Yedoma sites of the New Siberian Islands and the Dmitry Laptev Strait.

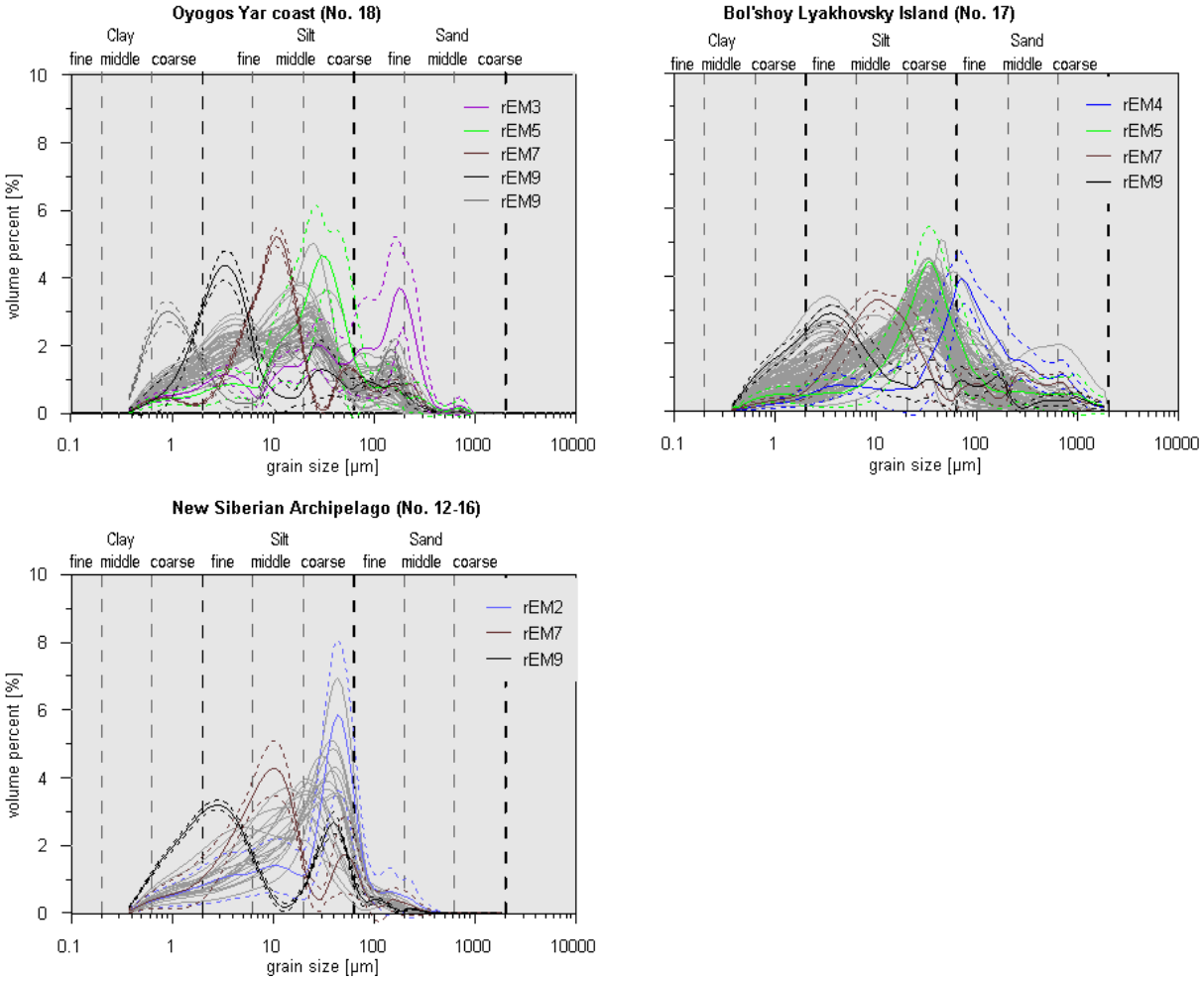


Fig. S4.4 Endmember modeling results from the Yedoma sites of the Yakutian inland.

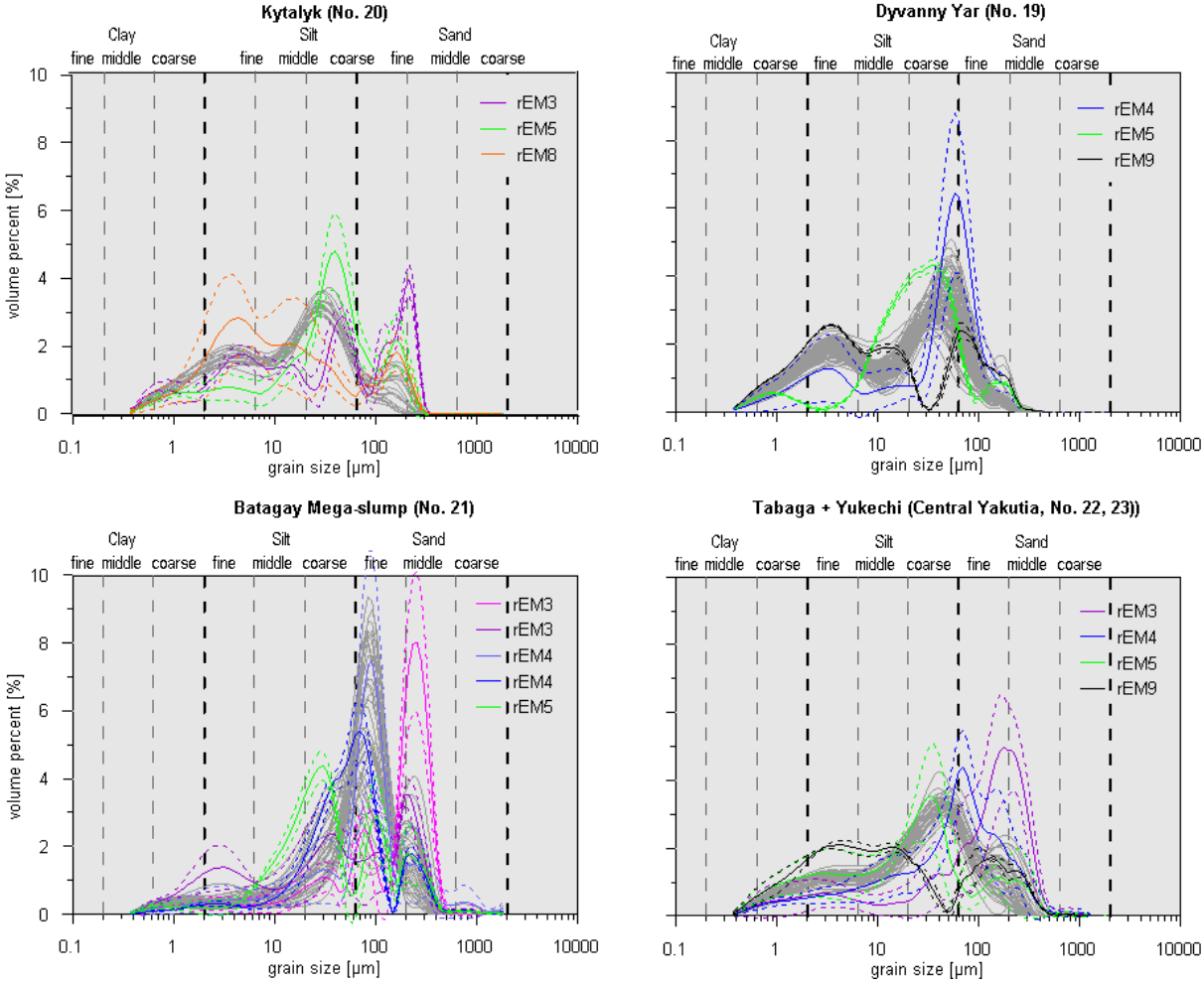
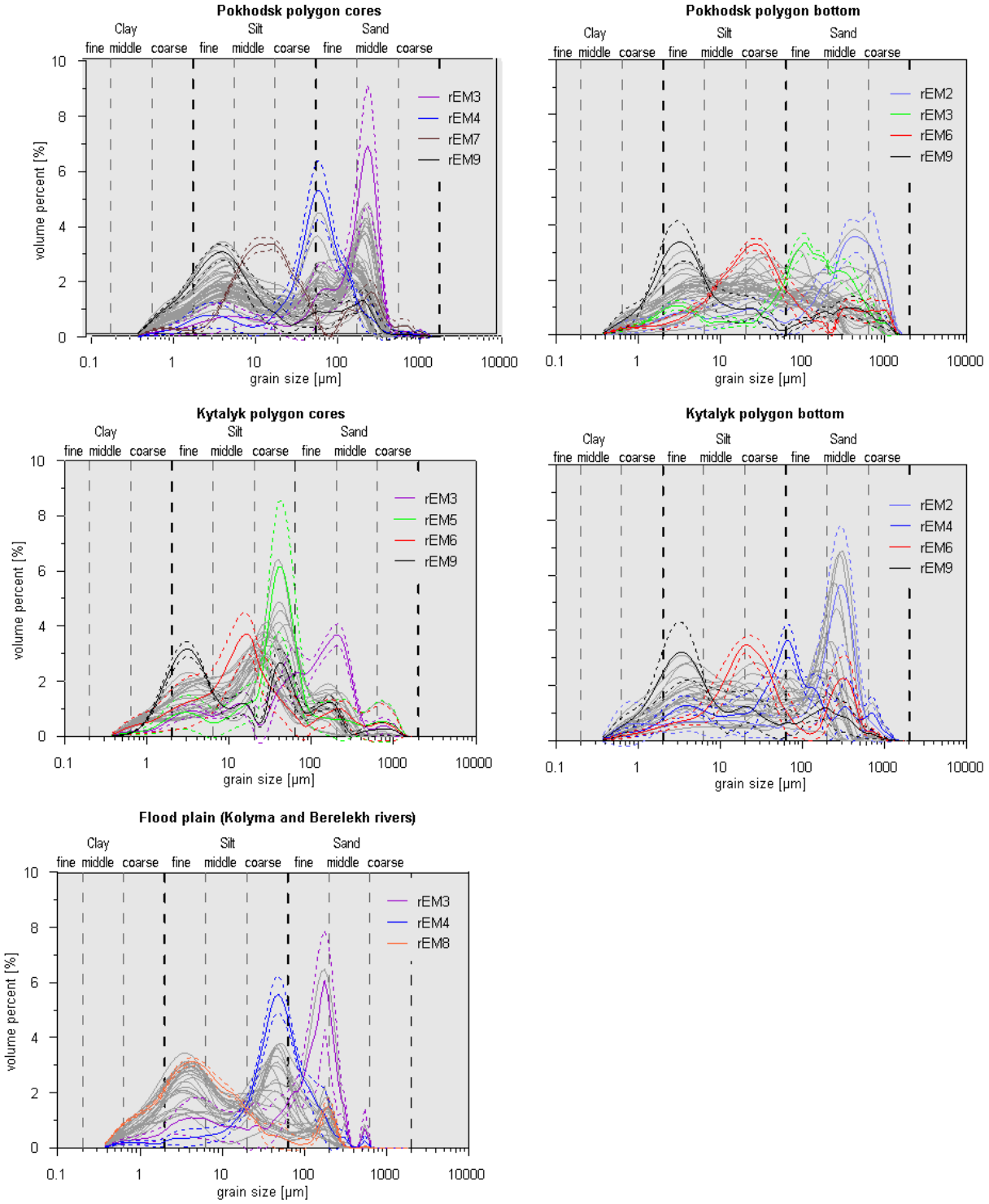


Fig.S4.5 Endmember modeling results from the non-Yedoma sites.



Figs. S5 The mean scores (the relative contribution of an endmember to each sample) for all the 17 studied Yedoma sites and the non-Yedoma ice-wedge polygon sites. Please note, for better visual clarity loadings are not plotted with depth but in the same stratigraphic order.

Fig. S5.1 Mean scores of the Alaska Yedoma sites

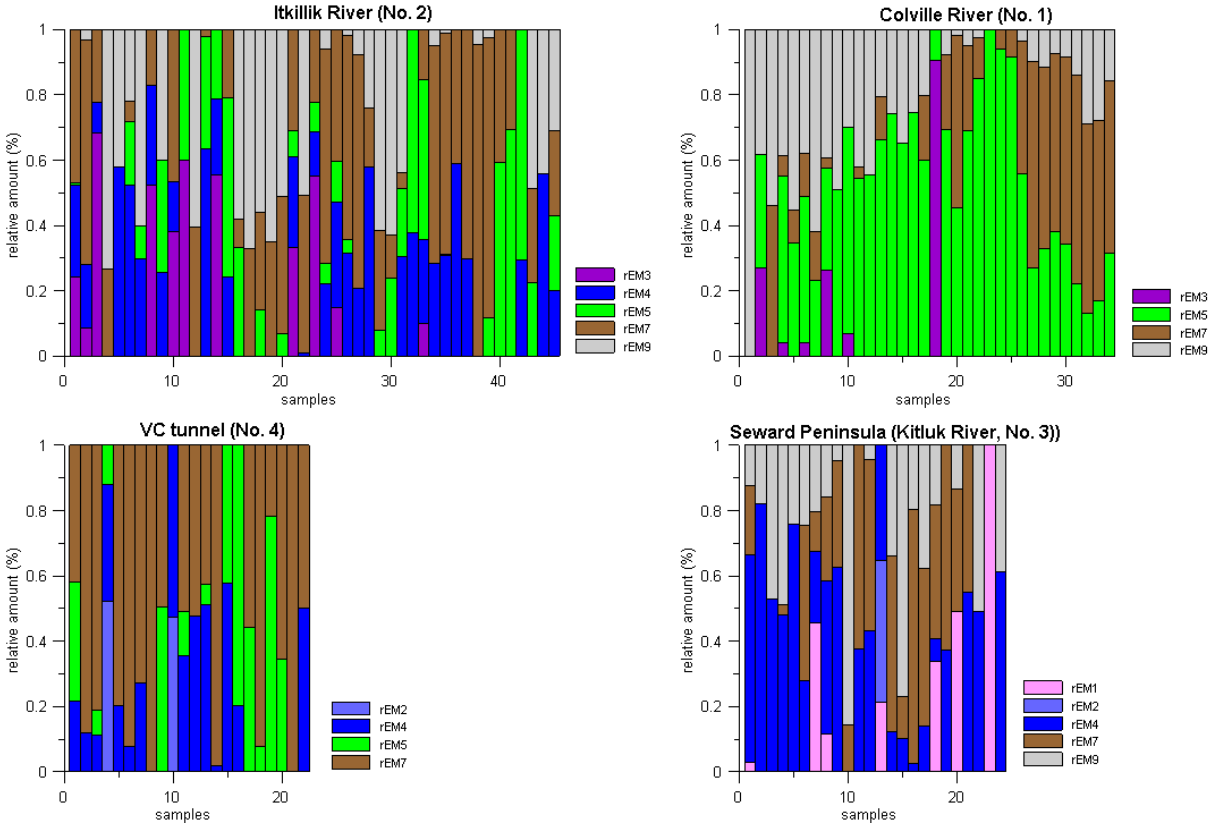


Fig. S5.2 Mean scores from the Laptev Sea coast and the Lena Delta Yedoma sites.

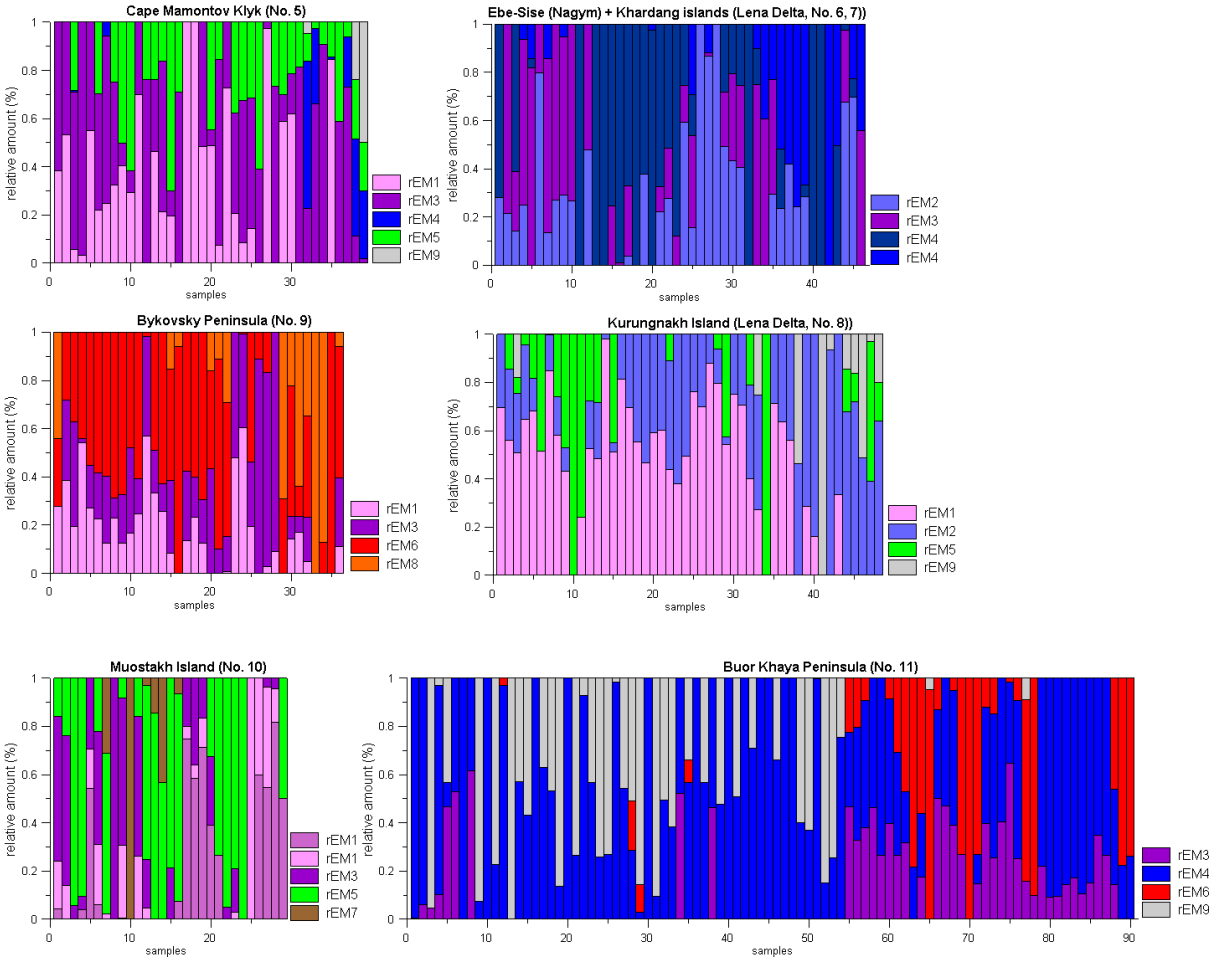


Fig. S5.3 Mean scores of the New Siberian Islands and Dmitry Laptev Strait Yedoma sites.

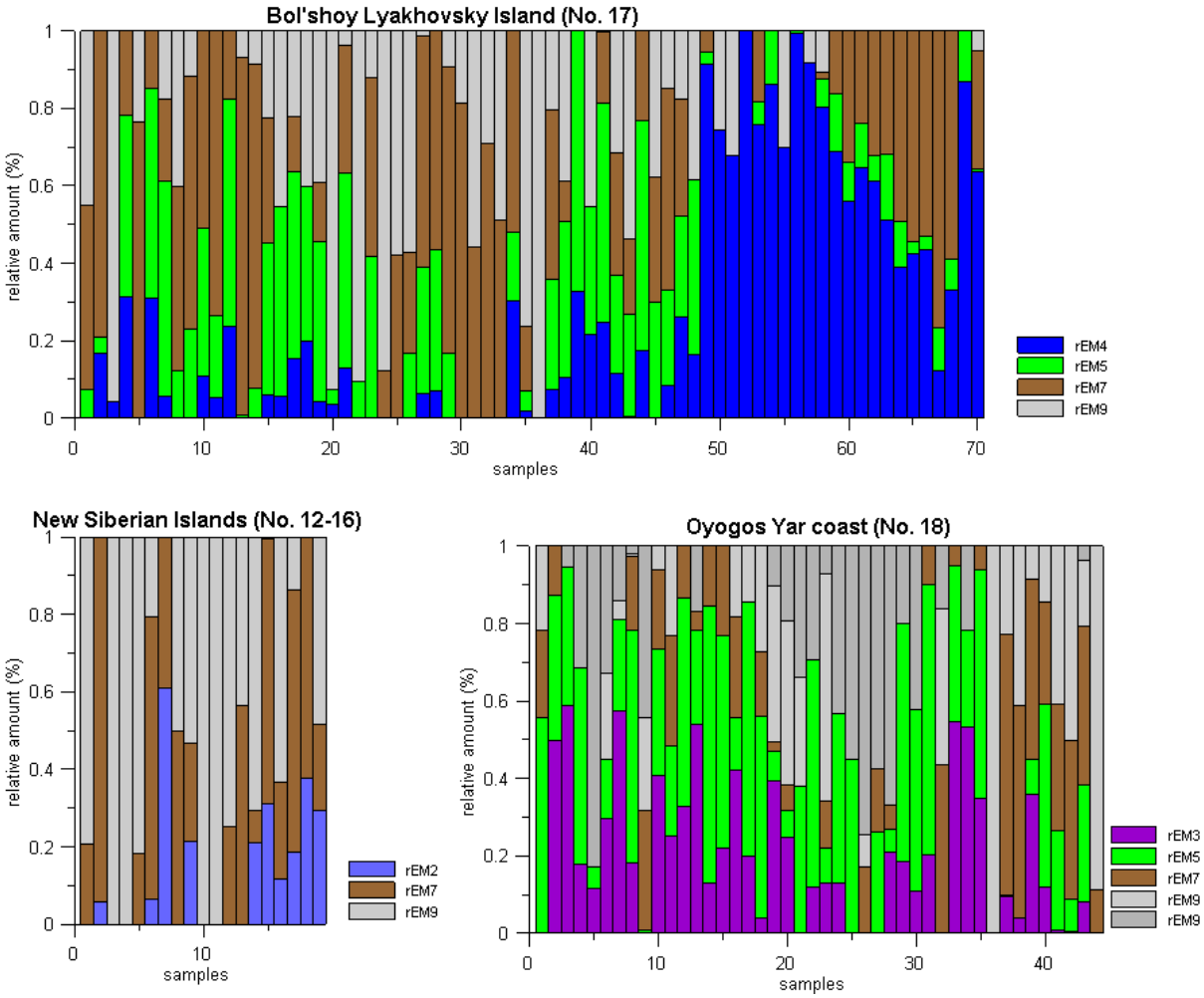


Fig. S5.4 Mean scores from the Yakutian inland Yedoma sites.

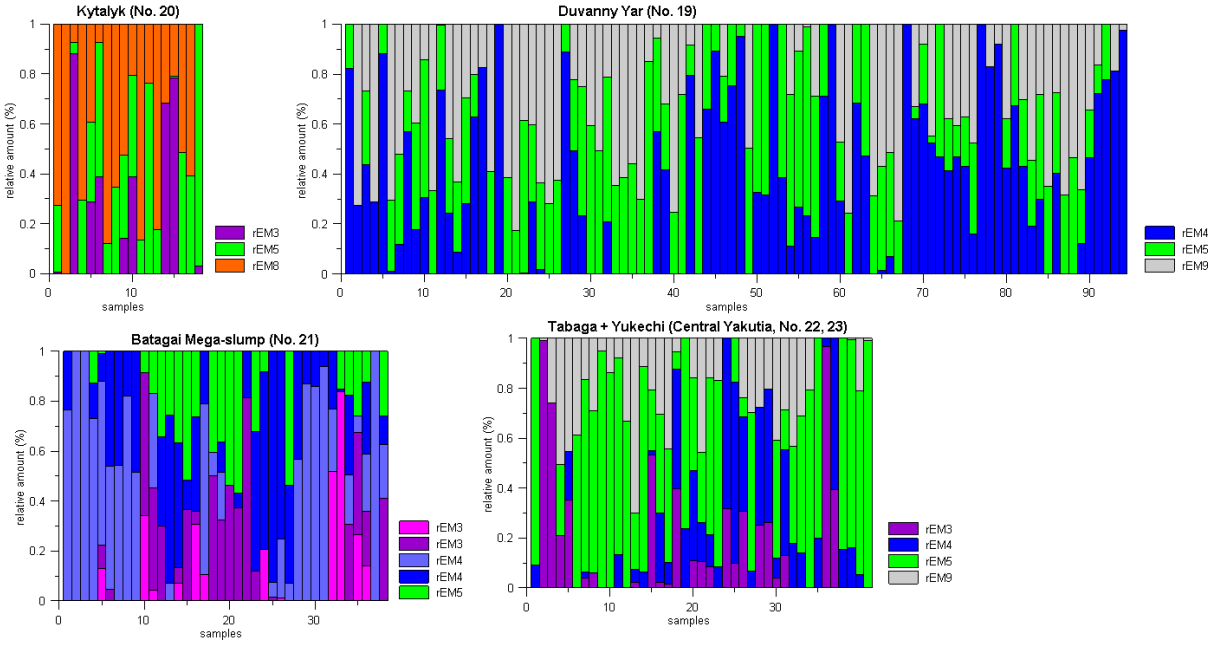
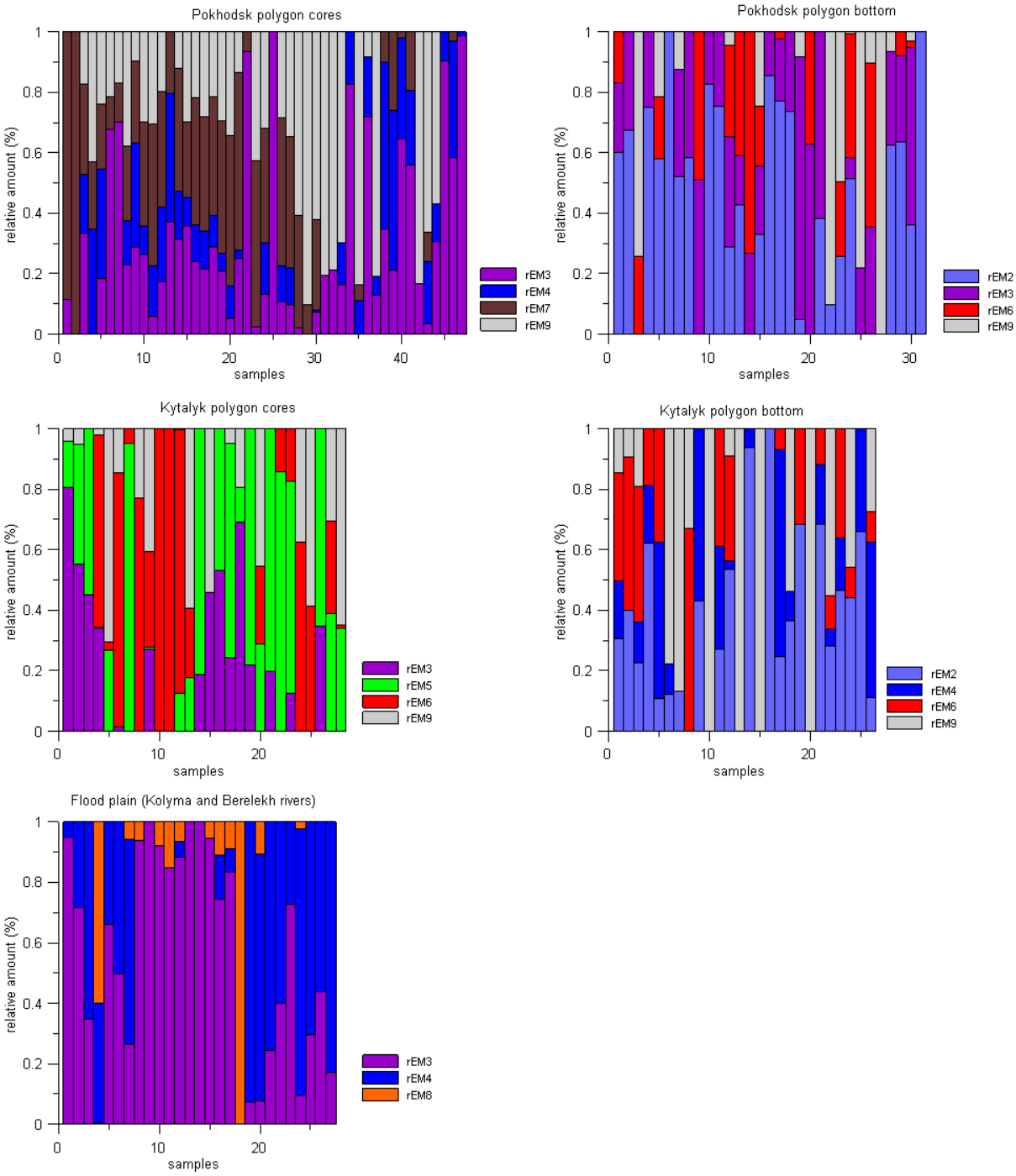


Fig. S5.5 Mean scores from non-Yedoma ice-wedge polygon sites.



Figs. S6 Regional and Arctic-wide end-member modeling results.

Fig. S6.1 Regional end-member modeling results (regional loadings) for the three study regions.

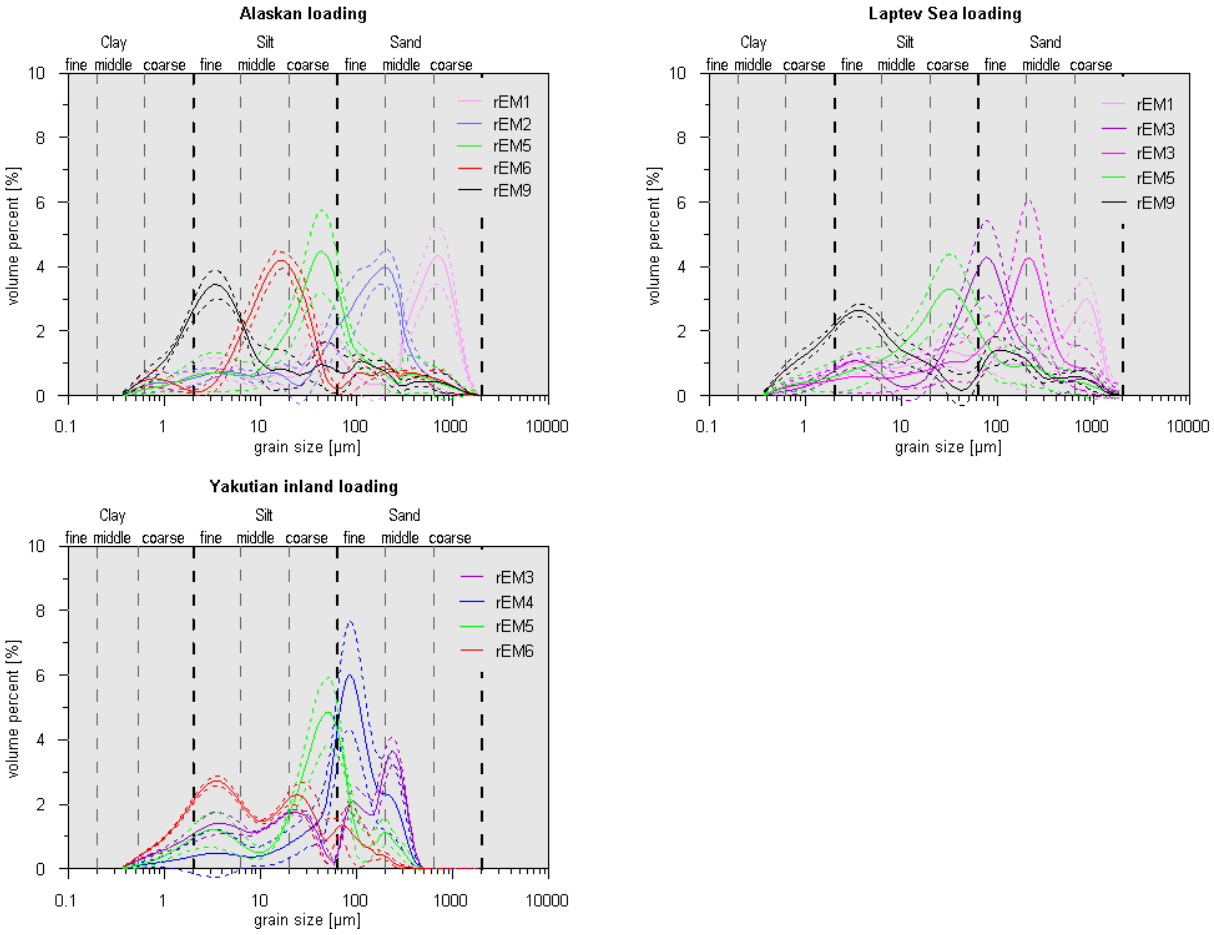


Fig. S6.2 The mean scores (the relative contribution of an endmember to each sample) for the three study regions. Please note, for better visual clarity loadings are not plotted with depth but in the same stratigraphic order.

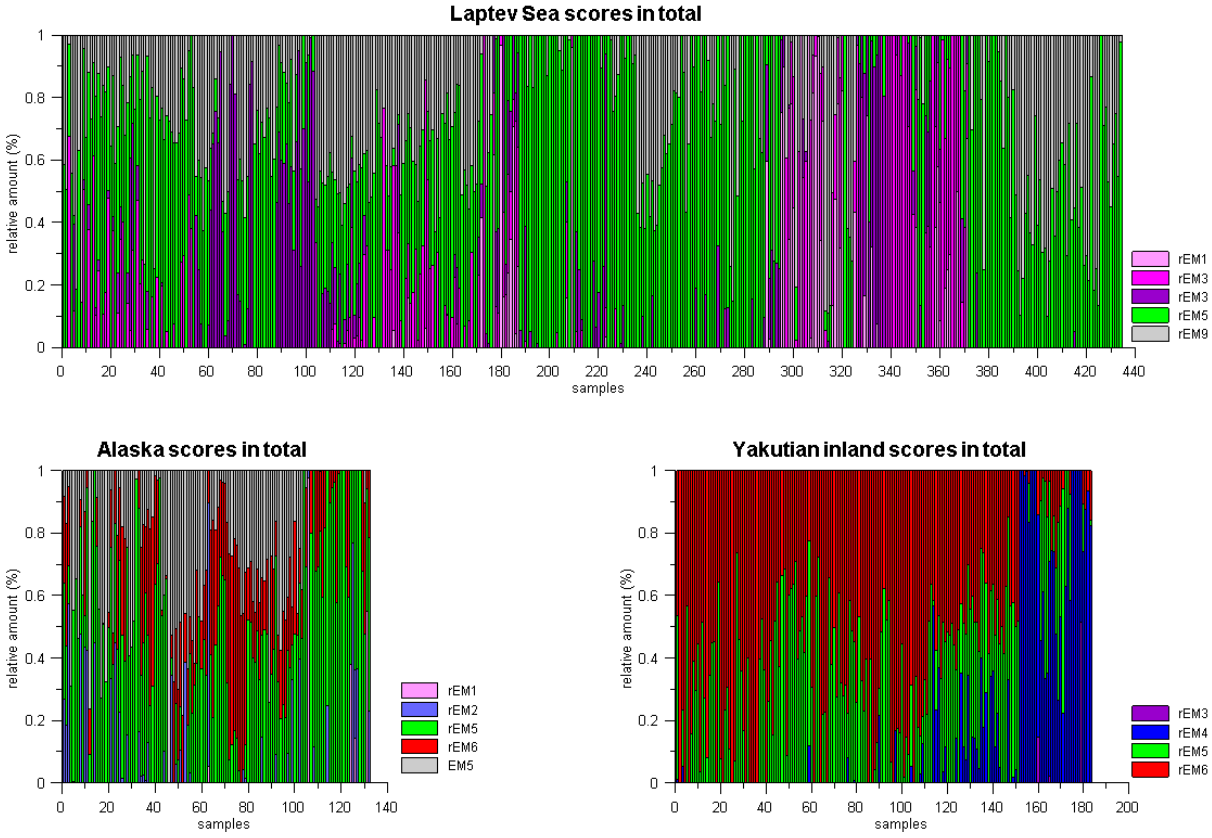
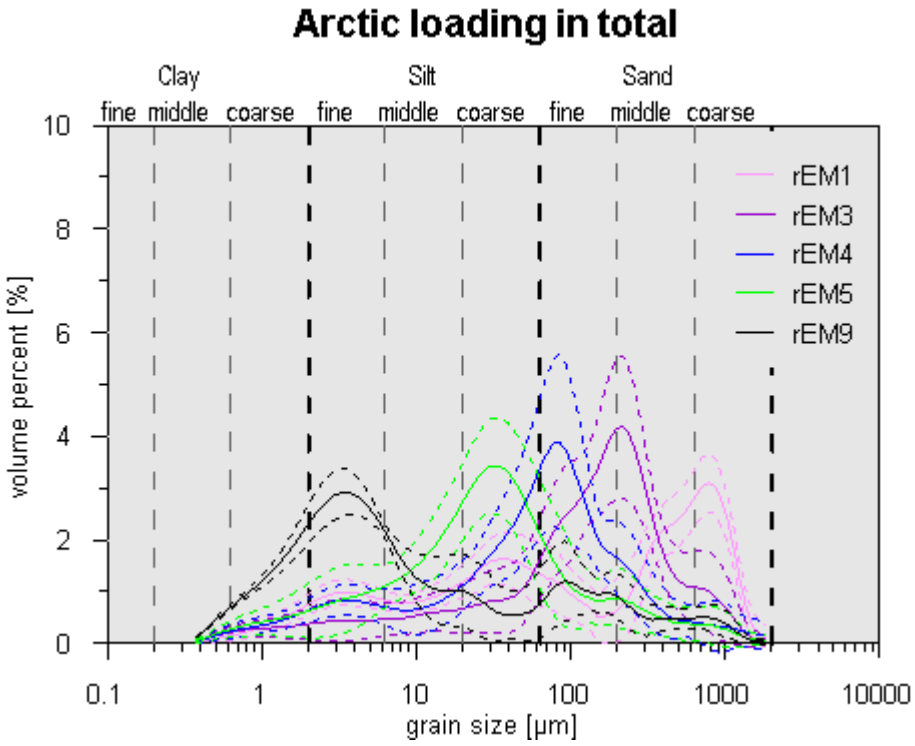
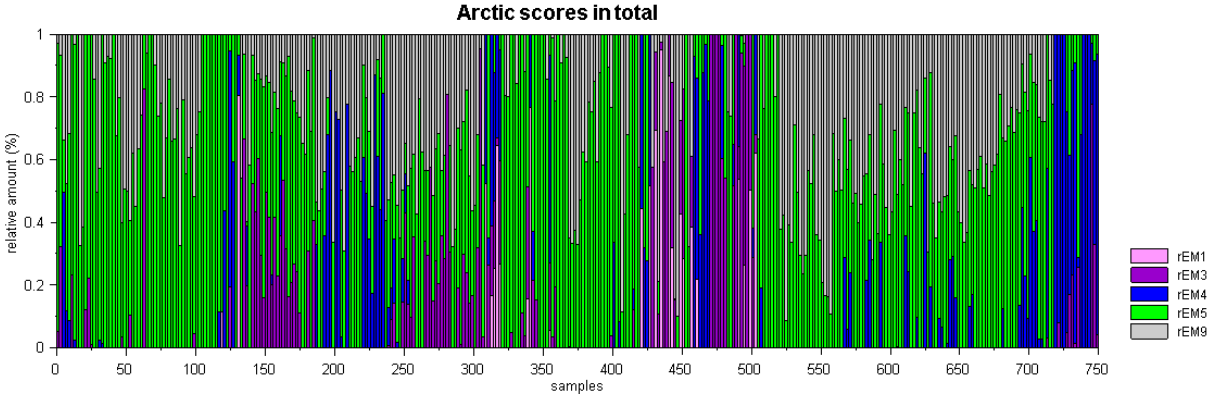


Fig. S6.3 Arctic-wide end-member modeling results and mean scores.





Figs. S7 Results of cluster analyses.

Fig. S7.1 Cluster dendrogram for the hierarchical clustering of the grouped endmember primary modes/explained variances. Distances between sites are assessed using the chi-squared method. Clustering method is "complete". Colors of the sample sites denote the cluster the site belongs to. Numbers at the dendrogram edges are for basic bootstrapping probability significance values (red) and corrected approximately unbiased significance values (green), statistical significances according to the bootstrapping approach used in pvclust.

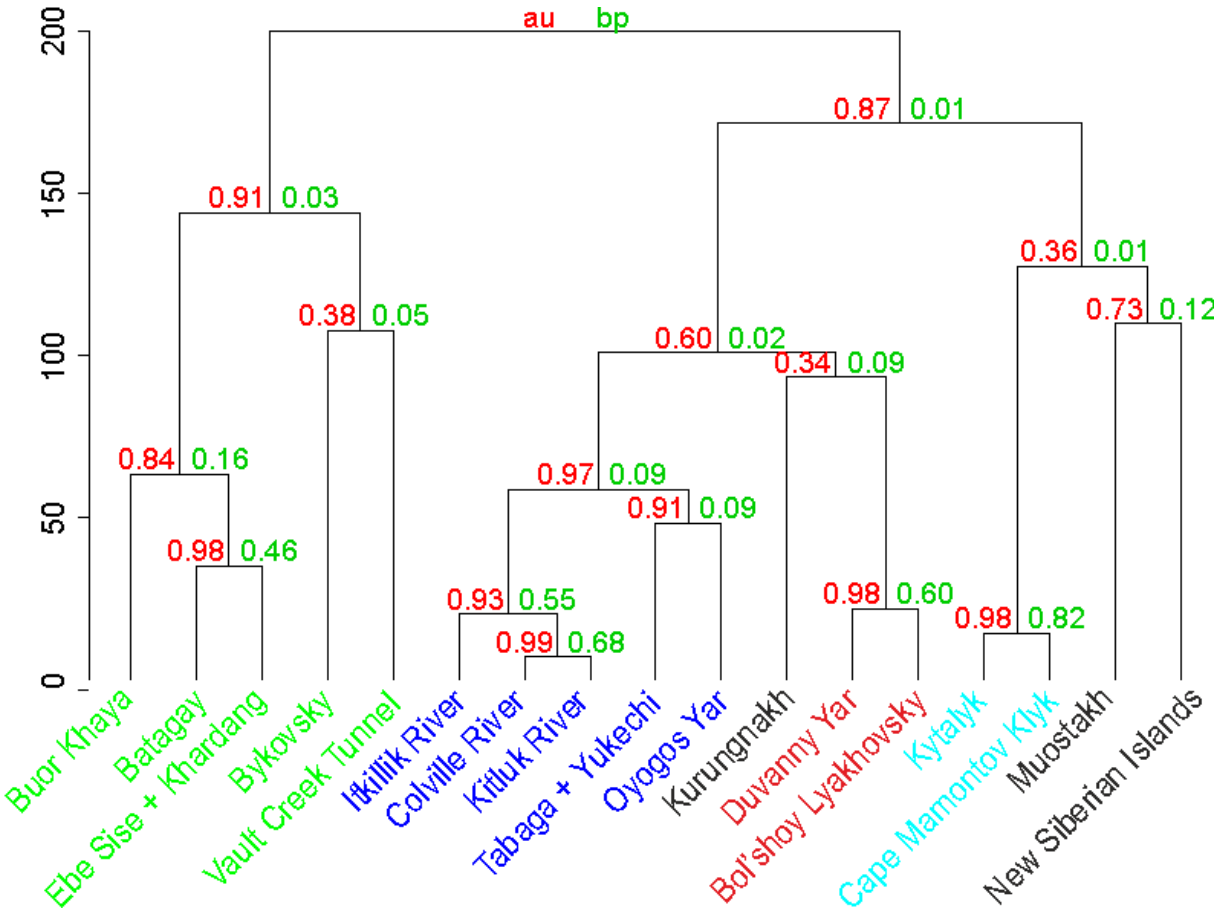


Fig. S7.2 Cluster means and standard deviations of each cluster for the grain-size groups following the classification described in the paper. Colors denote the four clusters. The post-hoc global p-values for each grainsize class are given at the top of the diagram.