Interactive comment on "Mineral element stocks in the Yedoma domain: a first assessment in ice-rich permafrost regions" by Arthur Monhonval et al.

Anonymous Referee #2

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RC= Reviewer comment ; **AR**= Authors response

RC: I appreciate the efforts from the authors. I understand the authors created a valuable dataset for the mineral elements in the yedoma regions, and they also tried to calculated the storage of these elements. I have some comments for the authors to improve the quality of the manuscripts.

We thank the reviewer for the valuable comments and suggestions to improve the manuscript. We have revised the manuscript accordingly. Please find the details in the responses to the following comments.

RC1: When the authors introduce the stocks or storage, it is necessary to clarify the depth or thickness of yedoma. At least, the authors should explain the characteristics of yedoma. This is important because the potential readers will be confused about the depth and height in the dataset.

AR : We agree that the choice of the thickness used to upscale to the whole Yedoma domain was not clear in the manuscript. Here, mineral element stocks are compared with C stocks using identical Yedoma domain deposits parameters (including thicknesses) like in Strauss et al., 2013 for deep permafrost carbon pool of the Yedoma region, i.e., a mean thickness of 19.6 meters deep in Yedoma deposits and 5.5 meters deep in Alas deposits. We have revised the manuscript to include that information (L 282):" *Thickness used for mineral element stock estimations in Yedoma domain deposits are based on mean profile depths of the sampled Yedoma (n=19) and Alas (n=10) deposits (Table 3; Strauss et al., 2013). Since the 10 000 step bootstrapping technique randomly picks one thickness at a time with replacement, we evaluated the stock estimation for a mean thickness of 19.6 meters deep in Yedoma deposits and 5.5 meters deep in Alas deposits."*

In addition, Table 3 has been added in the text to clarify the thickness used in the stock estimation.

Table 3: *Summary of key parameters for Yedoma deposits and Alas deposits. Parameters include thicknesses (in meters) and wedge ice volume (WIV, in %) from Strauss et al., 2013. Mineral element stock estimations are based on a mean thickness of 19.6 m for Yedoma and 5.5 m for Alas deposits.*

	Yedoma deposits		Alas deposits	
	Thickness (m)	WIV (vol%)	Thickness (m)	WIV (vol%)
Mean	19.6	49.1	5.5	7.8
Median	15.1	51.9	4.6	7.6
Min	4.6	34.7	1.2	0.8
Max	46	59	13.4	12.8
n	19	10	10	7

RC2: It is difficult to follow in the sampling sites section. What is the more than 20 years of sampling? Does that mean the samples were collected during the past 20 years? The authors explained 22 locations (or areas), and total 1292 samples, but did not present how many sites or profiles. How many soil profiles were measured? In the table 1, the authors introduced this, but is also necessary to explain the number of samples for each location and each yedoma profile. Just briefly introduce this.

AR: We have revised the manuscript according to the comment from the reviewer. A table (Table A1; Appendix A) has been added to provide i) the number of profiles sampled for each location; ii) the number of samples analyzed with pXRF method and iii) the number of samples analyzed with ICP-OES method, and iv) the number of samples analyzed by X-ray diffraction as well as general geomorphology of each site. We have also revised the text (Section 2.2, L138-140): "*More specifically, the dataset includes 22 locations and compiles 75 different profiles from West, North and Interior Alaska, the Kolyma region, the Indigirka region, the New Siberian Archipelago, the Laptev Sea coastal regions, and Central Yakutia (Fig. 1).*"

RC3: I did not check the references listed in the Table 1. What did these references mean? These references were conducted in the location (or area), or include environmental conditions for these areas? I suggest the authors add some information about the landform in the table, and so the readers can understand why you select the number of profiles.

AR: Each reference in Table 1 provides detailed description of landforms, cryostratigraphy and paleo-environmental characteristics of the sites and the sampled profiles. This has now been clarified in the caption of Table 1. We also added a more detailed Table (Appendix A) to present specific characteristics of the sites in each location.

RC4: For the 3.1 and 4.1 sections, the authors claimed they analyzed 144 samples using ICP, what are the 144 samples? What locations, profiles, depths or heights?

AR: We have revised the manuscript to add this information. In Table A1 (Appendix A), a specific column specifies how many samples were analyzed using ICP-OES measurements for each location. In Table C1 (Appendix C of the revised manuscript), we provide a list of the samples selected for linear regressions (n=144) with associated depth or height included.

RC5: Table 4, why the negative value for Si content?

AR: As specified in the caption of Table 4, the negative value is due to very high TOC content: "*For Si, excessive organic rich samples may result in lower concentration values and consequently in negative concentration value after correction. Only positive values have been considered for stock calculations.*" We have now included a * to refer to this information in the caption to clarify the point raised by the reviewer.

RC6: In the discussion section, I would like to see the disadvantage of pXRF, so the future users can be careful use this dataset. I do not know if there were similar datasets from pXFR, but I know some soil scientists do not believe this method, the authors should also explain why this dataset are valuable for future studies.

AR: A specific section discussing the advantages and the limitations of the pXRF method can be found in the revised version of the manuscript (section 5 in revised manuscript). The text emphasizes that "*The main limitation of the pXRF method is that raw concentration data cannot be used before applying a linear regression to correct for systematic error. This drawback related to inaccurate raw pXRF measurements can be rectified by correcting the raw pXRF values with accurate values obtained with the ICP-OES method after alkaline fusion (calibration based on 144 samples in this study)*". As explained in the revised manuscript (line 220-224, and revised Figure 4), raw pXRF measurements have low trueness (i.e. high systematic error) compare to true value. This is why raw pXRF measurements must be corrected using a calibration obtained with a complementary accurate method. In our case, this correction is made through a calibration line for each element comparing XRF measurements and ICP-

OES measurements after alkaline fusion on a subset of 144 samples (about 11% of the dataset). This correction is essential in order to use pXRF device is to obtain a reliable precision (i.e., low random errors; Table 2).

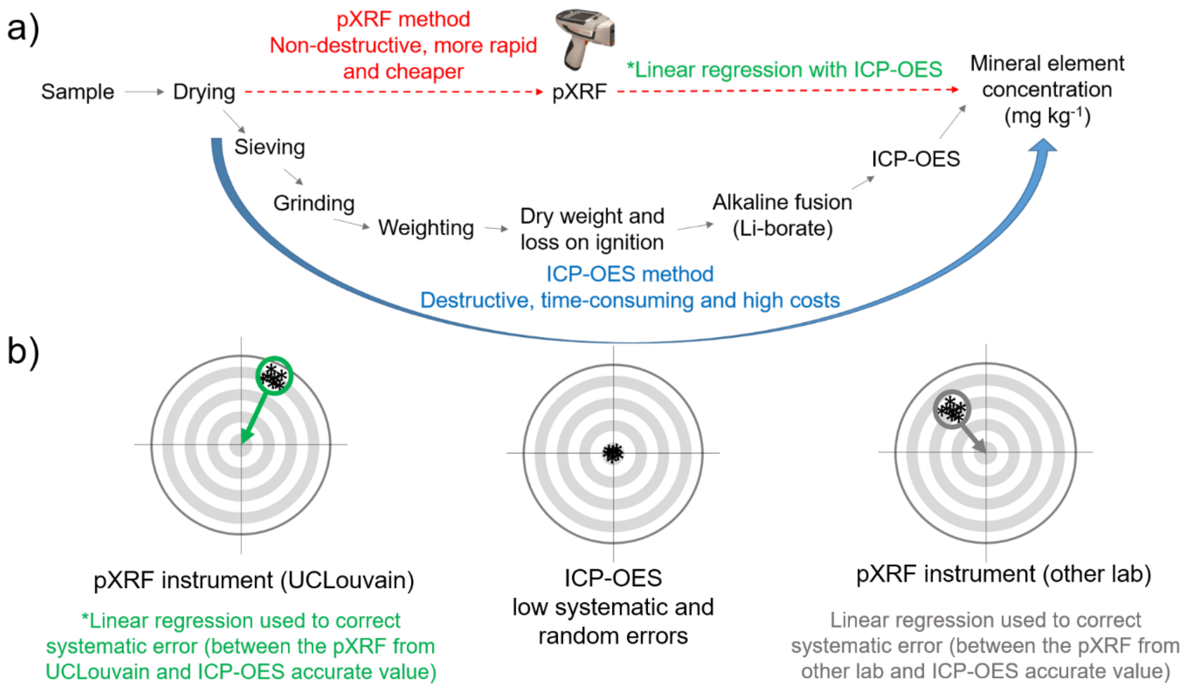

***Figure 4**: **(a)** Comparison between two methods to assess mineral element concentrations in deposit samples: the inductively coupled plasma optical-emission spectrometry (ICP-OES) method (large blue arrow) is destructive and time-consuming (involving several steps), whereas the portable X-ray fluorescence (pXRF) method (dotted red arrows) is non-destructive and allows a fast and reliable determination of element concentrations on a large set of samples in a cost-effective way when a correction with a linear regression is applied. **(b)** The pXRF bias (i.e., systematic error) is corrected with a linear regression specific to each pXRF device. Portable XRF devices from each lab require their own linear regression to correct for accurate value. The linear regression is obtained from a selection of samples (here 11 % of the samples) analysed by both methods, pXRF and ICP-OES.*

In his/her comment, the reviewer asks for clarification about how this dataset is valuable for future studies. Section 6 has been revised in order to present the main directions in which the dataset can provide useful insights, i.e., to investigate the evolution of mineral-organic carbon interactions (new Figure 8), and the influence of mineral weathering on the carbon cycle and nutrient supply to ecosystems. It has also been included in the revised version (Line 534-536 in revised manuscript) that we acknowledge that "*The YMCA dataset is a first step needed in order to evaluate the impact of widespread rapid permafrost thaw through thermokarst processes (Turetsky et al., 2020) on the mineral element concentrations in the deposits and the potential implications for OC and mineral nutrient supply.*"

RC7: I think it is necessary to compare the results with existing reports of the elements contents and stocks.

AR: To our knowledge, no mineral element stock assessment or mineral concentration assessment in Yedoma domain deposits exists. Some studies present the abundance of heavy mineral composition within some specific deposits profiles (Schirrmeister et al., 2002, 2003, 2008, 2010, 2011) but with no mineral concentration or stock assessment. In permafrost soils, the focus has been on soil properties such as exchangeable cations, cation exchange capacity (CEC), soil acidity, etc. (Ping et al., 1998, 2005). We have included references to existing work in permafrost soils in section 6.2 (Line 516).

RC8: The authors calculated the stocks and storage of these elements based on the pXFR methods and the distribution data of yedema. The uncertainties in the Yedoma distribution itself should be clarified.

AR: We agree that details were missing on how the total coverage of Yedoma and Alas deposits was estimated. We have revised the manuscript accordingly (L292-297 in revised manuscript):

"*The core Yedoma domain extent was estimated to ~1 387 000 km², based on digital Siberian Yedoma region map (Romanovskii, 1993) and the distribution of Alaskan ice-rich silt deposits equivalent to Yedoma (Jorgenson et al., 2008). The Yedoma deposit extent is estimated to 410 000 km², i.e., 30% of the Yedoma domain, based on the fact that 70% of the Yedoma domain area is affected by degradation (Strauss et al., 2013). Considering 10% of the area of the Yedoma domain covered with lakes and rivers, 4% covered with other deposits including deltaic and fluvial unfrozen sediments, this leaves 56% (780 000 km²) of the Yedoma domain covered by frozen thermokarst deposits in drained thermokarst lakes (Fig. 2).*"

RC9: I encourage the authors dig deeper about the relationship among the elements. For example, compare their contents and distributions with other soils, especially with soils in permafrost regions. These will be more interesting that the implications of the elements release in the present version. For what I see, it is a little speculative

AR: To address the comment from the reviewer, we have revised section 6. In section 6.1, we have included a new figure (Figure 8) to investigate the evolution of Fe to organic carbon ratio, and Al to organic carbon ratio upon thawing between Yedoma and Alas deposits.

In section 6.2, we consider the mineralogy of the deposits to investigate the evolution of mineral element concentration upon thawing between Yedoma and Alas deposits. This is the reason why we have included X-ray diffraction data providing the mineralogy of 40 samples from the Yedoma domain deposits (Table 6 here below). The associated methodology (section 3.3 in the revised manuscript) and results description (section 4.3 in the revised manuscript) have been included.

Table 6: Mineralogical composition in Yedoma (Y) and Alas and fluvial (A) deposits of Siberia and Alaska (Q, Quartz; Pl, Plagioclase; Ch, Chlorite; M, Mica; I, Illite; K, Kaolinite; D, Dolomite; Ca, Calcite; Sm, Smectites). The diffractograms for each profile (n = number of diffractogram per profile) are presented in Appendix G (a-b-c-d-e-f-g, respectively).

Site	n	Fraction	Profile label	Mineralogy	App. G
Sobo Sise	13	Bulk	Sobo T2-2 (Y), T2-3 (Y), T2-5 (A), T2-6 (A)	Q, Pl, Ch, M, K	a)
Buor Khaya	3	Bulk	Buo-02 (Y)	Q, Pl, Ch, M, K	b)
Buor Khaya	6	Bulk	Buo-04 (Y)	Q, Pl, Ch, M, K	c)
Buor Khaya	1	Clay	Buo-04-A-01 (Y)	Q, Pl, Ch, I, K, Sm	d)
Kytalyk	4	Bulk	KY T1-1 (Y), KY T2-2 (A)	Q, Pl, Ch, M, K	e)
Colville	3	Bulk	Col (Y)	Q, Pl, M, K, D, Ca	f)
Itkillik	10	Bulk	Itk (Y)	Q, Pl, M, K, D, Ca	g)

Appendix A: *Studied locations from the Yedoma domain with associated labels, total number of sampled profiles, number of samples analyzed with portable X-ray Fluorescence (pXRF), inductively coupled plasma optical emission spectrometry (ICP-OES) after alkaline fusion and X-ray diffraction method (XRD). A simplified geomorphological description of each sampling location is presented (detailed information is provided in the reference papers cited in Table 1). The site numbers (Site Nb) 1-17 are from Siberia, and 18-22 are from Alaska.*

Site Nb	Site Name	Label	Total sampled profiles	Samples analyzed with pXRF method	Samples analyzed with ICP-OES method	Samples characterized with XRD method	Geomorphology/ Landform
1	Cape Mamontov Klyk	Mak	3	80	-	-	Sedimentary coastal plain
2	Nagym (Ebe Sise Island)	Nag	3	29	-	-	Cliff section with thermokarst mounds
3	Khardang Island	Kha	1	31	1	-	Cliff section with thermokarst mounds
4	Kurungnakh Island	Bkh, KUR	4	143	2	-	Fragment of a broad foreland plain north of the Chekanovsky Ridge
5	Sobo Sise Island	Sob	4	58	58	13	Yedoma uplands but also features permafrost degradation landforms (thermokarst lakes, drained thaw lake basin, and thermo-erosional gullies)
6	Bykovsky Peninsula	Mkh, BYK	7	150	2	-	Remnants of an accumulation plain
7	Muostakh Island	Muo	1	11	-	-	Remnants of an accumulation plain
8	Buor Khaya Peninsula	Buo	5	80	44	10	Coastal lowlands - late Pleistocene accumulation plains
9	Stolbovoy Island	Sto	4	16	1	-	Step-like cryoplanation terraces with several levels
10	Belkovsky Island	Bel	2	12	-	-	Step-like cryoplanation terraces with several levels
11	Kotel'ny Island	KyS	1	10	-	-	Step-like cryoplanation terraces with several levels
12	Bunge Land	Bun	1	8	-	-	More-or-less homogeneous flat sandy plain
13	Bol'shoy Lyakhovsky Island	TZ, R, L	15	150	3	-	Gradually sloping terrain intersected by rivers and thermo-erosional valleys
14	Oyogos Yar coast	Oy	2	50	1	-	Very gently inclined step-like surface of the Yana-Indigirka Lowland
15	Kytalyk	KY, KH	3	50	4	4	Recent and sub-recent floodplains, Yedoma and Alas
16	Duvanny Yar	DY	6	143	5	-	Hills dissected by deep thermos-erosional valleys and thermokarst depressions
17	Yukechi	Yuk-Yul	4	87	2	-	Yedoma uplands and drained alas basins, indicating active thermokarst processes
18	Kitluk	Kit	2	45	2	-	Tundra-covered coastal plain
19	Baldwin Peninsula	Bal	4	70	1	-	Sequence of marine, fluvial and glaciogenic sediments, which are well exposed along coastal bluffs and in some regions covered by loess-like deposits
20	Colville	Col	1	23	8	3	High exposure along the Colville River
21	Itkillik	Itk, It	1	22	10	10	High exposure along the lower Itkillik River formed by active river erosion of a large remnant of originally gently undulating yedoma terrain
22	Vault Creek Tunnel	FAI	1	24	-	-	Permafrost tunnel about 40 m deep and 220 m long on north facing slope
TOTAL	22		75	1292	144	40	

Appendix C *: List of samples (n=144) analysed by both inductively coupled plasma optical-emission spectrometry (ICP-OES) and portable X-ray fluorescence (XRF) method for linear regressions determination. Depth (below surface level) or *height (above sea level) are provided (in meters) if available. Labels are associated to labels from the Yedoma domain Mineral Concentration Assessment (YMCA) dataset for additional characteristics*

n	Sample label	Depth/ Height* (m)	n	Sample label	Depth/ Height* (m)	n	Sample label	Depth/ Height* (m)
1	Sob14-T2-2-03	0.225	49	Sob14-T2-6-09	0.775	97	Buo-02-D-23	7
2	Sob14-T2-2-05	0.43	50	Sob14-T2-6-11	0.96	98	Col-5-1	1.8
3	Sob14-T2-2-07	0.6	51	Sob14-T2-6-13	1.085	99	Col-5-6	3.02
4	Sob14-T2-2-09	0.745	52	Sob14-T2-6-15	1.15	100	Col-5-10	5.4
5	Sob14-T2-2-11	0.87	53	Sob14-T2-6-16	1.2	101	Col-5-13	6.9
6	Sob14-T2-2-13	1.015	54	Buo-04-A-00	0.1	102	Col-5-15	9
7	Sob14-T2-2-15	1.15	55	Buo-04-A-01	1	103	Col-5-18	11.6
8	Sob14-T2-2-17	1.25	56	Buo-04-A-02	1.5	104	It-1	2.3
9	Sob14-T2-2-19	1.4	57	Buo-04-A-03	2	105	It-6	5.4
10	Sob14-T2-2-21	1.565	58	Buo-04-A-04	2.5	106	Itk-E-03	9.2
11	Sob14-T2-2-23	1.7	59	Buo-04-A-05	3	107	Itk-H-02	13.7
12	Sob14-T2-2-25	1.82	60	Buo-04-A-06	3.5	108	Itk-F-03	19.5
13	Sob14-T2-2-27	1.935	61	Buo-04-A-07	4.5	109	14C-1	20.6
14	Sob14-T2-2-29	2.14	62	Buo-04-A-08	5	110	Itk-D-06	23.8
15	Sob14-T2-2-31	2.3	63	Buo-04-B-09	8	111	Itk-C-02	25.9
16	Sob14-T2-3-03	0.265	64	Buo-04-B-10	8.5	112	Itk-B-02	27.5
17	Sob14-T2-3-05	0.52	65	Buo-04-B-11	9	113	Itk-J-02	28.9
18	Sob14-T2-3-07	0.66	66	Buo-04-B-12	9.5	114	Sob14-T2-2-03bis	0.225
19	Sob14-T2-3-09	0.835	67	Buo-04-B-13	10	115	Sob14-T2-2-07bis	0.6
20	Sob14-T2-3-11	1.045	68	Buo-04-C-14	9.5	116	Sob14-T2-2-15bis	1.15
21	Sob14-T2-3-13	1.22	69	Buo-04-C-15	10	117	Sob14-T2-2-20bis	1.5
22	Sob14-T2-3-15	1.45	70	Buo-04-C-16	10.5	118	Sob14-T2-2-30bis	2.2
23	Sob14-T2-3-17	1.685	71	Buo-04-C-17	11	119	KY-T1-1-9-14	0.125
24	Sob14-T2-3-19	1.885	72	Buo-04-C-19	11.7	120	KY-T1-1-90-95	0.925
25	Sob14-T2-3-21	2.04	73	Buo-04-C-20	12	121	KY-T2-2-27-32	0.295
26	Sob14-T2-3-23	2.2	74	Buo-04-C-21	12.5	122	KY-T2-2-94-100	0.97
27	Sob14-T2-3-25	2.4	75	Buo-04-C-22	13	123	Oy7-11-16	11.9*
28	Sob14-T2-5-03	0.125	76	Buo-04-C-23	13.5	124	52Mkh-KB-7-5	22.3*
29	Sob14-T2-5-05	0.375	77	Buo-02-A-01	0.3	125	DY-01-F-34	29.1*
30	Sob14-T2-5-07	0.48	78	Buo-02-A-02	0.6	126	DY-02-A-01	5*
31	Sob14-T2-5-09	0.635	79	Buo-02-A-03	0.7	127	DY-04-A-01	7.85*
32	Sob14-T2-5-11	0.775	80	Buo-02-A-04	1.2	128	DY-04-A-02	7.7*
33	Sob14-T2-5-13	0.945	81	Buo-02-A-05	1.7	129	DY-05-B-05	2.7*
34	Sob14-T2-5-15	1.15	82	Buo-02-A-06	2.2	130	Kit-8-5	-
35	Sob14-T2-5-17	1.32	83	Buo-02-B-07	2.5	131	Col-5-2	-
36	Sob14-T2-5-19	1.505	84	Buo-02-B-08	3	132	Col-5-17	-
37	Sob14-T2-5-21	1.75	85	Buo-02-B-09	3.5	133	Sto-1-1	0.25
38	Sob14-T2-5-23	2.03	86	Buo-02-B-10	4	134	1TZ-2-2	17.65*
39	Sob14-T2-5-25	2.19	87	Buo-02-B-11	4.5	135	L21+50-S-3	4.3*
40	Sob14-T2-5-27	2.39	88	Buo-02-B-13	5.5	136	L7-08-03	4.5*
41	Sob14-T2-5-29	2.57	89	Buo-02-C-14	5.2	137	126Mkh-6.1.1	1.25*
42	Sob14-T2-5-31	2.76	90	Buo-02-C-15	5.7	138	11KH-3007-1-4	0.6
43	Sob14-T2-5-33	2.94	91	Buo-02-C-16	6.3	139	Bkh2002 S17	32.5*
44	Sob14-T2-5-35	3.075	92	Buo-02-C-17	6.9	140	BAL16-B2-30	10.97
45	Sob14-T2-5-36	3.1525	93	Buo-02-D-18	4.5	141	YUK15-YUL7-5	7.75*
46	Sob14-T2-6-03	0.125	94	Buo-02-D-19	5	142	YUK15-YUL7-15	17.96*
47	Sob14-T2-6-05	0.325	95	Buo-02-D-20	5.5	143	K-10-14-4	14.38
48	Sob14-T2-6-07	0.525	96	Buo-02-D-22	6.5	144	Kit-7-2	-

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