EXPLORING THE USE OF WEATHERING INDEX IN ALLUVIAL FAN CHRONOLOGY

Ulrike HARDENBICKER*, Makiko WATANABE and
Roberta KOTOWICH*

Abstract Alluvial fan sediments can act as an archive of local environmental history. Sedimentation on alluvial fans is controlled by fluvial erosional processes occurring in upland drainage basins and slopes, and the subsequent transport processes which deliver the sediments from the catchment area to the fan. Low sedimentation rates are marked by buried soils and in situ weathering of sediments, while pedogenically unmodified sediment between buried soils reflects times of rapid sedimentation of the alluvial fan. Two borehole cores (FN 350 cm and AG 850 cm) from Holocene alluvial fans located in the Qu'Appelle Valley in southern Saskatchewan, Canada were analyzed in order to establish a relative chronology by using weathering indices. We evaluated if weathering indexes (the CaO/ZrO_2 molar ratio, the Product Index and the Parker Index) are suitable to assess sediment weathering within alluvial fan. To quantify the degree of weathering within the sediment samples the three indices of weathering were calculated using the proportions of elements measured by Energy Dispersive X-ray Spectroscopy. There was an inverse relationship between weathering index and sample age.

Key words: · weathering index, chronology, alluvial fan

1. Introduction

Alluvial fan sediments contain valuable information and function as an archive of landscape development. Since alluvial fan sediments are deposited in layers through time a relative chronology of sediments can be determined. A alluvial fan chronology of depositional events within a fan was established by combining lithostratigraphy of soils and sediments from two a borehole cores of Holocene alluvial fans located in the Qu'Appelle Valley, Saskatchewan, Canada (Fig. 1) (Kotowich and Hardenbicker 2015). Alluvial fans are gently sloping fan-shaped landforms, a common landform seen at the base of Qu'Appelle River Valley, where tributary valleys enter. When tributary valleys enter the main valley sediment-laden flow spreads out to form alluvial fans at the valley bottom along the boundary of the lower hill slopes and valley floors. Most of the sediments are deposited when suspended sediment in water at the end of the feeder channel spreads onto the fan apex. Alluvial sediments that are transported as bed-load and deposited during larger erosion events, especially when the feeder channel becomes entrenched on the fan, are typically coarser grained (Bull 1977; Blair and McPherson 1994).

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* Department of Geography and Environmental Studies, University of Regina, Canada

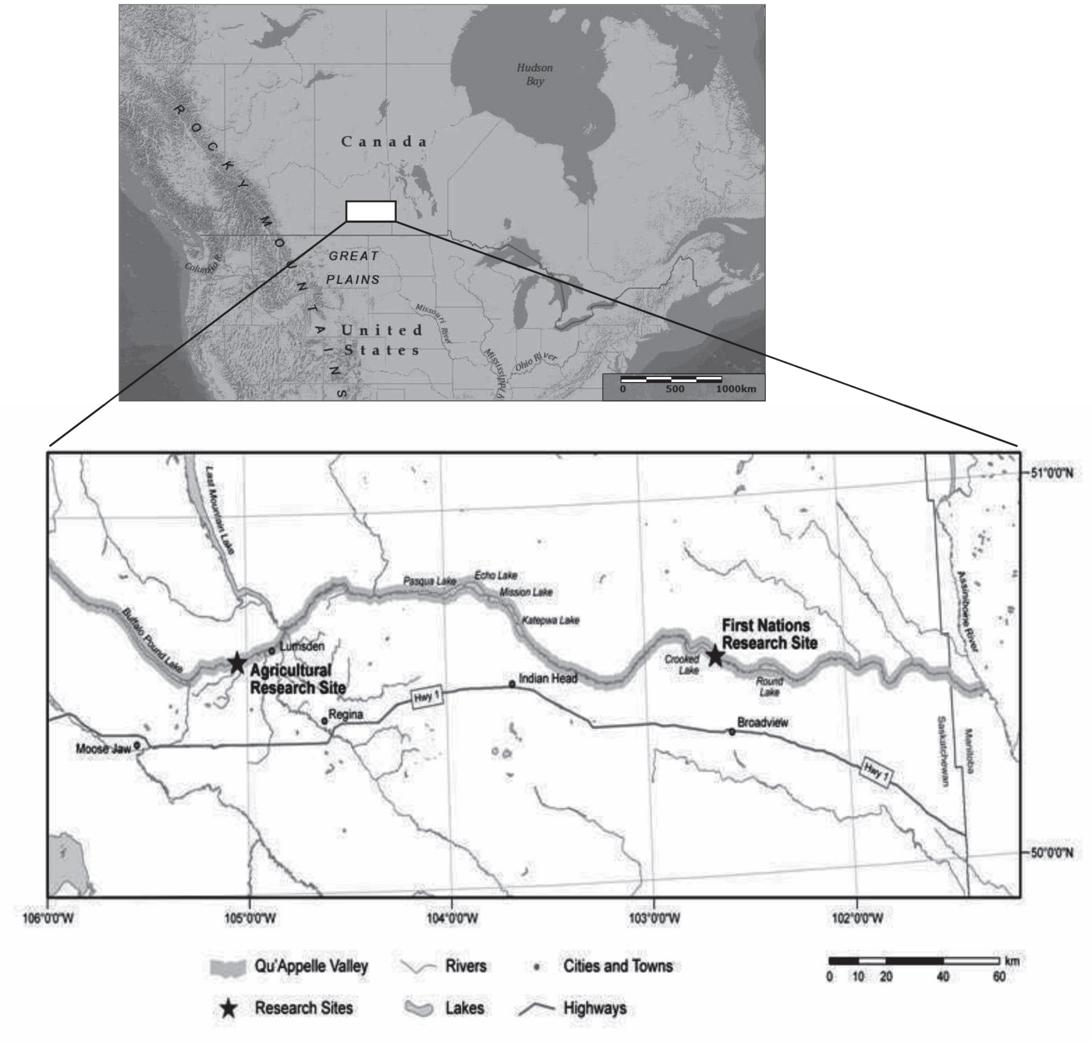

Fig. 1 Location of the two alluvial fans research sites in the Qu'Appelle Valley.

Study on soil and sediment weathering are usually conducted through physico-chemical characteristics. Product Index (Reiche 1950), the ratio of silica to silica and sesquioxides, is the well-known weathering index to quantify the degree of rock weathering. Parker index (Parker 1970), $([(Na)_a/0.35]+[(Mg)_a/0.9]+[(K)_a/0.25]+[(Ca)_a/0.7])\times100$, is another weathering index originally developed to study weathering of silicate rocks. Souri *et al.* (2006), and Souri and Watanabe (2011, 2013) examined the reliability of Product and Parker Indices to study soil weathering, where elemental basis of Parker index had advantage to track movements of alkali and alkaline earth metals throughout soil profile and suitable for evaluation of primary stages of leaching among calcareous soils. The molar ratio of CaO/ZrO_2 (Beavers *et al*. 1963) is an index to study calcareous soils weathering extended in arid, semiarid and Mediterranean regions. CaO/ZrO_2 not only takes calcium quantitative alterations into account but also considers zirconium as a highly stable element suitable to evaluate more advanced stages of leaching intensity among calcareous soils.

The objective of this study is to evaluate if Product, Parker and Beaver Indices, originally developed for studies of in situ weathering of bedrock, are suitable to assess sediment weathering within alluvial fan sediments.

2. Study Area and Borehole Cores

The investigated alluvial fans are located on the bottom of the Qu'Appelle Valley, Saskatchewan (Fig. 1). The mean annual precipitation of Regina is 388.2 mm, about 25% of the precipitation falls as snow and May, June and July are usually the months with the highest precipitation. The mean annual temperature is 2.8°C and the mean daily temperature during January over most of the region is about -18°C and during July it is 19°C. The Qu'Appelle Valley is one of the largest melt water channels in Canada and was carved approximately 14,000 years ago during the Wisconsinan Glaciation of the Quaternary into the drift deposits. Cut into the relatively flat plain, the valley provides an important sedimentation area for materials eroded from the surrounding agricultural cropland (Christiansen 1979; Klassen 1989).

The alluvial fan of the Agricultural research site (AG) is located 6 km west of the town of Lumsden (Fig. 1). The side-valley slopes and valley bottoms are especially affected by the deposition of soil and sediment eroded from agricultural fields by runoff, especially. The First Nations research site (FN) is located on Cowessess First Nation, at the east end of Crooked Lake (Fig. 1).

From each of the 1.5 m extracted cores, sub sampling was performed based on changes in colour, texture and other unique attributes such as the presence of charcoal, shells and roots. Along the length of the core, subsampling ranged from 2 cm to 10 cm intervals. Sampling units that were homogeneous over greater lengths were subsampled at 15 cm intervals. Two charcoal samples taken from 210 cm depth in the AG (Agricultural Borehole) and 220–230 cm in the FN (First Nation Borehole) assigned ^{14}C dates as modern and 4,530 ± 40 yr BP , respectively (Kotowich and Hardenbicker 2015).

Within the borehole cores fossil A-horizons are representing times of stability, whereas layers with high sand and coarse sediment content characterize times of strong erosion in the catchment and the fan (Figs. 2 and 4). Bedload transport requires higher flow velocities and greater volumes of water to transport gravel along with sand and to deposit the larger gravel oriented away from the direction of water flow. Sheet erosion as the dominant transport process results in high silt and sand content in the fan area (Kotowich and Hardenbicker 2015).

3. Methods

To quantify the degree of weathering within the sediment and soil samples the three indices of weathering were calculated using the proportions of elements measure by Energy Dispersive

X-ray Spectroscopy (Rainy EDX-700HS, Shimadzu, Kyoto). Samples from the core were crushed in an agate mortar and pressed by the force of 100 kN to form tablets. By measuring the top and bottom of the sample tablets all samples were measured twice. The average of the two measurements was taken for calculating the three weathering indices. In Parker Index, $(X)_a$ stands for atomic proportion of element X.

Beavers Index = CaO/ZrO_2
Product Index =$\{SiO_2/(TiO_2+Fe_2O_3+SiO_2+Al_2O_3)\} \times 100$
Parker Index= $([(Na)_a/0.35]+[(Mg)_a/0.9]+[(K)_a/0.25]+[(Ca)_a/0.7])\times 100$

These indices assume, as the intensity of weathering increases major oxides, including Al_2O_3, Fe_2O_3 , ZrO_2 and TiO_2, considered as ‘immobile’, remain constant and SiO_2 and CaO, considered as ‘mobile’, decrease. According the principle of the Beaver, Product and Parker indices, the lower the values the more intensive the weathering conditions and the older the samples (Duzgoren-Aydin *et al.* 2003).

Coarse fraction (≥2 mm) particle size analysis was performed by dry sieving. The fine fractions (<2 mm) were analyzed by using the Malvern Instruments Mastersizer 2000 laser diffractometer with Hydro 2000MU pump accessory (Sperazza *et al.* 2004).

For further statistical analyses the fan sediments were classified into three groups: a sheet flow facies of well sorted silt loam and sandy loam textures, bed load facies characterized by high sand and gravel content (Gray *et al.* 2000) and layers with high organic matter in combination with higher clay content indicative of in situ weathering and soil development. Principal component analysis (PCA) was carried out to evaluate the analytical data. All statistical calculations were performed by using a software package, e.g. SPSS version 10.0.

4. Results and Discussion

Na was below detection limit in the EDX measurements for the samples in FN cores. Consequently, the Parker index was calculated without atomic proportion of Na for the FN core data.

As presented in Table 1, the range of changes for the indices among the cores FN and AG were: 40.0–60.1 and 36.1–61.4 for Parker Index, 75.7–87.2 and 39.4–94.8 for Product Index, 197.5–849.8 and 57.3–904.9 for Beavers Index (CaO/ZrO_2 ratio), respectively. The FN core was less weathered and the range of the weathering indices was smaller compared with the AG core. The higher range of the weathering indices of the AG core could be the result of the changing sediment sources due to agriculture in the catchment area of this fan.

Layers of sand and gravel in a depth 280–275 cm, 223–210 cm and 45–40 cm in the FN core and at 420 to 415 cm, 342 to 340 cm, 335 to 315 cm, 312 to 285 cm, and 90 to 75 cm in the AG core (Figs. 2 and 3) had the highest values of the Product Index and the Beavers Index (CaO/ZrO_2). These sediments are transported as bed-load and deposited during larger erosion events, especially when the feeder channel becomes entrenched on the fan, and are typically coarser grained and not or only weakly chemically weathered.

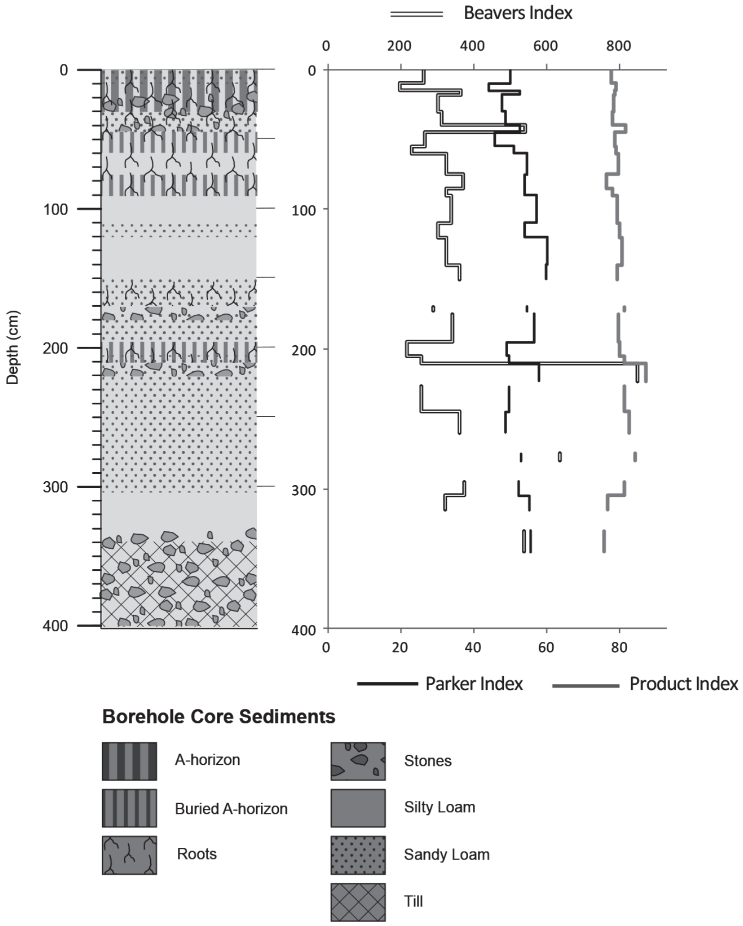

Fig. 2 Stratigraphy of the core FN and Beavers, Parker and Product Index of core FN. Stratigraphy data is taken from Kotowich and Hardenbicker (2015).

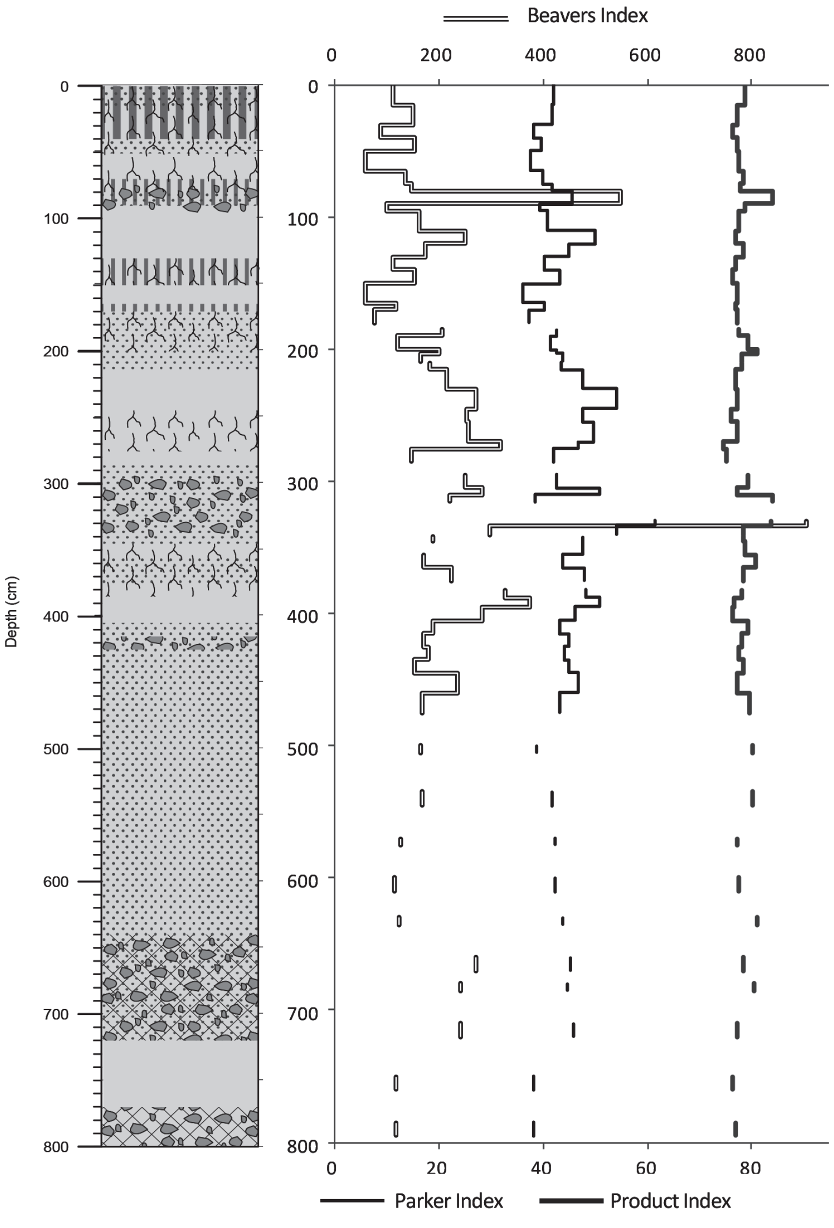

Fig. 3 Stratigraphy of the core AG and Beavers, Parker and Product Index of core AG.. Stratigraphy data is taken from Kotowich and Hardenbicker (2015)

Figure 4 presents a two dimensional coordinate system using Beavers index CaO/ZrO_2 and Parker index in each core. The coordinate system not only takes into account the absolute amount of the elements considered by the indices formula but also explains summation of Na, K, Mg and Ca (Parker index) to molar ratio of CaO/ZrO_2 so that the lower leaching intensity samples result in a counter clockwise tendency for their linear trend line toward Parker axis (Souri and Watanabe 2011). Conversely, the samples having higher leaching intensity may show a clockwise tendency for their linear trend line toward CaO/ZrO_2 axis. According to Figure 4, the samples of core FN were more likely to have linear trend line towards Parker axis, less leaching intensity, compared to AG core samples.

Nevertheless, the source of the coarse layer in the studied core is glacial till which contains dolomitic carbonate pebbles, whereas secondary pedogenic carbonates are mainly calcite (Rostad and St. Arnaud 1970). The weathering index such as Parker, of which formula includes only highly mobile alkali and alkaline elements (Na, Mg, K and Ca) may not act to detect the intensity of leaching or weathering for the alluvial fan deposits in this area. Further discussion on the evaluation of Parker Index for the alluvial fan deposit is expected by collecting additional information on basis of mineral analysis.

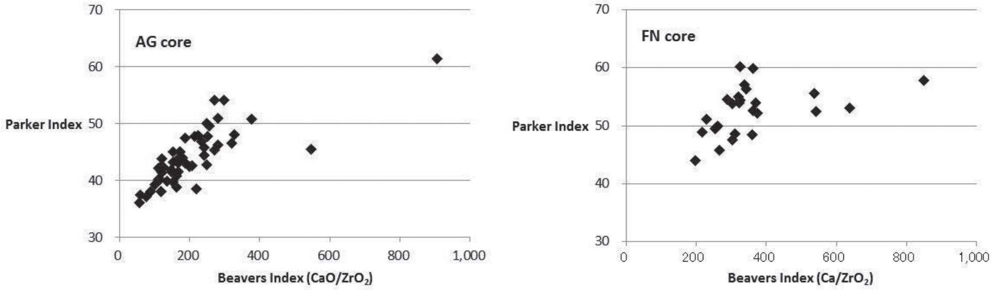

Fig. 4 Relation between Parker Index and Beaver Index for AG (left) and FN (right) cores

Table 1 Mean, standard deviation and range of grain size and weathering indices

	Mean	Standard deviation	Range	Minimum	Maximum
Grain size <50 µm	74.2	14.6	65.1	26.7	91.8
Grain size >2000 µm	5.2	5.4	18.9	0	18.9
Parker Index	52.5	4.0	19.9	40.0	60.1
Beavers Index	355.7	142.2	652.3	197.5	849.8
Product Index	79.8	2.4	11.5	75.7	87.2
Grain size <50 µm	76.8	13.7	9.6	74.6	84.2
Grain size >2000 µm	5.8	10.9	44	0	44
Parker Index	44.8	4.7	25.3	36.1	61.4
Beavers Index	206.6	130.3	847.6	57.3	904.9
Product Index	78.3	2	55.3	39.4	94.8

Table 2 Factor loading composition
Rotation method: Varimax with Kaiser normalization

	FN core (n=26)		AG core (n=54)	
	PC1	PC2	PC1	PC2
Product Index	0.959	0.105	0.909	0.246
Grain size >2000 μm	-0.051	0.972	0.051	-0.88
Grain size <50 μm	-0.925	0.225	-0.913	-0.005
Beavers Index	0.719	-0.526	0.376	0.728
Eigen value	2.524	1.052	2.092	1.077
Variance explained (%)	63.1	26.31	52.31	36.91

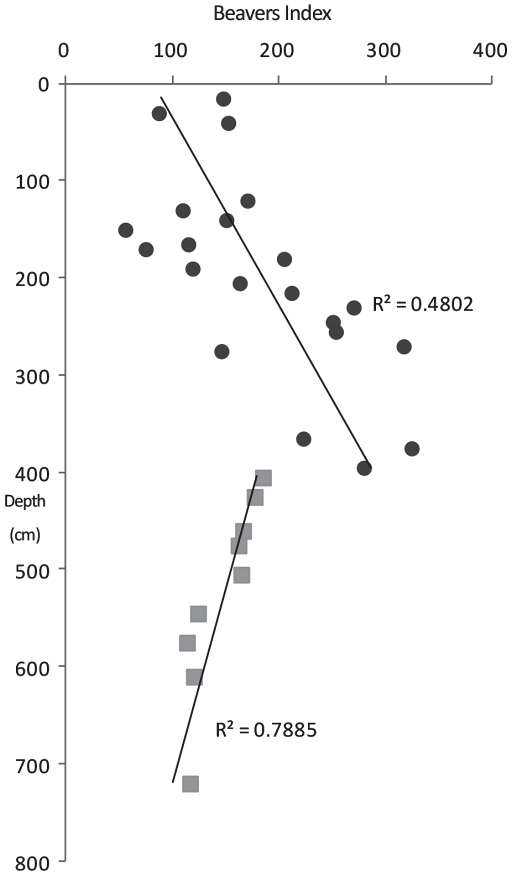

Fig. 5 Beavers Index of fine sediment (more than 50% smaller than 50 μm and less than 10% coarse) for AG core.

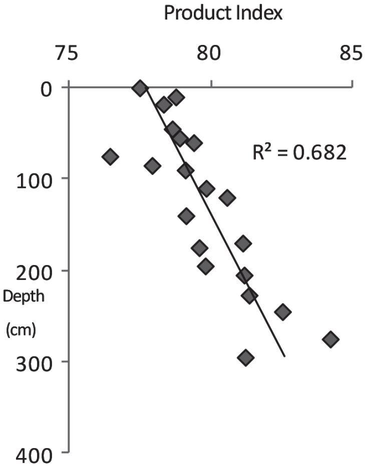

Fig. 6 Product Index of fine sediment (more than 50% smaller than 50 μm and less than 10% coarse) for FN core.

PCA loadings of the data for cores FN and AG excluding Parker Index are presented in Table 2. The first principal component (PC1) for the both cores showed a high positive loading with Product Index and a negative loading with grain size smaller than <50 μm, reflecting suspended sediment. The second principal component (PC2) loads were positively high with Beaver Index and negatively with grain size larger than 2000 μm reflecting bed load transport.

A distinct layer of sandy gravel at 425 cm (~220 cm above till) for the AG core suggests the occurrence of erosion events (Fig. 3), which may be a marker that indicates settlement and ground breaking in the catchment area. The high Beavers Index above this layer in Figure 3 could reflect time of intense erosion in the catchment area which mobilized less weathered fine sediment.

Figure 6 shows declining values of the Product Index for fine sediments with increasing depth in the FN core which could indicate slow aggradation of this fan allowing in-situ weathering and soil development. For the AG core the Beavers index increases with increasing depths up to 400 cm. This trend is not very strong (Fig. 5, R^2=0.4802) and could be attenuated by in situ soil development, since Zr is typically enriched in the silt fractions of the A and B horizons of the local soils (Sudom and St. Arnaud 1971). In the depths from 400 to 700 cm this trend reverses and the Beavers index declines with depth. This change could reflect a change in sediment source before and after ground breaking.

5. Conclusion and Outlook

This first results show that the Product Index and Beaver Index are suitable weathering indices to distinguish phases of fan aggradations dominated by bed load transport within a borehole core profile. For finer sediment the Product Index and Beaver Index do not detect any in situ soil development. Changes of the Beavers Index of fine sediment in the AG core could be the result of changing sediment sources upon the ground breaking in the catchment of the AG fan. More ^{14}C dates are needed to clarify the maximal age of the fan sediment above the till.

In general weathering indices do not take into account complexities of the weathering processes nor the overall environmental conditions in an alluvial fan. Since our samples are not from weathering profiles developed on homogeneous parent rock but sediments from heterogeneous sources and have undergone sorting during erosion and transportation within the fan, its catchment and in-situ weathering, the weathering indices could reflect variation in parent sediment composition rather than the degree of weathering. But chemical weathering indices accompanied by geophysical and geo-chemical information have value, especially when the amount of sample material is limited.

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