

Time development of soils in mountain landscapes—divergence and convergence of properties with age

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Abstract

Purpose Three previously published datasets of high-mountain soil variation in proglacial valleys in the Swiss Alps (80 soils) and a new dataset of high-mountain soil variation in a formerly glaciated valley in the Colorado Rocky Mountains (9 soils) are used to test the validity of the chronosequence approach and to study divergence and convergence of soil properties.

Materials and methods Standard field-based soil observations were done, complemented with simple laboratory measurements of pH and soil organic matter.

Results and discussion The mean values of soil properties change over time, as well as their standard deviations and coefficients of variation. Variation in soil properties between soils of the same age is significant. Although sampling was performed at locations that are assumed to be geomorphically stable, the observed variation in properties casts doubt on this assumption. Depending on the valley and the soil property, standard deviations and coefficients of variation increase over

time whereas in other cases, they decrease. This indicates divergence and convergence of soil properties over centennial and Holocene timescales, respectively. Both dynamics are explored quantitatively.

Conclusions Divergence is observed in settings that are unaffected by outside (hillslope) influences and presumably caused by vegetation differences and small-scale (diffusive) redistribution of the fine earth fraction. Convergence is observed in settings where soil formation is disturbed by outside influences. In the Swiss Alps, this influence is the provision of material from surrounding hillslopes. Chronosequence studies should sample and average multiple soils per age group, to characterize soil variation and minimize the uncertainty in the estimation of soil properties.

Keywords Divergence · Mountain soils · Soil chronosequence · Soil development · Soilscape

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1 Introduction

The mechanisms and rates of soil changes over time have inspired studies for more than a century. Darwin's seminal work on the slow soil forming effects of earthworms, linking them to the richness of English soil (1881), was one of the first of these. He studied the mechanism behind this accumulation of rich topsoil by placing worms in jars with soil, watching them eat and digest leaves, swallow and dissolve sand, and excreting the mixture on the soil surface. Although these direct observations of changes in soil over time can be used to derive development mechanisms, as Darwin did, this is rarely possible for rates of other types of soil development because they are usually too slow to observe directly with current techniques. Instead, a space-for-time substitution is typically used, in a method called soil chronosequences—which Darwin also used in the same study (1881). Such chronosequences study soils of different

age in different locations under the assumption that they isolate the effect of time from the effect of the other soil-forming factors—parent material, topography, climate and organisms (Jenny 1941). Chronosequences have been instrumental in much of the understanding that has been reached about rates of soil change.

The age control requirement for chronosequences is often met in high-mountain environments. Little Ice Age, Last Glacial Maximum or earlier moraines can be recognized, correlated or dated, and the age of soils on proglacial areas of currently retreating glaciers can often be derived from retreat records. A recent example of mountain chronosequence work is a compilation of the accumulation of clay and pedogenic iron in progressively older soils in the Colorado Front Range by Dethier et al. (2012). The study showed remarkably constant rates of accumulation in soils in the montane climate zone ranging in age from 5 to 150 ka, yet a more variable accumulation in younger soils in the colder and higher alpine climate zone, presumably because of microclimatic differences between alpine sites. In the Damma glacier proglacial area in Switzerland, amounts, respiration rates and leaching of soil organic matter were shown to increase with age (Guelland et al. 2013). Burga et al. (2010) and Egli et al. (2006b) found negative parabolic relations between the area covered by different soil types and time in the Morteratsch glacier proglacial area in Switzerland as soil development proceeded through different soil types. These parabolic relations were different for landscape positions with varying aspects and slope.

However, chronosequences have been effective worldwide. Sequences of marine and fluvial terraces are other popular settings on which to base soil chronosequences (e.g. Eppes et al. 2008; McFadden and Weldon 1987; Sauer et al. 2010). Harden (1982) defined the soil development index using a soil chronosequence based on a chronosequence of terraces of the Merced River in California. A soil development index is calculated from the values of a set of soil properties that are particularly sensitive to soil age. For example, Harden's first soil development index (1982) used these soil properties: clay cutans, texture, structure, consistence, the level of rubification (reddening), the colour value and pH. Among other uses, soil development indices can be used as indicators of (apparent) soil age, even in locations where soil development is interrupted or affected by active surface processes. An example of this approach that is relevant to the present study is the work of Birkeland et al. (1987), who used soil development indices to study a chronosequence of alpine soils of Holocene age in the Colorado Front Range. Conclusions were drawn about the direction of soil development and the effect of climate.

To ensure the success of chronosequence soil studies, soils are usually sampled from the same positions on landforms that only differ in age, that share (and have shared throughout their development, Sommer et al. 2008) the same parent material,

topographic setting, climate and organisms and that are geomorphically stable. The extent to which this approach is successful can be tested by sampling soils that share similar soil-forming factors on the same landform and landform position. If the variation in soil properties in such a sample is sufficiently small relative to the difference in properties caused by a difference in age, chronosequences can successfully isolate the effect of time. Although such chronosequence tests are relatively straightforward, they have rarely been performed (although post hoc comparisons between absolute and soil-based datings are performed regularly, e.g. Böhlert et al. 2011; Favilli et al. 2009; Dethier et al. 2012). This is a potential threat to their valuable use in soil science and geomorphology.

Next to a test of the validity of the chronosequence approach, a focus on variation in soil properties allows an assessment of its temporal dynamics. It has been argued that soil systems are characterized by divergence in properties (increasing variation, Phillips 2001), due to various mechanisms of pedogenesis enlarging small differences in initial conditions. Nevertheless, some of the oldest tropical soils, with most advanced weathering and soil formation, often homogeneously cover large areas (e.g. Dewitte et al. 2013), and the role of systematic, predictable, non-divergent soil formation is widely accepted (Phillips 2013). This suggests that factors other than initial conditions can be (or become) more important, such as a slowing down of weathering rates as the parent material becomes depleted or negative feedbacks between soil development and landscape activity. This would lead to convergence—a reduction in variation. An example of the latter are planosols, where extreme vertical textural differentiation within the soil profile results in a very sandy erodible topsoil. Sites where planosol formation is most advanced therefore run the risk of erosion of the sandy topsoil, which slows down their development and makes them more similar to less developed planosols (Agbenin and Tiessen 1995). Clearly, divergence and convergence of soil properties both occur in nature. Their mechanisms, rates and pathways are therefore of interest.

The aim of this paper is to perform chronosequence tests and study divergence and convergence on centennial and Holocene timescales in mountain environments. We will focus on soil properties rather than on soil types because variation in soil types (a nominal variable) is more difficult to define than variation in soil properties and because we study young mountain soils that vary only little in soil type.

We will use four case study sites: three in the Swiss Alps and one in the Colorado Front Range. Our research objectives are (1) to describe variation in properties of soils of the same and similar age, (2) to find whether such variation increases, decreases or remains stable over time and (3) to assess whether it is sufficiently small to allow successful chronosequence studies. The results are expected to be helpful when assessing

the outcomes of chronosequence studies and when designing future studies.

2 Study sites

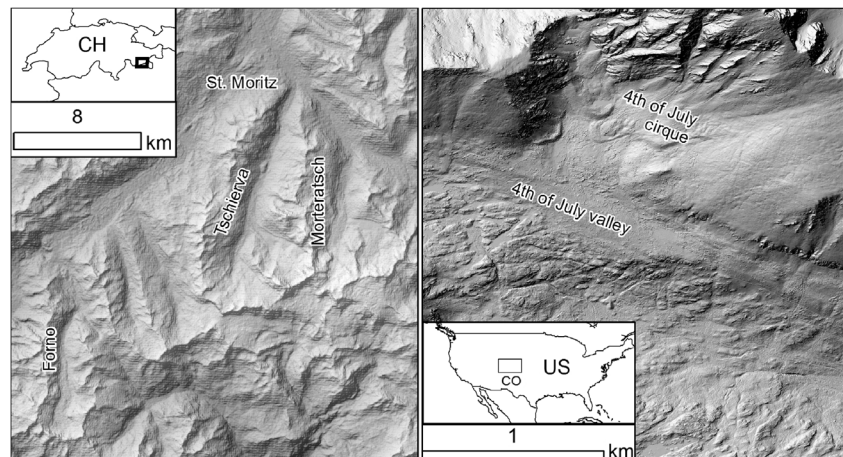
In the Eastern Swiss Alps, three currently deglaciating valleys were selected as study sites: the Forno, Tschierva and Morteratsch valleys (Fig. 1). This choice was made due to the existing soil-scientific literature in the case of the Morteratsch valley, and proximity and ease of access in the case of the Forno and Tschierva valleys. All three valleys are north exposed, and the lithology is mainly the Bernina and Stretta crystallines (intrusive rocks, Buchi 1994). Minor lithological differences between the three valleys concern the relative abundance of acidic rocks, with the Forno valley having the highest proportion of granites and the Tschierva valley having the lowest proportion (Swiss Federal Office for Topography 2010). Current mean annual temperature is approximately 0.5 °C and mean annual precipitation is about 1,000–1,300 mm (Egli et al. 2006a).

Glacial extent in the three valleys reached its most recent maximum during the Little Ice Age, around 1850 (indicated by the blue areas in Fig. 2). The subsequent glacial retreat, which initially may have been caused by deposition of soot from factories and trains (Painter et al. 2013) and later by increasing temperatures, has been documented in detail (SGMN 2010). In all three valleys, retreat since 1850 exceeds 1,400 m along the valley axis. Almost uninterrupted retreat was observed for the Morteratsch and Forno glaciers. For the Tschierva glacier, which separated into several tongues after it retreated up valley from a confluence, retreat was interrupted by an advance that measured about 250 m between 1959 and 1985. As a result, no soils that are currently on the surface started their formation in the Tschierva glacier's proglacial area between 1959 and 1985. Using the detailed retreat history (at annual temporal resolution and metre spatial resolution),

the time since the start of soil formation for all locations in the three proglacial zones has been accurately determined (Egli et al. 2006b; Temme and Lange 2014).

In general, soils in the three Swiss valleys are rocky, thin and acidic. Soil properties differ between different landforms in the valleys, with the young proglacial soils formed after 1850 the least developed and millennia-old soils in valley bottoms downstream of the 1850 end-moraine the best developed, typically into Podzols. The post-1850 proglacial moraine soils have been most extensively studied in the proglacial area of the Morteratsch valley. They vary from Lithic Leptosols (Ah/C profiles), which are most prevalent close to the glacier, to Dystric Cambisols (Ah/Bw/C profiles), which are found in some areas close to the 1850 moraine (Egli et al. 2006b). The relative proportion of different soil types in this proglacial area was found to be a function of topography and time since glacial retreat (e.g. Egli et al. 2011). Using these results and an assumed postglacial landscape, Egli et al. (2006a) were able to predict future prevalence of different soil types after deglaciation. The development of some individual soil properties (rather than soil types) with time in another set of locations in all three valleys was studied by Temme and Lange (2014). They concluded that a linear relation with soil age rarely explains more than half of the variation in soil properties within a valley. Development rates over time differed between the valleys and time explained less than half of the variation in soil properties over all three valleys for the combined dataset. Location factors such as slope and terrain curvature were also important in explaining a part of the variation, which suggested that small-scale or large-scale redistribution of soil material plays a role even in supposedly stable proglacial areas. Some of the unexplained variation in soil properties was linked to variability in the rock fraction of the glacial till parent material. In the present study, a subset of the dataset of Temme and Lange (2014) was used. Aeolian influence on the Swiss soils is not yet seen to be of major importance (Egli et al. 2006a), although this seems to be due more to their

Fig. 1 *Left*, position and morphology of the three study sites in the east of Switzerland, close to the city of St. Moritz. *Right*, position and morphology of 4th of July cirque in the Colorado Rocky Mountains. The background is a hillshade image of the ASTER GDEM 30-m resolution Digital Elevation Model. ASTER GDEM is a product of METI and NASA



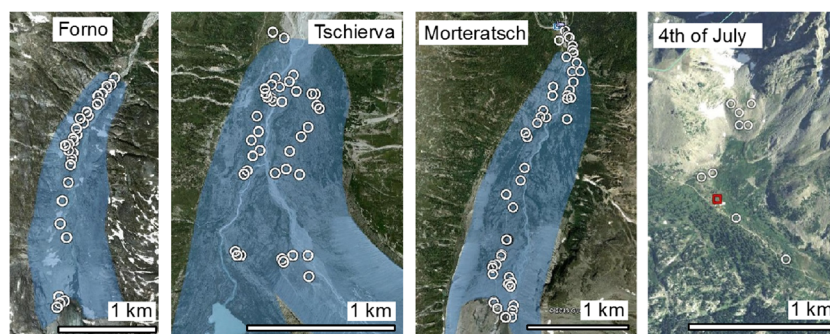


Fig. 2 Soil sample locations in the four studied valleys. The 1850 glacial extent in the Forno, Tschierva and Morteratsch valleys is indicated in blue, with the current glacial snout visible in the south of the maps of

Forno and Morteratsch, and just off to the southeast for the map of Tschierva. The location of the former mine in 4th of July cirque is indicated with a red square

young age than to an absence of influence (de Angelisi and Gaudichet 1991).

In the Front Range of the Colorado Rocky Mountains, the south-exposed deglaciated 4th of July cirque was selected because of the availability of soil-scientific literature and dating control on the glacial history (Fig. 2). The lithology consists of acidic igneous and high-grade metamorphic rocks (Kellogg et al. 2008; Cole and Braddock 2009). Current mean annual temperature is about -4°C and mean annual precipitation is about 1,000 mm (Dethier et al. 2012). The glacial history must be considered over larger timescales than that of the Swiss valleys. Ice of the Last Glacial Maximum covered the floor of 4th of July cirque and the 4th of July valley that it drains into. By about 15 kyr, glacial retreat from the main valleys in the Front Range including 4th of July valley was almost complete (Ward et al. 2009; Dühnforth and Anderson 2011) and presumably around this time, 4th of July cirque was deglaciated as well. A conventional radiocarbon age of 10.910 ± 320 years BP from the presumably earliest postglacial deposits in north-exposed Lake Dorothy 250 m higher in 4th of July valley suggests that complete deglaciation of the entire valley itself may have taken several thousand years longer (Davis et al. 1992).

Glacial retreat left a conspicuous lateral moraine between 4th of July cirque and 4th of July valley. At a later stage, a smaller glacier must have existed in the cirque, as evidenced in at least one 200-m-long well-preserved end-moraine. The age of this landform has not been determined absolutely and has been interpreted to be between 3 and 5 kyr based on morphological comparison with other radiometrically and lichenometrically dated landforms within 5 km of 4th of July cirque (Benedict 1973; Mahaney 1973a). An alternative interpretation, that the small end-moraine is of IOS stage 6 (locally called Bull Lake, approximately 140 kyr, by Williams 1973), is incompatible with the recent absolute dating results of Ward et al. (2009) from 4th of July valley. Around the time of its publication, the alternative interpretation was also challenged based on morphology: the end-moraine profile is sharper and less disturbed by erosion than would be expected

for a feature older than the Last Glacial Maximum (LGM) (Mahaney 1973b). Soils in 4th of July cirque were reported to be characterized by incipient weathering, indicated by a slight reddening of the soil colour relative to the parent material, increase of soil depth (Mahaney 1973a; Williams 1973) and an increase of clay percentage dominated by aeolian deposits (Williams 1973). Aeolian deposits in the Front Range were sourced from intramontane basins west of the Continental Divide (Muhs and Benedict 2006).

3 Methods

We selected 80 locations from the previously published dataset of 122 locations in the three valleys in the Swiss Alps that were visited and described by Temme and Lange (2014), with geomorphic stability as the selection criterion. This resulted in 31 locations in the Morteratsch valley, 29 in the Tschierva valley and 20 in the Forno valley (Fig. 2). Soil properties have been described by Temme and Lange (2014) using standard guidelines (WRB 2007). For this study, surface and soil stoniness, pH, texture class and the degree of sorting were used. In addition, the maximum depth of visible soil formation was defined and recorded as the combined thickness of the A, AB, AC and/or B horizons in each profile multiplied by the fine earth fraction to correct for stoniness (Table 1). pH was measured on a soil slurry in the field with a pH indicator of the Hellige type, which has an accuracy and precision of about 0.5 pH unit. Soil age, in years since glacial retreat for every location, was derived from one-dimensional glacial retreat histories (SGMN 2010) and two-dimensional glacial outlines for 1850, 1973 and 1999 from the Digital Atlas of Switzerland 3 (2010). The estimated accuracy of this age determination is 3 years.

For the new dataset of the 4th of July cirque, soils were observed on both the LGM lateral moraine, and the younger, presumably 4-ka-old end-moraine. Five soils were observed on the younger end-moraine and four soils were observed on the older lateral moraine. Observations on the older lateral

Table 1 Characteristics of datasets

Site	Locations	Age range (resolution)	Ratio variables	Interval variables	Ordinal variables
Forno (CH)	20	3–97 years	Surface stoniness, soil stoniness, depth of soil development	pH	Texture class, sorting
Tschierva (CH)	29	54–158 years			
Morteratsch (CH)	31	1–156 years	Soil colour (value and chroma) of B horizon, soil organic matter fraction	pH	
4th of July (CO, USA)	9	Young (possibly 4 ka)—old (about 15 ka)			

moraine were positioned at least 150 m away from a small nineteenth century mining operation (4th of July mine, Fig. 2) to avoid disturbance. Soil properties were described using standard guidelines (WRB 2007). Properties selected for analysis in the present study are colour value and chroma, the organic matter fraction and pH (Table 1), based on the fact that these were also included in earlier studies in the area (Mahaney 1973a, b; Williams 1973). The soil organic matter fraction was determined through combustion. Samples were first dried for 3 h at 105 °C and then an approximately 5 g subsample was brought to 550 °C for 3 h. The weight of the subsample before and after combustion was determined with a scale with 10^{-4} g precision, from which the organic matter fraction was calculated. pH (H₂O) was measured in a laboratory with accuracy of 0.01 pH unit. Because the age of the small end-moraine has not been accurately determined, the time since glacial retreat was dealt with in a qualitative fashion, with soils on the end-LGM lateral moraine classified as old and soils on the younger end-moraine classified as young. It must be noted that the older lateral moraine was deposited at least partly by the main glacier draining 4th of July valley and not only by the smaller glacier draining 4th of July cirque. This potentially invalidates the chronosequence assumption of equal parent material. However, the slopes overlying the 4th of July valley glacier upstream of the 4th of July cirque have similar geology as the 4th of July cirque itself (biotite schists and gneisses, Cole and Braddock 2009), meaning that such differences will be small or absent.

For our objectives, properties of soils of the same age must be compared. For 4th of July valley, this was done by comparing properties of the four soils on the older lateral moraine with those of the five soils on the younger end-moraine. For the Swiss dataset, soil ages are accurately known (and younger by more than an order of magnitude than soils from 4th of July cirque) but no soils with exactly the same age were sampled. Therefore, soils were grouped into two age classes of equal size per valley.

For summary statistics of ordinal variables, the median and the variation ratio were used. For interval variables, the mean and standard deviation were used and for ratio variables, the mean, standard deviation and coefficient of variation were used to express variation in soil properties. The coefficient

of variation (ν) is defined as the sample standard deviation divided by the sample mean and is valid only for ratio variables. The advantage of the coefficient of variation over the standard deviation is that it is a dimensionless measure of variation that allows comparison between samples and populations with different means.

A confidence interval for the coefficient of variation can only be calculated with an approximation (McKay 1931). However, McKay's approximation is only valid for about normally distributed measurements of (positive) values and for cases where the coefficient of variation is smaller than about one third. The latter condition was not met in our datasets even after normalization (Webster 2001)—coefficients of variation are typically over 0.5. Therefore, standard statistical inference was not available, and bootstrapping (Efron 1979) was used to test whether coefficients of variation were larger for young age groups. Bootstrapping repeatedly estimates a variable of interest (in this case the coefficient of variation) by randomly drawing with replacement from a set of observations. The set of values that is randomly drawn has the same size as the original set of observations. In our case, each bootstrapped estimate of the coefficient of variation for a variable of a young age group was compared to the similarly bootstrapped estimate for the same variable of the old age group. The comparison was repeated 100,000 times for every soil property for every age group, and the number of times that the coefficient of variation for a young age group was larger than for an old age group, relative to the 10,000 repeats, was recorded and presented as a probability.

4 Results

Swiss soils are typically Ah/C profiles, with the best developed soils in the old age groups sometimes having Ah/Bw/C profiles. Aggregated soil properties for the age groups are typical of young soils developing in moraine material of intrusive lithology (Table 2). Values of properties at this aggregated level confirm some of the conclusions of Temme and Lange (2014): that soils typically become substantially more acid, deeper and somewhat less stony with increasing age. As expected in these young soils, the texture class and the

Table 2 For groups of soils in the three Swiss valleys: sample means and standard deviations for ratio and interval properties, and medians and variation ratios for ordinal properties

Group	Number	Average age	Surface stoniness (%)	Soil stoniness (%)	Depth of soil development (cm)	pH	Texture class	Sorting
Forno								
Young	10	36	69±32	38±17	1.7±3.9	5.9±0.7	Sand (0)	Poor (0.10)
Old	10	72	61±26	35±15	3.1±2.0	5.8±0.7	Sand (0)	Poor (0.10)
Tschierva								
Young	14	15	49±29	22±12	1.6±0.9	6.8±0.7	Sand (0.2)	Poor (0.20)
Old	15	86	48±24	24±12	2.3±1.6	5.9±0.7	Sand (0.2)	Poor (0.15)
Morteratsch								
Young	16	86	78±19	39±13	0.6±1.3	6.7±0.7	Sand (0)	Poor (0.06)
Old	15	137	46±26	25±15	1.7±1.6	5.5±0.6	Sand (0)	Poor (0.40)

level of sorting of the fine earth fraction do not change perceptibly over the period under consideration. Soil properties clearly differ both between valleys and between age groups. Two-way analysis of variance for the four numerical properties indicates that age has a significant effect ($p < 0.05$) except for soil stoniness ($p = 0.14$). Differences between valleys are significant for pH and soil stoniness ($p < 0.05$) and almost significant for the depth of soil development and surface stoniness ($p < 0.06$). The interaction between both effects was significant only for pH ($p = 0.02$).

Variation around the mean is substantial. The standard deviation is close to the mean depth of soil development, and standard deviation is about half the mean for surface and soil stoniness. Variation in pH is about 0.7 unit. For the soil texture class and the level of sorting, variation is small. Table 3 presents results that highlight the change in variation over time in the three Swiss valleys. A hypothesis of equal variance (and equal standard deviation) cannot be rejected for any combination of valley and age. However, coefficients of variation are more variable. Coefficients of variation for surface and soil stoniness decrease substantially but not significantly with soil age in both the Forno and Tschierva valleys. This indicates a convergence in these properties. Coefficients of variation increase substantially and significantly for the Morteratsch valley, indicating a divergence in stoniness.

For pH, the coefficient of variation is undefined given its arbitrary zero value. Values of standard deviation hardly change with soil age (Table 2), and a hypothesis of equal variance cannot be rejected (Table 3). Therefore, the variation in pH seems to be independent of soil age. For the depth of soil development, coefficients of variation decrease strongly with soil age in the Forno and Morteratsch valleys (convergence, significant at $p < 0.01$ in the Forno valley), but stay about the same in the Tschierva valley (divergence).

Descriptions of soils in 4th of July cirque are given in the Electronic Supplementary Material (Table S1), and

summarized properties are reported in Table 4. At the highest level of aggregation, soils on the young end-moraine are incipient weathering profiles (Ah/Bw/C), whereas soils on the older lateral moraine are typically thicker, have more clearly expressed Bw horizons and, in one case, appear to have developed textural differentiation (Ah/Bt/C, profile 2). The latter profile was in a very slightly concave position on the crest of the lateral moraine, which may have allowed it to accumulate slightly more snow and water than other profiles. However, this morphological difference was subtle. The findings on the young end-moraine are consistent with those of Mahaney (1973a) who did not describe soils on the older lateral moraine. Values for pH are typically below 5.0, and organic matter percentages are rarely below 5, befitting the alpine environment where organic matter decomposition is limited by low temperatures. Colours, particularly the hue, indicate an intermediate stage of weathering of the parent material and correspond to the values observed by Mahaney (1973a).

Averaged over locations and over horizons, soils become more acid and somewhat more saturated in terms of colour value (with a median colour hue of 10YR) over time. Differences in chroma and organic matter fraction between age groups are small. The texture class and the level of sorting of the fine earth fraction do not change perceptibly over the period under consideration. These changes indicate increasing soil development with (assumed) age and therefore offer independent support for Mahaney's assertion that the end-moraine is younger than the lateral moraine (1973a, b).

Regardless of age, acidity decreases with depth along profile, particularly in the young soils, highlighting the impact of deposition of slightly calcareous loess in the region (Goldstein et al. 2008; Reynolds et al. 2006). This deposition has been recognized along an altitudinal and climatological transect through the Front Range from the alpine zone (in which 4th of July cirque is situated) to the lower and drier montane zone. The larger amounts of (summer and winter) precipitation in

Table 3 Coefficients of variation and probabilities that coefficient of variation is larger for the younger age group for surface and soil stoniness and the depth of soil development observed in the three Swiss valleys

Valley	Surface stoniness		Soil stoniness		Depth of soil development		pH
	$\nu_{\text{young}}, \nu_{\text{old}}$	$p(\nu_{\text{young}} > \nu_{\text{old}})$	$\nu_{\text{young}}, \nu_{\text{old}}$	$p(\nu_{\text{young}} > \nu_{\text{old}})$	$\nu_{\text{young}}, \nu_{\text{old}}$	$p(\nu_{\text{young}} > \nu_{\text{old}})$	$p(\sigma^2_{\text{young}} = \sigma^2_{\text{old}})$
Forno	0.47, 0.43	0.595	0.46, 0.43	0.590	2.28, 0.64	0.992	0.827
Tschierva	0.59, 0.50	0.557	0.56, 0.48	0.839	0.57, 0.68	0.305	0.642
Morteratsch	0.25, 0.57	0.000	0.33, 0.59	0.000	2.29, 0.68	0.811	0.582

For pH, where the coefficient of variation is undefined, the probability that the standard deviation of young and old soils are equal is given

the alpine zone may cause higher rates of loess deposition there, partially explaining the higher levels of clay observed relative to the montane zone for soils of equal age (Dethier et al. 2012).

A two-way analysis of variance was performed to assess the effect of age and position along the soil profile (expressed in the horizon code and excluding the BC and Bt horizons). The effect of horizon was significant for soil organic matter fraction, value and chroma ($p < 0.05$), and the effect of age was significant for value and pH ($p < 0.05$). The interaction between age and horizon was not significant for any of the four properties.

Variation in properties (Table 4) for the value and chroma is significant, with the standard deviation close to 1 unit. The organic matter fraction is highly variable, especially because of high values in some of the locations (skewness = -1.5). pH values vary substantially, but less so than for the three Swiss valleys. Coefficients of variation increase somewhat with soil age for value and chroma and strongly for the organic matter fraction, although the differences are not statistically significant (Table 5).

5 Discussion

5.1 Validity of chronosequence approach

The two types of sites that were studied are rather different. In the three Swiss valleys, soils were sampled from gently sloping, well drained and relatively undisturbed proglacial areas of currently retreating glaciers. In such proglacial environments, a relation between soil properties and time is expected, although it was found to be only partly the case in previous work in the Morteratsch valley (Egli et al. 2006a; Egli et al.

2006b; Temme and Lange 2014) and weakly the case in the Tschierva and Forno valleys (Temme and Lange 2014). In 4th of July valley, the proglacial area between the end-LGM side moraine and the younger end-moraine presumably spans about 10,000 years between 14 and 4 kyr, but it is badly drained and disturbed by large rockfalls from the sides of the cirque. With the proglacial valley thus disqualified, the well-preserved and therefore presumably stable lateral and end-moraines provided the best opportunities for a soil chronosequence. The present study suggests that geomorphic stability in this case is not a guarantee for low variation in soils on these landforms, as our earlier study suggested for the Swiss valleys (Temme and Lange 2014).

In all four study sites, variation in soil properties within an age group is substantial. In each of the Swiss valleys, we used two broad age groups, which allowed us to test whether groups had significantly and substantially different soil properties. In most combinations of valley and soil property, this was the case, suggesting that the soil chronosequence approach is valid if enough soils of the same or similar age are sampled so that internal variation can be accounted for. An additional test where soils were grouped into three rather than two age classes supports this conclusion (not shown). The importance of an assessment of within-group-variation is easily illustrated by calculating soil development rates from all possible pairs of observations from the young and old groups, excluding pairs of soils less than 40 years apart. In the case of the Morteratsch valley, for the soil property pH, resulting rates of lowering of pH with time ranged from -0.021 (rising pH with time) to 0.035 pH unit per year (lowering pH with time). The average lowering rate is 0.016 ± 0.009 pH unit per year. In 4th of July valley, soils of the same (albeit only weakly defined) age were compared, for a more stringent test of the chronosequence approach. The groups of young and old soils

Table 4 Sample means and standard deviations for selected ratio and interval properties of groups of soils in 4th of July valley

Age	Number	Hue	Value	Chroma	Organic matter fraction	pH
Young	5	10yr (0.06)	2.9±0.6	2.8±0.9	10.6±7.2	4.7±0.4
Old	4	10yr (0.14)	3.3±0.9	3.0±1.1	9.1±8.8	4.1±0.4

For hue, an ordinal property, median and variation ratio are reported

Table 5 Coefficients of variation and probabilities that coefficient of variation is larger for young soils than for old soils in 4th of July valley

Value	Chroma		Organic matter fraction		pH	
$\nu_{\text{young}}, \nu_{\text{old}}$	$p(\nu_{\text{young}} > \nu_{\text{old}})$	$\nu_{\text{young}}, \nu_{\text{old}}$	$p(\nu_{\text{young}} > \nu_{\text{old}})$	$\nu_{\text{young}}, \nu_{\text{old}}$	$p(\nu_{\text{young}} > \nu_{\text{old}})$	$(\sigma_{\text{young}}^2 = \sigma_{\text{old}}^2)$
0.22, 0.26	0.267	0.30, 0.36	0.308	0.67, 0.96	0.124	0.776

For pH, where the coefficient of variation is undefined, the probability that the standard deviation of young and old soils are equal is given

had significantly and substantially different colour value and pH. However, assuming an age difference between the groups of 10 kyr, the average lowering rate of pH here for all 25 possible combinations of B horizons between the horizons was 0.000066 ± 0.000053 pH unit per year. This illustrates the large and invisible uncertainty that comparisons between two profiles, one from each landform, would have. The Swiss and American valleys have roughly similar lithology, yet rather different climates and conditions for soil development (notably the aeolian contributions to the American soils, Muhs and Benedict (2006). Comparison of the average rates of pH change between sites is therefore not meaningful. pH values themselves are lower in the 4th of July valley, where soils are significantly older.

In many studies, observations of soil properties are often more expensive and time consuming than those that we have used here and multiple repeat observations with approximately similar age are therefore difficult to obtain. It is however imaginable that an exploratory field survey of a set of soils of similar age can give insight into which soil is closest to the average soil for the landform. This soil could then be selected to base the more elaborate analysis on, under the assumption that soils that are representative in some easily observed properties are also representative in the more elaborate properties of interest. The outcome of such selection procedure could be reported in scientific communication so that readers can assess the validity of the sampling approach underlying chronosequences.

5.2 Divergence and convergence

In the Swiss valleys, both surface and soil stoniness show divergence with increasing age in values in the Morteratsch valley and convergence in values in the Forno and Tschierva valleys. An additional test with three age groups reached the same conclusion (not shown). Field observations show that in the Forno and Tschierva valleys, there is large variation in the stoniness of the subglacial parent material. In the narrow Forno valley, fluvial deposition and full depth snow avalanches from the bordering hillslopes provide parent material with a higher fine earth fraction to the proglacial area, resulting in convergence of properties and a somewhat lower stoniness on the surface (even though we did not use samples from presently visible debris flows or avalanches, it is assumed that these processes have affected the proglacial area in the past as well). The effect is smaller below the surface.

The wider Tschierva valley has less impact from the side slopes, and convergence is therefore smaller. The divergence in the Morteratsch valley seems to be caused by progressive soil development in the absence of (outside) disturbance. The group of old soils here is about 50 years older than in the other valleys, and as a result, there is a more substantial vegetation cover (Burga 1999) which from visual evidence has provided substantial amounts of organic matter to the fine earth fraction. More importantly, subtle differences in topography over spatial scales of several metres have caused redistribution of the fine earth fraction (Temme and Lange 2014), leading to a divergence into slightly higher, more stony soils and slightly lower, less stony soils.

This proposed division between (geomorphically) undisturbed locations experiencing a divergence in soil properties and disturbed locations experiencing convergence works also for the depth of soil formation in the Forno valley and the Morteratsch valley. The slightly disturbed Tschierva valley also experiences convergence in this soil property. For pH, neither convergence nor divergence was observed in any of the three valleys.

In the 4th of July valley, where disturbances and contributions of material from the sides are virtually absent because the moraines are local topographical highs, the proposed division predicts a divergence in soil properties over time. Arguing from the coefficients of variation, this is indeed the case for all four soil properties under consideration. The divergence over time is weakest for pH, as it was in the Swiss cases, and is strongest for the organic matter percentage—conceivably because of the rather substantial difference in vegetation between the end-moraine (homogenous grasses) and the lateral moraine (grasses and groups of trees, as described by Litaor et al. 2008 for a similar site several kilometres north of our study site). Although vegetation can be expected to change as soils change, this difference is also due to the position of the study site close to the present treeline. The groups of trees at the lateral moraine could have caused divergence in organic matter. However, higher treelines during the Holocene climatic optimum may mean that both sites had (groups of) trees. This would limit the effect of altitudinal difference on organic matter divergence.

Although the thought model of convergence in soil properties resulting from (homogenous) external effects is easily understood from a simple mixing point of view, in our cases, we appear to have touched on one particular

type of outside effect: contribution of fresh parent material from the hillslopes surrounding proglacial areas. It is not argued that this is the only or even the most common outside effect, although it may be more common than commonly thought, nor is it argued that all outside effects are homogenous and therefore cause convergence in soil properties. Similarly, the apparent role for vegetation differences and small-scale (diffusive) redistribution of material in driving divergence of soil properties in otherwise undisturbed locations, which was observed in the Swiss valleys by Temme and Lange (2014), is not necessarily the most important or most common cause of divergence.

6 Conclusions

It is concluded that variation in soil properties of different age is substantial and sometimes substantial enough to make it impossible to distinguish the variation due to soil age from within-age-group variation. The amount of within-age-group variation must therefore be assessed and preferably accounted for in the course of soil chronosequence studies. Variation is not the same between age-groups. It appears to primarily increase with age (divergence) in settings that are undisturbed by outside effects, notably geomorphic effects, and it appears to be driven by the influence of vegetation differences and small-scale (diffusive) transport of soil material and water between locations. Conversely, variation in soil properties appears to primarily decrease with age (convergence) in situations where an (homogenous) external influence affects and disturbs soil formation. In our case, this influence was presumably the provision of fresh parent material from hillslopes surrounding proglacial areas.

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