PATTERNS OF SOIL DEVELOPMENT ON STRATH TERRACES ALONG THE COLORADO FRONT RANGE: SOIL MORPHOLOGY AND COSMOGENIC RADIONUCLIDE DATING

Paul R. Rindfleisch[1], Melissa A. Foster[2,3], Joanna R. Redwine[4]

[1]2020 Front Street, Golden, CO 80401, soilgeo18@gmail.com, [2]INSTAAR, University of Colorado, Boulder, CO 80309, USA [3]Dept. of Geological Sciences, University of Colorado, Boulder, CO 80309, USA [4]U.S. Bureau of Reclamation, Denver Federal Center, Denver, CO 80225

ABSTRACT, PAPER NO. 39-20

Large strath terraces adjacent to the Colorado Front Range record the local history of fluvial planation and incision, and soil development over time. These terraces are grouped into ~6 alluvial units, and regionally correlated largely by elevation above stream channels and soils geomorphology. We present detailed soil descriptions and preliminary soil analyses on three mapped terraces adjacent to Lefthand Canyon near Boulder, CO. Recent cosmogenic radionuclide (CRN) data indicate that the Table Mountain (mapped as Rocky Flats or Verdos) and Slocum terraces in this area are ~ 95 ka [Dühnforth et al., 2012] and 91 ka [Foster, unpublished data], much younger than the correlative units to the south which are >640 ka and 240 ka, respectively [Scott, 1960].

Generally, this chronosequence of soils follows an expected progression of soil development where older surfaces have more clay, thicker argillics, and redder hues. The oldest surface (Table Mountain) has a 95 cm thick argillic horizon (2.5YR to 5YR, 22-38% clay) formed in weakly sorted, stratified sandy and gravelly alluvium. Soils on the middle terrace (Slocum) have a 40 cm thick argillic horizon (7.5YR-10YR, 25-40% clay) formed in Holocene loess over sandy and gravelly alluvium; this is the only of the three surfaces with pedogenic carbonates (stage I-III), suggestive of genesis under a more arid climate regime. The lowest terrace we investigated (mapped as Louviers-age equivalent) has not yet been dated using CRN. This site also had loess overlying sandy, gravelly alluvium and the ~1 m thick argillic horizon (7.5YR, 20-38% clay) formed in both deposits. These soils classify as fine-loamy to loamy-skeletal Aridic Argiustolls or Calcidic Argiustolls.

Relative-age studies of soil development in this region indicate these surfaces are much older than recent CRN data indicate. This interpretation affects other regional studies based on soil development rates. Open questions include: what factors may accelerate soil development, what role do transient eolian caps play in CRN analyses and soil development in this area, and are development rates just faster than previously thought? Ultimately we will use soil development and time constraints provided by CRN dating to develop a model of soil evolution for these terraces, thereby shedding light on soil forming processes, paleoclimate, and landscape evolution in this area.

A LITTLE BACKGROUND

Strath terraces along the Front Range in the vicinity of Boulder, Colorado are a subset of terraces have been mapped and correlated north and south along the Front Range from the Wyoming border to Cañon City, Colorado. The five alluvial units of interest for this study are (from youngest to oldest) are the Broadway, Louviers, Slocum, Verdos, and Rocky Flats, (e.g., Scott, 1960). All terraces are considered to be Pleistocene in age. The Broadway and Louviers Alluvium are interpreted as coeval with the Pinedale glacial advance and Bull Lake glacial advances, respectively (Scott, 1969). The Slocum Alluvium has been dated using Uranium-series dating techniques on a horn core near Cañon City, yielding an age of 190 ± 50 ka (Szabo, 1980). The Verdos Alluvium has been dated in a gravel pit about 15 km south of Boulder, CO based on an ash equivalent to the Pearlette Ash which is correlated to the Lava Creek B ash (Van Horn, 1976) giving it an age of ~640 ka. The Rocky Flats type locality was dated by Riihamiki and others (2006), which shows a progressive abandonment of the Rocky Flats from 2 Ma to 400 ka; other studies utilizing soil developement in conjunction with paleomagnetics have resulted in an estimated age of the Rocky Flats as 1.35 Ma (Patterson and others, 1984; Birkeland and others, 1996).

In addition to numerical techniques, workers in the area have also used relative dating based on the principles of soil geomorphology for correlation purposes (Hunt, 1954; Malde, 1955; Scott, 1963; Machette, 1975; Machette and others, 1976; Van Horn, 1976). Common soil features and properties used to estimate relative age in the field include carbonate morphology, clay accumulation, and soil horizon reddening as well as a host of laboratory analyses (see Birkeland and others, 1991; Birkeland, 1999; Schaetzl and Anderson, 2005; and many others for detailed description of these techniques). Evaluation of soil mapping in the area (see discussion section) generally supports increasing soil development with increasing age.

Recent studies using cosmogenic radionuclide (CRN) dating techniques suggest that the terraces near Boulder, CO are significantly younger than previous work indicates. CRN dates on Table Mountain, deposited by Lefthand Canyon, is ~95 ka (Dühnforth and others, 2012; see Figure 1); new CRN data on the mapped Slocum surface is ~91 ka (Foster, unpublished data). In light of established numerical and relative dating of these surfaces within Colorado, these results were met by some surprise by some workers in the region. Previous studies had considered soil development rates to be much slower than what the results of the CRN study implies. Some of the questions that arise from these studies include: 1) are soil development rates near Lefthand Canyon much more rapid than regional rates calculated from dates on correlated alluvial units; and 2) does the soil record preserve a history of stratigraphic or erosional complications that may alter CRN age estimates.

Deciphering these apparent inconsistencies are part of the current efforts by M. Foster and others to analyze these surfaces using ^{10}Be and ^{26}Al isotopes and optically-stimulated luminescence (OSL); this effort is coupled with soils and stratigraphic descriptions of the sample site in an attempt to reconcile these disparities. Data analyses for the CRN are still pending, and OSL results forthcoming, but were waylaid due in part to the recent government shutdown.

Opening the door to soils-CRN relations:

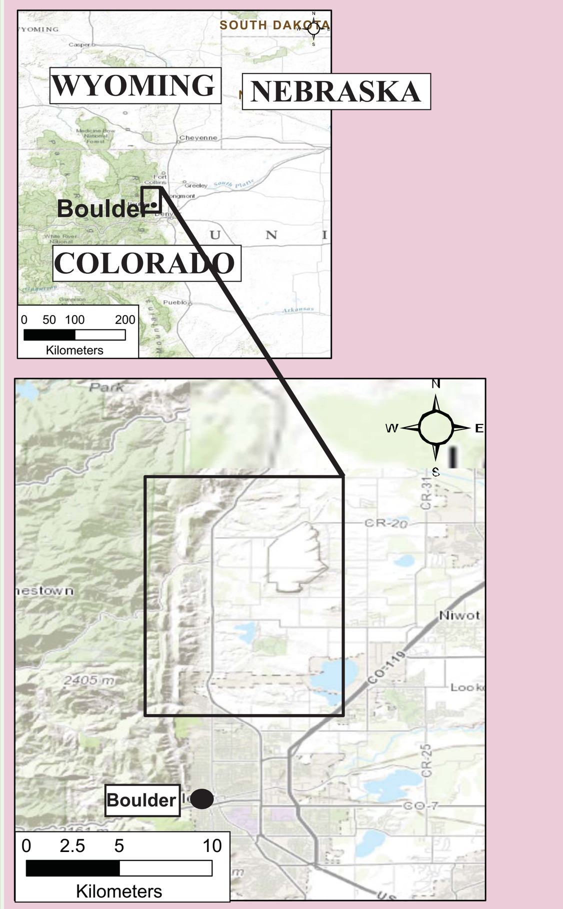
GOALS OF THIS STUDY

1) Examine the soils and stratigraphy of different-aged terrace surfaces in coordination with sampling for CRN dating in order to document changes in soil profiles and understand how soils are changing through time.

2) Observe stratigraphic and soil features in the exposure/profile that may elucidate depositional variations and/or post-depositional changes that could affect either soil development or CRN analyses.

3) Structure the sampling strategy and interpretation of CRN data to account for soil data. This includes collecting CRN samples by horizon, correcting CRN production rates for onset of loess (with the aid of OSL data), and collecting accurate bulk density data to account for soil density as well as gravel fractions.

LOCATION OF STUDY AREA



GEOMORPHIC MAP OF TERRACES ALONG THE FRONT RANGE

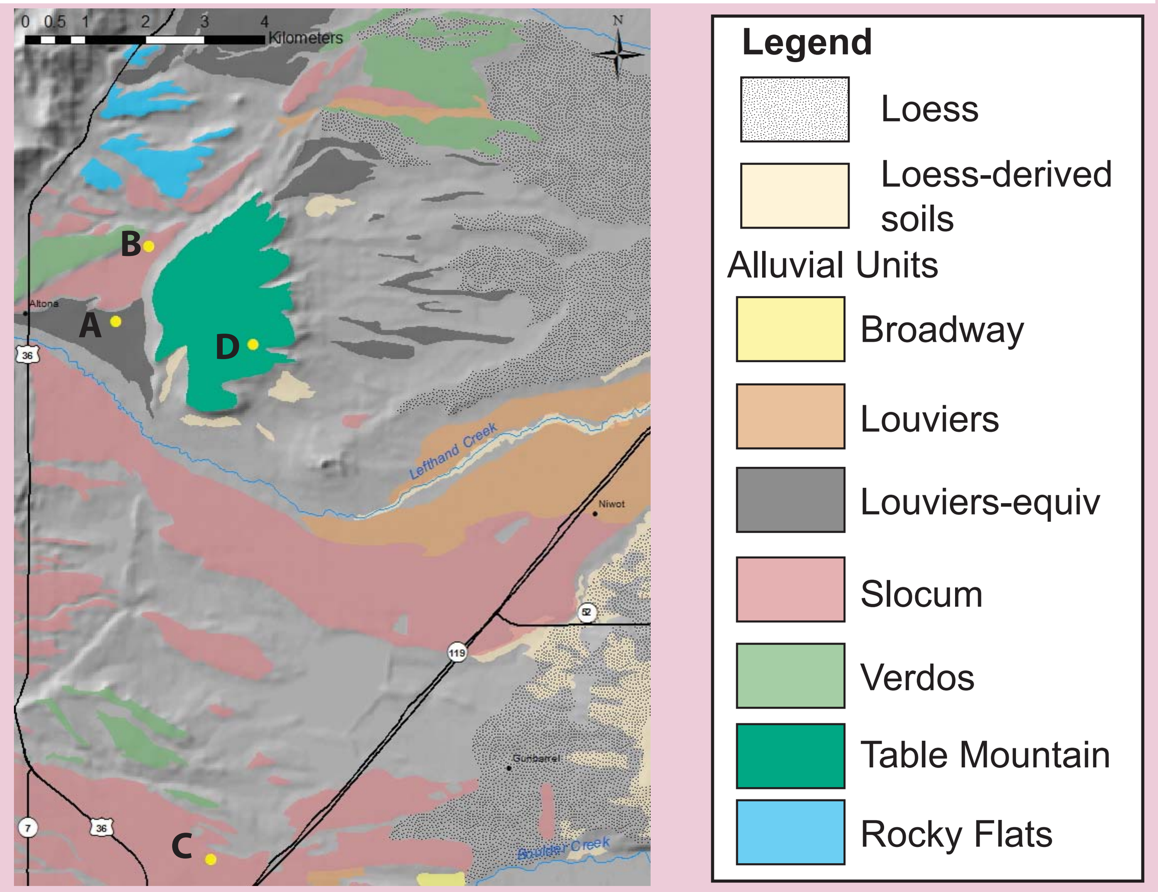
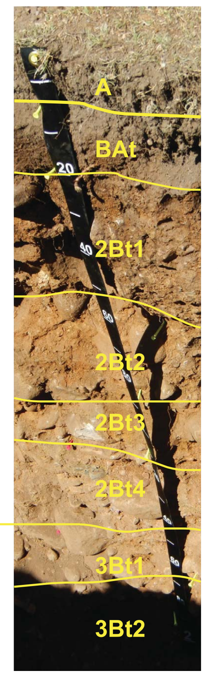


Figure 1. Hillslope imagery with mapped alluvial units (e.g. Scott, 1960; mapping adapted from Cole and Braddock, 2009; Moreland and Moreland, 2008). Alluvial units are largely correlated by elevation above the modern stream:(1) Rocky Flats, ~100 m; (2) Verdos, ~70 m, (3) Slocum, ~30 m; (4A) Louviers,~ 10m; (4B) Louviers-equiv, ~10 m (5) Broadway, ~5 m. Site letters correspond to below descriptions.

SOIL PROFILES AND DESCRIPTIONS

A
LOUVIERS-EQUIV SURFACE

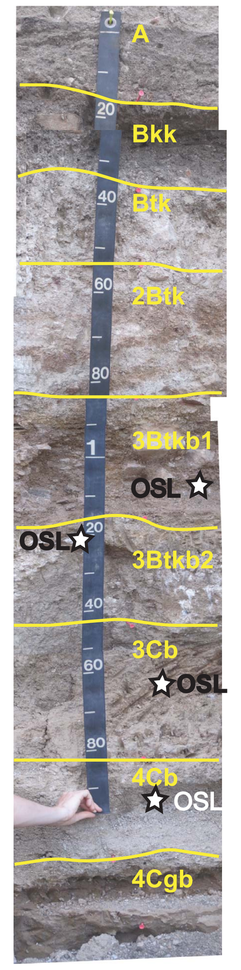


3Bt3

A—0 to 12 cm, 10YR 5/2D GR-L, 10YR 3/2M; 16% cly, 17% rfs.
BAt—12 to 25 cm, 7.5YR 4/4D&M CL; 38% cly, 10% rfs; P&V m d oaf pf & m d brf sg.
2Bt1—25 to 80 cm, 7.5YR 4/4D GR-CL, 7.5YR 3/4M; 30% cly, 16% rfs; P&V m p oaf rf, fw d clf pf, & m ft brf sg.
2Bt2—80 to 101 cm, 7.5YR 4/4D&M L; 26% cly, 13% rfs; P&V fw d clf pf & rf, & m ft brf sg.
2Bt3—101 to 117 cm, 7.5YR 4/4D&M CB-SL; 23% cly, 23% rfs; P&V fw d clf pf & rf, & m ft brf sg.
2Bt4—117 to 148 cm, 7.5YR 4/4D&M GRV-CoSL; 20% cly, 55% rfs; P&V fw d clf rf & fw ft clf pf.
3Bt1—148 to 166 cm, 7.5YR 4/4D&M GRX-SL; 17% cly, 74% rfs; c d P&V clf rf & c d brf sg.
3Bt2—166 to 198 cm, 7.5YR 4/4 D&M GRX-SL; 17% cly, 67% rfs; P&V fw clf pf & rf, & fw ft brf sg.
3Bt3—198 to 210 cm, 7.5YR 4/4D GR-CoSL; 12% cly, 17% rfs; P&V fw d clf rf & fw ft brf sg.

Classification: Fine-loamy, mixed, superactive, mesic Aridic Paleustalfs
Diagnostic features: Ochric epipedon 0-12 cm; Argillic horizon 12-148 cm
Notes: Profile was noneffervescent throughout.

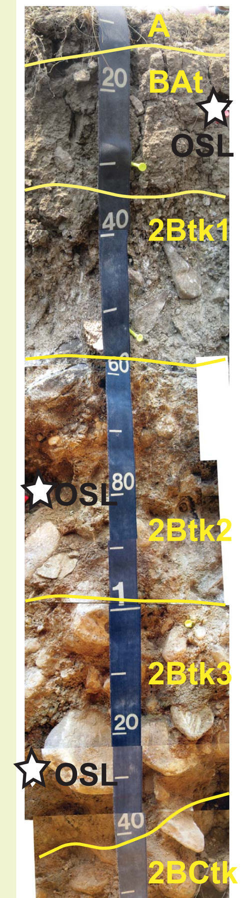
B
SLOCUM SURFACE I



A—0 to 20 cm, 10YR 3/2D L, 10YR 2/2M; 15% cly, 9% rfs; VE.
Bkk—20 to 38 cm, 60% 10YR 8.5/2D & 40% 2.5Y 7/3D L, 10YR 8/2M & 2.5Y 6/3M; 18% cly, 10% rfs; VE, Stage III Carb Morph, P&V m d caf rf, m ft cath.
Btk—38 to 67 cm, 60% 7.5YR 4/4D & 40% 2.5Y 9/2D SCL, 7.5YR 5/4M & 2.5Y 9.5/1M; 28% cly, 14% rfs; VE, Stage III Carb Morph, P&V m d caf rf, c p cath; fw clf pf & m d brf sg.
2Btk—67 to 99 cm, 10YR 5/6D GRV-S, 10YR 4/4M; 3% cly, 49% rfs; ST, Stage I Carb Morph, P&V c p caf rf & c p cath; m ft brf sg; RMF c mnf br bh.
3Btkb1—99 to 125 cm; 10YR 6/3D SCL, 10YR 5/3M; 32% cly, 6% rfs; wc; SL, Stage II Carb Morph, P&V c d cath & m d can; m ft clf pf.
3Btkb2—125 to 162 cm; 10YR 6/3D, SCL, 10YR 4/4M; 21% cly, 7% rfs; NE, Stage I Carb Morph, P&V fw d cath; fw clf pf & c brf sg.
3Cb—162 to 192 cm; 2.5Y 6/3D CoSL, 2.5Y 5/3M; 10% cly, 13% rfs; NE.
4Cb—192 to 206 cm; 70% 5YR 4/3D & 30% 2.5Y 5/2D SiCL, 5YR 4/3M & 2.5Y 4/2M; 35% cly; NE; m d 5YR 4/3 mot; c p 2.5Y 5/2 fed & m d 7.5YR 5/6 f2m.
4Cgb—206 to 219 cm; 50% 10YR 5/2D & 50% 5YR 4/3D L, 10YR 4/2M & 5YR 4/3M; 25% cly; NE; m p 5YR 4/3 mot; areas of rmx, m p 10YR 4/6 f2m.

Classification: Fine-loamy, mixed, superactive, mesic Aridic Calciustolls
Diagnostic features: Mollic epipedon 0-20 cm; Calcic horizons 20-67 cm and 99-125 cm; Redox concentrations: 192-219 cm; Redox depletions: 192-219 cm; Pedogenic carbonates: 20-162 cm.

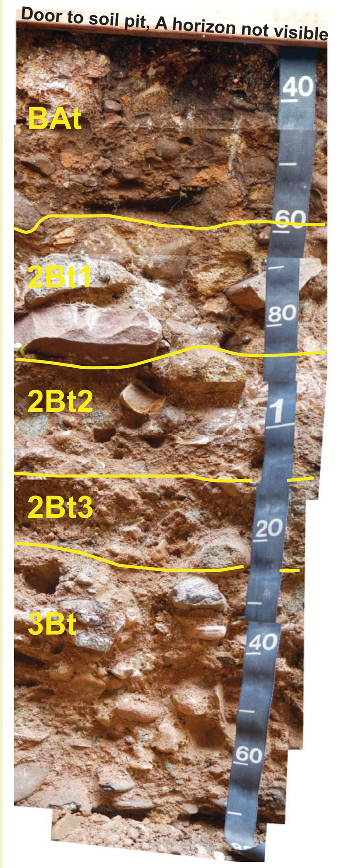
C
SLOCUM SURFACE II



A—0 to 9 cm; 10YR 5/2D SiL, 10YR 3/2M; 19% cly, 8% rfs; NE.
BAt—9 to 26 cm; 10YR 5/2D SiL, 10YR 3/2M; 42% cly, 8% rfs; NE; m d 10YR 5/2 oaf pf.
2Btk1—26 to 48 cm; 10YR 4/4D&M GR-L; 26% cly, 18% rfs; VE, Stage II-II+ Carb Morph, c d caf rf, c p cath, & m d cam; c ft brf sg.
2Btk2—48 to 96 cm; 7.5YR 6/6D GRV-SL, 7.5YR 4/6M; 17% cly, 51% rfs; ST, Stage II-II+ Carb Morph, c p caf rf, c p cam; vf d clf pf, c f brf sg.
2Btk3—96 to 151 cm; 7.5YR 5/6D STV-SL, 7.5YR 4/6M; 16% cly, 31% rfs, 4% prfs; VE, Stage II Carb Morph, fw d caf br, c d cam; c ft brf sg.
2BCtk—151 to 170 cm; 7.5YR 6/6D GRX-COSL, 7.5YR 4/6M; 18% cly, 61% rfs, 1% prfs; ST, Stage II-II+ Carb Morph, fw d caf br and c d cam; c ft brf sg.

Classification: Fine-loamy, mixed, superactive, mesic Aridic Argiustolls
Diagnostic features: Mollic epipedon 0 to 24 cm; Argillic horizon: 9 to 48 cm; Secondary carbonates: 26 to 170 cm.
Notes: Accurate estimation of cobbles and stone was difficult because of the limited exposure of the 2BCtk horizon.

D
VERDOS /ROCKY FLATS (?)



A—0 to 29 cm, 7.5YR 4/3D, GR-SL, 7.5YR 3/3M; 16% cly, 30% rfs.
BAt—29 to 59 cm, GRV-SCL, 5YR 4/6M; 22% cly, 48% rfs; P&V fw d clf pf, rf & m, d brf sg.
2Bt1—59 to 84 cm, STV-SCL, 5YR 4/6M; 28% cly, 33% rfs; P&V fw p clf pf, c ft clf rf, & m d brf sg.
2Bt2—84 to 109 cm, GR-SCL, 5YR 4/8M; 33% cly, 32% rfs; P&V fw p clf pf & m d clf rf, & m d brf sg.
2Bt3—109 to 125 cm, GRV-SCL, 5YR 4/8M, 22% cly, 40% rfs; P&V m p clf rf & m p brf sg.
3Bt—125 to 177 cm, CBX-CoSL, 5YR 4/6M; 17% cly, 65% rfs; P&V m p clf rf & m p brf sg.

Classification: Loamy-skeletal, mixed, superactive, mesic Aridic Argiustolls
Diagnostic features: Mollic epipedon 0-29 cm; Argillic horizon 29-125 cm
Notes: Profile was noneffervescent throughout.

YOUNG → OLD

RUBIFICATION →

OBSERVATIONS

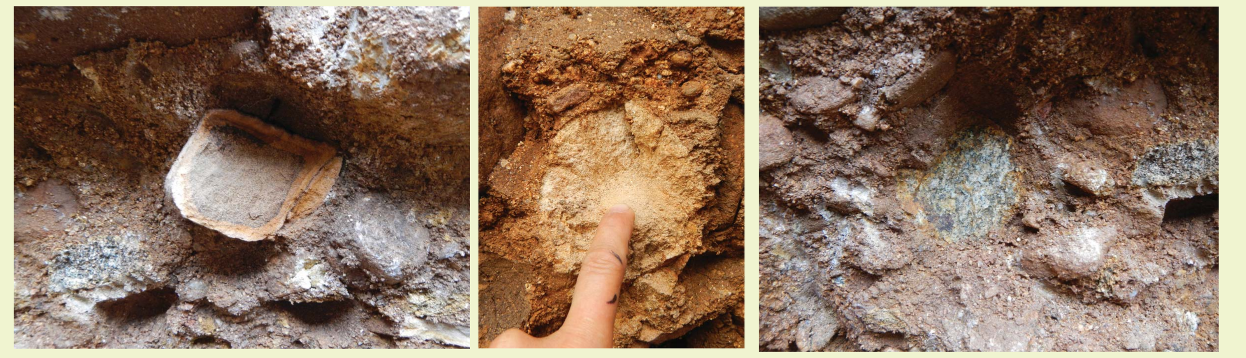
Soil color: Generally, soil color follows the expected age relations within the study area, with the oldest surface, the Table Mountain surface, being consistently redder (generally 5YR 4/6 or 4/8) than either the Louviers-equiv or Slocum surfaces. The soils on the Slocum tend towards yellower hues (10YR), particularly in the upper parts of the profile where the carbonate accumulation is greatest. The youngest, Louviers-equiv, surface dominantly had 7.5YR colors.

Clay content and argillic horizon thickness: The content and thickness of the diagnostic argillic pattern did not follow straightforward patterns relating to age (assuming higher clay with greater age). For example, the argillic horizon on Table Mountain had a weighted average of 26% clay with a clay maximum of 33%, and was 96 cm thick, whereas the Slocum surface II soil had an argillic with 33% clay (wtd avg, max of 42%) and a thickness of 39 cm. The argillic of the Louviers-equiv soil had 23% clay (wtd avg, max of 38%) and was 136 cm thick.

Carbonate morphology: The oldest and youngest surfaces investigated lacked visible pedogenic carbonates and evidence of disseminated carbonates. Both of the Slocum surface soils had carbonate morphologies of stage II to III, with carbonate coatings on rock fragments as well as carbonate masses in the matrix.

Parent materials: The Table Mountain site and Louviers-equiv surface soils formed in gravelly to stony sandy alluvium, with no overlying loess cap. Both Slocum sites had loamy or silty upper horizons consistent with either loess or over-bank deposition in a fluvial setting.

Weathering Rinds from Table Mountain Surface



KEY TO SOIL DESCRIPTIONS

Color:	Modifier:	Texture:	Clay & fragments (field estimates)
D = dry M = moist **Effervescence:** VE = violent ST = strong SL = slight NE = none	GR = gravelly GRV = very gravelly GRX = extremely gravelly CB = cobbly CBX = extremely cobbly STV = very stony	S = sand(y) Si = silt(y) C = clay L = loam(y) CO = coarse	cly = clay % rfs = rock frags % prfs = pararock frags % **Carbonate cementation:** wc = weak
FEATURES:			
P&V = Ped & void features			
Type: oaf = organoargillans brf = clay bridging clf = clay films caf = carbonate coats cath = carbonate threads can = carbonate nodules cam = carbonate masses	**Distinctness:** ft = faint d = distinct p = prominent **Mottles:** mot = geogenic	**Abundance:** vf = very few (< 5%) fw = few (5 - < 25%) c = common (25 - < 50%) m = many (50 - < 90%)	**Location:** pf = ped faces rf = rock fragments sg = between sand grains br = bottoms of rock fragments bh = base of horizon
RMF = Redoxymorphic features			
mnf = mangans	fed = iron depletions	f2m = masses of oxidized iron	rmx = reduced matrix

DISCUSSION

Currently, we have four soil descriptions. In order to determine the representativeness of our sites (chosen based on access and suitability for CRN, we reviewed the soil mapping (Moreland and Moreland, 2008; Price and Amen, 1984). The soils on the sampled terraces (Louviers-equiv, Slocum, and Verdos/Rocky Flats from youngest to oldest), are consistent with the observations above. The dominant soils on Table Mountain are the Flatirons (clayey-skeletal, smectitic Aridic Paleustolls) and Nederland (loamy-skeletal Aridic Argiustolls) series, have argillics that range in clay from 18 to 60 percent, colors ranging from 7.5YR to 2.5YR, and lack identifiable pedogenic carbonates. Slocum surfaces are typically mapped as either the Valmont (clayey over loamy-skeletal, smectitic Aridic Argiustolls) or Nederland series. The Valmont soils form in loess over coarse alluvium, have 35 to 60 percent clay in the argillic horizon (formed in the capping loess), and have pedogenic carbonates. The Nederland soils form in coarse alluvium, lack pedogenic carbonates, and have 18 to 35 percent clay in the argillic. Colors in the argillic horizon for the Valmont soils can be significantly yellower (5Y) than the Nederland soil, but overlap at the red end of the range. The Louviers alluvium is dominantly mapped as the Nunn series (fine, smectitic Aridic Argiustolls). Nunn soils form in loess over finer-grained alluvium and have pedogenic carbonates within 25 to 50 cm of the surface. The argillic horizons of Nunn soils have 35 to 60 percent clay and range in hue from 5Y to 7.5YR.

The presence or absence of pedogenic carbonates are quite variable across the surfaces investigated, making reliable relative age correlations using this soil feature difficult. For example, the oldest surface investigated (Table Mountain) and the youngest (Louviers-like) both lack pedogenic carbonates, though generally the Louviers surface is mapped as having secondary carbonates (Moreland and Moreland, 2008; Price and Amen, 1984). Other workers in the area (Malde, 1955; Machette and others, 1976; Price and Amen, 1984; Machette, 1985; Birkeland and others, 1996) recognized this variability in the occurrence of pedogenic carbonates in this part of the Front Range and have attributed it to the proximity of the area to the pedocal-pedalfer boundary (Machette, 1985), the location of which fluctuates with moisture availability due to climate, with wetter periods leaching out calcium carbonates and drier period enhancing carbonate accumulation. Conceivably, the soils on the Table Mountain surface have undergone at least one wetter period (glacial episode), and since Ca^{++} flux is low in this region (Machette, 1985), have not redeveloped these features.

Parent material type and texture no doubt plays a role in both the patterns of clay accumulation and argillic horizon thickness and the prevalence of pedogenic carbonates. Clay accumulation and argillic horizon thicknesses, like pedogenic carbonates, do not strictly adhere to expected trends of increasing clay and greater thickness with older age, with the oldest surface having slightly less clay than the Slocum surface, and slightly more than the Louviers-equiv surface. The open architecture presented by the sandy and gravelly alluvium on the Table Mountain and Louviers-equiv surfaces allow water to readily move through the profile and redistribute clay over meter or more, whereas the matric difference between the finer-grained "cap" of loess or overbank deposits over coarser grained sandy and gravelly alluvium has focused clay accumulation over a much narrower band with a higher clay content. These matric differences also appear to have focused carbonate precipitation and may serve to prevent the removal of precipitated carbonates at depth as leaching is inhibited.

WORKING HYPOTHESES

There is no question, regardless of age, that these soils are polygenetic; they have been subjected to a minimum of one glacial episode, millennia of bioturbation and vegetative change, and periods of enhanced eolian deposition and erosion since fluvial abandonment. Disentangling the signature of these events and the events overprinting them is no simple task. Regardless, it is hoped that meaningful correlation between soil features and the CRN dating technique can be achieved. Here we propose some current working hypotheses to help explain the observations made to this point in time.

Surface erosion: Most of the eluvial horizons for the pedons observed thus far seem thinner (9 to 30 cm) than would be expected given the amount and depth of clay illuviation (>2 m). This leads to the suggestion that some amount of surface erosion has occurred, diminishing the thickness of the eluvial horizon(s). Evidence supporting this hypothesis, however, has been difficult to establish because: (1) none of the surfaces observed showed significance evidence of modern erosion (see very flat surfaces depicted in photos to left), and (2) the soil profiles, with the exception of the buried soil at Slocum I fail to show conclusive evidence of erosion such as stonelines within the profiles, that one would expect if significant stripping of soils formed in gravelly to stony alluvium had occurred. Rock fragments were common on the surfaces of most terraces sampled, particularly on the Table Mountain surface; fragments on the Slocum surfaces most likely are the result of biological activities since the upper parts of these soils formed in loess. In the case of the Table Mountain surface, where a loess cap was absent, one possibility to account for the extensive clay illuviation is that this surface was at one time mantled with loess, and subsequently eroded leaving an erosional lag at the top of the argillic horizon (Figure 1, below) given that silty loess would be much more erodible than gravelly to stony sandy clay loam; this possibility was also reported by Dühnforth and others, 2012. This hypothesis is difficult to prove, however, since the modern surface has virtually no expression of modern or past erosion. This set of processes potentially could result in 1) younger CRN dates due to lower CRN production rates under a thicker eluvial horizon (ie. younger date than the fluvial abandonment of the surface; the effect of erosion on CRN dates is shown in Table I), and 2) enhanced translocation and soil development, making the soil appear older than it would had the cap been absent.

Progressive upbuilding: There is little doubt that loess has contributed to soil development in the region (Reheis, 1980); also see distribution of loess deposits and loess-derived soils in Figure 1. Indeed, loess forms the upper parent material at both Slocum sites and some or all of the parent materials for the Nunn series (Soil Survey Staff, 2013), which is the dominant soils on the Louviers surfaces to the east of the study area, where loess is more prevalent (or better preserved). In these two situations, the modern argillic horizon has formed within the loess. The fine-textured Nunn soils, may have been overwhelmed by loess deposition, only forming horizons after deposition ceased. The Louviers and Rocky Flat surfaces, however may have experienced loess deposition at a rate in which the material was steadily incorporated into the profile, resulting instead in progressive upbuilding of these soils as silt and clay translocated, readily filling the ample pore space of the coarse alluvium. This process would have little to no impact on the CRN dating method since sand-sized or gravel material was dated, but could conceivably result in soils appearing more developed than those that weren't subject to the same amount of loess deposition; see Harden and others, 1990) for an example of enhanced soil development due to dust deposition in the northern Mojave Desert.

Figure 1

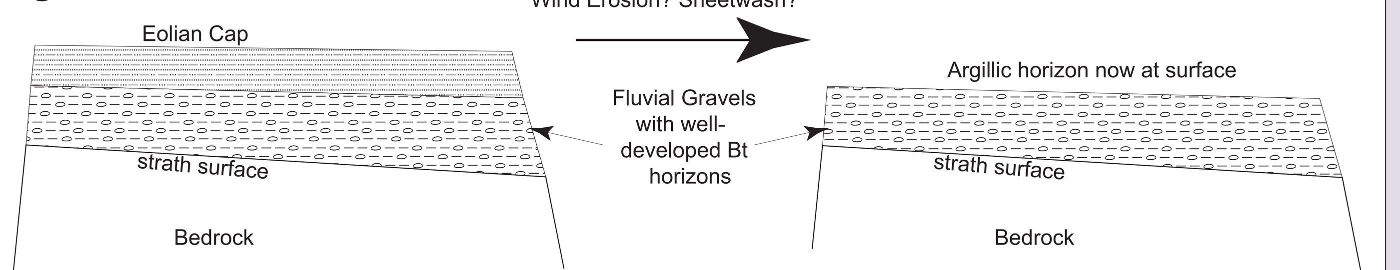


Table 1

This table shows ages for the Table Mountain surface calculated using the ^{10}Be data reported by Dühnforth and others (2012) with various thicknesses of loess. Age was calculated following the methodolgy of Dühnforth and others (2012) to find the best fit age and inheritance; the model used a timestep of 5 ka. For the purpose of these calculations, the thickness of loess is held constant over time, as if there was a constant thickness of loess on Table Mountain from deposition to present day. A loess density of 1.5 g/cm^3 was used for these calculations, based on the high end of values reported by Bettis III and others (2003). Error was not propogated for the purpose of these calculations, although ~ 10% error is a fair estimate for the measurement and bulk density error. Our age at 0-cm of loess cover is younger than Dühnforth and others (2012) due to slight differences in the bulk densites we used for the fluvial deposits.

Loess thickness (cm)	Age (ka)	Inheritance (atoms/g-qtz)
0	90	308500
20	110	307500
40	135	306000
60	165	307500
80	200	315000
100	245	320000
120	300	328000
140	370	336500
160	455	352000
180	560	374000
200	700	399500

REFERENCES

Bettis III and others, 2003, Last glacial loess in the conterminous USA, Quaternary Science Reviews, **Birkeland and others, 1991,** Soils as a tool for applied Quaternary geology, Utah Geological and Mineral Survey, Misc. Pubs. **Birkeland, 1999,** Soils and Geomorphology, Oxford University Press. **Dühnforth and others, 2012,** Unsteady late Pleistocene incision of streams bounding the Colorado Front Range from measurements of meteoric and in situ 10Be, Journal of Geophysical Research: Earth Surface. **Birkeland and others, 1996,** Soil-geomorphic relationships near Rocky Flats, Boulder and Golden, Colorado area…; Colorado Geological Survey Open-File Report 96-4. **Hunt, 1954,** Pleistocene and recent deposits in the Denver area, Colorado, USGS Bulletin 996-C. **Machette, 1975,** Quaternary Geology of the Lafayette Quadrangle, Colorado, MS Thesis CU Boulder. **Machette, 1985,** Calcic soils of the southwestern United States in Soils and Quaternary geology of the southwestern United States; GSA Special Paper 203. **Machette and others, 1976,** Soil development in Quaternary deposits in the Golden-Boulder portion of the Colorado Piedmont, in Professional Contributions of Colorado School of Mines. **Malde, 1955,** Surficial geology of the Louisville Quadrangle, Colorado; Geological Survey Bulletin 996-E. **Moreland and Moreland, 2008,** Soil Survey of Boulder County Area, Colorado: USDA-NRCS. **Patterson and others, 1990,** Paleomagnetic study of a succession of Early Pleistocene paleosols near Boulder, Colorado, GSA Abstracts with Programs, 16. **Price and Amen, 1984,** Soil Survey of Golden Area, Colorado; USDA-SCS. **Reheis, 1980,** Loess sources and loessial soil changes on a downwind transect, Boulder-Lafayette area, Colorado, The Mountain Geologist. **Riihamiki and others, 2006,** Longevity and progressive abandonment of the Rocky Flats surface, Front Range, Colorado, Geomorphology. **Schaetzl and Anderson, 2005,** Soils: Genesis and Geomorphology, Cambridge University Press. **Scott, 1960,** Subdivision of the Quaternary alluvium east of the Front Range near Denver, Colorado, GSA Bulletin. **Scott, 1963,** Quaternary geology and

ACKNOWLEDGEMENTS

This work was funded by the Boulder Creek CZO (NSF grant EAR-0724960), Colorado Scientific Society, CU Geology Department Student Research Grant, CU Beverly Sears Student Research Grant. We thank Tim Brown as well as Scott and Lisa Christiansen for allowing us to excavate soil pits on their property; we thank NEON and Markell construction for access to open pits on their sites. Field and Lab assistance was provided by: Francis Rengers, Cliff Riebe, Shannon Mahan, Harrison Gray, Eric Winchell, Pete Birkeland, Nate Rock, Clayton Jenson, Wendy Roth, and Clara Chew.