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Influence of Elevation on Carbonate Contents in Stratified Soils, Northern Great Basin and Adjacent Mountains, U.S.A.

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ABSTRACT

Many soils in the western USA contain one or several carbonate-enriched zones (CEZ). Their carbonate admixture is often attributed to steady eolian influx, with intermittent leaching episodes of variable intensity leading to pedogenic enrichment at various depths. This hypothesis would require carbonate contents to decrease and depths to those horizons to increase with elevation. Here I compute correlations for the upper three CEZ of the surface soil and of up to two buried soils between elevation, carbonate content, depth to horizon, and particle-size distribution to test for elevation-dependent trends. Actually, carbonate-content decreases with elevation indicate such trends exist and can be determined with this approach. However, some significant relationship of elevation and depth to CEZ is not supported by the data. Furthermore, influence of local carbonate on CEZ in the surface soils calls for lateral translocation. Gravelly, now-buried sediments collected eolian carbonate better than finer ones, which finding implies these sediments were at the surface once and fossilized later. Altogether, the data indicate cyclical evolution: Several cycles of the formation of colluvial slope deposits with admixed carbonate-bearing loess particles were each followed by pedogenic translocation of the carbonate just to the depth of the next parent-material disconformity. Thus, disconformities are major triggers of soil-carbonate accumulation.

Keywords: *Soils and Elevation, Paleosols, Soil Carbonate, Pedogenesis, Parent Materials*

1. Introduction

Ca^{2+}-ion content in rainwater alone is insufficient to explain the carbonate in western US soils [1-3]. Thus, the source of pedogenic calcium is commonly assumed to be approximately steady eolian influx as calcareous dust or as calcium ions [4-7] onto geomorphologically stable land surfaces [8]. Eolian contribution to soils is indicated by abundant silt-size particles in topsoils [9,10]. The contrasting idea of silt enrichment through physical weathering rather than by dust admixture [11] has been refuted by means of mineralogical and geochemical analyses, indicating allochthonous mineral admixture to the soils [10,12,13], and by the fact that carbonate has engulfed substrates that were primarily free of carbonate [2,6,14], or, that had been leached prior to carbonate enrichment as indicated by significant clay illuviation into the same horizon [4,5,15,16].

Using dust-trap devices to quantify eolian influx [17-19] neglects severe problems, if results are applied to past times: dust traps tend to overestimate deposition rates as they catch sediment being transported, but give no confident clue on which actual part of the dust would finally settle on the measurement plot [20]. Furthermore, vegetation cover has drastically changed in the Great Basin and surroundings since the advent of white man [21]. This, artificial desiccation of lakes, and greasing livestock are presumably important sources of dust, adding to natural sources [22]. Third, drastically different deposition rates under different paleoclimatic frameworks may be assumed. Actually, [23-25] concluded from properties of soils in the Great Basin that close to lake basins pulses of eolian deposition triggered by lake desiccation played a greater role than steady influx. Reference [16] could not explain bifurcating Great-Basin paleosols with multiple calcic horizons without considering cycles of colluviation and accompanying admixture of loess.

An important concept of the present paper is the carbonate-enriched zone (CEZ). It is defined as a soil section with pedogenetically enhanced carbonate concentration (indicated by properties as defined by [4]). It may comprise more than one soil horizons or even soil layers, but is characterized by peak enrichment usually at or near the top of the zone, at least higher in the profile than half the thickness of the whole zone. Increase in carbonate content beneath an identified CEZ constitutes another CEZ.

The occurrence of several CEZ at various depths is attributed to repeated climate-driven episodes of varying leaching intensity, each leading to an horizon of carbonate enrichment, which episodes interfered with the steady influx [26,27]. Because any intense leaching event would have caused the dissolution of older calcic horizons higher in the profiles [28], this implies a trend of decreasing leaching intensities with time, assumed to be glacial and post-glacial in time, respectively [27,29]. If so, at least the paleoclimatic framework of fossil CEZ at depths of several meters would come into question.

Paleoclimatic trends, in particular parallel to elevation, must have existed during the proposed leaching episodes, though not necessarily at modern rates. Effective moisture increased with elevation due to orographic precipitation and to temperature lapse reducing potential evapotranspiration. In addition, lower temperatures should have extended solubility due to increased CO_2 concentrations in soil water and, thus, the amount of carbonate leached to ground water [30]. Consequently, carbonate contents should decrease with increasing elevation [4,31]. The depth to the CEZ of any particular leaching episode should have been increased accordingly, because the depth at which carbonate accumulates is believed to closely relate to soil moisture [2,24,31-34]. This correlation between precipitation and depth to pedogenic carbonate, however, has been questioned by [35,36].

The present study tests for the existence of elevation-related trends in CEZ properties of the northern Great Basin and rim.

2. Materials and Methods

Soils with CEZ from throughout the area (**Figure 1**) and at various elevations up to timberline, covering an altitudinal range from ca. 1250 to 2800 m asl and current moisture conditions from arid (100 - 400 mm mean annual precipitation in basins) to semihumid (greater than 1000 mm in the Wasatch Range), were studied. Soils with present or relict natric soil properties were excluded because of possible effects of soluble salts on carbonate solubility [37]. Only soils developed from slope deposits were included. To minimize effects of aspect, only soils on flat relief <3˚ or with a northwestern to southwestern aspect regardless of slope inclination (22˚ being the steepest one) were selected. Of the remaining profiles, 42 contained at least one, 31 a second, and 20 a third CEZ. Additional CEZ, which were observed deeper in some soils, were not considered in this study.

Particle sizes <2 cm were determined after removal of organic material and carbonate by wet sieving and the pipette method (dispersant $Na_4P_2O_7$, cf. [38], but see for

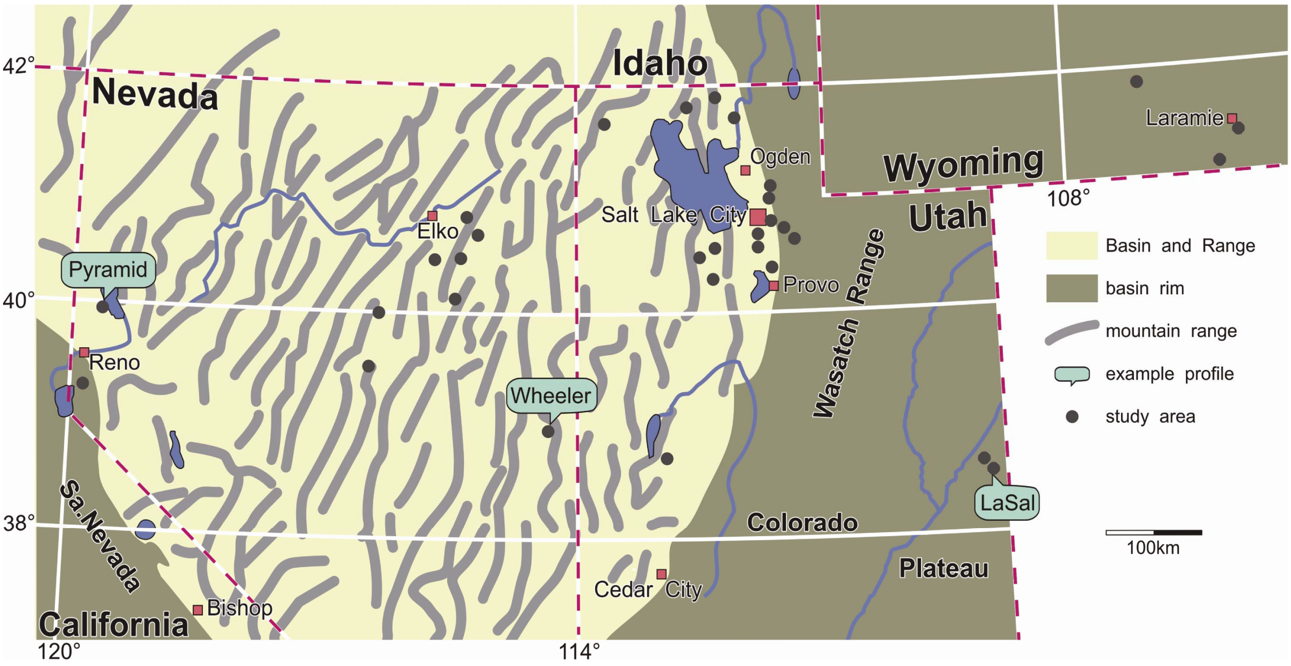

Figure 1. Study areas.

slightly deviating particle-size classes), larger ones were determined by volume in the field [26]. Soil organic C (C_{org}) was measured by rapid dichromate oxidation with $K_2Cr_2O_7$ (colorimetrical method [39]). pH was determined using $CaCl_2$ [39]. Total carbonate was determined by manometer measurement of CO_2 evolved after treatment with 3 M HCl (Scheibler Apparatus). For computations, peak carbonate contents of each CEZ and texture data of the corresponding and the directly overlying layer were used.

These data were used to compute linear (other curve fittings did not yield significantly better results) bi-variate correlations employing various sediment and soil properties, especially carbonate content, and elevation.

Only total carbonate contents will be reported, because primary carbonate contents may be subtracted from measured values to give a clue on the pedogenic share only if one homogenous parent material continues below the soil without further disconformities, which was not the case in the profiles under study.

Soil terminology follows Soil Survey Staff [40].

3. Results and Discussion

3.1. Example Profiles

Table 1 gives examples of soils at different altitudes with

Table 1. Selected properties of example paleosol profiles.

horizon	depth	clay	fSi	mSi	cSi	fS	mS	cS	fGr	cGr	pH	carb.	C_{org}
		<0.002	<0.006	<0.02	<0.064	<0.2	<0.64	<2	<20	20mm			
	cm	----------------------------------- % ------------------------------------										-- g·kg^{-1} --	
Profile 1		Typic Calciargid. Pyramid Lake, Nevada, 1250 m·asl, on lake gravel											
Bw	0 - 60	9.5	2.6	5.9	12.0	17.5	16.5	36.0	19.2	15	7.5	2.3	3.8
2Btbk	60 - 105	21.4	2.2	3.9	11.8	20.5	20.7	19.6	4.0	7	7.5	13.2	3.8
2Btb	105 - 135	9.3	2.4	3.1	10.3	22.5	25.1	27.3	9.0	7	7.1	1.8	2.1
3Bkb	135 - 185	5.0	2.3	3.6	11.3	21.5	24.9	31.4	11.0	2	7.9	35.7	2.6
4Btkb1	185 - 200	10.6	6.0	15.1	29.2	21.9	7.6	9.5	1.0	7	8.7	135.6	1.8
4Btkb2	100 - 215	10.8	7.4	13.2	29.0	22.0	7.5	10.1	1.0	7	8.7	10.3	1.8
5Bkb	215 - 225									100	n.d	n.d	n.d.
6Bkb	225 - 240	15.4	4.4	10.3	31.7	29.9	5.9	2.4	1.0	0	9.2	66.2	1.3
7Bkb	240 - 330+	5.3	0.7	2.2	9.8	17.5	19.4	45.2	32.6	20	7.9	37.4	2.0
Profile 2		Ustic Calciargid. Spring Valley, Nevada, 1770 m·asl, on alluvial gravel											
Bw	0 - 40	8.8	4.9	7.4	20.3	15.3	16.9	26.4	25.2	2	7.7	15.7	5.7
2Bk	40 - 110	3.4	1.4	2.1	7.3	8.2	28.9	48.6	50.8	30	7.5	34.4	8.2
3Btb	110 - 140	12.2	4.6	4.4	13.7	22.7	20.1	22.2	22.8	5	7.2	1.6	5.4
3Bkb	140 - 210	8.4	3.6	4.0	8.3	11.2	25.4	39.1	30.9	7	7.6	130.0	4.5
4Btkb	210 - 240	29.6	7.0	5.3	10.8	20.9	16.5	9.9	6.7	3	7.5	135.5	7.6
5Btb	240 - 260	20.6	5.2	4.0	11.1	19.7	20.9	18.5	33.4	15	7.6	62.9	4.6
6Bkb	260 - 295	15.6	6.3	8.7	7.4	20.9	21.6	19.4	5.0	5	7.7	498.0	5.3
7Btb	295 - 315	8.3	3.4	2.8	7.8	29.8	32.3	15.7	11.6	5	7.3	2.6	4.9
Profile 3		Typic Eutroboralf. LaSal Mountains, Utah, 2130 m·asl, on gravelly colluvium											
A	0 - 10	14.4	3.7	8.9	26.6	19.6	11.2	15.5	9.1	10	7.7	29.5	18.3
Bw	10 - 40	14.9	3.3	8.9	16.7	23.5	14.4	18.4	8.6	15	7.6	150.2	14.2
2Btbk1	40 - 65	27.0	5.4	8.6	22.2	23.1	7.3	6.4	0.9	2	7.7	170.5	5.4
3Btbk2	65 - 130	21.4	5.9	8.0	26.4	24.7	7.5	6.0	0.0	0	8.0	143.5	2.4
3Bkb	130 - 155	21.4	5.9	8.0	26.4	24.7	7.5	6.0	0.0	2	8.0	191.3	1.5
4Btb	155 - 180	18.9	5.9	8.4	19.9	21.2	12.7	13.0	4.8	10	8.1	68.8	2.3
5Bkb	180 - 225	24.3	6.5	11.2	4.5	16.4	22.2	14.8	6.1	25	7.7	185.0	9.4
6Btkb	225 - 245	18.8	3.3	6.5	23.3	22.0	10.9	15.3	6.5	5	8.1	68.9	1.6

n.d.: not determined. carb.: carbonate content. C_{org}: organic-carbon content. ≠: depth range of horizon. Particle size classes: Gr = gravel; S = sand; Si = silt; c = coarse; m = medium; f = fine. fGr = weight% of whole soil without cGr; cGr = vol% of whole soil, field estimate; other classes = weight% of fine earth < 2 mm. Class boundaries are mm.

at least three CEZ. Profile 1 is a Typic Calciargid overlying lacustrine gravel, exposed on a lake terrace southwest of Lake Pyramid, Nevada, at an elevation of 1250 m above sea level (asl). Its cambic horizon (Bw) overlies a carbonate-enriched argillic horizon (2 Btbk). Carbonate enrichment decreases downwards to almost invisibility (2 Btb), to increase again in the underlying 3 Bkb horizon, and even more in the subjacent argillic horizon (4 Btkb). Within the latter it decreases again (determined in the field by 10% HCl, not sampled) to reach a third maximum at greater depth (6 Bkb). Altogether the profile encompasses three CEZ.

Profile 2, a Ustic Calciargid, was exposed in Spring Valley, Nevada, in the western foot zone of Wheeler Peek, in a trench into alluvial fan gravel, at 1770 m asl. It has three zones of maximal carbonate enrichment starting with the 2 Bk, 3 Bkb, and 6 Bkb horizons, and several more down to at least 6.10 m (not included in **Table 1**).

Profile 3, a Typic Eutroboralf bordering a Mollisol, stems from the western slope of the La Sal Mts., Utah, at 2130 m asl, from a high river terrace mantled by meters of slope deposits (oldest terrace of [41]. Carbonate contents peak in the 2 Btbk1, 3 Bkb, and 5 Bkb horizons, and in some more horizons down to 5 m (not included in **Table 1**).

These soils have argillic properties at least below the first and the second CEZ, Profile 2 and Profile 3 also below the third CEZ, indicating that parts of the soils were leached prior to carbonate enrichment, because carbonate enrichment and clay illuviation, as far as the latter is not restricted solely to some vertical cracks or pipes, are mutually exclusive and, thus, cannot form simultaneously in the same horizon [16,30,42,43]: clay translocation is only viable while carbonate is being or has been depleted, because clay tends to flocculate as long as Ca^{2+} ions are abundant. (Effects of exchangeable sodium on clay translocation are not discussed here.)

3.2. Statistical Analyses

Average carbonate content in the first CEZ is lower (70 $g \cdot kg^{-1}$) than in the second and third (147 and 133 $g \cdot kg^{-1}$, respectively). Thus, steady influx/episodic leaching would require that the duration of influx prior to the most recent carbonate enrichment was shorter than for the leaching events before, because with the same amount of carbonate involved the weakest leaching event would have left the greatest carbonate content in the soil. In addition, enhanced soil moisture would have lead to a greater portion of the carbonate being translocated out of the soil profile to ground water.

Correlation between elevation and carbonate content is significant for all three CEZ (**Figure 2(a)**). Contents significantly decrease with elevation. Above 2850 m·asl, no more pedogenic carbonate was observed in the soils under study. This carbonate-content decrease with elevation is evidence of a paleoclimatic elevational trend throughout the studied areas. This result is almost trivial; it was mainly employed as a test whether the selection of the study sites was - with regard to other environmental factors influencing soil carbonate - sufficiently sophisticated to establish a relationship, and it demonstrates that this kind of trend may be determined using correlation analysis.

Steady influx/episodic leaching would imply strengthened leaching with climatic gradients, in particular with elevation that is a major control on mean annual precipitation, to result in greater depths to the CEZ. This, however, is not supported by the data (**Figure 2(b)**), as there is insignificant correlation between elevation and depth to carbonate enrichment. Rather, the depth to the first CEZ shows markedly low scattering throughout the elevational range. Depths to deeper CEZ vary to a greater extent, but this appears random and uncorrelated with elevation (**Figure 2(b)**) or other factors.

Because the depth to a CEZ could be related to the available calcium influx rate [4], which relation could have concealed an elevational trend, depth and carbonate content were also correlated. For all three CEZ, the results do not indicate such relationship (**Figure 2(c)**).

Beyond computations focusing on elevation, correlation of carbonate contents with various substrate properties was attempted. The carbonate contents of the deeper two CEZ are significantly correlated to certain aspects of the particle-size distribution within the respective overlying substratum (though not to the material of the particular carbonate-enriched horizon itself): The second CEZ displays a positive trend between carbonate and gravel content (**Figure 3(a)**), and a negative one between carbonate and clay content (**Figure 3(b)**). Only the former correlation is also significant for the third CEZ (**Figure 3(a)** and **(b)**). In contrast, the first CEZ does not at all show such behavior (**Figure 3(a)** and **(b)**). Rather, there is tight correlation between CEZ carbonate content and carbonate content of the deepest exposed parent material (**Figure 3(c)**), contrasting to the other two CEZ. This correlation remains highly significant ($r = 0.77^{***}$, $n = 19$), if only the deepest exposed parent materials of soils with more than one CEZ are considered, and does not improve much ($r = 0.89^{***}$, $n = 14$), if those multi-layered cases are just excluded from computation. These additional computations imply that carbonate in the uppermost CEZ predominantly stems from inheritance of carbonate from gross bedrock of the (probably upslope) area, because the shielding from on-site inheritance by underlying deposits does not considerably influence the results. A lack of significant correlation between carbonate contents of the first CEZ and of deeper

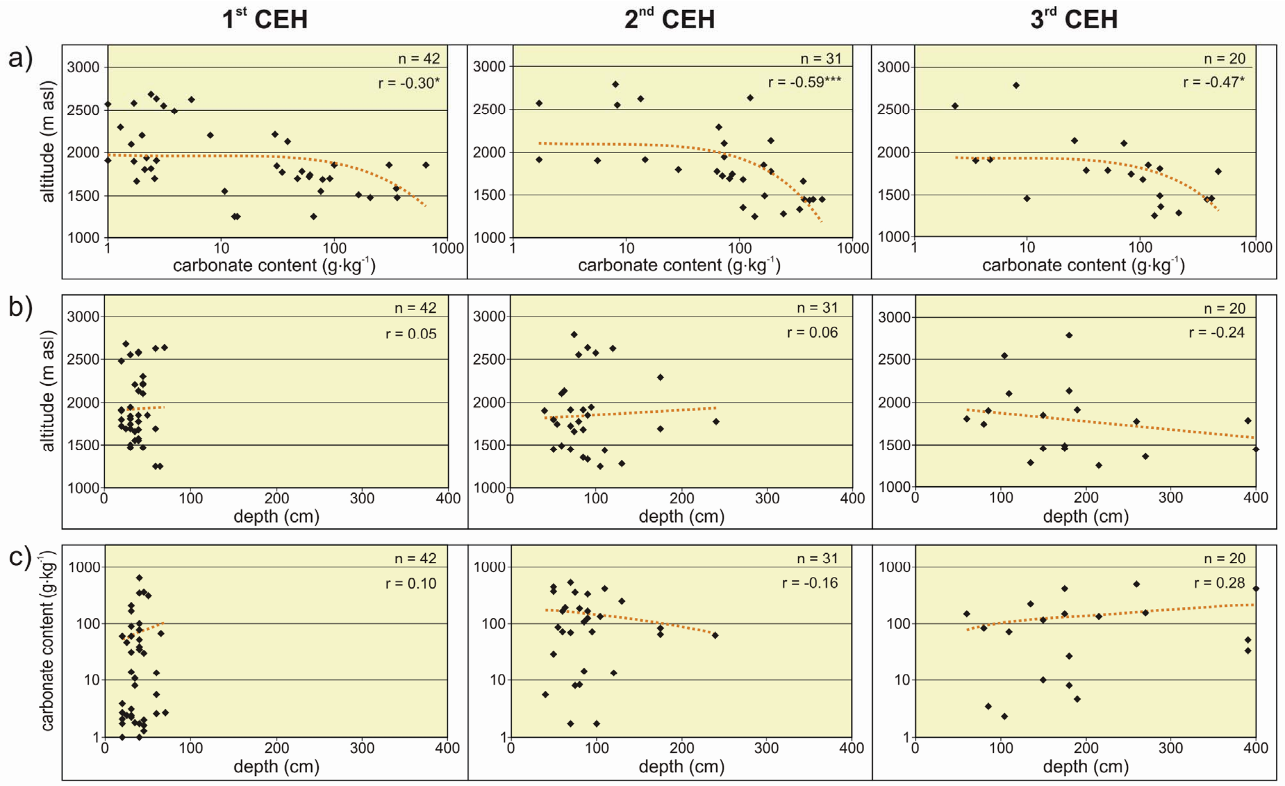

Figure 2. Correlation charts between elevation, carbonate content, and depth number of cases (n), fitting curve (broken line), and correlation coefficients (r) including levels of significance (* for p = 0.05, ** for p = 0.01, and *** for p = 0.001) are given. Note logarithmic scale of some axes.

ones supports this interpretation.

Other computed correlations (not reported here) between particle-size classes of the carbonate-enriched horizons themselves, relief properties (mainly slope angle), or overlying horizons and carbonate content or depth to horizon did not yield significant results.

Some relation between pedogenic carbonate and gravel content is not unexpected. However, model calculations indicate that gravel has greater influence on depth to carbonate enrichment than on carbonate content [2], which could not be supported by the data. Thus, the relationship between carbonate and gravel contents cannot be explained by water retention and permeability of the substratum alone. Rather, the proposed interpretation is that gravelly deposits are better suited for trapping eolian deposition [25,44-46]. This would imply that the trapping material was at the surface when the carbonate-bearing eolian dust accumulated, whereas now the substrates overlying the lower two CEZ are buried by at least one additional deposit.

There is no such relationship between carbonate content of the uppermost CEZ and gravel in its overlying substrate, indicating that the aforementioned trapping mechanism was less important than in the deeper horizons. This implies a smaller role of eolian, and a greater importance of local, probably detrital, carbonate sources. The tight relationship between carbonate contents of the deepest exposed parent material and of the upper CEZ, contrary to deeper CEZ, supports this interpretation. Both lines of evidence indicate a smaller influence of eolian addition on this surficial material than on subjacent ones, which conclusion is corroborated by other lines of evidence such as heavy-mineral contents and particle size distribution [47,48].

4. Conclusions

There are paleoclimatic trends governed by elevation and discernible by the approach used in this study as indicated by the significant decrease in carbonate content with elevation. However, depths to CEZ do not follow such trend. This finding is in conflict with steady influx/episodic leaching, because the expected relationship of elevation and depth to CEZ is unsupported. Furthermore, local influence, *i.e.* reworking of nearby, probably upslope calcareous materials, appears to influence carbonate contents in the uppermost CEZ, whereas there is evidence that eolian influx largely determines deeper CEZ. Steady eolian influx would require the relative proportion

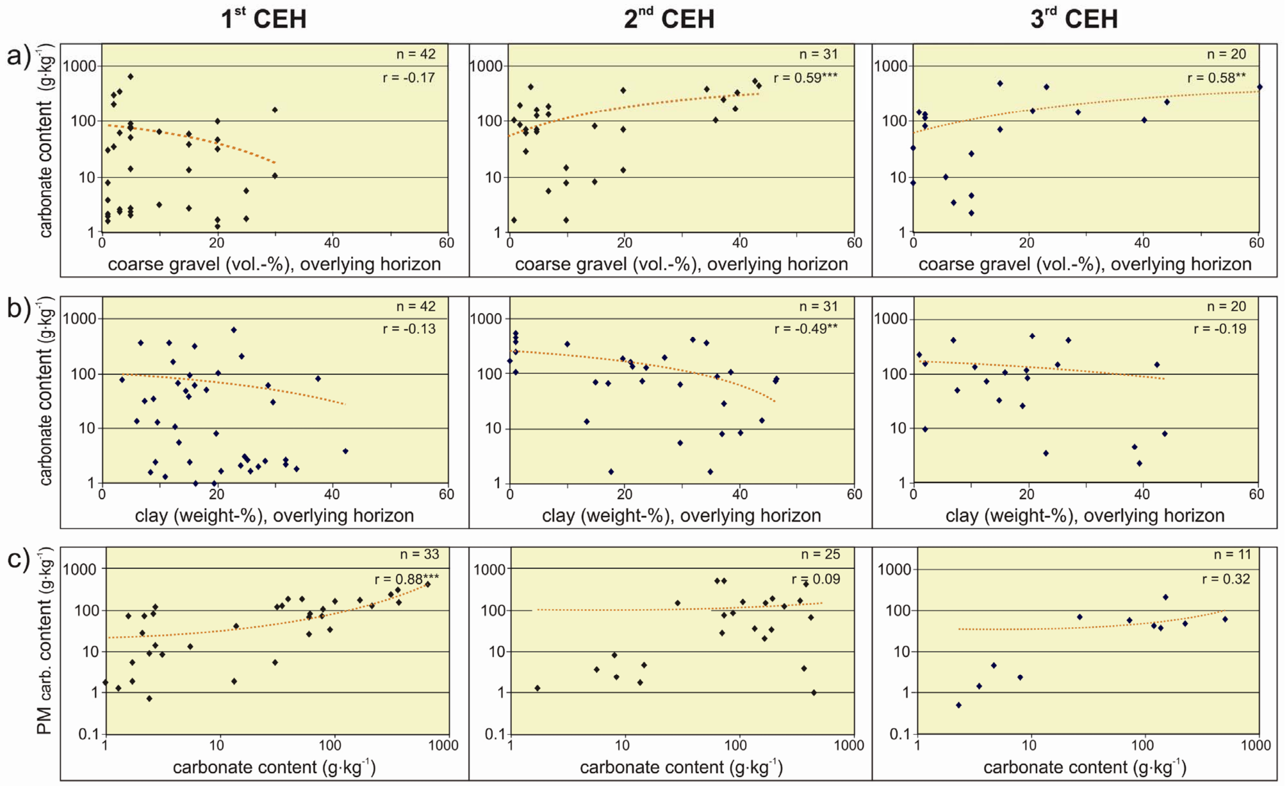

Figure 3. Correlation charts between carbonate content and substrate properties number of cases (n), fitting curve (broken line), and correlation coefficients (r) including levels of significance (* for $p = 0.05$, ** for $p = 0.01$, and *** for $p = 0.001$) are given. PM = parent material beneath deepest CEZ used for correlation. Note logarithmic scale of some axes.

of carbonate from eolian sources to be increased at shallower depths in the soils. Third, the conclusion that now-buried gravels were once surficial calls for decisive discontinuities in the geomorphic evolution.

Rather, the findings are consistent with multiple phases of colluviation (similar processes were inferred by [49] from ^{36}Cl-dating of surficial boulders and carbonate-enriched horizons), in parts with accompanying loess admixture, separated by pedogenic phases with the formation of soils including CEZ. The latter usually overprinted buried, older soil horizons to form welded soil profiles [16,47]. Then the carbonate may stem from these colluvial deposits, *i.e.* not directly from eolian influx on exactly the modern surface but through redistribution; the source of this contribution of carbonate apparently varies between the first and deeper layers. Such cycles may explain the burial of gravelly deposits. They also reduce the need for phases of varying leaching intensity, because the depth to the CEZ was not the same during pedogenesis as it is today, when additional deposits have been laid down on top of older surfaces, rendering depths to these horizons from the modern surface pretty much arbitrary. Hence, second and third CEZ, which have many properties in common, would not call for rather different paleoclimatic frameworks but may have been formed under similar conditions.

CEZ in the studied paleosols always occur below soil parent-material disconformities. This may be interpreted to the fact that disconformities are strong triggers of carbonate enrichment, whichever change takes place: Fining particle sizes and/or increased density at that boundary slow down the penetration of wetting fronts, favoring carbonate accumulation [50], whereas soil-air volume increases through abrupt parent-material coarsening, causing carbon dioxide to degas and the dissolved carbonate to precipitate. Thus, any disconformity may induce carbonate accumulation. However, this process acts against percolating water inertia, which explains that the carbonate enrichment does mainly not grow into overlying materials, at least during initial stages of the process, but affects underlying substrates. As soon as plugging effects at the disconformity play a role, inducing substrate anisotropy, lateral water flow through the soil will prevail on inclined relief [51], transporting dissolved carbonate out of the profiles, thereby slowing down further growth of the CEZ.

Temporarily enhanced rates of eolian accumulation have been reported before [6,23,24]. The results of the present study suggest they were not restricted to direct surroundings of waxing and waning lakes, and several such pulses occurred through the geologic history.

It should be in the scope of further research on western U.S. carbonate-enriched paleosol horizons, whether they are approximately age consistent and, thus, may be used as stratigraphical tools [41]. Relative dates were assigned to the youngest three CEZ in the northern Great Basin through their interference with lake deposits and paleolake related landforms [1,16], as well as by orbital tuning, as of ca. 12 - 8 ka, 50 -30 ka, and 120 - 80 ka, respectively [48]. Though still very scattered, numerical ages obtained by [52] from pedogenic carbonate of 16 - 11 ka, 52 - 33 ka, and <110 ka upon the youngest, second, and third river terraces, respectively, in the Wind River Range appear promising.

5. Acknowledgments

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