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Soil types and eolian dust in high-mountainous karst of the Northern Calcareous Alps (Zugspitzplatt, Wetterstein Mountains, Germany)

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Abstract

This study deals with the soil formation on pure limestone in the high-mountainous karst of Wetterstein Mountains (Northern Calcareous Alps). The study area in detail covers the alpine (2000 to 2350 m) and the subnivale zone (2350 to 2600 m) of Zugspitzplatt, a tertiary paleosurface situated next to the highest summit of Germany (Zugspitze 2963 m).

The formation of autochthonous soils is determined by the following parameters: uniform geology and geochemistry of Triassic limestone ($CaCO_3 + MgCO_3 \geq 98\%$), variable substrata (solid rock, debris, local moraine), hypsometric pattern of vegetation modified by microclimate and aspect, variety of micro-environments in karst relief.

In the subnivale zone, only leptosols (lithic, skeletic) and regosols (calcaric, humic) occur, whereas in the alpine zone different stages of folic histosols and rendzic leptosols prevail due to the diversity of vegetation. The purity of limestone prevents a distinct contribution of residues to soil formation. Instead of expected A–B–C profiles, the residues are mixed with organic matter of folic horizons (O–OB–C). Only in karst depressions or on local moraines small Bt horizons (2 to 5 cm) occur. They mark a developed stage of folic histosol (O–OB–Bt–C) representing the climax of autochthonous mineral soil genesis in the study area.

Special features are brown deposits (mean thickness 30 cm) covering large parts of the alpine zone. On the basis of mineralogical (X-ray diffraction, heavy minerals) and pedological data (grain size, soil chemistry), eolian origin is indicated. The resulting soils are classified as loess loam-like cambisols (Ah–Bw–2(Bt)–2C) and are related to late glacial loess deposition (Egesen-Stade of Younger Dryas). The abundance of mica and silt in the surface layers and the grain size distribution of snow dust samples prove that dust influx by southerly winds is still continuing. The major sources

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for both late glacial and present-day dust are magmatic and metamorphic rock formations of the Central Alps. Additionally, local dust transport from adjacent outcrops of Jurassic and Lower Cretaceous sediments is evident.

Keywords: Alpine karst; Soil formation; Eolian dust influx; Alpine loess; Northern Calcareous Alps

1. Introduction

There is only few published information on the soils above timberline in the Northern Calcareous Alps (Hüttl, 1997; Credner et al., 1998). The main reason for the paucity of data is the common opinion that the soil formation in high-mountainous karst only plays a minor role compared to the forested zones (Mishra, 1982; Bochter, 1983; Retallack, 1991).

According to literature, the soil genesis on limestone in general is the result of continuous accumulation of local bedrock residues by chemical weathering (Kubiena, 1953; Retallack, 1991). The resulting soils (A–Bt–C profiles) show two subtypes: the brown "terra fusca" and the red "terra rossa" as the climax of maximum accumulation of residues (Kubiena, 1953; Nihlén and Olsson, 1995). The autochthonous terra fusca soils (chromic cambisols or luvisols, according to ISSS-ISRIC-FAO, 1998) are considered to be relict and uncommon in alpine environments (Zech and Voelkl, 1979; Mishra, 1982). In spite of these definitions, the genesis of brown soils on limestone is still being discussed as numerous profiles in the forested zone show eolian influence (Schönhals and Poetsch, 1976; Dill and Zech, 1980; Rodenkirchen, 1986). Thus, some authors relate these silt-enriched soils to periglacial slope deposits of late glacial age (Solar, 1964; Mailänder and Veit, 2001).

In 1999 for the first time, the author discovered brown soils in the alpine zone of Wetterstein Mountains (Hüttl, 1999). Their origin could both be related to residues and eolian deposits with reference to the ongoing discussion. However, the widespread spatial distribution and the loess loam-like texture give evidence for eolian nature. Proofs of present-day dust influx are the high contents of silt and mica in the surface horizons and dust layers on snow patches. These observations were the impetus to intense research on soil genesis in the Northern Calcareous Alps. Since September 2002, these studies are financially supported by the Deutsche Forschungsgemeinschaft (DFG, Bonn, Germany).

The aims of the studies shall contribute to answer the following questions:

- What are the prevailing soil types in high-mountainous karst?
- Which soil parameters (e.g. soil chemistry, grain size) are characteristic?
- What clues as to eolian sedimentation can be identified?
- What role does eolian dust play and what are the related soils in high-mountainous karst?

2. Study area and methods of investigation

The Wetterstein Mountains cover 129 km^2 of the Northern Calcareous Alps and are situated in the extreme south of Germany near the Austrian border (Fig. 1).

The study area Zugspitzplatt (8 km^2)—located in the western part of Wetterstein Mts.—shows in a rough outline a typic hypsometric distribution of vegetation (Table 1), modified by variations of microrelief and topoclimate (e.g. shady depressions, perennial snow patches).

The altitudinal change of vegetation is a function of temperature. The average annual temperature is: − 4.7 °C on the Zugspitz summit (2963 m), − 0.8 °C at the limit of alpine tundra growth (2350 m) and 2 °C at the timberline (2000 m). Temperatures above 0 °C (monthly mean) occur from early June and reach the maximum in July (monthly mean at 2000 m: 11.1 °C; data: DWD, Germany (1963–1993); Hüttl, 1999). Mean annual precipitation ranges between 2580 and 3300 mm in the nival zone and 2005 mm at the wind-exposed summit (Baumgartner et al., 1983, p. 104ff). Winds from westerly and northerly directions, transporting humid air masses, prevail (Fig. 2).

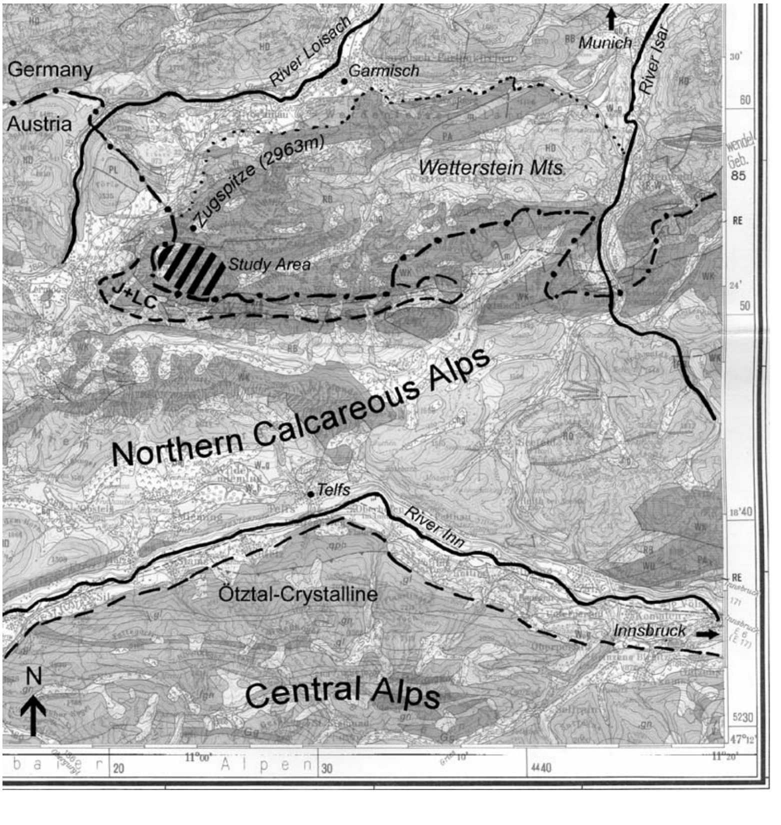
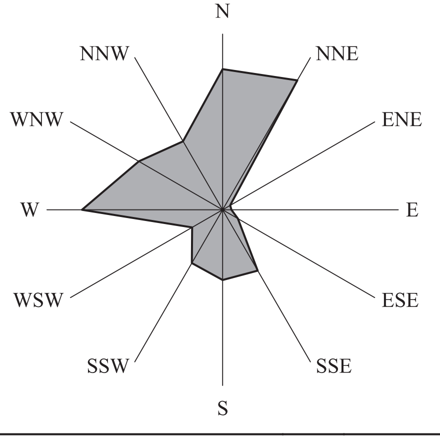


Fig. 1. Topographic situation of the study area with geological items. (J + LC = Jurassic and Lower Cretaceous outcrops; reference: CC 8726 Kempten; 1:200,000; Hannover 1983).

Table 1
Hypsometric distribution of vegetation on the Zugspitzplatt (dominant plant associations mapped by Hüttl, 1997; Credner et al., 1998)

Altitudinal zone	Dominant plant associations of vegetation
Nival (2600 to 3000 m)	lichens, mosses, pioneer plants (*Thlaspietum rotundifolii*)
Climatic limit of permanent snow at about 2650 m	
Subnivale (2350 to 2600 m)	associations of calcophile pioneers on debris and solid rock: *Tr: Thlaspietum rotundifolii* *Lm: Leontodontetum montani* *Ac: Arabidetum caeruleae* *Sr: Salicetum retuso-reticulatae*
Climatic limit of alpine tundra growth at about 2350 m	
Alpine (2000 to 2350 m)	associations of calcophile alpine meadows: different stages (initial, typic, well-developed) of: *Cf: Caricetum firmae* *S-Cs: Seslerio-Caricetum sempervirentis*
Climatic timberline at about 2000 m	
Subalpine (1650 to 2000 m)	associations of shrubs and krummholz *RhM: Rhododendro-hirsuti Mugetum*

As for the recent dust transport, southerly foehn winds in particular play the major role. They transport dry air masses loaded with dust across Austria to South Germany and are determined by high velocities (60–110 km/h) and storm events (110–150 km/h).



N	NNE	ENE	E	ESE	SSE	S	SSW	WSW	W	WNW	NNW	total
16	17	1	1	2	8	8	7	4	16	11	9	100

Fig. 2. Mean frequency [%] of wind directions on Zugspitz summit (2963 m) (data: DWD, Germany 1995–1997).

The alpine zone is characterized by an inclined limestone pavement (dip 30–37°) with distinct karst forms (e.g. sinkholes, solution runnels). Additionally, close arrays of terminal moraines and covers of moraine debris cause various environmental situations for plant growth and soil development. In contrast, the higher regions show a considerable increase of frost-shattered debris forming a monotonous periglacial environment. Thus, three soil forming substrata are identified: solid limestone (R horizon), debris (C horizon) and local moraine (CB, Cw horizons). The geology is uniform and consists solely of Triassic Wetterstein limestone (Ladin) with small amounts of residues (mean: 2 %; see Table 3; Section 3.3.1).

The results presented in the following section are based on the author's investigation of 50 soil profiles in the alpine and subnivale zone. The classification and the horizon nomenclature of these soils follows—wherever possible—the World Reference Base for Soil Resources (ISSS-ISRIC-FAO, 1998). If necessary, the nomenclature of the German classification (Kubiena, 1953) is added in brackets. Soil colours are characterized by use of the Munsell Soil Colour Charts (KIC, 1990). Soil parameters are determined by the following standard methods (Schlichting et al., 1995):

– soil pH in 1 n KCl using WTW electrodes
– $CaCO_3$ measured volumetrically (method Scheibler)
– organic matter [%] as loss on ignition at 430 °C
– grain size by wet sieving (>2 mm) and by Köhn pipette sedimentation (< 2 mm)

Mineralogy of soil and limestone was determined as follows (method Rast, 1991, 1993):

– determination of clay minerals by X-ray diffraction
– carbonate minerals and acid insoluble residue by dissolution in 10% HCl for 24 h
– heavy minerals

Additionally, first snow dust samples were taken for qualitative analysis.

3. Results

3.1. Prevailing soil types of the subnivale zone (2350 to 2600 m)

Periglacial processes determine soil genesis in the subnivale zone. On debris, lithic leptosols and calcaric regosols prevail. Their CA horizons are marked as follows:

– >70% of coarse debris or continuous hard rock within 10 cm from the soil surface
– high levels of carbonate (min.: 92%; max.: 96%; mean $CaCO_3$: 95%; mean pH: 8.0)
– high mean amounts of sand (50%) and silt (43%) in the fine matrix (Fig. 3)
– partly material of initial ochric A-horizon (3.75Y 5/2; 5Y 5/1; 7.5Y 4/1; 3.75 Y 8/2)

After the stabilization of coarse debris by pioneer communities (e.g. *Thlaspietum rotundifolii*, *Leontodontetum montani*, *Arabidetum caeruleae*) humic regosols appear

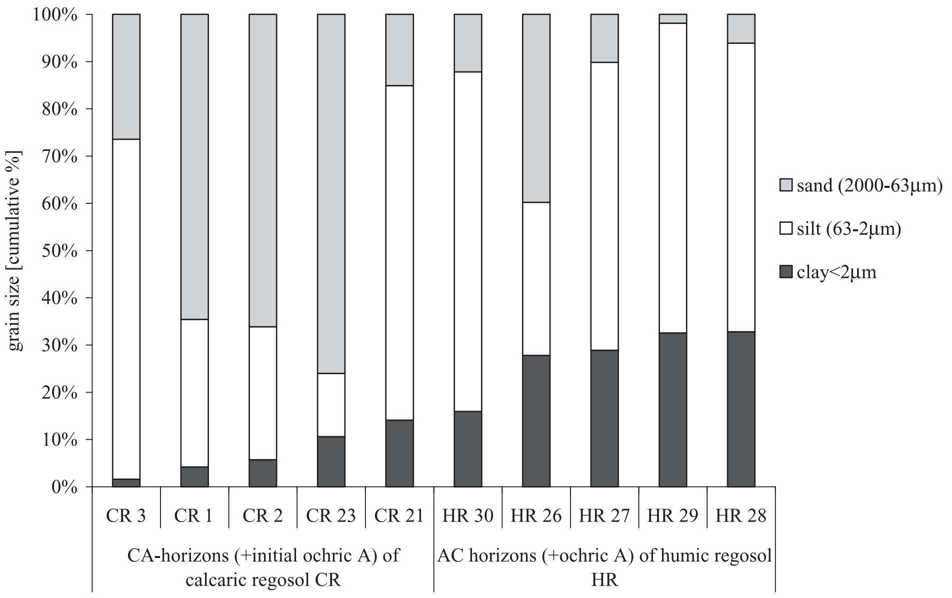


Fig. 3. Grain size distribution of calcaric and humic regosols.

showing alkaline pH values (mean pH: 7.8), coarse debris (min.: 5.4%; max.: 70.2%; mean: 50%), high amounts of silt (59%) and a decrease of sand (mean: 24%) in the fine matrix. The ochric A horizons (3.75Y 6/1; 7.5Y 6/1; 7.5Y 4/1) reflect the decay of organic matter (loss on ignition: min.: 2.5%; max: 11.6%; mean: 6.9%) and clearly distinguish the humic from calcaric regosols. Also, the grain size is a criterion as it shows an obvious increase of clay due to accelerated limestone weathering by humic acids (Fig. 3).

The high values of both sand and silt indicate that physical weathering is the main soil forming process in the subnivale zone (Latridou, 1988). However, the abundance of mica revealing eolian influence (see Section 3.3.2) exemplifies that frost action is not the only explanation for the silty texture of regosols.

3.2. Prevailing soil types of the alpine zone (2000 to 2350 m)

3.2.1. Rendzic leptosols and stages of folic histosols

Varying karst relief and different stages of grass vegetations (e.g. *Caricetum firmae* and *Seslerio-Caricetum sempervirentis*) create a mosaic of soil types in the alpine zone. The mapping of soils reveals a correlation to the succession of vegetation (Credner et al., 1998). According to the initial, typic and developed stages of the alpine grass association *C. firmae*, the following alpine soil types prevail (Table 2).

The folic O layers right on top of the substrata indicate the main pedogenetic process in the karst of Zugspitzplatt: the accumulation of humus as a result of cold and wet climate. Distinct criteria for categorizing the organic subtypes are the thickness, subdivision, and pH values of organic layers (Fries, 1985). The typic folic histosols are black coloured

Table 2
Soil types in the alpine zone in relation to vegetation succession

Stage and type of vegetation[a]	Soil type (German nomenclature)	Profile (characteristics[b])
Initial *Caricetum firmae* (also: Th + Lm; Sr)	initial rendzic leptosol (Polsterrendzina)	Ah–R; Ah–C (Ah < 10 cm; pH 7.2–8.2)
Typic *Caricetum firmae*	typic folic histosol (O/C Boden)	O–C; O–R (O>10 cm; pH 6.5–6.8)
Developed *Caricetum firmae* = transition between *Cf* typ. and *Seslerio-Caricetum sempervirentis*	developed folic histosol with initial cambic features (OB) or/and small Bt horizon (Terra f.-Rendzina)	(O)–OB–(Bt)–BC[c] (O>20 cm or OB>5 cm; pH 6.0–5.7); (Bt < 5 cm; pH 5.7–5.9)

[a] For the abbreviation., see Table 1, Section 2.
[b] O = organic matter >30%; Ah = organic matter <30%; horizons according to WRB (1998).
[c] Symbol in brackets means the horizon is not always developed, e.g. (Bt).

(2.5Y 2.5/1, 5Y 2.5/1, 10YR 2/1, 10YR 2/2), often skeletic (40% to 60% >2 mm) or almost free of fragments on solid rock. Accordingly, the contents of soil carbonates range between 3.3% and 41.6 % $CaCO_3$. In karst pits, calcareous dust is abundant, added by wind and/or water. This "natural liming" (Litaor, 1987, p. 142) improves the buffering against acids and thus raises pH values (pH 6.5 to 6.8). Developed folic histosol are marked by brown OB horizons (10YR 4/4, 7.5YR 4/4) and/or humic initial Bt-horizons (2 to 5 cm) confirming that the humus has merged with clayey residues. The Bt horizons only occur on local moraine or in karstic depressions.

The genesis of autochthonous soils on limestone in the study area is best described by the changing amounts of organic matter and mineral residues during soil formation (Fig.

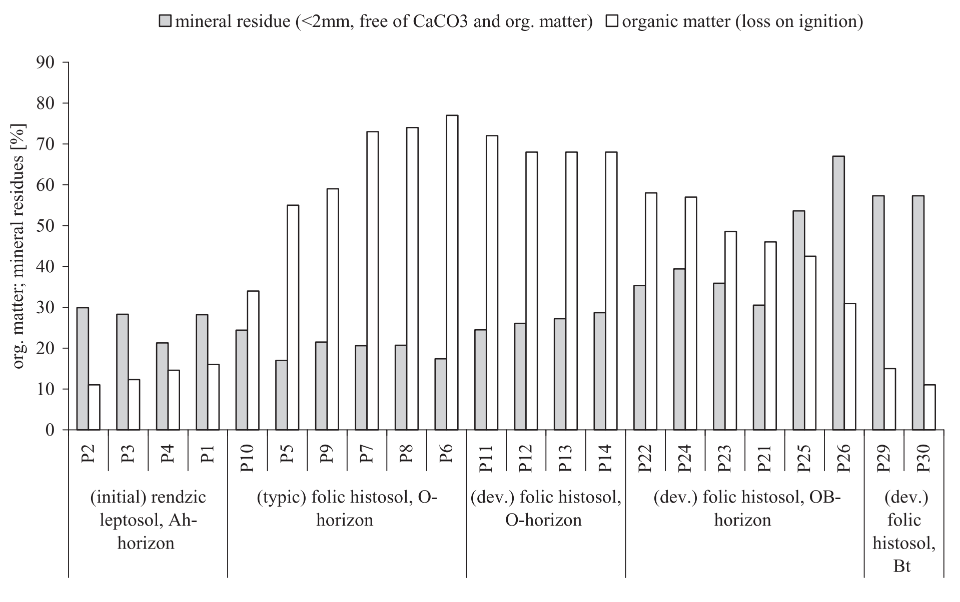


Fig. 4. Organic matter and mineral residue [%] in different soil types of alpine zone.

4). In this context, the amount of mineral residue (MR) is defined as the mass of soil material (< 2 mm) without organic matter and soil carbonate. According to Bochter (1983), it can be calculated on the basis of soil data as follows:

$$\mathrm{MR} = 100\%\ (\mathrm{soil} < 2\ \mathrm{mm}) - \mathrm{sum}(\mathrm{org.\ matter}\ [\%] + \mathrm{soil\ carbonate\ CaCO_3} < 2\ \mathrm{mm}\ [\%])$$

Rendzic leptosols mark the first stage of organic soil formation. A successive increase of organic matter determines the folic O horizons (max. P6: 77%; mean P5 to P14: 69%) whereas the high quantities of mineral residues (max.: 67% in P26) characterize the OB and B horizons. Their loamy texture is a proof of in situ limestone weathering. As there is no texture change with soil depth, lithologic discontinuities indicating stratification of OB and B horizons are unlikely (see Fig. 5; Section 3.2.2).

3.2.2. Loess loam-like cambisols

The exotic cambisols (Ah–Bw–2(Bt)–2C) play an extraordinary role in the genesis of mineral solum. They are found on SE- to S-exposed slopes between 1980 and 2200 m, exclusively covered with the grass community *S.-Cs. sempervirentis*. Their distinct Bw horizons are of brown colour (10YR 4/4, 10YR 5/3, 7.5YR 4/4, 7.5YR 5/4). According to relief and substratum, two subtypes of cambisols can be classified.

The first type is found on coarse moraine debris and shows stratification of solum (noted by an Arabian numeral). The surface Bw horizon is rich in silt and mica and poor in carbonates (pH: 5.1 to 6.2) whereas the 2Bt horizon is mostly formed of residues due to an accelerated limestone solution in coarse substratum (Hüttl, 1999).

The second subtype fills karstic depressions and shows uniform solum (Ah–Bw–2R). In contact to the bedrock, only clay coatings occur. In most cases, the Ah horizon is eroded as a result of periglacial slope processes. Often, coatings or marbled patches

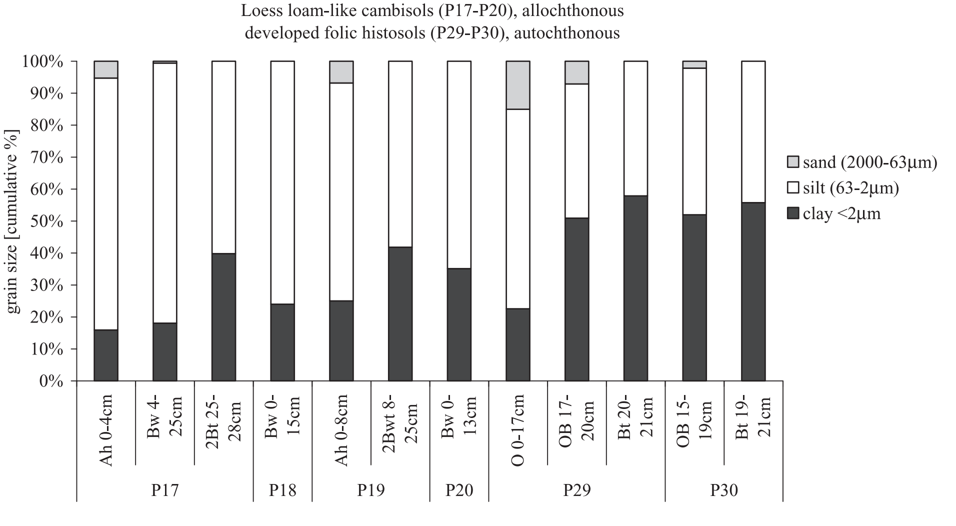


Fig. 5. Grain size distribution of selected cambisols and developed folic histosols.

indicate humus (org. matter: 8% to 20%) migration by soil water. Throughout the profile, visible mica prevails. In sinkholes, the thickness of B horizons reaches nearly 100 cm due to colluvial deposition. On moraine soil thickness varies from 10 to 40 cm. All B horizons show crumb to subangular structure and silty texture with changing amounts of clay (Fig. 5).

In profile P17 stratification is indicated by texture change from Bw horizons (clay–silt texture: 18.1% clay; 81.6% silt,) to 2Bt horizon (silt–clay texture: 39.8% clay; 60.4% silt). The boundary is typically abrupt and reveals the sequence loess/colluvium of residues.

In contrast, particle size of the developed folic histosols is quite different. The loam–clays of subsurface OB and Bt horizons show more than 50% of clay whereas the clay–silts of the surface O horizons prove the trapping of sand, silt, and mica. Additionally, mixed forms exist due to Holocene mass movements, denudation, and fluvial erosion (melt and rain water). Furthermore, migration and formation of clays in situ has to be considered (Birkeland et al., 1987; Solar, 1964; Thorn and Darmody, 1980).

3.3. Indications of late glacial loess deposition and eolian origin of cambisols

3.3.1. The purity of limestone

The analysis of 30 rock samples in the Zugspitzplatt area confirms the high solubility of Wetterstein limestone as a precondition for the genesis of alpine karst (Table 3).

In the study area, the postglacial rate of limestone solution is 28 cm/10,000 years (calculated from annual solutions rates, measured by Hüttl, 1999). Assuming constant solution rates, the calculated thickness of a residue layer built up over a time span of 10,000 years would be in the range of 0.97 cm. The calculation is based on the following variables: mean amount of acid insoluble residue (2%), mean dry bulk density of loam (taken as 1.5 g/cm^3) and of limestone (taken as 2.65 g/cm^3). Thus, the limestone solution rate is an answer to the clayey coatings and the Bt horizons of developed folic histosols but cannot explain the thickness of cambisols (mean: 30 cm on moraine debris; 25 cm on solid rock). As it would need 7 m of solid rock to derive 25 cm of mineral soil by solution, the formation of the huge cambic Bw horizons has to be associated to allochthonous material.

3.3.2. Mineral analysis of loess loam-like cambisols

The dominant constituent in selected cambisols is quartz followed by feldspar, mica, illite, and chlorite (Table 4a) that characterize loess and loess-like sediments (Pye, 1987; Dahms, 1991).

Especially the high amounts of chlorite (Table 4b) indicate its eolian origin because the residues of Wetterstein limestone are almost free of chlorite (Rast, 1993). Being weakly

Table 3
Amounts [%] of soluble components and residue of Wetterstein limestone

Wetterstein limestone (Trias, Ladin)	$CaCO_3$ [%]	$MgCO_3$ [%]	Residue [%]	Sum [%]
Zugspitzplatt[a] (according Hüttl, 1999)	95.6	2.4	1.9	99.9
Zugspitze summit (according Zöttl, 1950)	97.4	1.9	0.1	99.4
Wetterstein Mts. (according Zöttl, 1950)	98.8	1.0	0.16	100.0

[a] Means, calculated from 30 single rock samples ($n = 30$).

Table 4a
Relative abundance of clay-size (< 2 μm) minerals in selected soil horizons (based on X-ray diffraction peak height ratio)

Sample	Dominant	Major	Minor	Traces
P 17/1 Ah 0–4 cm	quartz	Chlorite Fs (plagioclase) illite or mica	–	Gypsum? amphibole hematite?
P 17/2 Bw 4–25 cm	quartz	Chlorite Fs (plagioclase) illite or mica	Dolomite	–
P 19/1 Ah 0–8 cm	quartz	Fs (plagioclase)	Chlorite illite or mica	Amphibole, Cm
P 19/2 Bwt 8–25 cm	quartz	Fs (plagioclase)	Chlorite illite or mica	Kaolinite amphibole hematite, Cm

Fs = feldspar; Cm = clay mineral (distance >10 Å); no differentiation between illite and mica.

Table 4b
Relative abundance of clay minerals (< 2 μm) in rel.-% (based on X-ray diffraction) in cambisols P17 and P19

Sample	Illite-rich mixed-layer-mineral	Illite (10 Å)	Kaolinite (7 Å)	Chlorite (7 Å)
17/1 Ah 0–4 cm	39	17	25	18
17/2 Bw 4–25 cm	9	43	15	33
17/3 2Bt 25–28 cm	60	7	16.5	16.5
P 19 Bwt 8–25 cm[a]	15	52[qu]	15	18

[a] qu-index = proof of expansive force of clay layers.

resistant to weathering, the chlorite is transformed into mica-like clay minerals (exemplified in P19).

Finally, the depth-distribution of heavy minerals in sample P17 confirms the influx of airborne dust in the Zugspitzplatt area (Table 5).

The bulk of heavy minerals is mica and chlorite-enriched and of pale yellowish colour. High percentages of garnet (weakly weathered) and epidote, as well as hornblende are remarkable (grain size fraction 0.1 to 0.25 mm). The opaque grains are rounded, often spherical diatoms occur. The Ah and 2Bw1 horizon of P 17 are poor in zircon, tourmaline and rutile but reach 44 grain-% (cumulative %) in the 2Bw2 horizon. This distribution and the diminishing grain size from Ah to 2Bw2 (grain size < 0.1 mm) give evidence for intense weathering; additionally single magnetite grains were found.

Garnet, epidote, staurolite, and disthene definitely originate from the metamorphic rocks whereas hornblende, micas, zircon, and quartz are common in the magmatic formations of Central Alps. Jurassic and Cretaceous marls, cherts, and marly limes are supposed to be a further source for clay minerals and also sedimentary quartz (see Section 3.5).

According to the glacial history of Zugspitzplatt, the local moraines of late- to post-glacial age can be divided into four stades (Hirtlreiter, 1992). The oldest is called Brünnl-Stade and is documented by a paleosol to Egesen-Stade of Younger Dryas (between 11,000 and 10,000 BP). As most of the cambisols are found within the moraines of Brünnl-Stade (1980 to 2070 m), the author relates the mass of loess deposition to Younger Dryas. Under the climatic conditions, at least a thin coverage of alpine grass vegetation had to be present to trap eolian dust. If the steep slopes had been completely bare of vegetation, the airborne dust would have been washed away in the course of either intense rainfalls or snowmelt events.

Table 5
Distribution of heavy minerals in cambisol/profile 17

Total spectrum of heavy minerals (amount of grains %); fraction 0.1 – 0.25 mm

	G	Z	T	R	Ap	St	Di	And	Hbl	Ep + Zo	Chlorite	Korn sum
Ah	19	1	3	0	3	13	2	0	31	25	3	134
2Bw1	27	1	4	1	4	9	0	0	33	21	–	300
2Bw2*	61	9	2	6	4	2	0	0	5	10	0	300

Rest spectrum without garnet (amount of grains %); percentages calculated to 100%; fraction 0.1 – 0.25 mm

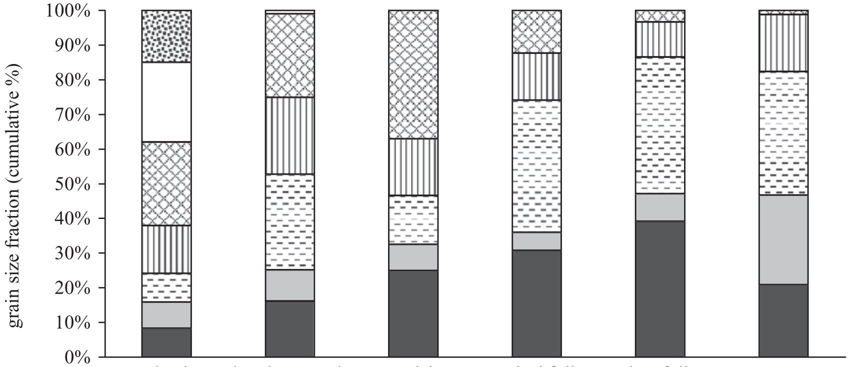
	Z	T	R	Ap	St	Di	And	Hbl	Ep + Zo	Chlorite	Korn sum
Ah	1	4	0	4	16	3	0	39	31	4	108
2Bw1	1	6	2	6	12	0	0	45	28	0	218
2Bw2*	24	4	16	11	5	0	0	14	26	0	116

G = garnet; Z = zircon (+ xenotime + monazite), T = tourmaline, R = rutile, Ap = apatite, St = staurolite, Di = disthene, And = andalusite, Hbl = hornblende, Ep + Zo = epidote + zoisite (+ clinozoisite + sometimes fine-grained aggregates of pumpellyite); *grain size < 0.1 mm.

3.4. Indications of contemporary eolian dust influx

3.4.1. Silt and visible mica in the surface horizons

The visible mica and the high quantities of silt in all the surface layers indicate that eolian dust input is still continuing. The mean grain size distribution reveals an increase of silt during soil genesis (Fig. 6).



	calcaric regosol, CA	humic regosol, A(h)C	rendzic leptosol, Ah	typical folic histosol, O	dev. folic histosol, O	cambisol, Ah
(630-2000µm) c sand	15	0	0	0	0	0
(200-630µm) m sand	23	1	0	0	0	0
(63-200µm) f sand	24	24,1	38,2	12,3	3,4	1,2
(20-63µm) c silt	13,8	22,1	16,8	13,6	10,3	16,5
(6,3-20µm) m silt	8,3	27,4	14,5	38	40,1	35,6
(2-6,3µm) f silt	7,5	9	7,8	5,1	8,1	25,9
<2µm clay	8,3	16,1	25,6	30,7	39,7	20,8

Fig. 6. Mean grain size distribution of the surface horizons of alpine and subnivale soils.

The main reason for this development is the vegetation cover that increases the surface roughness as a precondition for the dust trapping (Pye, 1987, 1992; Danin and Canor, 1991).

This is also proved by statistic calculation methods (linear regression): The silt sum [%] of each soil profile was correlated to its degree of vegetation cover [%] yielding in a significant correlation ($r = +0.89$; $R^2 = 0.79$; $n = 26$; $y = 0.9852 \times -3.089$). Especially the alpine grass communities, *C. firmae* and *S.-Cs. sempervirentis* are crucial in trapping silt and sand in the alpine karst of Zugspitzplatt.

The sand fraction (Fig. 6) almost totally consists of fine sand (200–63 μm) with exception of the calcaric regosols. Their total sand amount (mean: 62%) contains on an average 24% coarse, 23% medium, and 15% fine sand. This is a reference to mechanical weathering, because the residue of Wetterstein limestone reveals only 5% of medium and coarse sand in contrast to 20% of fine sand.

The calculation of the silt fractions up to the total silt content (100%) shows the following trends: dominance of coarse silt (63–20 μm) in the calcaric regosols (>50% silt of total silt), high quantities of medium and fine silt (20–2 μm) in the O and Ah layers of developed folic histosols and cambisols (75% of the total silt sum). This exemplifies a higher degree of weathering and/or a treatment of the coarse silt by rain or melt water.

3.4.2. Dust on snow patches

During ablation period (June to July), the surfaces of snow patches are discoloured by black to brown dust, accumulated during winter. In order to prove eolian origin, the grain size distribution of snow dust was compared to the one of limestone residue, gained by dissolution in 0.6*n* HCl (Table 6).

The results clearly confirm different genesis of material. The eolian origin of snow dust is proved by high quantities of coarse silt and fine sand whereas the silty loam of limestone residue is characterized by a striking lack of coarse silt.

The chemical analysis of snow dust samples shows a mixture of organic (66%) and mineral (34%) material with varying amount of calcareous material ($CaCO_3$ 10–35%). According to preliminary microscopic results (REM Leitz-AMR 1200; magnification 50 to

Table 6
Mean grain size distribution of snow dust and limestone residue (means, calculated from 10 single dust and rock samples; $n = 10$)

Grain size distribution (weight %)	Snow dust (2350 m, May 2002)	Residue of Wetterstein limestone
< 2 μm clay	0.6	24.4
2–6.3 μm fine silt	0.8	31.2
6.3–20 μm medium silt	11.1	19.5
20–63 μm coarse silt	50.2	0.0
63–200 μm fine sand	36.2	19.7
200–630 μm medium sand	0.8	4.6
630–2000 μm coarse sand	0.3	0.8
Sum silt	62.1	50.7
Sum sand	37.3	25.1
Silt/clay ratio	103.5	2.1
Texture	sandy silt	silty loam

1000 fold), fragments (pollen, leaves, plant hairs, etc.) of the following plants could be identified: *Pinus mugo*, *C. firmae*, *Dryas octopetala*, *Leontodontetum* sp., *Saxifraga paniculata*, *Aster bellidiastum*, *Aster alpinus*. Most probably they are of local origin (forested zones), transported by diurnal local valley winds. The mineral components (preliminary analysis by X-ray diffraction) indicate most significant eolian contribution to snow dust as allochthonous quartz, orthoclase, and biotite were identified among calcite and dolomite.

The snow dusts infiltrating along with the melt waterfront are very rich in nutrients and contain a lot of nitrogen (1.72% of total nitrogen N_t in dry residue), phosphorus (0.05 % P_t in dry residue), and also potassium. The snow sediments work as a fertilizer, and are very important for soil development in combination with the vegetation communities of the alpine grass and debris zones (Zöttl, 1950; Thorn and Darmody, 1980; Weisshaar et al., 1999).

3.5. Origin of dust and eolian dynamics

Three main sources of both late-glacial and recent dust erosion have to be considered:

– crystalline Central Alps
– Jurassic and Low Cretaceous outcrops adjacent to the study area
– surrounding Triassic chains of mountains

The Central Alps of Austria are situated to the south of the Northern Calcareous Alps and reach almost 3800 m. The zones above timberline are characterized by intense glaciation and periglacial dynamics leading to bare, loose, and mobile sediments. Especially fine-grained schists, phyllites and granitoid rocks provide an important source of silt and fine sand released by frost action, glacial grinding and periglacial slope processes (Latridou, 1988). Glacial outwash plains and alluvial debris fans are the most favourable surfaces for dust erosion (Smalley and Smalley, 1983).

The igneous rocks (e.g. granite, granitoid rocks, quartz phyllite) and metamorphic rocks (e.g. gneiss, schist, phyllite) contain various amounts of feldspar, mica, quartz and heavy minerals like epidote, hornblende, and garnet detected in the cambisols of Zugspitzplatt. These rocks are part of the Palaeozoic Phyllite- and Ötztal-Crystalline zone beyond the valley of river Inn (airline-distance to Zugspitzplatt 50 km) (see Fig. 1; Section 2).

Second sources for eolian dust are Jurassic (Lias) and Cretaceous rocks (Lower Cretaceous) adjacent to the western and southern rim of Wetterstein Mountains. These outcrops (1 km wide) were pressed upon the Triassic block during alpine tectogenesis. They consist of marls (Aptychus marl), coloured limestones, and interbedded radiolarites as sources for quartz and clay minerals (Miller, 1962). Furthermore, the surrounding mountains are a main source of organic constituents (leaves, humus) and calcareous dust (calcite, dolomite) transported by valley and western winds.

The eroded dust is transported by foehn winds under dry conditions or washed out by rains into the paleosurface acting as sediment trap. The foehn winds have high frequencies in spring and autumn, when the source areas in the Central Alps are at least partly free of snow and the mineral dust is not bound.

In summer 2002, first short-term measurements of dust deposition (31.05. to 07.09.2002) have started using plastic boxes (38 cm long, 17 cm wide, 20 cm deep) on five different monitoring sites. On the top of each dust trap, perforated and bristly plastic mats (646 cm^2 with 1-cm-long bristles) were installed in order to simulate the surface roughness of alpine grass communities. The boxes were installed almost plain to the surface of alpine soils or put into karst pits to guarantee that no upslope contamination by water could occur. Until more reliable data will be available, the following data will give a rough outline.

During the period of measurement (76 days) average dust rates of 0.29 g/day/m^2 (range: 0.02–1.2 g/day/m^2) are reported. A projection up to 1 year gives a calculated total dust input of 102 g/m^2/year (including the main components of organics, carbonates, and silicates) and forms an annual gross dust layer of 77 μm thickness (bulk density of dust 1.3 g/cm^3). The total mineral dust fraction (based on the acid insoluble silicate content only) reflects a mean deposition rate of 0.11 g/day/m^2 (range: 0.01–1.1 g/day/m^2). Thus, an annual mineral dust layer of 31-μm thickness may be built.

Water is the main distributor of eolian dust within the karst plateau. This is proved by the abundance of micas throughout the soil profiles and the author's observations that melt water draining from upslope adds dust to the snow surfaces.

4. Conclusions and discussion

The following processes characterize soil development in the alpine and subnivale zone of the Wetterstein Mts.:

(1) Limestone solution and deliming leading to mineral Bt horizons
(2) Accumulation of organic matter and development of organic alpine soils
(3) Late glacial eolian sedimentation and genesis of loess-loamy Bw horizons
(4) Recent dust influx and genesis of silt-enriched O and Ah horizons

Leptosols, regosols and folic histosols are the autochthonous soil types in the study area (processes 1 and 2) and refer to the acknowledged theory of soil genesis on limestone in the Northern Calcareous Alps (Kubiena, 1953; Mishra, 1982). The climax stage of "terra fusca" is not reached due to the purity of bedrock. Instead, developed folic histosols occur with thin Bt horizons proving that a considerable proportion of the soil parent material is derived from local limestone. A comparison of the clay/silt ratios between the autochthonous Bt horizons (1.3 to 1.4) and the Bw horizons of cambisols (0.2 to 0.7) confirms that texture is a significant indicator for their different origin.

The grain size distribution is among other factors a function of transport distance (Pye, 1987, 1992). Thus, the dominant fine and medium silt amounts and the rounded quartz grains in the surface layers are supposed to be the result of medium distance (50–200 km) dust transport (Stahr et al., 1989). Weathering and reworking by water is a further contributing process. The high proportions of coarse silt (20–63 μm), fine and medium sand of snow dust samples however indicate local transport (< 50 km).

The most decisive indicator of the source of sediment is the heavy mineral spectrum. It proves dust transport from crystalline rock formations of Central Alps (Ötztal-Crystalline formation). Similar results exist from soils in the forested zone (Schönhals and Poetsch, 1976; Biermayer and Rehfuess, 1985; Dill and Zech, 1980). Additionally, the Jurassic and Cretaceous outcrops nearby the Zugspitzplatt are a source of sedimentary quartz and clay minerals.

The effects of eolian dust on soil genesis in high-mountainous karst are manifold. The input of local dust (calcareous and organic material) is significant in buffering acidity, which is generated by plant growth on folic horizons and by leaching. The natural liming generates a loose crumble humus structure of mollic nature with high base saturation (>50%). Thus, extremely acid humus layers are astonishingly rare in spite of the cold and wet conditions. An extraordinary role plays wind blown organic material being the main source of humus and nutrients (N, P and K) for initial soil genesis in the subnivale zone.

The cambisols of Wetterstein Mts. have been the precondition for development of the thermophile grass community *S.-Cs. sempervirentis* demanding productive soils. Due to soil chemistry, texture, and depth, *S.-Cs. sempervirentis* is related to cambisols only. Acidophile plants associations with *Carex ferruginea*, *Huperzia selago*, *Rhododendron ferrugineum* indicating higher soil acidity, increase the diversity of alpine tundra vegetation. The effect is a soil-fixing, dense vegetation cover (>75%) that again is favourable in trapping present-day eolian dust (process 4) on south facing slopes.

The spatial distribution of loess loam-like cambisols within the moraines of Brünnl-Stade (Egesen, Younger Dryas, 11,000–10,000 years BP) justifies the relation to late glacial loess dynamics. This relative chronology is conform to most of the results on alpine loess respecting the transition Late Glacial/Holocene as the most productive time (Mahaney et al., 1996; Bockheim and Koerner, 1997; Weisshaar et al., 1999; Mailänder and Veit, 2001).

A rough estimation of the importance of eolian dust in the study area supports the calculation of potential mineral layers during the last 10,000 years (see Section 3.5). Using the somewhat unrealistic assumptions of no loss of material by erosion, weathering, or leaching, the calculated residue layer is within the range of 1 cm/10,000 years (residues) and 31 cm/10,000 years (deposited mineral dust). These proportions of residue and dust clearly indicate the contribution of eolian dust in periglacial limestone settings in the Northern Calcareous Alps.

A general comparison to other alpine loess or corresponding soils with regard to particle size and geochemistry is difficult due to the manifold environmental and eolian conditions (e.g. geology, vegetation, wind systems etc.). This is confirmed by numerous American studies (Colorado Front Range: Thorn and Darmody, 1980, 1985; Litaor, 1987; Wind River Range, Wyoming: Munn and Spackman, 1990; Dahms and Rawlins, 1996; Bockheim and Koerner, 1997/Uinta Mts., Utah). Moreover, these study areas are mostly characterized by calcareous dust in soils of crystalline bedrock.

However, the silicate-enriched soils found in alpine karst plateaus of the Eastern Calcareous Alps (Solar, 1964; Frisch et al., 2000) show parallels with regard to soil chemistry, stratification, grain size distribution and geochemistry. Nevertheless, the genesis of the B horizons is quite different to that of Zugspitzplatt as the silicates and heavy minerals are derived from residues of crystalline fluvial gravels (so-called "Augensteine") that were deposited on top of the Northern Calcareous Alps during Late Oligocene to Early Miocene. As they have not been conserved in the western parts of the

Northern Calcareous Alps due to steep relief conditions, this source of crystalline input is not relevant to the soils on Zugspitzplatt.

Summing up the main items of this paper, the source substratum of loess loam-like cambisols of Wetterstein Mountains has been originated of late glacial loess from crystalline Central Alps. However, the influx of silicate-enriched dust into soils above timberline is not only a "paleo-" but also an ongoing process and the major component of mineral soil genesis in high-mountainous karst.

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