

Joint analysis of geological map units and topography to support soil survey - lessons from a case study in South Tyrol OR From geological to soil parent material maps - a random forest-supported analysis of geological map units and topography in South Tyrol

Fabian E. Gruber^{a,*}, Jasmin Baruck^a, Clemens Geitner^a

^a*Institute of Geography, University of Innsbruck, Innrain 52f, 6020 Innsbruck, Austria*

Abstract

Keywords:

1. Introduction

general introduction. Geologic maps have always been an important aid in soil survey as parent material is a decisive factor in soil formation (Jenny, 1941). The importance of this relationship is highlighted by the fact that, vice versa, soil maps have themselves been applied to support and improve geologic mapping (Brevik and Miller, 2015).

Geologic maps have always been an important aid in soil survey as parent material is a decisive factor in soil formation (Jenny, 1941). The importance of this relationship is highlighted by the fact that, vice versa, soil maps have themselves been applied to support and improve geologic mapping (Brevik and Miller, 2015). Providing both the physical structure and the chemical composition of the mineral constituents, parent material plays a fundamental role regarding the direction as well as speed of soil evolution. This is particularly the case in young soils (e.g. Schaetzl et al. (2000)) such as those predominantly found in the Alps (Geitner et al., 2017). Thus, in order to understand the spatial pattern of soils in the Alps, it is essential to identify

*Corresponding author

Email address: `Fabian.Grubert@uibk.ac.at` (Fabian E. Gruber)

the types and origins of parent materials, which are, at least in the lower and medium elevations of the Alpine environment, dominated by quaternary unconsolidated sediments. These deposits vary considerably in thickness; they are often multi-layered and exposed to recent morphodynamics, all of which control soil horizon development and properties (Phillips and Lorz, 2008). In this context, it is indicated to include characteristics of the subsolum as often as possible, mainly in order to make soil information more suitable for a wide range of environmental issues, as discussed in detail by Juilleret et al. (2016). Consequently, geological maps at various scales have been used as an environmental variable in digital soil mapping (DSM), representing the soil forming factor parent material, or simply 'p'. In their study which presents the 'scorpan' framework of inferring soil information, McBratney et al. (2003) present a table of studies applying DSM, which also indicates in which of these studies the parent material was involved as an independent variable. How this important variable is classified, however, will vary greatly depending on the the available data, the soil classification system used, the specific mapping guidelines applied, and most importantly the particular geologic and geomorphological setting of the investigated area. In its guidelines for soil description, the Food and Agriculture Organization of the United Nations promotes a hierarchical system for describing lithologies that constitute the soil parent material, based on the major classes igneous rock, metamorphic rock, consolidated and unconsolidated sedimentary rock (FAO, 2006). KA5? While the lithologies regarding bedrock as parent material are similar to the types in the classification system used by the surveyors employed by the Forestry service, the latter system is closely adapted to the Alpine environment. Specifically, the major class of unconsolidated sedimentary rocks has a far greater number of types in order to satisfy the demands posed by the diversity of the glacial, but also the more recent deposits, driven mainly by the high relief present in Alpine regions.

While such an adaptation of the classes and types of soil parent material to the given circumstances is certainly necessary, communication between soil scientists regarding soil parent materials and comparability is hindered by the multitude of classifications. Juilleret et al. (2016), who stress the importance of describing the subsolum in soil survey, propose a morphogenetic procedure for characterising and classifying subsolum material applying a structure similar to that of the WRB.

Herbst zitat fr bedeutung der Schrfte der Geologischen Karte fr die genauigkeit von DSM??

55 A number of studies have compared the information from soil surveys
with geologic maps. HERE SOME MORE LITERATURE, like Miller and
Lee Burras (2015), Juilleret(2012), Brevik and Miller (2015). While most of
the previously mentioned studies analyse the possibility of using soil survey
information for mapping surficial geology, the aim of the presented study is
60 to highlight those geologic units of the study area where the soil parent ma-
terial cannot be simply derived from the detailed geologic map. McBratney
et al. (2003) list some examples of DSM studies which use geologic maps as
environmental variables.

Situation in the Alps bezüglich boden und geologie wäre auch noch in-
65 teressant

A second, immensely important soil forming factor is topography or relief.
It is considered in traditional soil survey, for instance by mapping landscape
position and local slope and curvature (FAO, 2006), and also DSM, where
the representing variables implemented in a given model can be chosen from
70 a wide set of available parameters. Examples of such terrain parameters can
be found, amongst others, in Böhner and Antonić (2009), Gallant and Wilson
(2000) and Olaya (2009) . Regarding the geomorphometric characterisation
of geologic or soil parent material units, a number of considerations have to
be taken into account when choosing which parameter groups to investigate.
75 While regional parameters well describe the, hydrologically relevant, relative
position in the landscape, they, as well as absolute and relative height-related
parameters, are strongly correlated to the underlying geological structure of
a given region. Local parameters such as slope and curvature are often used
to infer soil properties and give insight into local dynamics, but may also
80 vary strongly within a map unit. To characterise parent material units,
especially with regard to topographic, and as a result, soil, variability, an in-
termediate terrain parameter describing a unit's land surface is of particular
interest. Researchers have long investigated ways to quantify the roughness
or ruggedness of terrain, from the analysis of field data and topographic maps
85 to computing roughness indices on raster grids. Geology, geomorphology as
well as habitat modelling and wildlife management have been the main sci-
entific research areas in which such investigations were performed on land
surfaces. Hobson (1972) presented three different roughness values and ap-
plied them to field measurements, correlating them to rock type. In another
90 early study aimed at quantifying roughness, Beasom et al. (1983) presented
the land surface ruggedness index, which is based on the total length of con-
tour lines per area. Similarly analysing topographic maps, Nellemann and

Thomsen (1994) describe the calculation of a terrain ruggedness index based on the variability of contour lines along transects, which they correlate with caribou forage availability. Regarding field methods, they calculate micro-topographic diversity by analysing the horizontal distance of a chain laid on the ground in their study plots. Riley et al. (1999) proposed the topographic ruggedness index (TRI), which compares the elevation of a central pixel to the elevations of cells within a given search window. In an attempt to decorrelate roughness from slope, Sappington et al. (2007) expanded on the work of Hobson (1972) to introduce vector ruggedness measure (VRM), which is calculated based on the orientation of vectors normal to the surface in a given area. (Grohmann et al., 2010) analysed several roughness measures at different resolutions and window sizes with regard to their ability to depict terrain features. They highlight the ability of VRM to detect fine-scale roughness features and attribute low roughness values to steep but smooth slopes, but also acknowledge its inability to delimit slope breaks and identify regional relief. The Melton ruggedness index, which relates the elevation difference of a basin to the drainage area, was applied by Marchi and Dalla Fontana (2005) to investigate sediment transport, however compared to VRM it is more of a measure of general relief than roughness. Similar to VRM, roughness measures based on eigenvalue ratios of an orientation matrix have been used in geology to describe land surfaces, especially bedrock fabric. Coblenz et al. (2014) combined such a roughness measures with parameters representing the drainage network of the investigated geologic units to create terrain characterisation types to distinguish various lithologies, with emphasis on discriminating soft and hard rock areas.

Intention and aims. The objective of this study is to evaluate how to make best use of available geologic and topographic information (with emphasis on terrain roughness measures) for soils survey. By applying random forest classification and feature selection, we investigate which terrain parameters, with emphasis on roughness measures, are best suited to produce a parent material map based on an available geological maps as well as topography. Additionally, the same method is applied to distinguish terrain parameters that, for each soil parent material class, best separate those profile site points that are correctly classified in the geological map from those of the same class that are misclassified. Based on this analysis and a similar investigation into characteristic terrain parameters of the geological map units, each of these is characterised with regard to topography and soil and we highlight those

130 units were there is often dissent between soil parent material as mapped by
the soil surveyor and the geologic units mapped by geologists. The main aim
of the random forest classification is not necessarily to improve the geological
map with regard to its application as a parent material map, but foremost to
135 identify the topographic characteristics of the parent material units in order
to facilitate future, more detailed surveys.

2. Study area and data

2.1. General description

The study area includes the wide vale of Eppan-Kaltern, the Überetsch,
located just south-west of Bozen in the Autonomous Province of Bolzano
140 - South Tyrol, and extends in the north to the debris fan of Andrian in
the Etsch Valley and the adjacent hill slope on the orographic right of the
Etsch River. The western border of the study area is the steep slope of the
Mendola-Roèn-Ridge, whereas the eastern border of the Überetsch as well as
the study area is represented by the the Mitterberg, a ridge of Permian Vul-
145 canites from which steep slopes descend to the Etsch Valley (approx. 200 m
a.s.l.). The Kalterer Lake represents the southern limits of the investigated
area. The land use of the paleovalley and its debris cones as well as the
Etsch valley is dominantly apple orchards and vineyards, whereas the slope
of the Mendola-Roèn-Ridge and the hilly outcrops of Vulcanites are covered
150 by forests. Pastures are located mainly on till covering the flat areas of the
Mendola-Roèn-Ridge.

2.2. Surficial Geology

A detailed description of the geologic situation can be found in the com-
mentary to the new geologic map of Eppan (Avanzini et al., 2006). The
155 paleovalley of Überetsch is described by Scholz et al. (2005) as a complex
system of gravelly lateral moraines and large kame terraces, the result of the
'Kaltern lobe', a Pleniglacial tongue of the Etsch valley glacier. Additionally,
eroded remainders of debris flows that were deposited against the recessing
glacier can be found along the slopes of the Mendola-Roèn-Ridge, as well as
160 recent debris flow deposits, often composed of mainly limestone and dolomite
fragment. The vale bottom itself is filled with Pleistocene sediments and con-
tains a number of valleys carved into the gravels by fossil melt-water. At the
eastern and western borders of the Pleistocene sediments, outcrops of Per-
mian igneous Rhyolite and Lapilli-Tuff are responsible for a hilly relief, most

165 prominently at the eastern border of the study area where the Überetsch is
separated from the Etsch valley by a steep slope down from the Mitterberg
with an elevation difference of approximately 400 m. The steep slopes of the
Mendola-Roèn-Ridge are dominated by various Dolomite units, with inter-
mittent layers of sand and siltstones. Except for the very steep Dolomite
170 walls of the ridge, the rarely occurring outcrops of these formations are sur-
rounded and mostly covered by Pleistocene and Holocene slope debris, and
in locally flatter areas by till.

The study area comprises two map sheets of the new geologic map of Italy,
sheet Eppan, which covers the northern and major part of the area, as well as
175 sheet Mezzo-Lombardo in the southern part. The sheets were published at a
scale of 1 : 50,000 in 2007 and 2012, respectively. Mapping was performed at a
scale of 1 : 10,000, this information was kindly provided by the Department of
Geology and Building Material Tests of the Autonomous Province Bolzano,
South Tyrol, in shapefile format and used for the analysis performed in this
180 study.

As means for simplification of the analysis and data harmonisation, the
geologic map units were generalised to the 16 SGUs described in Table 1, that
allow for comparison with the parent material units described and identified
by the soil surveyors in the field.

SGU	Abbrev.	short description	% area
alluvial deposits	AD	Holocene and Pleistocene deposits of silt, sand and gravels	14.9
coarse blocky debris	CBD	Holocene and Pleistocene blocky deposits of mass movements	1.8
colluvial deposits	CD	footslope deposits	2.4
calcareous sedimentary rock	CSR	limestones and dolomites	8.4
debris cones	DC	Holocene conic deposits from debris flows and torrents	12.7
glacio- and lacustrine deposits	GLD	(fine) sand deposits (with dropstones)	2.5
ice-marginal sediments	IMS	clast-supported gravels	0.2
intermediate sedimentary rock	ISR	silt- and sandstones	0.2
landslide deposits	LD	large landslide deposits	1.2
mire deposits	MrD	Holocene and Pleistocene silt and peat deposits	3.3
mixed deposits	MxD	Pleistocene deposits from debris flows, torrents and avalanches	2.1
siliceous bedrock	SB	rhyolite and rhyodazite tuffs and ignimbrites	13.0
slope debris	SD	Holocene and Pleistocene debris on slopes	10.3
siliceous sedimentary rock	SSR	sandstones and siltstones	1.1
till in general	TG	undifferentiated glacial sediment	25.9

Table 1: Table of the generalised parent material units with abbreviations and short description. Additionally, the proportion of the study area covered by each unit is given. Anthropogenic deposits and water bodies are not included in the analysis.

185 2.3. Soils

Overview of soils of the study area.

2.3.1. soil classification

The soil classification scheme applied in this study is the Austrian system (Nestroy et al., 2011), as most of the soil profile descriptions available for
190 this study apply this system and it is generally recommendable to use local systems for large-scale mapping. Additionally, not all available soil profile data, especially those from points investigated only with augering, included sufficient information for deriving the reference soil group according to the World Reference Base for soil resources (IUSS Working Group WRB, 2015).
195 Table 2 gives an overview of which reference soil groups are correlated to the relevant soil types in the Austrian classification. Classification of the soil profiles was performed at the subtype level, a basic overview of the Austrian soil classification system can be found in Baruck et al. (2016).

data base 1: soil survey of agricultural areas in the Überetsch/Oltradige region. From 1993-1995 a soil survey of the farmlands in the region Überetsch
200 was conducted (Thalheimer, 2006). Soil types were classified according to Soil Taxonomy, resulting in a soil map with 18 different soil series. 58 detailed soil pit descriptions were incorporated into the presented study, all located either in vineyards or apple orchards. Using the horizon descriptions, chemical
205 properties as well as photographs of the pit face, theses soil profiles were reclassified applying the Austrian System.

data base 2: soil survey 'ReBo - Terrain Classification of ALS Data to support Digital Soil Mapping'. During this project which was funded by the Autonomous Province Bolzano - South Tyrol and had the aim to investi-
210 gate optimal cooperation between soil survey and terrain classification, 55 soil pit profiles were described in the presented studies area of interest. Soil classification was performed following Kilian (2015).

data base 3: data base of the Forestry Service of the Autonomous Province Bolzano - South Tyrol. 42 pit descriptions from the Forestry Service data set

215 *data base 4.* 227 auger observations (WLM)

2.4. Digital elevation data

3. Methods

3.1. General workflow

In a first step we analyse how well the geologic units of the high reso-
220 lution geologic map correspond to the parent material identified by the soil

soil type	possible WRB group	short description	soil class
Grobmaterial-Rohboden	Leptosol, Regosol, Histosol	same as Feinmaterial-Rohboden but with more than 40 V.-% coarse fraction	Terrestrische Rohböden
Feinmaterial-Rohboden	Leptosol, Regosol, Histosol, Arenosol	only initial soil formation (Ai horizon) on parent material with less than 40 V.-% coarse fraction.	Terrestrische Rohböden
Rendzina	Leptosols, Histosols	with organic horizon on calcareous bedrock.	Terrestrische Humusböden
Kalklehm-Rendzina	Leptosol	soils with a loamy organic horizon on calcareous bedrock.	Terrestrische Humusböden
Pararendzina	Leptosol, Regosol, Umbrisol, Histosol	with organic horizon on carbonatic siliceous bedrock.	Terrestrische Humusböden
Ranker	Leptosol, Regosol, Umbrisol	with organic horizon on siliceous bedrock.	Terrestrische Humusböden
Braunerde	Cambisol, Fluvisol, Luvisol, Umbrisol, Regosol	with brown B-horizon owing to weathering and re-formation of clay minerals.	Braunerden
Parabraunerde	Luvisol, Albiluvisol, Cambisol	with eluvial horizon over clay-enriched B-horizon.	Braunerden
Semipodsol	Podzol, Regosol	characterized by moderate podzolization.	Podsole
Kalkbraunlehm	Cambisol, Luvisol	with a yellow- to redbrown cohesive B-horizon on calcareous bedrock, often fossil soils.	Kalklehme
Farb-Substratboden	Regosol, Alisol, Ferralsol, Luvisol, Nitisol, Arenosol	strong influence of color of parent material, overprinting horizon differentiation.	Substratböden
Textur-Substratboden	Regosol, Arenosol, Vertisol	strong influence of texture of parent material, overprinting horizon differentiation.	Substratböden
Kolluvisol	Anthrosol	developed from fine soil material relocated by (often human-induced) erosion.	Umgelagerte Böden
Rigolboden	Anthrosol	influenced by deep, homogenizing human cultivation.	Umgelagerte Böden
Haftnsse-Pseudogley	Stagnosol, Planosol	influenced by shallow, capillary stagnation phases.	Pseudogleye

Table 2: Table relating the Austrian soil types to WRB reference groups along with a simplified description, based on Kilian (2015).

surveyor, thus evaluating the performance and reliability of geologic maps to support soil survey in South Tyrol. This requires generalisation of the geologic units into surficial geology units (SGUs) that can be compared to the parent material units used in the soil (or forestry) surveys. The result
225 is a confusion matrix that shows to which extent geologic units are in accordance with the parent material mapped by the surveyor. We highlight those units that are often confused or show overlap, and which should consequently be surveyed with greater detail and in consideration of relevant topographic information.

230 The next step is to perform a morphometric characterisation of the geological units. To better understand the topographic characteristics of a geologic unit, a data mining approach using random forest classification is performed. By applying a forward stepwise feature selection as well as the analysis of the parameter 'mean decrease accuracy', which quantifies the importance of a variable in the prediction procedure, we then identify which
235 terrain parameters best separate parent materials units as well as geological map units and discuss how they can be related to and interpreted with regard to soil formation and the distribution of soil units. This data mining

procedure was applied to several groups of terrain parameters. One group
240 included all computed terrain parameters, while other groups focus either on
local or regional terrain parameters, or parameters related to surface rough-
ness. An emphasis is set on the roughness measures, as they are deemed best
suited to enhance the geologic map, as the geological units already implicitly
contain information with regard to regional and local terrain parameters. In
245 this study, this analysis is presented only for the area-wise most relevant ge-
ologic units, and the focus is on separating those units which share common
borders.

The connection between the two important soil forming factors, parent
material and topography, on the one hand, and soil as the result of theses
250 factors on the other, is then investigated by analysing the diversity and dis-
tribution of soils for each geologic unit. This is performed from two points of
view: the soil type distribution is done for profile sites per geologic unit, but
also per parent material unit as attributed by the soil surveyor. This gives
insight into how the surveyors' soil landscape model relates specific parent
255 material units to specific soil types, especially when applying a morphologic-
genetic classification such as the Austrian soil classification (Nestroy et al.,
2011). The synthesis of this information then leads to a geologic-topographic
characterisation (GTC) that describes each geologic unit.

3.2. Terrain parameters with emphasis on roughness measures

260 3.2.1. Local and regional terrain parameters

3.2.2. surface roughness-related terrain parameters

ws=window size

Topographic roughness index (TRI). (Riley et al., 1999)

Terrain texture.

265 Vector-based roughness measures (VRM and vectorruggedness).

Landform diversity.

3.3. Random Forest classification

Random Forest classifications was performed for several applications in
the course of this study:

- 270 • To expand the geological map to a parent material map by model parent material based on the profile site descriptions, the topography of their location and the information provided by the new geologic map with its detailed information with regard to surficial geology
- 275 • To investigate which terrain parameters are best suited to discriminate for each SGU those points that were correctly classified to a parent material class by the geological map from those where this information differed to the parent material identified by the field surveyors.
- 280 • To analyse which terrain parameters best distinguish between adjacent soil parent material classes as identified by the soil surveyors during field survey
- To identify the terrain parameters that best separate and consequently characterise the SGUs as described by the geological map

285 Considering the confusion matrices and the accuracy measures calculated, this was performed as if the field observations described by the surveyors had been planned to validate the use of the geologic map as a map of soil parent material.

290 We can use the information on the confusion between certain classes implicitly contained in the sample point data, as well as the relative height information contained in the geologic map units. Consequently, roughness measure are sufficient to improve the parent material map.

4. Results and discussion

4.1. Comparison of soil parent material at soil profile sites with geologic map units

A comparison of the soil parent material class identified in the field survey and the SGU from the geological map for the same position shows that while these match for 186 of the profile sites, leading to an overall accuracy, or correct classification rate, of 49%, there is a high number of misclassifications. A first view at the confusion matrix (Table 3) indicates that a considerable amount of these misclassifications involve the classes till and slope deposits.

	AD	CBD	CD	CSR	DC	GLD	IMS	ISR	LD	MrD	MxD	SB	SD	SSR	TG
AD	7	0	0	0	0	1	0	0	0	0	0	0	1	0	3
CBD	0	4	0	0	0	0	0	0	0	0	0	0	8	0	2
CD	0	0	3	0	0	0	0	1	0	0	0	0	1	0	0
CSR	0	0	1	2	0	0	0	7	0	0	1	0	13	0	12
DC	4	0	3	0	5	0	0	2	0	0	0	0	20	0	2
GLD	0	0	0	0	0	5	0	0	0	0	0	0	0	0	2
IMS	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
ISR	0	0	0	0	0	0	0	0	0	0	0	0	3	0	0
LD	0	1	0	0	0	0	0	0	0	0	0	2	0	0	0
MrD	0	0	0	0	0	2	0	0	0	0	0	0	0	0	1
MxD	0	0	1	0	0	0	0	0	0	0	0	0	6	0	1
SB	0	1	1	0	0	2	0	1	0	0	2	14	3	1	24
SD	0	3	0	2	1	0	0	4	0	0	0	4	55	0	15
SSR	0	0	0	0	0	0	0	2	0	0	1	0	3	3	1
TG	1	0	0	1	0	1	0	3	0	1	5	0	9	0	88

Table 3: Tabular comparison of parent material geounits as observed by soil surveyor (columns) and in the geologic map (rows).

4.2. Random forest classification of parent material based on geologic map data and topography

Regional-scale terrain parameters and relative elevations were not identified as important predictor variables. One reason for this is that this information is implicitly accounted for by the geologic map, as the various SGU

classes are also closely linked to certain relative elevations, especially the vertical distance to channel base level, due to overall geologic structure of the study area. Roughness: TRI can be strongly related to slope.

4.3. *Geologic-topographic characterisation of the predominant SGUs*

310 Through synthesis of results of the comparison of the soil point data and the geologic map, the random forest analysis of terrain parameters as well as the distribution of soil types in the study area, a geologic-topographic characterisation of the SGUs is performed. Only those units with substantial areal extent and sufficient soil profile points are described in detail.

315 4.3.1. *Alluvial deposits*

The SGU alluvial deposits occupies 16.3 km, amounting to 14.9 % of the study area. It incorporates alluvial deposits in the paleovalley but also in the Etsch valley, with soil profile points limited to the former. The alluvial deposits share very long borders with the SGUs till in general, debris
320 cones, mire deposits and colluvial deposits, due to its bifurcated vertical transection of the study area. Long borders can therefore also be found with the units glaciolacustrine deposits, mixed deposits, slope debris and till in general. There is agreement between the geological map and the soil profile description in 7 (54%) of the 13 profiles for which the soil surveyors identified
325 this SGU as the soil parent material. Some confusion with the SGUs debris cones and till in general can be observed, the former from the viewpoint of producer's reliability and the latter as an error of commission.

An investigation of the soil profile sites that were identified by surveyors as having alluvial deposits as parent material but are located on a different
330 unit on the geological map, shows that these are characterized by consistently higher fischer k values, whereas slope shows less clear thresholds. Addressing the confusion of alluvial deposits with till, the random forest investigation shows the besides obvious channel-level related terrain parameters, which well separate the units, convexity contributes strongly to distinguish-
335 ing between alluvial deposits and till on the geologic map, with the former characterised by lower values concentrating around 0.42. It must however be considered that the SGU in the study area also incorporates parts of the wide Etsch valley floor, whereas the soil profile points are mostly situated in the paleovalley of the Überetsch. The same investigation, but performed
340 from the viewpoint of the surveyor (i.e. using the field data points and their

parent material information), identifies a very local (small window size) version of the TRI as best suited to distinguish between the two parent material groups, with AD interestingly characterised by higher values indicating higher ruggedness. The separation of the profile sites of the parent material classes AD and debris cones, the second most common confusion for AD, is less clear than for AD and TG. High resolution roughness values are less important than in the case of till, with texture computed with 50 m grid cell size being the most decisive parameter. A comparison of the geological map units' topography also highlights the importance of this roughness parameter, which is surpassed only the regional terrain parameter catchment slope, computed at the same low DTM resolution. The choice of these parameters seem closely linked to the transitional landscape position of debris cones, situated between the steep slopes of the Mendola-Roèn-Ridge and the flatter valley bottoms.

Of the 11 soil profile or auger points located on areas covered by alluvial deposits according to the reclassified geological map, the soil type Braunerde is predominant, with some occasional anthrosols. These brown soils are to be expected as the more or less pronounced stability of the flat alluvial deposits have allowed a certain degree of pedogenetic processes to occur. The Rigosols on the other hand are typical for the vineyards and orchards commonly found on alluvial deposits in the region, where landscape as well as soil have seen strong anthropogenic influence. The distribution of the soil types of the profile points identified to have alluvial deposits as parent material by the surveyors is comparable regarding the dominance of brown soils. Additionally, the soil types Kalklehm-Rendzina and Pararendzina were encountered, both characterised by organic horizons on more or less unweathered parent material, indicating that alluvial deposits were also identified at places lacking the stable conditions necessary for the development of a B-horizon as presented by the alluvial deposits unit of the geological map. So while the alluvial deposits unit is characterised on the geological map by the lowest mean slope aside from mire deposits, the soil data as well as the topographic analysis, indicate it is nevertheless necessary for future surveys to also investigate the less typical, rougher and sloping areas at the border or in proximity of alluvial deposit units.

4.3.2. *Siliceous bedrock*

The SGU siliceous bedrock in the study area is characterised by outcrops of rhyolitic ignimbrite in the Überetsch paleovalley, for instance forming the

Mitterberg which separates the paleovalley from the current Etsch valley. It represents 13 % of the study area, and shares a long border with the SGU till in general, but also the units coarse blocky debris and debris cones. Shorter borders exist with almost all other SGU, especially mixed deposits and slope deposits. Regarding the comparison of the unit on the geological map with the parent material as reported by the surveyors, there is an interesting discrepancy between user's accuracy and producer's reliability when attempting the use the geological map as a parent material map. While the parent material of only 14 of the 49 profile sites located on siliceous bedrock according to the geological map was identified as siliceous bedrock by the surveyors, 70 % of all soil pits with this parent material were actually on the correct unit of the geological map. This means that when investigating soils on siliceous bedrock, the probability that they are encountered in the unit SB is higher than for other units, however it is similarly probable to encounter other parent materials in this unit. The greatest confusion occurred with the unit till in general, which was found to be the parent material of almost every second soil profile located on the SGU siliceous bedrock. Further parent materials identified on the SB unit include mixed and slope deposits, as well as glaciolacustrine deposits (Table 3). Confusion with slope debris or mixed deposits is understandable due to the often fuzzy transition from weathered bedrock to slope debris, or the fact that mixed deposits may very well contain almost only siliceous material from bedrock units at higher elevations in the catchment or underneath the debris cover layer. Additionally, the soils resulting from such parent material must not necessarily be very different to that on siliceous bedrock. Till, as a parent material, is a different case, as the material may be derived from catchments with a very different geology and the grain distribution is not comparable to that of slope debris or siliceous bedrock. When evaluating the misclassification of the parent materials till and siliceous bedrock, it is essential to consider different mapping procedures. Furthermore, the parent material layer must not necessarily be very thick. So, whereas the soil surveyor is particularly interested in the parent material, i.e. the material which through pedogenic processes and weathering slowly becomes the solum, no matter the thickness of this specific layer, the geologist's main concern is the underlying material, and may consider cover layers of till only once their thickness reaches a certain threshold, for instance 1 m as conveyed by the surveyors of the geologic survey of South Tyrol.

The random forest-based analysis of how to topographically separate the profile sites with siliceous bedrock as parent material that are situated on

the SB unit of the geological map from those with the same parent material but on different SGUs showed that the latter group is situated in areas with lower convexity (computed with the 10 m DTM). Regarding roughness parameters, the vector ruggedness measure based on the 2.5 m grid and a large search window of approx. 130 m performed best. Soil profiles that evolved from siliceous bedrock and are also located on the SGU SB are characterised by higher vector ruggedness values. Given the strong confusion with the unit till in general, as well as the fact the these two units share a long border, it is of interest to examine the topographical differences between points that are attributed to one of these two parent material units. The TRI at a window size of approx. 100 m leads the terrain parameters with a 5-fold cross-validated classification error of approx. 15 %. The minimum curvature based on the 10 m grid performs best from the group of local terrain parameters. In general, soil profile sites with SB as parent material are consequently characterised by rougher topography (increased TRI values) and slightly positive minimal curvature values when compared with data points were till was identified as parent material. This is well in line with increased distribution of this parent material on convex, ridge-like structures in the SGU siliceous bedrock. As Table 3 shows, confusion with slope deposits is present from both the user's and the producer's point of view. The random forest-based data mining shows that, regarding the parent material as indicated by the surveyors, the terrain parameters that are most characteristic of the difference between the two units are based on landform diversity. In the case of SB and SD, the patch density of the geomorphon-based landform map computed with a lookout distance of 7.5 m helped separate the two parent units due to the latter groups lower values, implying that areas of slope deposits have a slightly more homogeneous landform distribution, in the specific case large polygons of the landform slope, which seem to be a good indicator for slope deposits. Furthermore, the same TRI mentioned when separating SB and TG can also be a very useful addition to the parameter set when distinguishing SB from SD.

4.3.3. Till in general

The unit till in general comprises lodgement and subglacial till, as well as other, undifferentiated till materials. It is found in the paleovalley as well as on flat terraces of the the Mendola-Roèn-Ridge. Covering more than 25 % of the study area, it is the most common SGU on the geological map, sharing borders with every single SGU, the longest, each with a length of at least

30 km, being those with the SGUs alluvial deposits, siliceous bedrock and slope deposits. According to the geologic map, 109 of the soil data points are located on the SGU till in general, accounting for 29% of the points. In 88 of these locations, the surveyors agreed with regard to the parent material being till, leading to a user's accuracy of 80%. The majority of the other soil data points on this SGU were attributed the parent materials slope deposits or mixed deposits, with some intermediary sedimentary rocks also identified as parent material. While the user's accuracy for till is the best amongst the SGUs, the producer's reliability is not comparable, as the surveyors also identified till as the parent material at 63 further locations on different SGUs. The relative majority of these locations are found on the unit siliceous bedrock, already discussed above, but a large number of soil profiles with this parent material were also located on the units calcareous sedimentary rock and slope debris. Furthermore, till was identified as the parent material of soils on the units SSR, MxD, MrD, GLD, DC, CBD and AD. An important takeaway point from these results is that, at least in this study area, while the SGU unit till in general is a good indicator for where to reliably encounter soils evolved from till, it is of great importance to expect this parent material also on various other SGUs.

A topographic comparison of those points with till as parent material located on the SGU till with points with the same parent material but on different SGUs (Table x), shows that the misclassified, latter group is characterized by a higher roughness (mean TRI of 25 compared to 13 for the correctly classified group) and steeper slope (mean value of 21 compared to 12°). Regarding confusion with the soil parent material unit calcareous sedimentary rock, data mining the terrain parameters of the relevant soil profile sites again highlights the role of the parameter TRI, in this case dominantly at a window size of 50 m, in topographically separating the unit till in general from other parent material units. CSR profile sites are characterised by TRI values in the upper quartile of the values characteristically displayed by TG profile sites. Of the local terrain parameters, slope, together with minimal curvature, performs well in separating the points of both groups, but not as clearly as it separates both units on the geological map, as TG profile points in the study area can be found at slope values higher than indicated in the geological map. To characterise the difference of the TG sites with slope deposits, the TRI with a window size in the range of 100 m performs best of all local, regional and roughness-related terrain parameters in the forward step-wise feature selection. Similar to the situation with CSR, slope is the best

performing local terrain parameter, but as before, the separation is clearer on the geological map, signifying that till can be found at steeper angles than expected from the geological map. Till as the parent material of soil profiles on the surficial geological map units CBD, DC and GLD is not as common
495 as for the above discussed units and additionally these units do not have as many overall members, nevertheless some interesting observations can be derived from the random forest-based investigation. For instance when compared with till, debris cones, which have a considerably uniform topography at the analysed grid cell size of 2.5 m, are characterised by lower local roughness (vectorruggedness with $ws = 50$ m or TRI with $ws=7.5$ m) and a low
500 landform diversity as represented by a high mean patch size of landforms calculated at a lookup distance of 7.5 m and a flatness threshold of 10° . On the contrary, the profile site topography of the unit coarse blocky debris is distinguishable from till by a higher TRI ($ws=125m$) as well as steeper slope.
505 Other aspects that may account for the high number of till parent material sites on units other than till in general have been discussed in the siliceous bedrock section.

4.3.4. *Slope debris*

Slope debris, as a SGU of the geologic map, occupies 10% of the study
510 area. Its by far longest border is shared with the unit siliceous bedrock, other important borders are with the units till in general, calcareous sedimentary rock and debris cones, the first three units greatly influencing the distribution of components in the slope debris units. When comparing the parent material of soil profile sites with the SGUs, the slope debris unit
515 has slightly better user's accuracy than producer's reliability, as surveyors established slope debris as the parent material of 55 of the 84 profile points on this SGU, but also for 69 soil data points on other SGUs. Similar to the SGU siliceous bedrock, the most confusion regarding parent material on the SGU slope debris occurred with the unit till in general, which was identified
520 at 15 soil profiles. As is the case with the SB unit, some of this confusion may be attributed to thin layers or punctual deposits of till. Considering slope debris, another important aspect is that the debris in question may very well be composed of till material that has been transported gravitationally. The same explanations may hold for other parent materials which were identified
525 on the slope debris unit, especially for the bedrock units SB, ISR and CSR. While some isolated outcrops are possible, the most likely cause is that the constituents of the slope debris are so dominated by transported material of

one of these bedrock classes, that the surveyors determine this unit as the parent material of the examined soil profile. On the other hand, misclassification between the units coarse blocky debris and slope deposits can be attributed to the fuzzy border between these units, ultimately linked to the grain size distribution, and the subjective interpretation thereof, especially during field survey. Contrary to most other SGUs (with the exception of CBD, LD and MxD), this unit itself does not provide information regarding the mineralogy of its component, which can only partially be derived through interpretation of its location in the catchment and the uphill geologic situation. Consequently, this unit is much better described by its topography than its material, as the latter may be highly diverse.

Those profile sites for which the geological map correctly proposes slope debris as the soil parent material differ from the slope deposit points on other SGUs mainly by higher slope heights and also higher slope angles, that is the geological map tends to under-represent slope debris situations in lower regions of the catchments and at less steep positions. 20 of the 122 soil profiles with slope debris as parent material are located on debris cones according to the geological map, which are good examples of the mentioned situation. This is presumably closely related to the furrowed and disturbed character of debris cones in the southern half of the study area, where the situation may not present itself clearly during field survey. Additionally, the material composition as well as its origin is basically the same for slope debris and debris cones in this area. Topographically, roughness measures do well in separating the slope debris points from the debris cones points of the field survey data set. Slope debris is characterised by higher vector-roughness ($ws=52.5$ m) values, which are very low for debris cones. Slope angles also differ considerably, implying that the surveyors tend to annotate slope debris if the topography does not show the low roughness and slope values characteristic of debris cones. This difference of roughness and slope with regard to the conceptual difference of slope debris and debris cones is also apparent when comparing the topography of both units as delineated by the geological map, however the difference is more distinct in this case. Similarly, calcareous sedimentary rock as parent material seems connected to roughness values slightly higher than those present for the average slope debris site, a relationship which is again more pronounced in the geological map. Consequently, it is in these transitional zones where the misclassification occurs. This topographical proximity of the units is of course reinforced by the fuzziness of distinguishing between the two parent material as such. As

is the case with siliceous bedrock and slope debris, the border between the source material, in this case the calcareous bedrock, and its derivative, the slope debris, is often not clear when considering the parent material of a soil profile. The degree of weathering of the source material certainly adds to the confusion. The issues are comparable for the parent material units intermediate and siliceous sedimentary rock. While the gradual transition from source material, in these cases bedrock of differing mineralogical composition, to slope debris poses various issues that cannot be explained only by topography, this is even more the case when considering the possibility of confusion between slope debris and coarse blocky debris, the distinction between which raises a number of questions with regard to the objectivity of estimating block or grain size of soil profile parent material. Misclassification between the units slope debris and mixed deposits are also predominantly a question of definition and the explanatory power of topography is very limited.

4.3.5. *Calcareous sedimentary rock*

The calcareous sedimentary rocks in the study area are predominantly responsible for the steep walls of the upper elevations of the Mendola-Roèn-Ridge (Dolomite and limestone), but also represent some thin layers in lower parts of that slope, interchanging with intermediate and siliceous sedimentary rock layers. Despite covering only 8.4% of the area, it has long borders due to its layers that span from north to south of the study area. Slope debris units often occupy locations downslope of the CSR units, accounting for the long border length of 40 km with this unit. The fuzzy transition from weathered bedrock to slope debris is a major issue also for this SGU. The confusion matrix representing the comparison of the parent material as indicated by the geologic map and the parent material identified in field survey (Table 3) shows that, consequently, this is the unit responsible for the most misclassification, contributing to the very low user's accuracy of this SGU. Additionally, due to its intermittent layering with ISR, it is not surprising that this unit was found to be the parent material for 7 investigated soil profiles in the calcareous sedimentary rock unit. The producer's reliability is slightly better, however, all in all only five of the soil profiles were attributed the parent material unit calcareous sedimentary rock, of which two were in fact situated on the SGU slope debris. This again accentuates the problem with differentiating these two units when adjacent, as one is often the result of weathering, and gravitational transport, of the other unit. Similarly

to the other bedrock units in the study area, till was reported also in this unit as the soil parent material at 12 sites, accounting for a third of the soil profile locations on this SGU and highlighting the necessity to expect thin layers of till in areas mapped as bedrock. Due to the small number of soil profile points actually identified as having CSR as parent material, the random forest classification approach of identifying important terrain parameter differences between the correctly classified points and those on other units is not very meaningful. Topographical separation from intermediate sedimentary rock, a major cause of misclassification, is also not very adequate, as the most important parameter in this case is slope height. This is to be expected, since the main difference is the vertical position in the overall geological structure of the study area, a difference which is however diminished by the above mentioned intermittent layering and gravitational movement down-slope, in addition to the above discussed problem regarding the definition of slope debris versus weathered bedrock.

4.3.6. *Debris cones*

The unit debris cones are located west of the center of the paleovalley, between the slope debris of the Mendola-Roèn-Ridge slope in the west, which are often the source area of these deposits, and the till deposited in the paleovalley in the east. Other units with which long borders exist are mixed, colluvial, and alluvial deposits. The number of profile sites is comparably small with 36 profile sites, considering that the unit occupies almost 13% of the study area. A reason is that a large part of the debris cones are covered by settlements. Although the soil surveyors noted debris cones as parent material for only 5 soil profile sites, it must be considered that 20 of the misclassified parent materials on the debris cones unit were identified as slope debris. Given the long mutual border and the fact that the source of the debris cones material is mainly the slope debris and the calcareous bedrock units which themselves are the origin of the slope debris, this misclassification may seem acceptable. In fact, it rather points out a difference in the point of view of the soil and the geologic surveyors, where the first are interested in the material and the latter more in the landform presented by the debris cones unit. The remaining misclassifications are all with units that border this SGU, or, in the case of intermediate sedimentary rock, are located in the source region of the debris cones.

4.3.7. *Intermediate sedimentary rock and siliceous sedimentary rock*

4.3.8. *MxD, LD, CD*

640 4.3.9. *GLD, IMS, MrD*

GLD, opposed to till, have a slightly higher landform richness at macro scale, but at the same time a higher landform at micro or meso scale.

4.4. *Differences between geologic survey and parent material from profile site descriptions*

645 4.4.1. *Differences with regard to mapping purpose*

Between the two different frameworks of mapping, geology on the one hand and soil on the other, it is important to acknowledge the main focus of attention of each branch of research. There may exist a difference with regard to how pronounced a certain feature or characteristic must be in order to be considered for mapping. Miller and Lee Burras (2015) note that the resulting maps of the two sciences try to communicate different aspects. While geology refers to geologic materials and general landform regions, soil science is concerned more with soil properties with regard to land use and management decisions.

655 A typical example is the unit landslide debris, which seems only of interest to the mappers with focus on geology, whereas the soil surveyor...

Regarding glacial deposits, the soil or forestry surveyors seldom differentiate between lodgement till and other glacial deposits, only when a decisively higher clay content was determined. On the other hand, the chemical properties, especially with regard to acidic properties of the tillic material are of much more interest to the soil surveyors who further differentiate till with regard to this aspect. The geologic map on the other hand also contains information with regard to the age and the geologic system(synthem) to which certain moraines belong, whereas this is only of interest to the soil surveyor if it features additional information with regard to the mineralogic content of the different constituents of the moraine.

665 Geologist only map regolith cover layers thicker than approximately 1 m.

4.4.2. *Nomenclatural differences and overlapping classes*

Congalton

670 4.5. *Pedologic interpretation of terrain parameters that best separate the geological units*

Do the points surveyed as moraine have different terrain parameters from those mapped as moraine on the geologic map.

675 4.6. *Distribution of soil types with regard to geologic unit as well as parent material unit*

4.7. *Influence of the Alpine environment on interpretability of geologic units as parent material units*

Heung et al. (2014) note that while traditional geologic maps focusing on bed rock are a valuable input for DSM when the residual materials form the soil parent material, but less so in areas distinguished by glaciation and high geomorphodynamics. Similarly, in their comparison of surficial geology maps derived from Soil Survey maps on the one hand and the Geologic Survey on the other, Miller and Lee Burras (2015) point out that the level of agreement was lower for areas with complicated geologic histories.

685 4.7.1. *High relief areas and multilayering*

Are there thresholds regarding terrain parameters?

4.7.2. *thin cover layers of till - an essential new parent material unit?*

Why is important to differentiate till and slope debris? While there may exist situations where the slope debris is composed of till material, the general difference is that soils from slope debris can be understood with knowledge of local geology and that they may not be so different from soils higher up in the catchment that evolved from bedrock, whereas till can consist of chemically very different components. Till can be found at steeper slopes than expected, is this due to lateral consolidation of tillic material by glaciers in these U-shaped valleys?

4.7.3. *Is the morphodynamic background of deposits a necessary distinctive attribute from a pedological point of view?*

In the study area, mixed deposits from mass movement and torrents have the same components as till or hillside debris, which themselves are often the same...

4.8. *Terrain parameters - issues and results*

- the landform diversities are all heavily correlated and have the same meaning in the end.
- beware of the different class sizes when using random forest and box-plots to investigate differences
- In general local terrain parameters and regional terrain parameters are only important if the parent material map does not apply the information already implicitly provided in the new detailed geological map.

5. Conclusion

We propose that future surveys focus increasingly on these units with greater uncertainty with regard to soil parent material to strengthen understanding of the pedologic relevance of these units. By performing a GTC prior to future detailed field soil surveys, the surveyor can make best use of available information and concentrate the time and money consuming task of field work, involving soil pits and auguring, on units identified as highly variable and uncertain regarding soils. This information can be additionally helpful for devising future sampling procedures and also for consideration when attempting to regionalise point information.

Acknowledgements

This research was performed within the project 'Terrain Classification of ALS Data to support Digital Soil Mapping', funded by the Autonomous Province Bolzano – South Tyrol (15/40.3).

additional tables

References

Avanzini, M., Bargossi, G., Borsato, A., Castiglioni, G., Cucato, M., Morelli, C., Prosser, G., Sapelza, A., 2006. Erläuterungen zur geologischen Karten von Italien im Maßstab 1:50000 Blatt 026 Eppan. Technical Report. Agenzia per la protezione dell'ambiente e per i servizi tecnici.

	CBD	CD	CSR	DC	GLD	IMS	ISR	LD	MrD	MxD	SB	SD	SSR	TG
AD	0.2	21.1	0.0	23.6	14.8	2.5	0.0	1.2	22.2	10.9	5.7	12.7	0.2	45.2
CBD		0.5	6.1	8.5	0.0	0.0	1.1	0.9	0.5	1.5	10.1	9.7	0.9	9.1
CD			1.3	17.6	10.7	2.8	0.0	0.6	0.7	10.0	5.8	4.0	0.0	31.1
CSR				11.8	0.0	0.0	5.5	0.8	0.0	1.3	0.6	40.7	5.0	23.1
DC					2.5	0.6	0.7	2.4	5.9	17.4	9.3	25.6	1.6	40.6
GLD						2.2	0.0	0.2	0.8	3.4	0.4	0.5	0.0	7
IMS							0.0	0.0	0.0	0.6	0.7	0.4	0.0	1.1
ISR								0.2	0.0	0.0	0.0	4.3	0.0	0.4
LD									0.0	0.1	1.4	3.7	0.5	4.2
MrD										0.2	1.2	0.6	0.0	1.9
MxD											2.7	2.7	0.1	19.5
SB												109.3	4.4	67.4
SD													8.3	50.4
SSR														5.5

Table 4: Length in kilometers of the borders of adjacent SGUs

- Baruck, J., Nestroy, O., Sartori, G., Baize, D., Traidl, R., Vraj, B., Brm, E., Gruber, F.E., Heinrich, K., Geitner, C., 2016. Soil classification and mapping in the alps: The current state and future challenges. *Geoderma* 264, 312 – 331. URL: <http://www.sciencedirect.com/science/article/pii/S0016706115300343>, doi:<http://dx.doi.org/10.1016/j.geoderma.2015.08.005>. soil mapping, classification, and modelling: history and future directions.
- Beasom, S.L., Wiggers, E.P., Giardino, J.R., 1983. A technique for assessing land surface ruggedness. *The Journal of Wildlife Management* 47, 1163–1166. doi:10.2307/3808184.
- Böhner, J., AntoniĆ, O., 2009. Chapter 8 land-surface parameters specific to topo-climatology, in: Hengl, T., Reuter, H.I. (Eds.), *Geomorphometry Concepts, Software, Applications*. Elsevier. volume 33 of *Developments in Soil Science*, pp. 195 – 226. URL: <http://www.sciencedirect.com/science/article/pii/S0166248108000081>, doi:[http://dx.doi.org/10.1016/S0166-2481\(08\)00008-1](http://dx.doi.org/10.1016/S0166-2481(08)00008-1).
- Brevik, E.C., Miller, B.A., 2015. The use of soil surveys to aid in geologic mapping with an emphasis on the eastern and midwestern united states.

- Soil Horizons 56. URL: <http://dx.doi.org/10.2136/sh15-01-0001>, doi:10.2136/sh15-01-0001.
- 750 Coblenz, D., Pabian, F., Prasad, L., 2014. Quantitative geomorphometrics for terrain characterization. *International Journal of Geosciences* 5, 247–266. URL: <http://dx.doi.org/10.4236/ijg.2014.53026>.
- FAO, 2006. Guidelines for soil description. Food and Agricultural Organisation of the United Nations. Rome.
- 755 Gallant, J.C., Wilson, J.P., 2000. Terrain Analysis - Principles and Applications. John Wiley & Sons, Inc.. chapter Primary Topographic Attributes. pp. 51–85.
- Geitner, C., Baruck, J., Freppaz, M., Godone, D., Grashey-Jansen, S., Gruber, F.E., Heinrich, K., Papritz, A., Simon, A., Stanchi, S., Traidl, R., von Albertini, N., Vraj, B., 2017. Chapter 8 - soil and land use in the alps challenges and examples of soil-survey and soil-data use to support sustainable development, in: Pereira, P., Brevik, E.C., Muoz-Rojas, M., Miller, B.A. (Eds.), *Soil Mapping and Process Modeling for Sustainable Land Use Management*. Elsevier, pp. 221 – 292. URL: <http://www.sciencedirect.com/science/article/pii/B9780128052006000086>, doi:<http://doi.org/10.1016/B978-0-12-805200-6.00008-6>.
- 765
- Grohmann, C.H., Smith, M.J., Riccomini, C., 2010. Multiscale analysis of topographic surface roughness in the midland valley, scotland. *IEEE Transactions on Geoscience and Remote Sensing* PP, 1 – 14. doi:10.1109/TGRS.2010.2053546.
- 770
- Heung, B., Bulmer, C.E., Schmidt, M.G., 2014. Predictive soil parent material mapping at a regional-scale: A random forest approach. *Geoderma* 214215, 141 – 154. URL: <http://www.sciencedirect.com/science/article/pii/S0016706113003443>, doi:<http://dx.doi.org/10.1016/j.geoderma.2013.09.016>.
- 775
- Hobson, R.D., 1972. Spatial analysis in geomorphology. Harper and Row, New York. chapter Surface roughness in topography: quantitative approach. pp. 221–245.
- IUSS Working Group WRB, 2015. World Reference Base for Soil Resources 2014, update 2015 International soil classification system for naming soils
- 780

and creating legends for soil maps. World Soil Resources Reports 106. FAO, Rome. Rome.

Jenny, H., 1941. Factors of Soil Formation - A System of Quantitative Pedology. Dover Publications, Inc. New York.

785 Juilleret, J., Dondeyne, S., Vancampenhout, K., Deckers, J., Hissler, C., 2016. Mind the gap: A classification system for integrating the subsolum into soil surveys. Geoderma 264, Part B, 332 – 339. URL: <http://www.sciencedirect.com/science/article/pii/S0016706115300604>, doi:<http://dx.doi.org/10.1016/j.geoderma.2015.08.031>.
790 soil mapping, classification, and modelling: history and future directions.

Kilian, W., 2015. Schlüssel zur Bestimmung der Böden Österreichs. volume 81. 2 ed., Österr. Bodenkundl. Ges.

Marchi, L., Dalla Fontana, G., 2005. Gis morphometric indicators for the
795 analysis of sediment dynamics in mountain basins. Environmental Geology 48, 218–228. URL: <http://dx.doi.org/10.1007/s00254-005-1292-4>, doi:10.1007/s00254-005-1292-4.

McBratney, A.B., Mendonca Santos, M., Minasny, B., 2003. On digital soil mapping. Geoderma 117, 3 – 52.

800 Miller, B.A., Lee Burras, C., 2015. Comparison of surficial geology maps based on soil survey and in depth geological survey. Soil Horizons 56. URL: <http://dx.doi.org/10.2136/sh14-05-0005>, doi:10.2136/sh14-05-0005.

Nellemann, C., Thomsen, M.G., 1994. Terrain ruggedness and caribou forage
805 availability during snowmelt on the arctic coastal plain, alaska. Arctic 47, 361–367. URL: <http://www.jstor.org/stable/40511597>.

Nestroy, O., Aust, G., Blum, W., Englisch, M., Hager, H., Herzberger, E., Kilian, W., Nelhiebel, P., G. Ortner and, E.P., und J. Wagner, A.P.W.S., 2011. Systematische gliederung der bden sterreichs. sterreichische boden-
810 systematik 2000 in der revidierten fassung von 2011. Mitt. sterr. Bodenkdl. Ges. 79.

- Olaya, V., 2009. Chapter 6 basic land-surface parameters, in: Hengl, T., Reuter, H.I. (Eds.), *Geomorphometry Concepts, Software, Applications*. Elsevier. volume 33 of *Developments in Soil Science*, pp. 141 – 169. URL: <http://www.sciencedirect.com/science/article/pii/S0166248108000068>, doi:[http://dx.doi.org/10.1016/S0166-2481\(08\)00006-8](http://dx.doi.org/10.1016/S0166-2481(08)00006-8).
815
- Phillips, J.D., Lorz, C., 2008. Origins and implications of soil layering. *Earth-Science Reviews* 89, 144 – 155. URL: <http://www.sciencedirect.com/science/article/pii/S001282520800055X>, doi:<https://doi.org/10.1016/j.earscirev.2008.04.003>.
820
- Riley, S.J., DeGloria, S.D., Elliot, R., 1999. A terrain ruggedness index that quantifies topographic heterogeneity. *Intermountain Journal of Sciences* 5, 23 – 27.
- Sappington, J.M., Longshore, K.M., Thompson, D.B., 2007. Quantifying landscape ruggedness for animal habitat analysis: A case study using bighorn sheep in the mojave desert. *Journal of Wildlife Management* 75. URL: <http://dx.doi.org/10.2193/2005-723>, doi:10.2193/2005-723.
825
- Schaetzl, R.J., Krist Jr., F.J., Rindfleisch, P.R., Liebens, J., Williams, T.E., 2000. Postglacial landscape evolution of northeastern lower michigan, interpreted from soils and sediments. *Annals of the Association of American Geographers* 90, 443–466. URL: <http://dx.doi.org/10.1111/0004-5608.00204>, doi:10.1111/0004-5608.00204.
830
- Scholz, H., Bestle, K.H., Willerich, S., 2005. Quartärgeologische untersuchungen im überetsch. *Geo.Alp* 2, 1–23.
835
- Thalheimer, M., 2006. Kartierung der landwirtschaftlich genutzten bden des Überetsch in südtirol (italien). *Laimburg Journal* 3, 135–177. URL: http://www.laimburg.it/de/projekte-publikationen/blickpunkte.asp?news_action=300&news_image_id=828290.