

# 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

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## Abstract

*Keywords:*

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## 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,

- 5 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  
10 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  
15 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

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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  
20 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  
25 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  
30 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 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  
35 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  
40 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  
45 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.  
50

Herbst zitat fr bedeutung der Schrfe 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.

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

<sup>130</sup> 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 identify the topographic characteristics of the parent material units in order <sup>135</sup> 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 <sup>140</sup> - 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 Vulcanites from which steep slopes descend to the Etsch Valley (approx. 200 m <sup>145</sup> 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 by forests. Pastures are located mainly on till covering the flat areas of the <sup>150</sup> Mendola-Roèn-Ridge.

### 2.2. Surficial Geology

A detailed description of the geologic situation can be found in the commentary to the new geologic map of Eppan (Avanzini et al., 2006). The <sup>155</sup> paleovalley of Überetsch is described by Scholz et al. (2005) as a complex system of gravelly lateral moraines and large kame terraces, the result if 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 <sup>160</sup> recent debris flow deposits, often composed of mainly limestone and dolomite fragment. The vale bottom itself is filled with Pleistocene sediments and contains a number of valleys carved into the gravels by fossil melt-water. At the eastern and western borders of the Pleistocene sediments, outcrops of Permian 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.

175 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  
 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 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 properties as well as photographs of the pit face, these soil profiles were  
200 reclassified applying the Austrian System.  
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*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 investigate 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).  
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*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 resolution geologic map correspond to the parent material identified by the soil  
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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, Umbrisol, Regosol	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-enrichened 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 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  
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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 roughness. 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 geologic 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 these factors on the other, is then investigated by analysing the diversity and distribution 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 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.  
250  
255

### *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*

A five-fold cross-validated forward step-wise feature selection was performed with random forest classification to produce a parent material map  
270 of the study area. Feature selection was performed to identify a small number of parameters capable of turning the geologic map into a parent material

map. In contrast to using all possible terrain parameters, this procedure that produces only a limited number of explanatory variables, has the advantage of being easier to interpret, as the main aim is also to identify, highlight, 275 and understand situations where the most confusion between parent material units as documented by surveyors and the geologic map occur. Additionally to a large number of terrain parameters, the geologic map, reclassified to the SGUs in Table 1, was added to the set of explanatory variables from which the random forest classifier could add features to the model. The unit mire 280 deposits removed due to only one class member. The whole feature selection procedure was also performed in 5-fold crossvalidation, and for four parameter sets: 1) all terrain parameters, 2) local terrain parameters, 3) regional terrain parameters, 4) surface roughness-related parameters.

This feature selection procedure with random forest classifications was 285 performed for several applications in the course of this study:

- 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
- 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.
- 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

Considering the confusion matrices and the accuracy measures calculated, 300 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.

## 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.

310 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	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. Geologic-topographic characterisation of the predominant SGUs

Through synthesis of 1) results of the comparison of the soil point data and the geologic map, 2) the random forest analysis of terrain parameters and 3) the distribution of soil types in the study area, a geologic-topographic characterisation of the SGUs for use in soil survey is performed. Only those units with substantial areal extent and sufficient soil profile points are described in detail.

320    4.2.1. *Alluvial deposits*

The SGU alluvial deposits occupies 16.3 km<sup>2</sup>, amounting to 14.9 % of the study area. It incorporates alluvial deposits in the paleovalley but also in the Etsch valley, with to soil profile points limited to the former. The alluvial deposits share very long borders with the SGUs till, debris 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 glacio-lacustrine deposits, mixed deposits, slope debris and till. 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 this SGU as the soil parent material. Some confusion with the SGUs debris cones and till 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 unit on the geological map, shows that these are characterized by consistently lower vector strength at 112.5 m, indicating rougher terrain. This is confirmed by higher landform richness values at meso scale (50 m search radius) for the incorrectly classified data points. Addressing the confusion of alluvial deposits with till, the random forest investigation shows that besides obvious channel-level-related terrain parameters, which well separate the units, convexity contributes strongly to distinguishing between alluvial deposits and till on the geologic map, with the former characterised by lower values concentrating around 0.42. It must however be taken into account 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 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. This can be attributed to the relative smooth surface of the till unit on the one hand, and the often entrenched location of alluvial deposits in the paleovalley. 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 by the regional terrain parameter catchment slope, computed at the same low DTM resolution. The choice of these parameters seems 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, were 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.

#### 4.2.2. Siliceous bedrock

The SGU siliceous bedrock in the study area is characterised by outcrops of rhyolithic 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, 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 to

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 occurs with the unit till, 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 glacio-lacustrine 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 exclusively 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 those 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 size 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 possible differences regarding the mapping procedures in geology and pedology. Furthermore, the parent material layer must not necessarily be very thick to act as such. 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 drapes 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 char-

acterised by higher vector ruggedness values. Given the strong confusion with the unit till, as well as the fact the these two units share a long border, it is of interest to examine the topographical differences between points  
435 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 char-  
440 acterised by rougher topography (increased TRI values) and slightly positive minimal curvature values when compared with data points where till was identified as parent material. This is well in line with the increased appearance 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  
445 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 com-  
450 puted 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, apparently a good indicator for slope debris. Furthermore, the same TRI applied to separate SB and TG can  
455 also be a very useful addition to the parameter set when distinguishing SB from SD. An investigation into the soil types classes of the soil profile sites located on the SGU siliceous bedrock shows that brown soils are the dom-  
460 inating soil type, represented by 37 of the 49 locations (75%). The class Terrestrische Rohböden, represented by the soil type Ranker, is second most common on this SGU, on which single examples of the soil types Semipodsol, Kalkbraunlehm, Farb-Substratböden and Kolluvisol were also encountered. Taking into account only the soil profile sites for which the surveyors identi-  
465 fied SB as parent material, whether or not actually located on this SGU, the soil type brown soils similarly dominates the soil type Ranker, with 13 and 6 profile sites, respectively. All of the other soil types found on the SGU on the geological map were not identified by the surveyors to have SB parent ma-  
470 terial, however one soil profile site with this parent material was attributed the soil type Grobmateriale-Rohboden. This soil type however does fit well for soils on siliceous bedrock outcrops, were only initial soil formation is pos-

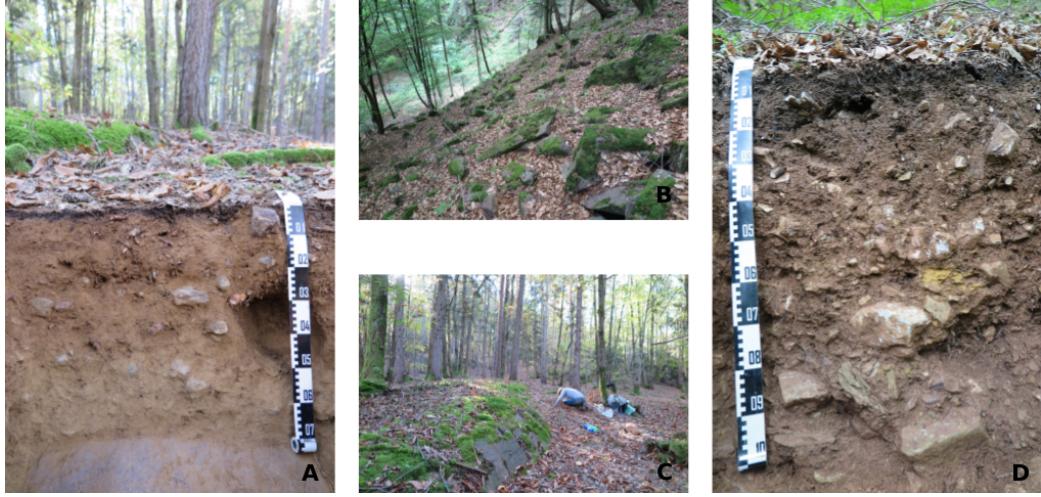


Figure 1: A) Soil profile 39 on the SGU siliceous bedrock with parent material identified as till, representative of the typical situation of till on siliceous bedrock. B) soil profile site 39 C) Soil profile site 43 D) Soil profile 43, located above the debris cone of Andrian on the SB map unit. The yellow components are from up-slope ISR layers, while calcareous components from even higher layers can also be identified.

470 sible, whereas the other soil types located on the SGU of the geological map  
 471 are less plausible on SB, especially Kalkbraunlehm. In addition, the vast  
 472 majority of the soil profile sites located on this SGU but identified to have  
 473 a different parent material class (mostly till) by the surveyors, also feature  
 474 the soil type Braunerde, thereby decreasing the severity of misclassifying SB  
 475 and TG, at least from a soil type perspective. Figure 1D shows an example  
 476 of such a situation, consisting of a brown soil developed from a cover layer  
 477 of till on siliceous bedrock. From this perspective, the soil type Ranker is  
 478 more characteristic of the SB unit, as it is less common on TG with its char-  
 479 acteristically more developed soils and the increased influence of calcareous  
 480 materials. Furthermore, an examination of the points where parent material  
 481 classes from observation and SGU map coincide, shows a decrease in domi-  
 482 nance of brown soils compared to Rankers, with proportions of 57 and 35 %  
 483 for both soil types, respectively. This is also well in line with the fact that SB  
 484 sites are characterized by higher roughness values and situated on convex,  
 485 ridge-like structures where decreased soil formation can be assumed. In con-  
 486 clusion, the soil types Braunerde and Ranker are characteristic of this unit,  
 487 with the former representing locations where weathering and clay-reformation

has led to horizon differentiation not present in the less developed Ranker soils which are found on siliceous bedrock outcrops.

490 *4.2.3. Till in general*

The unit till 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 495 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, accounting for 29% of the points. In 88 of these locations, the surveyors agreed with regard to the parent material being till, 500 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 505 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 are also located on the units calcareous sedimentary rock and slope debris. Furthermore, till was identified as the parent material of soils on the 510 units SSR, MxD, MrD, GLD, DC, CBD and AD. An important takeaway point from these results is that while, at least for this study area, the SGU unit till 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.

515 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 520 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 from other parent material units. CSR profile sites are characterised by TRI val-

525 uses 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  
530 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  
535 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 as for the above discussed units and additionally these units do not have as many overall members, nevertheless some interesting observations can be derived  
540 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 (VR with ws = 50 m or TRI with ws=7.5 m) and a low landform diversity as represented by a high mean patch size of landforms calculated at a lookup  
545 distance of 7.5 m and a flatness threshold of 10°. The profile site topography of the unit coarse blocky debris, on the other hand, is distinguishable from till by a higher TRI (ws=125m) as well as steeper slope. Other aspects that may account for the high number of till parent material sites on units other than till have been discussed in the siliceous bedrock section.

550 Typical for the study area, and especially characteristic of the till parent material unit, brown soils dominate the soil types of the profile sites on the corresponding map unit with 59%, but even more so when considering only the sites for which the surveyors identified till as parent material (70% of 151 profile sites). This proportion is comparable to that of brown soils for  
555 the data subset for which till is indicated as parent material by both the surveyors and the geological map. While brown soils also dominate on SB, the variety of subtypes on till is greater. While SB shows mainly typical brown soils and some with signs of beginning podzolisation, these subtypes are accompanied on till by brown soils containing calcareous components  
560 as well as brown soils characterised by higher clay contents, a strong influence of the clay on horizon differentiation (soil type Textur-Substratboden), and also vertical translocation of these particles (soil type Parabraunerde,

which develops only on this parent material in the study area). The latter soil types and subtypes are common on till parent material, especially  
565 when developed on sub-glacial or lodgement till. The presence of soils of the class of Umgelagerte Böden, i.e. soils that have been rearranged vertically or horizontally either directly or indirectly by human influence, can be accounted for by the fact that most vineyards or apple orchards are located on this unit. Of the class of less developed soils with only an organic horizon  
570 (Terrestrische Humusböden), accounting for 13% of the soils with the parent material till, the majority is influenced by the calcareous components of the till, separating these soils from those on SB. The role played by the calcareous till material, brought into the till mainly locally from the slope of the Mendola-Roèn-Ridge, is also highlighted by the presence of soils of the class  
575 Kalklehme. In summary, the soils of the SGU till are characterised by well developed soils, often with calcareous properties. This is will in line with the topography of this unit, distinguished by low roughness and gentle slopes.

#### 4.2.4. Slope debris

Slope debris, as a SGU of the geologic map, occupies 10% of the study  
580 area. Its by far longest border is shared with the unit siliceous bedrock, other important borders are with the units till, 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 has slightly better  
585 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, which was identified at 15 soil profiles. As is  
590 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  
595 may hold for other parent materials which were identified 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

600 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 it-  
self does not provide information regarding the mineralogy of its component,  
605 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  
610 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,  
i.e. 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  
615 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  
620 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-  
ruggedness ( $ws=52.5$  m) values, which are very low for debris cones. Slope  
angles also differ considerably, implying that the surveyors tend to annotate  
625 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.  
630 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  
635 occurs. This topographical proximity of the units is of course reinforced by  
the fuzziness of distinguishing between the two parent materials 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  
640 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  
645 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  
650 limited.

Given its confounding nature, due to its dynamic topography and great variability of components, this unit shows a high diversity of soil types, encompassed only by the parent material till due to its variety of anthrosols and well developed soils. With regard to soil type classes, the class incorporating soils with only organic layers on top of parent material (Terrestrische Humusböden) stands out, both with respect to the soil profiles on the map unit (70%) as well as those for which surveyors specified the parent material slope debris (64%). While both of these approaches of analysing the distribution of soil classes have brown soils (25 and 15%, respectively) as  
655 the most important secondary soil class, the main differences are the classes Kalklehme and Umgelagerte Böden, of which the latter is found only from the viewpoint of the soil profile descriptions. The presence of multiple soil profiles of the Kalklehm class shows that soil surveyors are more likely to identify slope debris as the parent material also for locations which are generally more favourable to soil formation than the areas indicated as this SGU on the geologic map. This is indeed consistent with the topographic analysis of the profile points. Similarly, these transitional locations between steeper slope and flatter regions are also indicative of the confusion between slope debris and debris cones, exemplified by the relatively large proportion (12%)  
660 of Rigosols, which also highlights that soil surveyors tend to emphasize the components, in this case slope debris, instead of the geomorphological form as presented by debris cones. In summary, soils with only organic horizons are the most common representatives of soils on this parent material, with those related to calcareous parent material (Rendzina aand Kalklehm-Rendzina)  
665 more prevalent than their siliceous counterparts, especially when considering  
670  
675

only those soil profile locations for which surveyors identified slope debris. Nevertheless, soils developed from slope debris can show signs of advanced soil formation in less sloping, smoother topography, for instance in bordering debris cones or other deposits.

680    *4.2.5. 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 seven 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 twelve 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  
715 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.

The Rendzina is the typical proponent of soil types on calcareous sedimentary rock, as exemplified by the two soil profile sites for which both the geologic map and the surveyors indicated this unit as the soil's parent material.  
720 The situation described in the topographical description of the unit leads to a high number of soil profiles along with a variety of different soil types. Although these include soils where soil formation processes have led to horizon differentiation such as Braunerde and Kalklehme, nevertheless the class Terrestrische Humusböden constitutes the majority. However, when considering only the soil profile sites that qualify for CSR parent material from  
725 the surveyor's point of view, this is the only class, represented by the soil types Rendzina and Kalklehme-Rendzina. Given the topographic situation and the complex geologic setting, it is necessary to assume the possibility of soils with signs of increased pedogenetic development on this map unit,  
730 however a different parent material such as till or slope debris of varying composition must be considered for any of these soil types.

#### 4.2.6. Debris cones

The unit debris cones is located west of the center of the paleovalley, between the slope debris of the Mendola-Roèn-Ridge slope in the west, which  
735 are often the source area of these deposits, and the till deposited in the paleovalley in the east. An additional debris cone is located in the north of the study area in the main Etsch valley. 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  
740 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 five 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  
745 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

750 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 the debris cones.

755 The topographic issues regarding the confusion with other parent materials such as AD, SD, TG have been discussed in the unit-specific subsections,  
highlighting this units landscape position as the main distinguishing characteristic.

760 As discussed, compared to the number of soil pit locations for which the  
surveyors identified the parent material class debris cones, the number of sites  
located on this unit of the geological map is much higher, which also leads  
765 to a greater soil type variability, especially at subtype level. While surveyors  
identified this unit only once for more developed soil types such as Braunerde  
or Kalklehme, they constitute 42% of the sites indicated on the map. Given  
the strong anthropogenic influence on debris cones, a large proportion of the  
770 profiles have experienced vertical anthropogenic rearrangement, in an effort  
to enhance the general conditions for viticulture and horticulture. Soils with  
only organic layers can also be found in areas with less intensive anthropogenic  
influence, though more commonly on areas where only the geologic  
map indicates debris cones, whereas the surveyors more commonly classified  
the parent material as slope debris, highlighting the issue of defining the  
775 difference, as discussed in section 4.2.4.

#### 4.2.7. Intermediate sedimentary rock and siliceous sedimentary rock

780 The units intermediate and siliceous sedimentary rock are situated in the  
slope of the Mendola-Roèn-Ridge and are characterised by more or less thin  
layers, often intermittent with layers of calcareous sedimentary rock, and  
785 only a limited amount of outcrops. Another common characteristic is that  
none of the soil profile points for which the surveyors identified one of these  
units as the soil's parent material is actually situated on the corresponding  
geological map unit. The parent material of all three soil profile sites on  
ISR was classified as slope deposits, which is understandable considering the  
issues discussed in the previous sections regarding slope debris and weathered  
790 bedrock. As further evidence of this issue, ISR was detected as the parent  
material of four soil profiles on the map unit slope debris. Additionally,  
intermediate sedimentary rock was identified as the parent material of 7 soils  
on the CSR map unit and two on the SSR unit. There is of course no question  
795 that the layers are correctly located on the geological map with regard to  
the underlying geological structure of the study area, these soil profile sites

rather highlight the possibility of finding any or all of the materials of these intermittent layers on these units as well as any potential down-slope slope debris units due to the prevailing geomorphological dynamics in the study  
790 area. Gravitational transportation leads to these materials serving as soil parent material not where the layer is indicated on the geological map, but in fact down-slope of these layers. Additionally, these materials are seldom found as homogeneous units due to mixing and multi-layering caused by gravitational transport. For these and other reasons discussed in the CSR  
795 section, topographical separation is limited for these units.

As the situation described above does not seem to favour soil formation processes to take place in a constant manner, it is surprising that while two out of the three soils on the geological map unit belong to the class Terrestrische Humusböden, the majority of the soil profile sites specified as  
800 having ISR or SSR as parent material are of the classes Braunerde or Kalklehme, i.e. soils with A and B horizons. More expected is the presence of colluvisol on the SSR units (both on the map and regarding field survey). In summary, it appears that in such a dynamic environment as on the SGUs ISR, SSR and slope debris, soil surveyors tend to annotate slope debris as  
805 the parent material of less developed soil such as those of the Terrestrische Humusböden class, while placing more emphasis on the mineralogical properties of the components when describing soils that experienced more pedogenetic processes. Nevertheless, this analysis implies that soils developed from any of these intermittent layers are more likely to be encountered  
810 in down-slope slope debris units, especially for ISR. Regardless of the present dynamics, more evolved soils are possible but may present very heterogenous parent material due to multi-layering. Figure 1D shows an example of such a profile site in steep topography with a typical slope debris parent material mixture containing ISR material, which has however been deposited on a SB  
815 unit located downslope of the layers.

#### 4.2.8. Colluvial, mixed, and landslide deposits

All three of these SGUs are characterised as material that has been transported down-slope by various processes. Regarding colluvial deposits, the surveyors indeed identified this parent material unit for three of the five profile sites on this map unit. The parent material of the remaining two sites was mapped as ISR and SD. While the latter can be attributed to the similarity of the material and the uncertainty of the definition of the difference between slope deposits and colluvial deposits, the former could indicate that  
820

the soil surveyor may value the information with regard to the mineralogy  
825 as being of greater importance to explaining a soil profile than the information regarding the morphodynamic history of the material. The definition of mixed deposits as deposits from debris flows, torrents and avalanches is similarly dominated by the means of transportation rather than the material components. Interestingly, none of the soil profiles located on this map unit  
830 were linked to this parent material by the surveyors, but five of the profiles on till were. With regards to soil parent material, an important issue is whether this material is in fact composed of the same material as till and has been simply transported by one of the aforementioned processes. The parent material of the majority of the soil profiles on the MxD unit of the geological  
835 map wsd identified as slope deposits, highlighting the definitional proximity of these units, at least concerning the view of surveyors focussing on soil. Compared to these two units, the issue regarding landslide depositions is a different one. This unit was never used by the soil surveyors to describe the parent material of a soil profile site. Of the three data points on this map  
840 unit, the surveyors explicitly chose the parent material siliceous bedrock for two locations, which is in fact the material of the landslide body in the study area. Coarse blocky debris was also used at one soil profile site, which well describes the structure of the material involved. This example provides insight into how the different emphasis and focus of soil and geologic surveyors  
845 influences their classification, each highlighting a different aspect of the same unit.

Topographically, these three units are not easy to differentiate, especially with regard to the unit slope debris, which is very close with regard to both definition as well as morphometry and discussed in the slope debris subsection.  
850

The soil types of the three soil profile sites with parent material which both geological map and surveyors identify as colluvial deposits, are of the classes Umgelagerte Böden and Brown soils and are representative of both the map unit and the soils as attributed by the surveyors, although the latter  
855 also link this parent material unit to a less developed soil like Ranker. In general, the colluvial deposits are characterised, or understood, as the accumulation of eroded slope material, which can also be A-horizon material for instance from agricultural lands. Consequently, disturbed soils but also better developed soils on older accumulations are conceivable examples of  
860 soils on CD. Given the similar genesis of mixed deposits, the soil classes distributed amongst the soil profiles with this parent material are comparable,

despite some of the points being located on TG according to geologic map. But as this parent material can actually be till or calcareous sediments transported from up-slope locations, the soil types Braunerde and Kalklehme are  
865 good fits and show that confusion between the units does not lead to severe misclassifications, at least from a soil surveyor's point of view. As discussed in the topography section, the landslide mass in the study area is composed of siliceous bedrock, with the soil types Ranker und Braunerde being as anticipated for soil developed from such parent material.

870 *4.2.9. Glacio-lacustrine deposits, ice-marginal sediments and mire deposits*

Even when taking into account that only seven soil profile sites are located on this map unit, the geological map has a relatively good user's accuracy for the soil parent material unit glacio-lacustrine deposits. It comprises both glacio-lacustrine and lacustrine deposits which are concentrated at the  
875 northern border of the paleovalley. The producer's reliability is below 0.5, as surveyors indicated this parent material also for soil profile sites on the SGUs alluvial deposits, mire deposits, siliceous bedrock and till. Confusion with the first two SGUs seems acceptable due to the common fluvial or hydromorphic history, although the other misclassifications do indicate the  
880 possibility of local glacio-lacustrine deposits as the parent material on these units. The topographical analysis of those points on other SGUs but with GLD as the surveyed parent material hints that these are located in regions where landform diversity is partly dominated by a single class at meso scale (ws=50 m), indicating a smoother surface than for the GLD map unit, as  
885 well as being characterised by a more pronounced negative minimal curvature suggesting concave topography. The random forest-based investigation into the topographical difference between soil profile points with SB and with GLD as parent material characterize the latter with lower roughness values (TRI and VR at window sizes between 100-130 m), indicating similar regions  
890 on SB as possible GLD areas. Regarding soil type, investigations from both viewpoints, i.e. from the geological map and the soil profile data, show the soils on this unit as belonging to either the soil type Braunerde or Rigolboden, the latter representing agriculturally used land. Due to the lack of profile points in mire deposits, GLD is the only SGU on which surveyors  
895 mapped a hydromorphic soil type, in this case Pseudogley.

Ice-marginal sediments are closely associated with till units and are mostly located in close proximity, consequently sharing long borders. Given their often thin, elongated form and the fact that they cover only 0.2% of the

study area, only one soil profile site is located on this SGU on the geologic map, of which the parent material however is classified as alluvial deposits. This situation again highlights the problem with fuzzy definitions that may overlap between closely related parent material units. Similarly, it may not be as important to the soil surveyors that the gravelly parent material is of ice-marginal origin, compared to alluvial, as it is to the geologic surveyor specialized on the quaternary. Similarly, on the SGU mire deposits the surveyors identified the soil parent material glacio-lacustrine deposits twice and till once, with the only soil profile with mire deposits as parent material being an anthrosol (filled mire deposit) located on the SGU till. The influence of stagnant water on both GLD and MrD can help understand the confusion between both units, and local mire deposits due to reduced permeability on clay-rich sub-glacial till is also rather likely. Given these local phenomena as well as the small number of sample profile sites, the topographical separation of the units IMS and MrD provides little relevant information, as does an analysis of soil type distribution.

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

The result of the feature selection procedure for predicting parent material classes was that, without exception, the SGU information from the geologic map was chosen first in every single feature selection run. This is important as it also contains information on the confusion between certain classes implicitly in the sample point data. Contrary to when investigating which terrain parameters best highlight the differences between two specific parent material units, local and regional terrain parameters, including relative elevations, were not identified as important predictor variables. Instead, the roughness-related measures dominated the selection process, even with the parameter set including all available terrain parameters, resulting in the choice of two of these measures and the SGU-information. The addition of further explanatory variables was not seen as an improvement with regard to both the model performance as well as its interpretability after evaluating some possible expanded models both with visual inspection of the results as well as the one-standard error rule (James et al., 2013). The reason for the decreased importance of regional, but also local, terrain parameters is that this information is already implicitly accounted for by the geologic map, as the various SGU classes are closely linked to certain relative elevations, especially the vertical distance to channel base level, due to overall geologic

structure of the study area. Additionally, at least to a certain degree, some units like till, slope debris or alluvial deposits also provide implicit information regarding slope angles. Furthermore, a certain amount of slope information is also included in the TRI, which increases with slope as well with increasing roughness. The vector ruggedness measure well compliments the TRI and the SGU as it provides information on surface roughness independent of the slope gradient. Figure 2 shows the original SGU map (A) as well as the parent material map based on SGUs, TRI and vector ruggedness (B). This modeled parent material map leads to an overall accuracy of approx.

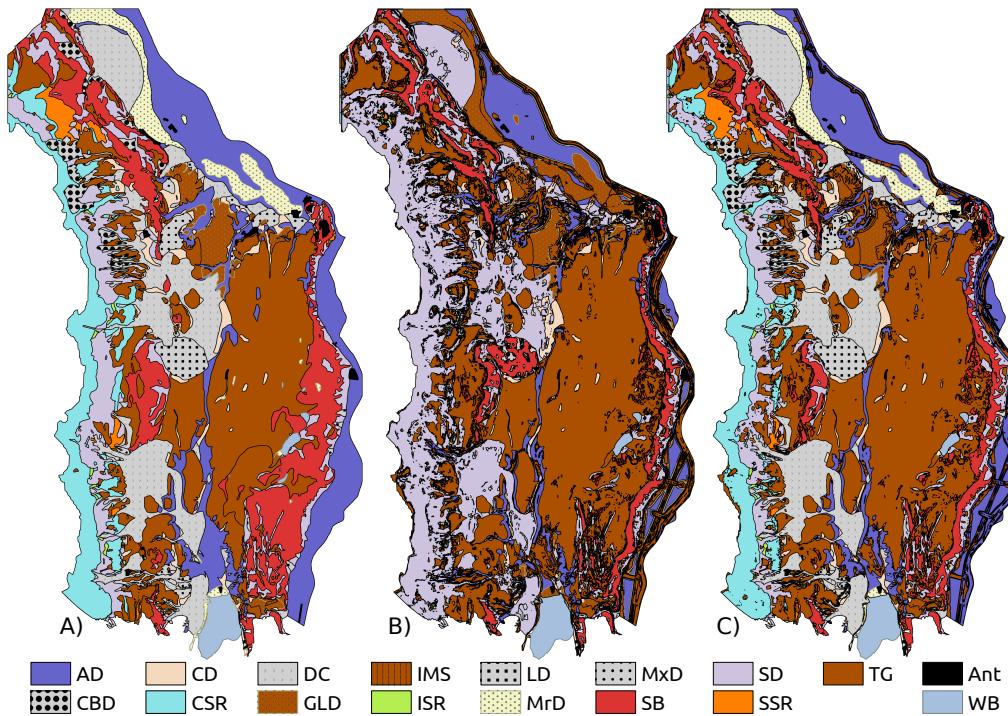


Figure 2: Original reclassified SGUs (A) and random forest-based parent material map modified based on vector ruggedness and TRI (B) and parent material map with only till modeled (C)

945 90%, however the out-of-bag correct classification rate= only 65%, implying quite substantial overfitting. Consequently, the predicted map must be evaluated with caution. A comparison of the resulting SGU map, adjusted only by adding two roughness parameters, with the original SGU map, reveals a considerable areal increase of the TG unit. This is perfectly understandable

950 given the low producer's reliability revealed in Table 3 by the high number  
of soil profile sites located on different SGUs but with TG as the surveyed  
parent material class. The most obvious errors linked to this unit are the  
roads as well as the mire deposits surrounding the large debris cone in the  
north, which are modelled as TG. Similarly conspicuous is the fact that the  
955 areas originally covered by the SGUs debris cones and mixed deposits now  
seem to be covered by the slope debris unit, which seems contrary to the  
good prediction results of these units. Detailed investigation into this is-  
sue shows that overfitting occurred in these cases, with very small, local DC  
and MxD polygons leading to the false impression of correct classification.  
960 On the other hand, the severity of this misleading results may appear less  
grave when considering the similarity of these three units. Given that they  
all represent material that has been transported down-slope by various pro-  
cesses and that their composition may in fact be the same in many cases, this  
misclassification may seem acceptable if one keeps in mind the information  
965 provided by the original map with regard to the geomorphological history  
of these units. Small units like CSR, ISR and SSR are taken over by slope  
debris and or till in a similar manner. An interesting unit in the predicted  
map is the former landslide deposit in the center of the study area. As the  
surveyors put more emphasis on describing the deposited material itself than  
970 its geomorphological history, the unit is now modelled as siliceous bedrock  
with coarse blocky debris, which well represents the view of the soil survey-  
ors. Another insightful aspect of the predicted parent materials are new,  
additional polygons which suggest small glacio-lacustrine deposits inside the  
largest till unit east of the Mitterberg. Based on the experience from pre-  
975 vious field work in this area, the authors deem this assumption worthy of  
future investigation.

After considering and evaluating the issue that arise with regard to the  
individual SGU as well as from modeling parent material for the study area,  
it was concluded that while the parent material is helpful in giving insights  
980 into issues that arise when using geologic maps and topography as a proxy for  
parentmaterial, to much of the information provided by the original SGU map  
is lost in the new, predicted parent material map. The under-representation  
of the class till, however, which had been identified as the main single issue  
when applying the geologic map for soil survey, seems to have dealt with  
985 appropriately by the random-forest classifier. Hence, a new approach was  
chosen by modelling only the till class and then overlaying this information  
onto the original SGU map. The forward step-wise feature selection pro-

cedure for the units till vs. not-till again chose one TRI and one VR map as model input features, but with slightly differnt window sizes (100 m and 990 102.5 m, respectively) than for the parent material model. This approach combines the models good performance with regard to modeling the often thin till layer, while retaining most of the information from the geologic map (Figure 2C), which can help in understanding the composition of slope debris and other transported materials. Compared to the original confusion matrix 995 (Table 3), the overall correct classification rate is improved form 49% to 65% with this approach.

#### *4.3.1. Discussion of accuracy*

As Olofsson et al. (2013) point out: uncertainty in remote sensing applications, but also in general, can be related to geolocation and interpreter 1000 variability. In this study...

-multiple interpreters, but not on same profiles, what about powell 2004 and their five interpretators

-Wickham 2013: constant communication in order to discuss and document difficult cases is important

1005 - in future: response protocols!

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

##### *4.5. General difficulties*

- confusion at categorical transitions
- 1010 • analyst biases (Foody 2010)
- Olofsson et al. (2013) state that with regard to reference labeling, in this case the parent material, difficult case need be noted for future reference and consensus development

##### *4.5.1. Differences with regard to mapping purpose*

1015 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 considered for mapping. Miller and Lee Burras (2015) note that 1020 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.

1025 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 differentiated between lodgement till and other glacial deposits, only when an decisively higher clay content was determined. On the other hand, the chemical properties, especially with regard to acidic properties of the tillic material 1030 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 1035 content of the different constituents of the moraine.

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

What is more important for soil mapping, the transportational history of material or information regarding its composition?

#### *4.5.2. Nomenclatural differences and overlapping classes*

1040 Congalton

#### *4.6. 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.

1045 4.7. Distribution of soil types with regard to geologic unit as well as parent material unit

4.8. 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 1050 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 hgh 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 1055 was lower for areas with complicated geologic histories.

#### *4.8.1. High relief areas and multilayering*

Are there thresholds regarding terrain parameters?

#### *4.8.2. thin cover layers of till - an essential new parentmaterial unit?*

Why is important to differentiate till and slope debris? While there may  
1060 exist situations were 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  
1065 expected, is this due to lateral consolidation of tillic material by glaciers in these U-shaped valleys?

#### *4.8.3. 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  
1070 the same components as till or hillside debris, which themselves are often the same...

### *4.9. 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.

## **1080 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  
1085

helpful for devising future sampling procedures and also for consideration when attempting to regionalise point information.

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**additional tables**

	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

<sup>1095</sup> **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.
- <sup>1100</sup> 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](https://doi.org/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](https://doi.org/10.2136/sh15-01-0001).

Coblentz, 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.

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 alpschallenges 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*

- 1135      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>.
- 1140      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](https://doi.org/10.1109/TGRS.2010.2053546).
- 1145      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>.
- 1150      Hobson, R.D., 1972. Spatial analysis in geomorphology. Harper and Row, New York. chapter Surface roughness in topography: quantitative approach. pp. 221–245.
- 1155      IUSS Working Group WRB, 2015. World Reference Base for Soil Resources 2014, update 2015 International soil classification system for naming soils and creating legends for soil maps. *World Soil Resources Reports* 106. FAO, Rome. Rome.
- 1160      James, G., Witten, D., Hastie, T., Tibshirani, R., 2013. An Introduction to Statistical Learning. Springer-Verlag New York. URL: <http://www-bcf.usc.edu/~gareth/ISL/index.html>, doi:[10.1007/978-1-4614-7138-7](https://doi.org/10.1007/978-1-4614-7138-7).
- 1165      Jenny, H., 1941. Factors of Soil Formation - A System of Quantitative Pedology. Dover Publications, Inc. New York.
- 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>. 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 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.
- 1170
- McBratney, A.B., Mendonca Santos, M., Minasny, B., 2003. On digital soil mapping. Geoderma 117, 3 – 52.
- 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.
- 1175
- Nellemann, C., Thomsen, M.G., 1994. Terrain ruggedness and caribou forage availability during snowmelt on the arctic coastal plain, alaska. Arctic 47, 361–367. URL: <http://www.jstor.org/stable/40511597>.
- 1180
- Nestroy, O., Aust, G., Blum, W., Englisch, M., Hager, H., Herzberger, E., Kilian, W., Nelhiebel, P., G. Ortner und, E.P., und J. Wagner, A.P.W.S., 2011. Systematische gliederung der bden sterreichs. sterreichische boden-systematik 2000 in der revidierten fassung von 2011. Mitt. sterr. Bodenkdl. Ges. 79.
- 1185
- 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).
- 1190
- Olofsson, P., Foody, G.M., Stehman, S.V., Woodcock, C.E., 2013. Making better use of accuracy data in land change studies: Estimating accuracy and area and quantifying uncertainty using stratified estimation. Remote Sensing of Environment 129, 122 – 131. URL: <http://www.sciencedirect.com/science/article/pii/S0034425712004191>, doi:<https://doi.org/10.1016/j.rse.2012.10.031>.
- 1195
- 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/S0014-4931\(07\)00020-2](http://www.sciencedirect.com/science/article/pii/S0014-4931(07)00020-2).
- 1200

[com/science/article/pii/S001282520800055X](https://doi.org/10.1016/j.earscirev.2008.04.003), doi:<https://doi.org/10.1016/j.earscirev.2008.04.003>.

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.

1210 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.

1215 Scholz, H., Bestle, K.H., Willerich, S., 2005. Quartärgeologische untersuchungen im überetsch. *Geo.Alp* 2, 1–23.

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](http://www.laimburg.it/de/projekte-publikationen/blickpunkte.asp?news_action=300&news_image_id=828290).