

# 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

Geologic maps have always been an important aid in soil survey as parent material is a decisive factor in soil formation (Jenny, 1941). The importance of this relationship is highlighted by the fact that, vice versa, soil maps have themselves been applied to support and improve geologic mapping (Brevik and Miller, 2015). Providing both the physical structure and the chemical composition of the mineral constituents, parent material plays a fundamental role regarding the direction as well as speed of soil evolution. This is particularly the case in young soils (e.g. Schaetzl et al. (2000)) such as those predominantly found in the Alps (Geitner et al., 2017). Thus, in order to understand the spatial pattern of soils in the Alps, it is essential to identify the types and origins of parent materials, which are, at least in the lower and medium elevations of the Alpine environment, dominated by quaternary unconsolidated sediments. These deposits vary considerably in thickness; they are often multi-layered and exposed to recent morphodynamics, all of which control soil horizon development and properties (Phillips and Lorz, 2008). In this context, it is indicated to include characteristics of the subsolum as often as possible, mainly in order to make soil information more suitable for a wide range of environmental issues, as discussed in detail by Juilleret et al.

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20 (2016). Consequently, geological maps at various scales have been used as an environmental variable in digital soil mapping (DSM), representing the soil forming factor parent material, or simply 'p'. In their study which presents the 'scorpan' framework of inferring soil information, McBratney et al. (2003) present a table of studies applying DSM, which also indicates in which of  
25 these studies the parent material was involved as an independent variable. In their study which models the carbonate-free depth of soils in Switzerland, Fracek and Mosimann (2013) attribute a large part of the modelling error to discrepancies between the map units of geologic maps and the actual soil parent material, highlighting the importance of this specific environmental  
30 variable in soil modelling. 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 for soil description, the Food and Agriculture Organization of  
35 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). While the lithologies regarding bedrock as parent material are similar to the types in the classification system used by the surveyors  
40 employed by the Forestry Services of the Autonomous Province of Bolzano - South Tyrol as well as North Tyrol (Englisch and Kilian, 1999; Amt der Tiroler Landesregierung, unknown), this 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  
45 posed by the diversity of the glacial deposits, but also the more recent deposits which are driven mainly by the high relief present in Alpine regions. While such an adaptation of the classes and types of soil parent material to the given circumstances is certainly necessary, communication between soil scientists regarding soil parent materials and comparability is hindered by  
50 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. A number of studies have compared the information from soil surveys with geologic maps. Juilleret et al. (2012)  
55 for instance compared C horizon data from soil profiles with parent material as derived from a geologic map, concluding that surficial geologic maps can be impored with available soil profile data. They also highlight the ne-

cessity of improved communication and exchange between the two sciences. Miller and Lee Burras (2015) compared surficial geology maps produced by  
60 a Geological Survey with comparable maps produced using Soil Survey maps of higher spatial resolution, reporting an agreement of 81%. In their review covering the subject of improving geologic maps with soil maps, Brevik and Miller (2015) argue that information from both mapping approaches should be integrated, but always under consideration of the limitations and differences  
65 between the disciplines. Whereas most of the previously mentioned studies analyse the possibility of using soil survey information, which generally comes at a higher spatial resolution, for mapping surficial geology, the aim of the presented study is to analyse the application of detailed geologic maps as parent material maps, highlighting those geologic units of the  
70 study area where the derivation of soil parent material from geology is not as straightforward as assumed.

A second 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 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  
75 be taken into account when choosing which parameter groups to investigate. 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  
80 to infer soil properties and give insight into local dynamics, but may also vary strongly within a map unit. To characterise parent material units, especially with regard to topographic, and as a result, soil, variability, an intermediate terrain parameter describing a unit's land surface is of particular interest. Researchers have long investigated ways to quantify the roughness  
85 or ruggedness of terrain, from the analysis of field data and topographic maps to computing roughness indices on raster grids. Geology, geomorphology as well as habitat modelling and wildlife management have been the main scientific research areas in which such investigations were performed on land surfaces. Hobson (1972) presented three different roughness values and applied them to field measurements, correlating them to rock type. Beasom  
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et al. (1983) and Nellemann and Thomsen (1994) applied contour line analysis as a way of characterizing terrain ruggedness. Grid-cell based roughness measures were proposed as the topographic roughness index (TRI) by Riley et al. (1999) or the vector ruggedness measure (VRM) by Sappington et al. 100 (2007), who expanded on the work of Hobson (1972). Similar approaches based on eigenvalue ratios of an orientation matrix were proposed for application in geology for instance by Woodcock (1977) and Coblenz et al. (2014).

The objective of the presented study is to evaluate how to make best 105 use of available geologic and topographic information for soil survey. The study area in the Überetsch/Oltradige region of the Autonomous Province Bolzano – South Tyrol was chosen for its detailed geologic maps as well as the diversity of soil forming factors, especially geology and topography. By applying random forest classification and feature selection, we investigate 110 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 115 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. We highlight those units where there is often dissent between soil parent material as mapped by the soil surveyor and the geologic units 120 mapped by geologists. The main aim of the random forest classification is to identify the topographic characteristics of the parent material units in order to facilitate future, more detailed soil surveys, and not necessarily to improve the geological map with regard to its application as a parent material map.

## 2. Study area and data

### 125 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 – 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 130 Etsch River. The western border of the study area is the steep slope of the Mendola-Roèn-Ridge (max. 2116 m.a.s.l.), whereas the eastern border of the

Überetsch as well as the study area is represented by the the Mitterberg, a ridge of Permic Vulcanites from which steep slopes descend to the Etsch Valley (approx. 200 m a.s.l.). The Kalterer Lake represents the southern limits of  
135 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 Mendola-Roèn-Ridge. Figure 1 shows the study area as well as  
140 the surficial geologic units and soil profile locations. The study area is characterised by the mild and humid transition zone between the Mediterranean and Continental climate zone. The longtime mean annual precipitation in Montiggl, located in the southeastern quadrant of the study area is 802 mm along with longtime mean annaul temperature of 11.9° (Thalheimer, 2006).

#### 145 *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 paleovalley of Überetsch is described by Scholz et al. (2005) as a complex system of gravelly lateral moraines and large kame terraces, the result of the  
150 'Kaltern lobe', a Pleniglacial tongue of the Etsch valley glacier. Additionally, laterally eroded remainders of debris fans that were deposited against the retreating glacier can be found along the slopes of the Mendola-Roèn-Ridge, as well as recent debris flow deposits, often composed of mainly limestone and dolomite fragment. The vale bottom itself is filled with Pleistocene sediments  
155 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 Permic igneous Rhyolite and Lapilli-Tuff are responsible for a hilly relief, most 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  
160 Mitterberg with an elevation difference of approximately 400 m. The steep slopes of the Mendola-Roèn-Ridge are dominated by various Dolomite units, with intermittent layers of sand and siltstones. Except for the very steep Dolomite walls of the ridge, the rarely occurring outcrops of these formations are surrounded and mostly covered by Pleistocene and Holocene slope debris, and in locally flatter areas by till.

The study area comprises two map sheets of the new geologic map of Italy, sheet Eppan, which covers the northern and major part of the area, as well as sheet Mezzo-Lombardo in the southern part. The sheets were published at a

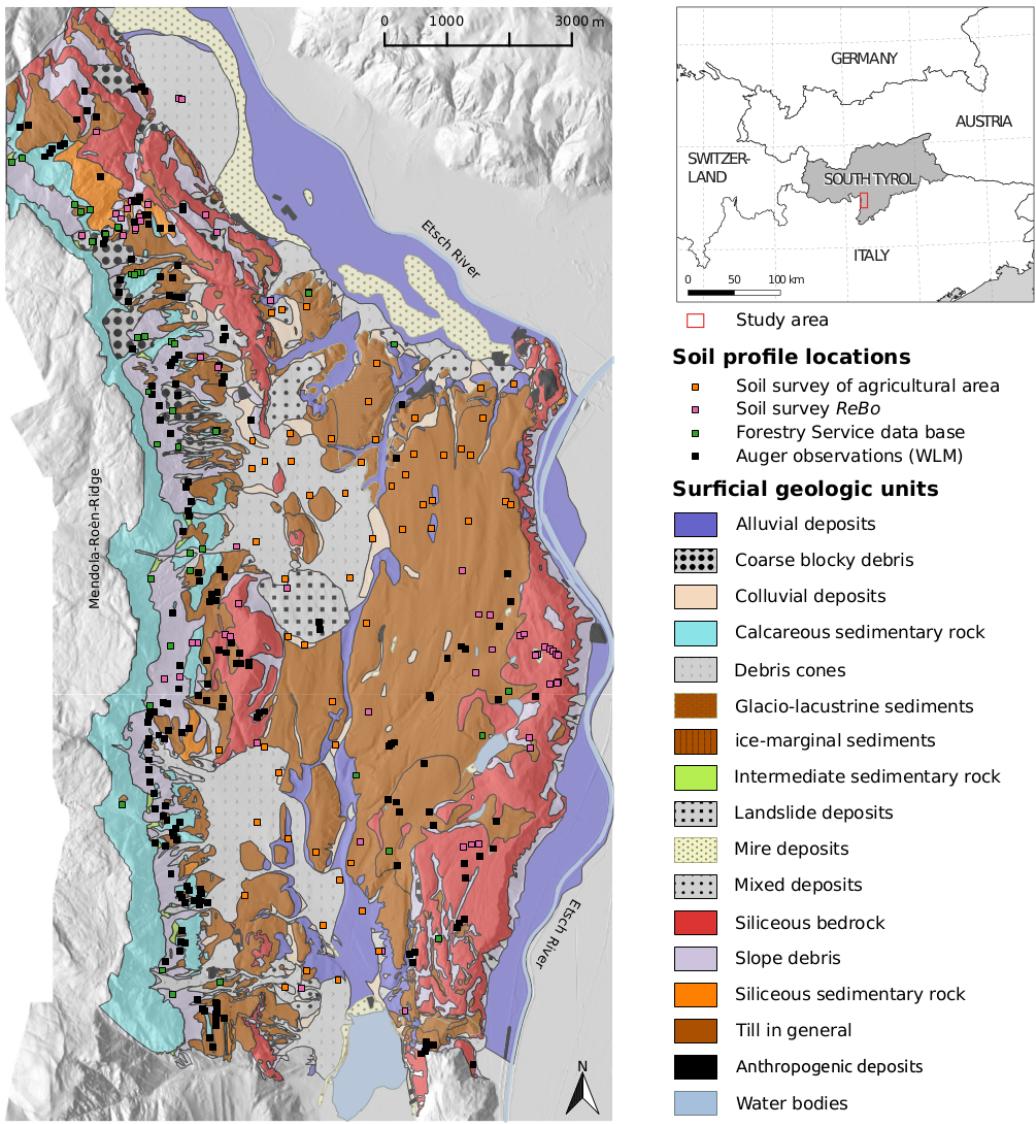


Figure 1: Overview of the study area showing the surficial geology as well as the locations of the soil profile sites analysed in this study. Computations were performed only for the areas covered by surficial geologic units.

scale of 1 : 50,000 in 2007 and 2012, respectively. Mapping was performed at  
 170 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

study.

For simplification of the analysis and data harmonisation, the original geologic map units were generalised into the 16 surficial geology units (SGUs) described in Table 1, that allow 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
glaciolacustrine 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	silt- and sandstones	1.1
till in general	TG	undifferentiated glacial deposits	25.9

Table 1: Generalised surficial geology units in alphabetic order with abbreviations and short descriptions. Additionally, the proportion of the study area covered by each unit is given. Anthropogenic deposits are not included in the analysis.

### 2.3. Soil data sets and soil classification

Figure 2 gives an overview of the distribution of the soil types amongst the soil profiles incorporated into the analysis and located within study area. The soil classification scheme applied in this study is the Austrian system (Nestroy et al., 2000, 2011), as most of the soil profile descriptions available for this study apply this system which is also well adapted to the Alpine environment (Baruck et al., 2016). Furthermore, it is generally recommendable to use local systems for large-scale mapping and 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). Table 2 gives an overview of which reference soil groups are best 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).

*Soil 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

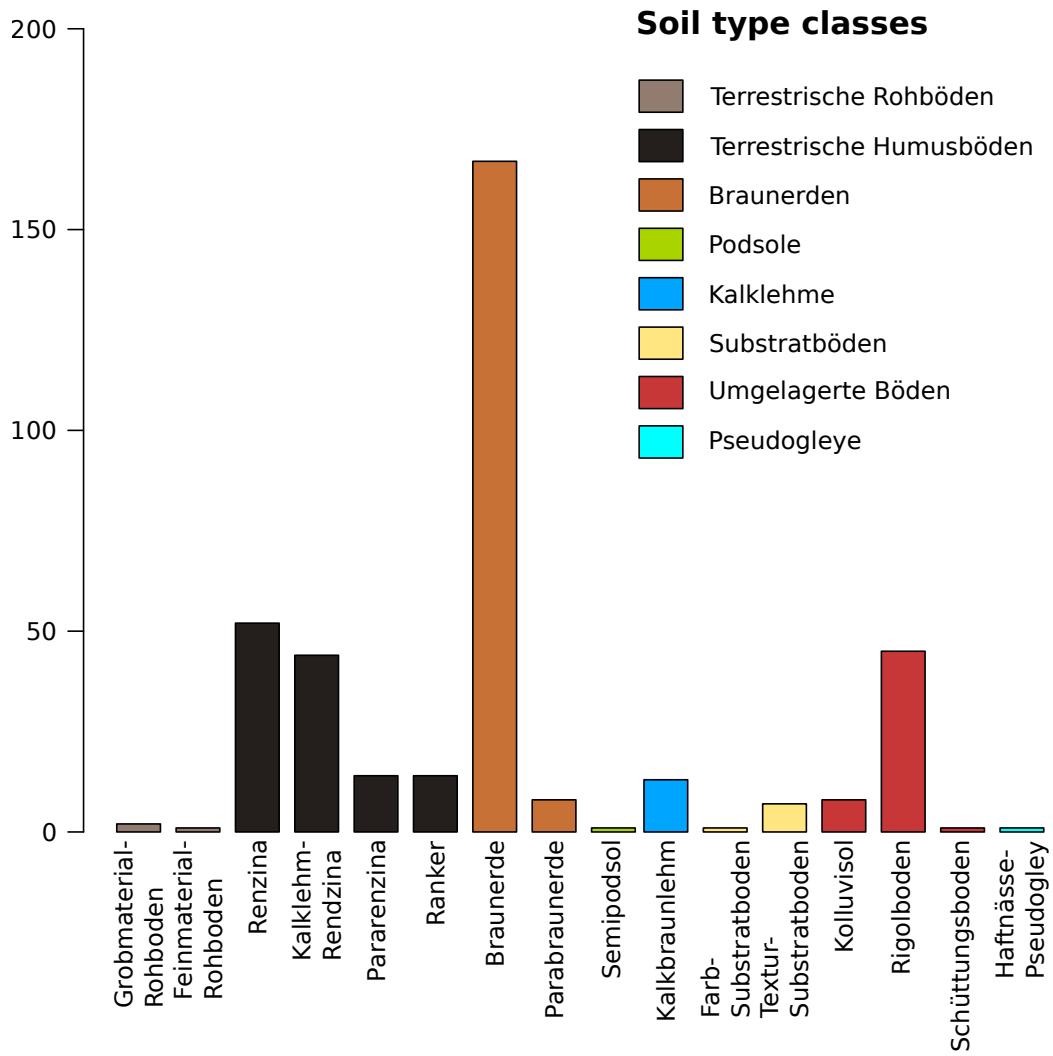


Figure 2: Barplot showing the number of soil profiles for each of the soil types identified at least for one of the data points in the study area. Coloring indicates the soil type classes. Classification was performed according to the Austrian soil classification (Nestroy et al., 2000, 2011). Relationships with WRB reference groups can be found in Table 2

<sup>195</sup> 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

soil type	corresponding groups	WRB	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 ( $A_i$ horizon) on parent material with less than 40 V.-% coarse fraction	Terrestrische Rohböden
Rendzina	Leptosols, Histosols		only an A or organic horizon on calcareous bedrock.	Terrestrische Humusböden
Kalklehmrundzina	Leptosol		soils with a loamy A horizon on calcareous bedrock.	Terrestrische Humusböden
Pararendzina	Leptosol, Regosol, Umbrisol, Histosol		only an A horizon on carbonate-containing unconsolidated sediment or bedrock.	Terrestrische Humusböden
Ranker	Leptosol, Umbrisol, Regosol		only an A or 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 A horizon over clay-enriched B-horizon.	Braunerden
Semipodsol	Podzol, Regosol		characterized by moderate podzolization.	Podsole
Kalkbraunlehm	Cambisol, Luvisol		with a yellow- to redbrown cohesive B-horizon on calcareous bedrock, often fossil soils	Kalklehme
Farb-Substratboden	Regosol, Luvisol		strong influence of color of parent material, overprinting horizon differentiation	Substratböden
Textur-Substratboden	Regosol		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
Haftnässe-Pseudogley	Stagnosol, Planosol		influenced by shallow, capillary stagnation phases	Pseudogleye

Table 2: Corresponding WRB reference groups for the Austrian soil types encountered in the study area, along with a simplified description based on Nestroy et al. (2011).

properties as well as photographs of the pit face, these soil profiles were  
200 reclassified applying the Austrian System (Nestroy et al., 2000, 2011).

Soil 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  
205 profiles were described in the presented study area based on field work in 2014 and 2015. In addition to detailed soil profile descriptions, grain size distribution and pH analyses were performed in the lab. Soil classification was performed following Kilian (2015), based on Nestroy et al. (2000, 2011).

Soil data base 3: data base of the Forestry Service of the Autonomous Province  
210 Bolzano – South Tyrol. From the point data base provided by the Forestry Service of the Autonomous Province Bolzano – South Tyrol, 42 soil pit locations are situated in the study area discussed in this article. For each of these sites, which either belong to the Forestry monitoring scheme or were mapped during the course of the Forestry type survey (APB, 2006), soil type, parent material and a detailed soil pit description are provided.  
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*Soil data base 4.* While performing field work for the Forestry type survey (APB, 2006), the engineering office 'Wald Landschaft Mensch' (WLM) also produced a model of the forest substrate for South Tyrol for use in modeling forest types. For validation, a large number of augur points were described 220 and geolocated, of which 227 are located within the study area and were kindly provided by the company. The information for each point includes the soil type as well as a description of the geologic situation, including information on cover layers if present.

#### *2.4. Digital terrain model*

The digital terrain model applied in this study has a grid cell size of 2.5 m and was computed as the result of an airborne laser scanning mission. For the flatter valley bottoms and densely inhabited areas, the average achieved last-pulse point density is reported as 1.3 pts/m<sup>2</sup> by Wack and Stelzl (2005), while this measure is lower for the remaining, less populated 230 areas and mountain (0.8 pts/m<sup>2</sup>). Using 8 independent sites with 60 ground points for elevation accuracy assessment, the average standard deviation of heights was established as 6.7 cm. While all tiles were previously available for download at the homepage the Autonomous Province of Bolzano – South Tyrol, they entire data set is provided freely only upon request per email, 235 while smaller areas can still be downloaded. In addition to being used at this high resolution, the DTM was also resampled to 10 and 50 m, using average aggregation with the tool 'r.resamp.stats' implemented in GRASS GIS (GRASS Development Team, 2016), in order to consider the issue of scale in the analyses.

### **240 3. Methods**

#### *3.1. General workflow*

In a first step we investigate how well the geologic units of the high (both spatial and thematic) resolution geologic map correspond to the parent material identified by the soil surveyor at the soil pit locations, thus evaluating 245 the performance and reliability of available geologic maps to support soil survey in South Tyrol. This is of special interest as, while the quaternary deposits were often neglected in older geologic surveys or aggregated in a single unit, the new generation of geologic maps created within the CARG (Geologic and geothematic cartography of Italy) framework exhibit high detail

250 regarding these surficial deposits. This data comparison requires generalisation  
of the geologic map units into surficial geology units (SGUs) that can  
be compared to the parent material units used in the various surveys that  
contributed to the used soil data set. The result is a confusion matrix that  
shows to which extent geologic units are in accordance with the parent ma-  
255 terial mapped by the surveyor. We consequently emphasize those units that  
are often confused or show overlap, and which should therefore be surveyed  
with greater detail and in consideration of relevant topographic information.

260 The next step, a data mining approach using random forest classification,  
is performed to better understand the topographic characteristics of the sur-  
ficial geologic units. 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 geo-  
265 logical map units. An emphasis is set on the roughness measures, which  
are deemed best suited to enhance the geologic map, as the geological units  
already implicitly contain information with regard to regional and local ter-  
rain parameters. The results are presented in detail only for the area-wise  
most relevant geologic units, focussing on separating those units which share  
common borders.

270 The connection between the two important soil forming factors, parent  
material and topography, on the one hand, and soil as the result of theses  
factors on the other, is then investigated by analysing the diversity and dis-  
tribution of soils for each geologic unit. This is performed from two points of  
view: the soil type distribution is done for profile sites per geologic unit, but  
275 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.,  
2000, 2011). The synthesis of this information then leads to a geologic-  
topographic characterisation (GTC) that describes each geologic unit.

### *3.2. Terrain parameters with emphasis on roughness measures*

#### *3.2.1. Local and regional terrain parameters*

280 The terrain parameters used in this study were computed using the open  
source GIS GRASS (GRASS Development Team, 2016) and SAGA (Conrad  
et al., 2015). They were performed at different spatial resolutions (2.5, 10  
and 50 m) and, where applicable, at different moving window sizes. Local

290 terrain parameters, including slope and minimal, maximal, profile, longitudinal as well as cross-sectional curvature were computed based on the algorithms of Wood (1996) as implemented in the tool 'r.param.scale' in GRASS, which allows varying the computational window size. Regional terrain parameters, amongst them catchment area, topographic wetness index, height above channel network and others, were computed with SAGA both at high (2.5 m) and low (50 m) spatial resolution.

### 3.2.2. Surface roughness-related terrain parameters

295 *Topographic roughness index.* The topographic roughness index was presented by Riley et al. (1999) for use in habitat analyses. It compares the elevation of a central pixel to the elevations of cells within a given search window by calculating the square root of the sum of the squared differences.

300 *Terrain texture.* In their automated landform classification algorithm, Iwahashi and Pike (2007) present terrain texture, or feature frequency, which can also be interpreted as a measure for surface roughness. This measure is quantified by the number of features, i.e. pits or peaks, in a specified search window. These features are extracted by computing the difference between a DTM and its median-filtered version.

305 *Vector-based roughness measures.* 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. Its implementation as the tool 'r.vector.ruggedness' in GRASS was used for computation in this study. Grohmann et al. (2010), who also authored GRASS ('r.roughness.vector') 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.

320 *Landform diversity.* Landform diversity can also be interpreted as a form of surface roughness, i.e. a high number of landforms in a given search window signifies high terrain roughness. (Jasiewicz and Stepinski, 2013) present an automated landform classification based on a pattern-recognition approach using line-of-site calculations. The two main parameters that can be tweaked for landform segmentation are the search radius up to which the surroundings

of a central raster cell are scanned and the flatness threshold angle, under which a surface is considered as flat. In this study, the resulting map featuring a maximum of ten landform classes is used as the input for the calculation of patch indices such as edge density or mean patch size (mps) and diversity indices like dominance of richness with the GRASS module 'r.li' for landscape structure analysis. The landform maps were calculated at micro and meso scale(search radii of 7.5 and 50 m, respectively) applying flatness thresholds of 1 and 10°.

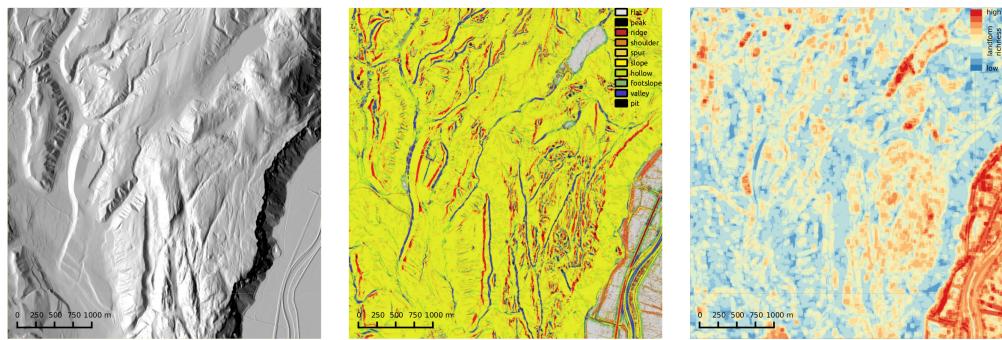


Figure 3: Richness.

### 330 3.3. Random Forest classification

Random forests (Breiman, 2001) belong to the family of machine learning algorithms, meaning that based on test data, statistical patterns between explanatory variables and the dependent variables are sought and then applied to predict the latter based on new data sets comprised of the dependent variables. A comparison of machine learning approaches for classification in soil mapping can be found in Heung et al. (2016). Contrary to single classification trees, random forests use an ensemble of classification trees to predict class affiliation, each based on a bootstrap sample of the test data and a limited number of randomly chosen explanatory variables. Random forest classification as implemented in the R (R Core Team, 2014) package 'randomForest' also has the advantage of computing variable importance measures such as 'mean decrease accuracy' and 'mean decrease Gini' that provide insight into the role and importance of each predictor variable in a specific model.

345 In this study a five-fold cross-validated forward step-wise feature selection  
was performed with random forest classification to produce a parent mate-  
rial map of the study area. Feature selection was performed to identify a  
small number of parameters capable of turning the geologic map into a par-  
ent material map. In contrast to using all possible terrain parameters, this  
350 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 iden-  
tify, highlight, and understand situations where the most confusion between  
parent material units as documented by surveyors and the geologic map oc-  
cur. Additionally to a large number of terrain parameters, the geologic map,  
355 reclassified to the SGUs in Table 1, was added to the set of explanatory vari-  
ables from which the random forest classifier could add features to the model.  
The unit mire 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,  
360 3) regional terrain parameters, 4) surface roughness-related parameters.

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

- 365 • To expand the geological map to a parent material map by modeling  
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  
370 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  
375 characterise the SGUs as described by the geological map

## 4. Results and discussion

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

For the following results and discussion, the confusion matrices and the accuracy measures are calculated and interpreted 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. 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 misclassification.

A first view at the confusion matrix (Table 3) indicates that a considerable amount of these misclassifications involve the classes till and slope deposits.

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

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

### 4.2. Geologic-topographic characterisation of the predominant SGUs

Through synthesis of i) results of the comparison of the soil point data and the geologic map, ii) the random forest analysis of terrain parameters

and iii) the distribution of soil types in the study area, a geologic-topographic characterisation (GTC) of the SGUs for use in soil survey is performed. Only  
395 those units with substantial areal extent and sufficient soil profile points are described in detail.

#### 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  
400 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  
405 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  
410 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  
415 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  
420 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 paleoval-

430 ley. 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 435 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-Ro n-Ridge and the flatter valley bottoms.

440 Figure 3 gives an overview of the distribution of three roughness measures for the most common SGUs from the point of view of both the geologic map (large boxplots) as well as the surveyors (smaller boxplots incorporated in the larger boxplots). It also differentiates between those soil profile sites for which the classification by surveyor and SGU map agree (green), and those for which this is not the case (red).

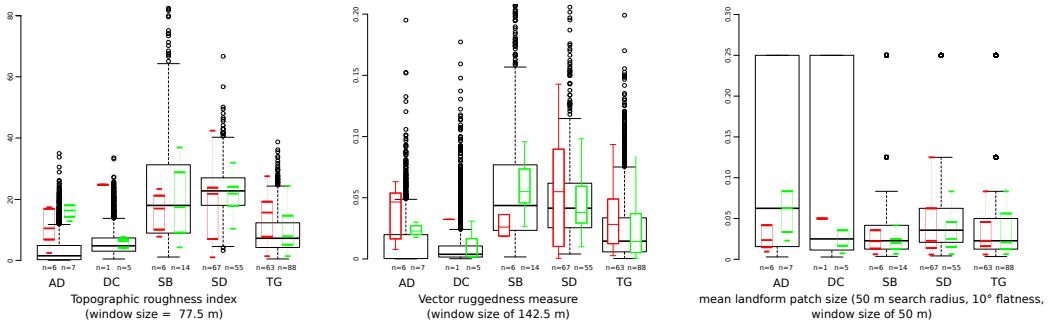


Figure 4: Boxplots of three different roughness measures for the most common and confused parent material classes. The large black boxplots characterise the topography of the respective units of the geologic map, while the smaller boxplots inside the larger ones represent the values of the soil profile sites for which the surveyors identified the corresponding parent material class. Green boxes indicate the distribution of the terrain parameters for those profile sites for which surveyor and SGU map agreed regarding the parent material, whereas red boxes represent sites located on a different SGU.

445 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 450 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  
455 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  
460 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  
465 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  
470 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  
475 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,  
480 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  
485 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 characterised by higher vector ruggedness values. Given the strong confusion with the unit till, as well as the fact that these two units share a long border, it is of interest to examine the topographical differences between points that are attributed to one of these two parent material units. The TRI at a window size of approx. 100 m leads the terrain parameters with a 5-fold cross-validated classification error of approx. 15 %. The minimum curvature based on the 10 m grid performs best from the group of local terrain parameters. In general, soil profile sites with SB as parent material are characterised 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, confu-

sion with slope deposits is present from both the user's and the producer's point of view. The random forest-based data mining shows that, regarding the parent material as indicated by the surveyors, the terrain parameters that are most characteristic of the difference between the two units are based  
 530 on landform diversity. In the case of SB and SD, the patch density of the geomorphon-based landform map computed with a lookout distance of 7.5 m helped separate the two parent units due to the latter groups lower values, implying that areas of slope deposits have a slightly more homogeneous landform distribution, in the specific case large polygons of the landform slope,  
 535 apparently a good indicator for slope debris. Furthermore, the same TRI applied to separate SB and TG can also be a very useful addition to the parameter set when distinguishing SB from SD. An investigation into the



Figure 5: 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 43. C) soil profile site 39. 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.

soil types classes of the soil profile sites located on the SGU siliceous bedrock shows that brown soils are the dominating soil type, represented by 37 of the  
 540 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 identified SB as parent material, whether or not  
545 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 material, however one soil profile site with this  
parent material was attributed the soil type Grobmateriale-Rohboden. This  
550 soil type however does fit well for soils on siliceous bedrock outcrops, were  
only initial soil formation is possible, whereas the other soil types located  
on the SGU of the geological map are less plausible on SB, especially Kalk-  
braunlehm. In addition, the vast majority of the soil profile sites located on  
this SGU but identified to have a different parent material class (mostly till)  
555 by the surveyors, also feature the soil type Braunerde, thereby decreasing the  
severity of misclassifying SB and TG, at least from a soil type perspective.  
Figure 4D shows an example of such a situation, consisting of a brown soil de-  
veloped from a cover layer of till on siliceous bedrock. From this perspective,  
the soil type Ranker is more characteristic of the SB unit, as it is less com-  
560 mon on TG with its characteristically more developed soils and the increased  
influence of calcareous materials. Furthermore, an examination of the points  
were parent material classes from observation and SGU map coincide, shows  
a decrease in dominance of brown soils compared to Rankers, with propor-  
tions of 57 and 35 % for both soil types, respectively. This is also well in line  
565 with the fact that SB sites are characterized by higher roughness values and  
situated on convex, ridge-like structures where decreased soil formation can  
be assumed. In conclusion, the soil types Braunerde and Ranker are charac-  
teristic of this unit, with the former representing locations were weathering  
and clay-reformation has led to horizon differentiation not present in the less  
570 developed Ranker soils which are found on siliceous bedrock outcrops. Fig-  
ure 5 shows the distribution of soil types on alluvial deposits as well as other  
SGUs from different points of view, i.e. according to the SGU map, the soil  
survey, and a union of both.

#### 4.2.3. *Till in general*

575 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  
borders with every single SGU, the longest, each with a length of at least  
580 30 km, being those with the SGUs alluvial deposits, siliceous bedrock and

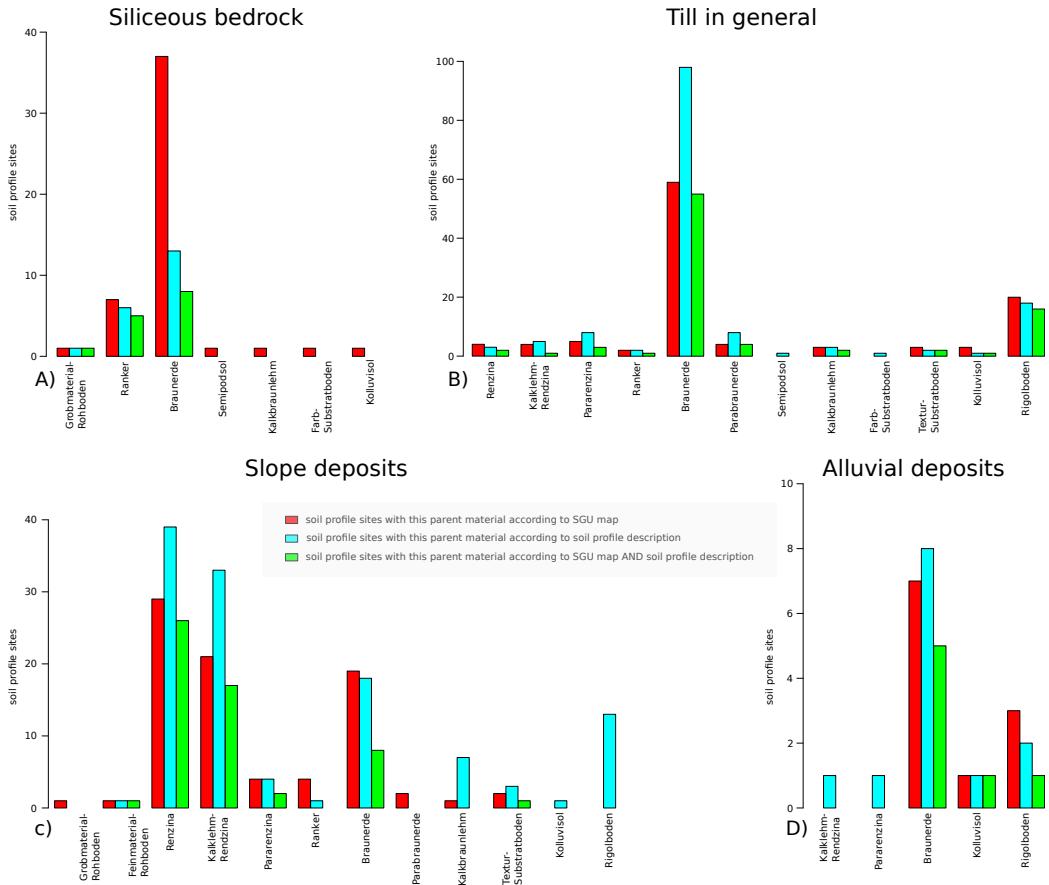


Figure 6: Distribution of soil types for the most common SGUs or parent material units from different points of view. Red bars indicate the number of profile sites with this soil type according to the SGU map while the turquoise bar represents the number of profile sites for which the surveyors identified this parent material, regardless of the SGU it is located on. The green bar shows the number of profile sites for which both points of view agree.

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, leading to a user's accuracy of 80%. The majority of the other soil data points on this SGU were attributed the parent materials slope deposits or mixed deposits, with some intermediary sedimentary rocks also identified as parent material. While the user's accuracy for till is the best amongst the SGUs, the producer's reliability is not comparable, as the surveyors also identified

till as the parent material at 63 further locations on different SGUs. The  
590 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  
units SSR, MxD, MrD, GLD, DC, CBD and AD. An important takeaway  
595 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.

A topographic comparison of those points with till as parent material  
600 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 char-  
acterized by a higher roughness (mean TRI of 25 compared to 13 for the  
correctly classified group) and steeper slope (mean value of 21 compared to  
12°). Regarding confusion with the soil parent material unit calcareous sedi-  
605 mentary 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-  
ues in the upper quartile of the values characteristically displayed by TG  
610 profile sites. Of the local terrain parameters, slope, together with minimal  
curvature, performs well in separating the points of both groups, but not as  
clearly as it separates both units on the geological map, as TG profile points  
in the study area can be found at slope values higher than indicated in the  
geological map. To characterise the difference of the TG sites with slope de-  
615 posits, the TRI with a window size in the range of 100 m performs best of all  
local, regional and roughness-related terrain parameters in the forward step-  
wise feature selection. Similar to the situation with CSR, slope is the best  
performing local terrain parameter, but as before, the separation is clearer on  
the geological map, signifying that till can be found at steeper angles than ex-  
620 pected 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  
from the random forest-based investigation. For instance when compared  
625 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 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.

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 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 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 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 (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 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 area. Its by far longest border is shared with the unit siliceous bedrock, 665 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 user's accuracy than producer's reliability, as surveyors established slope debris 670 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 the case with the SB unit, some of this confusion may be attributed to thin 675 layers or punctual deposits of till. Considering slope debris, another important aspect is that the debris in question may very well be composed of till material that has been transported gravitationally. The same explanations may hold for other parent materials which were identified on the slope debris unit, especially for the bedrock units SB, ISR and CSR. While some isolated 680 outcrops are possible, the most likely cause is that the constituents of the slope debris are so dominated by transported material of one of these bedrock classes, that the surveyors determine this unit as the parent material of the examined soil profile. On the other hand, misclassification between the units coarse blocky debris and slope deposits can be attributed to the fuzzy border 685 between these units, ultimately linked to the grain size distribution, and the subjective interpretation thereof, especially during field survey. Contrary to most other SGUs (with the exception of CBD, LD and MxD), this unit itself does not provide information regarding the mineralogy of its component, which can only partially be derived through interpretation of its location in 690 the catchment and the uphill geologic situation. Consequently, this unit is much better described by its topography than its material, as the latter may be highly diverse.

Those profile sites for which the geological map correctly proposes slope debris as the soil parent material differ from the slope deposit points on 695 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

according to the geological map, which are good examples of the mentioned  
700 situation. This is presumably closely related to the furrowed and disturbed character of debris cones in the southern half of the study area, where the situation may not present itself clearly during field survey. Additionally, the material composition as well as its origin is basically the same for slope debris and debris cones in this area. Topographically, roughness measures  
705 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 slope debris if the topography does not show the low roughness and slope  
710 values characteristic of debris cones. This difference of roughness and slope with regard to the conceptual difference of slope debris and debris cones is also apparent when comparing the topography of both units as delineated by the geological map, however the difference is more distinct in this case. Similarly, calcareous sedimentary rock as parent material seems connected  
715 to roughness values slightly higher than those present for the average slope debris site, a relationship which is again more pronounced in the geological map. Consequently, it is in these transitional zones where the misclassification occurs. This topographical proximity of the units is of course reinforced by the fuzziness of distinguishing between the two parent materials as such. As  
720 is the case with siliceous bedrock and slope debris, the border between the source material, in this case the calcareous bedrock, and its derivative, the slope debris, is often not clear when considering the parent material of a soil profile. The degree of weathering of the source material certainly adds to the confusion. The issues are comparable for the parent material units  
725 intermediate and siliceous sedimentary rock. While the gradual transition from source material, in these cases bedrock of differing mineralogical composition, to slope debris poses various issues that cannot be explained only by topography, this is even more the case when considering the possibility of confusion between slope debris and coarse blocky debris, the distinction  
730 between which raises a number of questions with regard to the objectivity of estimating block or grain size of soil profile parent material. Misclassification between the units slope debris and mixed deposits are also predominantly a question of definition and the explanatory power of topography is very limited.

735 Given its confounding nature, due to its dynamic topography and great variability of components, this unit shows a high diversity of soil types, en-

compassed 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 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 Kalklehme 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%) 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 Kalklehme-Rendzina) more prevalent than their siliceous counterparts, especially when considering 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.

#### *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  
775 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  
780 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  
785 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  
790 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  
795 important parameter in this case is slope height. This is to be expected,  
since the main difference is the vertical position in the overall geological  
structure of the study area, a difference which is however diminished by the  
above mentioned intermittent layering and gravitational movement down-  
slope, in addition to the above discussed problem regarding the definition of  
800 slope debris versus weathered bedrock.

The Rendzina is the typical proponent of soil types on calcareous sedi-  
796 mentary 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 ma-  
terial. 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  
805 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 con-  
sidering only the soil profile sites that qualify for CSR parent material from  
810 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 developement on this map unit, 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 paleavalley, between the slope debris of the Mendola-Roèn-Ridge slope in the west, which are often the source area of these deposits, and the till deposited in the paleovalley in the east. 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 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 the source of the debris cones material is mainly the slope debris and the calcareous bedrock units which themselves are the origin of the slope debris, this misclassification may seem acceptable. In fact, it rather points out a difference in the point of view of the soil and the geologic surveyors, where the first are interested in the material and the latter more in the landform presented by the debris cones unit. The remaining misclassifications are all with units that border this SGU, or, in the case of intermediate sedimentary rock, are located in the source region of the the debris cones.

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.

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 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 profiles have experienced vertical anthropogenic rearrangement, in an effort

to enhance the general conditions for viticulture and horticulture. Soils with  
850 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 difference, as discussed in section 4.2.4.

855 *4.2.7. Intermediate sedimentary rock and siliceous sedimentary rock*

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 only a limited amount of outcrops. Another common characteristic is that  
860 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  
865 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 that the layers are correctly located on the geological map with regard to  
870 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 area. Gravitational transportation leads to these materials serving as soil  
875 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 section, topographical separation is limited for these units.

880 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 having ISR or SSR as parent material are of the classes Braunerde or Kalk-lehme, i.e. soils with A and B horizons. More expected is the presence of  
885

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 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 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 4D 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 unit located downslope of the layers.

#### 900 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 the soil surveyor may value the information with regard to the mineralogy 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 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 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 unit, the surveyors explicitly chose the parent material siliceous bedrock for  
925 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 influences their classification, each highlighting a different aspect of the same  
930 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.

935 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 also link this parent material unit to a less developed soil like Ranker. In  
940 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 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.  
945 But as this parent material can actually be till or calcareous sediments transported from up-slope locations, the soil types Braunerde and Kalklehme are good fits and show that confusion between the units does not lead to severe  
950 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.

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

955 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 northern border of the paleovalley. The producer's reliability is below 0.5,

960 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 fluviaile or hydromorphic history, although the other misclassifications do indicate the possibilty of local glacio-lacustrine deposits as the parent material on these  
965 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 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 on SB as possible GLD areas. Regarding soil type, investigations from both  
970 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 mapped a hydromorphic soil type, in this case Pseudogley.

975 980 Ice-marginal sediments are closely associated with till units and are mostly located in close proximity, consequently shareing 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.  
985 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 querternary. Similarly, on the SGU mire deposits the sur-  
990 veyors 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  
995 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 the most 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 (TRI with a window size of 77.5 m and VRM with a window size of 142.5 m) 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 the general 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 some roughness measures, especially the TRI, which increases with slope as well with increasing roughness. The vector ruggedness measure well complements the TRI and the SGU as it provides information on surface roughness independent of the slope gradient. Figure 6 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. 90%, however the out-of-bag correct classification rate amounts to only 65%, implying quite substantial overfitting, especially for the parent material classes with small sample sizes. Consequently, the predicted map must be evaluated with caution. A comparison of the resulting parent material map, adjusted only with

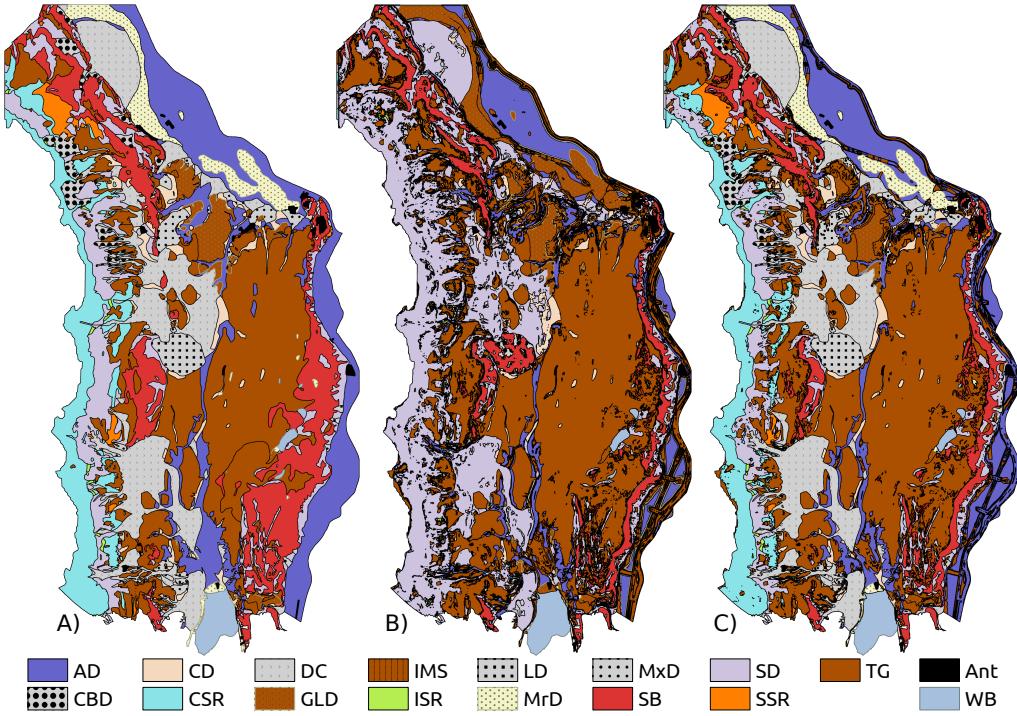


Figure 7: Original reclassified SGUs (A) and random forest-based parent material map modified based on vector ruggedness and TRI (B) and parent material map with only till modeled (C)

1035 two roughness measure, with the original SGU map, reveals a considerable  
 areal increase of the TG unit. This is perfectly understandable 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 highways in the  
 1040 Etsch valley 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 areas originally covered by the SGUs debris cones and mixed deposits  
 now seem to be covered by the slope debris unit, which seems contrarian to  
 the good prediction results of these units. Detailed investigation into this  
 1045 issue shows that overfitting occurred in these cases, with very small, local DC  
 and MxD polygons leading to the false impression of correct classification.  
 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 processes 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 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 its geomorphological history, the unit is now modelled as siliceous bedrock with coarse blocky debris, which well represents the view of the soil surveyors. 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 previous field work in this area, the authors deem this assumption worthy of future investigation.

After considering and evaluating the issues 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 modelled parent material map is helpful in giving insights into issues that arise when using geologic maps and topography as a proxy for parentmaterial, too much of the information provided by the original SGU map is lost. 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 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 procedure for the units till vs. not-till again chose one TRI and one VRM map as model input features, but with slightly differnt window sizes (100 m and 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 6C), which can help in understanding the composition of slope debris and other transported materials. Compared to the original confusion matrix (Table 3), the overall correct classification rate is improved form 49% to 65% with this approach.

#### 4.4. General difficulties and specific issues

- As Olofsson et al. (2013) point out: uncertainty in remote sensing applications, but also in general, can be related to geolocation and

interpreter variability. In this study...

- confusion at categorical transitions (Olofsson et al., 2013)
  - analyst biases (Foody 2010), multiple interpreters, but not on same profiles, what about powell 2004 and their five interpreters
- 1090 • Olofsson et al. (2013) state that with regard to reference labeling, in this case the parent material, difficult cases need be noted for future reference and consensus development; Wickham 2013: constant communication in order to discuss and document difficult cases is important; response protocols?

1095 *4.4.1. Differences with regard to mapping purpose*

Between the two different frameworks of mapping, geology on the one hand and soil on the other, it is important to acknowledge the main focus of attention of each branch of research. Miller and Lee Burras (2015) note that the resulting maps of the two sciences try to communicate different aspects. 1100 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. A typical example is the unit landslide debris, which seems only of interest to the mappers with focus on geology, whereas the soil surveyors pay attention to the chemical and physical properties of the 1105 material. This leads to the latter group classifying the parent material of soil profile sites on this unit as either siliceous bedrock (emphasis on mineralogic properties) or coarse blocky debris (emphasis on physical properties such as grain size distribution). The mapping of glacial deposits highlights a similar issue. While the geologists map a number of different glacial deposit 1110 units, soil or forestry surveyors seldom differentiated between lodgement till and other glacial deposits, only when a decisively higher clay content was determined. On the other hand, the chemical properties, especially with regard to acidic or calcareous properties of the till material are of much more interest to the soil surveyors, who further differentiate till with regard to 1115 this aspect. The geologic map on the other hand also contains information with regard to the age and the geologic system (synthem) to which certain moraines belong, whereas this is only of interest to the soil surveyor if it features additional information with regard to the mineralogic content of the different constituents of the moraine. The rather low producer's reliability 1120 of the till unit leads to an additional issue linked to different mapping

purposes or approaches, as there may exist a difference with regard to how pronounced a certain feature or characteristic must be in order to be considered for mapping. While a soil surveyor does note underlying layers in his profile description, the main focus is on the material from which the soil developed and which consequently plays an important role in characterising a soil and its location. The geologist on the other hand may not place as much emphasis on the thin layer that actually acts as the soil parent material, but more on the thick layers of different origin beneath the soil, as its role in describing the geological setting is greater. The case of a thin till layer on siliceous bedrock, as illustrated in Figure 4A, exemplifies such a situation. Consultations with the geologic mappers showed that for their purpose, only regolith cover layers thicker than approximately 1 m are usually mapped. This is an important insight that must always be considered when using geologic maps to infer information regarding soil parent material. It must however also be kept in mind that natural differences can be expected between any two mappers (Miller and Lee Burras, 2015), even of the same scientific field.

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

Congalton

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

An issue that involves both the differences in mapping purposes and nomenclatural difficulties is the question of what is more relevant, the transportational history of a parent material or information regarding its composition?

In the study area, mixed deposits from mass movement and torrents have the same components as till or hillside debris, which themselves may possibly be composed of the same material and have the same source area.

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

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

Survey on the other, Miller and Lee Burras (2015) point out that the level of agreement was lower for areas with complicated geologic histories. High morphodynamics in high relief areas and the issue of multilayered soil

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

1160 Why is it important to differentiate till and slope debris? While there may exist situations where the slope debris is composed of till material, the general difference is that soils from slope debris can be understood with knowledge of local geology and that they may not be so different from soils that evolved from bedrock at higher elevations in the catchment, whereas till can consist  
1165 of chemically very different components. Till can be found at steeper slopes than expected, is this due to lateral consolidation of tillic material by glaciers in these U-shaped valleys?

#### *4.6. Terrain parameters - issues and results*

- 1170
- the landform-diversity measures are all heavily correlated and have the same meaning in the end.
  - the roughness measures also show high correlations and the various window sizes show similar results. Consequently it cannot be said that one parameter combination is better than the other for separating parent material classes, but only that the feature selection procedure chose this combination over others, with no quantification of the increase in prediction rate, which may have been minimal.
  - 1175
  - beware of the different class sizes when using random forest and box-plots to investigate differences. For future studies, a sampling scheme that leads to a more balanced distribution of the samples per parent material unit can decrease the problem of overfitting classes with small sample sizes and high confusion rates.
  - 1180
  - 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.

1185 **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  
1190 available information and concentrate the time and money consuming task  
of field work, involving soil pits and auguring, on units identified as highly  
variable and uncertain regarding soils. This information can be additionally  
helpful for devising future sampling procedures and also for consideration  
when attempting to regionalise point information.

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