Response to review of manuscript soil-2020-3 by Topical Editor

We would like to thank David Dunkerley for his additional constructive comments to improve the manuscript. The main issues raised by the topical editor are:

- Lack of clear hypothesis stated
- Water content variations with depth should be considered.
- Discussion of hillslope up-scaling should be shortened.
- Stronger emphasis / discussion of Correlation coefficients and PCA in main text.

All of these concerns are addressed in the revised manuscript as explained below in detail. Of particular note, we have added available water content measurements from the study areas, although they are not available in the same spatial fidelity as the pedon geochemical measurements. Further suggested changes are also addressed in the revised manuscript. We hope that our corrections improve the quality of this manuscript in the expected way.

Thank you for your time!
M. Schaller on behalf of all co-authors.
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Note: The *topical editor's comments are in italic text*, **our response is in bold text**.

Topical Editor Decision: Revision (05 Sep 2020) by David Dunkerley

Comments to the Author:
Dear Dr Schaller and co-authors,

I have read both the reviewer reports and your paper carefully, and have recommended that some moderate revisions be undertaken. Some indication of the areas requiring attention is provided below; I have added some additional comments from my own perspective.

The two reviewers have provided some helpful and informative commentary on the manuscript, especially as regards the need to adopt a systematic nomenclature for the weathered materials being discussed. The authors' proposed revisions to the manuscript in light of these comments appear to be entirely appropriate, and should adequately address this issue.

Reviewer #2 also commented on the extent to which the work described goes beyond prior published work from the same field sites and using the same GPR methods. All of the soil chemical data analysed in the present paper were derived from prior work at these sites. I therefore think that a fundamental issue to be considered during revision of the manuscript is to make a clear demarcation of what is new and what is derived from prior published studies. For example, in lines 152-155, the paper reports that various soil locations were 'described, sampled, and analysed'. Yet all of this was done *in previous studies, not for the current manuscript, as the text may tend to suggest. This needs to be more clearly acknowledged; this is not done until much later (lines 190-191).*

Sentences in lines 152-155 have been rewritten and clarified. The sentences read now in such a way that it is clear from beginning what is reused and what is new material. "From north to south (Figs 1 and 2), the four selected study areas in the climatic and vegetation gradient observed in the Chilean Coastal Cordillera are: a) Pan de Azúcar (~26.1° S); b) Santa Gracia (~29.8° S); c) La Campana (~33.0° S); and d) Nahuelbuta (~37.8° S). The study areas were investigated for regolith physical and chemical properties by Bernhard et al. (2018) and Oeser et al. (2018) as well as studied with GPR by Dal Bo et al. (2019) (see Tables 1 and 2)."

I think that the prior published work could also be cited to avoid the repeated descriptions of methods, since they are in many cases not new. The procedural descriptions make the current manuscript rather long. For instance, in lines 222-22 there is no need to explain what LOI (loss on ignition) means; likewise, I suggest omitting the simple introductory description of GRP in lines 235-240. Readers can either refer to the literature or to a standard text to find this material if they are unfamiliar with GPR methods. Again, I think that you could omit lines 273-285, where the processing of the GPR signals is described, and merely cite the prior published studies from the field sites. At the least, it ought to be possible to greatly abbreviate this material.

The method section has been shortened as suggested by the topical editor.
The closer description of LOI has been removed (Line 222-224).
The chapter 3.2 reads now as: "Ground Penetrating Radar (GPR), a geophysical technique based on the emission of pulsed electromagnetic waves into the subsurface, are applied in this study for frequencies of 500 and 1000 MHz (for more details see Dal Bo et al., 2019). Fourteen new transects going from hillslope toe (near valley) to top (ridge crest) are collected crossing the pedons where physical and chemical properties were collected (Figs. 2 and 3). Of these 14 transects, two were collected in the Pan de Azúcar study area (for 500 and 1000 MHz), six in Santa Gracia (for 500 and 1000 MHz), three in La Campana (for 500 and 1000 MHz), and three in Nahuelbuta (only for 500 MHz). Wide-angle-reflection-refraction (WARR) are used to retrieve velocity and physical properties at the point scale. For each pedon, a WARR is measured in a relatively flat location (red stars, Fig. 2).
GPR data were processed and analyzed using MATLAB as described in Dal Bo et al. (2019). In addition, signal envelopes were calculated using a Hilbert transform (Green, 2004; Liu and Marfurt, 2007). At each pedon location, a certain number of traces depending on the measurement step size (i.e. between 10 and 50) were sampled for 0.5 m uphill and 0.5 m downhill the pedon and laterally averaged for comparison to the pedon physical and chemical properties. The averaging assumes that both chemical and GPR signatures do not change with depth

across that interval, an assumption that may not hold everywhere. As the GPR envelope is directly related to the electric impedance (Telford et al., 1990; Jol, 2009), the envelope onset and energy intervals could be compared to variations in physical, and potentially chemical, regolith properties.

Reviewer #2 also points to a concern over unmeasured water content in the weathered materials examined using GPR. Given that this can strongly influence GPR signals, I think that some further comment is required, especially in light of the likely site-to-site (especially N to S) differences in water content among the sites and at the various depths within the weathered material. In the absence of such data, unknown variation in water content may be confounded with other properties of the materials such as the chemical properties. Presumably, samples for water content determination could readily have been collected in sealed bags for later water content analysis.

The pedons described and analyzed in Bernhard et al. (2018) and Oeser et al. (2018) were excavated in early 2016 and promptly refilled due to their locations in national parks and a nature preserve. Unfortunately, water content was not analyzed in pedon samples which were analyzed for the other physical and chemical measures. However, during the 2017 acquisition of the GPR data presented in this study, regolith water content was determined for several auger locations (new Table S3A to C). While these auger samples provide insights into water content variations, they do not exactly spatially coincide with the pedons, and due to the sampling approach (augers) were not sampled at the same depth intervals as in the pedon. Given this – we were not able to include them in the correlation or PCA analysis. However, we do now provide the water content data and refer to it throughout the results and discussion sections.
Nevertheless, the available moisture content gives information about the water distribution in space at a given time. Whereas other physical and chemical properties than water content are less time sensitive (e.g., bulk density, clay content) water content changes over days especially in humid areas such as Nahuelbuta.

I would like to raise some further issues for consideration, from my own reading of the manuscript.

First, I found there to be a lack of clear hypotheses or objectives, though two are listed in the Abstract but not enumerated in the body of the manuscript. Clearly, the study relates to the possible use of GPR methods to extend the available information on soil thickness that can be derived from pit sections. The reasons for seeking to do this are not immediately clear.

Aims of this study are incorporated into the introduction. We also now (more explicitly) state the hypothesis tested. With this addition we hope to improve the manuscript and incorporate the editor's suggestion. The introduction finishes now with the following paragraph: *"In this paper we build upon the previous work of Dal Bo et al. (2019) and compare the pedon measured physical and chemical observations (from Bernhard et al. (2018) and Oeser et al. (2018)) to a large newly acquired GPR data set from the same area to gain insight into regolith variations along a climate and ecological gradient. Our approach is to relate GPR observations adjacent to pedons to depth varying regolith properties caused be weathering as well as to evaluate if these properties can be extrapolated along a hillslope using GPR transects. In doing this, we test the hypothesis that if weathering processes produce depth varying physical and chemical changes in regolith observed in pedons, then (a) GPR based observations of these locations should produce observable changes in the GPR envelope and reflectors correlative to weathering horizons, and (b) GPR can be used to upscale geochemical observations from pedons to the hillslope scale. In general, we find that our new GPR measurements can be correlated to changes in pedolith physical properties if these changes are of sufficient magnitude and laterally coherent. If such a correlation is observed, we discuss the links between the physical and chemical properties. The comparison of physical and chemical properties with field observations and GPR data helps to better understand the regolith at point locations (e.g., pedolith thickness) and in some cases allows for up-scaling point observations to the hillslope scale along a GPR measurement profile."*

Moreover, in line 141 (under '2. Study areas', rather than in the Introduction where it would be more appropriate) the manuscript refers to the issue of how climate and vegetation affect soil thickness and GPR observations. This might, for instance, have been listed as an objective in the Introduction. Was investigating this issue indeed an objective of the present work, or not? If it was an objective, then I felt that more information on the site conditions was needed, including for instance NDVI data or some comparable information on the vegetation, perhaps supplemented by aridity indexes, data on seasonality and seasonal variation in climate conditions, and so on.

Chapter "2.1 General climate, vegetation, and geologic setting" now includes precipitation and temperature data for the study areas as well as vegetation cover information in the four study areas.

In this context, moisture content in the weathered materials would again have been informative. Later in the manuscript, the role of aspect (equator-facing or pole-facing slopes) is raised: was there also an hypothesis underlying this, in light of which the N and S faces were sampled separately? If so, this provides another subject that might be listed in the Introduction as an objective of the current work, if that was indeed the case. Regardless, the reason for sampling both N and S facing sites warrants some explanation, as does the denser sampling of pedon locations on the S-facing slopes than on the N-facing slopes, where only a single site was examined. Readers are likely be interested in the rationale behind such choices.

Chapter “5.3 Changes of pedolith thickness with hillslope position, aspect, and latitude” is removed as the closer study of hillslope position, aspect and latitude are not the major objective in this study. The major objective was the comparison of physical and chemical regolith properties with GPR data as well as their up-scaling to hillslopes. Nevertheless, some sentences addressing hillslope position, aspect, and latitude are added to Chapter 5.2 in order to state that the observations from this study are comparable with Bernhard et al. (2018) and Dal Bo et al. (2019).

In relation to the field sites, I noted that the hillslope study sections are in some cases extremely short: apparently < 3 m in the N-facing site at Nahuelbuta, to judge from Figure 3. Extrapolation from the pedon to the hillslope scale over a distance of < 3 m amounts to only a very limited extension of the pedon data. Similarly, the S-facing slope at Pan de Azucar appears to be < 10 m long, raising similar issues. In general, I think that some additional commentary on the scale of the topography being studied would be helpful for readers. For instance, is the challenge of extrapolating from pedon to hillslope over such short hillslopes typical of the challenge faced more generally in such work? In other words, do these sites constitute an informative test case?

In order to avoid questions such as raised by the topical editor, the following text is added to the manuscript in Chapter “2.2 Regolith characteristics”: “Only one pedon was investigated in the N-facing slopes due to time and financial restrictions. In addition, transect lengths in some settings are limited due to the availability of weathered hillslopes in the same lithologies (e.g., Pan de Azucar; Fig. 3A) as well as restriction of access due to intense vegetation (e.g., Nahuelbuta; Fig., 3D).”

The manuscript touches on hillslope aspect and its relationship to soil thickness (lines 622-624). Here I felt that if this topic is to be discussed, then wider acknowledgment of the growing published literature on this topic was needed. I mention here a few studies that came to mind only as examples. The literature on this topic is now quite large.

Yetemen, O., E. Istanbulluoglu, J. H. Flores-Cervantes, E. R. Vivoni, and R. L. Bras (2015), Ecohydrologic role of solar radiation on landscape evolution, Water Resour. Res., 51, 1127–1157, doi:10.1002/2014WR016169.

Yetemen, O., E. Istanbulluoglu, and A. R. Duvall (2015), Solar radiation as a global driver of hillslope asymmetry: Insights from an ecogeomorphic landscape evolution model, Water Resour. Res., 51, 9843–9861, doi:10.1002/2015WR017103.

Srivastava, A. et al. (2019). Aspect-controlled spatial and temporal soil moisture patterns across three different latitudes. 23rd International Congress on Modelling and Simulation, Canberra, ACT, Australia, 1 to 6 December 2019 *mssanz.org.au/modsim2019.*

Inbar, A. et al. (2018). Climate dictates magnitude of asymmetry in soil depth and hillslope gradient. Geophysical Research Letters 45, 6514-6522.

Chapter 5.3 discussing hillslope position, aspect, and latitude, is removed and replaced by a short section in Chapter 5.2. Therefore, we do not incorporate all the suggested references. The removal of Chapter 5.3 not only shortens the already long paper but hopefully also helps to improve the focus of this paper.

In the Discussion section, I think that there is much speculative material that would likewise benefit from additional supporting references. For example, there is the unreferenced claim that

"From the top- to toe-slope position along a catena the potential for physical erosion decreases downslope due to decreasing physical potential whereas the potential for deposition increases".

There are certainly many situations where this does not apply; in drier climates the volume of overland flow may increase downslope, and whilst hillslope gradients might decrease there, the surface roughness may decline such that the surface runoff becomes faster and more erosive. Rilling and gullying are consequently often characteristic of footslopes, not the steeper upper slopes. The more general point is that, in order to interpret soil thickness and the variables that influence it, some knowledge of the erosional and geomorphic processes that operate at the site concerned is really needed. None is provided in the current manuscript, and it would be helpful if something could be said. Similarly, in discussing the different patterns of soil thickness on N and S-facing slopes (lines 624-642) the manuscript is almost entirely speculative. The authors hypothesise that some differences might perhaps relate to aspect-related differences in soil moisture (lines 624-625) or vegetation cover (line 627) or subtle lithological changes (line 630) or local heterogeneities in erosion (lines 634-635) or even other processes such as differences in evaporation (line 641). Given that the manuscript presents no evidence bearing on these issues, I think that this discussion might be curtailed somewhat. Reference to prior published work on this topic (see suggestions above) would support some brief comments. The authors also raise some issues in passing, that are not given further attention in the manuscript. For instance, they mention possible site-to-site differences in bedrock joint spacing (line 165), but do not discuss how important such variation might be in affecting their results. In this context, I was conscious of the recent work of Leone et al. (reference below) in Arizona where regolith thickness was influenced not primarily by aspect but by the orientation of the foliation in the underlying bedrock, in relation to the topography. This is an instance that reminds us that weathering and soil production can be influenced by much more than surface climate, vegetation, or three-dimensional hillslope curvature.

Leone JD, et al. (2020). Strong slope-aspect control of regolith thickness by bedrock foliation. Earth Surface Processes and Landforms. Available in Early View.

As explained above Chapter 5.3 has been removed and replaced with a paragraph in Chapter 5.2. The speculative material does not need more discussion nor more references. This rearrangement should shorten and clarify this manuscript.

Finally, I think that the Pearson correlation analysis that is set out in section 3.3 ('statistical correlation and principal components analysis') is poorly utilised in the paper. This is suggested as one of the new contributions of the manuscript (lines 37-39). No correlations are actually presented in the paper; rather, these are only briefly qualitatively referred to, and the actual data are relegated to the Supplementary information. Little appears to be said about the correlations, and therefore perhaps the long methods description relating to this work (lines 296-311) could be abbreviated. Alternatively, if the correlations are regarded as important, then perhaps more analysis of these results could be incorporated.

The discussion of the reported correlations for the four study areas and the entire Earth Shape climate and vegetation transect is extended. Therefore, the previous Table S3 with the correlation information is now moved to the main text as suggested. The main text contains now 3 Tables. The method section is shortened.

Response to review of manuscript soil-2020-3 by RC1

Preface to the response to reviews by the authors:
We would like to thank Colin Pain for his constructive comments to improve the manuscript. The regolith terminology has been adjusted to World Reference Base for Soil Resources (WRB). This adjustment should clarify some of the confusion created. Furthermore, all of the following changes we've made to the manuscript have been implemented in the manuscript text file.

Note: The *reviewer's comments are in italic text*, **our response is in bold text**.

Thank you for your time,
M. Schaller on behalf of all co-authors.
****

General comments
This paper reports on correlations between GPR profile data and physical and chemical soil properties. The soil properties come from work that has previously been published, while the GPR data are new. The correlations are discussed and demonstrate that GPR can be used to infer soil thicknesses and to a lesser extent soil properties. The paper is well written and is a very useful contribution to our knowledge of the value of using geophysical methods to study soil properties and distribution. I suggest a change to the title: "Comparison of regolith physical and chemical characteristics with geophysical data along a climate and ecological gradient, Chilean Coastal Cordillera (26◦ to 38◦ S)"..

Line 1-3: The title has been changed as suggested by the referee. Only soil has been replaced by regolith to be consistent with the rest of the manuscript and reviewer comments.

Specific comments
There is some confusion in soil/regolith terminology. Regosol, cambisol, and umbrisol are World Reference Base for Soil Resources (WRB) classes. I think it would be useful to mention this, and to briefly discuss the soil classification. Part of the confusion is the distinction between soil and saprolite – the saprolite is the C horizon and is therefore part of the soil. While there is clearly a difference between the mobile zone (A and B horizons) and the underlying saprolite zone (C horizon), both are parts of the soil profile. (The mobile zone may be transported by creep or surface wash, or it may simply be re-sorted, as by termites or earthworms, or it may be a combination of both, so it is a very general term.) For this reason, I disagree with Riebe and Granger (2013) when they restrict the term "soil" to the mobile zone.

The terminology of used in this manuscript has been adjusted to "World Reference Base for Soil Resources".

Response to review of manuscript soil-2020-3 by RC2

Summary of revisions made for the benefit of the Editor, and reviewer:

We thank the reviewer for the time she spent reviewing this manuscript, although the tone of many of the comments was unnecessary. This reviewer's comments are in stark contrast to the positive and constructive comments of the first reviewer. Nevertheless, we've tried our best to address this reviewer's concerns. The reviewer's comments revolve around:

a) Not clearly understanding the differences in data and analysis presented between our previous study (Dal Bo et al., 2019) and this one.
b) Suggesting many changes for this paper to have a different scope than what we state are our aims in the introduction.
c) Continually emphasizing the importance of moisture data (which is not available), while many other difficult to acquire geochemical data sets are compared to extensive new GPR data with a multivariate analysis.

To address these items, we have modified the text to more explicitly state the differences between our previous work and this study, and to highlight more prominently caveats associated with this study – such as no regolith moisture data availability. We note, however, that although this reviewer comments on the need for additional referencing of "gray" literature, no references (peer reviewed or otherwise) were provided in their entire review.

Finally, we honestly struggled in many places to understand what the reviewer was trying to say in her comments below and edits to the manuscript text. The edited manuscript she provided also changed text in many places to be grammatically incorrect (e.g. removal of the verb in a sentence, or incorrect preposition use, etc), and more confusing. We've tried to implement all these changes as best we could, and highlight below where we disagree with the reviewer's strong opinions for what the study should be.

Note: The *reviewer's comments are in italic text*, **our response is in bold text.**

Thank you for your time,
M. Schaller on behalf of all co-authors.
****

General comments

This paper is a somewhat disappointing addition to work already published by the team working on the German-Chilean priority research program EarthShape (www.earthshape.net). The published work has already established that GPR could be used to map "soil" materials in the four study areas, and that interpretation can be "up scaled" from point observations to transects (Dal Bo et al. 2019). The Dal Bo et al. paper correctly identifies the importance of observations about soil moisture content and clay content to refinement of GPR data interpretation. Note, increases in both soil *moisture and clay content often mark the transition from pedolith to saprolith. Unfortunately, Schaller et al. do not expand on the soil property dataset already available to Dal Bo et al., and so, unsurprisingly, do not come up with any new insights into the interpretation of their new - or the old (Dal Bo et al.) - GPR data acquired in the EarthShape Chilean study areas.*

With all due respect, we disagree with the reviewer's assessment of our previous work and this manuscript. The following items were stated in the manuscript, although we've modified the text (sections 1 (introduction) and 5.2 (discussion) to make this clearer for other reviewers. More specifically, our disagreement with the reviewer stems from:

- **There is NO overlap in GPR or regolith property data presented in this manuscript or the Dal Bo et al., 2019 manuscript. Entirely new GPR profiles are presented here. Dal Bo et al. (2019) only use the observed transitions from B-C horizons in Bernhard et al. (2018), and the boundary between mobile and immobile layer from Oeser et al. (2019).**
- **At the time the Dal Bo et al. (2019) manuscript was prepared in February 2018, the physical and chemical properties of the regolith used in this (current) SOIL journal manuscript were not available for use. This is in part to our honoring of Bernhard et al. (2018) and Oeser et al. (2018), having the right to publish their data first, and also due to extremely long editorial handling (~1.5 years) of the Dal Bo et al. (2019) in CATENA.**
- **Thus, these regolith property data were not available to use in our 2019 study as the review suggests and there is no duplication of regolith property data. In fact, the scope of the Dal Bo et al. (2019) study and this manuscript are different and we are perplexed why the reviewer is criticizing a previously published study for not including additional data. This simply wasn't possible.**
- **The focus of Dal Bo et al. (2019) is on identifying the boundary between the pedolith and saprolite. This is a very different scope than the current (Schaller et al.,) manuscript in the journal SOIL where the focus is on comparison to a large number of chemical and physical property data.**
- **In contrast, this manuscript (Schaller et al.) tries to correlate the observed signal with physical and chemical changes provided by Bernhard et al. (2018) and Oeser et al. (2018). This is the logical next step for a study where there are co-located and potentially complementary data sets.**
- **Finally, it is true that envelopes of the GPR signal are already presented in Dal Bo et al. (2019) although these envelopes come from a different data set, and slightly different geographic positions such that a robust comparison to pedons was not possible. In contrast, this manuscript by Schaller et al. correlates the envelope intensity with physical and chemical changes. This in turn allowed a more quantitative determination of the pedolith depth over a hillslope transect.**
- **Concerning clay and water content variations in our study area – we address this comment below. In short, clay content variations are**

accounted for in our PCA analysis, whereas water content variations have not been measured and are not available for study.

In summary, while we strongly disagree with the reviewer's statements concerning our previous work, we take their comment to highlight that the manuscript could provide a clearer distinction to our previous work. Given this, we have expanded the introduction to more explicitly state the differences with previous work.

I would suggest that the authors, and the EarthShape team, take a closer look at some of the work that is being done on using GPR to map regolith materials and processes elsewhere in the southern hemisphere, especially in Australia. Some of this work is published in "grey" literature, but it is still relatively easy to find on the internet. There is also a lot of work being done in Australia, some in collaboration with European geophysicists, on the use of electromagnetic surveys to map regolith materials and processes. The inversion of this data has become quite sophisticated and AEM surveys, designed in part to map regolith thickness, are now taking place on a continental scale.

The EGU SOIL journal guide for authors states (https://www.soil-journal.net/submission.html#references) states that "Grey" literature should not be cited, specifically: "*Informal or so-called "grey" literature may only be referred to if there is no alternative from the formal literature. Works cited in a manuscript should be accepted for publication or published already*". In our manuscript, we cite related published literature so citation of 'Grey' literature is not needed. Furthermore, the reviewer's request to cite other 'southern hemisphere, especially in Australia' studies was not accompanied with specific references to consider. We've conducted literature searches to see what other relevant literature could be cited, but without specific recommendations from the reviewer we cannot accommodate this statement, nor will we cite grey literature as this is not commonly accepted for high-quality peer review journals (such as this one).

Further, Schaller et al. perpetuate some of the confusion in soil and regolith terminology that is apparent in earlier work by this team. In particular, the confusion relates to the use of the term "soil" variously as a descriptor for the entire regolith profile (pedolith and saprolith), and as a descriptor solely for the pedolith. This confusion is exacerbated by reference to soil materials that are mobile (pedolith) and immobile (saprolith). Note, the saprolith includes saprolite and saprock.

Reviewer 1 had a similar comment. There is a difference in terminology between the surface processes and soils communities, and we had provided a reference for the terminology we were following. However, given that this journal is a soil sciences community journal, we have adjusted the terminology as requested. The terminology of soil used in this manuscript has been adjusted to "World Reference Base for Soil Resources" as suggested by reviewer 1.

The distinction between these units can be important for the interpretation of geophysical data, although the EarthShape Chilean study does not appear to have properly investigated beyond the pedolith. A visit to some of Chile's open cut mines might be a salutary experience in this regard.

We thank the reviewer for this suggestion, but in practicality, we are not sure how this would be useful at this time. In particular,

- **The investigation of the pedolith is the main topic of this manuscript and much of the EarthShape Phase 1 research. Several months ago other EarthShape projects completed drill cores within about 10 km of each study area to study soprolite, saprock, and bedrock. What we learned is that the bedrock is hard to reach and is reached at ~30 to ~80 m depth. These drill cores and data from them are still 1-2 years away from publication (at the earliest) and are not available for this study.**
- **We are not sure what insights the proper investigation beyond the pedolith in an open cut mine would change the interpretations made in this study, particularly because they would be located far off site from the actual study area where physical and chemical measurements were made and lateral extrapolations from regolith formed in different host lithologies where we have no chemical or physical measurements would not provide a robust comparison.**

Note, these general comments are supplemented with detailed comments and suggested amendments as per the attached pdf. The comments and suggested amendments have been added to the pdf using Adobe Acrobat.

Detailed comments and changes are addressed below in supplemental comments.

Supplement comments
Please also note the supplement to this comment:
https://soil.copernicus.org/preprints/soil-2020-33/soil-2020-33-RC2-supplement.pdf

Line 48-52:
"Pedolith" may be a better term than "soil" with reference to a regolith profile
"Saprolith " may be a better term than "saprolite" with reference to a regolith profile esp as saprolith includes both saprolite and saprock
"Meaningless sentence in this context, as the saprolith is, by definition, immobile. It is only after it's weathering products engage with biological and hydrological processes that they "enrich" the pedolith"

The use of soil for the mobile layer is replaced by the term pedolith. The entire manuscript has been checked for consistent use. Also, the remaining regolith

terminology has been adjusted to “World Reference Base for Soil Resources” as suggested by Reviewer 1. The sentence reads now the following: ”Most biota is found in the mobile pedolith, which overlies the immobile saprolith. The pedolith is replenished with nutrients from the saprolith through chemical weathering and erosion that drives nutrient uplift towards the surface (e.g., Porder et al., 2007).

Line 52-54:
This list of factors does not follow a logical sequence and as such is confusing. In my view the list should progress from the local to the regional. Aspect, which is highlighted in proceeding published work, has been omitted altogether.
Regolith thickness or "soil" thickness?? Having started with regolith I think it is best to stick with regolith.

The sequence of the list has been adjusted as suggested by referee 2. Aspect is added as a factor. The term “soil” is not used anymore. The investigated depth sequence is named “regolith” and the so far named “soil” is relabeled “pedolith”. The sentence reads now as follows: “The thickness and production of regolith is influenced by aspect, topography, composition (mineral content), biota, climate, tectonically driven rock uplift, and time (e.g., Hilgard, 1914; Jenny, 1994).

Line 55-56:
Regolith thickness or "soil" thickness?? Having started with regolith I think it is best to stick with regolith.

The sentence reads now as follows: “However, sub-surface variations in pedolith thickness at the scale of hillslopes are difficult to quantify because of lack of exposure.”

Line 56-59:
See previous comment and ditto for all references to "soil" in this section

The use of regolith terminology has been adjusted as suggested by the referee in the entire manuscript. The sentence reads now as follows: “Thus, subsurface imaging by geophysical techniques, when calibrated to regolith excavations (pedons), offers potential to characterize spatial variability in pedolith thickness and regolith properties (e.g., Mellett, 1995; Doolittle and Collins, 1995; Miller et al., 2004).

Line 83-85:
However, on a theoretical basis, the importance of certain properties has been identified eg soil moisture content and clay content cf proceeding work by this team published in Dal Bo et al 2019.

Not sure we understand what change the reviewer is asking for. The sentence reads now: "Interpreting the interplay of GPR signals with physical and chemical regolith properties is challenging (e.g., Saarenketo, 1999; Sucre et al., 2011; Tosti et al., 2013; Sarkar et al., 2019)."

Line 89-92:
Biotic processes are "critical zone" or more properly "regolith" processes

The term 'critical zone" is replaced by "regolith".
"The region is home to four study areas of the German-Chilean EarthShape priority program (www.earthshape.net), where investigations of biotic interactions with regolith are conducted (e.g., Bernhard et al., 2018; Oeser et al., 2018)."

Line 141:

Soil has been replaced by pedolith: "To compare the effect of climate and vegetation on pedolith thickness and GPR observations, differences in lithologies need to be minimal.

Line 158-161:
a saprolith (which includes saprolite and saprock and thus includes the "C horizon"

The sentence has been changed to: "In this study, we refer to depth profiles as regolith profiles that are composed of a mobile pedolith that includes the A and B horizons, and an immobile saprolith including the C horizon."

Line 162-163:
Alternatively "has been described as"
WRB ref needed

The sentence has been corrected as suggested by referee 1 and reads like:' In Pan de Azúcar, the regolith, a regosol (IUSS Working Group WRB, 2015), consists of A and B horizons with a combined thickness of 20 to 25 cm and an underlying saprolith (the C horizon), which is coarse-grained and jointed (Oeser et al., 2018). The requested reference has been added.

Line 165-166:
The entire regolith profile ie pedolith and saprolith or just the pedolith??

The sentence has been corrected to: "The average bulk density of the A and B horizons is 1.3 g cm^{-3}.".

Line 166-168:

"The cambisol in Santa Gracia consists of 30 to 55 cm thick layers of soil with A and B horizons overlying the saprolite (Bernhard et al., 2018)." The sentence has been changed to: "In Santa Gracia, the 30 to 55 cm thick pedolith overlying the saprolith is a cambisol (Bernhard et al., 2018)."

Line 234:
As previously noted, both the physics of GPR data acquisition and work carried out elsewhere suggests the importance of soil moisture content. Why wasn't data on this property acquired?

We agree with the reviewer that regolith moisture content is important and would be nice to know. Unfortunately, this data is not available. The pedons that we compare our GPR data to were excavated in March 2016, and promptly filled in by July 2016 because they were located in national parts. Regolith moisture measurements were not made on samples collected in 2016, and no pedons were available for sampling at the time the GPR data for this manuscript was collected in 2017. Furthermore, as the reviewer likely knows, regolith moisture varies both seasonally and annually, such that comparison to regolith water content measurements from a previous year would be difficult to assess the robustness of.

To address this reviewer's comment – we have modified the text (Section 3.1 methods/data compilation) to also state more clearly that regolith moisture is important (amongst other factors) for GPR data interpretation, but that this data is not available. We had already mentioned this in the text, but we make it clearer now to hopefully reach a happy middle ground with this reviewer. We also address this topic in the new concluding discussion section 5.4.

Furthermore, we addressed this topic, and other limitations / caveats of the study, in a new concluding discussion section "5.4 Comparison to previous work and study caveats". Hopefully this reaches a happy middle ground with the reviewers concern.

Finally, clay content is also important for GPR data interpretation (as the reviewer mentioned earlier). We note that clay content was measured and reported by Bernhard et al. (2018), and we have included this in our PCA analysis.

Line 344-346:

pedolith/saprolith

“Mobile/immobile” has been changed in the entire manuscript “mobile and immobile” as suggested by referee 1. The terminology “pedolith/saprolith” is not used because Oeser et al. (2018) used the terms “mobile/immobile” for the boundary they observed. The sentence reads as follows: “In Pan de Azúcar (Fig.1, 2A), a gradual transition from the B to the C horizon was visually observed in the pedons at 20 to 40 cm (shaded gray areas after Bernhard et al., (2018); Fig. 4, Fig. S1 to S3), whereas the mobile and immobile boundary is considered to be at 20 to 25 cm (black lines after Oeser et al., (2018);); Fig. 4, Fig. S1 to S3).

Line 390:
pedolith/saprolith

See response above for line 344-346.

Line 385-387:
pedolith/saprolith

See response above for line 344-346.

Line 387-390:
?pedolith
? pedolith or total regolith

Sentence reads now as: “Bulk density and grain size change gradually with depth and no clear pedolith thickness could be determined.”.

Line 409:
pedolith/saprolith

See response above for line 344-346.

Line 416:
pedolith/saprolith

See response above for line 344-346.

5.1 Synthesis of GPR data with physical and chemical properties from point locations

Suggest that theory and the findings of previous studies throughout the world should be the starting point ie properties such as soil moisture content, salinity and clay content, should be the starting point for this discussion. Some of the measured properties could be considered proxies for these properties of known importance, and the discussion should be explicit in that regard.

We thank the reviewer for this comment. We agree that more general discussion of factors influencing GPR data could be discussed. However, we did not include this in section 5.1 because this section focuses on synthesizing our results and interpreting them. However, to accommodate the reviewers concern, we have added a new section 5.4. We hope that this addition improves the manuscript further.

Line 443:
Soil moisture content is known to be important so why has this been neglected in this study?

Please see our response to this reviewer's comment for line 234 above. The data is not available! However, we'd like to emphasize that while regolith moisture content would be nice to have for inclusion into our PCA analysis, the lack of having this data does not invalidate the observations we present. The addition of this data would help constrain the interpretations better, but it's not available. We expanded text related to regolith moisture in section 3.1, and 5.4.

Line 448:
Was "basal saturation" as reported by et al 2019 useful? If not, why not?

We apologize, but we do not understand what the reviewer is referring to here. We conducted a "find" on the manuscript text and do not see the word "basal saturation" used by us. The same words do not appear in the work of Dal Bo et al. (2019). Also – we are unclear why the reviewer is commenting on a previous (published) study whose data are different from this study, and not collected in the same location.

Line 449:
? pedolith/saprolith

Sentence has been changed by referee 1 and reads now as: "In addition, the determination of the boundary between the pedolith and saprolith in the field causes its own problems because observed changes are not discrete but transitional over a depth interval of 5 to 10 cm".

Line 457-459:
? within the saprolith

Sentence has been changed:” Whereas the 500 MHz signal shows interfaces in the saprolith, the maximum in the 1000 MHz energy interval signal agrees with the pedolith thicknesses observed in the field (Fig. 4 and Figs S1 to S3).””.

Line 459-461:
? pedolith and saprolith

Sentence has been changed: ”However, the boundary between pedolith and saprolith is probably too shallow to be detected with the 1000 MHz antennae.”.

Line 461-462:
? pedolith and saprolith

Sentence has been changed: ”An even higher frequency would be required to detect the pedolith/saprolith boundary.”.

Line 473:
Theory would suggest that in such shallow dry and uniformly sandy "soils" GPR might be useful in mapping changes in moisture content over time

We don’t disagree with the reviewer that GPR data are also sensitive to regolith moisture, but we don’t understand what the reviewer is asking for in this comment.

Line 474-478:
Does this mean that the visual observations are not supported by physical and chemical measurements?

Correct. The sentence reads as: “Although the 500 MHz and 1000 MHz GPR envelopes indicate changes at depth, the physical and chemical properties observed with depth show only a few distinct changes implying that the pedolith thickness cannot easily be determined using only physical or chemical properties.”.

Line 486-488:
Well known, which is why forward modeling of "remote" geophysical data should be supported by the best available petrophysical data

Sentence changed to: "These observations again underscore, that for different locations with variable regolith type, vegetation, and physical and chemical properties local calibration between pedons and GPR data are required." Forward modeling of GPR data is not the stated intent of this manuscript, and is beyond the scope of this study. This manuscript focuses on comparisons between geochemical and geophysical data, not forward modeling of geophysical data.

Line 497-498:
Is this a consequence of an increase moisture levels?
"Chemical properties seem to have a considerable influence on GPR signals in this setting"

We are unclear as to what the reviewer is asking for here. Regolith moisture was not available for comparison. What the PCA analysis tells us is the variables that co-vary with each other. Any other variables not included in the PCA analysis (e.g. moisture levels) would be lumped into the unexplained variance in the analysis. If regolith moisture co-varies with the chemical properties measured, then it would also show up in the analysis. However, we are not aware of any published work that shows co-variation of regolith moisture with the chemical properties measured here. As such, we do not see a basis for adding speculation on this here.

Line 505:
The most important of which are?

Physical properties have been listed. The sentence reads now as: "The pedolith thickness is easily identifiable based on physical properties (e.g., bulk density, grain size variation)."

Line 508-510:
Related properties

We are not sure what properties the reviewer is asking for here since we already mention relevant properties we can constrain. The sentence reads: "The variance is strongly explained by PC1 containing physical properties (e.g., bulk density, clay content, LOI) and less by PC2 including chemical properties (e.g., pH, τ of Na and Zr).

Line 545-547:
How do these results compare with those reported by Dal Bo et al 2019?

Figures 12 to 15 and figures S14 to S23 show the pedolith thickness based on visual observations in the GPR signal as well as the pedolith thickness based on amplitude signal in the GPR envelope signal. The pedolith thickness determined by the GPR signal generally agrees with the pedolith thickness based on GPR envelopes. However, pedolith thickness based on GPR signals is not always possible, GPR envelopes give continuous information where a change from pedolith to saprolith is to be expected. The sentence in questions is changed to: "However, the complications which frequency of GPR antenna to use for analysis (Dal Bo et al., 2019) in addition to what envelope interval to select (section 5.1) requires careful up-scaling of the pedolith thickness to hillslopes."

Line 557-559:
? down

Sentence corrected as suggested: "The pedolith thickness based on the 1000 MHz GPR envelope at the top-slope position (SGPED20) decreases first downhill and then increases again, thereby demonstrating laterally variability down the hillslope."

5.3 Changes of soil thickness with hillslope position, aspect, and latitude
This topic is throughly explored in preceding publications by this group

Yes, we know we've written about this topic before. We address it again here because a lot of new (and different types) of data are presented and it is important point for the community to know if the previous results still stand. Furthermore, the study areas presented in here were specifically chosen to address variations due to hillslope position and latitude and we'd be remiss not to cover this.

Line 660-662:
?pedolith to saprolith
Although the correlations are not consistent from one area to the next

Sentence corrected: "The visually observed transition from the mobile pedolith to immobile saprolith coincides with one or more changes in measured physical and chemical properties in each study area."

Line 662-665:
This could be because the data on "soil" properties did not include data on properties known to be an important influence on GPR responses eg soil moisture content. As a consequence, the work could be considered to be inherently flawed.

The way in which this comment is worded is unnecessarily offensive. Nevertheless, we don't disagree that regolith moisture can also be important. As stated before, regolith moisture data was not available. However, many other relevant data sets were available and a multivariate analysis was conducted to identify where signals do lie within the data. In some cases - a large amount of variance in the data set is explained by these data. In other cases not. In the cases where all the variance is not explained, yes – this could be due to other factors like regolith moisture.
To address this comment, we have modified the text in section 3.1, and also in the new 'caveats' section in the discussion section (section 5.4) to more explicitly state these caveats and the other factors (such as regolith moisture) could also be important for observed GPR signals.
To say the study is inherently flawed when a comparison of GPR data to difficult to acquire chemical data is frankly surprising. There are very few studies to our knowledge that conduct this detailed comparison between chemical and geophysical data over a ~1300 km ecological and climate gradient in a similar lithology. We apologize if the reviewer doesn't see the merits in this. Reviewer 1 did explicitly recognize the utility of this.

Line 6742-674:
Not new findings. Petrophysical data, or an understanding of the variation in the properties being investigated at a local scale, are fundamental to proper design, processing and interpretation of all geophysical surveys.

Yes – we are aware that the GPR community frequently conducts subsurface point calibrations to their data. The sentence the reviewer is referring to here is the last sentence of the conclusions and is a wrap up sentence. We've deleted the sentence for the reviewer's benefit. We've added a new concluding sentence to this section that gives more details about what frequency antennas work better in which climate/vegetation zones.

I would find photos of the soil/saprolite profiles useful. Perhaps you could include photos and soil profile descriptions in the supplementary file? Or refer to Figure 2 in Bernhard et al (2018) – perhaps even reproduce it. It is a very useful figure and should be easily available to readers of this paper.

We thank the reviewer for this suggestion. We prefer not to republish figures from other figures, but to accommodate this suggestion we have add reference in the main text (section 2.2) and the figure caption for our Figure 3 to say: (for complete characterization and interpretation of the pedons see Fig. 2 in Bernhard et al. (2018) and Figs 3 to 6 in Oeser et al. (2018))..

Lines 162 and 163. "In Pan de Azúcar, the soil is part of a regosol and consists of a 20 to 25 cm thick A and B horizon." A regosol is a soil, so how can the soil be part of it? I suggest rewording: "In Pan de Azúcar, the soil, a regosol, consists of A and B horizons with a combined thickness of 20 to 25 cm and an underlying saprolite zone (the C horizon), which is coarse-grained and jointed (Oeser et al., 2018). The total organic carbon content of the A and B horizons is <0.1% (Bernhard et la., 2018). Angular fragments in the soil increase in size (> 1 mm) with depth."

Sentences have been reworded as suggested: "In Pan de Azúcar, the regolith, a regosol, consists of A and B horizons with a combined thickness of 20 to 25 cm and an underlying saprolith (the C horizon), which is coarse-grained and jointed (Oeser et al., 2018). The total organic carbon content of the A and B horizons is <0.1% (Bernhard et la., 2018). Angular fragments in the pedolith increase in size (> 1 mm) with depth."

I also suggest rewording soil descriptions for the other areas in the same section.
Soil descriptions have been adjusted in all sections to terminology used in first section.

Section 2.2. For La Campana and Nahuelbuta there is no mention of the characteristics of the saprolite.

For Santa Gracia, La Campana, and Nahuelbuta the saprolith is now mentioned and shortly described in section 2.2.

Technical corrections
Line 88. What do you mean by "sub-surface"?

"sub-surface" has been changed to "regolith" where not used in connection with GPR analysis.

Figure 3 caption – what do the colours in the pedons represent?

A legend for the colors used in this figure has been added to the figure.

Line 254, also 278 "In this way, the move-outs of linear events" – I/m not sure what this means – what are "move-outs"?

The sentence with the term "move-outs" has been replaces by: "Using this type of survey, we can distinguish between signals that increase linearly in traveltime with increasing receiver-transmitter distance (e.g., air wave and ground wave) and signals that increase hyperbolically in traveltime with increasing receiver-transmitter distance (e.g., subsurface reflections). In this analysis, we assume that internal reflection horizons are not dipping.

Check figures for text size. In some (e.g. Figure 4, Figure 6, some of the text is too small. I attach a file with suggested edits.

Figure 4, 6, 8, and 10: Font sizes have been enlarged where possible. The same changes have been applied on the supplementary figures in question.

Additional comments
This is not a comment on your paper, but a general comment on the research. Have you considered using ground-based electromagnetic sensing? This measures conductivity and might supplement GPR as a way of mapping sub-surface soil units. See, for example: Ahmed, M.F., Odeh, I.O.A. and Triantafilis, J. 2002. Application of a mobile electromagnetic sensing system (MESS) to assess cause and management of soil salinization in an irrigated cotton- growing field. Soil Use and Management 18, 330-339. Triantafilis, J. and Buchanan, S.M. 2009. Identifying common near-surface and subsurface stratigraphic units using EM34 signal data and fuzzy k-means analysis in the Darling River valley. Australian Journal of Earth Sciences 56, 535-558. Amezketa, E. 2007. Use of an electromagnetic technique to determine sodicity in saline - sodic soils. Soil Use and Management 23, 278-285.

Unfortunately, electromagnetic induction EMI was applied, but did not produce reliable results. Therefore, EMI analyses were not included in Dal Bo et al. (2019) and did not get measured in the second field campaign performed for this manuscript. Thank you for this suggestion and the references addressing this kind of investigations.

Supplement comments
Please also note the supplement to this comment:
https://soil.copernicus.org/preprints/soil-2020-33/soil-2020-33-RC1-supplement.pdf

All suggested changes have been taken into account in the manuscript.

Comparison of regolith physical and chemical characteristics with geophysical data along a climate and ecological gradient, Chilean Coastal Cordillera (26° to 38° S)

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Abstract

We combine geophysical observations from Ground Penetrating Radar (GPR) with regolith physical, and chemical properties from pedons excavated in four study areas spanning 1,300 km of the climate and ecological gradient in the Chilean Coastal Cordillera. Our aims are to: (1) relate GPR observations to depth varying regolith physical and weathering-related chemical properties in adjacent pedons, and (2) evaluate the lateral extent to which these properties can be extrapolated along a hillslope using GPR observations. Physical observations considered include regolith bulk density and grain size distribution, whereas chemical observations are based on major and trace element analysis. Results indicate that visually-determined pedolith thickness and the transition from the B to C horizons generally correlate with maximums in the 500 and 1000 MHz GPR envelope profiles. To a lesser degree, these maximums in the GPR envelope profiles agree with maximums in weathering related indices such as the Chemical Index of Alteration (CIA) and the chemical index of mass transfer (τ) for Na. Finally, we find that up-scaling from the pedon to hillslope scale is possible with geophysical methods for certain pedon properties. Taken together, these findings suggest that the GPR profiles down hillslopes can be used to infer lateral thickness variations in pedolith horizons in different ecologic and climate settings, and to some degree the physical and chemical variations with depth.

Keywords: regolith, pedolith, hillslope, climate, vegetation, geophysics,

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1 Introduction

Weathering of bedrock by biotic and abiotic processes produces regolith which provides resources for life. Most biota is found in the mobile pedolith, which overlies the immobile saprolith. The pedolith is replenished with nutrients from the saprolith through chemical weathering and erosion that drives nutrient uplift towards the surface (e.g., Porder et al., 2007). The thickness and production of pedolith is influenced by aspect, topography, composition (mineral content), biota, climate, tectonically driven rock uplift, and time (e.g., Hilgard, 1914; Jenny, 1994). However, subsurface variations in pedolith thickness at the scale of hillslopes are difficult to quantify because of lack of exposure. Thus, subsurface imaging by geophysical techniques, when calibrated to regolith excavations (pedons), offers a potential means to characterize spatial variability in pedolith thickness and regolith properties (e.g., Mellett, 1995; Doolittle and Collins, 1995; Miller et al., 2002). Here, we evaluate the utility of applying Ground Penetrating Radar (GPR) to map variations in physical and chemical regolith properties caused by diverse climate and ecological settings.

Previous work has attributed spatial variations in pedolith thickness to hillslope curvature (Heimsath et al., 1997; Heimsath et al., 1999), which determines the downslope rate of mass transport assuming a diffusion-based geomorphic transport law (e.g., Roering et al., 2001). However, this single point information is spatially restricted and pedon excavations are time-intensive. To further understand spatial variations in pedolith and saprolith thickness, other approaches such as modeling (e.g., Scarpone et al., 2016) and geophysical imagining (e.g., see summary in Parsekian et al., 2015) have been applied. For example, pedolith thickness variations were extrapolated from Digital Elevation Models (DEMs) in combination with several different observations at single locations (e.g., Scarpone et al., 2016). Different geophysical techniques have provided a non- or minimally invasive approach to view pedolith variations down to the saprolith and bedrock interface (e.g., Parsekian et al., 2015). Whereas high frequency GPR has proven suitable for investigating pedolith layering and thickness (e.g., Doolittle et al., 2007; Gerber et

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al., 2010; Roering et al., 2010; Dal Bo et al., 2019), other methods such as seismics (e.g., Holbrook et al., 2014), Electrical Resistivity Tomography (ERT, e.g., Braun et al., 2009), and low frequency GPR (e.g., Aranha et al., 2002) are better suited to image saprolith and bedrock interfaces (e.g., Parsekian et al., 2015). GPR methods were also previously used to indirectly measure water flow (e.g., Zhang et al., 2014; Guo et al., 2020) as well as root density (e.g., Hruska et al., 1999; Guo et al., 2013). Interpreting the interplay of GPR signals with physical and chemical regolith properties is challenging (e.g., Saarenketo, 199; Sucre et al., 2011; Tosti et al., 2013; Sarkar et al., 2019).

The Chilean Coastal Cordillera (Fig. 1) contains an extreme climate and vegetation gradient and is a natural laboratory to study the influence of climate and vegetation on the surface of the Earth in a setting with similar tectonic history and lithology. The region is home to four study areas of the German-Chilean EarthShape priority program (www.earthshape.net), where investigations of biotic interactions with regolith were conducted (e.g., Bernhard et al., 2018; Oeser et al., 2018). The study areas were selected to show a range from arid climate in the northernmost location (~26.1° S), to temperate rain forest conditions in the southernmost location (~37.8° S). These four study areas were investigated to qualitatively and quantitatively describe the differences between the four settings. Our previous work in these areas has identified from field observations and GPR based methods an increase in pedolith thickness from north to south and major and trace element compositional variations within pedons (e.g., Bernhard et al., 2018; Oeser et al., 2018; Dal Bo et al., 2019). However, in our previous GPR work (Dal Bo et al., 2019) we were not able to present a detailed comparison of physical, chemical, and regolith observations which has yet to be reported for these areas.

In this paper we build upon the previous work of Dal Bo et al. (2019) and compare the pedon measured physical and chemical observations (from Bernhard et al. (2018) and Oeser et al. (2018)) to a large newly acquired GPR data set from the same area to gain insight into regolith variations along a climate and ecological gradient. Our approach is to relate GPR observations adjacent to pedons to depth

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Deleted: In this study, we investigate how physical as well as chemical observations measured at point locations (pedons) relate to GPR observations to gain further insight into the sub-surface variations. In general, we find that GPR signals can be correlated to changes in soil

varying regolith properties caused be weathering as well as to evaluate if these properties can be extrapolated along a hillslope using GPR transects. In doing this, we test the hypothesis that if weathering processes produce depth varying physical and chemical changes in regolith observed in pedons, then (a) GPR based observations of these locations should produce observable changes in the GPR envelope and reflectors correlative to weathering horizons, and (b) GPR can be used to up-scale geochemical observations from pedons to the hillslope scale. In general, we find that our new GPR measurements can be correlated to changes in pedolith physical properties if these changes are of sufficient magnitude and laterally coherent. If such a correlation is observed, we discuss the links between the physical and chemical properties. The comparison of physical and chemical properties with field observations and GPR data helps to better understand the regolith at point locations (e.g., pedolith thickness) and in some cases allows for up-scaling point observations to the hillslope scale along a GPR measurement profile.

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2 Study areas

From north to south (Figs 1 and 2), the four selected study areas in the climatic and vegetation gradient observed in the Chilean Coastal Cordillera are: a) Pan de Azúcar (~26.1° S); b) Santa Gracia (~29.8° S); c) La Campana (~33.0° S); and d) Nahuelbuta (~37.8° S). The study areas were investigated for regolith physical and chemical properties by Bernhard et al. (2018) and Oeser et al. (2018) as well as studied with GPR by Dal Bo et al. (2019) (see Tables 1 and 2).

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2.1 General climate, vegetation, and geologic setting

The Chilean Coastal Cordillera with its climate and vegetation gradient is a natural laboratory to study the influence of climate and vegetation on denudation (Fig. 1). From north to south (~26° to 38° S), present climate ranges from arid to humid-temperate. The mean annual precipitation increases from nearly zero to ~1500 mm yr^{-1}, and mean annual temperature decreases from ~20° C to ~5° C.

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Vegetation cover increases from nearly zero to ~100%. The flora consists of small shrubs, geophytes and annual plants (Armesto et al., 1993) in the north and changes to lower-stature deciduous trees and shrubs intermix with tall evergreen mixed forest in the south.

Climate and vegetation in the primary study areas changed over time from the Last Glacial Maximum (LGM) to present. Mean annual precipitation during the LGM was higher than at present in all four study areas (Mutz et al., 2018). Mean annual temperature during the LGM was lower than at present except in the southernmost study area where mean annual temperature stayed the same (Mutz et al., 2018). Hence, the climate gradient observed today is comparable to the gradient during the LGM. Even though the climate was wetter and cooler during the LGM, no glaciers covered any of the study areas (Rabassa and Clapperton, 1990). Because of these climatic changes over time, vegetation zones during the LGM were shifted northward by ~5° and vegetation cover was slightly (~5-10%) lower compared to present (Werner et al., 2018). This shift of vegetation zones to the north and the decrease in vegetation cover also likely influenced the fauna present, but to an unknown degree.

To compare the effect of climate and vegetation on pedolith thickness and GPR observations, differences in lithologies need to be minimal. However, these conditions are not always fulfilled and need to be taken in to account. Whereas bedrocks in Pan de Azúcar, La Campana, and Nahuelbuta are granites to granodiorites, the bedrocks in Santa Gracia range from Granodiorites to Gabbros (Oeser et al., 2018). Hence, the parent material in Santa Gracia is lower in SiO_2-content (50-65%) in comparison to the other three study areas (SiO_2-content >65%). Chemical weathering and physical erosion, which in turn influence pedolith formation and thickness, may be affected by this difference.

2.2 Regolith Characteristics

In each study area, regolith transects (Figs 2 and 3; Table 1) from a catena consisting of three pedons on the S-facing slope (top-slope, mid-slope, and toe-

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slope) and one pedon on the N-facing slope (mid-slope) were described, sampled, and analyzed (see Bernhard et al., 2018; Oeser et al., 2018; Schaller et al., 2018; Dal Bo et al., 2019). Only one pedon was investigated in the N-facing slopes due to time and financial restrictions. In addition, transect lengths in some settings are limited due to the availability of weathered hillslopes in the same lithologies (e.g., Pan de Azúcar; Fig. 3A) as well as restriction of access due to intense vegetation (e.g., Nahuelbuta; Fig. 3D).

These previous studies from pedons in each area identify O, A, B, and C horizons that overlie weathered bedrock (for complete characterization and interpretation of the pedons see Fig. 2 in Bernhard et al. (2018) and Figs 3 to 6 in Oeser et al. (2018)). In this study, we refer to depth profiles as regolith profiles that are composed of a mobile pedolith that includes the A and B horizons, and an immobile saprolith including the C horizon.

In Pan de Azúcar, the regolith, a regosol (IUSS Working Group WRB, 2015), consists of A and B horizons with a combined thickness of 20 to 25 cm and an underlying saprolith (the C horizon), which is coarse-grained and jointed (Oeser et al., 2018). The total organic carbon content of the A and B horizons is <0.1% (Bernhard et al., 2018). Angular fragments in the pedolith increase in size (> 1 mm) with depth. The average bulk density of the A and B horizons is 1.3 g cm^{-3}. In Santa Gracia, the 30 to 55 cm thick pedolith overlying the saprolith is a cambisol (IUSS Working Group WRB, 2015). Total organic carbon content of the A and B horizons is 0.4%. Whereas the A horizon consists of a silt- to fine sand-sized matrix supporting up to 2 mm sized fragments, the underlying B horizon shows a transitional increase of fragments to a coarse fragment-supported fine-grained matrix. The weathered granodiorite of the saprolith consists of up to 1 cm-sized fragments which are surrounded by fine-grained material and fine roots (Oeser et al., 2018). The average bulk density of the pedolith is 1.5 g cm^{-3}. The regolith in La Campana is a cambisol (IUSS Working Group WRB, 2015). The A and B horizons are 35 to 60 cm thick and have a total organic carbon content of 1.9% (Bernhard et al., 2018). The fine sand- to silt-sized A horizon contains fragments of up to 3 mm.

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The matrix in the underlying B horizon is coarsening downwards and the number of fragments increases such that the horizon shifts from matrix- to clast-supported. In the saprolith, which shows a granodioritic fabric, fine roots are common and fractures are abundant (Oeser et al., 2018). The average bulk density is 1.3 g cm^{-3}. The regolith in Nahuelbuta, an umbrisol (IUSS Working Group WRB, 2015), consists of a 60 to 90 cm thick pedolith and a readily disaggregating saprolith. Total organic carbon content in these pedoliths is 6.1% (Bernhard et al., 2018). The A horizon is composed of silt-sized particles forming nodular aggregates. In the upper part there are up to 1 mm large quartz grains embedded whereas the lower part contains large fragments. The fine sand-sized matrix of the transitional B horizon hosts subangular fragments. The amount and size of these fragments increases with depth. The average bulk density of the pedolith is 0.8 g cm^{-3}.

3 Data compilation and methods

New data from 25 GPR profiles in the four study areas were collected at frequencies of 500 and 1000 MHz. These data are compared to physical and chemical properties from point locations (pedons) from previous studies (Bernhard et al., 2018; Oeser et al., 2018). Unfortunately, no regolith water content was measured in samples from the pedons excavated in 2016. The new GPR profiles (collected in 2017) complement previous GPR data collected 2016 at the same frequencies, in the same catchments (Dal Bo et al., 2019). The difference between this study and that of Dal Bo et al. (2019) lies in the new, more extensive, GPR data coverage, the analysis of regolith water content in augers in the study areas, and its comparison to physical and chemical subsurface variations.

Using physical and chemical properties collected in pedons to understand the corresponding radar signatures is a difficult task requiring multiple steps. First, it would require identifying relationships between the measured pedon properties and corresponding permittivity changes in the radar signal. Second, it would require a radar forward model that successfully predicts the convolution of the emitted radar

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pulse with the subsurface reflectivity. This includes handling constructive and destructive interference caused by closely-spaced vertical permittivity changes. For applications to regolith this is currently not possible because the permittivity relationships are unclear. We therefore take a step back from the more sophisticated methods, and use simpler statistical metrics to isolate regolith properties (i.e. Pearson correlation) or combinations thereof (i.e. Principal Component Analysis) that may explain parts of the radar signatures.

3.1 Data compilation

In this study, GPR data are compared to previously published pedolith and saprolith physical and chemical properties (Table 2) such as: 1) bulk density, grain size distribution, acid and base properties - pH, and cation exchange capacity - CEC (Bernhard et al., 2018); and 2) Loss On Ignition - LOI, Chemical index of Alteration - CIA, mass transfer coefficient - τ, and volumetric strain - ε_{strain} (Oeser et al., 2018). The grain size distributions provide a measure of the weight percent of different grain sizes smaller than 2 mm in the regolith, and the bulk density provides a measure of how dense the pedolith and saprolith material is packed. The geochemical data used provide major and trace element analysis, pH, and CEC. Major and trace element analyses allow the investigation of the LOI, Tau τ, and volumetric strain ε_{strain}. The degree of weathering can be quantified by CIA which is sensitive to the removal of alkalis such as calcium, sodium, and potassium from feldspars (Nesbiitt and Young, 1982). τ_{strain} reflects chemical gains and losses during weathering based on the elemental concentrations of mobile and immobile elements in weathered and unweathered material (e.g., Brimhall et al., 1985; Chadwick et al., 1990), ε_{strain} in a regolith is based on the density ρ (g cm^{-3}) and immobile element concentrations of the weathered regolith in comparison to the unweathered bedrock indicating volumetric gain or loss (Brimhall and Dietrich, 1987).

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GPR signals are sensitive to regolith water content variations with depth (e.g., Steelman et al., 2012; Ardekani et al., 2014). In addition to our compilation of previously published chemical and physical properties, we present here newly collected regolith water content data from regolith augers in Santa Gracia, La Campana, and Nahuelbuta (supplement Tables S3A to C). Although this data provides insight into regolith water content variations with depth, regularly spaced sampling with depth was not possible in the field. As a result, the regolith water content data are sparse, and not directly overlying the GPR profile locations. Given the sparseness of this data, we were not able to include it in our correlations or correlation and PCA analysis (described below), but we do discuss trends present in the regolith water content (gravimetric basis) with depth and potential implications for the rest of our analysis. Furthermore, we note that the GPR data were not collected with an approach that allowed for the inversion for regolith water content (e.g., Steelman et al., 2012).

3.2 Ground Penetrating Radar (GPR)

Ground Penetrating Radar (GPR), a geophysical technique based on the emission of pulsed electromagnetic waves into the subsurface, are applied in this study for frequencies of 500 and 1000 MHz (for more details see Dal Bo et al., 2019). Fourteen new transects going from hillslope toe (near valley) to top (ridge crest) are collected crossing the pedons where physical and chemical properties were collected (Figs. 2 and 3). Of these 14 transects, two were collected in the Pan de Azúcar study area (for 500 and 1000 MHz), six in Santa Gracia (for 500 and 1000 MHz), three in La Campana (for 500 and 1000 MHz), and three in Nahuelbuta (only for 500 MHz). Wide-angle-reflection-refraction (WARR) are used to retrieve velocity and physical properties at the point scale. For each pedon, a WARR is measured in a relatively flat location (red stars, Fig. 2).

GPR data were processed and analyzed using MATLAB as described in Dal Bo et al. (2019). In addition, signal envelopes were calculated using a Hilbert transform (Green, 2004; Liu and Marfurt, 2007). At each pedon location, a certain number of

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Twenty-eight COP

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traces depending on the measurement step size (i.e. between 10 and 50) were sampled for 0.5 m uphill and 0.5 m downhill the pedon and laterally averaged for comparison to the pedon physical and chemical properties. The averaging assumes that both chemical and GPR signatures do not change with depth across that interval, an assumption that may not hold everywhere. As the GPR envelope is directly related to the electric impedance (Telford et al., 1990; Jol, 2009), the envelope onset and energy intervals could be compared to variations in physical, and potentially chemical, regolith properties.

3.3 Statistical Correlation and Principal Component Analysis

Comparison between the physical and chemical pedon information (Bernhard et al., 2018; Oeser et al., 2018) and GPR data was conducted. Where available, we used the bulk density, clay content, LOI, CIA, Tau (τ), volumetric strain (ε_{strain}), pH, and CEC for comparison to the GPR 500 and 1000 MHz antennae envelope data. The GPR envelopes were resampled and averaged, such that the depth intervals were the same as for the derivates of the regolith data (see Table S2). Furthermore, because the envelope of GPR data is sensitive to changes along the vertical direction, we also calculated the vertical gradient of the ground truth information at each sampled depth using a centered difference approximation. Following this, the R package function corrplot (Wei, 2012) was used to calculate the Pearson's correlation coefficient to identify correlations between the variables (Sedgwick, 2012). We further conducted a multivariate analysis of the data based on principal component analysis (PCA; Wold et al., 1987). This was done using the factoextra R package (Kassambara, 2017). Correlation coefficients and PCA are done for each study area along the entire climate gradient.

4 Results

Physical and chemical properties of pedons are shown with the 500 and 1000 MHz GPR profiles and their envelopes with depth as well as investigated

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correlations and PCA results for the four study areas (Figs 4 to 11; Figs S1 to S12; Table 3; Tables S1A to D, S2A to D, S3A to C, and S4A to E). For brevity, comparisons between pedon observations and GPR data are presented only for the S-facing mid-slope positions in the main text (Figs 4, 6, 8, and 10) and the remaining locations are provided in the supplementary material. Note that the envelopes are averaged over the common offset profile data, collected over a lateral distance of 1 m in total, and are therefore not point information. Given that the pedolith thickness increases towards the southern study areas, the 1000 MHz GPR antenna is interpreted for the northern two study areas Pan de Azúcar and Santa Gracia, whereas in La Campana and Nahuelbuta the 500 MHz GPR signal was used because it has a deeper penetration depth. However, we show results below for both frequency antennas to demonstrate the difference in penetration depth and resolution between the two antennae. Details for each study area (from north to south) follow.

4.1 Pan de Azúcar (northern most and driest study area)

In Pan de Azúcar (Figs 1 and 2A), a gradual transition from the B to the C horizon was visually observed in the pedons at 20 to 40 cm (shaded gray areas after Bernhard et al. (2018); Fig. 4; Figs S1 to S3), whereas the mobile and immobile boundary is considered to be at 20 to 25 cm (black lines after Oeser et al., (2018); Fig. 4; Figs S1 to S3). No water content measurements for this area were available due to poor recovery of auger samples from the impenetrable substrate. The available physical properties for this location do not indicate a strong change in material properties with depth. LOI and CIA indicate a minor change in properties at ~20 cm depth. A maximum in the energy envelope in the 1000 MHz frequency is present at about 20 to 30 cm, and could be related to the transition of material properties between the B and C horizons and the location of mobile and immobile boundary observed in the field.

Due to the sparse depth information for bulk density and clay content, the statistical analyses for this location were not very insightful. Whereas clay content

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shows a medium correlation (0.54) with the 1000 MHz GPR envelope, no strong correlation between LOI, CIA, Tau τ, and the 1000 MHz GPR envelope could be found (Table 3). In the PCA, three principal components (PC) explain over 80% of the variance (Table S4A). PC1 has the biggest contribution from CIA, clay content, and the 500 MHz envelope whereas PC2 has the biggest contribution from LOI, the 1000MHz envelope, and τ of Na and Zr (Fig. 5).

4.2 Santa Gracia

In Santa Gracia (Figs 1 and 2B), a gradual transition from the B to the C horizon was observed in the field between 20 to 60 cm depth (shaded gray region Fig. 6; Figs S4 to S6). The boundaries between the pedolith and saprolith were observed between 30 to 55 cm depth. Water content near pedon locations ranges between 7.6% to 1.8% and is highly variable with sample locations and with no clear spatial or depth dependent trend (Table S3A). Bulk density and volumetric strain show slight changes around 15 and 30 cm depth. Whereas LOI and CIA do not show any changes with depth, τ shows changes between 30 and 50 cm depth. The 500 and 1000 MHz GPR profiles and envelopes show increased irregular and strong reflections at ~25 cm (1000 MHz) and 45 cm (500 MHz) depth, and also maximums in the envelope at ~25 cm (1000 MHz) and 45 cm (500 MHz) depths. These variations in the reflections and maximums in the envelopes coincide with either the top or central position of the transition from the B to the C horizon.

A weak to moderate correlation (~0.30) between clay content as well as CIA and the 1000 MHz GPR envelope is present (Table 3). Results from a PCA analysis of the Santa Gracia data indicate that 3 components explain over 80% of the observed variance (Table S4B). PC1 explains over 35% of the variance, and includes bulk density, CIA, and the 500 and 1000 MHz envelopes (Fig. 7). PC2, explaining 31% of the variance, includes clay content, LOI, and τ of Na and Zr.

4.3 La Campana

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Field observations from the La Campana area (Figs 1 and 2C) document a layer of cobbles (5 to 10 cm diameter) between the A and B horizon at a depth of ~30 cm (Bernhard et al., 2018). The transition between the B to C horizons does not contain rock fragments. The transition from the B to C horizon (shaded gray area, Fig. 8) and the mobile and immobile boundary (black line, Fig. 8) are observed at 34 to 110 cm and 35 to 60 cm, respectively (see also Figs S7 to S9). The pedolith extends deeper in La Campana than in Pan de Azúcar or Santa Gracia and physical properties were available for greater depths. Bulk density and grain size change gradually with depth and no pedolith thickness could be determined. Also, LOI, CIA, and τ do not show an abrupt change in regolith properties. Water content near pedons ranges between 3.1% to 1.5% and shows only a slight (~0.5%) decrease between depths of ~30 to 90 cm (Table S3A). Reflection hyperbolas and irregular reflection horizons appear in the 500 and 1000 MHz GPR data at about 40 to 60 cm depth above the B to C horizon transition. The second peaks of the 500 and 1000 MHz GPR envelopes coincide with the B to C horizon transition.

In contrast to the previous study areas, the 500 MHz GPR envelope correlates moderately with CIA (0.56), pH (-0.57), and CEC (-0.39, Table 3). Three components from the PCA analysis explain about 80% of the total variance (Table S4C). PC1 (~35% of the total variance) includes LOI, Tau τ, and CEC, whereas PC2 (31%) contains CIA, volumetric strain ε_{strain}, and the envelopes (Fig. 9). PC3 is dominated by pH as well as τ of Zr. In general, whereas the first energy interval (1000 MHz) could be attributed to the stone layer between the A and B horizon, the second energy interval occurs close to (<10 cm) with the mobile and immobile boundary (Fig. 8).

4.4 Nahuelbuta (southernmost and wettest study area)

In Nahuelbuta, the B horizon contains pebbles and cobbles at around 60 to 80 cm depth (Bernhard et al., 2018). The B to C horizon transition appears at 50 to 100 cm depth (shaded gray region, Fig. 10; see also Figs S10 to S12). The mobile and

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immobile boundary was identified at 60 to 90 cm depth (Oeser et al., 2018). Density measurements in the pedon indicate a transition in bulk density between about 30 to 60 cm depth where the grain size distribution also changes. The LOI and τ generally show large changes with depth, in contrast to the CIA and volumetric strain which are more homogenous with depth. In general water content near pedons and in near-surface (10 to 30 cm depth) samples is between 23 and 39% and decreases ~3% to ~10% over regolith depths of 30 to 90 cm (Table S3A). In addition, water content increases from top- to toe-position in the S-facing slope and is lower in the N-facing mid-slope position than in the S-facing position. The 500 MHz GPR profile indicate the existence of point targets/objects appearing as reflection hyperbola or undulating features at depths greater than 60 cm. This depth is approximately the same depth at which the mobile and immobile boundary was identified, as well as changes in the physical properties (e.g. bulk density, percent sand) and chemical properties (LOI, Tau τ). The hyperbolas do not add up coherently during the lateral averaging and therefore do not produce a significant energy interval in the average envelope. The envelope is dominated by the energy intervals given by two reflections at about 30 to 50 cm depth. The lower set of these energy intervals could be linked with the upper physical pedolith boundary.

Results from the correlation analysis indicate that the 500 MHZ GPR envelope is strongly positively correlated with bulk density (0.74), strongly inversely correlated with LOI (-0.60), and moderately inversely or positively correlated with clay content (-0.37), pH (0.46), and CEC (-0.53) (Table 3). Results from the PCA analysis show that two PC components explain ~75% of the variance. PC1 (~57 %) includes bulk density, clay content, LOI, and CEC, and PC2 (~18 %) contains τ of Zr and pH (Fig. 11; Table S4D). In general, as the 500 MHz GPR envelope signal correlates well with bulk density and clay content, the envelope signal reflects changes in regolith properties.

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5 Discussion

Here we evaluate the physical, chemical, and geophysical observations from the pedons. Using this information, we attempt to up-scale information from the pedons to the hillslopes scale along the GPR transects.

5.1 Synthesis of GPR data with physical and chemical properties from point locations

GPR data image subsurface changes that could be caused by variations in physical (e.g., bulk density, grain size variation, water content) and chemical properties (e.g., pH, CEC, CIA). The interplay between these different properties can have a complicated influence on the GPR signal and therefore can be difficult to disentangle. Disentangling any relationship between GPR data and physical and chemical properties is further complicated because not all properties influencing GPR data are measured in the pedons (e.g., water content; Jol, 2009). In addition, the determination of the boundary between the pedolith and saprolith in the field causes its own problems because observed changes are not discrete but transitional over a depth interval of 5 to 10 cm. In the following, we start by discussing if GPR data can be used to image pedolith thickness as well as physical and chemical properties at the pedon locations where *in-situ* observations were made in each study area.

In Pan de Azúcar (Figs 4 and 5; Figs S1 to S3), the locations where GPR data can be compared to pedons show low variability in the observed pedolith thickness (~20 to 30 cm) at each pedon location. Whereas the 500 MHz signal shows the interface with the saprolith, the maximum in the 1000 MHz energy interval signal agrees with the pedolith thicknesses observed in the field (Fig. 4 and Figs S1 to S3). However, the boundary between the pedolith and saprolith is probably too shallow to be detected with the 1000 MHz antenna. An even higher frequency would be required to detect the pedolith and saprolith boundary. Hence the Pearson correlations and PCA results from Pan de Azúcar are restricted not only because of GPR analysis but also due to restricted physical properties. The physical and

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chemical properties correlate only weakly to moderately with the 1000 MHz envelopes (Table 3). The PCA results indicate that bulk density is not likely correlated with either the 1000 MHz signal or LOI. In Pan de Azúcar, LOI does not represent organic matter because regoliths of arid zones generally have low or no organic matter content. The volatile loss measured in the LOI is more likely associated with the combustion of carbonates. In general, shallow pedoliths in the arid zone do not show much variability in pedolith thickness nor do they provide insight into the influence of physical or chemical properties on GPR signals.

In Santa Gracia (Figs 6 and 7; Figs S4 to S6), the field-observed pedolith thicknesses of the different pedons are more variable than in Pan de Azúcar. Although the 500 MHz and 1000 MHz GPR envelopes indicate changes at depth, the physical and chemical properties observed with depth show only a few distinct changes implying that the pedolith thickness cannot easily be determined using only physical or chemical properties. The PCA indicates that most of the variance in PC1 is explained by the envelope signals, bulk density, and CIA whereas PC2 is dominated by clay content and Tau τ of Na and Zr. The clay content does not seem to be a dominant factor for the envelope signal, but rather represents a complex interaction between physical and chemical property changes that cannot be disentangled with available data. It appears that the second energy interval in the 1000 MHz envelope may agree with the observed pedolith thickness in Santa Gracia, and (in contrast to the Pan de Azúcar location) the first maximum in the 500 MHz envelope does agree with the observed pedolith thickness. These observations again underscore, that for different locations with variable regolith type, vegetation, and physical and chemical properties local calibration between pedons and GPR data are required.

The determination of pedolith thickness from GPR data in La Campana is as difficult as in the previous settings (Figs 8 and 9; Figs S7 to S9). Field observations indicate relatively thick transition zones from the B to C horizons, and some physical properties vary only weakly with depth. As a result, the determination of pedolith thickness with physical and chemical properties is difficult, despite the moderate to

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strong correlation of 500 MHz GPR envelopes with derivatives of physical and chemical properties. Whereas PC1 explains much of the variance in terms of bulk density, LOI, Tau τ of Na and Zr, and volumetric strain ε_{strain}, the PC2 consists out of the envelopes, CIA, pH, and CEC. Chemical properties seem to have a considerable influence on GPR signals in this setting. In La Campana, the first energy interval in the 500 MHz envelope is interpreted to reflect the presence of the stone layer whereas the second energy interval seems to match the observed pedolith thickness. Given these uncertainties in local conditions, a clear identification of pedolith thickness from GPR data is difficult, even with local calibration to a pedon.

Finally, in Nahuelbuta (Figs 10 and 11; Figs S10 to S12), the observed pedolith thickness in the field is the deepest of all the four study areas and reaches from 50 to 100 cm. The pedolith thickness is easily identifiable based on physical properties (e.g., bulk density, grain size variation). The derivatives of the physical properties correlate moderately with the available 500 MHz envelope (Table 3). Furthermore, the chemical properties correlate weakly with the GPR envelope. The variance is strongly explained by PC1 containing physical properties (e.g., bulk density, clay content, LOI) and less by PC2 including chemical properties (e.g., pH, Tau τ of Na and Zr). Even though changes in properties are more pronounced in Nahuelbuta than in the drier locations, a clear correlation between maximums in the 500 MHz energy envelope and pedolith thickness is not present. The second energy interval of the 500 MHz envelope best agrees with the observed pedolith thickness. However, due to local inhomogeneities caused by intense vegetation, every pedon and its attributed GPR envelope looks different.

In summary, the 500 and 1000 MHz envelopes at point locations have the potential to be used to determine pedolith thickness. But the clarity with which this can be done is variable and requires calibration to local pedons. Even with local calibration, the relationships are not always clear (e.g., Fig. 8). Physical and chemical properties with depth exert a complex influence on measured GPR signals. If a certain combination of physical and chemical properties is dominant in one

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setting, another combination may influence the measured GPR signal in another. For example, whereas clay content correlations are moderately positive with GPR envelopes in the dry area of Pan de Azúcar, the relationship is weaker at more southerly latitudes and is moderately negatively correlated in Nahuelbuta. Other physical properties (e.g., bulk density, LOI) only correlate well with the envelopes in the southernmost study area of Nahuelbuta. The more pronounced correlation of bulk density and LOI with the envelope signal can be attributed to the abundance of organic matter in the regolith. The presence of organic matter influences not only bulk density and LOI but also CEC and pH (all organic matter related variables). Analysis of the PCA results in light of organic matter variations identifies the following variables as being best explained from north to south: (1) in Pan de Azúcar: the GPR envelope, clay content, and CIA are most closely related; (2) in Santa Gracia: the GPR envelope, bulk density, and CIA are most closely related; (3) in La Campana: the GPR envelope, bulk density, organic matter related variables are related; and (4) in Nahuelbuta: the organic matter related variables, bulk density, and GPR envelope are most closely related.

Thus, the influence of vegetation and the continuous addition of organic matter to regolith properties influencing GPR signals are strengthen from north to south. Therefore, which GPR frequency works best for the individual study area (due to different physical and chemical properties) needs to be investigated with information from point locations/pedons. For the arid Pan de Azúcar and semi-arid Santa Gracia we suggest using the 1000 MHz frequency (or higher), whereas for the Mediterranean climate setting of La Campana and temperate Nahuelbuta the 500 MHz frequency proved better. Improvements in our approach to determine pedolith thickness from GPR data might be possible by applying multifrequency GPR techniques, which are freed from antenna effects by fusion of different frequency measurements (e.g., De Coster and Lambot, 2018). Nevertheless, the point information of pedolith thickness has the potential to be up-scaled to hillslopes in some settings using GPR transects after local calibration is conducted.

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5.2 Up-scaling to hillslopes

Here we use insights gained from comparisons between GPR and point locations to extrapolate the pedolith thickness along the hillslope GPR profiles (Figs 2 and 3). Our efforts here complement previous work by Dal Bo et al., (2019) by adding 25 new GPR profiles that cover a larger geographic region. The up-scaling is carried out using a combination of amplitude and envelope depth-converted profiles. To do this up-scaling, we calculated the envelope along each profile. Then, using the known pedolith depth data from all pedons in one study area, this interface was estimated along the profiles by searching for the corresponding signal in the envelope at every meter. Even though the information of three-point locations is at the lower limit, the combination of field observations with GPR transects allows estimation of the lateral variability of pedolith thickness over hillslopes. However, the complications which frequency of GPR antenna to use for analysis (Dal Bo et al., 2019) in addition to what envelope interval to select (section 5.1) requires careful up-scaling of the pedolith thickness to hillslopes.

In Pan de Azúcar (Fig. 12; Fig. S14) the observed B to C horizon transition at point locations is typically between ~14 to 50 cm. No clear pedolith thickness could be determined based on GPR profiles. Nevertheless, pedolith thicknesses identified from 1000 MHz GPR envelopes seem to be relatively homogeneous over the entire S-facing transect with an average value of 25 ±3 cm (Table 1). In contrast, the N-facing transect indicates a thinner pedolith uphill than downhill where it reaches a maximum depth of ~50 cm (Fig. S14). In Santa Gracia (Fig. 13; Figs S15 to 17), the pedolith thicknesses from point locations/pedons in the S-facing transect increases downslope and ranges between 20 to 60 cm (Table 1). The pedolith thickness based on the 1000 MHz GPR envelope at the top-slope position (SGPED20) decreases first downhill and then increases again, thereby demonstrating laterally variability down the hillslope. The pedolith thickness in the mid-slope position (SGPED40) is variable and reaches from 25 to 50 cm. At the toe-slope position (SGPED60) a mostly constant thickness of 30 cm is identified. In the N-facing transect almost no variability in pedolith thickness (~25 cm) is observed. Although the pedolith

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thickness based on GPR envelopes cannot be used to decipher the exact pedolith thickness, the method still offers a close approximation of pedolith thicknesses determined by field observations and GPR profiles. In La Campana (Fig. 14; Figs S18 to 20) the pedolith thickness from the 500 MHz GPR envelope is 35 to 70 cm (Table 1). Whereas the top- and mid-slope positions in the S-facing hillslope (LCPED10 and LCPED20, respectively) show variable pedolith thickness between 50 and 70 cm, the toe-slope position (LCPED30) contains pedolith thicknesses between 35 and 70 cm. Relatively constant pedolith thickness of 50 to 60 cm are identified for the N-facing mid-slope position (LCPED40). Field observations do not always agree with pedolith thicknesses based on GPR envelopes. In the La Campana location, pedolith thicknesses based on GPR envelopes need to be considered with caution, but contain valuable information such as the existence of pebble layers. However, GPR profiles show hyperbolas and continuous reflections, which can be interpreted along almost all the covered length. These interfaces can be reliably used to infer pedolith thicknesses, when a previous calibration with pedons has been done. In Nahuelbuta (Fig. 15; Figs S21 to 23), pedolith thickness in the S-facing top-slope position (NAPED10) increase downhill from 60 to 110 cm (Table 2). At the mid-slope position (NAPED20), the pedolith thickness is highly variable and ranges from 50 to 110 cm. Pedolith thickness at the toe-slope position (NAPED30) is 80 to 110 cm. In the N-facing mid-slope position the pedolith thickness ranges from 60 to 110 cm. Pedolith thicknesses based on GPR envelopes are generally thicker than pedolith thicknesses observed in the field and do also not agree well with thicknesses based on GPR profiles. The discrepancy between GPR measurements and field observations could result from the high water content in Nahuelbuta at the time of GPR acquisition. Alternatively, the discrepancy could also result from the heterogeneity of regolith observed in pedons at each location (Berhard et al., 2018). The application of GPR envelopes to determine pedolith thicknesses needs to be treated with care in this setting. On the contrary, GPR profiles display rather continuous reflections that might represent interfaces within

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the pedolith, and could therefore be used to extrapolate point-scale ground-truth information over the profile scale.

In summary, the application of GPR envelopes to determine pedolith thicknesses provides more information than pedolith thicknesses determined from GPR transects alone where in some cases no clear reflections may be visible. Generally, the findings of this study agree with the findings of Bernhard et al. (2018) as well as Dal Bo et al., (2019). Pedolith thicknesses increase from north to south in latitude. Due to the increase in vegetation amount pedolith thicknesses are also less homogenous from increasing latitude (north to south). Due to the increasing heterogeneity in pedolith thickness, no clear trend in increasing pedolith thickness from top- to toe-slope is easily detectable. Only in Santa Gracia, the constantly thin pedoliths at the S-facing top-slope are in contrast to the thicker and more variable pedolith thickness in the mid-slope position. Bernhard et al., (2018) describe an increase of the A to BC horizon from top- to toe-slope in the S-facing hillslope. In addition, a clear difference between pedolith thickness from S- and N-facing slopes could not be detected for the more heavily vegetated study areas in the south. Again, only in Santa Gracia with little vegetation an expected difference in pedolith thickness between S- and N-facing slopes was detectable. The increase in vegetation under increasing precipitation rates causes not only more heterogenous pedolith depths, but also stabilization of hillslopes (e.g., Langbein and Schumm, 1958; Schmid et al., 2018; Starke et al., 2020).

5.3 Comparison to previous work and study caveats

Geophysical studies focusing on the critical zone are a relatively new topic and have gained emphasis in the past decades (e.g., Parsekian et al., 2001). The results presented in this study complement a range of previous studies. Previous studies have used near surface geophysical methods to non-invasively measure subsurface properties and structures of the regolith and help to characterize critical zone related processes in the shallow subsurface (e.g., Scott and Pain, 2009). In this study, we focused in particular on deploying surface ground penetrating radar (GPR). The

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5.3 Changes of soil thickness with hillslope position, aspect, and latitude¶
The soil thickness imaged with

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Deleted: study non-invasively possible changes in soil thickness over hillslope position, aspect, and latitude (Fig. 12 to15; Fig. S14 to S24; Table 2). Here we summarize any regional trends in soil thickness between the four study areas and different aspect (N- vs. S-facing) hillslopes (Fig. 2).¶
Soil thickness in a catena that develop under comparable climate and on similar lithologies are expected to increase downhill (e.g., Birkeland, 1999). From the top- to toe-slope position along a catena the potential for physical erosion decreases downslope due to decreasing physical potential whereas the potential for deposition increases. In Pan de Azúcar, the soil thickness based on the GPR envelopes in the S-facing hillslope are constant, whereas the N-facing hillslope indicates soil thickness increasing from top- to toe-slope. The possible slight increase in soil thickness from top- to toe-slope can be explained by low denudation rates due to very low precipitation rates in Pan de Azúcar. In Santa Gracia, the constantly thin soils

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Deleted: In Santa Gracia, precipitation and minor vegetation cover may cause the increase of the soil thickness downslope as well as the variable soil thickness in the mid-slope position. In La Campana, the soil thickness based on GPR envelopes is highly variable. Bernhard et al., (2018) observed the thickest soil also in the mid-slope position, describe a disturbed hillslope with recent erosion events (e.g., possibly due to a past fire and temporary mobilization of sediment). Therefore, the S-facing hillslope in La Campana is a disturbed system and therefore difficult to laterally extrapolate horizons. Due to the differences in soil thickness information from the different methods, soil thickness changes in hillslopes from Nahuelbuta are not further considered.¶
In the southern hemisphere the N-facing hillslope is expected to be slightly warmer (higher solar irradiation) and drier (due to higher evaporation) than the S-facing hillslope (e.g., Anderson

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Deleted: Different vegetation on S-facing and N-facing slope positions in La Campana could explain the higher variability in soil thickness in the S-facing mid-slope positions (35 to 70 cm) than the N-facing hillslope (50 to 60 cm). However, the aspect-related differences in La Campana may represent local ... [5]

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Deleted: due to increasing precipitation rates electromagnetic properties of the subsurface affect the propagation (i.e. velocity), attenuation (i.e. the energy loss), and reflectivity of the electromagnetic waves (e.g., Jol, 2009). The electromagnetic wave velocity and attenuation can be linked to the dielectric permittivity and electrical conductivity of the subsurface, respectively. Previous work provides examples of environments, where GPR is suitable for mapping subsurface properties. These include karst areas, where structures in the regolith have been identified up to the bedrock interface (e.g., Estrada-Medina et al., 2010; Fernandes Jr. et al., 2015; Carriere et al., 2013), volcanic environments (e.g., Gomez et al., 2012; Ettinger et al., 2014), and dry environments (e.g., Bristow et al., 2007; Harari, 1996) as generally these regimes are characterized by low clay and water content. The primary new contribution of this study with respect to existing regolith studies is the comparison of GPR data to a wide range of physical and chemical properties that are commonly interpreted in projects studying surface processes.

Previous work has highlighted the primary factors that GPR data can be sensitive to, and we briefly discuss these in the context of caveats associated with our work. Important factors that influence GPR data are the presence of water, solute content, and conductive materials such as clay (e.g., Scott and Pain, 2009; Huisman et al., 2003). In particular, clay as a highly conductive material has a significant impact on GPR signal as it affects the permittivity and the electrical conductivity at the same time (e.g., Daniels, 2004). With increasing amounts of clay in the subsurface, the signal penetrating is decreased due the increased attenuation of the waves. However, this behavior can be used to identify fine material in the subsurface, since in GPR profiles clay layers could be identified starting from spatial differences in signal penetration (e.g., Gómez-Ortiz et al., 2010; De Benedetto et al., 2010; Tosti et al., 2013). Furthermore, particle size beyond just clay content also plays a major role in GPR measurements, as the closer the particle size is to the wavelength of the emitted electromagnetic waves, the stronger are the reflections generated by these particles that can be seen in the detected signals (e.g., Jol, 2009). In this

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study, we incorporated clay content into our PCA and correlation analysis to identify if, and by how much, it may influence GPR observations.

Previous studies have also documented how mineralogical variations with depth influence GPR signals. For example, the presence of minerals such as iron and aluminum oxides/hydroxides can play an important role in limiting the depth of penetration for GPR waves (e.g., Čeru et al., 2018) as iron-oxides have been linked with variations of relative permittivity, which might have in turn a considerable effect in the propagation of the GPR signals and effect the interpretation (e.g., Van Dam et al., 2003: Van Dam and Schlager, 2000; Havholm et al., 2003). Other studies showed that with increasing mafic mineral content in the subsurface, GPR signal attenuation is higher (e.g., Breiner et al., 2011). The presence of clay lenses in the regolith, alongside the layering, can influence the preferential flow path for regolith water, which can enhance reflectivity of the surfaces and therefore produce detectable reflections (e.g., Zhang et al., 2014). In this study, mineralogical variations with depth in the pedons were not available for comparison to our GPR data. However, we note that many of the processes described above may be responsible for the subsurface reflectors observed in Figures 12 to 15, and the fairly uniform granitoid composition of the different study areas means that mineralogical variations along any given hillslope profile are likely minimal and not a dominant source of signal in our GPR data.

The presence of volumetric water limits GPR signal penetration, with an increasing effect at higher frequencies (e.g., Utsi, 2017; Miller et al., 2002). GPR techniques have been used in the past two decades as a tool to detect water content variations in the subsurface as it has a strong effect on the dielectric permittivity (e.g., Klotzsche et al., 2018). In compact regoliths, where the volumetric water content is small, it has been shown that the bulk density has an important effect on the wave velocity, which is positively correlated (Wang et al., 2016). When solutes are present in the groundwater, the electrical conductivity of the medium increases, generating more signal loss, and therefore increasing wave attenuation (e.g., Benedetto and Palewski, 2015). One shortcoming of our study is that no information about subsurface water content within the pedon depth profiles was available for comparison to GPR observations as we did with the regolith physical and chemical properties. The depth varying chemical weathering indices we present (e.g., CIA, Tau, Fig. 4 to 10) would not be expected to correlate with present-day water content as these weathering indices developed over the timescale of regolith development (millennia and longer). Nevertheless, we find that out of the four study areas investigated, the present-day water content appears to influence the GPR signals and interpretations presented here only in the southernmost and wettest study area Nahuelbuta. As a result, the subsurface correlations between the GPR envelopes and physical or chemical properties at this location are likely influenced, to an unknown degree, by regolith water content. The exclusion of regolith water content in our analysis may very well be a reason why we are not able to explain the full radar signature. Although without the inclusion of this data, peaks in the radar envelopes were still interpretable when compared to available physical and chemical property variations with depth. Thus, although the inclusion of regolith water content would be preferred, the omission of it does not negate the observed signals we were able to interpret.

In locations, where the aforementioned regolith properties are not dominant, GPR can be used as a tool to identify structures and layering in both sediments (e.g., Bristow and Jol, 2003) and regoliths, where interfaces ranging from the regolith-bedrock limit to the B horizon have been identified due to changes in the dielectric permittivity (e.g., Yoder et al., 2001; Lambot et al., 2006). In particular Zhang et al. (2018) showed the potential of mapping regolith layering in grasslands obtaining differences between GPR reflections and real regolith layer depth within 3 cm. In many situations, the interplay between different regolith properties make it difficult to understand the subsurface architecture without validation through regolith samples, as shown by Orlando et al. (2016) in the Rio Icacos watershed (Puerto Rico), where the stress regime, climate, and lithology are controlling the structures visible in GPR profiles. In comparing the previous studies to this one, we note that ‘in general’ the results of this study were able to identify subsurface regolith structure and explain them, in many cases, with available physical and chemical properties. However, the complexity in GPR signals observed necessitates having pedons for local calibration when comparing to regolith weathering indices.

6 Conclusions

Pedolith thickness and physical and chemical properties are investigated in four study areas along a climate and vegetation gradient. This gradient spans from arid and Mediterranean to temperate humid conditions. The visually observed transition from the mobile pedolith to immobile saprolith coincides with one or more changes in measured physical and chemical properties in each study area. These physical and chemical properties in turn, influence return signals generated by Ground Penetrating Radar (GPR) in the regolith, but no systematic trend is visible for which physical or chemical properties correlate with GPR based observations of pedolith thickness. Given this, the measurements and interpretation of GPR signals for systematically identifying subsurface changes in physical and chemical properties is not straightforward and differs for each study area. In general, the better developed the pedolith the better the correlation of GPR signals from point locations with physical and chemical regolith properties. We note that choosing the GPR antenna frequency that is best suited for identifying pedolith thickness is difficult, and calibration to local point locations (e.g., pedons) is always required. Furthermore, we found that the higher-frequency (1000 Mhz) antenna worked best for imaging pedolith layers for comparison to chemical indicators in the arid and semi-arid study areas (Pan de Azuár and Santa Gracia). In contrast, the lower frequency antenna (500 Mhz) worked better in the Mediterranean and temperature study areas (La Campana and Nahuelbuta) for imaging pedolith structure and for comparison to chemical observations.

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Figure captions

Fig. 1:

Digital elevation model (Data source: GTOPO30) for the Chilean Coastal Cordillera and the Central Andes showing the four investigated study areas (from north to south): Pan de Azúcar (~26° S); Santa Gracia (~30° S); La Campana (~33° S); and Nahuelbuta (~38° S).

Fig. 2:

Satellite images (Data source: Google Earth©) of the four study areas from N to S in latitude: A) Pan de Azúcar; B) Santa Gracia; C) La Campana; and D) Nahuelbuta. Red stars indicate the pedon positions whereas the blue lines represent the locations of the geophysical investigations.

Fig. 3:

N- and S-facing hillslopes of the four study areas with locations of pedons and transects of ground penetrating radar indicated by the red double arrows. For complete characterization and interpretation of the pedons see Fig. 2 in Bernhard et al. (2018) and Figs 3 to 6 in Oeser et al. (2018).

Fig. 4:

Compilation of physical and chemical investigations with depth at the pedon location in the mid-slope position of the S-facing hillslope in Pan de Azúcar. Properties shown are: 1) GPR transect and the envelope profile of the 500 MHz measurement; 2) GPR transect and the envelope profile of the 1000 MHz measurement; 3) Bulk density; 4) Grain size distribution of sand, silt, and clay; 5) Loss on ignition LOI; 6) Chemical index of alteration CIA; 7) Chemical index of the mass transfer coefficient Tau τ; and 8) volumetric strain ε_{strain}. The black line indicates the boundary between the mobile pedolith and the immobile saprolith (after Oeser et al., 2018) and the gray area with green lines reflects the transition zone from B to C horizon (after Bernhard et al., 2018).

Fig. 5:

Primary component analysis PCA of properties for all four pedons in Pan de Azúcar. A) Scree plot showing the percentage of explained variances and B) Variables - PCA.

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Fig. 6:

Compilation of physical and chemical investigations at the pedon location in the mid-slope position of the S-facing hillslope in Santa Gracia. Properties shown are listed in caption of Fig. 4.

Fig. 7:

Primary component analysis PCA of properties for all four pedons in Santa Gracia.

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Fig. 8:

Compilation of physical and chemical investigations at the pedon location in the mid-slope position of the S-facing hillslope in La Campana. Properties shown are listed in in caption of Fig. 4.

Fig. 9:

Primary component analysis PCA of properties for all four pedons in La Campana.

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Fig. 10

Compilation of physical and chemical investigations at the pedon location in the mid-slope position of the S-facing hillslope in Nahuelbuta. Properties shown are listed as in caption of Fig. 4. Note that only the 500 MHz signal and envelope profile exist.

Fig. 11:

Primary component analysis PCA of properties for all four pedons in Nahuelbuta.

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Fig. 12:

A) 1000 MHz GPR transect and B) envelope for the S-facing hillslope in Pan de Azúcar. The hillslope transect spans over ~20 m and includes pedon AZPED60, AZPED50, and AZPED40 (black boxes). The potential pedolith thickness based on the envelopes is indicated by stars (in B). The red bar indicates the B to C horizon transition as given in Bernhard et al. (2018). Uphill is from left to right. Note that in the radar data the air wave and background removal is applied.

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Fig. 13:

1000 MHz GPR signal and envelope for the mid-slope position of the S-facing hillslope position in Santa Gracia (SGPED40). The hillslope transect spans over ~20 m. Interpretation of the radar signal are indicated where possible (stippled lines in A and B). The potential pedolith thickness is indicated based on the envelope profile. Uphill is from left to right. Lines and symbols in figures as described in Fig. 12.

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Fig. 14:

500 MHz GPR signal and envelope for the mid-slope position of the S-facing hillslope in La Campana (LCPED20). The hillslope transect spans over ~8 m. Interpretation of the radar signal are indicated where possible (stippled and black lines in A and B). The potential pedolith thickness is indicated based on the envelope profile. Uphill is from left to right. Lines and symbols in figures as described in Fig. 12.

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Fig. 15:

500 MHz GPR signal and envelope for the mid-slope position of the S-facing hillslope in Nahuelbuta (NAPED20). The hillslope transect spans over ~20 m. Interpretation of the radar signal are indicated where possible (stippled lines in A and B). The potential pedolith thickness is indicated based on the envelope profile. Uphill is from left to right. Lines and symbols in figures as described in Fig. 12.

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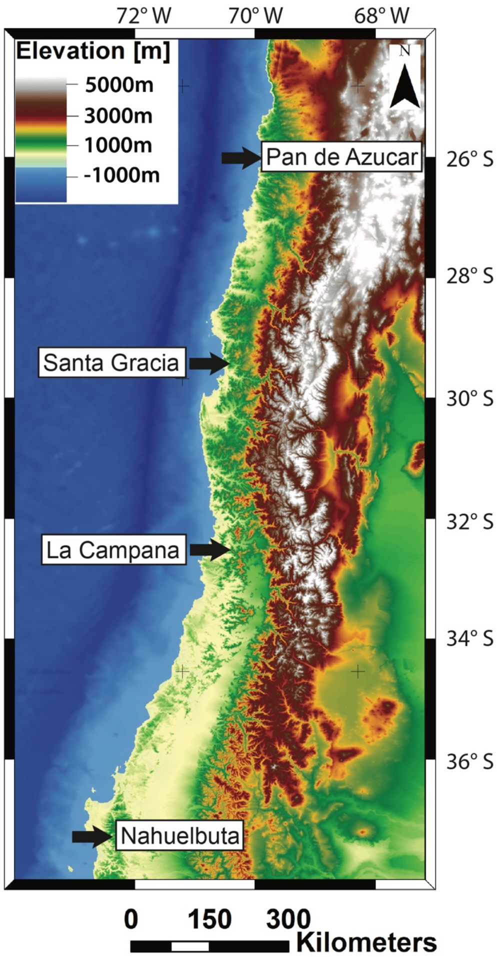

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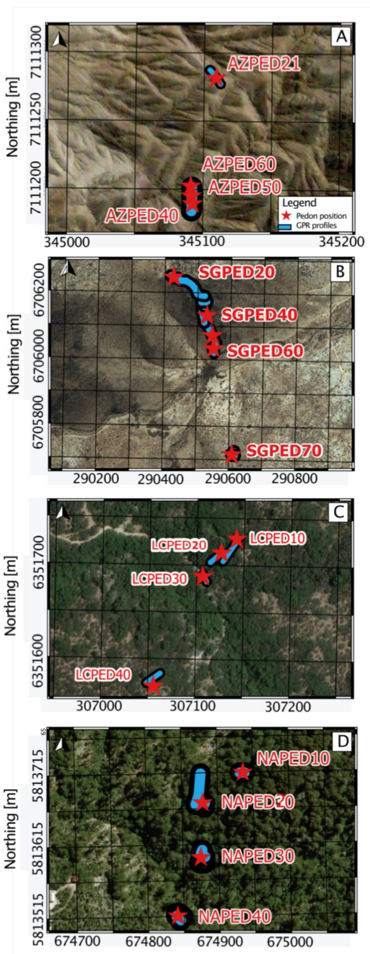

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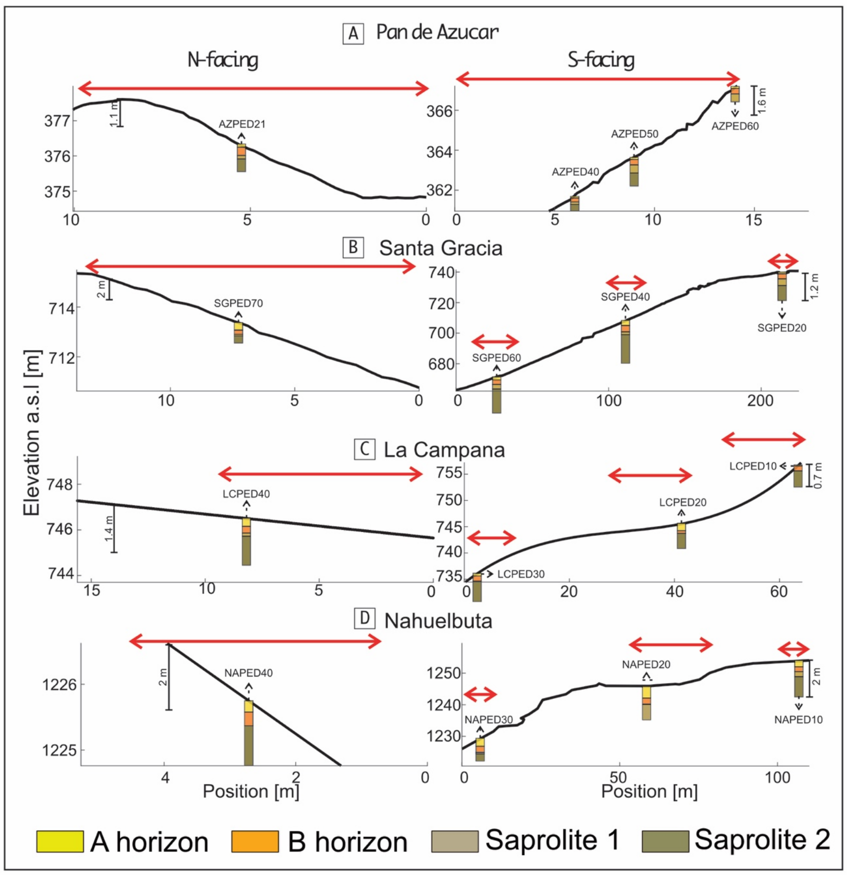

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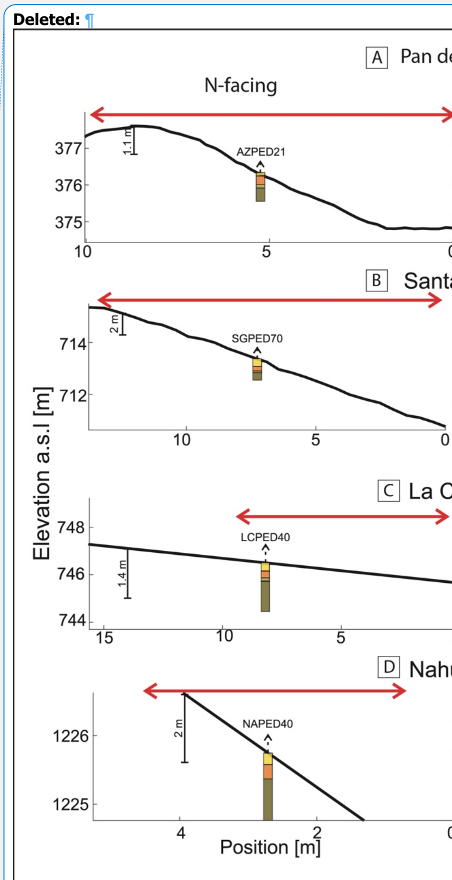

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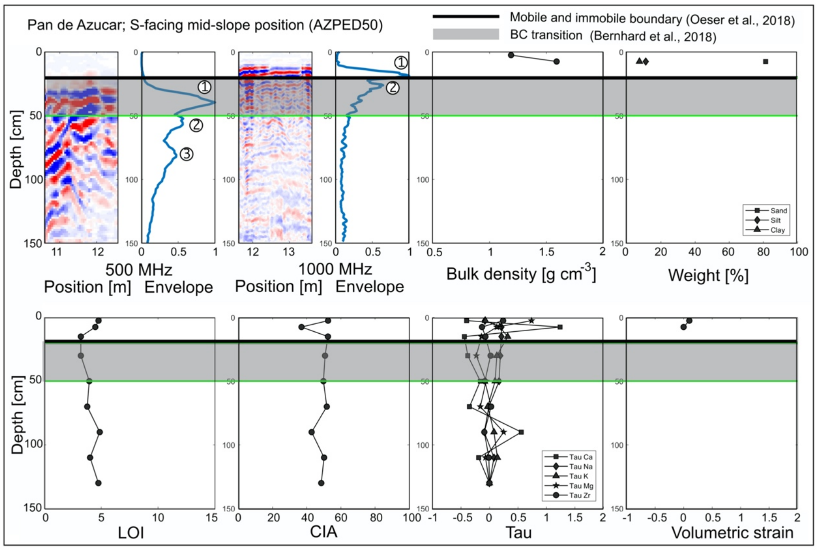

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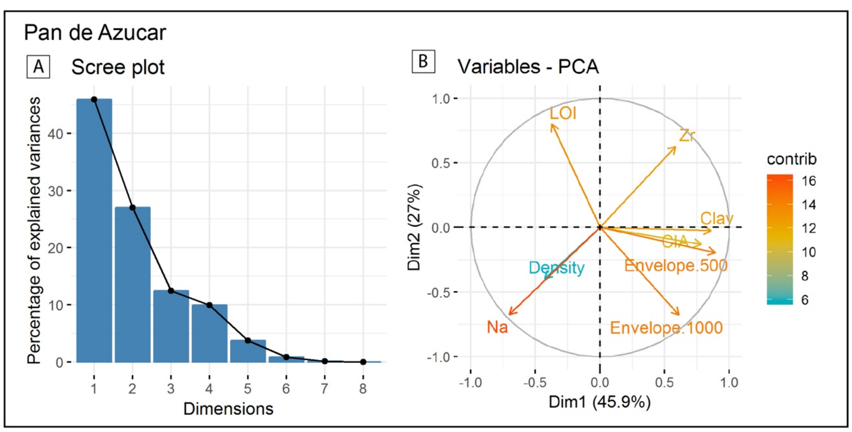

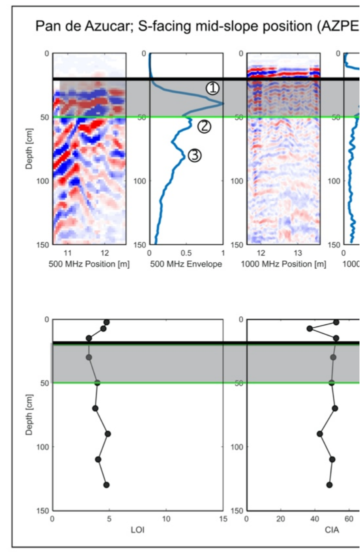

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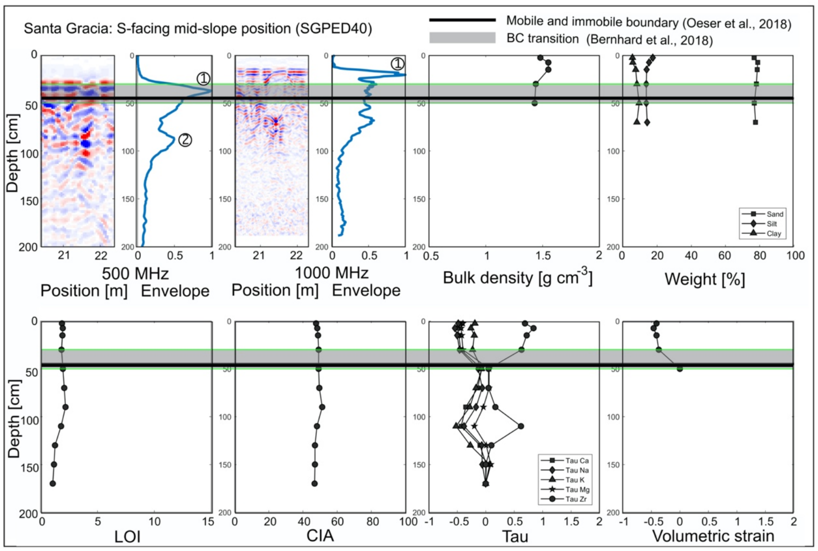

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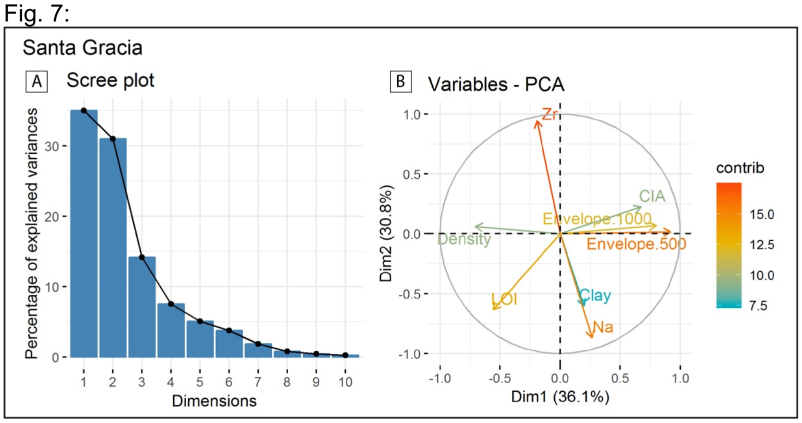

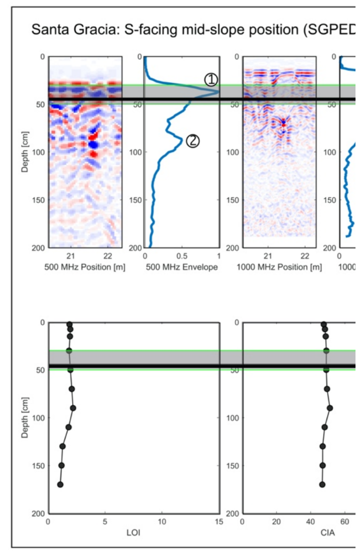

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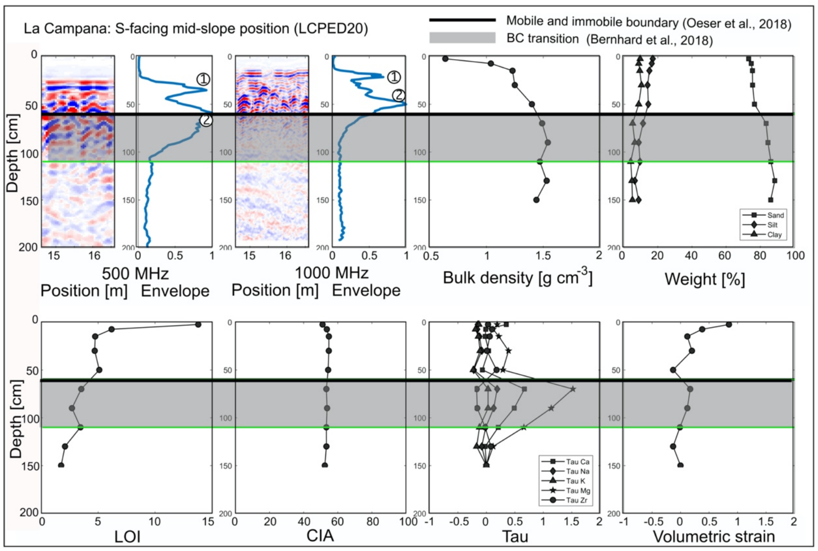

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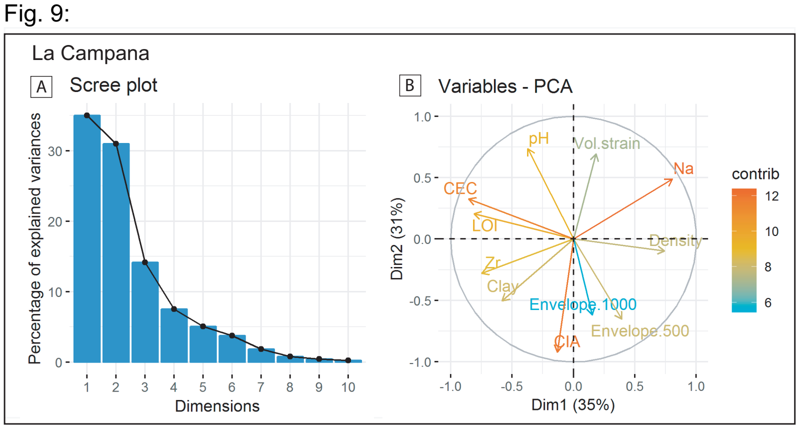

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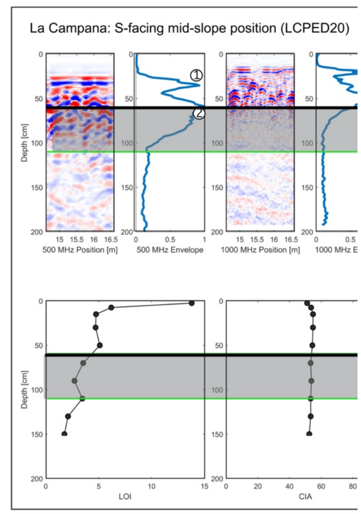

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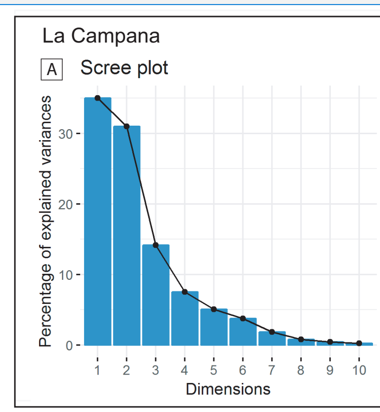

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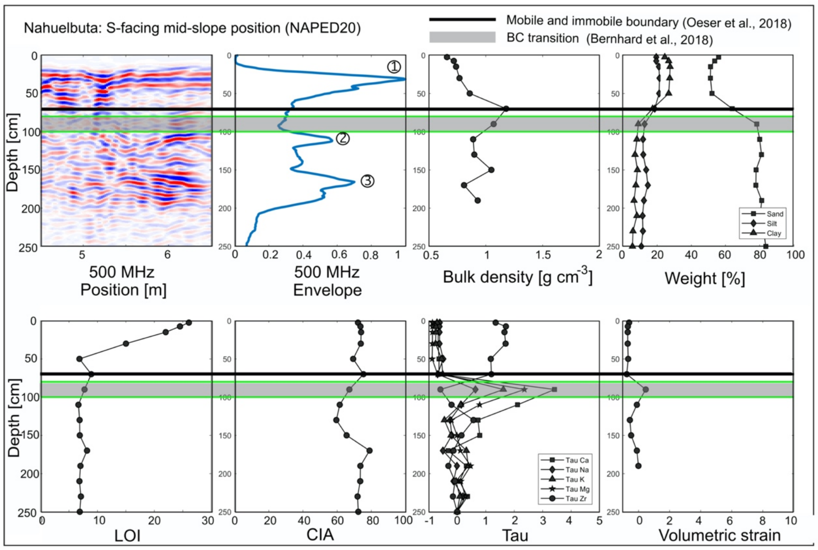

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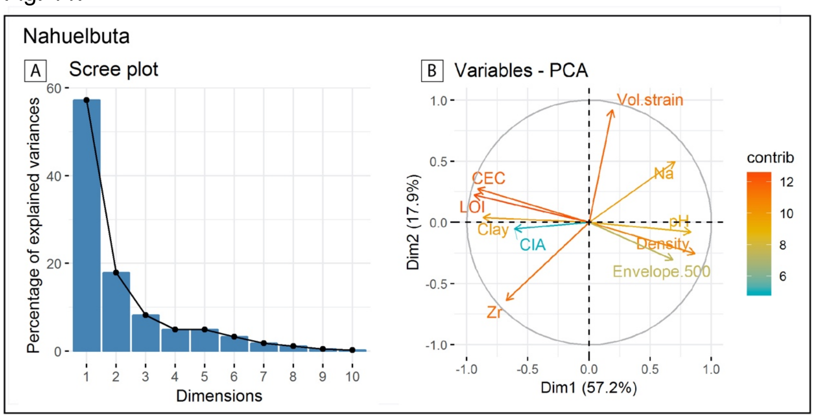

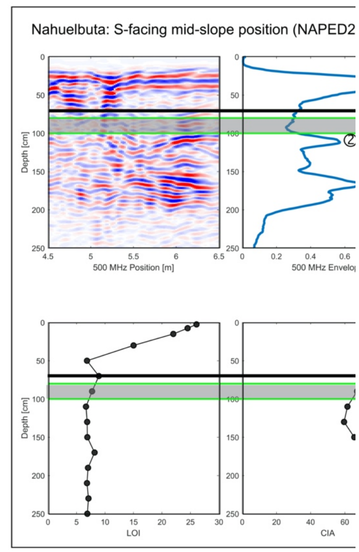

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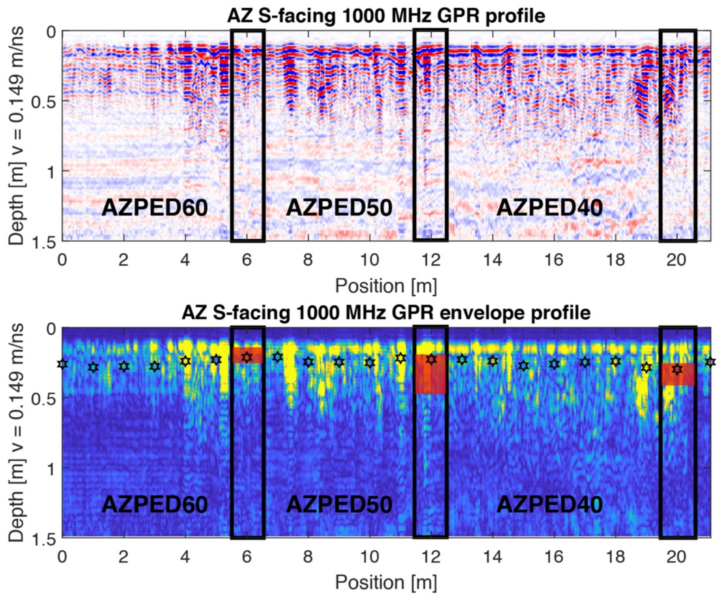
AZ S-facing 1000 MHz GPR profile
Depth [m] v = 0.149 m/ns
Position [m]
AZPED60
AZPED50
AZPED40
AZ S-facing 1000 MHz GPR envelope profile
Depth [m] v = 0.149 m/ns
Position [m]
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AZPED50
AZPED40

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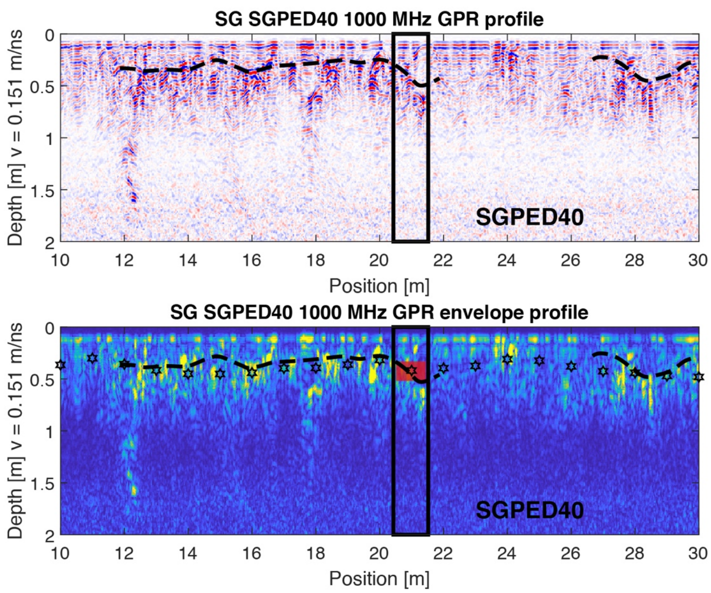

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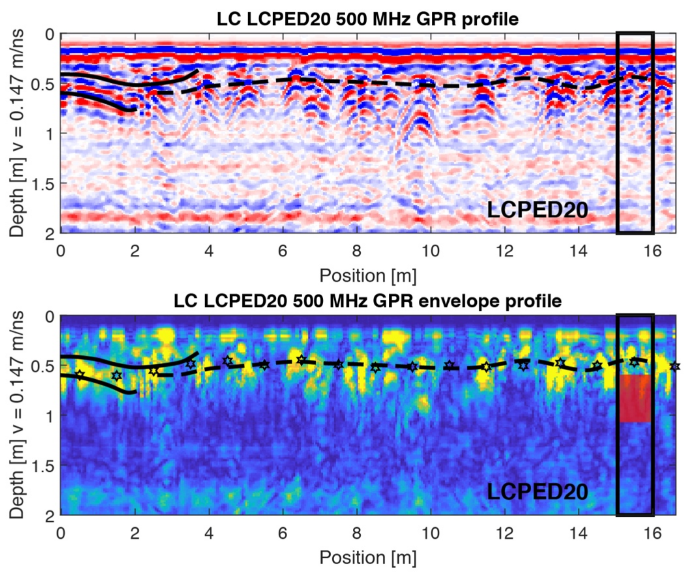

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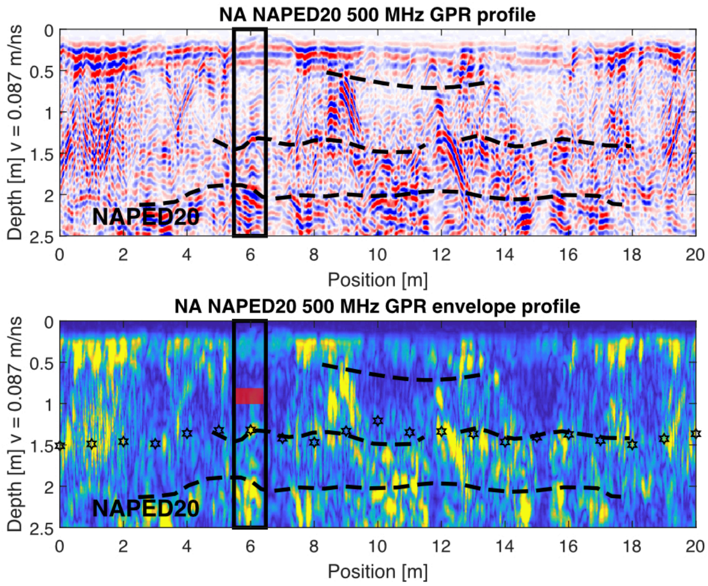

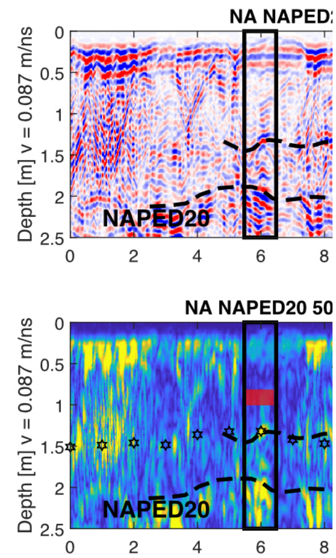

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Table 1:

Table 1: Data compilation for pedons in the investigated four study areas in the Chilean Coastal Cordillera

							Field observations				GPR point depth[5]		GPR transect depth[6]	
Pedon	Location		Altitude	Position	Aspect	Slope	BC-horizon transition[1]	Mobile/immob.[2]	Mobile/immob.[3]	GPR[4]	500 MHz	1000 MHz	500 MHz	1000 MHz
	°S	°W	m		°	°	cm	cm	cm	cm	cm	cm	cm	cm
Pan de Azucar														
AZPED60	26.11012	70.54922	343	top	60	5	14-26		22	30-55 (?)	40	20/25/45		
AZPED50	26.11027	70.54922	333	mid	0	40	20-50	20	20	20-55	40/50/70	20/25/35/45	36 ± 1	25 ± 3
AZPED40	26.11024	70.54921	326	toe	0	33	23-40		25	20-40	40/55	20/30		
AZPED21	26.10936	70.54907	342	mid	180	25	20-30	20	20	30-45	37/55/75	20/30/45/55	40 ± 2	28 ± 7
Santa Gracia														
SGPED20	29.75636	71.16721	718	top	240	5	20-30		30	30	40	20/30/40/50	37 ± 5	34 ± 3
SGPED40	29.75738	71.16635	682	mid	0	25	30-50	50	45	60	45	20/30/40/55/65	40 ± 7	36 ± 5
SGPED60	29.75826	71.16615	638	toe	0	20	40-60		55	-	37/50	20/30	39 ± 7	35 ± 6
SGPED70	29.76120	71.16559	690	mid	180	15	25	35	35	NA	40	20/30	35 ± 3	28 ± 2
La Campana														
LCPED10	32.95581	71.06332	734	top	60	7	34		45	40/50	35/50/70	20/30/35/50/65	55 ± 6	44 ± 5
LCPED20	32.95588	71.06355	718	mid	0	23	60-110	60	60	50/60	35/60/70	20/38/50	59 ± 6	45 ± 4
LCPED30	32.95615	71.06380	708	toe	60	35	34-55		55	45/50	35/70	20/30/38	50 ± 9	41 ± 4
LCPED40	32.95720	71.06425	724	mid	120	12	36-103	35	35	-	35/65	20/30/40	56 ± 6	47 ± 6
Nahuelbuta														
NAPED10	37.80735	73.01285	1248	top	60	5	50-75		70	70/75	35/45/120		82 ± 15	
NAPED20	37.80770	73.01357	1239	mid	60	15	80-100	95	70	75/95	35/110/170		101 ± 8	
NAPED30	37.80838	73.01345	1228	toe	0	20	63-85		90	-	35/90/120/140		96 ± 6	
NAPED40	37.80904	73.01380	1200	mid	180	13	65-90	70	60	40/50	40/80/120		95 ± 11	

(1) Depth of BC-horizon transition from Bernhard et al., 2018
(2) Depth of mobile pedolith from Schaller et al., 2018
(3) Depth of mobile pedolith from Oeser et al., 2018
(4) Depth based on data from Dal Bo et al., 2019
(5) Depth based on single point GPR envelopes (This study)
(6) Average depth based on envelopes from GPR transect data (This study)

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Table 1: Overview of physical, chemical, and geohpysical properties determin

Property	Abreviation	Units
Soil bulk density	ρb	g/cm^3
Grain size distributioin	GSD	%
Potential hydrogene	pH	
Cation exchange capacity	CEC	cmol$_c$/kg
Loss on ignition	LOI	%
Chemical index of alteration	CIA	
Mass trasnfer coefficient	τ	m/s
Volumetric strain	ε_{strain}	
Electric permitivity	ε_r	
Electrical conductivity	σ	mS/m

Table 2:

Table 2: Overview of physical, chemical, and geohpysical properties determined in the four different study areas

Property	Abreviation	Units	Meaning	Reference
Pedolith bulk density	ρb	g/cm^3	Weight of unit volume	Bernhard et al., 2018
Grain size distributioin	GSD	%	Weight percent of different grain sizes smaller than 2 mm	Bernhard et al., 2018
Potential hydrogene	pH		Acid and base properties	Bernhard et al., 2018
Cation exchange capacity	CEC	cmol$_c$/kg	Soil ability to hold positively charged ions	Bernhard et al., 2018
Loss on ignition	LOI	%	Loss of volatiles due to excessiv heating	Oeser et al., 2018
Chemical index of alteration	CIA		Degree of weathering	Oeser et al., 2018
Mass trasnfer coefficient	τ	m/s	Chemical gain or loss	Oeser et al., 2018
Volumetric strain	ε_{strain}		Volumetric grain or loss	Oeser et al., 2018
Electric permitivity	ε_r		Structural changes, porosity/soil water content	Dal Bo et al., 2019; This study
Electrical conductivity	σ	mS/m	Clay, salinity	Dal Bo et al., 2019; This study

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Table 2: Data compilation for pedons in the investigated four study areas in the Chilean

Soil profile	Location		Altitude	Position	Aspect	Slope	BC-horizon
	°S	°W	m		°	°	c
Pan de Azucar							
AZPED60	26.11012	70.54922	343	top	60	5	
AZPED50	26.11027	70.54922	333	mid	0	40	
AZPED40	26.11024	70.54921	326	toe	0	33	
AZPED21	26.10936	70.54907	342	mid	180	25	
Santa Gracia							
SGPED20	29.75636	71.16721	718	top	240	5	
SGPED40	29.75738	71.16635	682	mid	0	25	
SGPED60	29.75826	71.16615	638	toe	0	20	
SGPED70	29.76120	71.16559	690	mid	180	15	
La Campana							
LCPED10	32.95581	71.06332	734	top	60	7	
LCPED20	32.95588	71.06355	718	mid	0	23	
LCPED30	32.95615	71.06380	708	toe	60	35	
LCPED40	32.95720	71.06425	724	mid	120	12	
Nahuelbuta							
NAPED10	37.80735	73.01285	1248	top	60	5	
NAPED20	37.80770	73.01357	1239	mid	60	15	
NAPED30	37.80838	73.01345	1228	toe	0	20	
NAPED40	37.80904	73.01380	1200	mid	180	13	

(1) Depth of BC-horizon transition from Bernhard et al., 2018
(2) Depth of mobile layer from Schaller et al., 2018
(1) Depth of mobile layer from Oeser et al., 2018
(4) Depth based on data from Dal Bo et al., 2019
(5) Depth based on single point GPR envelopes (This study)
(6) Average depth based on envelopes from GPR transect data (This study)

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Table 3:

Table 3: Correlation coefficients R of 1000 and 500 MHz GPR envelope with derivatives of physical and chemical properties for each study area

Study area		Bulk density	Clay content	pH	CEC	LOI	CIA	Tau Na	Tau Zr	Vol. strain
1000 MHz										
Pan de Azucar	GPR	0.05	0.54			-0.1	-0.2	-0.1	-0.15	
Santa Gracia	GPR	-0.03	0.3			0.14	0.33	-0.16	0.1	
La Campana	GPR	-0.04	0.19	-0.34	-0.35	-0.19	0.43	-0.12	0.07	-0.18
Nahuelbuta	GPR									
Earth Shape	GPR	0.01	0.25	-0.15	-0.24	0.02	0	-0.14	0.01	
500 MHz										
Pan de Azucar	GPR	-0.29	0.17			-0.27	0.28	0.16	-0.07	
Santa Gracia	GPR	-0.39	0.26			-0.02	0.26	-0.08	0.02	
La Campana	GPR	0.2	0.22	-0.57	-0.39	-0.26	0.56	0.09	-0.26	-0.12
Nahuelbuta	GPR	0.74	-0.37	0.46	-0.53	-0.60	-0.24	0.21	-0.28	-0.01
Earth Shape	GPR	-0.16	-0.02	-0.39	-0.45	-0.03	0.45	0.11	-0.15	

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