Geophysical imaging of regolith in landscapes along a climate and vegetation gradient in the Chilean Coastal Cordillera

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ABSTRACT

Many studies have recently shown the potential of geophysical tools in bridging the information gap between individual point-scale measurements. Here, we upscale and extend the point-scale layering information from pedons (excavated pit of 1 m$^2$) using geophysical methods. We applied multi-frequency ground-penetrating radar (GPR) in four study areas in the extreme climate and vegetation gradient of the Chilean Coastal Cordillera. The main goals of this study were to understand how granitic based regolith material varies depending on climate, vegetation cover, aspect, and topography.

GPR was successfully used in all four study areas. Reflections, which were imaged up to a depth of 8 m, could be associated with boundaries visible in the pedons. The main recognizable reflections were linked with the interface between the mobile soil and the immobile saprolite. This boundary is characterized by hyperbolic-shape features, probably connected to heterogeneities (e.g. pebbles). A deeper GPR penetration depth in south-facing hillslopes was observed than in north-facing hillslopes. This is probably due to less sun exposure in the south facing slopes, which results in higher soil water content and denser plant growth, facilitating weathering processes. Furthermore, thicker layers in the GPR profiles are visible going from north to south along the latitude. Most of these observations were in agreement with the soil pedons.

These results demonstrate the utility of the GPR technique for characterizing subsurface variations in regolith properties (e.g. thickness, boundaries). Additional soil pedons should be excavated based on GPR results. Applying noninvasive geophysical methods could improve the understanding of the interactions between soil formation, vegetation, and other environmental parameters.
Keywords: ground-penetrating radar; geophysical imaging; granitic regolith; hillslope aspect; weathering processes.
1. INTRODUCTION

The decomposition of rock by physical erosion and chemical weathering is driven by tectonic, climatic, and biological processes. The thickness of the weathered rock material and the degree of weathering are influenced by time, the type of parent material, topography, climate, and hence biota (Jenny, 1994). The direct investigation of the extent and degree of regolith is restricted to excavated soil pedons, augers, and drilling of boreholes. Point observations are not only time consuming and expensive but provide little information about the spatial variation of regolith in a landscape. These point observations can be combined with non-invasive tools such as geophysics to gain more spatial coverage (Beauvais et al., 2004; De Benedetto et al., 2012).

Geophysical techniques like electrical resistivity tomography (ERT), electro-magnetic induction (EMI), ground-penetrating radar (GPR), and seismic have been widely applied to classify soil properties (Breiner et al., 2011; Dominic et al., 1995; Novakova et al., 2013) and soil and rock stratigraphy (Afshar et al., 2017; Befus et al., 2011; Brandt et al., 2007; Davis and Annan, 1989; Dominic et al., 1995; Parsekian et al., 2015; van Overmeeren, 1998; Zaremba et al., 2016). GPR was successfully applied in karst areas to recognize shallow regolith layering and bedrock (Estrada-Medina et al., 2010; Fernandes et al., 2015). GPR has been combined with EMI, showing how the effectiveness of the two methods is strongly dependent on the electrical properties of the soil (Doolittle and Collins, 1998). Carrière et al. (2013) coupled ERT and GPR techniques for the geological characterization of karst media. Similarly, the thickness of the weathering horizons was determined using ERT and GPR in a two-stepped lateritic regolith (Beauvais et al., 2004). This roughly corresponded to the thickness measured in
boreholes, which showed significant lateral variability (Beauvais et al., 1999). GPR has
also been used in sub-humid tropic areas to analyze and obtain indirect geological,
geomorphological, and pedological information about regolith with a relatively high
degree of detail (Aranha et al., 2002). The combination of GPR and borehole
observations revealed the influence of lithology on weathering processes, where
laterally discontinuous zones of fractures were shown hosting corestones and colluvial
material (Orlando et al., 2016). The combination of seismic refraction and ERT with
observations from road cuts revealed that the interaction between tectonic stress and
topography influences the depth of the critical zone, and thus the regolith formation
(Holbrook et al., 2014; St. Clair et al., 2015).

The combination of geophysical techniques with field observations and geochemical
data for regolith characterization has shown a large potential to investigate spatial
variability of weathered rock and parent material at the hillslope scale (Braun et al.,
2009; Breiner et al., 2011). Furthermore, GPR, EMI, and ERT techniques have been
successfully applied to retrieve information about soil layering and properties (André et
al., 2012; Busch et al., 2013). However, the combination of several geophysical
methods has not been tested for characterizing variations in regolith related to changes
in climate and biota. Whereas geophysical methods cannot directly measure the degree
of weathering (a chemical and biologic process), they can identify spatial variations in
physical properties caused by weathering processes. Thus, layering differences sensed
by geophysical methods provide a proxy for subsurface variations in regolith.

In this study, we applied a multi-frequency GPR method in combination with
observations from pedons (the smallest volume that can represent soil horizons and
properties variability, see Soil Survey Staff (1999)) to characterize variations in the soil and saprolite layer thicknesses. Four study areas along the climate and vegetation gradient of the Chilean Coastal Cordillera have been investigated (Fig. 1). These study areas were chosen because of their pronounced latitudinal variations in climate and vegetation, but similar parent material (i.e. granitic) and tectonic setting. We address the following questions:

1) how does regolith vary within a single hillslope;
2) how does regolith vary in hillslopes of the same area but with different aspects (e.g., north- and south-facing hillslopes); and
3) how does regolith vary in different climate settings?

2. STUDY AREAS AND PEDON INFORMATION

In the framework of the DFG-SPP Program 1803 project EarthShape (2016) four study areas located in the Chilean Coastal Cordillera (Fig. 1) with latitudes ranging from 26°S to 38°S were selected. These areas include from north to south: Parque Nacional Pan de Azúcar, Reserva Santa Gracia, Parque Nacional La Campana, and Parque Nacional Nahuelbuta (Fig. 1b and c). In these areas, the climate changes from desert to arid, Mediterranean, and humid conditions from north to south. We retrieved mean annual precipitation (MAP) and temperature (MAT) for the pedon locations from the model of Karger et al. (2017), which is based on the reanalysis of the data assimilation model ERA-Interim (Dee et al., 2011). This simulates temperature and precipitation using ground, radiosonde, and remote sensing observations, downscaling the final result at a resolution of 100 m. Going from north (Pan de Azúcar) to south (Nahuelbuta),
we derived MAT of 20.1°, 15.1°, 14.9°, and 12.9° C, and MAP of 15, 77, 326, and 1050 mm, respectively (Karger et al., 2017). Average soil thickness for the four study areas was retrieved from Bernhard et al. (2018) and Oeser et al. (2018). The bulk rock composition is comparable in all four sites and can be defined as a granitic lithology (Charrier et al., 2015; Sernageomin, 1982). Going from south to north, older rocks can be found spacing from Carboniferous to Cretaceous in age (Sernageomin, 1982). No influence by Alpine glaciers and last glacial maximum (LGM) glaciation is reported in the four study areas (Rabassa and Clapperton, 1990). The calculated tectonic uplift is 0.2±0.1 mm yr⁻¹ (Kukowski and Oncken, 2006).

2.1. Pan de Azúcar
Parque Nacional Pan de Azúcar (~26°S and 71°W) is located in the south-westernmost branch of the Atacama Desert. It is classified as an arid desert zone. The streams in this region are ephemeral and rarely have water in them, except during seldom rainstorms. Vegetation is mostly observed in the coastal area and sustained by fog (Lehnert et al., 2018). Instead, in the pedons' area vegetation is only sparsely present in the valley bottoms (gullies) and absent on crests. The main lithology comprehends tonalites, diorites, granodiorites, monzodiorites, and gabbros (Fuentes et al., 2016; Sernageomin, 1982). Many basaltic dykes are present crossing the granitic material. Fewer amounts of argillite and andesite can be found in the area as well. Soil is thin and has an average thickness of 0.20 m (Table 1, Bernhard et al., 2018; Oeser et al., 2018).
2.2. Santa Gracia
Reserva Santa Gracia (\(\sim 29^\circ\)S and 71\(^\circ\)W) is classified as transitional from arid to semi-arid/Mediterranean climate zone. Vegetation is represented by shrubs and cacti and sustained by fog (Arroyo et al., 1993). The lithology is mainly composed of tonalities, diorites, monzodiorites, granodiorites, and monzogranites (Sernageomin, 1982). The interface between soil and saprolite ranges from 0.35 to 0.60 m (Table 1, Bernhard et al., 2018; Oeser et al., 2018).

2.3. La Campana
Parque Nacional La Campana (\(\sim 32^\circ\) and 71\(^\circ\)W) has a semi-arid/Mediterranean climate and the vegetation is mainly represented by palm trees, bushes, and evergreen sclerophyllous plants (Table 1, Arroyo et al., 1993; Di Castri et al., 1981; González et al., 2009; Zunino and Saiz, 1991). The lithology is made of diorites, monzodiorites, granodiorites, and monzogranites (Sernageomin, 1982). The soil has an average thickness of 0.40 to 0.60 m (Table 1, Bernhard et al., 2018; Oeser et al., 2018).

2.4. Nahuelbuta
Parque Nacional Nahuelbuta (\(\sim 38^\circ\) and 73\(^\circ\)W) is classified as a humid temperate zone without dry season. Water flows permanently in the streams. As a result of this type of climate, the park is characterized by dense vegetation which comprehends extensive remains of pristine temperate Araucaria forests (Table 1, Cisternas et al., 1999). The parent material is mainly made of granites, granodiorites, tonalities, and diorites (Sernageomin, 1982). In the southern side of the park metamorphic rocks are
present, such as metasandstones, phyllites, marbles, metabasalts, and metaconglomerates (Sernageomin, 1982). The thickness of the soil ranges between 0.70 and 1.00 m (Table 1, Bernhard et al., 2018; Oeser et al., 2018).

2.5. Pedon information

Several pedons have been described (Table 1) for the four study areas as shown in Fig. 1 (Bernhard et al., 2018; Oeser et al., 2018). In the south-facing slopes at least three pedons were excavated along a transect (top-, mid-, and toe-slope), whereas only one was excavated in the north-facing mid-slopes as cross-check for aspect-related differences (Oeser et al., 2018). In this study, we have taken into account only the regolith layering visible in the pedons as a direct link between ground truth data and geophysical data (Scott and Pain, 2009). The main master horizons have been identified as O, A, B, and C horizons, where O, A, and B horizons are called soil and the weathered C horizon saprolite (Soil Survey Staff, 1996). Specific emphasis was put in the boundary between B and C horizons as the variation from mobile soil materials to immobile saprolite could result in a dominant physical contrast (Beauvais et al., 2004). Inner-horizon layering (e.g. A and B horizons, saprolite) was also considered as this might produce a significant contrast identifiable by geophysical methods. Moreover, the bottom boundary of each pedon was taken into account, as it could produce significant variations in the material properties detectable by geophysical methods. It was planned to excavate all the pedons up to 2.00 m depth. However, in most cases (e.g. Pan de Azúcar, Santa Gracia, La Campana) a transition towards unfractured rock was reached before 2.00 m that made deeper excavation difficult.
3. GEOPHYSICAL METHODS

In each study area, GPR common offset (CO) measurements were conducted at the profile scale, whereas at the point-scale GPR wide-angle reflection-refraction (WARR) were measured. The covered areas in the four study sites were restricted due to a combination of dense vegetation and steep slopes.

3.1. Multi-frequency Ground-penetrating Radar (GPR)

GPR is based on the propagation of electromagnetic (EM) waves. A typical on-ground GPR is assembled with transmitting (Tx) and a receiving (Rx) antennae. Whenever a contrast in the physical parameters of the subsurface is present, the EM signal is reflected and scattered, and measured by the receiving antenna (Jol, 2008).

The material properties that influence the GPR applications are the relative dielectric permittivity $\varepsilon_r$, the electrical conductivity $\sigma$, and the magnetic permeability $\mu$, which is often simplified to the value of the free space and it has seldom an influence on the EM wave propagation. However, $\varepsilon_r$ and $\sigma$ have a stronger influence on the signal and are associated to two key wave field properties that are the velocity $v$ and the attenuation $\alpha$, respectively. Generally, $\alpha$ is a combination of electrical losses and scattering losses, both of which increase with enhanced frequency (Jol, 2008). Thus, with a high frequency a shallower penetration and a higher resolution are obtained (for constant attenuation of the EM wave). The transmitting antenna generates a signal characterized by a certain central frequency $f_c$ that is directly related to the wavelength of the emitted signal $\lambda$ (Jol, 2008).
The most common way of measuring with GPR consists in using a single transmitter and receiver, where the distance (offset) between the antennae can be fixed or variable. In the first case, a common offset (CO) profile is measured, with the goal of mapping subsurface reflectivity versus spatial position. A topographic correction might be necessary in the cases of sensible elevation changes (Heincke et al., 2005). In the second case, a common midpoint (CMP) or wide-angle reflection-refraction (WARR) survey is measured, with the goal of estimating the velocity of the EM wave and the relative dielectric permittivity $\varepsilon_r$, analyzing the recorded signal with a semblance approach (Jacob and Urban, 2016; Tillard and Dubois, 1995; van der Kruk et al., 2010; Yilmaz, 2001).

3.2. Data acquisition

Within each study area, we measured 10 to 100 m transects going from the toe to the top of the hillslopes deploying GPR and using the excavated pedons as reference points (see Fig. 1, green lines and red stars, respectively). At these locations, WARRs were measured if possible (see Fig. 1, yellow circles). Whereas steepness was the main factor limiting the surveyed length in Pan de Azúcar, denser vegetation towards southern latitudes was also a limitation. The GPR surveys were carried out using the pulseEKKO system (Sensors&Software, Mississauga, Canada), with several antennae having a central frequency in air of 100, 200, 500, and 1000 MHz. The 100 and 200 MHz antennae were unshielded and mainly used stepwise, whereas the 500 and 1000 MHz were shielded and employed using a sledge and an odometer as trigger, with a step size between 0.02 and 0.1 cm. The sampling rate of GPR measurements
depended on the used frequency (Jol, 2008) and varied between 0.2 and 0.4 ns. The GPR systems were equipped with a Novatel GPS with a maximum horizontal precision of 2 m.

3.3. Data processing

GPR and WARR data were processed using Matlab. A novel combined linear move-out (LMO) – hyperbolic move-out (HMO) semblance analysis approach was developed for analyzing CMP/WARR data (Fig. 2, see Fig. 1c for the position). LMO is carried out for small travel times and can be used to estimate the velocity of the ground wave – the direct wave travelling through the first few centimeters of the subsurface (Fig 2a). HMO is carried out for large travel time and can be used to estimate the velocity of reflections (Fig. 2a). This procedure is performed for a range of velocities \(0.05 < v < 0.3 \text{ m ns}^{-1}\) and times by calculating the semblance (Heincke et al., 2006) over a window \(T = 1.2 \cdot \left(\frac{1}{f_c}\right)\),

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\]

where \(f_c\) is the nominal antennae frequency.

High values of semblance (warm colors, Fig. 2c) indicate velocities of ground wave and reflections (Fig. 2b), which can be used for the time-to-depth conversion and for the calculation of physical parameters of the subsoil (e.g. permittivity). The selected waveforms within the semblance window are shown in Fig. 2d and e for the LMO corrected groundwave and the HMO corrected reflected wave, respectively. The highest alignment in Fig. 2d and e is obtained when the signal after correction is mostly horizontal. To compare pedon interfaces and WARR reflections, depths (Table 1) were converted into travel times using the average ground wave velocity for each location.
GPR CO data were processed following a standard routine: dewow filter, time-zero correction, frequency domain butterworth filter, energy decay gain, and time-to-depth dynamic conversion using the calculated average velocity for each location (Jol, 2008). In some cases (e.g. noisy 1000 MHz profiles) we applied an average removing filter for the ringing, as described by Kim et al. (2007). We extended the amplitude analysis calculating instantaneous attributes of common-offset profiles (Gross et al., 2003). In particular, the instantaneous amplitude (envelope) resulted to be a valuable tool to enhance interpretation, as it gave a quantitative estimation of the subsoil reflectivity (Forte et al., 2012; Gross et al., 2003; Zhao et al., 2013).

4. RESULTS

We present in the following subsections GPR CO and WARR geophysical results of the four study areas (see Fig. 1c for the measured data positions). Sometimes, the measurements couldn’t be carried out due to logistical problems. Where possible, profiles were gathered to investigate the crossline -variability within a specific hillslope (e.g. Santa Gracia and La Campana in Fig. 1).

4.1. Pan de Azucar geophysical results

An average ground wave velocity of 0.147 m ns\(^{-1}\) was obtained from WARR measurements (Table 2). In addition, a reflection was present in the north-facing hillslope (WARR of Fig. 1c) at a travel time of 9 ns indicating a velocity of 0.121 m ns\(^{-1}\).
that is probably related to an interface at 0.45 m within the saprolite layer (see Table 1 and Fig. 3, blue dot).

GPR profiles were measured with 500 MHz and 1000 MHz central frequency antennae for 8 m along the north-facing mid pedon (Fig. 3, see Fig. 1c for the position). The pedon bottom boundary at 1.10 m (green arrows in Fig., 3, see also Table 1) can be linked with reflections in both 1000 MHz (Fig. 3a) and 500 MHz (Fig. 3b) CO profiles measured on north-facing hillslopes. This reflection is visible between the position of 2 and 4 m and 7.5 and 8.5 m (Fig. 3a and b) and characterized by strong reflectivity in the envelope profile (Fig. 3c, black ellipses). On the contrary, reflections connected with inner saprolite layering at 0.45 m (blue arrows, Table 1) appear to be nearly horizontal between position of 3 and 7 m and closing with an unconformity on the reflector linked with the pedon bottom boundary. The reflector linked with the boundary mobile soil to immobile saprolite at 0.20 m can be followed in the position between 3 and 5 m along the profile (red arrows, Fig. 3a and Table 1).

A 1000 MHz antennae GPR profile was measured along toe and mid pedon positions for 11 m in the south-facing hillslope (Fig. 4, see Fig. 1c for the position). GPR CO data towards the south-facing top pedon were not measured due to a steep slope and unstable loose material on the surface. No clear continuous reflection could be identified, although between the position of 8 and 9 m an upwards dipping reflector is visible and linked with inner saprolite layering at about 0.55 m (blue arrows, Table 1).

Insights of GPR signal penetration depth are highlighted in the reflection strength (Fig. 4b), where deeper high-reflectivity values were obtained in the mid slope and shallower in the toe slope (red line).
4.2. Santa Gracia geophysical results

WARRs with 500 and 1000 MHz GPR antennae were measured at each pedon position (Fig. 1c) and an average ground wave velocity value of 0.153 m ns⁻¹ was obtained (Table 2). A decreasing gradient of ground wave velocities was determined at the south-facing hillslope going uphill: 0.162 m ns⁻¹ at the toe, 0.151 m ns⁻¹ at the mid and 0.147 m ns⁻¹ at the top slope. Ongoing soil core investigations are necessary to understand this gradient. A ground wave velocity of 0.159 m ns⁻¹ was obtained for the north-facing slope. When reflections were present, a rather constant velocity value of 0.130 m ns⁻¹ was calculated between a depth of 0.80 and 1.50 m, probably indicating a transition towards a more homogeneous and compacted medium.

Several 500 MHz GPR profiles were measured going uphill over south- and north-facing hillslopes in Santa Gracia study area (Fig. 1c). Portions of the GPR CO over the north-facing mid slope (Fig. 5a), south-facing toe (Fig. 5b), mid (Fig. 5c), and top (Fig. 5d) slopes are shown here, alongside with their envelopes (see Fig. 1c for the exact locations). No reflections are visible in the profile in the north-facing slope and signal penetration is shallow (about 10 ns or 0.4 m). Deeper reflectors are visible in the south-facing slope, where hyperbolic features are identifiable up to a travel time of 30 ns (~2.5 m). In particular, they are linked with inner saprolite layering at 0.80 m in toe and at 0.75 m in mid slope and with the boundary mobile soil-immobile saprolite at 0.35 m in the top slope (Table 1). Hyperbolas are highlighted by the envelope profiles, being less present towards the top slope, where also signal penetration is shallower (Fig. 5d).
4.3. La Campana geophysical results

WARRs were measured at the bottom of the south-facing hill due to difficulties in measuring along the slope (Fig. 1c), by which an average value of 0.134 m ns\(^{-1}\) was obtained for the ground wave velocity (Table 2).

Hyperbolas are the main features visible in GPR CO profiles of La Campana study area, indicating a rather heterogeneous subsurface. In particular, these features can be seen in Fig. 6, where four 500 MHz GPR CO cross- and inlines were measured over an 11 m x 11 m area at the south-facing mid slope (see rectangle in Fig. 1c for the position). The pedon layers were projected accordingly to the semi-3D volume (Fig. 6). The boundary between B horizon and saprolite at 0.60 m (Table 1) was linked to the presence of hyperbolic features on crossline 1, inline 1, and inline 2. Two continuous reflections of about 5 m are present on crossline 2 (Fig. 6, cyan dashed lines) that are linked to the boundary between A and B horizon, and B horizon and saprolite, at 0.30 and 0.60 m depth respectively (Table 1). The transition mobile to immobile soil appeared at a rather constant depth (0.40 to 0.60 m) in the whole area and was characterized by heterogeneities, with a slightly thicker mobile soil in the south-facing mid slope (Table 1).

4.4. Nahuelbuta geophysical results

At each pedon location a WARR was measured (Fig. 1c) and an average value of ground wave velocity of 0.115 m ns\(^{-1}\) was obtained (Table 2). Reflections were present both in the 500 MHz WARR (Fig. 2b, see Fig. 1c for the position) and 200 MHz WARR (Fig. 7a) measured in the south-facing mid pedon. Hyperbolic features were found at
the same travel time as the high-amplitude reflectors in the respective GPR CO profiles (Fig. 7b and 8a). In particular, the reflection at 34 ns is consistent with the depth of the bottom of the south-facing mid pedon at 2.04 m (Table 1) in both WARRs (Fig. 2 and 7a). No clear reflections were linkable with toe and top pedons in the respective WARRs, although high energy patches in the semblance analysis could be related to hyperbolic features in the CO profiles.

Fig. 7 and 8 show 500 and 200 MHz GPR CO profiles, respectively, measured at the south-facing mid pedon, which is located at the position of 3 m along the profiles. Two high amplitude reflectors are recognizable that are linked with the pedon layering. The reflector linked with the pedon bottom boundary at 2.04 m shows lateral variability and high reflectivity in the envelope profile (green arrows, Fig. 8a and b, and Table 1). It is nearly horizontal in the positions between 0 and 15 m, whereas it dips upwards from 40 (~2 m) to 20 ns (~1 m) between the positions of 15 and 32 m. The same reflection could be related to an inner saprolite layering in the south-facing top pedon at about 90 cm (Table 1). This reflection at 34 ns (~2 m) is also visible in the 200 MHz CO profile (Fig. 7b), which covers the first 12 m of transect in Fig. 8. Hyperbolic features enhanced by the envelope are present between 7 and 18 ns (0.40 to 0.80 m) in the 500 MHz CO profile (Fig 8a) that are probably indicating heterogeneities within the B horizon (Table 1). These are imaged as a continuous reflection between 20 and 30 ns (1 to1.5 m depth) in the 200 MHz CO profile (Fig. 7b). Here, deeper structures are visible at about 100 - 120 ns (5 to 7 m, Fig. 7b). To identify whether these reflections were coming from objects above the surface (van der Kruk and Slob, 2004), we analyzed the WARR measurements to exclude that the reflections were travelling with the speed of air.
At the north-facing hillslope, a 6 m long GPR profile was gathered (Fig. 1c) that showed undulated reflections at about 0.40 m linked with the interface between A and B horizon (Table 1). A further down-dipping reflection was linked with the boundary between B horizon and saprolite at about 0.90 m. A WARR measured at the pedon location confirmed the presence of semi-continuous reflections with lateral variations.

4.5. GPR envelope-based observation

To compare the GPR data measured at all sites and slopes, the calculated envelopes from 500 MHz GPR profiles were averaged for transects of similar length (about 10 m) for the four study sites on the north- and south-facing mid slopes (Fig. 9). The signal-to-noise threshold, indicating the maximum travel time and penetration depth, was calculated for each curve regarding the interval between 55 and 60 ns as noise. This value was multiplied by 3 (obtained value after estimation of best signal-to-noise approximation for all the envelopes) and the intercept with each envelope curve was calculated and shown in Table 2. Except for Pan de Azucar, the envelope curves showed larger maximum travel time - and consequently increasing penetration depth - at the south-facing slopes compared to north facing slopes (Table 2). In addition, larger maximum travel time and deeper penetration depths could be observed from north to south in latitude (Table 2), except for Pan de Azucar.

5. DISCUSSION

5.1. General findings
Four different reflection patterns could be identified from GPR CO profiles (Fig. 10a): continuous reflections, discontinuous reflections, hyperbolic features, and zones where no clear reflections could be seen. These were constrained and validated by WARRs measured at the soil pedon key locations (Fig. 1c). Continuous reflections in GPR CO profiles were associated with clear continuous hyperbolas on WARRs. Discontinuous reflections were seen as fragmented hyperbolic trajectories on WARRs, still producing high semblance values. Hyperbolic features were imaged as chaotic and fragmented hyperbolic trajectories, not generating large values of semblance. Where no clear reflection was visible, the GPR signal looked similar both in GPR CO profiles and WARRs (Fig. 10b).

We extracted the GPR facies defined in Fig. 10 from 1000, 500, and 200 MHz CO profiles across the studied hillslopes. These have been combined with approximate elevation profiles and pedon layering, plotted accordingly to Table 1 using a specific color code (Fig. 11, Orlando et al., 2016; van Overmeeren, 1998). In some cases, pedons were vertically exaggerated to enhance visibility of the layers and overcome the 1:1 scale used for the topographic data (Fig. 11b, d, f, g, and h). Deploying GPR systems with different frequencies over the same transects helped identifying common reflections at specific depths, reaching a relatively high degree of detail in the definition of the regolith layering and of pedological processes (Aranha et al., 2002). A maximum horizontal precision of 2 m was reached measuring topographic data during the first campaign due to the GPS system; hence, preliminary DGPS high-precision data (max 3 cm horizontally) from a second measurement campaign have been used to improve the topography. Still, particularly in vegetated environments (La Campana and Nahuelbuta,
Fig. 11e, f, g, and h), positioning artifacts are sparsely present that were smoothed by a moving average filter.

The interface between A and B horizons could be linked with continuous reflections on 500 MHz GPR CO profiles only in the two southernmost locations, La Campana and Nahuelbuta (Fig 11f and h, respectively). This was not possible in the two northern study areas as this boundary is usually shallow and not detectable by the used GPR systems. Deploying higher frequencies systems (1.6 GHz and 2.6 GHz) could possibly enhance the detectability of the shallower layers. High-amplitude reflections from 500 and 1000 MHz GPR CO profiles at the four locations were mainly linked with the boundary between B horizon and saprolite, which produced distinct amplitude variations when present (Beauvais et al., 2004). This interface is often represented by hyperbolic features, making the interpretation more challenging and less straightforward (Aranha et al., 2002). Hyperbolas are generated when subsurface heterogeneities form a sensible contrast in $\varepsilon_r$ relatively to the surrounding medium. The frequency dependent dominant wavelength of the emitted wave plays an important role on the resolution and size of the objects that can be sensed. Whereas high frequencies show undulated reflections and individual features from which the interfaces are being built up (e.g. Fig. 8a), low frequencies have reduced resolution and show a more continuous interface (Fig. 7b).

We believe that in this case hyperbolic features on GPR CO profiles are generated by pebbles and fractured blocks having dimensions in the order of the dominant wavelength of 500 and 1000 MHz GPR antennae (5 to 25 cm, Table 2), as it was reported in the description of the pedons (Bernhard et al., 2018; Oeser et al., 2018, see Table 1). Furthermore, corestones were visible on outcrops in this study areas
That could generate such a contrast in the electromagnetic properties (Orlando et al., 2016). Such signals could also be generated in La Campana and Nahuelbuta study areas by the presence of roots, although the maximum reported root diameter for the two sites is 5 cm (Oeser et al., 2018, see Table 1), which is too small for the deployed frequencies (Butnor et al., 2001; Hirano et al., 2009). Inner saprolite layering and pedon bottoms were mainly imaged as continuous reflections on 500 and 1000 MHz GPR CO profiles, as it is for examples in Pan de Azucar north-facing hillslope and Nahuelbuta south-facing hillslope (Fig 11a and h, respectively). In only one situation no clear reflection patterns were identifiable by GPR measurements (Santa Gracia north-facing hillslope, Fig. 5a and 11c), which is probably related to the presence of homogeneous media and/or to a shallow saprolite interface.

Denser soil coring and sample analyses (e.g. texture, soil water content, OC, EC_{eff}) would help understanding the detected GPR signals in the four study areas.

5.2. Changes within a hillslope

Beauvais et al. (1999), Befus et al. (2011), and Holbrook et al. (2014) showed that the thickness of regolith is decreasing from about 35 m at the center of the catchment to about 5 m at the top of the slope. Compressional seismic wave velocity (Vp) and ERT were deployed over profiles of 200 to 1300 m, showing high lateral variability and thickness variations up to tens of meters. Similarly, our observations from GPR at a smaller scale (5 to 200 m CO profiles) indicate that the target regolith layers are found at deeper depths (between 0.40 and 2 m) in the toe – mid slopes than in the top slopes (between 0.30 and 1 m), probably because of gravitational effects (Walker and Ruhe,
1968). However, whereas Beauvais et al. (1999), Befus et al. (2011), and Holbrook et al. (2014) focused on imaging the deep regolith and the interface with the bedrock, we focused on the first 3 to 5 m of the subsurface.

We were able to image vertical variations of GPR reflection thickness that could be roughly linked with interfaces (e.g. A, B horizons, and saprolite) visible in the pedons (Table 1) and extrapolated to the profile scale for tens of meters (Fig. 11, Beauvais et al., 2004).

5.3. Variations between south- and north-facing hillslopes

Befus et al. (2011) found deeper interfaces (up to 4 m) on north-facing slopes than on south-facing slopes in the northern hemisphere within the critical zone in terms of compressional seismic velocity ($V_p$). Here, in the southern hemisphere we similarly observe larger penetration depths of GPR reflections (up to 0.80 m) for south-facing hillslopes compared to north-facing hillslopes (Table 2). These observations are consistent with the soil pedons (Bernhard et al., 2018, see Table 1). This smaller difference if compared with Befus et al. (2011) is probably related to the higher mobility of the upper regolith layer and/or to different stages of soil development in the study areas (Bernhard et al., 2018). We believe that aspect-driven differences could reflect lower temperature and greater soil moisture retention of the south-facing slopes due to denser vegetation and less sun radiation (Anderson et al., 2013; Rech et al., 2001). As moisture content a dominant factor in soil formation, soil horizons tend to be thicker, soil organic carbon higher, and parent material more weathered on south-facing slopes in the southern hemisphere, as shown by Bernhard et al. (2018). This could be valid for
Santa Gracia, La Campana, and Nahuelbuta, where precipitation events (and therefore water availability) are increasing with increasing latitude, leaving the south-facing hillslopes with more water and available nutrients, developing denser and taller vegetation. In contrast, for Pan de Azucar, the identified pedon boundaries, GPR CO profiles, and envelopes were relatively similar for north- and south-facing slopes, which might be due to the fact that here almost no precipitation and no vegetation is present.

5.4. Variations in latitude

From north to south, mostly increasing regolith thicknesses have been found in the key pedons (Bernhard et al., 2018; Oeser et al., 2018, see Table 1). This is roughly consistent with increasing GPR signal penetration towards southern latitudes (Fig. 9, Beauvais et al., 2004). An increasing trend of dielectric permittivity is as well present from Pan de Azucar to Nahuelbuta (Table 2). This is probably related to increasing soil water content and/or increasing organic matter and clay fraction in the soil (Bernhard et al., 2018). For these reasons, the applied multi-frequency GPR approach was essential for getting optimal resolution for different reflection depths and velocities (Brandt et al., 2007; Orlando et al., 2016). In this way, the target boundaries could be imaged (Table 1), as in Pan de Azucar 1000 MHz antennae returned the highest resolution (Fig. 3 and 4), whereas in Nahuelbuta the deepest reflectors are visible on a 200 MHz GPR CO profile at a depth of about 8 m (Fig. 7). A single frequency GPR approach might be enough when measuring at one single location (e.g. Beauvais et al., 2004). However, the present study shows the necessity of deploying multi-frequency GPR systems.
depending on the subsurface targets when the spectrum of environmental parameters (i.e. climate and vegetation) is broad.

5.5. Implications of the selected study areas on the obtained results

Our study focuses on a specific climate and vegetation gradient and is restricted to soil-covered hillslopes, where the bedrock is made of granitic materials (Bernhard et al., 2018; Oeser et al., 2018; Schaller et al., 2018). Hence, deploying geophysical methods in study areas with different parent material, climate, vegetation, slope gradient, and aspect, and drawing the same conclusions might be non-trivial. However, it has been shown that comparable observations are valid if soil generated from a different parent material is investigated, as for example basalt, gneiss, or sandstones (Befus et al., 2011; Carter and Ciolkosz, 1991). Furthermore, with increasing MAP and time, the influence of parent material on soil formation is negligible (Birkeland, 1984; Kutiel and Lavee, 1999; Ollier and Pain, 1996). Hence, differences from this study might be more evident studying in arid to hyper-arid environments than humid climates. On the other hand, when rainfall is the dominant weathering process, similarities to what has been found here could be expected, unless a significant slope difference is present (Leopold et al., 2012).

6. CONCLUSIONS

In this study, we applied multi-frequency GPR geophysical imaging techniques to characterize regolith in four locations at north and south facing slopes in the Chilean Coastal Cordillera. We were able to link reflection patterns from GPR profiles with soil
data retrieved from pedons excavated in the four study areas. At the point scale, soil layering was related to reflections visible in WARRs, which were analyzed with a novel combined LMO-HMO semblance approach. For the first time, continental and aspect-related differences in GPR signals are investigated in the southern hemisphere. The primary conclusions of this study are:

1) GPR CO profiles showed both reflections and horizon interfaces shifting towards deeper depths going from north to south along the studied gradient, consistent to what was visible in the soil pedons. The same trend could be seen in the signal penetration depths of the envelope. This is interpreted to result from higher water content, organic matter, and soil thickness in the more southern study areas due to the wetter climate.

2) For the same reasons as in the previous point, south-facing hillslopes have thicker horizons and deeper boundaries visible in GPR CO profiles than their north-facing slope counterparts in each study area. This is summarized in the proposed envelope approach.

3) These latitudinal and aspect differences are negligible in Pan de Azucar study area, where no vegetation is present that could influence pedological processes, and hence give a distinct signature on obtained geophysical values.

4) The main geophysical contrast visible from GPR results could be linked with the boundary between the mobile soil and immobile saprolite layers. When present, hyperbolas indicate this heterogeneous layer interface. At some locations (La Campana and Nahuelbuta), this interface could be recognized as a continuous reflection.
Ongoing research in these four areas will take into account additional soil properties (e.g. soil water content, texture, organic carbon), geochemical observations (e.g. cosmogenic nuclides, Schaller et al. (2018)), and evolution of the studied hillslopes.

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BIBLIOGRAPHY


Bernhard, N. et al., 2018. Pedogenic and microbial interrelations to regional climate and local topography: New insights from a climate gradient (arid to humid) along the Coastal Cordillera of Chile. Catena, 170, 335-355.


Jacob, R.W., Urban, T., 2016. Ground-penetrating radar velocity determination and precision estimates using common-midpoint (CMP) collection with hand-picking, semblance
analysis and cross-correlation analysis: a case study and tutorial for archaeologists. 
Archaeometry, 58, 987-1002.

Corporation.


Karger, D.N. et al., 2017. Climatologies at high resolution for the earth's land surface areas. 
Scientific data, 4, 170122.


Kutiel, P., Lavee, H., 1999. Effect of slope aspect on soil and vegetation properties along an 

Lehnert, L.W. et al., 2018. A Case Study on Fog/Low Stratus Occurrence at Las Lomitas, 
Atacama Desert (Chile) as a Water Source for Biological Soil Crusts. Aerosol and Air 
Quality Research, 18, 254-269.

Corporation.

Novakova, E., Karous, M., Zajiček, A., Karousova, M., 2013. Evaluation of ground penetrating 
radar and vertical electrical sounding methods to determine soil horizons and bedrock at 
the locality Dehtáře. Soil and Water Research, 8, 105-112.

Oeser, R.A. et al., 2018. Chemistry and microbiology of the Critical Zone along a steep climate 
and vegetation gradient in the Chilean Coastal Cordillera. CATENA, 170, 183-203.


critical zone in the Río Icacos watershed (Luquillo Critical Zone Observatory, Puerto 
Rico) inferred from drilling and ground penetrating radar (GPR). Earth Surface Processes 
and Landforms, 41, 1826-1840.


Rabassa, J., Clapperton, C.M., 1990. Quaternary glaciations of the southern Andes. Quaternary 
Science Reviews, 9, 153-174.


Schaller, M., Ehlers, T., Lang, K., Schmid, M., Fuentes-Espoz, J., 2018. Addressing the 
contribution of climate and vegetation cover on hillslope denudation, Chilean Coastal 


Santiago.

St. Clair, J. et al., 2015. Geophysical imaging reveals topographic stress control of bedrock 

Resources Conservation Service, 644.

USA.


Table 1: Pedons, climate, and vegetation in the four study areas

<table>
<thead>
<tr>
<th>Study areas</th>
<th>Pedons</th>
<th>Elevati on [m]</th>
<th>A/B(^1) [m]</th>
<th>B/C(^1) [m]</th>
<th>C inner layering(^1) [m]</th>
<th>bottom boundary(^1) [m]</th>
<th>Regolith features(^1)</th>
<th>Vegetation(^2)</th>
<th>MAP(^3) [mm/y]</th>
<th>MAT(^3) [°C]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pan de Azucar</td>
<td>S-top (AZPED60)</td>
<td>367</td>
<td>0.05</td>
<td>0.20</td>
<td>0.53</td>
<td>-</td>
<td>0-0.20 m: 1 cm clasts 0.20-0.45 m: fractured blocks (5-10 cm) 0.45- m: fractured blocks (20 cm)</td>
<td>None</td>
<td>15</td>
<td>20.1</td>
</tr>
<tr>
<td></td>
<td>S-mid (AZPED50)</td>
<td>364</td>
<td>0.05</td>
<td>0.20</td>
<td>0.55</td>
<td>0.80</td>
<td>1.60</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td></td>
<td>S-toe (AZPED40)</td>
<td>361</td>
<td>0.07</td>
<td>0.25</td>
<td>0.45</td>
<td>0.80</td>
<td>1.25</td>
<td></td>
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<td></td>
</tr>
<tr>
<td></td>
<td>N-mid (AZPED21)</td>
<td>376</td>
<td>0.05</td>
<td>0.20</td>
<td>0.30</td>
<td>0.45</td>
<td>1.10</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Santa Gracia</td>
<td>S-top (SGPED20)</td>
<td>740</td>
<td>0.05</td>
<td>0.35</td>
<td></td>
<td>1.15</td>
<td>0-0.30 m: clasts (2 mm), roots (1 cm) 0.30- m: fractured blocks (5-20 cm)</td>
<td>Shrubs and cacti</td>
<td>77</td>
<td>15.1</td>
</tr>
<tr>
<td></td>
<td>S-mid (SGPED40)</td>
<td>709</td>
<td>0.35</td>
<td>0.60</td>
<td>0.75</td>
<td>2.05</td>
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<tr>
<td></td>
<td>S-toe (SGPED60)</td>
<td>668</td>
<td>0.35</td>
<td>0.50</td>
<td>0.80</td>
<td>2.1</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td></td>
<td>N-mid (SGPED70)</td>
<td>711</td>
<td>0.20</td>
<td>0.35</td>
<td>0.42</td>
<td>2.00</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>La Campana</td>
<td>S-top (LCPED10)</td>
<td>757</td>
<td>0.05</td>
<td>0.40</td>
<td></td>
<td>0.68</td>
<td>0-0.20 m: 2 mm particles 0.20- m: fractured blocks (10-20 cm), roots (5 cm)</td>
<td>Mediterranean, shrubs, and sclerophyllous trees</td>
<td>326</td>
<td>14.9</td>
</tr>
<tr>
<td></td>
<td>S-mid (LCPED20)</td>
<td>747</td>
<td>0.30</td>
<td>0.60</td>
<td></td>
<td>1.85</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>S-toe (LCPED30)</td>
<td>735</td>
<td>0.20</td>
<td>0.60</td>
<td></td>
<td>3.65</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>N-mid (LCPED40)</td>
<td>748</td>
<td>0.15</td>
<td>0.45</td>
<td>1.00</td>
<td>1.40</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nahuelbuta</td>
<td>S-top (NAPED10)</td>
<td>1270</td>
<td>0.45</td>
<td>0.70</td>
<td>0.90</td>
<td>2.05</td>
<td>0-1.00 m: clasts (1-10 cm), roots (2 cm) 1.00- m: fractured blocks (10-20 cm)</td>
<td>Humid temperate forest with <em>Araucaria araucana</em> and <em>Nothofagus sp</em> trees</td>
<td>1050</td>
<td>12.9</td>
</tr>
<tr>
<td></td>
<td>S-mid (NAPED20)</td>
<td>1250</td>
<td>0.50</td>
<td>1.00</td>
<td></td>
<td>2.04</td>
<td></td>
<td></td>
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<tr>
<td></td>
<td>S-toe (NAPED30)</td>
<td>1227</td>
<td>0.55</td>
<td>0.85</td>
<td>0.90</td>
<td>1.15</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>N-mid (NAPED40)</td>
<td>1226</td>
<td>0.40</td>
<td>0.85</td>
<td></td>
<td>2.00</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Depth of horizons from Bernhard et al. (2018); Oeser et al. (2018)
Vegetation data from Arroyo et al. (1993)
Mean annual precipitation (MAP) and temperature (MAT) from Karger et al. (2017)
Table 2: Values of geophysical parameters for south- and north-facing hillslopes in the four study areas

<table>
<thead>
<tr>
<th>Study areas</th>
<th>Aspect</th>
<th>GW velocity¹ [m/ns]</th>
<th>$\varepsilon$²</th>
<th>avg energy 55-60 ns³</th>
<th>Maximum travel time⁴ [ns]</th>
<th>Penetration depth⁴ [m]</th>
<th>Dominant wavelength GPR wavelength $\lambda^5$ [m]</th>
<th>Total GPR measurement's length [km]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pan de Azucar</td>
<td>S-facing</td>
<td>0.147 ± 0.003</td>
<td>3.95</td>
<td>2.74*10¹¹</td>
<td>26.8</td>
<td>1.97</td>
<td>0.74 (500 MHz) 0.29 (1000 MHz) 0.14 (1000 MHz)</td>
<td>1.23</td>
</tr>
<tr>
<td></td>
<td>N-facing</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Santa Gracia</td>
<td>S-facing</td>
<td>0.153 ± 0.006</td>
<td>3.59</td>
<td>2.89*10¹¹</td>
<td>24.6</td>
<td>1.81</td>
<td>0.77 (500 MHz) 0.31 (1000 MHz) 0.15 (1000 MHz)</td>
<td>1.58</td>
</tr>
<tr>
<td></td>
<td>N-facing</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>La Campana</td>
<td>S-facing</td>
<td>0.134 ± 0.011</td>
<td>4.98</td>
<td>2.83*10¹¹</td>
<td>28.4</td>
<td>2.09</td>
<td>0.68 (500 MHz) 0.27 (1000 MHz) 0.14 (1000 MHz)</td>
<td>0.48</td>
</tr>
<tr>
<td></td>
<td>N-facing</td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nahuelbuta</td>
<td>S-facing</td>
<td>0.115 ± 0.006</td>
<td>6.26</td>
<td>1.31*10¹²</td>
<td>45.2</td>
<td>3.32</td>
<td>0.58 (500 MHz) 0.23 (1000 MHz) 0.12 (1000 MHz)</td>
<td>0.38</td>
</tr>
<tr>
<td></td>
<td>N-facing</td>
<td></td>
<td></td>
<td></td>
<td></td>
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</tr>
</tbody>
</table>

1. Average ground wave velocities in each study area obtained from WARR measurements
2. Relative dielectric permittivity for each location derived from the average ground wave velocity
3. Average GPR energy for the north- and south-facing envelopes in each study area in the travel time range between 55 and 60 ns multiplied by a factor of 3
4. Maximum travel times and penetration depths derived from the envelope in north- and south-facing slopes in each study area
5. Dominant wavelength within each location calculated using the average ground wave velocity and the deployed GPR central frequency
Fig. 1: a) Map with the four study areas along the Chilean Coastal Cordillera (black rectangles). From north to south are the study areas Pan de Azucar, Santa Gracia, La Campana, and Nahuelbuta. b) Denser vegetation is observed from north to south in...
latitude. c) In the overview maps, locations of the pedons are indicated by red stars. GPR CO profiles and WARRs are indicated by green lines and yellow circles. Specific locations shown in the text are indicated by blue arrows and labels.

Fig. 2: Novel combined LMO-HMO approach for the velocity analysis of ground and reflected waves. a) Theoretical wave trajectories for air wave, ground wave, and reflections in a WARR measurements. b) WARR profile for 500 MHz antennae from Nahuelbuta study area. The ground wave and one reflection (black hyperbola) have been picked. The red hyperbolas represent theoretical signal produced by known soil layers at a known depth. c) The white dashed line separates LMO and HMO semblance panels. The white circles indicate the picked velocities of the ground wave and the reflection. d) And e) semblance window widths (see Eq. 1) after the move-out correction for the picked velocities. d) Shows the linear move-out correction for the ground wave picking; e) shows the hyperbolic move-out correction for the reflection. Red color and blue color indicate positive and negative amplitudes, respectively. The WARR data were measured in Nahuelbuta south-facing mid slope (see Fig. 1c).
Fig. 3: Common-offset (CO) profiles along the north-facing mid pedon in Pan de Azucar
study area measured with a) 1000 MHz and b) 500 MHz GPR antennae. In a) a
background removal was applied to remove horizontal noise in the later travel times. c)
Reflection strength (envelope) of the profile in b), where red color indicates high
reflectivity values and blue color low reflectivity values. Arrows indicate continuous
reflections linked with the correspondent color boundary.
Fig. 4: a) GPR CO profile measured with 1000 MHz antennae over the south-facing hillslope of Pan de Azucar study area, where layering from toe pedon (left) and mid pedon (right) is plotted. b) Shows the envelope of the GPR profile in a). The red line indicates the variation in signal penetration along the profile.
Fig. 5: Four parts of GPR CO profiles from Santa Gracia measured on a) north-facing mid pedon, b) south-facing toe pedon, c) south-facing mid pedon, and d) south-facing top pedon. The envelope is plotted alongside each profile.

Fig. 6: 2.5D combined 500 MHz GPR CO inlines and crosslines measured around the mid pedon (indicated by the black arrow) of south-facing hillslope in La Campana study area. The layering visible in the pedon was superimposed in transparency on the profiles as shown. The cyan dashed lines indicate continuous reflections.
Fig. 7: a) 200 MHz GPR WARR measured at the south-facing mid pedon in Nahuelbuta study area. Cyan trajectories indicate picked velocities in the semblance panel; the red hyperbola indicates the theoretical signal produced by the pedon bottom boundary. b) 200 MHz GPR CO profile measured along the south-facing hillslope mid pedon in Nahuelbuta study area. The green dot indicates the bottom of the pedon. It fits with a high-amplitude continuous reflector at a depth of around 40 ns (2 m).
Fig. 8: a) 500 MHz GPR CO profile along the south-facing mid pedon in Nahuelbuta study area. Arrows indicate continuous reflections linked with the correspondent color boundary. b) Envelope of the 500 MHz GPR CO profile, color between yellow and red indicates high reflectivity. Green arrows indicate the reflectivity associated with the reflection related to the bottom of the pedon boundary.

Fig. 9 Average envelopes for north- and south-facing mid slopes in the four study areas. The horizontal dashed lines correspond to the calculated signal-to-noise thresholds.
Fig. 10 Main GPR reflection patterns classified as 1) continuous reflections, 2) discontinuous reflections, 3) hyperbolic features, and 4) no clear reflection recognizable in a) GPR CO profiles, b) GPR WARR measurements, and c) indicated as facies.
Fig. 11: Red lines show topography obtained at the north-facing and south-facing slopes in a) and b) Pan de Azucar, c) and d) Santa Gracia, e) and f) La Campana, and g) and h) Nahuelbuta, respectively. On each slope, the excavated pedons have been plotted with the layering indicated in the legend. The scale of pedons and GPR features is exaggerated as indicated by the axis on the top of each hillslope. Hyperbolic features and (dis-)continuous reflections recognized in the GPR profiles have been drawn to
enable a correlation between layer boundaries and geophysical information. Horizontal black arrows indicate the positions where GPR profiles shown in the results were measured.