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Chemistry and microbiology of the Critical Zone along a steep climate and vegetation gradient in the Chilean Coastal Cordillera

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ABSTRACT

The Chilean Coastal Cordillera features a spectacular climate and vegetation gradient, ranging from arid and unvegetated areas in the north to humid and forested areas in the south. The EarthShape project ("*Earth Surface Shaping by Biota*") uses this natural gradient to investigate how climate and biological processes shape the Earth's surface. We explored the Critical Zone, the Earth's uppermost layer, in four key sites located in desert, semi-desert, Mediterranean, and temperate climate zones of the Coastal Cordillera, with the focus on weathering of granitic rock. Here, we present first results from 16 approximately 2 m-deep regolith profiles to document: (1)

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architecture of weathering zone; (2) degree and rate of rock weathering, thus the release of mineral-derived nutrients to the terrestrial ecosystems; (3) denudation rates; and (4) microbial abundances of bacteria and archaea in the saprolite.

From north to south, denudation rates from cosmogenic nuclides are ~10 t km^{-2} yr^{-1} at the arid Pan de Azúcar site, ~20 t km^{-2} yr^{-1} at the semi-arid site of Santa Gracia, ~60 t km^{-2} yr^{-1} at the Mediterranean climate site of La Campana, and ~30 t km^{-2} yr^{-1} at the humid site of Nahuelbuta. A and B horizons increase in thickness and elemental depletion or enrichment increases from north (~26°S) to south (~38°S) in these horizons. Differences in the degree of chemical weathering, quantified by the chemical depletion fraction (CDF), are significant only between the arid and sparsely vegetated site and the other three sites. Differences in the CDF between the sites, and elemental depletion within the sites are sometimes smaller than the variations induced by the bedrock heterogeneity. Microbial abundances (bacteria and archaea) in saprolite substantially increase from the arid to the semi-arid sites.

With this study, we provide a comprehensive dataset characterizing the Critical Zone geochemistry in the Chilean Coastal Cordillera. This dataset confirms climatic controls on weathering and denudation rates and provides prerequisites to quantify the role of biota in future studies.

1. Introduction

The Earth's surface, where rock, the atmosphere, the hydrosphere, and the biosphere interact, is often referred to as the Critical Zone (Anderson et al., 2007). Soils, mantling 95% of the terrestrial Earth's surface, are the top layer of this zone. Soil is made “from below” by weathering, the breakdown of rocks and minerals (Riebe et al., 2017), and “from above” by the addition of organic matter and atmospheric inputs (Chorover et al., 2007). Weathering turns fresh rock into a loosely consolidated “regolith” (comprising both mobile soil at the top and weathered rock beneath it). The inorganic chemical process of weathering involves the dissolution of primary minerals and their partitioning into solutes and secondary minerals (e.g. amorphous and crystalline oxides, clays). These abiotic weathering products, as well as organic compounds, are exported from catchments via erosion and rivers (Gaillardet et al., 1999; Hilton, 2017). The Critical Zone thus plays an important role in the cycling of mineral nutrients across the Earth's surface and the mechanisms of weathering are key.

Numerous studies have shown that soil physico-chemical parameters, such as soil organic matter, soil acidity, exchangeable ions, extractable oxides, and volumetric strain (ε) systematically change with temperature and precipitation (e.g. Bardelli et al., 2017; Bojko and Kabala, 2017; Khomo et al., 2013; Khomo et al., 2011; Khormali et al., 2012). Egli et al. (2003) have shown that the amount of smectite and the degree of weathering in Alpine soils increase with precipitation. Moreover, the degree of plagioclase weathering seems to increase exponentially with temperature and linearly with precipitation (Dere et al., 2013). Still, from studies that make use of climatic gradients no clear relationship between climate and denudation rates has yet emerged. Large variations in denudation rates in any given climate indicate that a potential climatic imprint might have been severely overprinted by factors such as uplift, physical and chemical bedrock characteristics, and biota (e.g. Dixon et al., 2009; Egli et al., 2004; Ferrier et al., 2012; Riebe et al., 2004; Schaller et al., 2018; Starke et al., 2017). In this context, Owen et al. (2011) postulated that a mean annual precipitation threshold exists below which bedrock denudation is precipitation-dependent and above which soil production from bedrock is controlled by complex feedback mechanisms between tectonics, temperature, and biota.

One of the key players in weathering processes is biota, which is receiving increasing scientific attention in this context (Amundson et al., 2015b; Brantley et al., 2011; Egli et al., 2014; Hahm et al., 2014). A broad spectrum of biota (plants, animals, and microorganisms) interacts with the Earth's surface, although the direction and magnitude of the effects biota has on Earth-surface processes, and conversely the Earth surface effects on biota, are still not well understood (e.g. Wilcke et al., 2017). For example, little is known about microorganisms that live beneath soil, even though more than one third of the microbial biomass is concentrated in regolith depths deeper than 25 cm (Fierer et al., 2003; Schutz et al., 2010). Several studies demonstrated that even in the saprolite active bacterial cells exist (Buss et al., 2005; Richter and Markewitz, 1995). Biogenic weathering is a potentially important mechanism because microorganisms in the regolith are highly specialized to their environment (Fritze et al., 2000; Ghiorse and Wilson, 1988; Zvyagintsev, 1994). Fungi and their associated bacteria can directly weather minerals (Balogh-Brunstad et al., 2008; Quirk et al., 2014; Smits et al., 2012). In this process they mobilize mineral-bound nutrients (e.g. P, Ca, Mg, K) that are essential elements to plants. When these nutrients are made available for plants, a biogeochemical cycle is induced that, for some elements, exceeds the weathering flux measured in rivers up to a factor of 40 and more (e.g. Uhlig et al., 2017; Wilcke et al., 2017). This biotically modulated silicate weathering is of major significance for global atmospheric CO_2 cycles in the Phanerozoic (Doughty et al., 2014; Pagani et al., 2009; Quirk et al., 2012) and for sustaining a continuous soil cover (Amundson et al., 2015a). Whether these biological mechanisms overwhelm the abiotic weathering mechanisms and whether they serve to provide a feedback balancing soil erosion and soil production have never been shown, owing to the lack of diagnostic observables that allow distinguishing between abiotic and biotic drivers.

To resolve the control of climate and biota on rock disintegration, we combined the fields of geochemistry, soil science, biogeochemistry, and geomorphology and applied these to different study sites along the Chilean Coastal Cordillera. We did this within the German-funded “EarthShape” (Earth surface shaping by biota) research priority program along four Critical Zone field sites along a latitudinal transect in the Chilean Coastal Cordillera. The Coastal Cordillera of Chile encompasses a prominent climate and vegetation gradient that provides a natural laboratory for investigating biotic and abiotic weathering processes. Soil formation processes in this region were previously explored by Owen et al. (2011). The authors found a 40-fold increase in soil production rate from 1 m My^{-1} in the hyper-arid to 40 m My^{-1} in the arid region. Vázquez et al. (2016) described a > 30 m thick weathering profile developed on granitic bedrock in the Coastal Cordillera in the Mediterranean climate of central Chile. The authors calculated denudation rates (derived from cosmogenic ^{10}Be) from 20 to 70 m My^{-1}, leading to mean residence times of 0.5 to 1.8 Ma for minerals in the saprolite.

The investigated areas of this study include (from north to south) the Pan de Azúcar National Park (~26°S), Santa Gracia Nature Reserve (~30°S), La Campana National Park (~33°S), and Nahuelbuta National Park (~38°S). Site selection for these areas was based on the minimal tectonic and lithologic differences, and their position along the climate (arid to humid) gradient. We thus followed the “climosequence” approach (e.g. Egli et al., 2003). In each of these four study sites, four regolith profiles were excavated on different slope positions.

In this paper, we (1) describe the architecture of the weathering zone; and quantify (2) the degree and rate of rock weathering, thus the