Geoderma 300 (2017) 32–43

Contents lists available at ScienceDirect

Geoderma

journal homepage: www.elsevier.com/locate/geoderma

# Biota and geomorphic processes as key environmental factors controlling soil formation at Elephant Point, Maritime Antarctica

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ARTICLE INFO

*Keywords:*
Maritime Antarctica
Phosphate minerals
Glacial abrasion
Mineralogy

ABSTRACT

We examined the main soil forming factors affecting the soil composition, soil properties and the associated soil-forming processes at Elephant Point, a small ice-free environment in the South Shetland Islands, Maritime Antarctica. For this purpose, we collected twenty soil samples from each of ten different sites distributed along a linear transect running from the coast to the front of the Rotch Dome glacier. The samples were obtained from surface layers (0–10 cm) and at depth (40–50 cm), although collection was limited in the moraine area by the permafrost table. We determined pH, electrical conductivity, size particle distribution, total organic carbon, total nitrogen and total concentrations of Al, Fe, Ca and P, for physical and chemical characterization of the samples. We also analysed the samples to determine the bioavailability of nutrients and Fe, Al and P partitioning and finally examined them by isotopic ($\delta^{15}N$) and X-ray diffraction (XRD) analysis. The results of the analyses revealed two clear geochemical environments corresponding to the two most extensive geomorphological units in this peninsula: moraine and marine terraces. Soils from the moraine were characterized by alkaline reaction and high quantity of minerals with a low degree of crystallinity, whereas soils from the marine terraces showed acid reaction, high concentration of organometallic complexes and a high diversity of phosphate minerals (taranakite, minyulite, struvite, hydroxylapatite and leucophosphite), which seem to be generated by phosphatization of faecal matter deposited by seabirds and seals. Consequently, biota activity is the most relevant soil differentiating factor in the marine terraces, which add organic matter and activate geochemical cycles. On the other hand, geomorphic processes strongly affected by physical weathering processes such as glacial abrasion (by grinding process), frost shattering, and wind abrasion are the main soil-forming factors in moraine. These forces break up the parent material, transform it and translocate the products formed.

## 1. Introduction

Knowledge about soil formation and evolution in Antarctica has increased substantially during the last few decades; however, the role of physical and chemical weathering in soil development remains unclear. Some researchers have recently examined the main chemical (Dixon, 2013; Otero et al., 2015a, 2013) and physical (Hall et al., 2002) processes associated with soil formation in cold climates. Among the latter, cryoturbation, wind and stream erosion (Bhatia et al., 2013; Hawkings et al., 2015; Hodson et al., 2004; Wadham et al., 2013), glacial grinding (Cowton et al., 2012; Gengnian et al., 2009; Jari, 1995; Keller and Reesman, 1963a), solifluction (Matsuoka, 2001), sedimentation (Hawkings et al., 2015), salt weathering and freeze-thaw activity (Campbell and Caridge, 1987) are the main processes described, all of which contribute to the heterogeneity of Antarctic soil. Some of the above-mentioned are geomorphic processes which modify the relief and are consequently important soil-forming factors. Moisture conditions are also important in cold regions, and they either limit soil formation (Allen et al., 2001; Thorn et al., 2001) or enhance chemical weathering (Hall, 2004). In areas close to the coast, such as Maritime Antarctica,

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http://dx.doi.org/10.1016/j.geoderma.2017.04.001
Received 28 July 2016; Received in revised form 3 January 2017; Accepted 2 April 2017
Available online 25 April 2017
0016-7061/ 

chemical weathering may be as important as physical weathering (Anderson et al., 1997; Beyer et al., 2000; Dixon, 2013) and freeze-thaw cycles are more frequent (de Pablo et al., 2014) than in continental Antarctica (Hall, 1997). Chemical weathering is strongly influenced by living organisms, which must adapt to harsh climatic conditions (Otero et al., 2013). Living organisms depend on the existence of ice free areas, which have increased over the last decades as a result of glacial retreat in Livingston Island (Molina et al., 2007), despite recent deceleration of glacier mass loss in the area (Navarro et al., 2013).

Pioneer biota (mainly microorganisms and plants) modifies and adjusts the substrate, thus improving the conditions for new living organisms colonizing these areas. This can create a positive feedback and accelerate soil formation (Moura et al., 2012; Otero et al., 2015a), especially in summer in Maritime Antarctica areas, including the northern tip of Antarctic Peninsula, where the greater availability of water supports chemical weathering processes (Pereira et al., 2013a, 2013b; Simas et al., 2007; Ugolini, 1972). In addition, seabirds and mammals contribute to the establishment and growth of vegetation and enhance mineral weathering due to the high inputs of organic matter, nitrogen and phosphorus via their faecal matter (Pereira et al., 2013b; Schaefer et al., 2008; Simas et al., 2008). The incorporation of organic matter into the mineral soil strongly influences the formation of clay minerals and secondary phosphates, forming the characteristic ornithogenic soils, which are some of the most well developed soils in Maritime Antarctica (Moura et al., 2012).

The original objective of this study was to examine the combined effects of the parent material (Moraines and Marine Terraces) and time (terraces of different ages) on soil formation processes. For this purpose, we established a sampling transect between the coast and the glacier. After observing that soil properties and soil-forming processes were not greatly affected by either parent material or age of the geomorphological units, we decided to refocus the study aims. The final objectives were therefore to identify the main soil forming factors affecting the soil composition, soil properties and the associated soil-forming processes. We analysed several physical and chemical properties of the soil samples taken along the transect, which follows the deglaciation in the environment, including the two most extensive geomorphological units: marine terraces and moraine (Oliva and Ruiz-Fernández, 2017).

## 2. Material and methods

### 2.1. Study area

The study was carried out at Elephant Point (62°41′12″ S; 60°51′33″ W), a small peninsula in the westernmost part of Livingston Island (South Shetland Islands, SSI, Antarctica) (Fig. 1). Livingston Island is one of the largest ice free areas in Antarctica (16% of the 818 $km^2$ is ice free surface), and Elephant Point is included in this ice-free terrain. In this area, the Rotch Dome glacier was significantly more extensive during the Early-Mid Holocene, covering most of the western fringe of Livingston Island until the Late Holocene (Oliva and Ruiz-Fernández, 2017). Consequently, the current ice-free environment at Elephant Point (1.16 $km^2$) was covered by glacial ice during most of the Holocene. Evidence of this is found in the bedrock plateaus, where some of the blocks are slightly polished and exhibit traces of glacial striae running N–S (Oliva and Ruiz-Fernández, 2015). Subsequently, the glacial retreat that occurred during the Late Holocene, together with the concurrent postglacial isostatic rebound, exposed the low lands of this peninsula, where a sequence of five marine terraces were formed following the glacial retreat (Fretwell et al., 2010; Watcham et al., 2011). The marine terraces thus show a geochronological sequence ranging from 500 years BP (closest to the coast) to 1800 years BP (furthest from the sea) (Table 1). The retreat of the Late Holocene glacier led to formation of a polygenic moraine, with a succession of different ridges due to minor retreats and advances during this time (Oliva and Ruiz-Fernández, 2015). The age of moraine is not as clear as that of marine terraces, although the moraine is known to have been formed later than the terraces, in the last 1.800 years BP.

Field sampling included both of the above-mentioned geomorphological units: marine terraces (MT) and moraine (M). The first five sampling sites correspond to the five marine terraces. The first terrace formed was the farthest from the sea, represented by sample EP5, and the most recent terrace is represented by sample EP1 (closest to the sea) (Table 1 and Fig. 1). The other five sampling sites were further from the sea, in the moraine, and the furthest site (EP10) was very close to Rotch Dome glacier (3 m away). The elevation from the sampling sites ranged from sea level to 55 m·a.s.l. at the internal moraine ridge (Table 1) (Oliva and Ruiz-Fernández, 2017).

### 2.2. Environmental setting

The climatic conditions at Elephant Point are characteristic of polar oceanic environments. The mean temperature between 2002 and 2010 in the nearby Byers Peninsula was −2.8 °C at 70 m·a.s.l., and the annual precipitation oscillated between 500 and 800 mm, mostly concentrated during the summer season and falling either as rain or snow (Bañón et al., 2013). Freeze-thaw cycles in the ground are also more frequent during this season (de Pablo et al., 2014).

These SSI (South Shetland Islands) are calc-alkaline island arcs (Lee et al., 2004) and are mainly formed by schists, basalts, dacites, conglomerates, rhyolites and andesite (Smellie et al., 1984). The lithology of Elephant Point is mainly formed by weathered basalts, schist, some granodiorites and some shales found in moraine sediments, which are mobilized down-slope by slow mass-wasting processes (Oliva and Ruiz-Fernández, 2017).

Vegetation cover is very sparse and predominantly occurs on the flat marine terraces, where seabirds are present and where they are protected from the wind and from the trapping of penguins (Vera, 2011; Victoria et al., 2013).

The predominant vegetation forms comprise mosses (*Andreaea gainii, Calliergon sarmentosum, Calliergidium austro-stramineum*), lichens (*Usnea antarctica, Usnea aurantiaco-atra, Rhizocarpon geographicum*) and two native vascular plants (*Deschampsia antarctica* and *Colobanthus quitensis*).

### 2.3. Soil sampling

The initial purpose was to identify any trends in the soil properties relative to the age of the terraces, parent material and the distance from the glacier in the moraine environment. For this purpose, a linear transect was sampled from coast to the glacier in late January 2014 and twenty soil samples were obtained at ten different representative sites at Elephant Point peninsula. Finally, this type of design enabled identification of the main soil-forming factors in the field as well as the associated soil forming processes.

In MT one sampling point was established in each terrace, and in M the same number of sampling points was established at different distances from the glacier. Two samples were taken at each sample point: one from the surface ($EP_S$: 0–10 cm) and the other at depth ($EP_D$: 40–50 cm), (Table 1). In accordance with Bockheim et al. (2013), Ramos et al. (2009), Serrano et al. (2008) and Vieira et al. (2010), continuous permafrost was only found in moraine at elevations higher than 30–40 m·a.s.l. However, in MT the compact material was the factor limiting the depth of the sample, which was very homogeneous. The soil samples were stored in PVC boxes until being transported to the laboratory.

### 2.4. Soil analysis

All samples were sieved through a mesh of 2 mm pore size and analysed in duplicate.