

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

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## 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. Twenty soil samples were collected from each of ten sites along a transect running from the coast to the front of the Rotch Dome glacier. Samples were taken from surface layers (0–10 cm) and at depth (40–50 cm), except in the moraine area where sampling was limited by permafrost. We determined pH, electrical conductivity, particle size distribution, total organic carbon, total nitrogen, and total concentrations of Al, Fe, Ca and P. We analysed nutrient bioavailability, Fe–Al–P partitioning,  $\delta^{15}\text{N}$ , and performed X-ray diffraction.

The results revealed two distinct geochemical environments corresponding to the two main geomorphological units: moraine and marine terraces. Moraine soils showed alkaline pH and higher amounts of minerals with low crystallinity, whereas marine terrace soils were acidic, richer in organometallic complexes, and showed greater diversity of phosphate minerals (including taranakite, minyulite, struvite, hydroxylapatite and leucophosphate), apparently generated by phosphatization of faecal matter from seabirds and seals. Consequently, biotic activity is the most relevant soil-forming factor in marine terraces, while geomorphic processes driven by physical weathering—glacial abrasion, frost shattering and wind erosion—dominate soil formation in moraine environments.

## Keywords

Maritime Antarctica; Phosphate minerals; Glacial abrasion; Mineralogy

## 1. Introduction

Knowledge about soil formation and evolution in Antarctica has increased substantially over recent decades; however, the relative contribution of physical and chemical weathering processes in soil development remains unclear. Recent research has examined key chemical processes (Dixon, 2013; Otero et al., 2013; Otero et al., 2015a) and physical processes (Hall et al., 2002) that influence soil formation in cold climates. These processes include 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; Gengnial 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 Claridge, 1987). Together, these processes contribute to the strong heterogeneity of Antarctic soils.

Moisture availability is another key driver of soil development in cold environments, either limiting pedogenesis (Allen et al., 2001; Thorn et al., 2001) or enhancing chemical weathering (Hall, 2004). In Maritime Antarctica—an area with more frequent freeze–thaw cycles (de Pablo et al., 2014) and higher liquid water availability compared to continental Antarctica—chemical weathering can be as important as physical weathering (Anderson et al., 1997; Beyer et al., 2000; Dixon, 2013). Chemical weathering is strongly influenced by biota, which must withstand extreme environmental conditions (Otero et al., 2013).

Living organisms, including pioneer microorganisms and plants, alter the substrate and improve conditions for subsequent colonizers. This feedback can accelerate soil formation, particularly in summer when water availability is higher (Moura et al., 2012; Otero et al., 2015a; Pereira et al., 2013a, 2013b; Simas et al., 2007; Ugolini, 1972). Seabirds and mammals also strongly influence soil development by contributing organic matter, nitrogen and phosphorus through their excreta, thereby increasing mineral weathering and fostering vegetation establishment (Pereira et al., 2013b; Schaefer et al., 2008; Simas et al., 2008). The incorporation of organic matter promotes formation of clay minerals and secondary phosphates, characteristic of ornithogenic soils—some of the best-developed soils in Maritime Antarctica (Moura et al., 2012).

The original objective of this study was to examine the combined effects of parent material (moraines vs. marine terraces) and surface age on soil formation. We established a sampling transect from the coast to the glacier front. However, our initial analyses showed that soil properties and soil-forming processes were not clearly correlated with terrace age or distance from the glacier. Therefore, the study was reframed to focus on identifying the main soil-forming factors controlling soil composition, properties and associated pedogenic processes. For this purpose, multiple physical and chemical parameters were examined along the transect, which spans the deglaciation sequence and intersects the two dominant geomorphological units: marine terraces and moraine (Oliva and Ruiz-Fernández, 2017).

## 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<sup>2</sup> 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<sup>2</sup>) 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).

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 (EPS: 0–10 cm) and the other at depth (EPD: 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

#### 2.4.1. Physical and chemical analysis

All samples were sieved through a mesh of 2 mm pore size and analysed in duplicate. The pH was determined in water (pH<sub>w</sub>) and in 0.1 M KCl (pH<sub>KCl</sub>), at a ratio of 1:2.5 (Rowell, 1994), and in NaF 1 M (pH<sub>NaF</sub>), at a ratio of 1:50, for 2 min. Abrasion pH (pH<sub>abrasion</sub>) was determined in the sand fraction. For this purpose, 25 mL of distilled water was added to 10 g of grinded sand (previously washed with Milli-Q water) (Ferrari and Magaldi, 1983). Particle size was determined by the pipette method (Gee and Bauder, 1986).

The total organic carbon (TOC), after removal of carbonates with 10% HCl, and total nitrogen (TN) were measured in a LECO CNS-2000 autoanalyzer. The total amounts of Fe (TFe), Al (TAl), P (TP), P sand fraction (TP<sub>sand</sub>) and Ca (TCa) were extracted in an Ethos Plus microwave lab station by adding 12 mL of a mixture of HNO<sub>3</sub>/HCl (3:9, v/v). The efficiency of the extraction process (> 90%) was determined by analysis of certified reference material (Soil SO3).

Three fractions of iron and two of aluminium were extracted:

Fe and Al extracted with 0.1 M sodium pyrophosphate (Fepyro and Alpyro) (Bascomb, 1968);

Fe and Al extracted with 0.2 M acid ammonium oxalate at pH 3 (Aloxa and Feoxa) (Blakemore, 1983);

Fe extracted with sodium dithionite–citrate–bicarbonate (Fedit) (Mehra and Jackson, 1960).

The fractions are considered indicators of different compounds, as follows:

- Fepyro and Alpyro provide an estimate of the metallo-organic complexes (Bascomb, 1968);
- Feoxa – Fepyro provide an estimate of amorphous iron oxides (Feamorp) (Blakemore, 1983);
- Aloxa – Alpyro provide an estimate of amorphous aluminium oxides (Alamorp) (Blakemore, 1983);
- Fedit – Feoxa provides an estimate of crystalline iron oxyhydroxides (Fecrys) (Mehra and Jackson, 1960).

The concentration of C in the pyrophosphate extracts was also determined by a modified version of the method described by Walkley and Black (1934).

Bioavailable macro (P, Ca, Mg, K) and micronutrients (Fe, Co, Cu, Zn and Ni) were extracted with Mehlich 3 extractant (Mehlich, 1984).

Simulation of glacial abrasion by grinding was studied by carrying out a small experiment (Keller and Reesman, 1963a). The sand was separated from eight samples (4 from MT and 4 from M, chosen randomly). The sand was then washed with Milli-Q water and an equal portion of each was ground in a mortar. The ground and unground sand samples were extracted with ammonium oxalate at pH 3 to enable comparison of the concentration of low crystalline phases in each (Blakemore, 1983).

For  $\delta^{15}\text{N}$  analysis, eight samples were chosen randomly (4 from MT and 4 from M). The samples were combusted in an elemental autoanalyzer FlashEA1112 (ThermoFinnigan) and the isotope ratios were determined in a mass spectrophotometer (Deltaplus, ThermoFinnigan).

#### 2.4.2. Phosphorus partitioning

Partitioning of solid-phase P was determined in fresh samples (2 g) by a sequential extraction method that enabled identification of six operationally defined P fractions, which are described as follows (Paludan and Jensen, 1995; Paludan and Morris, 1999):

Adsorbed P: the most labile and reactive phosphorus (stirring 1 h with Milli-Q water).

P-Fe: the P associated with reducible Fe and Mn oxyhydroxides (stirring with 0.11 M  $\text{NaHCO}_3$  and 0.11 M  $\text{Na}_2\text{S}_2\text{O}_4$  for 1 h).

P-Al/Clay: the fraction associated with aluminium and clays (stirring with NaOH 0.1 M for 1 h).

P-HA: the fraction bound to humic acids (HA) (extracted by precipitation of the HA in the P-Al/Clay supernatant with sulphuric acid, filtration, burning at 520 °C and digestion with HCl 1 M at > 90 °C for at least 10 min).

P-Ca: the phosphorus associated with calcium (by stirring the residue from P-Al/Clay with HCl 1 M for 1 h).

P-Residual: the phosphorus bound to recalcitrant compounds as organic matter or which is contained in sand with larger particles (ignition of the residue of P-Ca at 520 °C and subsequent digestion with HCl 1 M at > 90 °C for 10 min).

In all extraction steps, the residue was washed twice with 50 mL of Milli-Q water and centrifuged at 6000 rpm for 15 min (4 °C) to clean any possible residues from the previous extraction.

The contents of Fe, Al, Ca, Mg, K, Co, Cu, Zn were quantified by atomic absorption spectrometry (PERKIN ELMER 1100B), while P was measured in a spectrophotometer following the procedure described by Murphy and Riley (1962).

#### 2.4.3. Mineralogy

Mineralogical analysis was carried out on clay (< 2 µm), silt (0.05–0.002 mm) and coarse sand fractions (2–1 mm) by X-ray diffraction (XRD). The sand and silt plus clay fractions were then separated by moist sieving and the silt and clay were then separated by decantation (Jackson, 1979).

X-ray diffraction (XRD) analysis was carried out on glass slides for oriented aggregates of the clay fraction saturated with Mg<sup>2+</sup>, and for random powder mounts of unsaturated clays, silt and sand (fine and coarse). The Mg<sup>2+</sup> saturated samples were processed as oriented aggregates (Mg) and also solvated in glycerol (Mg-Gli). These samples were also analysed after heating for 3 h at 550 °C and 700 °C (Mg-K550 and Mg-700) (Jackson, 1979).

The XRD patterns were obtained with a Shimadzu XRD 6000 diffractometer, using Cu-Kα radiation, with a graphite monochromator and applying 40 kV and a 30 mA current, with a velocity of 1.0°2θ min<sup>-1</sup> and a step size of 0.02°2θ. The analyses were conducted in the range 2–40°2θ for oriented aggregates and 3–70°2θ for random powder.

#### 2.4.4. Statistical analysis

Owing to the lack of a clear continuous gradient in relation to the age of the terraces and the distance from the glacier, we decided to group the data into four data sets for each main geomorphological unit and depth (MT surface, MT depth, M surface, M depth). Differences between depths and geomorphological units were assessed by ANOVA or by Mann–Whitney U test when data did not meet ANOVA assumptions.

Principal component analysis (PCA) with Direct Oblimin rotation was used to identify correlations among variables. All statistical analyses were performed using SPSS 2.0 (Pallant, 2011; Jolliffe, 2002).

### 3. Results

#### 3.1. Physical and chemical properties

The pH values in water (pH<sub>w</sub>) ranged from 4.5 to 7.8 in marine terraces (MT) and from 6.9 to 8.4 in moraine (M) (Table 2). In general, the pH<sub>w</sub> values were lower in MT than in M. The pH values in KCl (pH<sub>KCl</sub>) ranged from 3.9 to 7.1 in MT and from 6.6 to 8.1 in M (Table 2). As occurred with pH<sub>w</sub>, pH<sub>KCl</sub> values were lower in MT than in M.

The pH values in NaF (pH<sub>NaF</sub>) ranged between 9.8 and 11.3 in MT and between 9.4 and 10.6 in M. The pH<sub>NaF</sub> values were higher in MT than in M (Table 2). Abrasion pH (pH<sub>abrasion</sub>) ranged from 7.6 to 8.2 in MT and from 8.0 to 8.3 in M (Table 2).

In general, the contents of organic carbon (TOC), total nitrogen (TN) and the C/N ratio were higher in MT than in M (Table 2). The particle size distribution showed that the sand content

was higher in M than in MT, whereas the silt and clay fractions were more abundant in MT than in M.

The total Fe (TFe) content ranged from 0.9 to 3.1% in MT and from 0.9 to 2.1% in M; the total Al (TAl) content ranged from 0.6 to 2.4% in MT and from 0.5 to 1.5% in M (Table 2). The total P (TP) content ranged between 0.3 and 2.9 g·kg<sup>-1</sup> in MT and from 0.3 to 0.9 g·kg<sup>-1</sup> in M. The total Ca (TCa) content ranged from 0.4 to 7.8 g·kg<sup>-1</sup> in MT and from 0.7 to 8.7 g·kg<sup>-1</sup> in M (Table 2).

The concentrations of Fe extracted with sodium pyrophosphate (Fepyro) and with acid ammonium oxalate (Feoxa) were considerably higher in MT than in M (Table 2). The aluminium extracted with pyrophosphate (Alpyro) and with acid ammonium oxalate (Aloxa) showed the same behaviour. The concentration of crystalline iron oxyhydroxides (Fedit) was higher in M than in MT (Table 2).

The content of bioavailable phosphorus (P-M3) was higher in MT than in M (Table 2). The same pattern was observed for the rest of the macro- and micronutrients (Mg, Ca, Fe, Co, Cu, Zn, Ni) (Table 2).

The δ<sup>15</sup>N values ranged from 3.3 to 18.5‰ in MT and from -0.3 to 5.9‰ in M (Table 2). The highest δ<sup>15</sup>N values were recorded in MT.

### 3.2. Phosphorus partitioning

The adsorbed P fraction ranged from 0.02 to 0.22 g·kg<sup>-1</sup> in MT and from 0.01 to 0.05 g·kg<sup>-1</sup> in M (Table 2). The P-Fe fraction ranged from 0.03 to 0.38 g·kg<sup>-1</sup> in MT and from 0.01 to 0.05 g·kg<sup>-1</sup> in M. The P-Al/Clay fraction ranged from 0.03 to 0.42 g·kg<sup>-1</sup> in MT and from 0.01 to 0.06 g·kg<sup>-1</sup> in M (Table 2).

The P-HA fraction ranged between 0.03 and 0.29 g·kg<sup>-1</sup> in MT and from 0.00 to 0.03 g·kg<sup>-1</sup> in M. The P-Ca fraction ranged from 0.07 to 0.48 g·kg<sup>-1</sup> in MT and from 0.02 to 0.10 g·kg<sup>-1</sup> in M. The P-Residual fraction ranged from 0.10 to 0.87 g·kg<sup>-1</sup> in MT and from 0.04 to 0.27 g·kg<sup>-1</sup> in M (Table 2).

All phosphorus fractions showed higher values in MT than in M.

### 3.3. Mineralogy

The mineralogical composition of the clay fraction was dominated by quartz, feldspar, chlorite, kaolinite and illite in most samples (Fig. 2). In some MT samples, amorphous minerals were also identified.

The silt fraction was mainly composed of quartz, feldspar and mica (Fig. 3). The sand fraction was dominated by quartz, feldspar and minor amounts of pyroxenes and amphiboles (Fig. 4).

Several phosphate minerals were identified, particularly in MT samples, including:

Taranakite, minyulite, struvite, hydroxylapatite, leucophosphate

These minerals were absent or present in very low quantities in M samples.

### 3.4. PCA analysis

The principal component analysis (PCA) revealed clear differences between MT and M samples (Fig. 5). The first two components explained 64.4% of the total variance.

Variables such as TOC, TN, C/N ratio, pHNaF, Feoxa, Aloxa, Fepyro, Alpyro and P-M3 were strongly associated with marine terrace soils. Conversely, variables such as sand content, pHw, pHKCl, pHabrasion, Fedit and TCa were associated with moraine soils.

### 3.5. Glacial abrasion experiment

The grinding experiment showed a substantial increase in the Feoxa and Aloxa contents in the ground sands compared with unground sands (Table 2). This increase was observed in both MT and M samples, but it was more pronounced in M samples.

These results support the hypothesis that glacial abrasion promotes the generation of low crystalline Fe and Al oxides, especially in the moraine environment.

## 4. Discussion

Some authors have suggested that temperature and humidity play essential role in various soil-forming processes in cold climate and humid environments (e.g. Campbell and Claridge, 1982; Matsuoka et al., 1990), as they strongly influence freeze–thaw cycles (Henry, 2007), frost shattering (Lautridou and Ozouf, 1982) and glacial advances or retreats (Cook et al., 2005). These factors also affect edaphic processes, which are spatially very variable (Tanner et al., 2013), as well as geomorphological activity (Oliva and Ruiz-Fernández, 2017). Other authors have noted the great differences in soil properties that can be generated by the presence of seabirds and seals, which disturb the soil by trampling and by input of organic compounds in their droppings, which can accumulate to form guano and favour establishment of vegetation (Brimble et al., 2009; Otero et al., 2015b; Ugolini, 1972).

The findings of the present study revealed two clearly different geochemical environments (Fig. 7). These environments are closely related to the geomorphological units studied. One of them includes the marine terrace samples and the variables affected by biota activity. In this respect, biota seems to be the main soil forming factor in marine terraces, responsible for the enrichment in nutrients and labile forms of metals and P in MT soils. The moraine environment is defined by those variables associated with geomorphological activity (Fig. 7). In the moraine, geomorphological activity seems to be the most important soil forming factor, yielding fine particles and high pH.

### 4.1. Biota action

Biota is an important soil-forming factor, as already described in several other Antarctica environments (Lee et al., 2004; Otero et al., 2013; Ziótek and Melke, 2014). Seabird colonies established along the coast physically and chemically modify the soil properties via the input of faecal matter and also via trampling (Bockheim, 2015; Cannone et al., 2008). In the present study, the seabird and seal colonies present on the marine terraces are the main source of organic matter, as reflected in the high values of TOC in MT (~1%) relative to values in M (~0.17%), in which organic matter may be accumulated by permafrost table and to favour the humification process.

The biota is also responsible for the higher concentration of TN in MT, which is well correlated with the values of TOC. This element is more abundant in the first 10 cm of soil due to the release of faecal matter (Simas et al., 2007). Although faecal matter is initially

alkaline, deposition by seabirds and seals has promoted soil acidification and leaching of base cations and enhanced microbial degradation of organic matter; this is common in cold environments where higher temperatures prevail, as in Maritime Antarctica (Bockheim, 2015).

The high concentrations of TP and PMeh in MT, respectively 2 and 10 times higher than in M (Table 2), should also be interpreted as a direct effect of the seabird and elephant seal colonies on the soils. The droppings that these animals produce are rich in phosphorus compounds and thus substantially increase the natural fertility of the soil in the breeding areas (Anderson and Polis, 1999; Ligeza and Smal, 2003; Otero et al., 2015b; Ziótek and Melke, 2014).

The results of the mineralogical and  $\delta^{15}\text{N}$  analyses are consistent with this interpretation. The MT mineralogy shows a high diversity of phosphate minerals, which are typically associated with faecal matter (Pereira et al., 2013b; Simas et al., 2007). The high concentration of P favours phosphatization processes (Tatur and Barczuk, 1985). These processes imply the formation of secondary minerals such as taranakite [ $\text{K}_3\text{Al}_5(\text{PO}_4)_2(\text{HPO}_4)_6 \cdot 18\text{H}_2\text{O}$ ], minyulite [ $\text{KAl}_2(\text{OH},\text{F})(\text{PO}_4)_2 \cdot 4\text{H}_2\text{O}$ ], leucophosphite [ $\text{KFe}_2(\text{PO}_4)_2(\text{OH}) \cdot 2\text{H}_2\text{O}$ ], struvite [ $(\text{NH}_4)\text{Mg}(\text{PO}_4) \cdot 6\text{H}_2\text{O}$ ] and hydroxylapatite [ $\text{Ca}_5(\text{PO}_4)\text{OH}$ ] (Pereira et al., 2013a; Tatur and Myrcha, 1984), as clearly indicated by the composition of the MT clay fraction.

However, hydroxylapatite may be derived from hydrated mass of decomposing faecal matter in earthy aggregates of calcium phosphate or from geological material. This occurs in the M unit (silt fraction of Fig. 5), where there is no biota, probably due to recent deglaciation, higher slope and active cryoturbation processes. Thus, hydroxylapatite is not exclusively formed as a result of phosphatization processes (Tatur and Myrcha, 1984).

The P partitioning also shows the importance of phosphatization processes in the soil, reflected in the very different distribution of P relative to that in seabird faecal matter (Otero et al., 2015b). The amount of P associated with reducible Fe and Mn oxyhydroxides was much higher in MT due to the low pH (Sims and Pierzynski, 2005; Wild, 1993). The P fraction associated with Al and clays (P-Al/Clay) is much more abundant in MT than in M. This is mainly because this fraction is one of the common forms in seabird faecal matter. However, this great difference between geomorphological units is presumably also due to the background level, which was higher than found in previous studies (Otero et al., 2015b; Ziótek and Melke, 2014).

The P-HA also seems to be strongly related to the effect of seabirds on soil due to the higher concentration of MT (Otero et al., 2015b). The concentration of the PeCa fraction is similar in both areas. This is a dominant fraction in seabird excrements (Otero et al., 2015b; Ziótek and Melke, 2014), which could therefore explain the high concentration in MT unit. However, the high concentration of this fraction in M may be a consequence of the weathering of parent material and allochthonous rocks such as granodiorite, which contain apatite. Thus, allochthonous material transported from Antarctic Peninsula by icebergs (Oliva and Ruiz-Fernández, 2017) may account for the presence of struvite, leucophosphite and hydroxylapatite in the silt fraction of M and may also explain the basal level of Psand (Table 2).

The isotopic composition of N in the MT unit ( $\delta^{15}\text{N}$ : from 13 to 17.7‰) was much higher than in M ( $\delta^{15}\text{N}$ : from 3 to 7.8‰), indicating different sources. The values for M are similar

to those for particulate organic material (POM) ( $6.8 \pm 0.3\text{‰}$ ) and algae ( $5.1 \pm 0.3\text{‰}$ ) (Yuan et al., 2010) which can grow on the moraine. On the other hand, the high values of  $\delta^{15}\text{N}$  in MT soils were similar to those obtained in soils (Mizutani et al., 1991), sediments (Liu et al., 2006; Nie et al., 2014; Yuan et al., 2010) and excrements derived from seabird and mammalian colonies ( $\delta^{15}\text{N}$  = from 11.3 to 16.2‰) (Liu et al., 2006).

These findings reinforce the important influence that seabird and seal colonies (biota) have on soil formation and consequently on soil properties and composition. The presence of biota leads to input of organic matter, which changes the geochemical properties and contributes to the development of the A horizon. The biota is also responsible for other soil-forming processes such as podsolization. This process is highly incipient in Maritime Antarctica (Bockheim and Ugolini, 1990), but can be observed in different dark and grey lines in some horizons of marine terraces. This is favoured in the summer season when the ice melts on well-drained acid soil (Bockheim and Ugolini, 1990). The process is caused by the chemical migration of aluminium, iron or organic matter in depth as reflected in the values of Al and Fe extracted by pyrophosphate (Table 2). The decomposition of faecal matter also promotes acidolysis and enhances chemical weathering and plant development.

In addition to causing eutrophication of soils, waters and sediments, seabirds are also efficient vectors of seed dispersion (Calviño-Cancela, 2002), thus favouring biodiversity of the vegetation in this extreme environment (Myrcha and Tatur, 1991). In this respect, in the current scenario of climate change, plant colonization in these distant coastal areas may be accelerated by the action of seabirds, with the associated consequences, such as the increased discharge of phosphorus to the ocean, lakes or rivers (Hawkings et al., 2016).

#### 4.2. Geomorphic action

Despite the length of time that has passed since the retreat of the glacier, the moraine sediments show evidence of intense glacial abrasion. Glaciers exert high pressure on rocks and minerals. They grind and break the substrate, thus forming finer particles ( $< 32 \mu\text{m}$ ) (Haldorsen, 1981; Jari, 1995; Keller and Reesman, 1963b). Physical weathering explains the presence of primary minerals in clay fraction of moraine sediments and also the high pH. Glacial abrasion leads to changes in mineral structure (Fig. 5, Table 2), increasing the pH to values close to those obtained in the abrasion pH as a consequence of the release of OH groups of the crystalline structure (Gonzalez Garcia et al., 1991; Miller and Oulton, 1970; Takahashi, 1957). This loss generates amorphous minerals, e.g. of Al (Campbell and Caridge, 1987; Jari, 1995; Keller and Reesman, 1963a, 1963b; Ramesh and d'Anglejan, 1997) in the moraine. The results of the simulated glacier abrasion by grinding are consistent with this idea (Fig. 3).

Unconsolidated sediments of the M unit are affected by very intense post-glacial activity of periglacial processes, particularly during the paraglacial stage (Oliva and Ruiz-Fernández, 2017). The effectiveness of cryogenic processes in the Maritime Antarctica is enhanced during the summer season when freeze-thaw cycles are frequent and moisture is abundant. This favours physical weathering processes, namely the frost-induced shattering of the boulders left by the glacier (Woronko and Pisarska-Jamrozy, 2016). This action is more intense when the grain surface is encrusted by amorphous phases (Woronko and Hoch, 2011). These processes may also explain the finer particles found in M than in MT (Campbell and Caridge, 1987), as well as the pH values close to pH abrasion and the presence of

inherited primary minerals resulted from physical weathering. After the actions of the above-mentioned processes, strong winds and retreating and advancing movements of glaciers are the main causes of erosion as they move the soil material to new sites, thus contributing to the pedogenic processes as losses and additions (e.g. alluvial fans).

The absence of these properties in the MT is related to their non-glacial origin and to the horizontal surface of the terrain, which facilitates development of the vegetation cover, reducing periglacial slope processes and encouraging geomorphologic stability. The vegetation cover also limits the effects of frost on the ground and the effects of wind abrasion, which can strongly influence the geological material (Matsuoka et al., 1996) and may be another factor explaining the differences between two geomorphological units. However, more detailed studies are required to clarify the role of this weathering agent in soil formation.

Finally, the lack of any differences in the variables at the depths of soil considered can be explained by mixing of materials and homogenization of the soil profile due to cryogenic processes such as cryoturbation (Ugolini et al., 2006).

## 5. Conclusions

The study findings showed clear differences in soil properties and composition of marine terraces and moraine as a consequence of the biotic and geomorphic actions.

Biotic activity, driven mainly by seabird and seal colonies, seems to be the most important soil forming factor in the marine terraces. The faecal matter adds different types of organic matter, favours chemical weathering and contributes to eutrophication of the environment due to the high concentration of nutrients. Phosphatization may thus be considered the most representative soil forming process in this unit, as a consequence of the high concentration of P in faecal matter. The formation of new P minerals favours accumulation of P (and to a lesser extent N) in soils, although the increased erosion of the Antarctic coast due to ice melting may lead to eutrophication in nearby seas and lagoons.

In the moraine unit, soil formation is mainly driven by glacial abrasion. Rock abrasion destroys the crystalline structure of primary minerals, releasing Fe and Al; this leads to neoformation of secondary minerals with low degree of crystallinity and with high reactivity. This process is also driven by the alkaline reaction in moraine soils. Additionally, freeze-thaw cycles and frost shattering also contribute to the disintegration of rocks (e.g. sharp-edged clasts) and consequently generate fine particles such as silts and clays.

Finally, future studies should aim to clarify the role of geomorphological and physical processes in the development of soils in the Maritime Antarctica. Information about how glacial abrasion by grinding influences soil development is scarce. This research topic is of potential interest for advancing knowledge of soil texture, mineralogy and pH in ice-free environments. Study of the consequences of the weathering, such as the losses of Fe to the ocean is also of interest, as Fe is a limiting nutrient for primary productivity.

## Acknowledgements

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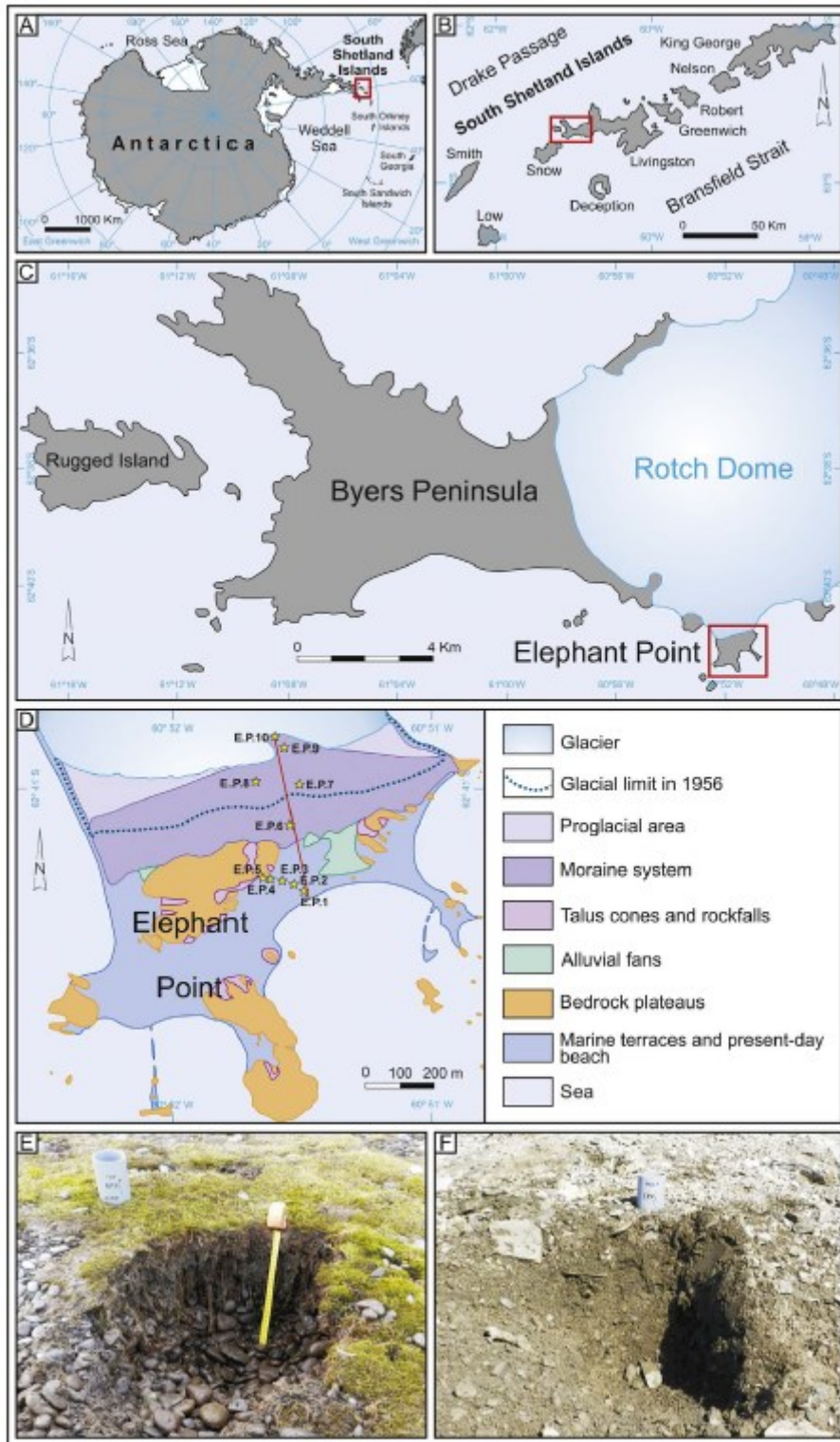


Fig. 1. Location of the study area: (A) location of the South Shetland Islands (SSI) within the Antarctic continent; (B) western fringe of Livingston Island within the SSI; (C) Byers Peninsula and Elephant Point Peninsula within Livingston Island; (D) sampling transect at Elephant Point; (E, F) soil sections EP 3 and EP 8, respectively, showing different type of pebbles on the ground. Rounded pebbles are frequent on the marine terraces, and angular to subangular pebbles are found on the moraine.

Table 1: Geographical description of the sampling sites, together with a general description of the soil sections.

Sample	Depth (cm)	Unit	Elevation (m a.s.l.)	Vegetation cover	Geographical Coordinates	Texture, field observations and age of terraces
EP 1S	< 10	MT 5	4	≈ 10%	62°41'21.1''S – 60°51'23.0''W	Sandy loam. Presence of small lichens and mosses on the surface. Formed over 500 cal yr BP
EP 1D	< 40	MT 5	4	≈ 10%	62°41'21.1''S – 60°51'23.0''W	Sandy loam
EP 2S	< 10	MT 4	9	≈ 30%	62°41'11.0''S – 60°51'10.7''W	Loamy sand and sand respectively. Higher organic matter content, mosses and little roots. Formed over 1.2 ka cal BP
EP 2D	< 40	MT 4	9	≈ 30%	62°41'11.0''S – 60°51'10.7''W	Sandy loam
EP 3S	< 10	MT 3	11	≈ 50%	62°41'10.4''S – 60°51'05.0''W	Loamy sand. Presence of rounded pebbles. Flat terrain, flooded during some periods. Formed over 1.8 ka cal BP
EP 3D	< 45	MT 3	11	≈ 50%	62°41'05.2''S – 60°51'06.2''W	Sandy
EP 4S	< 10	MT 2	12	≈ 40%	60°51'37.6''W 62°41'13.0''S	Presence of roots and grey material. Close to semi-permanent lagoons. Formed over 1.8 ka cal BP
EP 4D	< 40	MT 2	12	≈ 40%	60°51'37.6''W – 62°41'13.0''S	Sandy
EP 5S	< 10	MT 1	16	≈ 35%	62°41'29.8''S – 60°51'38.9''W	Sandy. Rounded pebbles in a sandy matrix. Close to an elephant seal colony. Formed over 1.8 ka cal BP
EP 5D	< 40	MT 1	16	≈ 35%	62°41'29.8''S – 60°51'38.9''W	Sandy
EP 6S	< 10	M	18	≈ 5%	62°41'45.9''S – 60°51'17.8''W	Sandy loam. Presence of angular pebbles next to the moraine slope
EP 6D	< 45	M	18	≈ 5%	62°41'45.9''S – 60°51'17.8''W	Sandy loam
EP 7S	< 10	M	55	0%	62°41'32.7''S – 60°51'24.2''W	Sandy loam. No differences between horizons were observed in this homogeneous soil section collected from the external moraine ridge
EP 7D	< 45	M	55	0%	62°41'32.7''S – 60°51'24.2''W	Sandy loam
EP 8S	< 10	M	26	0%	62°41'54.1''S – 60°51'45.1''W	Sandy loam. These samples were collected from the internal moraine.

Sample	Depth (cm)	Unit	Elevation (m a.s.l.)	Vegetation cover	Geographical Coordinates	Texture, field observations and age of terraces
						Evidence of glacial abrasion and recent slope activity remobilizing sediments
EP 8D	< 45	M	26	0%	62°41'53.8''S – 60°51'38.4''W	Sandy loam
EP 9S	< 10	M	28	0%	62°41'52.8''S – 60°51'36.0''W	Sandy loam. High moisture content due to snow melting and thawing of the active layer
EP 9D	< 45	M	28	0%	62°41'52.8''S – 60°51'36.0''W	Sandy loam
EP 10S	< 10	M	26	0%	62°41'52.9''S – 60°51'36.8''W	Sandy loam. Humid environment located only 3 m from the glacier front
EP 10D	< 45	M	26	0%	62°41'52.9''S – 60°51'36.8''W	Sandy loam

Table 2. Mean values and standard deviations obtained from the physical, chemical and isotopic analysis of samples. Values in the same row indicated by the same letter are not significantly different ( $p < 5\%$ ). Underlined variables were analysed by U-Mann-Whitney test, and the other variables by ANOVA followed by a post-hoc Tukey test. \* indicates that only samples 2, 4, 7 and 9 were analysed and \*\* indicates that only samples 4, 5, 7 and 9 were analysed.

Variable	Unit	MT surface Mean	MT surface σ	MT depth Mean	MT depth σ	M surface Mean	M surface σ	M depth Mean	M depth σ
pHw	–	5.3	0.8 a	5.2	0.9 a	6.2	0.4 b	6.8	0.2 b
pHKCl	–	4.6	0.8 a	4.1	0.4 a	6.1	0.3 b	6.9	0.2 b
pHNaF	–	8.6	0.3 a	8.8	0.5 a	9.3	0.2 b	9.9	0.2 b
pHabrasion	–	8.2	0.2 b	8.1	0.3 b	8.3	0.1 a	8.3	0.1 a
Sand	%	84	5 b	88	10 b	93	6 a	89	3 b
Silt	%	11	4 a	12	4 a	6	2 b	5	1 b
Clay	%	5	2 a	6	2 a	1	1 b	5	1 b
TOC	%	1.27	0.81 a	0.54	0.27 ab	0.18	0.02 b	0.16	0.01 b
Cpyro	%	0.7	0.3 a	0.3	0.1 ab	0.1	0.0 b	0.0	0.0 b
TN	%	0.15	0.08 a	0.06	0.04 ab	0.02	0.01 b	0.02	0.01 b
δ15N	‰	15.4	3.3 a	16.5	0.3 a	4.4	2.0 b	1.1	1.2 b
Conductivity	μS·cm <sup>-1</sup>	157	103	158	74	42	18	< LD	–
Fe_pyro	mg·kg <sup>-1</sup>	2754	1072 a	4122	2720 a	147	60 b	319	368 b
Al_pyro	mg·kg <sup>-1</sup>	959	297 a	1028	775 a	52	52 b	65	110 b
Fe_amorp	mg·kg <sup>-1</sup>	3912	1802 a	3195	1708 a	579	512 b	686	518 b
Al_amorp	mg·kg <sup>-1</sup>	3132	291 a	3112	1567 a	7479	6141 b	5188	1018 b
TFe	mg·kg <sup>-1</sup>	49,900	16,000 a	42,960	11,475 a	58,500	32,400 a	52,600	23,200 a
TAI	mg·kg <sup>-1</sup>	29,800	7539 a	25,660	11,576 a	48,560	4245 b	40,640	2293 b
TP	mg·kg <sup>-1</sup>	2727	1174 a	2631	1133 a	1207	187 b	732	98 b
TSand	mg·kg <sup>-1</sup>	445	157 a	480	92 a	83	38 b	60	39 b
TCa	mg·kg <sup>-1</sup>	420	172 a	484	109 a	53	17 b	69	17 b
Mg_M3	mg·kg <sup>-1</sup>	2.46	1.3 a	2.02	0.5 a	0.95	0.4 b	1.04	0.1 b
Ca_M3	mg·kg <sup>-1</sup>	18.4	16.7 a	13.1	8.1 a	1.6	1.2 b	4.0	0.8 b
Fe_M3	mg·kg <sup>-1</sup>	2.47	2.0 a	1.74	0.4 a	1.62	1.3 a	1.24	0.48 a
Co_M3	mg·kg <sup>-1</sup>	0.23	0.3 a	0.08	0.2 a	0.45	0.3 a	0.14	0.1 a
Cu_M3	mg·kg <sup>-1</sup>	4.6	3.6 a	3.4	1.7 a	1.6	0.8 b	1.4	0.3 b
Zn_M3	mg·kg <sup>-1</sup>	8.1	4.9 a	7.4	4.5 a	2.2	0.9 b	0.6	0.3 b
Ni_M3	mg·kg <sup>-1</sup>	2.2	0.9 a	1.7	0.8 a	2.9	2.7 a	2.0	1.3 a
P_M3	mg·kg <sup>-1</sup>	37.0	5.5 a	42.8	9.3 a	10.4	3.9 b	17.2	6.1 b
Soluble-P	mg·kg <sup>-1</sup>	10.7	4.9 a	8.8	6.0 a	3.0	2.9 b	3.2	2.9 b
P-Fe	mg·kg <sup>-1</sup>	184	102 a	145	48 a	63	56 b	36	26 b
P-Al/Clay	mg·kg <sup>-1</sup>	1127	665 ab	1105	398 ab	117	56 b	236	139 b
P-HA	mg·kg <sup>-1</sup>	465	145 ab	414	154 ab	86	34 b	100	65 b
P-Ca	mg·kg <sup>-1</sup>	421	121 a	454	141 a	66	39 b	79	39 b
P-sand	mg·kg <sup>-1</sup>	185	47 a	178	53 a	46	29 b	64	20 b
TP(residual)	mg·kg <sup>-1</sup>	123	43 a	166	86 a	59	46 b	64	39 b

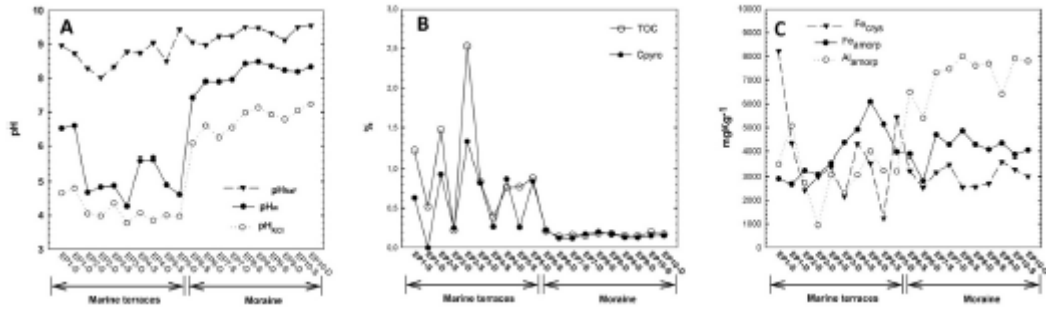


Fig. 2. Spatial variation in the transect of TOC and Cpyro (A); pHw, pHKCl, pHNaF (B); Feamorp, Alamorp and Fecrys (C).

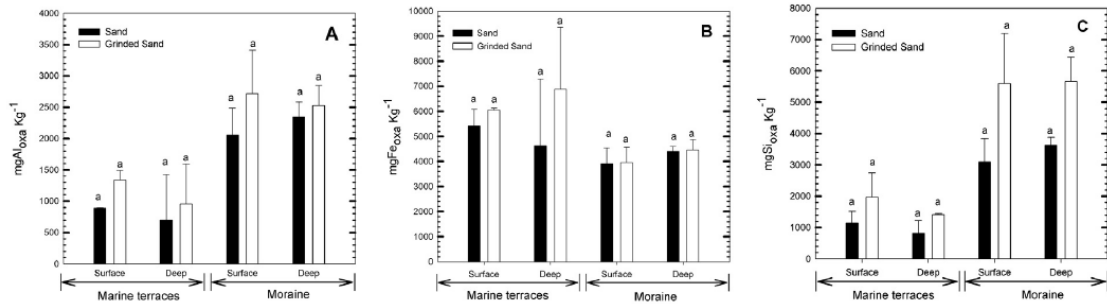


Fig. 3. Concentrations of Si, Al and Fe extracted in ammonium oxalate after simulation of glacial abrasion by grinding process. N=2.

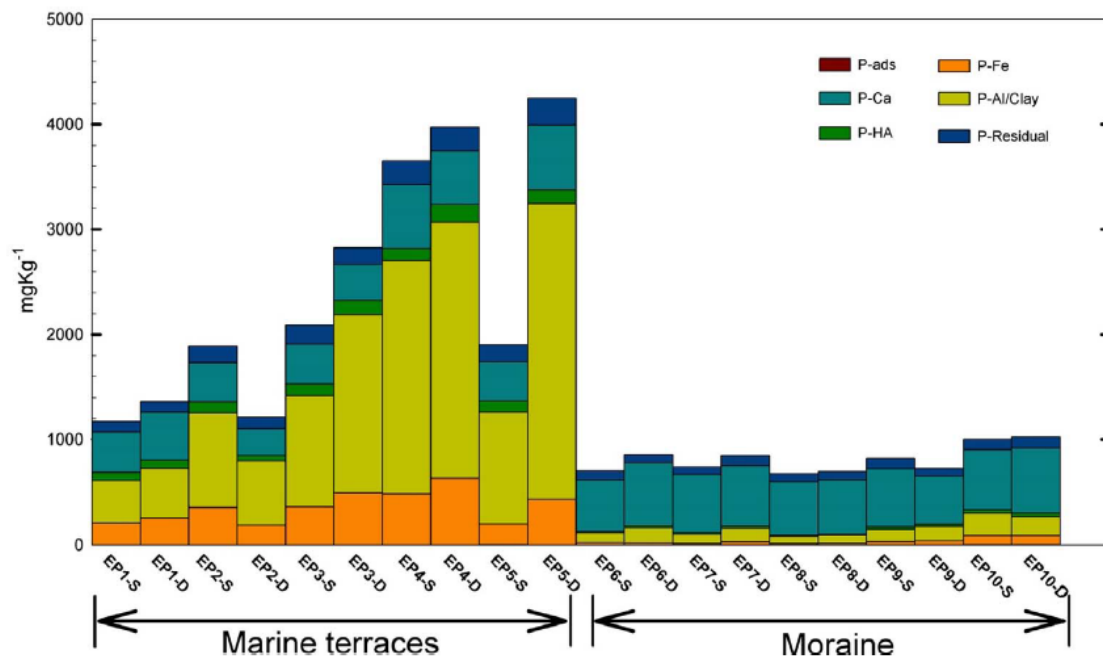
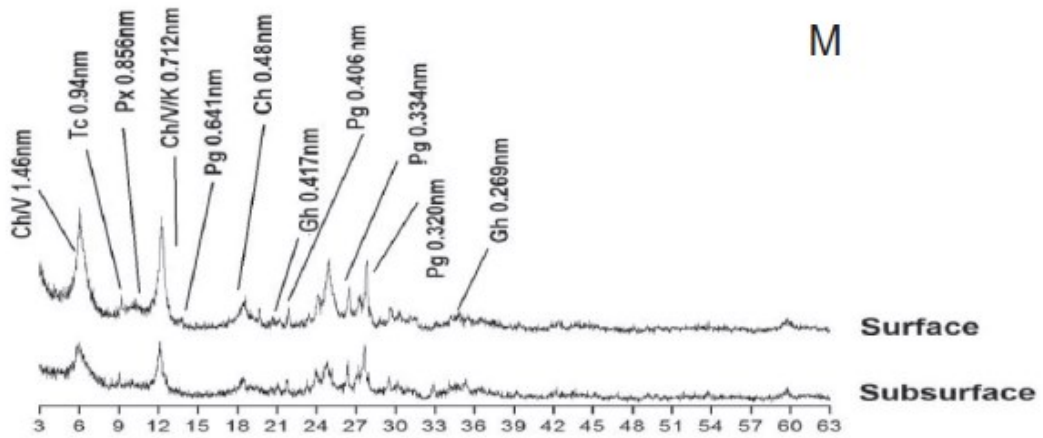
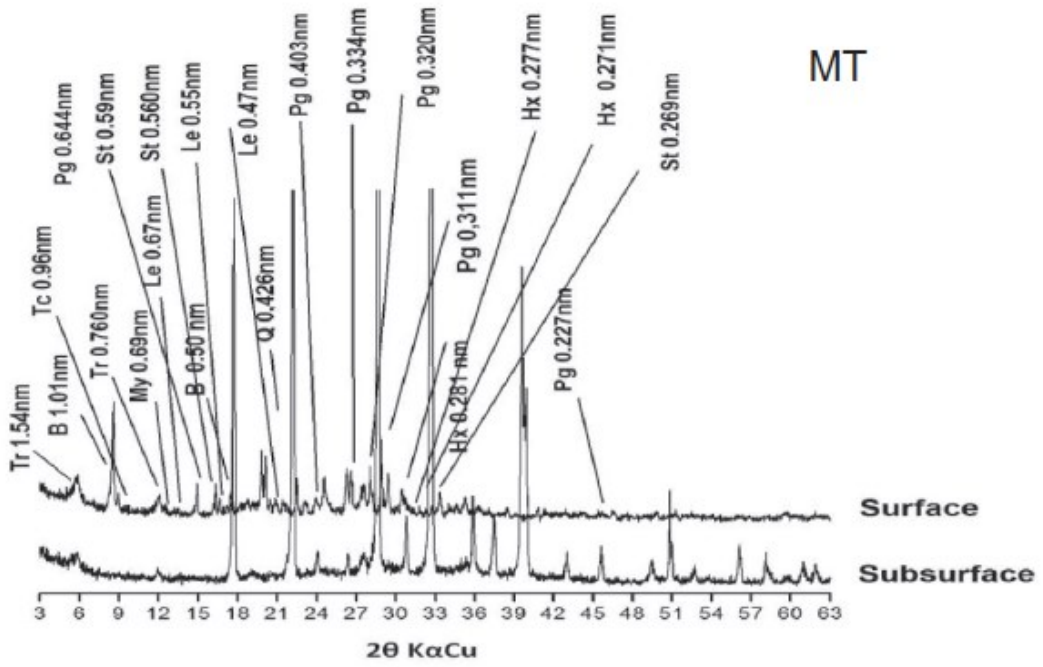


Fig. 4. Phosphorus partitioning. Deep samples are indicated by "D" and surface samples by "S".

# Clay fraction



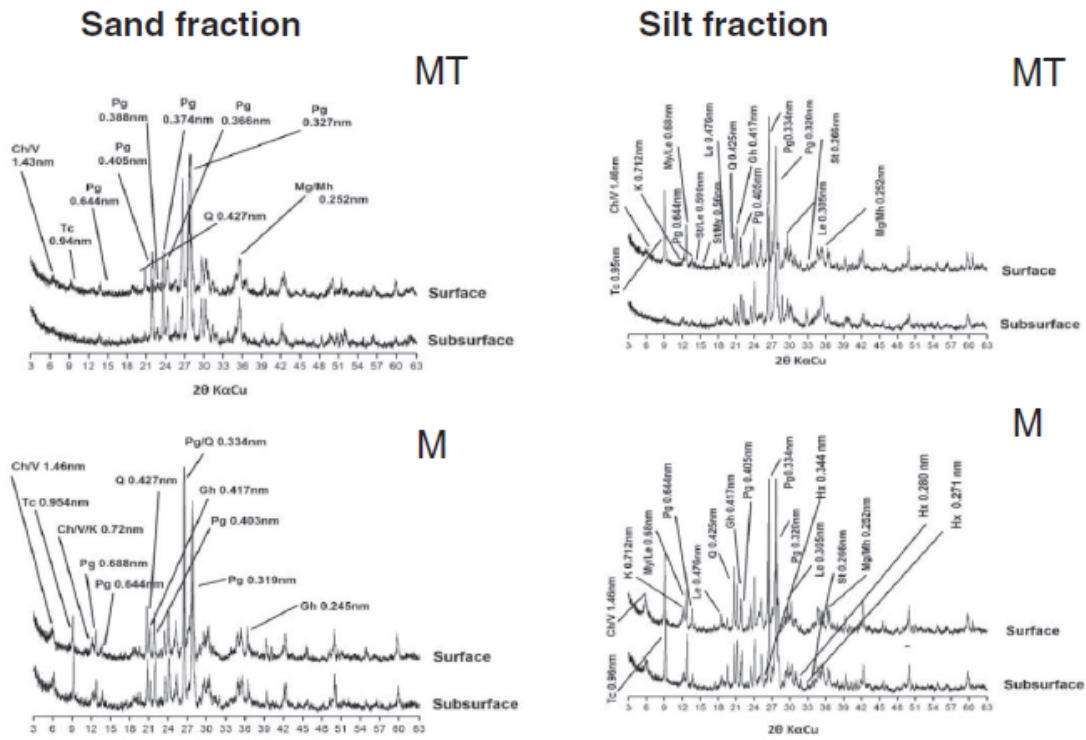


Fig. 5. XRD analysis of clay, silt and sand fraction showing minerals present in MT and M. Ch-Chlorite; V-Vermiculite; Px-Pyroxone; K-Kaolinite; B-Biotite; Pg-Plagioclases; Q-Quartz; Gh-Goethite; Hx-Hydroxylapatite; Tr-Taranakite; St-Struvite; Le-Leucophosphite and My-Minyulite

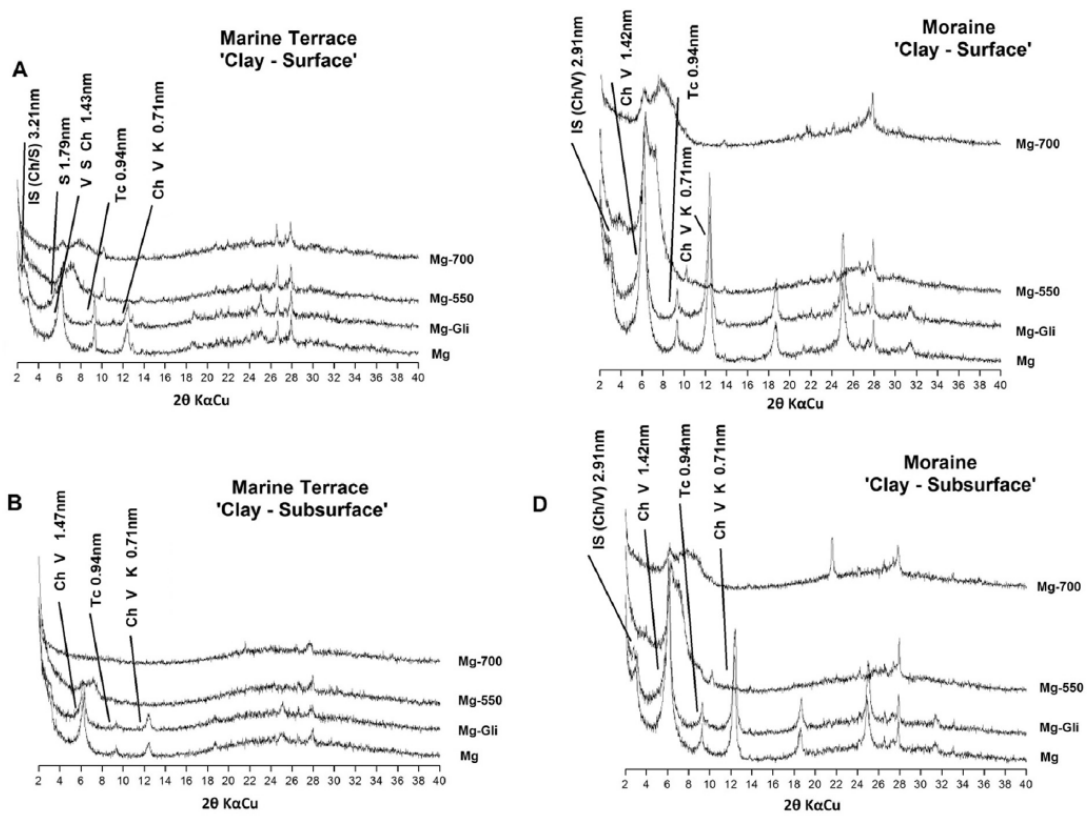


Fig. 6. XRD analysis of oriented aggregates of the clay fraction saturated with Mg<sup>2+</sup> in MT and M, in surface or subsurface samples. Ch-Chlorite; V-Vermiculite; K-Kaolinite; S-Smectite; Tc-Talc and interstratified (IS) minerals as Ch/V and Ch/S.

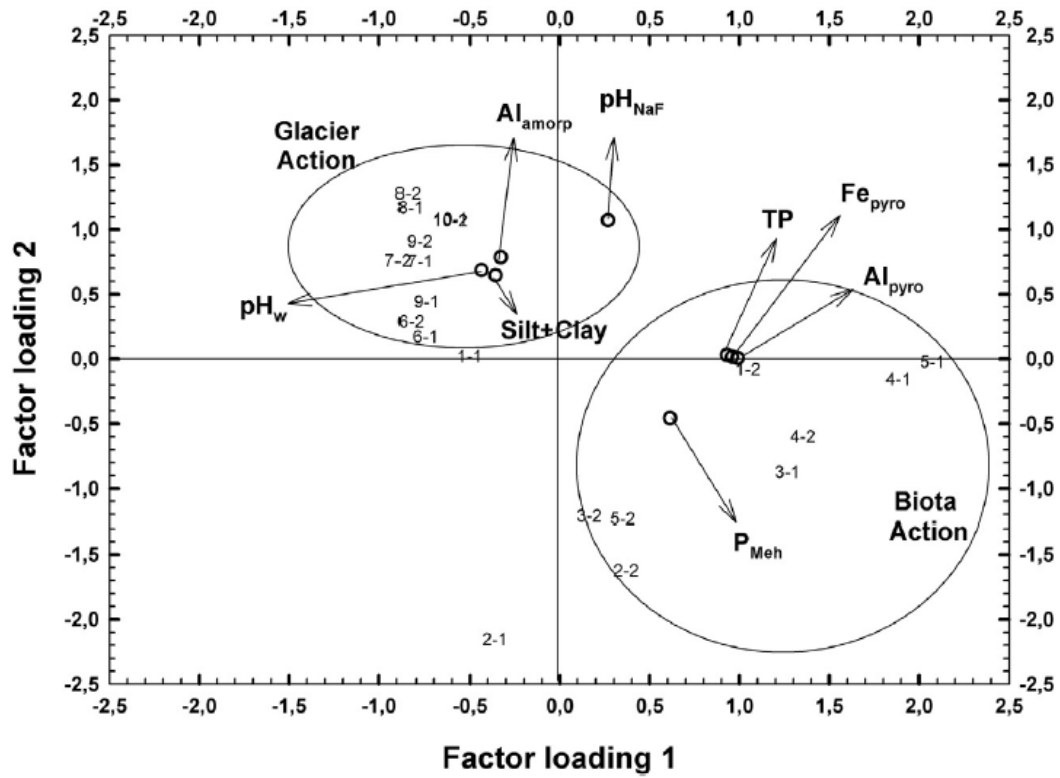


Fig. 7. Principal component analysis (PCA) of the soil variables analysed. Two groups of correlated variables and two groups of samples associated with them (indicated by ellipses) are shown. Note: Sampling points were labelled without the prefix “EP” (Elephant Point) to make them easier to read.