

MAYARA DAHER DE PAULA

**GENESIS AND CLASSIFICATION OF SEMI-ARID SOILS FROM JAMES ROSS  
ISLAND, WEDDELL SEA REGION, ANTARCTICA**

Tese apresentada à Universidade Federal de Viçosa, como parte das exigências do Programa de Pós-Graduação em Solos e Nutrição de Plantas, para obtenção do título de *Doctor Scientiae*.

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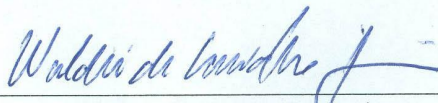
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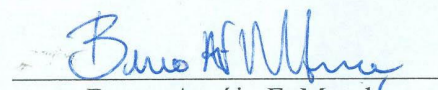
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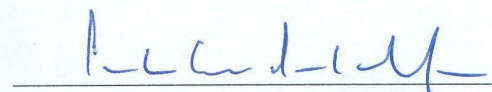
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## Abstract

DAHER, Mayara, D.Sc., Universidade Federal de Viçosa, December, 2018. **Genesis and classification of semi-arid soils from James Ross Island, Weddell Sea region, Antarctica.** Adviser: Elpídio Inácio Fernandes Filho. Co-advisers: Carlos Ernesto Gonçalves Reynaud Schaefer and Márcio Rocha Francelino.

The objective of this research was to investigate pedogenetic processes and soil formation factors in the region of the Weddell Sea and South Shetland Islands in the Peninsular Antarctic region. The work was divided into three papers. In the first paper the objective was to investigate the pedogenesis of a volcano-sedimentary topolithosequence, located in the James Ross Island, Weddell Sea region, through morphological, physical, chemical and mineralogical characterization, and classification of soils according to the international systems Soil Taxonomy and WRB / FAO. Soils are predominantly Gelisols/Cryosols and present cryoturbation features. Vegetation is scarce and nesting birds are absent, so that most soils can be characterized as ahumic. All profiles have a skeletal character, with a high percentage of coarse materials. The soil pH varied from neutral to alkaline and the potential acidity values were null. The mineralogy of the clay fraction presented kaolinite, which was likely inherited from warmer and wetter paleoclimatic conditions during sedimentation. The soils have mixed properties between maritime and continental Antarctic, such as cryoturbation and redoximorphism, side-by-side with desert pavements and ahumic character. In the second paper, the soils developed on different parent materials along the Ulu Peninsula, located on James Ross Island were analyzed geochemically through the quantification of major oxides and traces in soils, as well as the study of the uniformity of the parent material and the degree of weathering of soils, through geochemical indexes. Based on the major and trace oxides geochemistry, the soil types are well differentiated indicating that geochemical composition of soils is highly affected by their parent materials. Therefore, based on the major oxides abundances, chemical weathering seems insignificant. According to the high chemical index of alteration and mineralogical composition which have kaolinite in the clay fraction, soils developed on sedimentary rock of showed a pre-weathered nature. In the third paper the objective was to construct a database with all soil profiles collected since 2002 in the South Shetland Islands Group and the James Ross Islands Group to statistically analyze the physical and chemical properties of these soils located in different climatic regions. The results support the predominance of physical weathering rather than chemical weathering. However, in certain areas, chemical weathering and/or the parent material are more



influential. The mean pH values of JRIG soils are closer to those found in Continental Antarctica. SSIG soils are the most acidic in Antarctica, given both the presence of sulfides, and the biological influence associated with the area's greater precipitation and temperature. The highest P values (Mehlich-1) found in the two island groups were due to the influence of birds, mainly penguins, which are more significant in the SSIG. In the two island groups, the soils affected by avifauna activity have the highest amount of organic material, thereby resulting in high total organic carbon content. Climate is the factor that most influences the development of SSIG soils. Greater precipitation combined with higher temperatures considerably increases the organic matter content in these soils, in addition to the leaching of base elements, resulting in a more acidic pH, and more developed soils

## Resumo

DAHER, Mayara, D.Sc., Universidade Federal de Viçosa, dezembro de 2018. **Gênese e classificação de solos semiáridos da Ilha James Ross, Setor do Mar de Weddell, Antártica.** Orientador: Elpídio Inácio Fernandes Filho. Coorientadores: Carlos Ernesto Gonçalves Reynaud Schaefer e Márcio Rocha Francelino.

O objetivo desta pesquisa foi investigar os processos pedogenéticos e os fatores de formação dos solos do setor do Mar de Weddell e Ilhas Shetland do Sul, região da Antártica Peninsular. O trabalho foi dividido em três artigos. No primeiro artigo o objetivo foi investigar a pedogênese de uma toplotosequência vulcano-sedimentar, localizada na Ilha James Ross, setor do Mar de Weddell, através da caracterização morfológica, física, química e mineralógica, e a classificação dos solos de acordo os sistemas internacionais *Soil Taxonomy* e WRB/FAO. Os solos são predominantemente *Gelisols/Cryosols* e apresentam feições de crioturbação. A vegetação é escassa e a atividade da avifauna é ausente, assim a maior parte dos solos são caracterizados como *ahumic*. Todos os perfis têm caráter *skeletal*, com uma porcentagem alta de materiais grosseiros. O pH do solo variou de neutro a alcalino e os valores de acidez potencial foram nulos. A mineralogia da fração argila apresentou caulinita, provavelmente herdada de condições paleoclimáticas mais quentes e úmidas. Os solos apresentaram propriedades intermediárias entre a Antártica Marítima (crioturbação e redoximorfismo) e a Continental (pavimentos desérticos e caráter *ahumic*). No segundo artigo os solos desenvolvidos sobre diferentes materiais de origem ao longo da Península Ulu, localizada na Ilha James Ross foram analisados geoquimicamente através da quantificação dos óxidos maiores e traços nos solos, além do estudo da uniformidade do material de origem e do grau de intemperismo ao longo dos perfis, através de índices geoquímicos. Com base nos óxidos geoquímicos maiores e traços, os tipos de solo são bem diferenciados, indicando que a composição geoquímica dos solos é altamente afetada pelo material de origem. De acordo com o índice de intemperismo químico e a composição mineralógica, que possui caulinita na fração argila, os solos desenvolvidos sobre rocha sedimentar apresentaram uma natureza pré-intemperizada. No terceiro artigo, o objetivo foi a construção de uma base de dados com todos os perfis de solos coletados pelo Grupo TERRANTAR, desde 2002, no Grupo de Ilhas Shetland do Sul (GISS) e Grupo de Ilhas James Ross (GIJR) e analisar estatisticamente as propriedades físicas e químicas destes solos localizados nestas duas regiões climáticas distintas. Os resultados demonstram a predominância do intemperismo físico, em relação ao intemperismo químico. No entanto, em determinadas áreas, o intemperismo químico e/ou o

material de origem são mais influentes. Os valores médios de pH dos solos do GIJR estão mais próximos daqueles encontrados na Antártica Continental. Os solos do GISS são os mais ácidos da Antártica, dada a presença de sulfetos e a influência biológica associada à maior precipitação e temperatura da área. Os maiores valores de P (Mehlich-1) encontrados nos dois grupos de ilhas estão relacionados à influência de aves, principalmente pinguins, que são mais significativos no GISS. Nos dois grupos de ilhas, os solos afetados pela atividade da avifauna têm maiores quantidades de matéria orgânica, resultando em alto teor de carbono orgânico total. O clima é o fator que mais influencia o desenvolvimento dos solos do GISS. A maior precipitação combinada com temperaturas mais elevadas, aumentam consideravelmente o conteúdo de matéria orgânica nestes solos, além da lixiviação das bases trocáveis, resultando em um pH mais ácido e solos mais desenvolvidos.

## Introdução geral

Desde 2002, o Núcleo TERRANTAR, grupo pioneiro no Brasil em pesquisas de solos afetados por *permafrost*, vem realizando trabalhos com o intuito de entender a dinâmica climática, ecológica, microbiológica e geoambiental nesta importante região.

O estudo e monitoramento dos solos afetados por *permafrost* na região Antártica é importante para indicar, principalmente, mudanças relativas ao clima (Hoelzle e Haeberli, 1995). Esses ambientes estão sujeitos a elevadas transferências de energia em superfície, que podem alterar o ecossistema, reconhecidamente sensível a qualquer mudança climática (Reijmer e Oerlemans, 2002). Tem-se observado uma tendência geral de aumento das temperaturas do solo/*permafrost* da Antártica (Turner *et al.*, 2014). Dentre as alterações decorrentes do aumento da temperatura está o recuo das geleiras e com isso a maior exposição de solos, com conseqüente alteração nos seus processos de formação e intensidade de intemperismo, tratando-se de um ambiente em constante transformação, de pedoambientes únicos para o estudo de formação de solos.

Neste contexto, a tese objetiva investigar os processos pedogenéticos e os fatores de formação dos solos na região do Mar de Weddell e Ilhas Shetland do Sul, na região da Antártica Peninsular. Para isto, ela foi dividida em três artigos. No primeiro artigo o objetivo foi investigar a pedogênese de uma topolitosequência vulcano-sedimentar, localizada na Ilha James Ross, região do Mar de Weddell, através da caracterização morfológica, física, química e mineralógica, e classificação dos solos de acordo os sistemas internacionais *Soil Taxonomy* e WRB/FAO.

No segundo artigo o objetivo foi analisar geoquimicamente os solos desenvolvidos sobre diferentes materiais de origem ao longo da Península Ulu, localizada na Ilha James Ross, através da quantificação dos elementos maiores e traços nos solos, além do estudo da uniformidade do material de origem e do grau de intemperismo dos solos, através de índices geoquímicos.

No terceiro artigo o objetivo foi a construção de uma base de dados com todos os perfis de solos coletados, desde 2002, no Grupo de Ilhas Shetland do Sul e Grupo de Ilhas James Ross para analisar estatisticamente as propriedades físicas e químicas destes solos localizados em regiões climáticas distintas.

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## ARTIGO 1

### **Semi-arid soils from a topolithosequence at James Ross Island, Weddell Sea region, Antarctica: Chemistry, mineralogy, genesis and classification**

#### **Abstract**

Climate and parent material have a significant impact on the development of Antarctic soils, and areas dominated by basaltic-andesitic volcanic rocks, sedimentary rocks, and metamorphic rocks have been widely studied. James Ross Island, located in the semi-arid transition between East Antarctic Peninsula/Weddell Sea sector, receives both continental and maritime climatic influences, resulting in distinct, transitional soil formation process. In Antarctica, there is little research on semi-arid soils formed on volcano-sedimentary rocks, as well as their pedogenetic processes. In this study, a topolithosequence of volcanic and sedimentary rocks in this semi-arid transitional climate was investigated. Nine profiles, three on marine terraces, four on sedimentary rocks, and two on volcanic rocks were described, sampled, and analyzed for morphological, physical, chemical, and mineralogical properties. Soils are predominantly Gelisols/Cryosols and present cryoturbation features despite the current dry climate. Vegetation is scarce and nesting birds are absent, so that most soils can be characterized as ahumic. All profiles have a skeletal character, with a high percentage of coarse materials. The soil pH varied from neutral to alkaline and the potential acidity values were null. The mineralogy of the clay fraction presented kaolinite, which was likely inherited from warmer and wetter paleoclimatic conditions during sedimentation. The soils have intergrade properties between maritime and continental Antarctic, such as cryoturbation and redoximorphism, side-by-side with desert pavements and ahumic character. Soil

properties were more sensitive to the variations in parent material than to the topographic position in the landscape.

Keywords: Cryosols; Periglacial soils; Pedogenesis; Magnetite

## **1. Introduction**

In Antarctica, climatic variations and parent material are key factors to understand the spatial distribution of soils and their properties. In continental Antarctica (Transantarctic Mountains), the mean annual water-equivalent precipitation can reach 10 mm and the mean annual temperature is around  $-45.0$  °C, while in maritime Antarctica (South Shetland Islands), precipitation can reach 800 mm and the mean annual temperature is  $-1.8$  °C (Bockheim, 2015).

Due to high aridity in the continent, soil formation is very slow; even the most developed soils are closely related to the parent material (Campbell and Claridge, 1987). Salinization, rubification, carbonation, and wind ablation are dominant soil-forming processes (Bockheim and Ugolini, 1990). On the contrary, higher temperatures and moisture levels in maritime Antarctica favor chemical weathering and greater soil development, accumulation of organic matter, cryoturbation, acidification, redoximorphism, phosphatization, and podsolization are the main soil-forming processes (Bockheim, 2015).

Most Antarctic soils are affected by freezing and thawing processes and therefore classified as Gelisols by Soil Taxonomy (Soil Survey Staff, 2010; Bockheim, 1995). Permafrost is continuous in continental Antarctica, with thicknesses of  $> 900$  m in the Transantarctic

Mountains (Decker and Bucher, 1980) and appear mainly in the form of ice-cemented permafrost or dry permafrost. Most soils are classified as Anhyorthels, Anhyturbels, and Haploturbels (Bockheim and McLeod, 2008). The great group Anhy is predominant in Antarctica's inland mountains due to the following conditions: i) the mean annual water-equivalent precipitation <50 mm; ii) occurrence of dry permafrost and; iii) moisture content of <3% by weight, a requirement for anhydrous conditions (Soil Survey Staff, 2010).

In ice-free areas of the maritime Antarctic, permafrost is discontinuous, with depths of <100 m (Woo, 2012), but most soils have permafrost within 1 m of the surface, or show intense cryoturbation (Hall and Walton, 1992). There is a predominance of Haploturbels, demonstrating the importance of cryoturbation in the region. Aquiturbels are also abundant, reflecting the effect of ice-cemented permafrost on drainage, with redoximorphism process. Haploorthels are common on stable and high surfaces (Simas et al., 2015). However, in the South Orkney Islands and South Shetland Islands, permafrost is absent or sporadic, at elevations <20 m above sea level (m a.s.l.) (López-Martínez et al., 2012) and other classes of soils (Entisols, Inceptisols, Histosols, and Spodosols) are found (Simas et al., 2015).

In addition to climate, parent material has an important influence on the development of Antarctic soils (McCraw, 1967), although it plays a secondary role (Campbell and Claridge, 1987). In maritime Antarctic, several soil studies focused on areas dominated by andesitic basalts (Michel et al., 2006, 2014; Simas et al., 2006; 2008; Schaefer et al., 2008; Francelino et al., 2011; Mendonça et al., 2013; Poelking et al., 2015), basalts (Daher et al., 2019), pyritized andesites (Simas et al., 2008; Souza et al., 2012), pyroclastic materials (Simas et al., 2015), and sandstones and conglomerates (Navas et al., 2008; Moura et al., 2012).



In the Antarctic Peninsula, most studies have been conducted in sandstone, siltstone, mudstone, conglomerate, and schists (Engelen et al., 2008, Delpupo et al., 2013) and glacial deposits (till) (Wilhelm et al., 2016). In the continental Antarctic, soil studies are more diverse but most have been conducted in areas of phyllites and quartzites (Delpupo et al., 2017), sandstones (Denton et al., 1989; Bockheim, 2007), granites and gneisses (Bockheim and McLeod, 2006; Bockheim et al., 2008).

James Ross Island is located in the Weddell Sea, at the eastern Antarctic Peninsula, being influenced by both continental and maritime climate. The lithology is composed of volcanic rocks – basalts (James Ross Island volcanic group) in the upper section, which represent the largest Cenozoic mafic volcanic field in the Antarctic (Smellie, 1990), and Mesozoic sedimentary rocks – marine sandstone (Marambio Group) in the lower part, as well as Quaternary marine terraces. Despite its vast extension, there are still no records of soils formed on this extensive back-arc volcano-sedimentary sequence, which makes this study a unique contribution to the knowledge of the formation and distribution of Antarctic soils.

The aim of this study was to investigate the pedogenetic factors and soil-formation processes in a volcano-sedimentary topolithosequence on James Ross Island, eastern Antarctic Peninsula, focused on morphological, physical, chemical and, mineralogical studies, classifying the soils according to the Soil Taxonomy and the WRB/FAO systems.

## **2. Material and methods**

### **2.1. Study area**

James Ross Island is located on the northeastern coast of the Antarctic Peninsula and covers an area of 2500 km<sup>2</sup> (Fig. 1a). The northern sector of the island, called the Ulu Peninsula, represents the largest continuous deglaciated area in the whole region (Fig. 1b), representing 1.2% of the total ice-free area in Antarctica (Kavan et al., 2017).

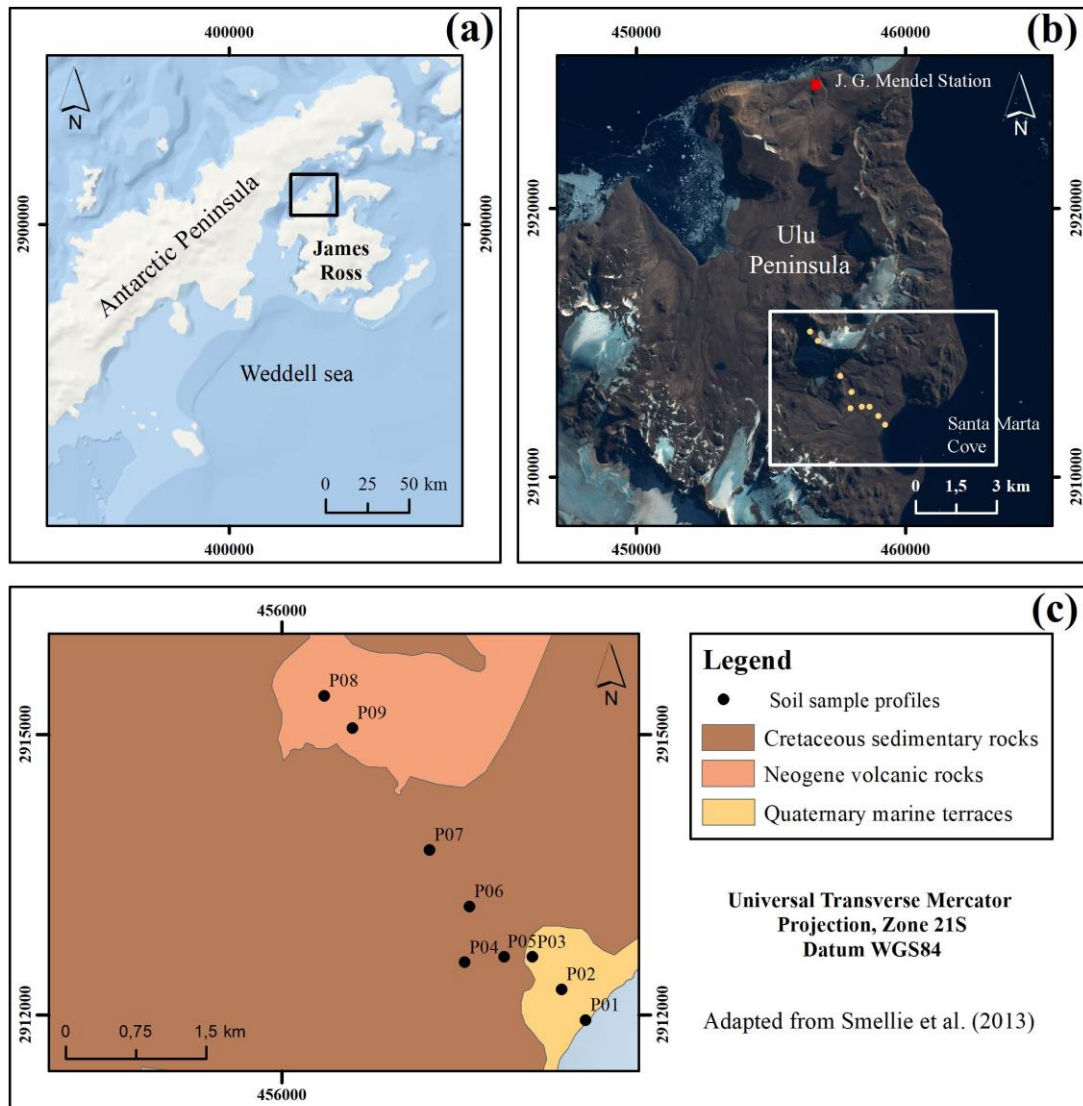


Fig. 1. Location of James Ross Island (a), location of the Ulu Peninsula and sampling sites (b), and position of the sampling sites on different parent material (c).

According to the zonal division of the Southern Circumpolar Region (Bockheim and Ugolini, 1990), the island is included in the polar desert zone and supposedly underlain by continuous permafrost (Schaefer et al., 2015). The mean annual air temperature at the Czech station,

Johann Gregor Mendel, was  $-7.0$  °C during 2006–2015 (Hrbáček et al., 2016). Mean daily temperatures above  $5$  °C and below  $-30$  °C are observed in the summer and winter season (Láska et al., 2011). The mean annual precipitation ranges from 300 to 500 mm (van Lipzig et al., 2004).

The island flora is composed of mosses, lichens, soil algae, and cyanobacteria (Barták et al., 2015). Vegetation cover is limited, compared to the South Shetland Islands, due to the drier and colder climate, and dependent on topography and snow accumulation (Láska et al., 2011). Lichens are predominant, but some mosses can also be found, especially in shallow depressions (Láska et al., 2011).

During the field campaigns and soil survey, a topolithosequence located in Santa Marta Cove was chosen (Fig. 1b). The area has four levels of uplifted marine terraces: a lower terrace: 3–5 m a.s.l., a mid terrace: 10–17 m a.s.l., and two upper terraces: 21–24 and 32–35 m a.s.l. (Fukuda et al., 1992). The active layer has a depth of approximately 1 m on the terraces, while the depths of the permafrost base in the upper, middle, and lower terraces are estimated at 40 m, 3.4 m, and 5.8 m, respectively (Fukuda et al., 1992).

Geologically, the area is underlain by volcanic rocks (James Ross Island Volcanic Group) in the upper part, forming structural lava flows (plateau), and sedimentary rocks (Marambio Group) in the lower slopes (Fig. 1c). The James Ross Island Volcanic Group consists mainly of olivine-basalt lavas, typical of shallow marine volcanic eruptions, as well as tuff/palagonite breccia, all dated to the late Miocene ( $\sim 6$  Ma) (Nelson, 1975; Smellie et al., 2008). In the Marambio Group, there are highly fossiliferous places, with the presence of fossil plants, vertebrates, invertebrates, and concretions  $>20$  cm. This group is composed of a variety of

medium- to fine-grained sandstones, siltstones, silty mudstones, and coquinas dating to the Cretaceous-Eocene (~75 Ma) (Francis et al., 2006).

## 2.2. Soil sampling and characterization

In January 2016, nine soil profiles were described along the topolithosequence: three on marine terraces, four on sedimentary rocks, and two on the highest volcanic rocks (Fig. 1c). Soil sampling and morphological descriptions followed the recommendations established by the Antarctic Permafrost and Soils (ANTPAS) group (Bockheim et al., 2006). Soils were classified according to the Soil Taxonomy (Soil Survey Staff, 2010) and WRB/FAO (IUSS Working Group, 2006). At the time of sampling, the land surface temperature (LST) was recorded using a hand-held temperature probe.

Dry soil colors were determined using the Munsell chart (1994). The percentage of coarse material was determined by weighting. Soil texture was determined by using the slow mechanical dispersion in the fine-earth fraction (<2 mm) in pH 10 distilled water, sieving, and weighing of coarse and fine sand, sedimentation of silt + clay, followed by syphoning of the <0.002 mm fraction (Ruiz, 2005).

Soil pH was determined in distilled water and 1 mol L<sup>-1</sup> KCl solution (ratio 1:2.5) (EMBRAPA, 2017). Ca<sup>2+</sup> and Mg<sup>2+</sup> were determined by atomic absorption spectroscopy and Al<sup>3+</sup> by titration after extraction with 1 mol L<sup>-1</sup> KCl. P, Na<sup>+</sup>, and K<sup>+</sup> were extracted with Mehlich-1 (0.05 M HCl + 0.0125 M H<sub>2</sub>SO<sub>4</sub>, 1:10 soil-extractor ratio). P content in the extracts was determined spectrophotometrically, whereas Na<sup>+</sup> and K<sup>+</sup> were measured by flame emission photometry (EMBRAPA, 2017). The potential acidity (H + Al) was determined by

titration, after extraction with  $0.5 \text{ mol L}^{-1}$  Ca ( $\text{CH}_3\text{COO}_2$ ) at pH 7.0 (EMBRAPA, 2017).

Total organic carbon (TOC) was determined using the dry combustion method (PerkinElmer 2400 Series II CHNS/O Elemental Analyzer). Electrical conductivity (EC) was measured in the aqueous extract using a 1:5 soil-water ratio (Richards, 1954) and subsequently corrected as a function of soil particle size, as suggested by Slavich and Petterson (1993).

Two representative profiles of soils developed on sedimentary rocks in different positions in the landscape (P04 and P07) and one representative profile of the soils developed on volcanic rocks (P09) were selected for detailed mineralogical characterization of sand, silt, and clay fractions. For the clay fraction, representative horizons of each profile were selected.

The minerals present in the fine-earth fraction ( $<2 \text{ mm}$ ) were detected by X-ray diffraction (XRD). A diffractometer (PANalytical/X'Pert Pro) was used, with  $\text{CoK}\alpha$  radiation in the  $4\text{--}50^\circ 2\theta$  range, at the intervals of  $0.017^\circ 2\theta$  with 1-s steps, at 40 kV and 30 mA. To detail the 2:1 type clay (Whittig and Allardice, 1986); with Fe oxides concentration (Norrish and Taylor, 1961; Kämpf and Schwertmann, 1982). The following treatments were performed:  $\text{Mg}^{2+}$  saturation and glycerol solvation,  $\text{K}^+$  saturation at room temperature, heating in an oven at  $350^\circ\text{C}$  and  $550^\circ\text{C}$ , and NaOH treatment. The diffractograms were interpreted using Chen (1977) charts for mineral identification.

In the fine-earth fraction ( $<2 \text{ mm}$ ), the following chemical extractions were also performed: sodium pyrophosphate at pH 10 (Dahlgren, 1994), ammonium oxalate at pH 3.0 ( $0.2 \text{ mol L}^{-1}$ ) (McKeague and Day, 1966), and dithionite-citrate-bicarbonate (Mehra and Jackson, 1960). After all extractions, the amounts of Fe and Al were determined by atomic absorption

spectroscopy.

The low frequency magnetic susceptibility ( $X_{lf}$ ) was determined for the samples of the sand, silt, clay, and fine-earth fraction (<2 mm) of the same profiles studied for the mineralogical characterization by X-ray diffraction (P04, P07 and P09). The samples were measured at low frequency (0.47 kHz), using a Bartington MS2 Magnetic Susceptibility System coupled with an MS2B sensor, according to the methodology described by Dearing (1994).

### 3. Results and Discussion

#### 3.1. Soil Properties

The morphological, chemical, physical, and mineralogical properties were characterized for all soils collected in Santa Marta Cove on James Ross Island. The nine profiles (P01–P09) represents the entire range in topography and geology found at Santa Marta Cove (Fig. 2, Table 1).

Table 1. Location, land surface temperature (LST), classification, and geology of soil profiles sampled.

Profile	Elevation (m a.s.l.) <sup>a</sup>	LST (°C)	Location <sup>b</sup>	Classification		Geology	Period
				Soil Survey Staff (2010)	IUSS Working Group (2006)		
P01	01	4.4	459254 W 2911942 S	Psammentic Aquiturbel	Turbic Cryosol (Reductaquic, Skeletal)	Marine sediment	Quaternary
P02	18	3.9	459000 W 2912272 S	Psammentic Aquiturbel	Turbic Cryosol (Reductaquic, Skeletal)	Marine sediment	Quaternary
P03	39	2.5	458684 W 2912618 S	Typic Psammoturbel	Turbic Cryosol (Skeletal)	Marine sediment	Quaternary
P04	43	6.0	458077 W 2912724 S	Typic Psammoturbel	Turbic Cryosol (Skeletal)	Marine sandstone	Cretaceous- Eocene

P05	134	13.0	458382 W 2912620 S	Typic Psammorthels	Turbic Cryosol (Skeletal)	Marine sandstone	Cretaceous- Eocene
P06	282	14.0	458009 W 2913157 S	Psammentic Aquiturbel	Turbic Cryosol (Reductaquic, Skeletal)	Marine sandstone	Cretaceous- Eocene
P07	367	9.7	457583 W 2913764 S	Typic Psammoturbel	Turbic Cryosol (Skeletal)	Marine sandstone	Cretaceous- Eocene
P08	435	7.0	456457 W 2915414 S	Typic Psammoturbel	Turbic Cryosol (Skeletal)	Volcanic	Neogene
P09	582	2.5	456731 W 2915027 S	Lithic Aquiturbel	Turbic Cryosol (Reductaquic, Skeletal)	Volcanic	Neogene

<sup>a</sup> Meters above sea level (m a.s.l.) ; <sup>b</sup> UTM coordinate, Zone 21S, datum WGS 84.

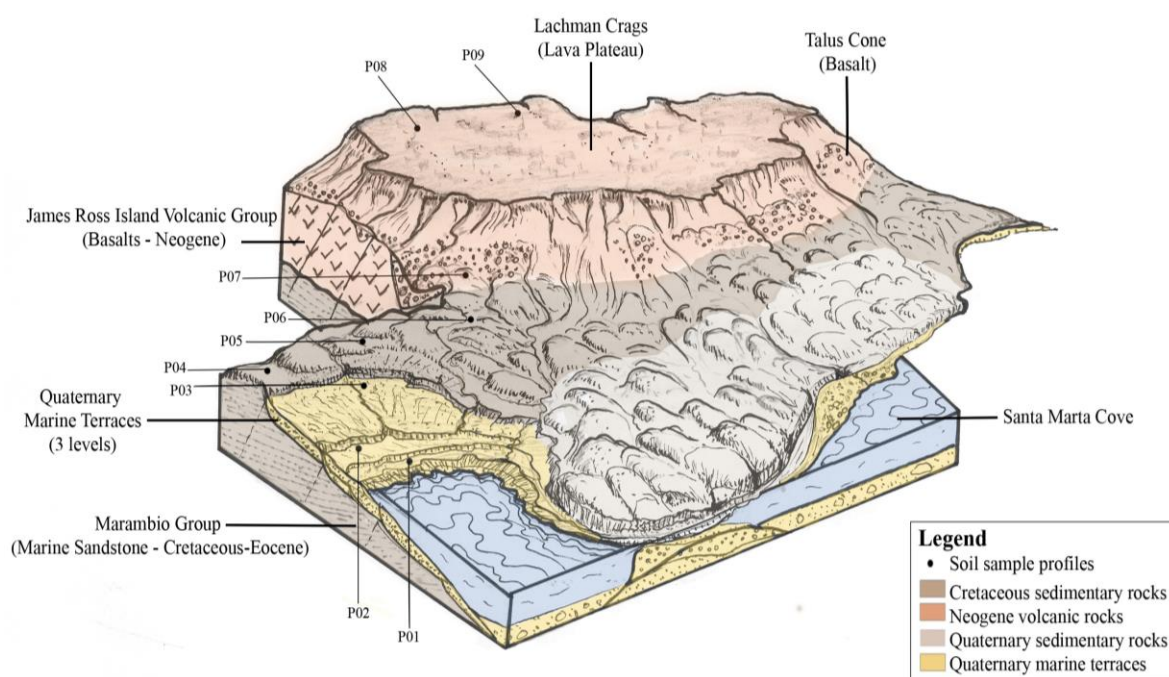


Fig. 2. Block-diagram of the studied area at Santa Marta Cove, James Ross Island, from the Lachman Crags (Basalt Plateau) to the Quaternary marine terraces and shallow marine foreland basin of the Weddell Sea.

### 3.1.1. Soil Morphology

According to the field observations, all soils collected on sedimentary material (P01 to P07) are mixed with other materials derived from volcanic rocks from the upper landscape surfaces (Fig. 3). This mixing resulted from drift deposition (till), intense subglacial erosion of

highland lava plateau, as well as aeolian contributions following glacier retreat.

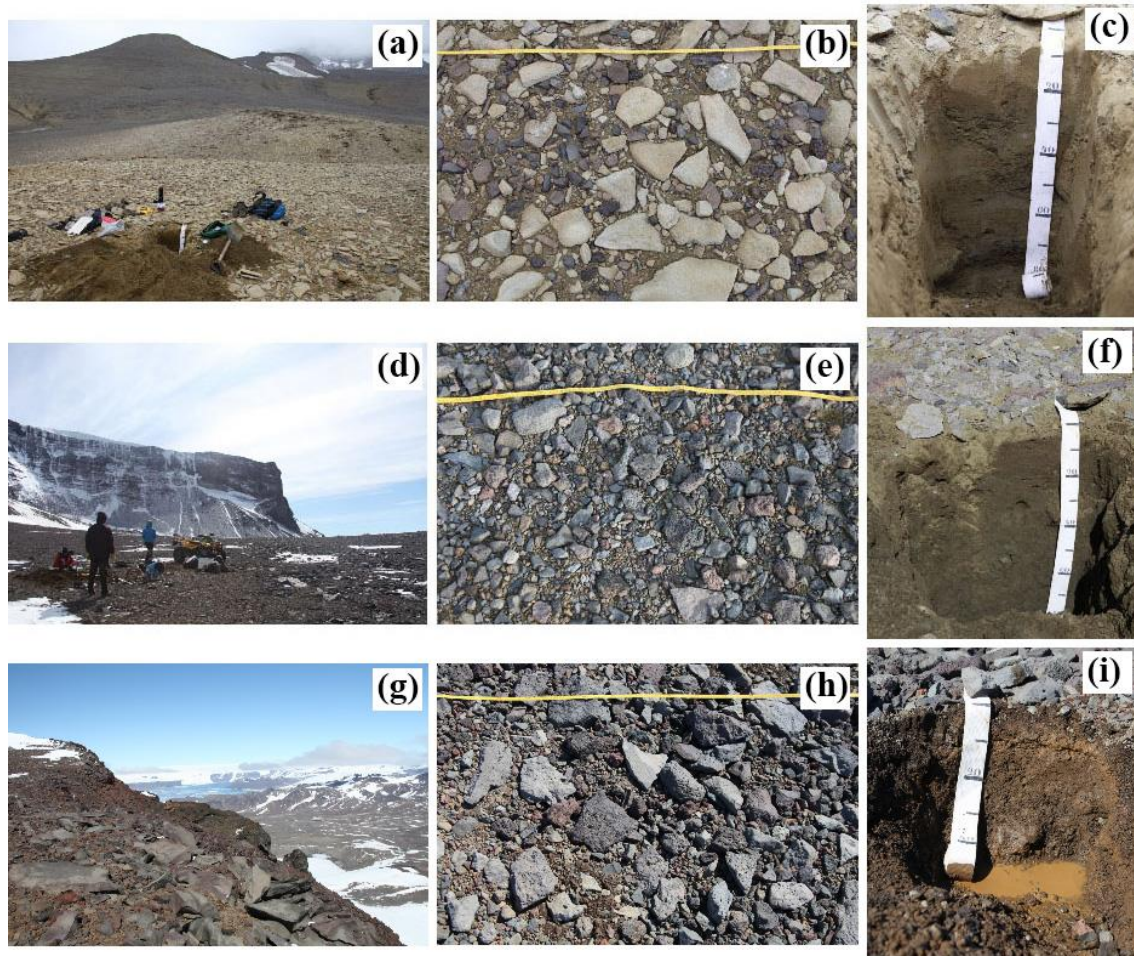


Fig. 3. Landscape (a), soil surface (b), and sampled profile (P04) on sedimentary rocks with less influence of the volcanic materials (c); landscape (d), soil surface (e), and sampled profile (P07) on sedimentary rocks with high influence of volcanic material (f); landscape (g), soil surface (h), and sampled profile (P09) on volcanic rocks (i).

The main pedogenic processes observed along this topolithosequence were: cryoturbation, desert pavement formation by wind ablation (selective erosion of fine particles), and redoximorphism in wet soils of lower marine terraces. Soils showed general features of cryoturbation, such as irregular and broken horizons, vertical orientation of stones within the soil profile, and granular structure. Only P07, at 367 m a.s.l., showed a stripe-patterned ground, associated with wet conditions at the active layer.



James Ross Island is underlain by continuous permafrost and was found within 180–200 cm of the ground surface (Fukuda et al., 1992). This was also observed during fieldwork, and all soils showed evidence of ice-cemented permafrost within the control section (down to 100 cm), being classified as Gelisols, within the Turbel suborder (Soil Survey Staff, 2010) and the Turbic suffix qualifier (IUSS Working Group, 2006) (Table 1). Dry permafrost was not observed at any soil depth. The widespread cryoturbation at James Ross Island contrasts with the nearby Seymour Island, where soils showed little cryoturbation when developed from Cretaceous marine sediments (Schaefer et al., 2015).

The average land surface temperature (LST) for the lowland soil on sedimentary marine terraces (P01, P02 and P03) was 3.6 °C, whereas on the mixed drift (basalts with aeolian and till) (P04, P05, P06 and P07) was much higher (10.7 °C) (Table 1). The two highland soils on the plateau at the top (P08 and P09) showed average LST of 4.8 °C, even higher than those from lowland soils (Table 1). Hence, the dark color of the basalt rock and drifts absorbs and transmits more heat than lowland sediments.

In general, the dry color of the soils was homogeneous along the profile, and tend to yellowish colors (5Y and 2.5Y hue) (Table 2) and low value (<4). These dark color result from the mixture of sedimentary material with dark basaltic material. In P01 and P02, located on the marine terrace, and in P06, the soils were water-saturated in subsurface, with a predominance of neutral colors (gley) (Table 2).

The highland soils of the topolithosequence (P09 and P10, both volcanic) had greater color development, with a 10YR hue, high chroma and value (Table 2). In P09, aquic conditions resulted from episaturated conditions caused by the lithic contact in a closed depression,

having no change of color.

Table 2. Morphological and physical properties of soils at James Ross Island.

Horizon	Depth cm	Color dry	Gravel <sup>a,h</sup>	CS <sup>b,i</sup>	FS <sup>c,h</sup>	Silt <sup>d,h</sup>	Clay <sup>e,h</sup>	S+C <sup>f</sup>	CS/FS <sup>g</sup>	Texture <sup>j</sup>
			%							
<b>Profile 01 – Psammentic Aquiturbel/Turbic Cryosol</b>										
A	0–10	5Y 4/3	60	22	44	12	22	35	0.5	Sandy clay loam
AB	10–22	5Y 4/3	39	11	61	10	19	29	0.2	Sandy loam
Bi	22–40	5Y 4/3	37	7	62	11	19	31	0.1	Sandy loam
Cgjj	40–85	5Y 4/2	38	5	63	14	18	32	0.1	Sandy loam
Cgf	85–100	5Y 4/2	36	4	64	13	19	32	0.1	Sandy loam
<b>Profile 02 – Psammentic Aquiturbel/Turbic Cryosol</b>										
A	0–8	5Y 4/3	73	12	63	9	17	26	0.2	Sandy loam
AB	8–20	2.5Y 4/3	40	5	68	12	15	27	0.1	Sandy loam
Bi	20–45	5Y 4/3	43	7	65	10	19	29	0.1	Sandy loam
Cgjj	45–80	5Y 4/2	37	5	65	16	15	30	0.1	Sandy loam
Cgjff	80–100	5Y 4/2	39	5	66	13	17	30	0.1	Sandy loam
<b>Profile 03 – Typic Psammenturbel/Turbic Cryosol</b>										
A	0–10	5Y 4/4	72	9	63	6	23	28	0.1	Sandy clay loam
AB	10–30	5Y 4/3	43	7	64	15	14	29	0.1	Sandy loam
Bi	30–60	5Y 4/3	41	6	66	14	15	29	0.1	Sandy loam
Cjjf	60–100	5Y 4/3	40	3	70	11	16	26	0.0	Sandy loam
<b>Profile 04 – Typic Psammenturbel/Turbic Cryosol</b>										
A	0–20	2.5Y 5/4	64	8	73	8	11	18	0.1	Loamy sand
C1	20–55	2.5Y 4/4	58	13	71	7	10	17	0.2	Loamy sand
Cjjf	55–80	5Y 4/3	59	12	72	9	8	17	0.2	Loamy sand
<b>Profile 05 – Typic Psammorthels/Turbic Cryosol</b>										
A	0–8	2.5Y 4/4	72	9	64	12	15	27	0.1	Sandy loam
Bi	8–35	2.5Y 4/4	43	3	72	11	14	26	0.0	Sandy loam
C1	35–45	2.5Y 4/3	39	3	66	14	18	31	0.0	Sandy loam
Cjjf	45–55	2.5Y 4/3	39	11	60	12	17	29	0.2	Sandy loam
<b>Profile 06 – Psammentic Aquiturbel/Turbic Cryosol</b>										
A	0–10	2.5Y 4/3	83	10	64	12	15	27	0.2	Sandy loam
Bi	10–50	2.5Y 4/3	65	5	63	28	5	33	0.1	Loam
Cjj	50–80	5Y 4/3	41	4	64	27	6	32	0.1	Loam
Cgjff	80–100	5Y 4/2	38	5	63	21	11	32	0.1	Sandy loam
<b>Profile 07 – Typic Psammenturbel/Turbic Cryosol</b>										
A	0–5	5Y 4/3	80	7	72	7	13	21	0.1	Sandy loam
AC	5–20	2.5Y 4/4	68	9	66	13	13	26	0.1	Sandy loam
C1	20–40	2.5Y 5/4	62	12	59	15	15	30	0.2	Sandy loam
Cjjf	40–80	2.5Y 5/4	59	14	51	20	15	34	0.3	Sandy loam
<b>Profile 08 – Typic Psammenturbel/Turbic Cryosol</b>										
A	0–10	10YR 4/3	70	50	17	19	14	33	2.9	Sandy loam
AC	10–40	10YR 4/4	35	28	37	26	10	36	0.7	Sandy loam
Cjjf	40–90	10YR 4/4	35	34	42	14	10	24	0.8	Sandy loam
<b>Profile 09 – Lithic Aquiturbel/Turbic Cryosol</b>										
A	0–10	10YR 5/6	69	36	35	19	11	29	1.0	Sandy loam
Bi	10–22	10YR 5/6	40	24	39	30	7	37	0.6	Loam
Cgjff	22–40	10YR 5/6	42	44	20	28	7	36	2.2	Loam

<sup>a</sup> Gravel: >2.00 mm Ø; <sup>b</sup> Coarse sand: 2–0.2 mm Ø; <sup>c</sup> Fine sand: 0.2–0.05 mm Ø; <sup>d</sup> Silt: 0.05–0.002 mm Ø; <sup>e</sup> Clay: <0.002 mm Ø; <sup>f</sup> Sum of Silt and Clay; <sup>g</sup> Sand fine/Sand coarse ratio; <sup>h</sup> Percentage of particles in total soil mass (>2 mm Ø); <sup>i</sup> Percentage of fine-earth fraction (<2 mm Ø); <sup>j</sup> Texture according to EMBRAPA (2017).

### *3.1.2. Soil Physical and Chemical Properties*

All profiles are skeletal (IUSS Working Group, 2006) with a high percentage of gravels (>2 mm), reaching >60% in the surface horizons, decreasing to 30–40% with depth (Table 2). Only in P06, there is a stony layer at the surface. The skeletal character, caused by dominant physical weathering, is typical of soils on volcanic rocks in the maritime Antarctic (Simas et al., 2008, Francelino et al., 2011, Michel et al., 2014, Daher et al., 2019). In contrast, on nearby Seymour Island, because of the sedimentary material (pelitic/psammitic), there is an absence of skeletal character in soils (Delpupo et al., 2014).

The fine-earth fraction (<2 mm) was dominated by sand (>60%) and loamy sand textures (Table 2). The profile collected on sedimentary rocks with a small influence of volcanic materials, P04, presented the highest sand content (>80%) and was classified as loam sandy. The highest coarse/fine sand (CS/FS) ratio occurs on volcanic soils (P09 and P10) (Table 2).

Silt and clay contents of soils in the topolithosequence are lower than those of the volcanic soils in the maritime Antarctic studied by Michel et al. (2006, 2014), Simas et al. (2006, 2008), Schaefer et al. (2008), Francelino et al. (2011), and Poelking et al. (2015). The dry climate on James Ross Island combined with the absence of ornithogenesis and sulphides likely prevent greater weathering rates in this semi-arid environment.

In soils from the Transantarctic Mountains, Bockheim (1982) observed inherently higher levels of silt and clay (>25%) in Dry valleys on sedimentary parent material (Arena Valley), regardless of the weathering process. Hence clay/silt may be also inherited from sedimentary materials.

Soils on James Ross Island are eutrophic (percentage of bases sum >90%) and can be classified as hypereutric (IUSS Working Group, 2006), with high levels of exchangeable  $\text{Ca}^{2+}$  and  $\text{Mg}^{2+}$ , followed by  $\text{K}^{+}$  and  $\text{Na}^{+}$  (Table 3). The hypereutric character of these soils is consistent with the current environmental conditions (low leaching). In the semi-arid Hope Bay Island, Pereira et al. (2013), showed low leaching of the bases in the Antarctic Peninsula compared to soils from South Shetland Islands (both with or without ornithogenic influence) results from the lower amount of liquid water in the summer, and a drier climate.

The Mehlich-1 extractable P (bioavailable) levels are relatively high along the topolithosequence, with higher levels on the profiles located on the lower marine terrace (P01) and on the volcanic plateau (P08) (Table 3). Soils showed increasing levels of P with depth, due to parent material richness, olivine-basalts are naturally rich in P-apatite (Francelino et al., 2011). We found no evidence of surface phosphatization by bird guano or any bioavailable P amount comparable with previous phosphatized soils reported from Antarctica (Michel et al., 2006; Simas et al., 2007; Pereira et al., 2013; Delpupo et al., 2014; Daher et al., 2019),

$\text{Na}^{+}$  levels increased in soils closer to the sea shore, reaching above 1000 mg/kg in the profiles located on the lower (P01) and middle (P02) marine terraces (Table 3). High levels of  $\text{Na}^{+}$  in P01 and P02 are attributed to periodic waterlogging by seawater invading marine terraces at high tide, as well as marine aerosols.  $\text{Na}^{+}$  levels sharply decreased in the soil located in the upper marine terrace (P03) (Table 3) due to the distance to the sea and less exposure to winds.

Table 3. Chemical properties of soils at James Ross Island.

Horizon	Depth cm	pH H <sub>2</sub> O	P	K	Na	Ca	Mg	H+Al	BS	CEC <sub>e</sub>	CEC <sub>p</sub>	Alsat	PSB	TOC	EC dS/m
			— mg/kg —						— cmolc/kg —			— % —			
<b>Profile 01 – Psammentic Aquiturbel/Turbic Cryosol</b>															
A	0–10	8.5	118.2	427.0	1494.6	2.87	3.40	0.70	13.86	13.86	14.56	0.00	95.20	0.15	2.56
AB	10–22	9.2	110.7	317.0	1094.9	2.60	3.36	0.30	11.53	11.53	11.83	0.00	97.50	0.18	1.37
Bi	22–40	8.9	97.2	187.0	695.2	2.11	2.61	0.20	8.22	8.22	8.42	0.00	97.60	0.11	0.85
Cgjj	40–85	6.6	98.3	218.0	445.4	2.39	3.85	0.20	8.74	8.74	8.94	0.00	97.80	0.11	0.62
Cgf	85–100	8.7	110.3	238.0	845.1	1.09	3.60	0.20	8.97	8.97	9.17	0.00	97.80	0.13	1.50
<b>Profile 02 – Psammentic Aquiturbel/Turbic Cryosol</b>															
A	0–8	7.9	89.4	169.0	165.5	5.84	2.95	0.20	9.94	9.94	10.14	0.00	98.00	0.14	0.64
AB	8–20	7.8	87.3	173.0	99.5	4.52	3.59	0.30	8.99	8.99	9.29	0.00	96.80	0.14	0.48
Bi	20–45	7.5	97.2	183.0	126.5	3.55	4.31	0.30	8.88	8.88	9.18	0.00	96.70	0.16	0.62
Cgjj	45–80	8.5	86.9	169.0	495.4	1.74	5.90	1.30	10.23	10.23	11.53	0.00	90.70	0.16	0.60
Cgjff	90–100	8.0	102.0	202.0	1025.0	1.17	3.74	0.50	9.88	9.88	10.38	0.00	95.20	0.14	1.86
<b>Profile 03 – Typic Psammenturbel/Turbic Cryosol</b>															
A	0–10	7.1	72.0	99.0	142.5	6.04	2.87	0.30	9.78	9.78	10.08	0.00	97.00	0.13	0.37
AB	10–30	7.4	65.8	73.0	69.5	5.12	3.30	0.30	8.91	8.91	9.21	0.00	96.70	0.12	0.25
Bi	30–60	7.8	54.3	52.0	42.5	3.61	3.10	0.30	7.03	7.03	7.33	0.00	95.90	0.10	0.24
Cjff	60–100	7.3	65.8	57.0	46.5	3.31	3.49	0.20	7.15	7.15	7.35	0.00	97.30	0.08	0.34
<b>Profile 04 – Typic Psammenturbel/Turbic Cryosol</b>															
A	0–20	7.6	46.7	43.0	192.4	2.31	1.79	0.20	5.05	5.05	5.25	0.00	96.20	0.11	0.38
C1	20–55	5.3	43.2	44.0	60.5	1.92	2.48	0.30	4.78	4.78	5.08	0.00	94.10	0.13	0.26
Cjff	55–80	7.7	52.7	46.0	97.5	2.83	2.70	0.30	6.07	6.07	6.37	0.00	95.30	0.10	0.54
<b>Profile 05 – Typic Psammorthels/Turbic Cryosol</b>															
A	0–8	7.3	59.5	201.0	177.4	8.25	2.76	0.80	12.30	12.30	13.10	0.00	93.90	0.13	0.59
Bi	8–35	7.5	65.2	126.0	67.5	7.64	2.89	0.20	11.15	11.15	11.35	0.00	98.20	0.12	0.23
C1	35–45	7.3	62.7	85.0	56.5	9.50	3.13	0.30	13.09	13.09	13.39	0.00	97.80	0.12	0.26
Cjff	45–55	7.3	76.3	197.0	107.5	10.22	2.98	0.20	14.17	14.17	14.37	0.00	98.60	0.16	0.29
<b>Profile 06 – Psammentic Aquiturbel/Turbic Cryosol</b>															
A	0–10	8.3	74.0	98.0	167.5	9.45	3.29	0.20	13.72	13.72	13.92	0.00	98.60	0.15	0.85
Bi	10–50	8.0	56.7	85.0	101.5	9.84	4.26	0.30	14.76	14.76	15.06	0.00	98.00	0.13	0.41
Cjj	50–80	6.3	73.6	93.0	202.4	9.58	3.96	0.20	14.66	14.66	14.86	0.00	98.70	0.14	0.55
Cgjff	80–100	8.7	145.0	104.0	255.5	9.39	2.91	0.20	13.68	13.68	13.88	0.00	98.60	0.14	0.37
<b>Profile 07 – Typic Psammenturbel/Turbic Cryosol</b>															
A	0–5	7.2	53.7	150.0	111.5	8.31	4.16	0.50	13.34	13.34	13.84	0.00	96.40	0.13	0.48
AC	5–20	7.7	72.7	258.0	109.5	12.55	5.16	0.30	18.85	18.85	19.15	0.00	98.40	0.18	0.25
C1	20–40	8.2	79.0	268.0	152.5	12.10	4.45	0.20	17.90	17.90	18.10	0.00	98.90	0.10	0.41
Cjff	40–80	7.8	89.0	516.0	205.6	14.05	3.93	0.20	20.20	20.20	20.40	0.00	99.00	0.12	0.42
<b>Profile 08 – Typic Psammenturbel/Turbic Cryosol</b>															
A	0–10	8.6	117.4	456.0	515.3	6.14	4.52	0.30	14.07	14.07	14.37	0.00	97.90	0.20	0.31
AC	10–40	7.8	141.0	625.0	415.4	6.06	6.54	1.00	16.01	16.01	17.01	0.00	94.10	0.17	0.38
Cjff	40–90	6.3	111.1	496.0	375.4	4.67	4.80	0.30	12.37	12.37	12.67	0.00	97.60	0.16	0.49
<b>Profile 09 – Lithic Aquiturbel/Turbic Cryosol</b>															
A	0–10	7.5	32.1	427.0	189.4	5.10	3.18	0.80	10.20	10.20	11.00	0.00	92.70	0.16	0.24
Bi	10–22	6.7	32.4	496.0	225.6	6.69	4.39	0.80	13.33	13.33	14.13	0.00	94.30	0.11	0.26
Cgjff	22–40	7.8	34.3	427.0	225.6	5.34	3.37	0.50	10.79	10.79	11.29	0.00	95.60	0.16	0.29

P, Na e K (Mehlich-1 extractor); Ca, Mg, Al (KCl 1 mol L<sup>-1</sup> extractor); H+Al (Ca(CH<sub>3</sub>COO<sub>2</sub>) 0.5 mol L<sup>-1</sup> extractor at pH 7.0); BS: bases sum; CEC<sub>e</sub>: effective cation exchange capacity; CEC<sub>p</sub>: potential cation exchange capacity; Alsat: Al saturation; PSB: percentage of bases sum; TOC: total organic carbon; EC: electrical conductivity.

The electrical conductivity values (EC) ranged from 0.23 to 2.56 dS/m (Table 3). These values are higher than those reported by Navas et al. (2008) in soils of Livingston Island,

maritime Antarctic, which were lower than 0.15 dS/m. In contrast, soils in the polar desert of Ellsworth Mountains had EC up 14.5 dS/m (Delpupo et al., 2017). The semi-arid transitional climate of James Ross Island is reflected in the intermediate EC values.

However, most soils were classified in salt stage 0 due to the EC values <0.6 dS/m. Only P01 and P02 had higher values and classified in salt stage 1 (EC 0.6–5.0 dS/m) (Table 3), according to the criteria proposed by Bockheim (1990).

Soil pH values varied from neutral to alkaline and the highest pH value (9.2) was observed in P01 (Table 3). Only P04, developed on sedimentary rocks with a smaller influence of volcanic materials, had an acid pH value (5.3) at a depth of 20 cm (Table 3). Marine aerosols, the absence of vegetation, and limited number of birds, together with low temperatures and precipitation, influenced the alkaline pH of most semi-arid soils from James Ross Island.

In contrast to the neighbouring Seymour Island, where ornithogenic soils and soils developed on marine sediments containing sulfides have pH values below 4.0 (Delpupo et al., 2014), James Ross soils are normally alkaline. Consequently, soils on Seymour Island are more weathered than the soils from James Ross Island, demonstrating that chemical weathering by sulphurization and ornithogenesis are key factors for greater development of soil in a semi-arid climate.

The absence of  $\text{Al}^{3+}$  (Table 3) is a consequence of high pH, since this element is not exchangeable under alkaline conditions. The contents of H + Al are also low, not exceeding 1.30 cmol<sub>c</sub>/kg (Table 3), a result of both high pH and low organic matter and vegetation growth.

The potential cation exchange capacity ( $CEC_p$ ) is high, exceeding 10  $cmol_c/kg$  in most profiles; similar values are also observed for effective cation exchange capacity ( $CEC_e$ ) (Table 3). The high values of CEC observed in all soils are related to the 2:1 clay minerals in soils with weak weathering. pH-dependent charges associated with organic matter are not expected because organic matter amounts are negligible, accounting for the small difference between  $CEC_p$  and  $CEC_e$ .

The TOC contents are very low (<0.2%) (Table 3). The drier and colder climate of James Ross Island does not favor the bird habitat or the development of plant communities, as found in the ice-free areas of the maritime Antarctic (Myrcha and Tatur, 1991; Michel et al., 2006; Simas et al., 2007, Daher et al., 2019). Vegetation cover is limited to rare lichens and mosses along the topolithosequence, resulting in very low TOC contents in most soils (Table 3), that can be considered ahumic, typical of the cold desert zone (Tedrow and Ugolini, 1966). Even in older moss fields, little organic matter accumulation was observed.

### *3.1.3. Soil mineralogy*

The concentrations of Al and Fe extracted with pyrophosphate ( $Al_p$  and  $Fe_p$ ) were lower than 0.05% in all profiles (Table 4), as expected for an environment where the organic matter contents are negligible. In the maritime Antarctic,  $Fe_p$  concentrations varied from 0.9% in soil with a higher TOC content to null in soils with low TOC content (Simas et al., 2007).

Table 4. Fe and Al values extracted with dithionite-citrate-bicarbonate, ammonium oxalate, and sodium pyrophosphate of the sampled soil profiles.

Horizon	Depth cm	Fe <sub>a</sub>	Al <sub>d</sub>	Fe <sub>o</sub>	Al <sub>o</sub>	Fe <sub>p</sub>	Al <sub>p</sub>
%							
<b>Profile 01 – Psammentic Aquiturbel/Turbic Cryosol</b>							
A	0–10	0.80	0.05	0.80	0.24	0.02	0.01
AB	10–22	0.76	0.06	1.16	0.33	0.02	0.01
Bi	22–40	0.59	0.06	1.13	0.30	0.01	0.01
Cgij	40–85	0.60	0.06	1.43	0.37	0.01	0.01
Cgf	85–100	0.56	0.06	1.54	0.41	0.02	0.01
<b>Profile 02 – Psammentic Aquiturbel/Turbic Cryosol</b>							
A	0–8	0.73	0.06	0.48	0.17	0.02	0.00
AB	8–20	0.59	0.06	0.50	0.18	0.02	0.00
Bi	20–45	0.60	0.06	0.51	0.18	0.02	0.00
Cgij	45–80	0.54	0.05	0.87	0.27	0.02	0.00
Cgjff	90–100	0.39	0.04	0.84	0.37	0.02	0.01
<b>Profile 03 – Typic Psammoturbel/Turbic Cryosol</b>							
A	0–10	0.83	0.06	1.07	0.23	0.02	0.01
AB	10–30	0.69	0.06	0.69	0.22	0.02	0.01
Bi	30–60	0.56	0.05	0.76	0.21	0.02	0.01
Cjff	60–100	0.49	0.05	0.87	0.25	0.01	0.01
<b>Profile 04 – Typic Psammoturbel/Turbic Cryosol</b>							
A	0–20	0.71	0.04	0.23	0.08	0.07	0.03
C1	20–55	0.76	0.04	0.23	0.08	0.05	0.05
Cjff	55–80	0.77	0.04	0.59	0.14	0.05	0.04
<b>Profile 05 – Typic Psammorthels/Turbic Cryosol</b>							
A	0–8	0.80	0.07	1.00	0.30	0.02	0.01
Bi	8–35	0.87	0.08	0.82	0.27	0.02	0.01
C1	35–45	0.80	0.09	1.04	0.28	0.02	0.01
Cjff	45–55	0.69	0.07	0.91	0.30	0.01	0.01
<b>Profile 06 – Psammentic Aquiturbel/Turbic Cryosol</b>							
A	0–10	0.65	0.05	1.17	0.33	0.02	0.01
Bi	10–50	0.65	0.06	0.72	0.23	0.01	n.d.
Cjj	50–80	0.51	0.05	0.74	0.26	0.01	n.d.
Cgjff	80–100	0.37	0.05	1.49	0.46	0.02	n.d.
<b>Profile 07 – Typic Psammoturbel/Turbic Cryosol</b>							
A	0–5	0.49	0.04	0.59	0.21	0.02	0.01
AC	5–20	0.77	0.05	0.70	0.32	0.01	0.00
C1	20–40	0.67	0.04	0.45	0.27	0.01	0.00
Cjff	40–80	0.69	0.04	0.58	0.33	0.01	0.00
<b>Profile 08 – Typic Psammoturbel/Turbic Cryosol</b>							
A	0–10	0.68	0.05	0.41	0.28	0.01	0.01
AC	10–40	0.89	0.06	0.47	0.32	0.01	0.01
Cjff	40–90	1.00	0.07	0.32	0.24	0.01	0.01
<b>Profile 09 – Lithic Aquiturbel/Turbic Cryosol</b>							
A	0–10	1.14	0.13	0.91	0.58	0.02	0.03
Bi	10–22	1.13	0.11	0.91	0.59	0.01	0.02
Cgjff	22–40	0.90	0.08	0.78	0.45	0.01	0.02

n.d. below detection limit

The concentrations of free-Fe extracted with dithionite-citrate-bicarbonate (Fe<sub>d</sub>) varied from 0.39 to 1.14% (Table 4). The concentrations of Al<sub>d</sub> were low and did not exceed 0.13% (Table



4). The concentrations of Fe extracted with ammonium oxalate ( $Fe_o$ ) were higher than those extracted with  $Fe_d$  in most profiles, highlighting the low weathering degree of these semi-arid soils.

The free crystalline iron values ( $Fe_d$  minus  $Fe_o$ ) can be used to indicate the relative soil age because the amount of free Fe increases with increasing soil age at the expense of the amorphous forms (Walker, 1983). In cold desert soils,  $Fe_d$  values of 0.07–0.14% were detected in less weathered soils (weathering stage 1) and values of 2.8–3.5% in more weathered soils (weathering stage 6) (Campbell and Claridge, 1975).

However, in most profiles of this topolithosequence, the amount of  $Fe_o$  (supposedly amorphous Fe) exceeds  $Fe_d$  (crystalline Fe) (Table 4). The abnormally high  $Fe_o$  values is not entirely associated with low crystallinity Fe-oxides, but attributed to the presence of magnetite, detected by high magnetic properties of the basalt soils. Since magnetite influences the amount of iron extracted by oxalate and dithionite treatments (Baril and Bitton, 1969; McKeague et al., 1971; Walker, 1983), we cannot take quantification of free Fe causes errors in the estimation.

The occurrence of magnetite is expected since it is a common primary mineral in volcanic rocks, especially basalts (Simas et al., 2006). Moreover, the soils presented magnetization, attested both in the field through the hand magnet, and in the laboratory through the low frequency magnetic susceptibility ( $X_{lf}$ ) where the highest values were found in the fine-earth (<2 mm) and sand fractions (Fig. 4). P04, which was formed from sedimentary rocks, showed low  $X_{lf}$  values in all soil fractions, not exceeding  $25 \times 10^{-8} \text{ m}^3 \text{ kg}^{-1}$  in the fine-earth fraction (<2 mm), suggesting a low degree of contamination by volcanic material. In P07,  $X_{lf}$  in the

fine-earth fraction (<2 mm) was  $110 \times 10^{-8} \text{ m}^3 \text{ kg}^{-1}$ , showing a greater influence of volcanic material. In P09, which was directly formed on basalt, values were higher, reaching  $430 \times 10^{-8} \text{ m}^3 \text{ kg}^{-1}$  in the fine-earth fraction (<2 mm) (Fig. 4).

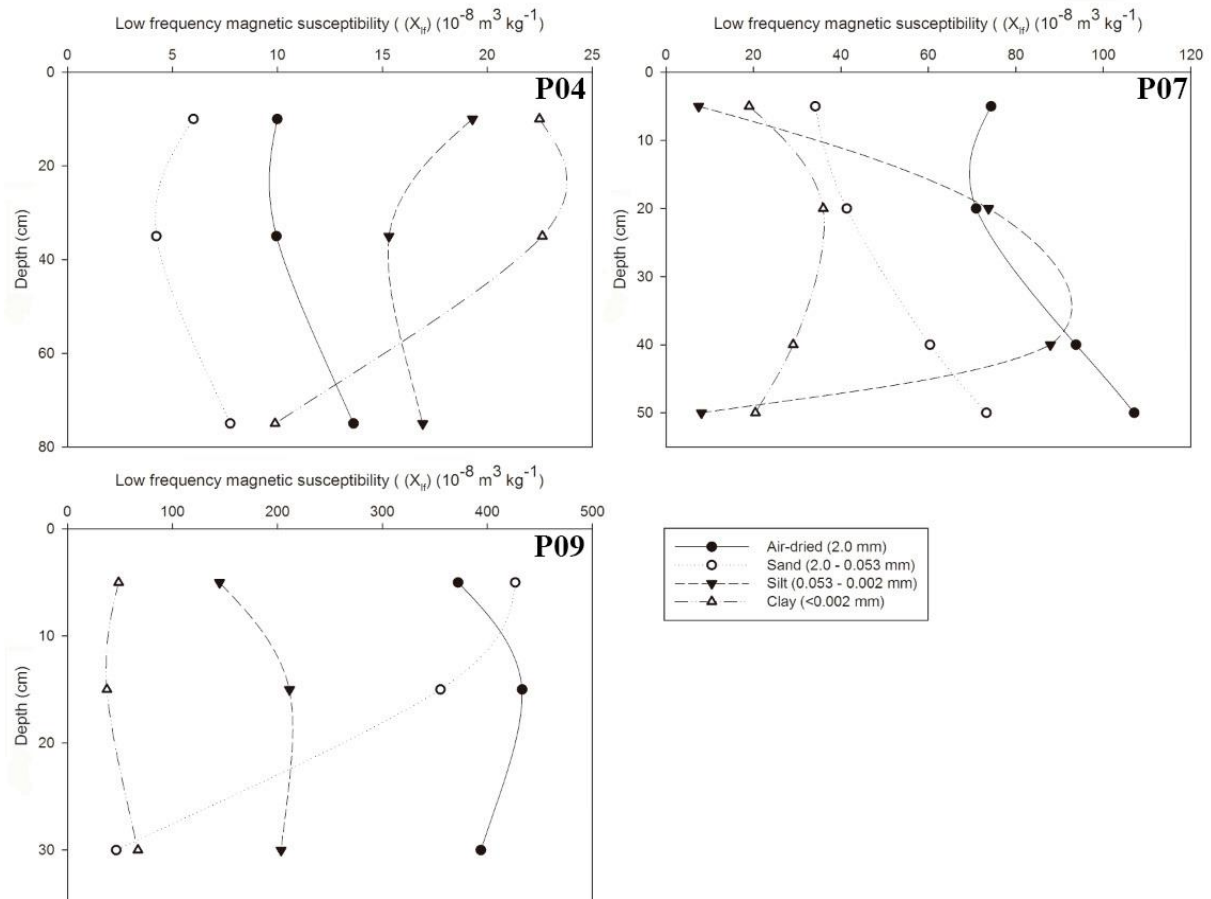


Fig. 4. Distribution of the low frequency magnetic susceptibility ( $X_{lf}$ ) in the air-dried fine earth fraction, sand, silt, and clay in P04 and P07 (sedimentary rocks) and P09 (volcanic rocks).

The vertical distribution of  $X_{lf}$  within the profiles showed that there were no abrupt changes in values with depth (Fig. 4). This is typical of young soils because  $X_{lf}$  increases with soil age. Thus, more weathered horizons (B) tend to have higher values of  $X_{lf}$  (Fine et al., 1989; Singer et al., 1996). The  $X_{lf}$  values of the soils of the topolithosequence are much lower than those calculated by Costa et al. (1999) in deep weathered Oxisols/Ferralsols derived from basalts in Brazil, that reached  $91,000 \times 10^{-8} \text{ m}^3 \text{ kg}^{-1}$ .

X-ray diffraction (XRD) patterns of the representative profile of sedimentary rock (P04) in the sand fraction indicated the presence of quartz and feldspar (Fig. 5). The silt fraction is composed by a similar mineral assemblage, vermiculite, mica, and kaolinite (Fig. 5). The clay fraction presented the same XRD pattern of the silt, marked of the most intense with vermiculite and kaolinite peaks and the expected transformation of mica into illite (Fig. 5).

In the XRD pattern of clay (P04), the illite peaks remained unchanged after all the treatments for identifying the 2:1 clay mineral (Fig. 6). According to Fanning (1989), these peaks disappear only at temperatures above 800 °C. The presence of vermiculite in P04 was confirmed by the chemical treatment, where the peak of 1.30 nm in natural clay expanded to 1.46, and intensified when saturated with  $Mg^{2+}$  and solvated with glycerol. After saturation with  $K^+$  at room temperature, the peak dropped to 1.30 nm; when heated to 350 °C and 550 °C, it collapsed to 1.00 nm (Fig. 6). The peaks of 0.70 and 0.35 nm could be confirmed as kaolinite because they only dropped with  $K^+$  saturation at 550 °C (Fig. 6). The XRD pattern of soil on sedimentary rock (P07), with greater volcanic influence (Fig. 7), was similar to that of P04. The only difference was that after the concentration of iron oxides, the magnetite peak appeared in P07 (Fig. 8).

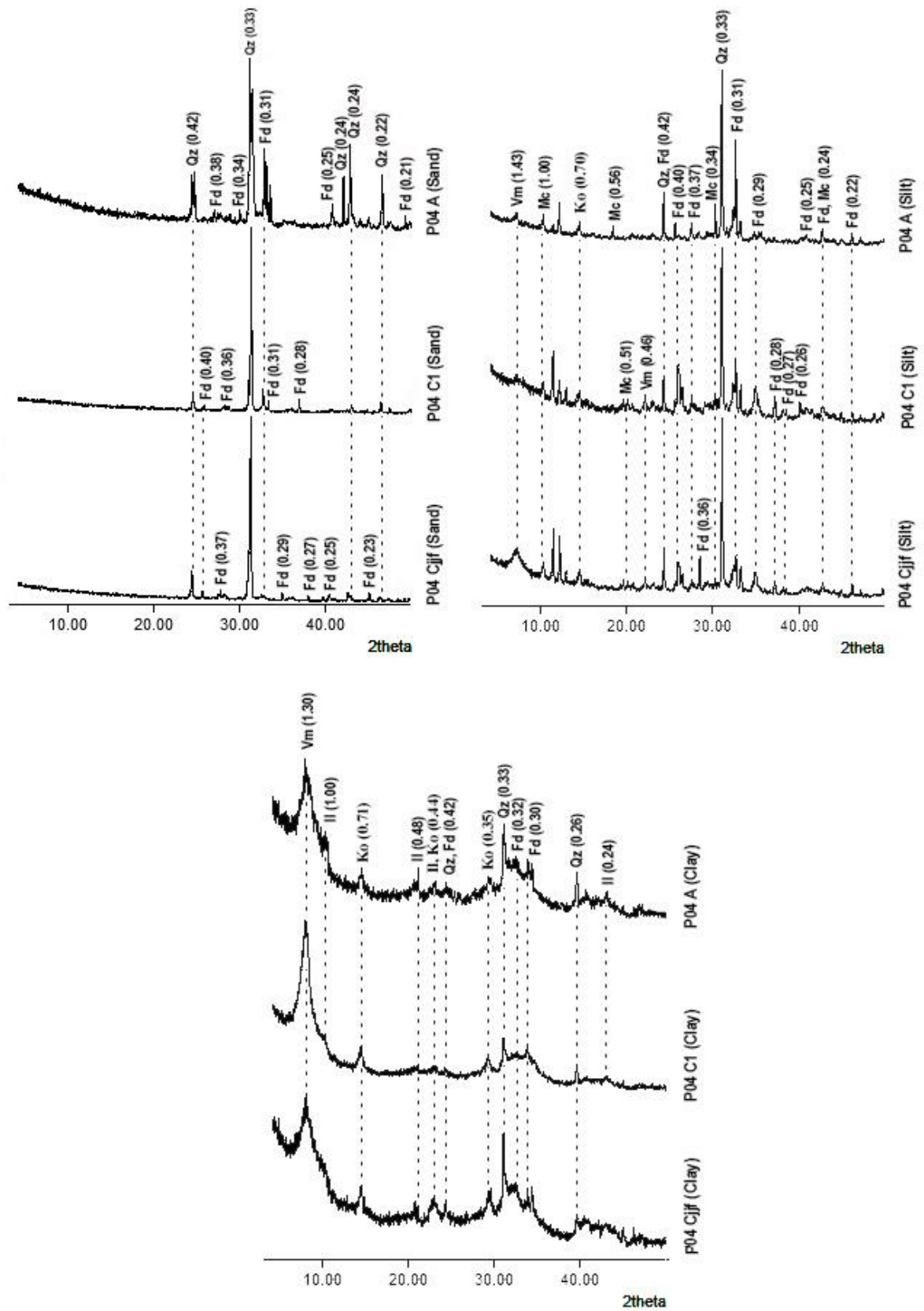


Fig. 5. XRD patterns of soil (P04) developed on sedimentary rock of the topolithosequence on James Ross Island. (Sand, silt, and clay fractions). Ko: Kaolinite, Fd: Feldspar, Il: Illite, Mc: Mica, Qz: Quartz, Vm: Vermiculite. "d" in nm.

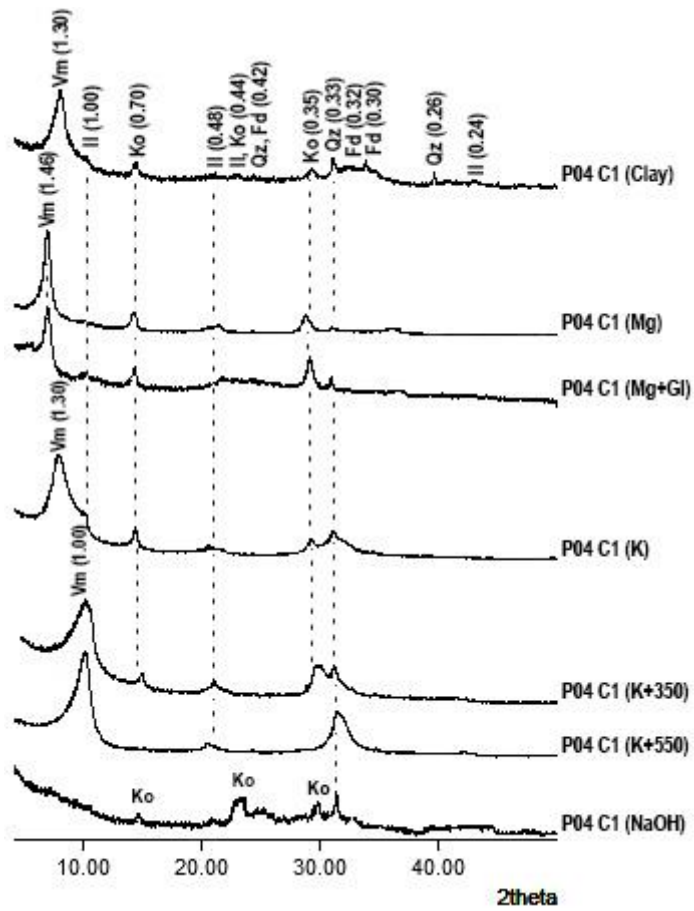


Fig. 6. XRD patterns of soil (P04, C1 horizon) developed on sedimentary rock of the topolithosequence located on James Ross Island. (Clay fraction). Vm: Vermiculite, Il: Illite, Ko: Kaolinite, Qz: Quartz, Fd: Feldspar. "d" in nm.

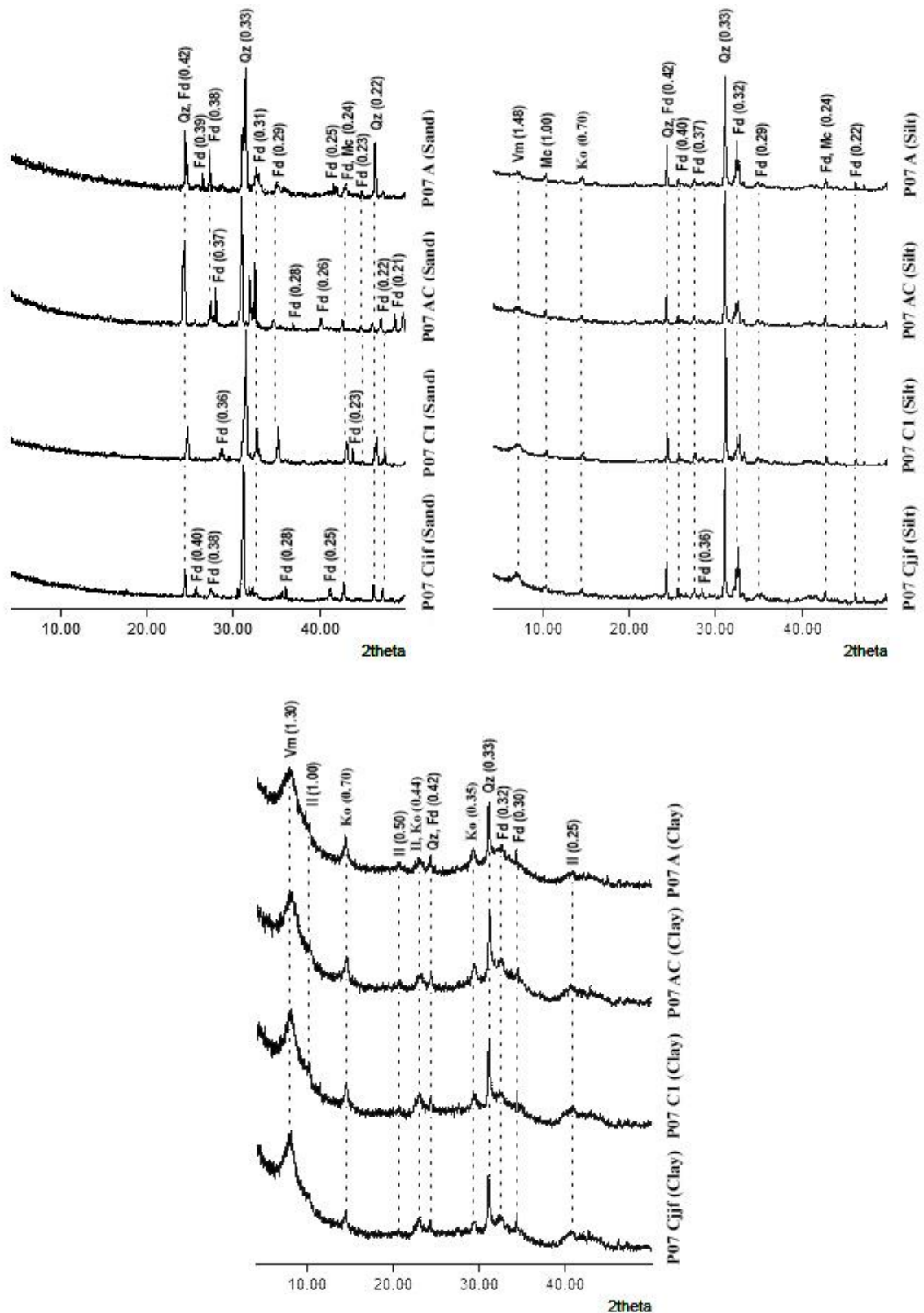


Fig. 7. XRD patterns of soil (P07) developed on sedimentary rock of the topolithosequence on James Ross Island. (Sand, silt, and clay fractions). Ko: Kaolinite, Fd: Feldspar, Il: Illite, Mc: Mica, Qz: Quartz, Vm: Vermiculite. "d" in nm.

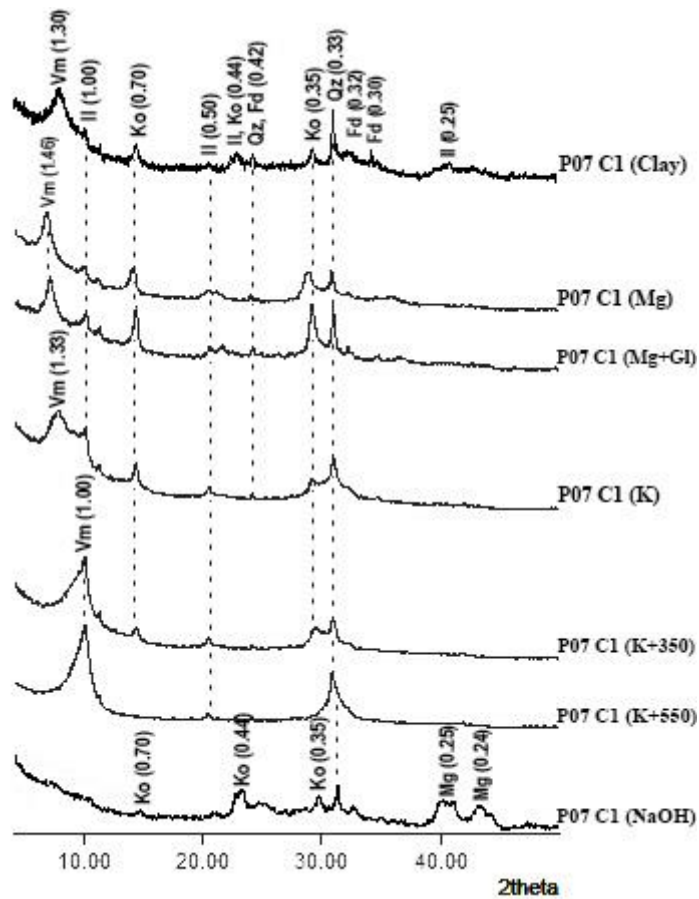


Fig. 8. XRD patterns of soil (P07, C1 horizon) developed on sedimentary rock of the topolithosequence on James Ross Island. (Clay fractions). Vm: Vermiculite, Il: Illite, Ko: Kaolinite, Qz: Quartz, Fd: Feldspar, Mg: Magnetite. "d" in nm.

The XRD patterns of the sand and silt fractions of the soil on basalt (P09) (Fig. 9) did not differ from those of soils on sedimentary rock (P04 and P07). However, in the clay fraction of P09, the vermiculite peaks were discrete after clay treatments and kaolinite was not detected (Fig. 10). As in the XRD of P07, the magnetite peak appeared after the Fe concentration by NaOH (Fig. 10).

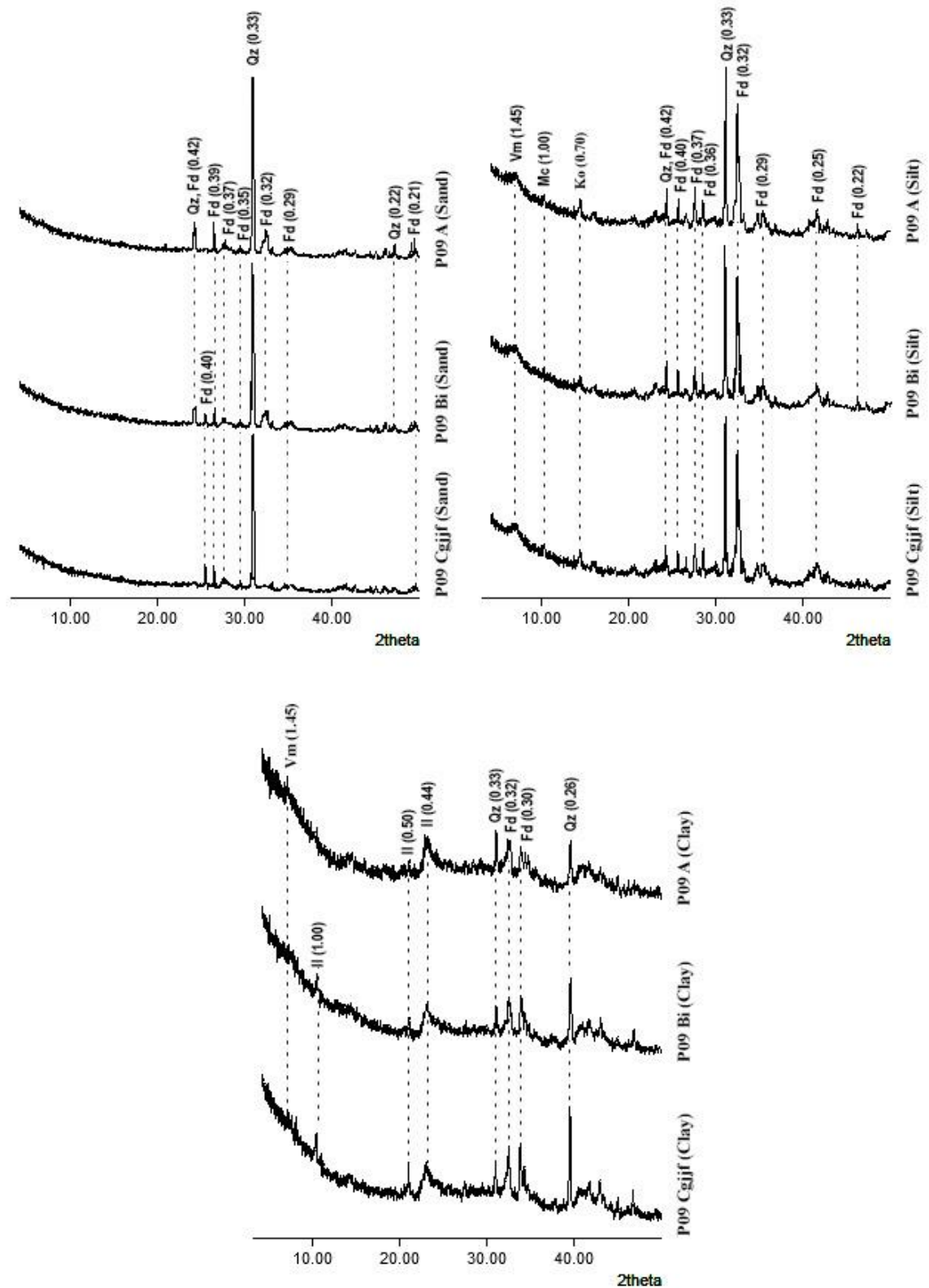


Fig. 9. XRD patterns of soil (P09) developed on volcanic rock of the topolithosequence on James Ross Island. (Sand, silt and clay fractions). Ko: Kaolinite, Fd: Feldspar, Il: Illite, Mc: Mica, Qz: Quartz, Vm: Vermiculite. "d" in nm.



The higher vermiculite peak in the profiles developed on sedimentary rocks indicates that this mineral may be inherited from the sediment, highlighting its stability in the sedimentary environment, corroborating the pre-weathered nature of these soils.

The presence of magnetite in both P07 (Fig. 8) and P09 (Fig. 10) was attributed to the influence of volcanic material. P07, although geologically located on sedimentary rocks, is at the foot slopes of the basalt plateau, and has a great deal of volcanic materials coming from erosion of uplands. Owing to the low amount of magnetite in the clay fraction, as observed in the values of  $X_{If}$  (Fig. 4), the peaks only appeared after iron oxides concentration.

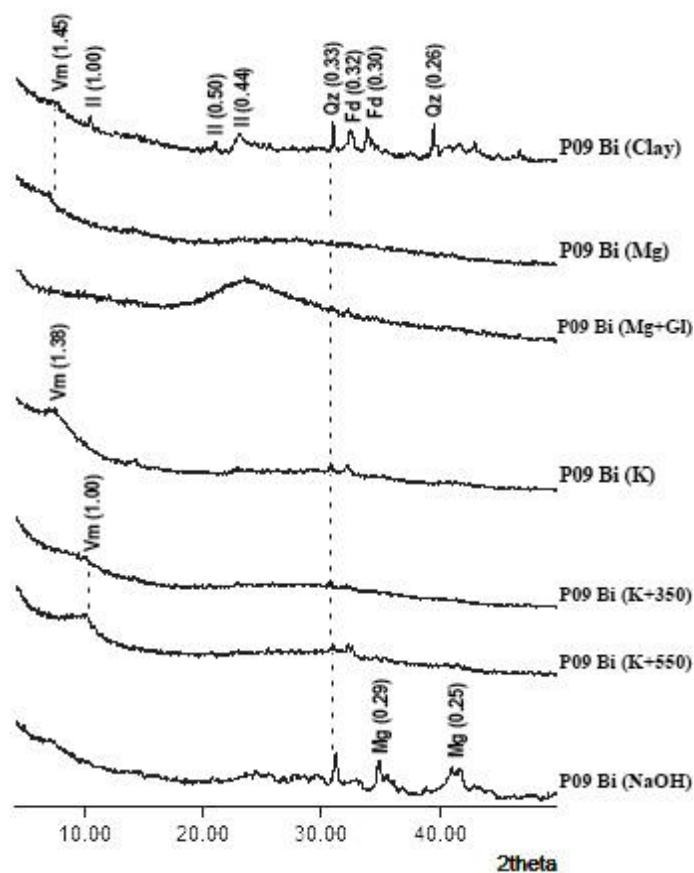


Fig. 10. XRD patterns of the soil (P09, Bi horizon) developed on volcanic rock of the topolithosequence on James Ross Island. (Clay fractions). Vm: Vermiculite, Il: Illite, Qz: Quartz, Fd: Feldspar, Mg: Magnetite. "d" in nm.

The differentiation of magnetite and maghemite in XRD is difficult because these minerals have a similar crystalline structure with very close peaks (Fontes et al., 2000). However, considering the generalized presence of primary minerals in the clay fraction in Antarctic soils, the peaks identified after the NaOH treatment were solely assigned to magnetite (Fig. 8, Fig. 10). In P04 and P07, the dissolution in the NaOH removed the vermiculite and illite peaks, but the kaolinite peaks remained (Fig. 6, Fig. 8). Maghemite is unlikely, since dithionite treatments indicated very little amounts of free-Fe oxides.

The presence of primary minerals such as quartz, illite, feldspar, and magnetite in the clay fraction proves the intense physical weathering, in contrast to the incipient chemical weathering. Therefore, semi-arid Antarctic soils reflect the mineral composition of the parent material, as has been previously reported in studies in the maritime Antarctica (Simas et al., 2006; Moura et al., 2008), Antarctic Peninsula (Pereira et al., 2013; Delpupo et al., 2014), and the dry valleys between the Transantarctic Mountains (Claridge, 1965; Vennum and Nejedly, 1990).

Vermiculite is formed by weathering of micas (Claridge, 1965; Bockheim, 1980). Kaolinite may be either inherited, or have originated from wetter climates in the past, as described by Simas et al. (2008) and Mendonça et al. (2013) in basaltic soils under ornothogenic influence at King George Island (maritime Antarctic), and Pereira et al. (2013) on sedimentary rocks without the ornothogenic influence in Hope Bay (Antarctic Peninsula). Kaolinite was also recorded in the Transantarctic Mountains (continental Antarctic) by Parker et al. (1982) and Vennum and Nejedly (1990).

#### **4. Conclusions**

1. The semi-arid soils from James Ross Island have transitional features between typical maritime Antarctic soils (cryoturbation and redoximorphism), and continental Antarctic (desert pavement and ahumic character).

2. The very dark basaltic parent material influences surface heating and thawing of the snow on basalt outcrops and debris slopes. Hence, availability of liquid water and cryoturbation processes are dominant, although it possesses a colder and drier climate compared with maritime Antarctica.

3. The weathering degree of soils was not directly associated with the highest topographic positions at the topolithosequence, since soil properties were more sensitive to parent material variations than to the topographic changes across the landscape.

4. The soils of James Ross Island are more alkaline, with negligible organic matter accumulation and incipient chemical weathering compared to nearby ornithogenic soils of Hope Bay, and sulfate affected soils and ornithogenic soils from adjacent Seymour Island, both semi-arid. This highlights the importance of sulfurization and phosphatization (ornithogenesis) for allowing greater pedogenetic evolution in semi-arid soils in this transitional Antarctic environment.

5. The mineralogy of the profiles was not significantly different between substrates. The presence of kaolinite is assigned to past warmer and wetter paleoclimatic conditions than those present on James Ross Island.

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## ARTIGO 2

### **Geochemistry characterization of soils developed on volcanic and sedimentary parent materials from James Ross Island, Antarctic**

#### **Abstract**

In most parts of Antarctica, specifically in arid and semi-arid condition, soils are the results of weak weathering and pedogenic processes. Thus, the use of geochemical data is considered an important tool to interpret pedological processes that occurs through the changing molecular ratios of elements with depth. The pedological studies are few in Antarctica. In this study, geochemistry characterization of soils developed on different parent material in the semi-arid climate was investigated. The quantification of the elements in soils allows using various methods of pedological investigation. Based on the major and trace oxides geochemistry, the soil types are well differentiated showing that geochemical composition of soils is highly affected by their parent materials. Therefore, based on the major oxides abundances, chemical weathering seems insignificant. When crossing the parameters to identify lithologic discontinuity, five profiles had this characteristic. However, this conclusion must be made cautiously, since often has a bit of subjectivity to it. According to the high chemical index of alteration and mineralogical composition which have kaolinite in the clay fraction, soils developed on the sedimentary rock showed a pre-weathered nature.

Keywords: Pedogenesis; Weathering; Geochemical indices; Cryosols

## **1. Introduction**

Antarctica has continuous sub-zero temperatures and most of the continent is permanently ice-covered throughout the year. Ice-free areas represent less than 5% of the continent and are of direct concern to soil studies (Tedrow and Ugolini, 1966), with unique conditions for soil formation (Campbell and Claridge, 1987).

In most parts of Antarctica, soil formation is extremely slow due to the dry climate and lack of moisture (Ugolini and Anderson, 1973). Specifically in arid and semi-arid condition, soils are the results of weak weathering and pedogenic processes (Bockheim, 1997). Consequently, soils geochemistry is very much related to the nature of parent materials (Schaetzl and Anderson, 2005a).

The use of geochemical data is considered an important tool to interpret pedological processes through the analysis of changing molecular ratios of elements with depth (Buggle et al., 2011; Barshad, 1964; Ruxton, 1968). The elemental mobility ratio is based on ionic potential (ionic charge/radius). Soluble cations with high mobility (Ca, Mg, K, Na) are elements with low ionic potential, while cations with low mobility (Al, Th, Zr, Ti) are elements with intermediate ionic potential and more resistant to weathering (Buggle et al., 2011).

From the selection of mobile and immobile elements in soils, various geochemical indices can be used, being possible to identify parent material uniformity and degree of weathering. The parent material uniformity provides the reconstruction of ancient geologic depositional histories (Chapman and Horn, 1968) while soil development (Haseman and Marshall, 1945) and the degree of weathering allow to determine weathering status of soils (Price and Velbel,

2003) and can be a valuable indicator of the (past) climatic characteristics (Buggle et al., 2011).

The geochemical composition of soils have been studied in Antarctica, highlighting some works on environmental monitoring (Guerra et al., 2011; Lima Neto et al., 2017), distribution and sources of rare earth elements (Nie et al., 2014; Santos et al., 2007), dynamics of penguin colonies (Zhu et al., 2005), and geochemistry as an important controlling factor for soil carbon storage (Doetterl et al., 2015). Application of geochemistry studies to understand soil fotation are less common (Lee et al., 2004; Navas et al., 2008).

James Ross Island, composed of volcanic and sedimentary rocks, provides an opportunity for studying geochemistry characterization of soils developed on different parent material in a cold semi-arid climate. In the present work we focused on how the different geologies impact soil geochemical data and on the use of geochemical indices to study parent material uniformity and soils weathering degrees.

## **2. Material and methods**

### **2.1. Study area and soil sampling**

James Ross Island is located on the northeastern coast of the Antarctic Peninsula and covers an area of 2500 km<sup>2</sup> (Fig. 1a). The northern sector of the island, the Ulu Peninsula, represents the largest continuous deglaciated area in the whole region (Fig. 1b), representing 1.2% of the total ice-free area in Antarctica (Kavan et al., 2017). According to the zonal division of the Southern Circumpolar Region (Bockheim and Ugolini, 1990), the island is included in the

polar desert zone. The mean annual air temperature at the Czech station, Johann Gregor Mendel, was  $-7.0\text{ }^{\circ}\text{C}$  during the period of 2006–2015 (Hrbáček et al., 2016). Mean daily temperatures above  $5\text{ }^{\circ}\text{C}$  and below  $-30\text{ }^{\circ}\text{C}$  are observed in the summer and winter seasons, respectively (Láska et al., 2011). The mean annual precipitation ranges from 300 to 500 mm (van Lipzig et al., 2004).

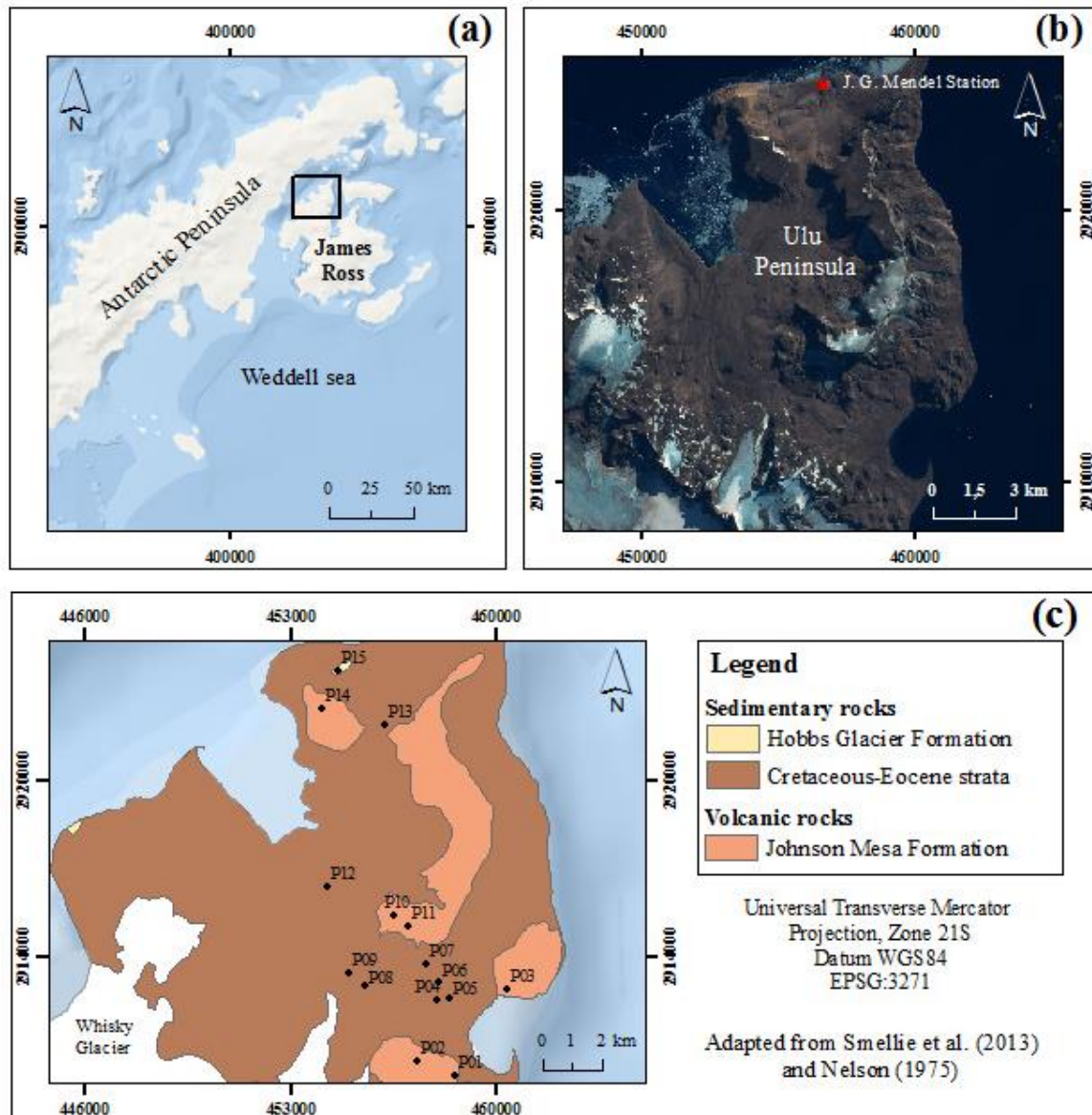


Fig. 1. Location map of James Ross Island (a), the location of the Ulu Peninsula (b), and position of the sampling sites on different parent material (c).

Soil sampling followed the recommendations established by the Antarctic Permafrost,



Periglacial Environments and Soils expert group (ANTPAS) (Bockheim et al., 2006). Fifteen soil profiles were described along the Ulu peninsula, nine on sedimentary material (Cretaceous-Eocene strata and Hobbs Glacier Formation) and six on volcanic material (Johnson Mesa Formation) (Fig. 1c, Table 1).

Table 1. Geology of soil profiles sampled.

Samples <sup>1</sup>	Profile	Parent material	Formation	Period
1-5	P01	Volcanic	Johnson Mesa	Neogene
6-7	P02			
8-10	P03			
34-36	P10			
37-39	P11			
47-50	P14			
11-13	P04	Sedimentary	Cretaceous-Eocene strata	Cretaceous
14-17	P05			
18-21	P06			
22-25	P07			
26-29	P08			
30-33	P09			
40-43	P12			
44-46	P13			
51-54	P15			

<sup>1</sup>Samples represent the horizons of each profile.

The Cretaceous-Eocene strata is highly fossiliferous, with the presence of fossilized plants, vertebrates, invertebrates. This group is composed of a variety of medium to fine-grained sandstones, siltstones, silty mudstones, and coquinas dating from the Cretaceous-Eocene (~75 Ma) (Francis et al., 2006). The Hobbs Glacier Formation is originated from glacial depositions, being constituted by erratics of different rocks (plutonic, metamorphic, volcanic or even reworked from the underlying sedimentary lithologies), dating from the Neogene-Quaternary (Nelson, 1975). The Johnson Mesa Formation consists mainly of olivine-basalt lavas, typical of shallow marine volcanic eruptions, as well as tuff/palagonite breccia, all

dated to the late Miocene (~6 Ma) (Nelson, 1975; Smellie et al., 2008).

## 2.2. Soil geochemical analysis

Soil samples were air-dried, sieved to 2 mm and submitted to geochemical analysis. The total contents of major (Si, Al, Fe, Ca, K, Mg, Na) and trace elements (Ti, S, Co, Mn, Ni, Sc, V, P, Cr, Cu, Sr, Zn, Zr, Cl) were determined by micro energy-dispersive X-ray fluorescence spectrometer  $\mu$ -XRF ( $\mu$ -XRF-1300 Shimadzu). The powdered samples (200 mesh) were pressed into pellets at 4 t for 60 s. The Certified Reference Material - Montana II Soil (NIST SRM 2711a) was used for calibration of the sensitivity coefficients of the equipment for each element. The elements were expressed as oxides, and the results were reported as the average of 1200 repetitions.

## 2.3. Geochemical indices

The analysis of vertical changes of stable soil constituents such as Ti and Zr have long been used to study soil uniformity in relation to parent materials (Anda et al., 2009; Brewer, 1965; Smeck and Wilding, 1980). Both Ti and Zr are considered weathering-resistant when present in stable and insoluble mineral phases such as tourmaline and zircon, respectively (Ahr et al., 2017).

Uniformity is identified when stable constituents show little or no variation with depth within the soil profile (Brewer, 1965). It is recommended a difference greater than 100% in the  $\text{TiO}_2/\text{ZrO}_2$  ratio between adjacent horizons to indicate discontinuities within the soil profile (Chapman and Horn, 1968).

However, to be more efficient, the evaluation of lithological discontinuity should consider two or more criteria (Schaetzl and Anderson, 2005b). Therefore, we also used soil particle-size analysis to calculate the uniformity value (UV) index to distinguish discontinuities. Soil particle-size analysis was determined by using the slow mechanical dispersion in the fine-earth fraction (<2 mm) in pH 10 distilled water, sieving, and weighing of coarse (CS) and fine sand (FS), sedimentation of silt (S) + clay, followed by syphoning of the <0.002 mm fraction (Ruiz, 2005).

The clay-free basis was calculated to remove the effects of the more mobile clay fraction (Schaetzl and Anderson, 2005a). The CS (Eq. (1)), FS (Eq. (2)), and S (Eq. (3)) clay-free was calculated as:

$$CS_{\text{clay-free}} = \frac{\%CS}{\%CS + \%FS + \%S} \times 100 \quad (1)$$

$$FS_{\text{clay-free}} = \frac{\%FS}{\%CS + \%FS + \%S} \times 100 \quad (2)$$

$$Silt_{\text{clay-free}} = \frac{\%S}{\%CS + \%FS + \%S} \times 100 \quad (3)$$

The UV index (Eq. (4)) compares particle size data with data from the overlying horizon and values >0.60 between adjacent horizons indicate nonuniformity (Cremeens and Mokma, 1986). It is calculated as:

$$UV = \frac{(\%S + \%FS)/(\%S - \%FS) \text{ in upper horizon}}{(\%S + \%FS)/(\%S - \%FS) \text{ in lower horizon}} - 1 \quad (4)$$

The use of ratio between immobile Al and more mobile ions is considered a good measure to express of the degree of weathering (Ruxton, 1968). We used the Chemical Index of Alteration (CIA) (Eq. (5)) that considers Al as a relative immobile element (Nesbitt and Young, 1982).

$$\text{CIA} = \frac{\text{Al}_2\text{O}_3}{\text{Al}_2\text{O}_3 + \text{Na}_2\text{O} + \text{CaO} + \text{K}_2\text{O}} \times 100 \quad (5)$$

Low values (<50) of chemical index of alteration (CIA) are associated with poorly altered soils and with the presence of primary minerals, and values close to 100 refer to more weathered soils, composed of kaolinite and gibbsite (Nesbitt and Young, 1982).

Two representative horizons developed on volcanic and sedimentary rocks were selected for detailed mineralogical characterization. The minerals present in the clay fraction (<0.002 mm) were detected by X-ray diffraction (XRD). A diffractometer (PANalytical/X'Pert Pro) was used, with CoK $\alpha$  radiation in the 4–50° 2 $\theta$  range, at the intervals of 0.017° 2 $\theta$  with 1-s steps, at 40 kV and 30 mA, to detail the 2:1 clays (Whittig and Allardice, 1986), and Fe oxides after concentration (Kämpf and Schwertmann, 1982; Norrish and Taylor, 1961). The following treatments were performed: Mg<sup>2+</sup> saturation and glycerol solvation, K<sup>+</sup> saturation at room temperature, heating in an oven to 350 °C and 550 °C, and NaOH treatment. The diffractograms were interpreted using charts for mineral identification (Chen, 1997).

#### 2.4. Statistical analyses

The descriptive statistical analyses included calculations for mean, coefficient of variation (CV), and maximum and minimum values of the major and trace oxides of soils. For this analysis, we used the fBasics package (Diethelm et al., 2017) in the R program (R core team, 2018). The t-Student test was used to compare the effect of the different parent materials on major and trace oxides of soils. The data were analyzed using the Minitab statistical software (Minitab, Inc. 2010) to assess differences among the means.

The Principal Component Analysis (PCA) was used to better interpretation of the dataset. For this analysis, we used FactoMineR package (Sebastien et al., 2008). Moreover, the aqp (Beaudette et al., 2013), dplyr (Wickham et al., 2018), ggplot2 (Wickham, 2016), and ggrepel (Slowikowski, 2018), libraries were used for plotting the graphs with real values of  $\text{TiO}_2/\text{ZrO}_2$  ratio, CS, FS, and silt clay-free, and UV index. In the ordering diagram, an ellipse of the safety area (coefficient of 0.95) was drawn from the set of samples of each soil group. The probability that the values fall within the area marked by the ellipse is a function of the value of the coefficient that controls the size of the ellipse.

### **3. Results and Discussion**

#### **3.1. Major and trace oxides**

Table 2 summarizes data for major and trace oxides in the investigated soils of the two different parent materials. The mean concentration of the major oxides observed on soils formed by the volcanic and sedimentary rocks were statistically different ( $p \leq 0.05$ ), except for  $\text{Na}_2\text{O}$  (Table 2).

Table 2. Summary statistics of major and trace oxides for the different parent material.

<i>Major oxides %</i>	Soils on sedimentary rock				Soils on volcanic rock			
	<b>Mean</b>	<b>SD</b>	<b>Min</b>	<b>Max</b>	<b>Mean</b>	<b>SD</b>	<b>Min</b>	<b>Max</b>
SiO <sub>2</sub>	50.33 <b>a</b>	10.42	30.57	66.48	44.56 <b>b</b>	4.93	36.90	55.96
Al <sub>2</sub> O <sub>3</sub>	9.48 <b>a</b>	1.00	6.41	10.95	10.67 <b>b</b>	0.69	9.38	11.78
Fe <sub>2</sub> O <sub>3</sub>	5.10 <b>a</b>	1.49	1.17	7.57	7.00 <b>b</b>	0.99	5.28	8.82
CaO	2.54 <b>a</b>	1.28	1.01	5.95	3.32 <b>b</b>	0.61	2.33	4.38
K <sub>2</sub> O	1.77 <b>a</b>	0.52	0.64	2.43	1.38 <b>b</b>	0.25	0.99	1.97
MgO	1.32 <b>a</b>	0.49	0.14	2.12	1.77 <b>b</b>	0.49	0.48	2.58
Na <sub>2</sub> O	1.51 <b>a</b>	0.62	0.00	2.42	1.45 <b>a</b>	0.50	0.53	2.29
<i>Trace oxides %</i>								
TiO <sub>2</sub>	0.73 <b>a</b>	0.14	0.49	1.02	1.09 <b>b</b>	0.14	0.88	1.44
SO <sub>3</sub>	0.30 <b>a</b>	0.44	0.00	1.67	0.04 <b>b</b>	0.01	0.01	0.06
MnO	0.06 <b>a</b>	0.03	0.01	0.14	0.11 <b>b</b>	0.03	0.01	0.15
V <sub>2</sub> O <sub>5</sub>	0.02 <b>a</b>	0.00	0.01	0.02	0.02 <b>a</b>	0.00	0.02	0.03
P <sub>2</sub> O <sub>5</sub>	0.18 <b>a</b>	0.09	0.00	0.46	0.24 <b>b</b>	0.06	0.12	0.35
Cr <sub>2</sub> O <sub>3</sub>	0.02 <b>a</b>	0.01	0.01	0.03	0.03 <b>b</b>	0.01	0.01	0.04
CuO	0.01 <b>a</b>	0.00	0.01	0.01	0.01 <b>a</b>	0.00	0.01	0.01
SrO	0.02 <b>a</b>	0.01	0.01	0.04	0.03 <b>b</b>	0.01	0.03	0.05
ZnO	0.01 <b>a</b>	0.00	0.01	0.01	0.01 <b>a</b>	0.00	0.01	0.01
ZrO <sub>2</sub>	0.04 <b>a</b>	0.02	0.02	0.07	0.03 <b>b</b>	0.01	0.02	0.05
Cl	0.12 <b>a</b>	0.03	0.04	0.16	0.14 <b>b</b>	0.02	0.08	0.19

*Different letters indicate significant differences ( $p \leq 0.05$ ).*

*n=34 samples collected on sedimentary rock.*

*n=20 samples collected on volcanic rock.*

SiO<sub>2</sub> is the major oxide of all soils regardless of parent material, with values varying from 30.57% to 66.48%, with the highest standard deviation (SD) amongst all oxides (Table 2). For the others studied oxides, SD was below 1.5%. In P15, the concentrations of SiO<sub>2</sub> were lower (30%). P15 is located in the Hobbs Formation, and according to a previous study glauconite is present in all of the samples examined in this formation (Pirrie et al., 1997). Glauconite is an indicator of a calm marine environment with low sedimentation rate, common in sandstones. Additionally, it was observed low quartz content in the presence of high levels of glauconite in the Sobral Formation, on the neighboring Seymour Island, also sedimentary (Marensi et al., 2012). Therefore, the lower SiO<sub>2</sub> contents could be associated with the presence of

glauconite in this profile as well as in Sobral Formation.

The oxides concentrations in these soils are influenced by the element abundance of soil-forming volcanic and sedimentary rocks. Soils formed by the volcanic rocks showed means concentrations of  $\text{Al}_2\text{O}_3$ ,  $\text{Fe}_2\text{O}_3$ ,  $\text{CaO}$ , and  $\text{MgO}$ , significantly higher, and lower  $\text{SiO}_2$  and  $\text{K}_2\text{O}$  than the soils formed by the sedimentary rocks (Table 2).

The  $\text{Na}_2\text{O}$  contents did not correlate with any other oxide (Fig. 2), indicating little contribution of the parent materials to the input of this oxide in the system. Thus, the presence of  $\text{Na}_2\text{O}$  in the soils of James Ross Island is attributed to external sources, such as atmospheric precipitation as well as marine aerosols.

P15 (samples 51 to 54), developed on sedimentary rock (Figs. 2 and 3) showed the characteristics of soils developed on volcanic rock. This profile was collected on Hobbs Glacier Formation (Fig. 1), which is an area of glacial sediments. The principal facies are diamictite and mudstone, overlain by a variety of volcanic rocks (Francis et al., 2006). So, the sedimentary material is mixed with other materials derived from volcanic rocks. Similarly, according to the geological map of James Ross Island Group (Smellie et al., 2013), soils P1, P2, and P3 (samples 1 to 10) belong to the Andreassen Point Formation, formed by sedimentary rocks. However, geochemical characterization (Figs. 2 and 3), show that these profiles had characteristics of soils developed on volcanic rocks. This fact is in agreement Nelson (1975), which showed the distribution of the Johnson Mesa Formation in these areas.

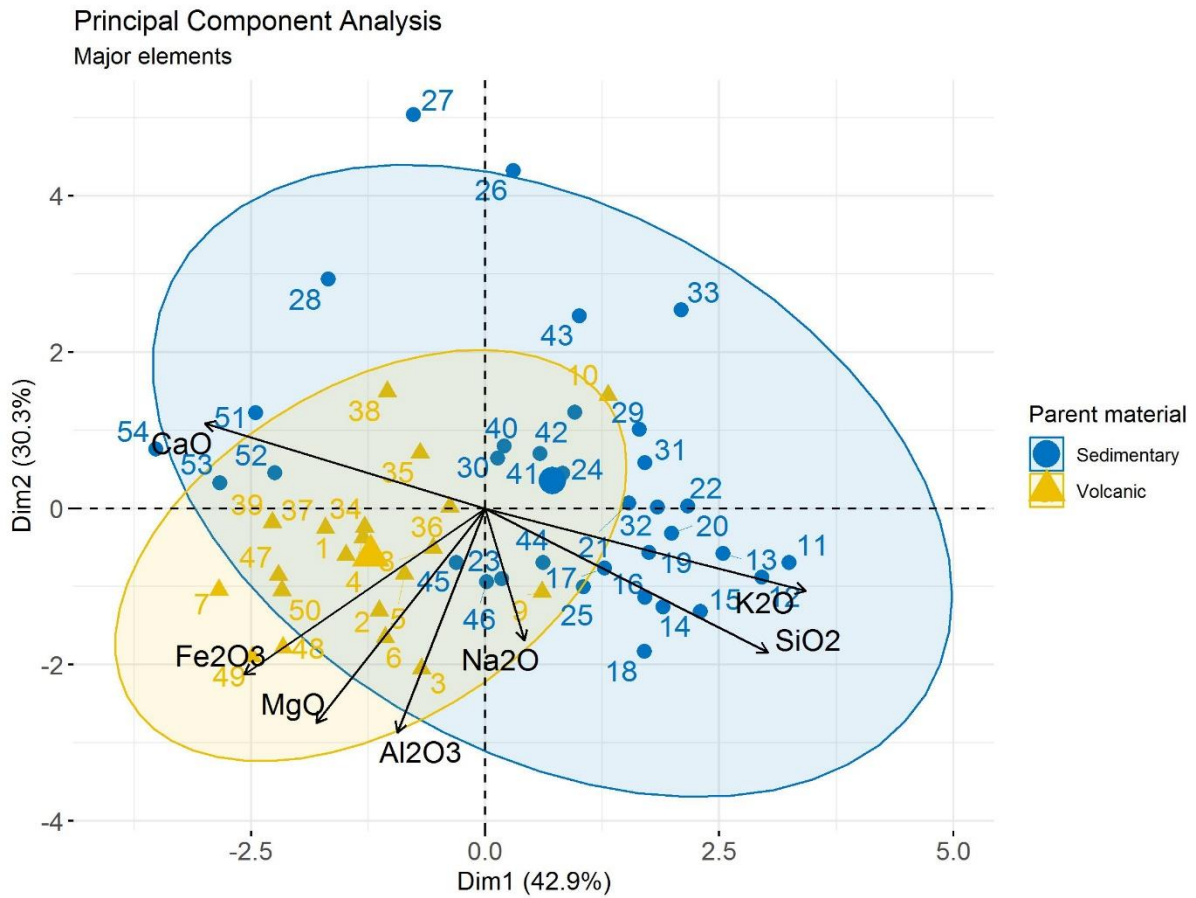


Fig. 2. Principal Component Analysis of major oxides for the different parent material.

The means concentrations of the trace metals observed on soils formed by the volcanic and sedimentary rocks were statistically different ( $p \leq 0.05$ ), except for  $V_2O_5$ ,  $CuO$ , and  $ZnO$  (Table 2). The soils derived from sedimentary rocks had higher levels of  $SO_3$ , and the soils derived from volcanic rock presented higher levels of  $TiO_2$  and  $P_2O_5$  (Table 2). The  $SO_3$  was considered as a separating oxide for the soils derived from sedimentary rock in relation to soils from volcanic materials (Fig. 3).



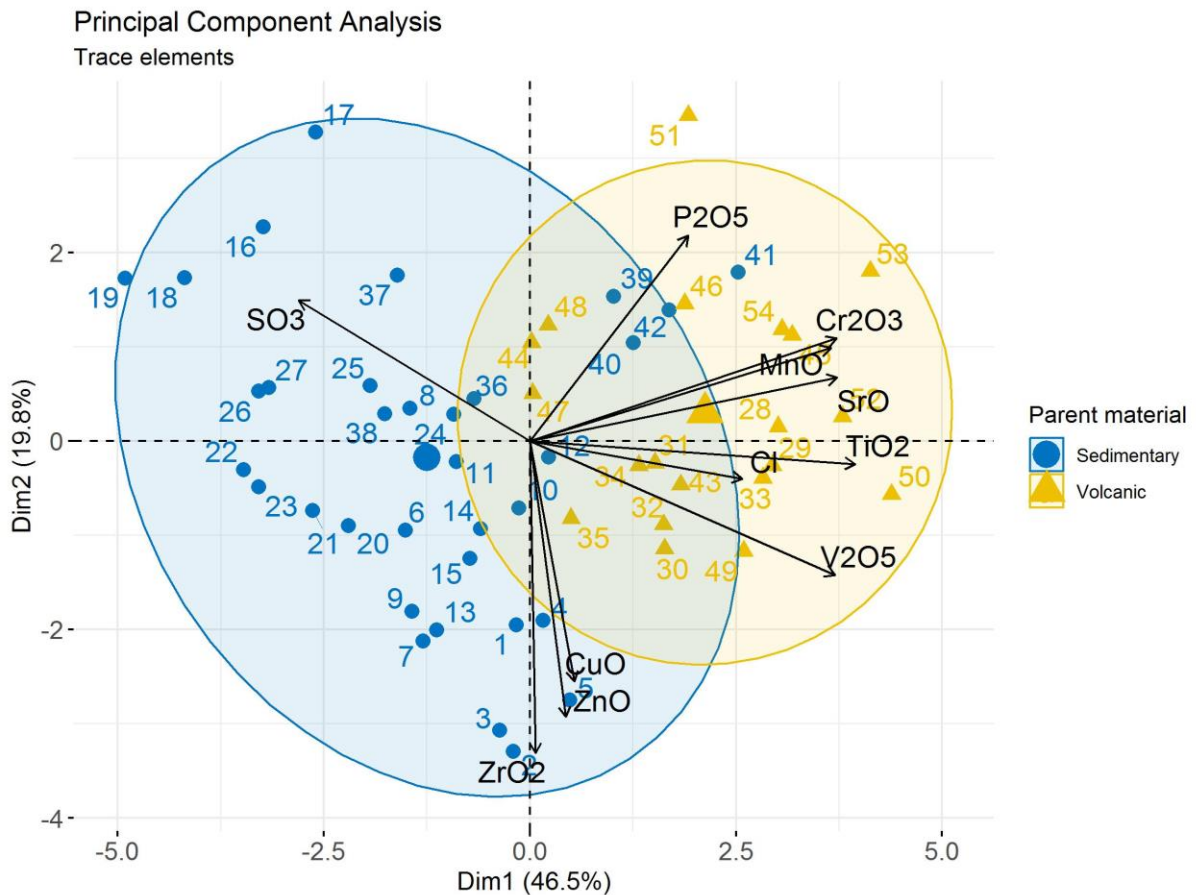


Fig. 3. Principal Component Analysis of trace oxides for the different parent material.

Most of the Cretaceous sediments contain sulfides as reported by previous works on nearby Seymour (Macellari, 1988; Souza et al., 2014; Tatur et al., 1993) and Vega Islands (Moreno et al., 2012). Higher  $\text{SO}_3$  levels are also found in this type of rocks in James Ross Island. As expected, soils derived from volcanic rocks showed higher levels of  $\text{TiO}_2$  and  $\text{P}_2\text{O}_5$ .

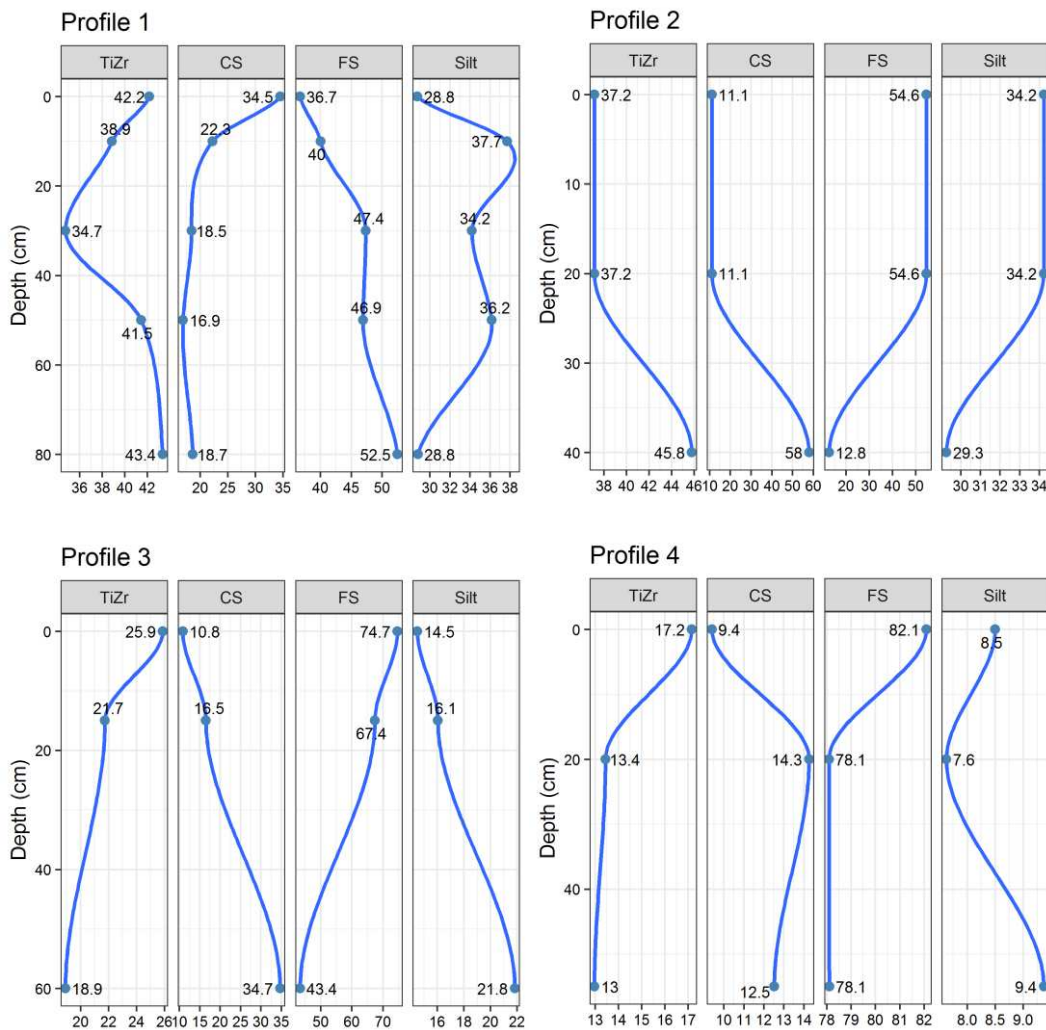
### 3.2. Geochemical indices and soil-forming processes

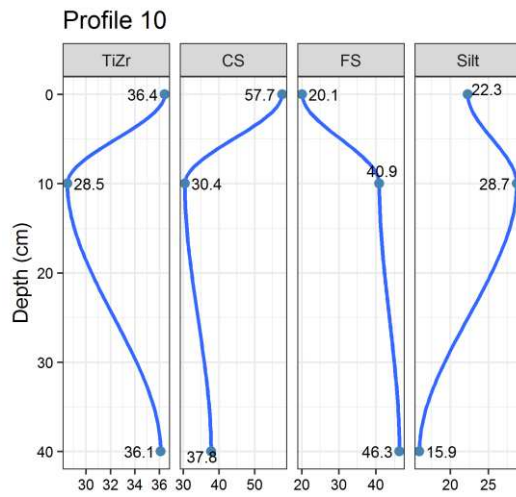
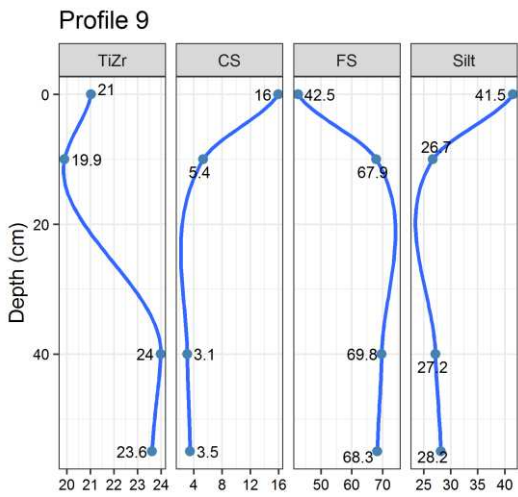
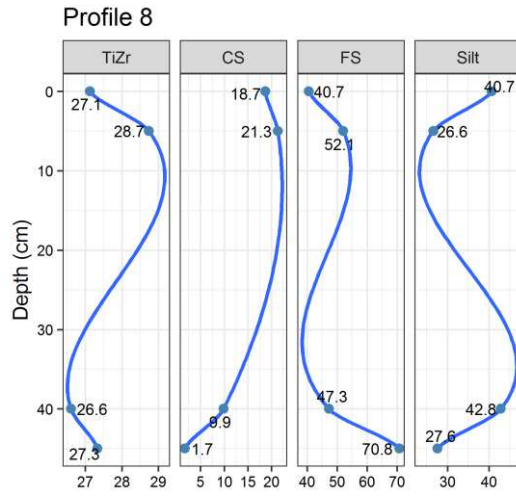
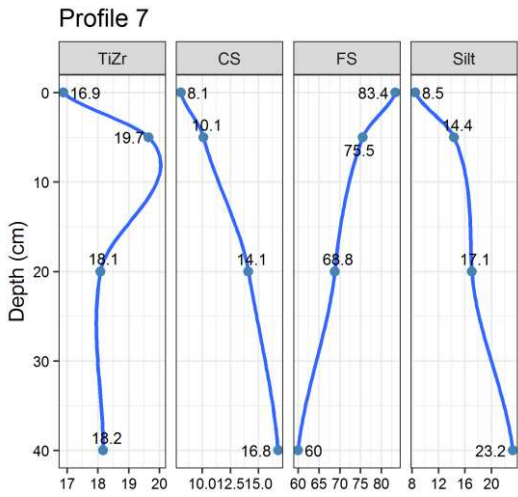
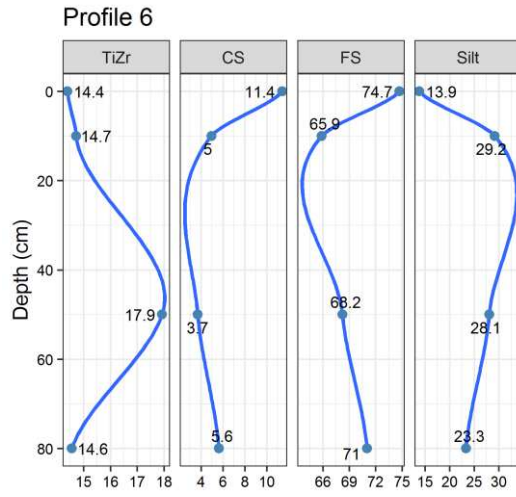
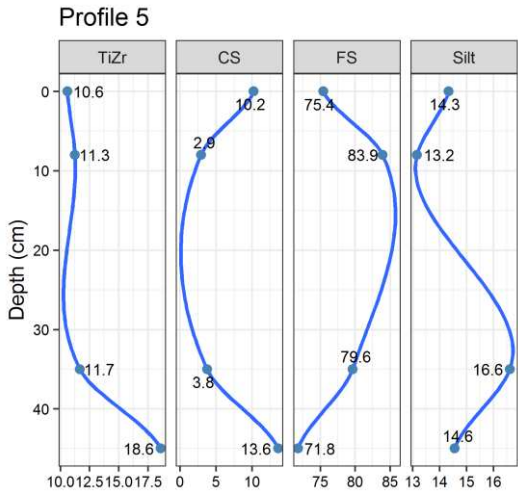
#### 3.2.1. Parent material uniformity

The soils derived from volcanic rocks had  $\text{TiO}_2/\text{ZrO}_2$  ratios higher than soils derived from

sedimentary rock because of higher  $\text{TiO}_2$  content, typical of volcanic rocks (Table 2). However, in P15, derived from sedimentary rock, the values were as high as in the soils derived from volcanic rock (Table 2). This fact is confirming once again the influence of the volcanic material in this sedimentary profile.

We found no variations higher than 100% in  $\text{TiO}_2/\text{ZrO}_2$  ratio between adjacent horizons (Fig. 4). The highest value found was in the P5 (35 to 55 cm), amounting only to a 59% in relation to adjacent horizons. This doesn't indicate lithologic discontinuity and variations of lesser magnitudes may be attributed to mineralogy of the parent material prior to soil formation (Brewer, 1965).





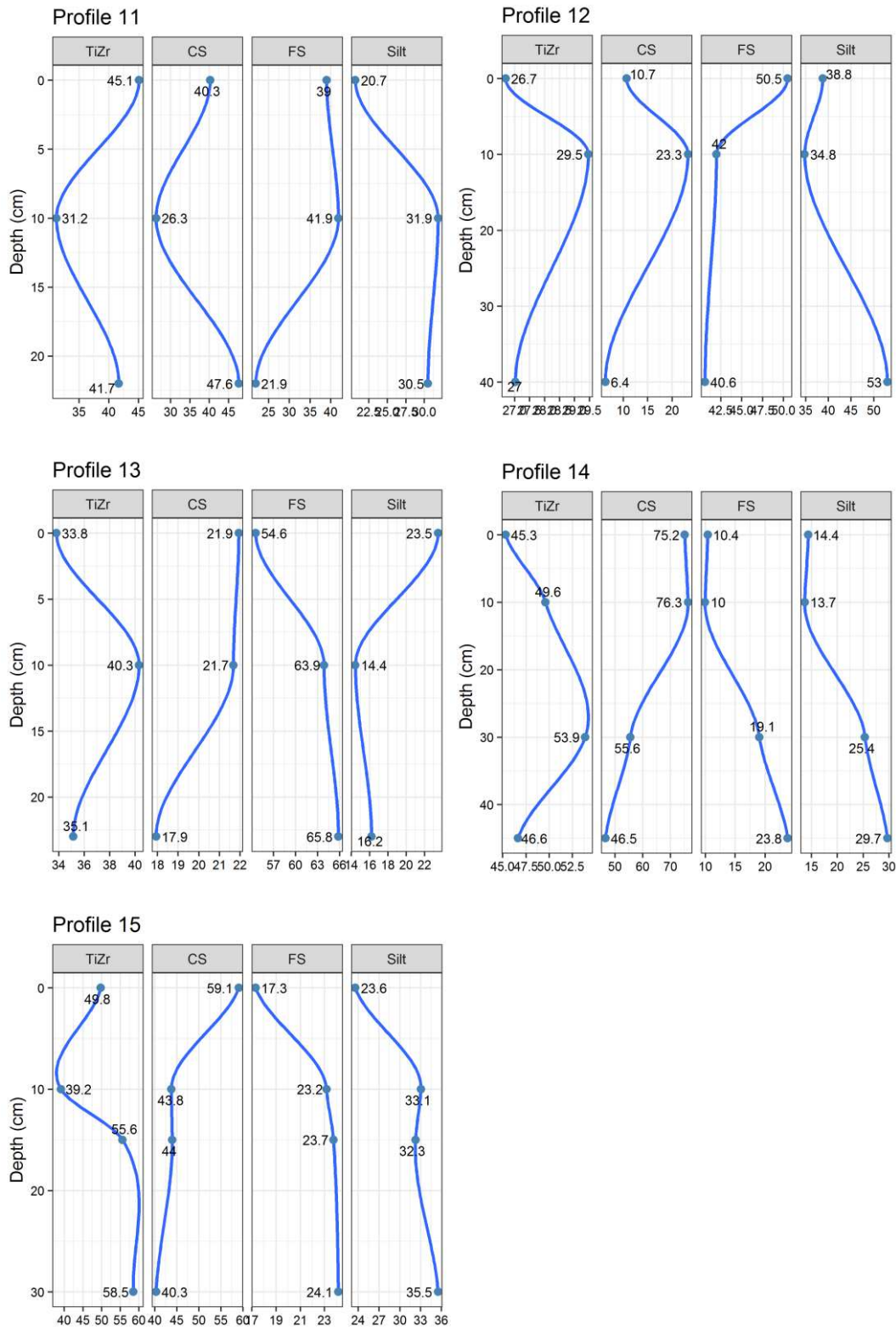
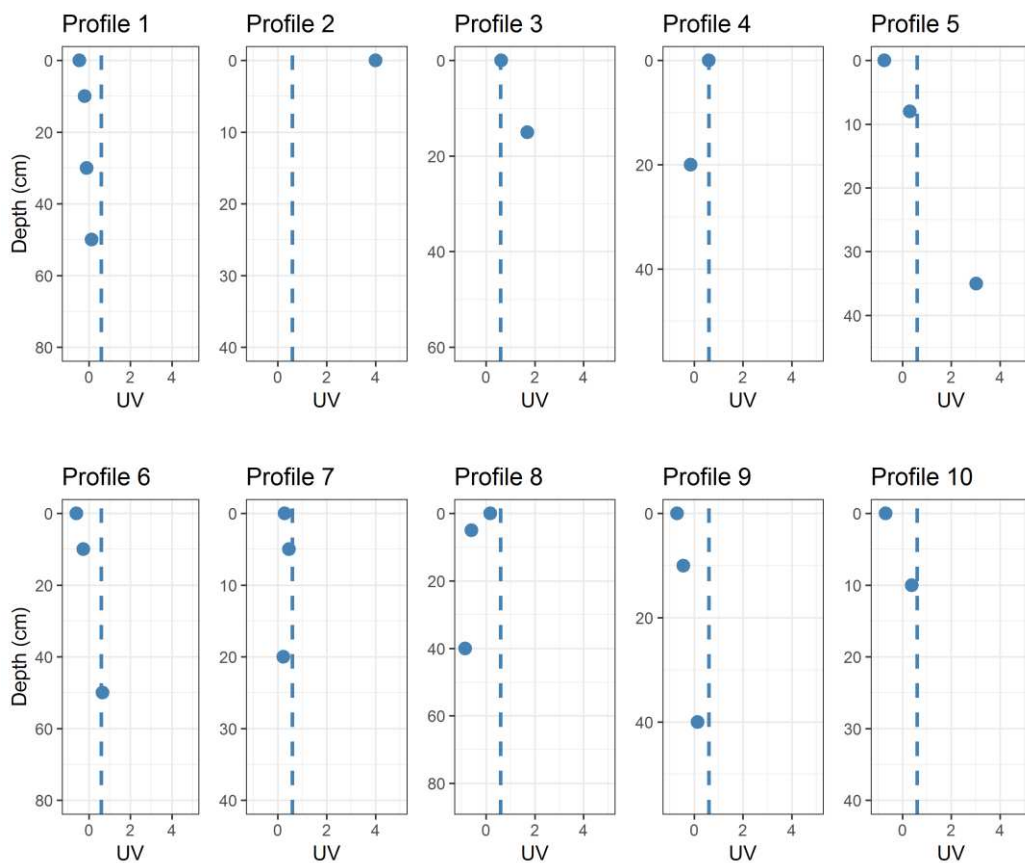


Fig. 4.  $\text{TiO}_2/\text{ZrO}_2$  ratio and distribution of clay-free particle-size fractions as a function of soil depth.

Considering the other criteria to evaluate lithological discontinuities, the graphic of sand and

silt on a clay-free basis showed variations higher than 100% between adjacent horizons in many profiles (P1, P3, P5, P6, P7, P8, P9, P10, P11, P12, P14 and P15) (Fig. 4), suggesting a change of materials within the profile. However, in some profiles this inflection occurs only in clay-free coarse sand fraction, which is the lowest in sedimentary soils. Low quantities of a particular fraction, tend to magnify changes in ratios and potentially overinflate the number of observed discontinuities, or indicate lithologic discontinuities where there is none (Ahr et al., 2017).

When using the third parameter, UV index, seven profiles (P2, P3, P4, P5, P6, P11, and P12) showed lithologic discontinuity (values  $>0.60$  between adjacent horizons) (Fig. 5). However, using the three parameters (TiO<sub>2</sub>/ZrO<sub>2</sub> ratio, sand and silt clay-free, and uniformity value) and checking the same depths, one might assume that a lithologic discontinuity exists only in five profiles (P2, P3, P5, P6, and P12).



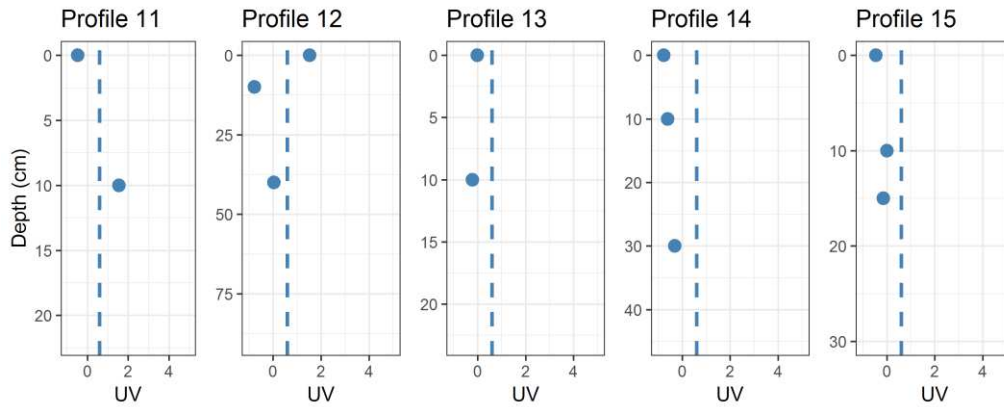


Fig. 5. Uniformity value (UV) index between adjacent horizons of each soil profile.

### 3.2.2. Soils weathering degree and mineralogy

The CIA values of all profiles ranged between 42.6 and 76.6 (Fig. 6) with an average of 62.9, suggesting some degree of weathering. This interpretation can be proved because the values are higher compared to the King George Island, in which showed an average of 59.2 (Lee et al., 2004). The King George Island, located in the maritime Antarctica, has a high potential for weathering because of its warmer and more humid climate (Simas et al., 2008) than the semi-arid transitional climate of James Ross Island (Daher et al., 2019).

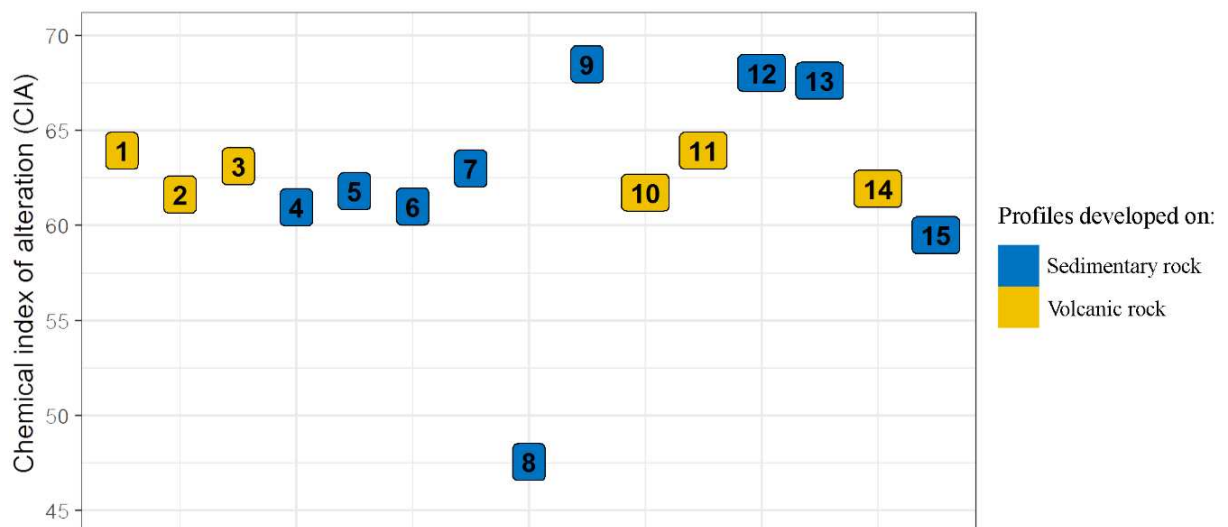


Fig. 6. Chemical index of alteration (CIA) median values of each profile.

The lowest CIA value was observed in P8 (Fig. 8). This soil is characterized by enrichment of CaO and Na<sub>2</sub>O and depletion of Al<sub>2</sub>O<sub>3</sub> contents, compared with other soil samples. As in P8, there are others profiles that have index values lower in subsurface than in depth, but most still display appropriate trends, increasing upwards in the soil profile.

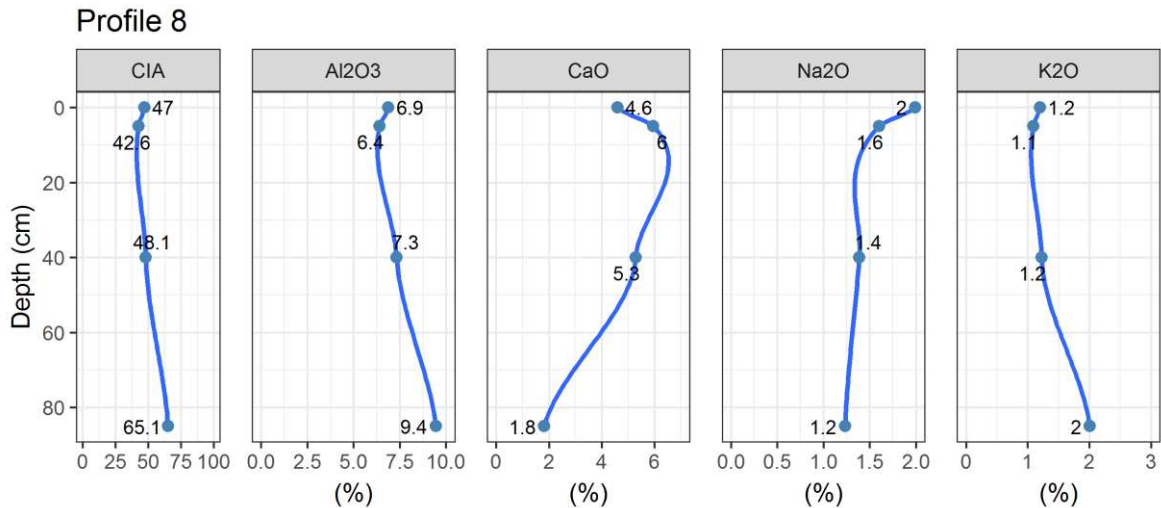


Fig. 7. Profile with a lowest chemical index of alteration (CIA) value.

The high CIA values of James Ross Island is assigned to warmer past climate conditions than currently present and also can be confirmed with the presence of kaolinite in the clay fraction of these soils (Fig. 8a, b). Kaolinite can be originated from wetter climates in the past (Pereira et al., 2013; Simas et al., 2008; Vennum and Nejedly, 1990). However, the presence of primary minerals such as quartz, illite, feldspar, and magnetite in the clay fraction (Fig. 8a, b) showed the intense physical weathering, in contrast to the incipient chemical weathering.

X-ray diffraction (XRD) pattern of the representative profile of sedimentary rock (P04) in the clay fraction after the treatments indicated the presence of vermiculite, illite, kaolinite quartz, and feldspar (Fig. 8a). The XRD pattern of the representative profile of volcanic rock (P11) was similar to that of the representative profile of sedimentary rock. However, the kaolinite peaks were not detected, and after the concentration of iron oxides, the magnetite peak

appeared (Fig. 8b).

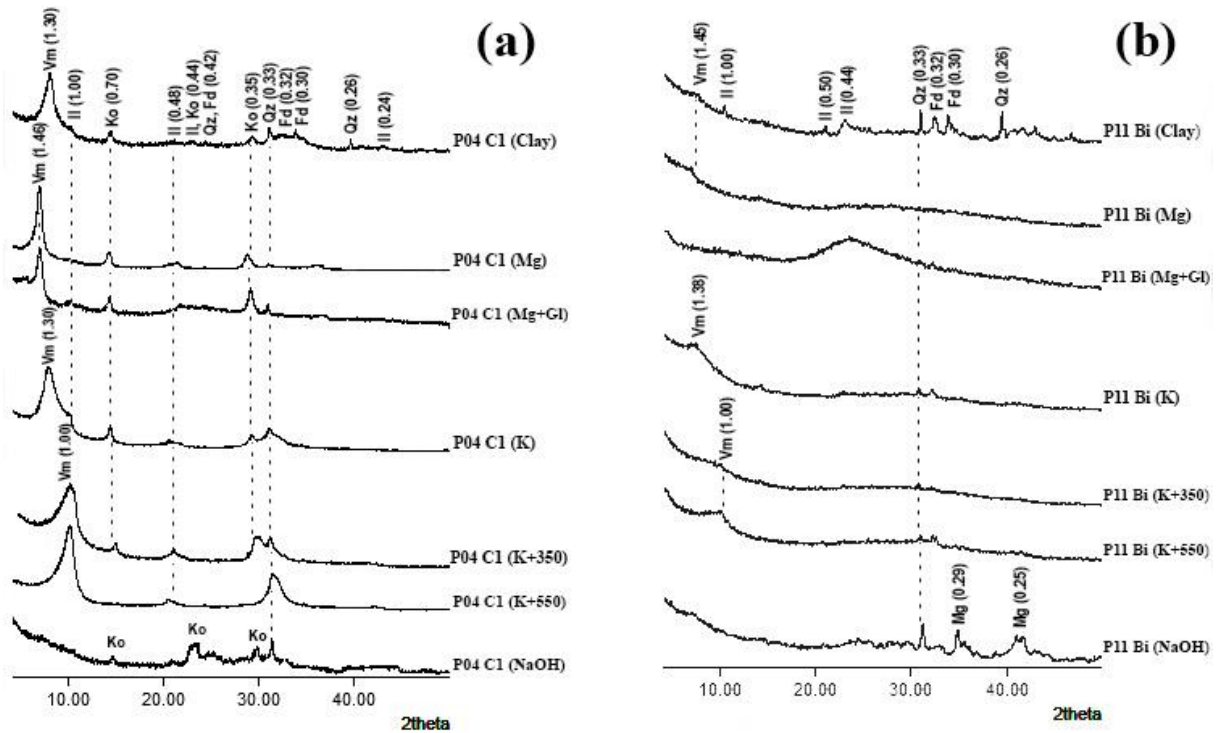


Fig. 8. XRD pattern of representative soil (P4, Bi horizon) developed on sedimentary rock, (Clay fraction) (a), and XRD pattern of representative soil (P11, Bi horizon) developed on volcanic rock, (Clay fractions) (b). Vm: Vermiculite, Il: Illite, Ko: Kaolinite, Qz: Quartz, Fd: Feldspar, Mg: Magnetite. "d" in nm.

All profiles plotted in the CIA average graphic showed the same trend of weathering despite the sedimentary or volcanic parent rocks (Fig. 6), although soils developed on more recent geology (volcanic) were expected to have lower CIA values. This result may indicate that pre-weathering intensity in the soils developed on sedimentary rocks was not intense enough to weather more this soils than the developed on most recent lavas, and/or that the soils developed on olivine-basalt lavas because these are more easily weathered, reaching the same condition of alteration than soils formed from sedimentary materials.



#### **4. Conclusions**

1. Based on the major and trace oxides geochemistry, the semi-arid soil types of James Ross Island are well differentiated, indicating that geochemical composition of soils is highly affected by their parent material. Therefore, based on the major oxides abundances, chemical weathering is less significant.

2. When crossing the three parameters ( $\text{TiO}_2/\text{ZrO}_2$  ratio, sand and silt clay-free, and niformity value) to identify lithologic discontinuities, five profiles (P2, P3, P5, P11, and P12) showed this characteristic, highlighting the polycyclic nature of these semi-arid soils.

3. According to the high CIA values and mineralogical composition, with kaolinite in the clay fraction, soils developed on the sedimentary rock of James Ross Island showed a pre-weathered nature. However, there was no difference in CIA values between the two groups of soils.

#### **Acknowledgments**

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## Additional file

Table 1. TiO<sub>2</sub> and ZrO<sub>2</sub> content and ratio, distribution of coarse (CS) and fine sand (FS) and silt clay-free, uniformity value (UV) index, and chemical index of alteration (CIA) of soil profiles sampled on James Ross Island, Antarctic.

Profile	Sample	Depth	TiO <sub>2</sub>	ZrO <sub>2</sub>	TiO <sub>2</sub> /ZrO <sub>2</sub>	Clay-free base			UV	CIA
			%			CS	FS	Silt		
P1	1	0-10	1,22	0,03	42,17	34,52	36,72	28,76	-0,46	62,13
	2	10-30	1,26	0,03	38,87	22,26	40,02	37,71	-0,21	63,94
	3	30-50	1,10	0,03	34,73	18,45	47,36	34,19	-0,10	63,73
	4	50-80	1,09	0,03	41,45	16,91	46,91	36,17	0,13	70,93
	5	80-85	1,09	0,03	43,38	18,68	52,50	28,82		69,65
P2	6	0-40	1,21	0,03	37,17	11,12	54,65	34,23	4,00	62,81
	7	40-50	1,44	0,03	45,80	12,75	57,97	29,28		60,45
P3	8	0-15	1,18	0,05	25,89	10,83	74,65	14,52	0,63	63,12
	9	15-60	0,99	0,05	21,75	16,51	67,43	16,06	1,69	59,49
	10	60-75	0,91	0,05	18,92	34,73	43,44	21,84		67,12
P4	11	0-20	0,64	0,04	17,15	9,40	82,10	8,50	0,61	60,96
	12	20-55	0,66	0,05	13,44	14,27	78,10	7,63	-0,14	60,52
	13	55-90	0,71	0,05	12,97	12,53	78,10	9,37		61,16
P5	14	0-8	0,76	0,07	10,63	10,22	75,44	14,34	-0,74	61,58
	15	8-35	0,82	0,07	11,26	2,91	83,92	13,17	0,30	62,03
	16	35-45	0,78	0,07	11,69	3,76	79,64	16,61	3,03	62,38
	17	45-55	0,85	0,05	18,59	13,60	71,84	14,56		60,80
P6	18	0-10	0,91	0,06	14,40	11,41	74,71	13,88	-0,60	59,19
	19	10-50	0,68	0,05	14,73	4,95	65,86	29,19	-0,26	61,52
	20	50-80	0,76	0,04	17,93	3,71	68,22	28,07	0,65	60,49
	21	80-100	0,70	0,05	14,56	5,64	71,03	23,34		61,61
P7	22	0-5	0,71	0,04	16,88	8,08	83,37	8,55	0,28	62,49
	23	5-20	0,85	0,04	19,65	10,11	75,52	14,37	0,46	62,96
	24	20-40	0,83	0,05	18,09	14,12	68,82	17,06	0,23	66,96
	25	40-60	0,90	0,05	18,18	16,76	60,02	23,21		63,04
P8	26	0-5	0,49	0,02	27,13	18,69	40,65	40,65	0,18	46,96
	27	5-40	0,49	0,02	28,74	21,35	52,06	26,59	-0,60	42,61
	28	40-45	0,52	0,02	26,61	9,88	47,30	42,83	-0,85	48,12
	29	85-100	0,49	0,02	27,33	1,65	70,76	27,58		65,14
P9	30	0-10	0,69	0,03	21,04	15,95	42,54	41,50	-0,70	59,16
	31	10-40	0,66	0,03	19,91	5,36	67,93	26,70	-0,44	70,65
	32	40-55	0,63	0,03	23,99	3,09	69,76	27,15	0,14	66,35
	33	55-60	0,57	0,02	23,62	3,51	68,33	28,17		76,58
P10	34	0-10	1,07	0,03	36,44	57,66	20,07	22,27	-0,68	61,74
	35	10-40	0,93	0,03	28,50	30,39	40,88	28,73	0,39	63,22



Profile	Sample	Depth	TiO <sub>2</sub> ZrO <sub>2</sub>		TiO <sub>2</sub> /ZrO <sub>2</sub>	Clay-free base			UV	CIA
			%			CS	FS	Silt		
P11	36	40-90	0,89	0,02	36,11	37,75	46,33	15,92		59,84
	37	0-10	1,12	0,02	45,09	40,27	39,04	20,69	-0,47	63,42
	38	10-22	0,88	0,03	31,22	26,26	41,87	31,86	1,55	67,43
	39	22-40	1,20	0,03	41,68	47,63	21,88	30,50		63,94
P12	40	0-10	0,74	0,03	26,70	10,71	50,53	38,76	1,53	63,11
	41	10-40	0,68	0,02	29,47	23,26	41,97	34,77	-0,78	68,69
	42	40-90	0,65	0,02	27,03	6,37	40,60	53,03	0,03	67,39
	43	90-120	0,64	0,03	23,01	6,57	45,53	47,90		71,09
P13	44	0-10	0,67	0,02	33,82	21,93	54,57	23,49	-0,02	62,78
	45	10-23	0,65	0,02	40,33	21,67	63,88	14,45	-0,21	70,03
	46	23-55	0,72	0,02	35,15	17,94	65,84	16,22		67,62
P14	47	0-10	0,91	0,02	45,33	75,15	10,42	14,42	-0,77	60,58
	48	10-30	1,16	0,02	49,61	76,31	9,96	13,73	-0,61	62,82
	49	30-45	1,15	0,02	53,89	55,57	19,06	25,37	-0,30	61,05
	50	45-75	1,07	0,02	46,64	46,54	23,77	29,69		63,88
P15	51	0-10	0,90	0,02	49,75	59,06	17,33	23,60	-0,46	67,11
	52	10-15	0,94	0,02	39,16	43,76	23,17	33,07	0,01	59,55
	53	15-30	1,00	0,02	55,61	43,98	23,74	32,28	-0,14	59,43
	54	30-70	1,02	0,02	58,50	40,32	24,15	35,53		52,68

Table 2. Geochemical composition of the major oxides of soil profiles sampled on James Ross Island, Antarctic.

Profile	Sample	Depth	SiO <sub>2</sub>	Al <sub>2</sub> O <sub>3</sub>	Fe <sub>2</sub> O <sub>3</sub>	CaO	K <sub>2</sub> O	MgO	Na <sub>2</sub> O
			%						
P1	1	0-10	42.95	10.64	7.54	3.48	1.31	1.64	1.69
	2	10-30	47.63	11.35	7.87	3.27	1.51	1.65	1.62
	3	30-50	48.37	11.40	7.29	2.61	1.59	1.97	2.29
	4	50-80	42.27	10.82	7.04	2.56	1.34	1.94	0.54
	5	80-85	45.85	11.37	6.94	2.53	1.45	1.73	0.97
P2	6	0-40	46.63	11.08	7.81	2.93	1.48	1.85	2.15
	7	40-50	40.11	10.81	8.82	4.38	1.10	2.11	1.60
P3	8	0-15	50.65	10.66	6.96	3.39	1.61	1.51	1.23
	9	15-60	55.96	9.99	6.02	2.86	1.97	1.79	1.97
	10	60-75	53.98	9.53	5.32	2.33	1.80	0.48	0.53
P4	11	0-20	66.48	9.82	3.32	1.60	2.42	1.17	2.27
	12	20-55	65.45	9.75	3.73	1.67	2.40	1.35	2.29
	13	55-90	63.10	9.23	4.00	1.63	2.25	1.56	1.98
P5	14	0-8	63.04	9.85	5.81	2.01	2.35	1.62	1.79
	15	8-35	65.12	9.86	5.54	1.77	2.43	1.57	1.83
	16	35-45	59.74	9.60	5.79	1.76	2.28	1.77	1.74
	17	45-55	57.87	9.53	5.91	2.25	2.09	1.60	1.80
P6	18	0-10	62.68	9.80	6.14	2.04	2.31	1.83	2.42
	19	10-50	57.53	9.30	4.88	1.83	2.15	1.67	1.83
	20	50-80	60.04	8.95	5.35	1.88	2.22	1.41	1.75
	21	80-100	55.85	8.74	5.28	1.93	2.07	1.54	1.44
P7	22	0-5	59.18	8.99	4.49	1.62	2.09	1.32	1.69
	23	5-20	51.61	9.96	6.14	2.45	1.77	1.97	1.64
	24	20-40	53.31	9.34	5.64	2.18	1.87	1.48	0.57
	25	40-60	59.56	10.53	5.89	2.55	2.00	1.46	1.63
P8	26	0-5	35.38	6.89	1.17	4.59	1.20	0.49	1.99
	27	5-40	30.57	6.41	1.56	5.95	1.09	0.61	1.60
	28	40-45	35.81	7.32	7.54	5.29	1.23	0.53	1.39
	29	85-100	48.48	9.45	4.01	1.82	2.01	0.93	1.23
P9	30	0-10	46.81	10.20	5.09	3.82	1.86	1.07	1.37
	31	10-40	47.37	10.29	4.06	1.14	1.96	0.89	1.17
	32	40-55	48.58	10.00	3.74	1.21	2.07	1.28	1.80
	33	55-60	45.69	9.50	3.59	1.01	1.90	0.14	0.00
P10	34	0-10	45.35	10.27	6.83	3.74	1.40	1.82	1.22
	35	10-40	42.06	9.74	5.56	3.15	1.38	1.52	1.13
	36	40-90	44.25	10.04	5.28	3.23	1.48	1.53	2.03
P11	37	0-10	43.61	10.62	7.51	3.63	1.13	1.57	1.36
	38	10-22	36.90	9.38	5.77	2.61	0.99	1.23	0.92
	39	22-40	40.10	11.10	8.14	3.95	1.01	1.36	1.30

Profile	Sample	Depth	SiO <sub>2</sub>	Al <sub>2</sub> O <sub>3</sub>	Fe <sub>2</sub> O <sub>3</sub>	CaO	K <sub>2</sub> O	MgO	Na <sub>2</sub> O
			%						
P12	40	0-10	44.11	9.55	4.85	2.59	1.55	1.27	1.44
	41	10-40	44.82	9.96	4.66	1.90	1.66	1.28	0.98
	42	40-90	45.63	10.11	4.49	2.20	1.78	0.70	0.91
	43	90-120	44.37	9.27	4.32	2.08	1.69	0.49	0.00
P13	44	0-10	53.50	10.94	5.42	2.64	1.65	1.12	2.20
	45	10-23	46.46	10.87	6.28	1.86	1.37	1.63	1.42
	46	23-55	50.29	10.95	6.17	2.04	1.45	1.53	1.75
P14	47	0-10	38.08	10.42	6.44	3.86	1.20	2.58	1.72
	48	10-30	42.31	11.78	7.65	3.86	1.34	2.27	1.78
	49	30-45	43.12	11.62	7.92	4.34	1.32	2.49	1.75
	50	45-75	41.04	10.83	7.33	3.66	1.27	2.47	1.20
P15	51	0-10	37.84	9.85	6.73	3.97	0.85	1.83	0.00
	52	10-15	37.05	9.26	7.03	3.72	0.80	1.85	1.77
	53	15-30	35.24	9.50	7.57	4.10	0.71	1.94	1.68
	54	30-70	32.58	8.86	7.37	5.41	0.64	2.12	1.92

Table 3. The geochemical composition of the trace oxides of soil profiles sampled on James Ross Island, Antarctic.

Profile	Sample	Depth	%										
			TiO <sub>2</sub>	SO <sub>3</sub>	MnO	V <sub>2</sub> O <sub>5</sub>	P <sub>2</sub> O <sub>5</sub>	Cr <sub>2</sub> O <sub>3</sub>	CuO	SrO	ZnO	ZrO <sub>2</sub>	Cl
P1	1	0-10	1.22	0.03	0.12	0.02	0.26	0.04	0.01	0.03	0.01	0.03	0.15
	2	10-30	1.26	0.06	0.12	0.02	0.25	0.03	0.01	0.03	0.01	0.03	0.14
	3	30-50	1.10	0.05	0.11	0.02	0.17	0.03	0.01	0.03	0.01	0.03	0.13
	4	50-80	1.09	0.04	0.11	0.02	0.22	0.03	0.01	0.03	0.01	0.03	0.14
	5	80-85	1.09	0.04	0.11	0.02	0.16	0.03	0.01	0.03	0.01	0.03	0.14
P2	6	0-40	1.21	0.06	0.15	0.02	0.12	0.03	0.01	0.03	0.01	0.03	0.13
	7	40-50	1.44	0.03	0.14	0.03	0.24	0.04	0.01	0.04	0.01	0.03	0.14
P3	8	0-15	1.18	0.03	0.11	0.02	0.22	0.04	0.01	0.03	0.01	0.05	0.15
	9	15-60	0.99	0.04	0.08	0.02	0.22	0.02	0.01	0.03	0.01	0.05	0.17
	10	60-75	0.91	0.04	0.07	0.02	0.19	0.02	0.01	0.03	0.01	0.05	0.14
P4	11	0-20	0.64	0.00	0.04	0.02	0.18	0.01	0.01	0.02	0.01	0.04	0.15
	12	20-55	0.66	0.02	0.05	0.02	0.21	0.02	0.01	0.03	0.01	0.05	0.11
	13	55-90	0.71	0.03	0.05	0.02	0.17	0.01	0.01	0.03	0.01	0.05	0.12
P5	14	0-8	0.76	0.01	0.06	0.02	0.21	0.01	0.01	0.03	0.01	0.07	0.15
	15	8-35	0.82	0.01	0.05	0.02	0.15	0.02	0.01	0.03	0.01	0.07	0.10
	16	35-45	0.78	0.01	0.05	0.02	0.20	0.02	0.01	0.02	0.01	0.07	0.12
	17	45-55	0.85	0.01	0.06	0.02	0.18	0.02	0.01	0.03	0.01	0.05	0.15
P6	18	0-10	0.91	0.05	0.06	0.02	0.13	0.01	0.01	0.03	0.01	0.06	0.16
	19	10-50	0.68	0.01	0.06	0.02	0.18	0.01	0.01	0.02	0.01	0.05	0.11
	20	50-80	0.76	0.05	0.06	0.02	0.08	0.01	0.01	0.02	0.01	0.04	0.11
	21	80-100	0.70	0.07	0.06	0.02	0.25	0.01	0.01	0.02	0.01	0.05	0.10
P7	22	0-5	0.71	0.04	0.05	0.02	0.11	0.01	0.01	0.02	0.01	0.04	0.13
	23	5-20	0.85	0.01	0.07	0.02	0.23	0.01	0.01	0.03	0.01	0.04	0.11
	24	20-40	0.83	0.02	0.07	0.02	0.21	0.02	0.01	0.02	0.01	0.05	0.08
	25	40-60	0.90	0.01	0.08	0.02	0.22	0.02	0.01	0.03	0.01	0.05	0.10
P8	26	0-5	0.49	1.24	0.02	0.01	0.28	0.02	0.01	0.02	0.01	0.02	0.14
	27	5-40	0.49	0.56	0.03	0.01	0.46	0.02	0.01	0.01	0.01	0.02	0.13
	28	40-45	0.52	1.67	0.01	0.01	0.31	0.01	0.01	0.02	0.01	0.02	0.07
	29	85-100	0.49	1.39	0.02	0.01	0.07	0.01	0.01	0.02	0.01	0.02	0.04
P9	30	0-10	0.69	0.35	0.01	0.01	0.19	0.01	0.01	0.02	0.01	0.03	0.12
	31	10-40	0.66	0.27	0.02	0.01	0.08	0.01	0.01	0.01	0.01	0.03	0.11
	32	40-55	0.63	0.64	0.02	0.01	0.00	0.01	0.01	0.02	0.01	0.03	0.12
	33	55-60	0.57	0.59	0.02	0.01	0.00	0.01	0.01	0.01	0.01	0.02	0.14
P10	34	0-10	1.07	0.05	0.11	0.02	0.28	0.03	0.01	0.03	0.01	0.03	0.12
	35	10-40	0.93	0.03	0.09	0.02	0.24	0.02	0.01	0.03	0.01	0.03	0.08
	36	40-90	0.89	0.01	0.09	0.02	0.20	0.01	0.01	0.03	0.01	0.02	0.15
P11	37	0-10	1.12	0.03	0.01	0.02	0.24	0.03	0.01	0.03	0.01	0.02	0.18
	38	10-22	0.88	0.02	0.10	0.02	0.19	0.02	0.01	0.03	0.01	0.03	0.12
	39	22-40	1.20	0.03	0.15	0.02	0.29	0.04	0.01	0.04	0.01	0.03	0.13
P12	40	0-10	0.74	0.21	0.07	0.02	0.15	0.02	0.01	0.03	0.01	0.03	0.14

Profile	Sample	Depth	TiO <sub>2</sub>	SO <sub>3</sub>	MnO	V <sub>2</sub> O <sub>5</sub>	P <sub>2</sub> O <sub>5</sub>	Cr <sub>2</sub> O <sub>3</sub>	CuO	SrO	ZnO	ZrO <sub>2</sub>	Cl
			%										
	41	10-40	0.68	0.08	0.05	0.01	0.16	0.01	0.01	0.02	0.01	0.02	0.12
	42	40-90	0.65	1.01	0.05	0.01	0.12	0.01	0.01	0.02	0.01	0.02	0.07
	43	90-120	0.64	0.84	0.05	0.01	0.09	0.01	0.01	0.02	0.01	0.03	0.10
	44	0-10	0.67	0.35	0.09	0.02	0.26	0.01	0.01	0.03	0.01	0.02	0.14
P13	45	10-23	0.65	0.10	0.07	0.01	0.14	0.01	0.01	0.02	0.01	0.02	0.15
	46	23-55	0.72	0.15	0.07	0.02	0.14	0.01	0.01	0.02	0.01	0.02	0.10
	47	0-10	0.91	0.03	0.12	0.02	0.35	0.04	0.01	0.04	0.01	0.02	0.11
P14	48	10-30	1.16	0.06	0.15	0.02	0.29	0.03	0.01	0.04	0.01	0.02	0.19
	49	30-45	1.15	0.06	0.15	0.02	0.33	0.04	0.01	0.05	0.01	0.02	0.16
	50	45-75	1.07	0.03	0.14	0.02	0.24	0.04	0.01	0.04	0.01	0.02	0.17
	51	0-10	0.90	0.10	0.12	0.02	0.23	0.03	0.01	0.03	0.01	0.02	0.15
P15	52	10-15	0.94	0.09	0.12	0.02	0.19	0.03	0.01	0.03	0.01	0.02	0.14
	53	15-30	1.00	0.03	0.14	0.02	0.31	0.03	0.01	0.04	0.01	0.02	0.15
	54	30-70	1.02	0.05	0.13	0.02	0.33	0.03	0.01	0.03	0.01	0.02	0.12

## ARTIGO 3

### Multivariate analysis of soils from Antarctica based on a large database

#### Abstract

In 2002, the TERRANTAR Research Group, linked to the Brazilian Antarctic Program (PROANTAR), began soil studies on King George Island (South Shetland Islands Group - SSIG). Throughout these 16 years of research, soil collection has expanded to the neighboring islands, reaching as far as the Weddell Sea (James Ross Island group - JRIG) and Continental Antarctica. The research group currently accounts for approximately 20% of all soil collection conducted in Antarctica, with a compiled database of 412 soil profiles from the SSIG and JRIG combined. It allows to examine and compare the physical and chemical properties, through a descriptive statistical analysis of the soils of these distinct climatic regions. The results points to a predominance of parent material inheritance and over physical weathering over chemical weathering, although in certain condition, chemical weathering is more influential. The mean pH values of JRIG semi-arid soils are closer to those found in arid Continental Antarctica. SSIG soils are the most acidic in Antarctica, due to either the presence of sulfides on the marked biological influence under greater moisture and temperature. In the JRIG, the values of Na are much higher due drier climates. Conversely, greater precipitation in the SSIG region favors greater leaching of the exchangeable bases, particularly Na and K. The highest bioavailable P values (Mehlich-1) found in the two regions are attributed to external inputs of bird guano, mainly by penguins, which are more significant in the SSIG, where a greater population occurs. In both regions, soils affected by bird activity have the highest amount of organic material, thereby resulting in high total organic carbon content. Climate is

the key factor for the development of SSIG soils. Greater precipitation combined with higher temperatures considerably increases vegetation growth, organic matter accumulation and leaching of base elements, resulting in a more acidic pH. On the other hand, in the JRIG, alkaline soils with higher salt contents, have negligible vegetation, low organic matter contents, closely matching aridic soils from Dry Valleys of Continental Antarctica.

Keywords: Cryosols; Ornithogenesis; Parent material; Climate

## **1. Introduction**

The first pedological study in Antarctica was published by Jensen (1916). Since then, approximately 2,500 soil profiles have been described, collected and analyzed, of which 75% from Continental Antarctica, more specifically in the Transantarctic Mountains in Victoria Land (Bockheim, 2015). In 2002, the TERRANTAR Research Group, linked to the Brazilian Antarctic Program (PROANTAR), initiated soil studies on King George Island (South Shetland Islands - SSIG), where the Brazilian base is located. Until then, this region was less studied. Alongside these 16 years of continuous research, descriptive analyses, and soil collection and analysis. TERRANTAR expanded to the neighboring islands, reaching as far as the Weddell Sea (James Ross Island group - JRIG), and is currently accountable for over 400 soil studied soil profiles, approximately 20% of the total soils studied in Antarctica.

As in other regions of the world, soil development in Antarctica is influenced by climate, parent material, relief, and biological activity over time. Climate is one of the most critical factors for soil formation in this region, as it influences the amount of water availability thus determining soil genesis (Campbell and Claridge, 1987).

In Continental Antarctica, there may be less than 10 mm of average annual rainfall, and the average annual temperature is around  $-45.0\text{ }^{\circ}\text{C}$  (Bockheim, 2015). Physical weathering determines development of soils in this region (Bockheim and Tarnocai, 1998). The SSIG presents a maritime climate, where the average annual rainfall reaches 800 mm, and the average annual temperature is around  $-1.8\text{ }^{\circ}\text{C}$  (Bockheim, 2015). The higher temperatures and the greater availability of water results in more developed soils. The JRIG is located along the border between the Maritime and Continental climate zones (Tatur et al., 1993), and soils have characteristics of both maritime and continental regions (Daher et al., 2019).

In this work, we present the multivariate analysis and compare the chemical and physical properties of soils from the SSIG and JRIG regions, based on a comprehensive database of 412 soil profiles, and provide a descriptive the soils from these two distinct climatic regions.

## **2. Material and methods**

### **2.1. Study Area**

The South Shetland Islands (SSIG) are located northwest of the Antarctic Peninsula and consist of 11 main islands: Low, Smith, Deception, Snow, Livingston, Greenwich, Robert, Nelson, King George, Elephant, and Clarence, as well as numerous islets. The James Ross Island group (JRIG) lies southeast of the Antarctic Peninsula and consists of four main islands, Vega, James Ross, Seymour, and Snow Hill, and several smaller islands including Cockburn, Lockyer, and Humps, among others. The present study includes ten SSIG islands (Barrientos, Deception, Elephant, Half Moon, King George, Livingston, Nelson, Penguin,



Robert, and Snow), and four JRIG islands (Cockburn, James Ross, Seymour, and Vega) (Fig. 1).

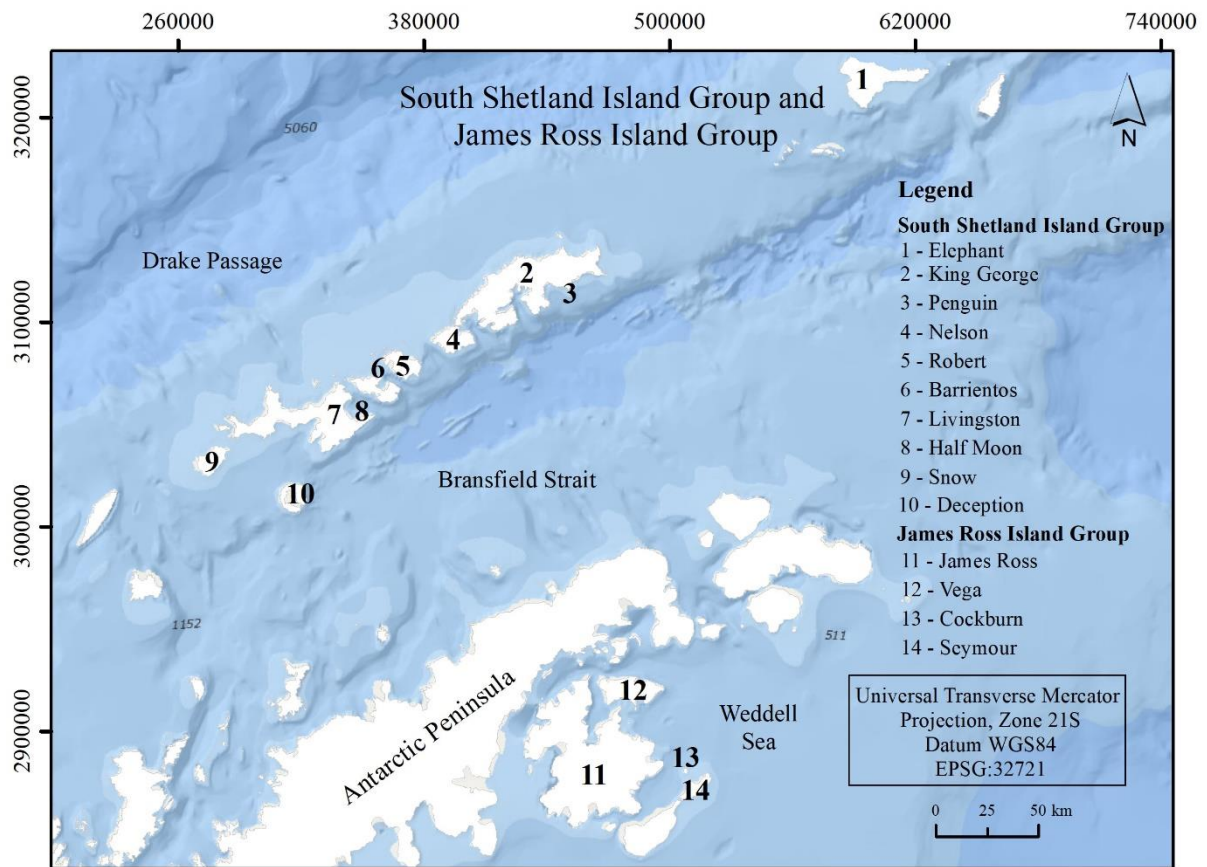


Fig. 1. Location of the islands where the profiles were described, collected and analyzed.

## 2.2. Database and statistical analysis

Four hundred and twelve soil profiles were described, collected, and examined, including 311 profiles distributed throughout the SSIG, and 101 profiles distributed throughout the JRIG, totaling 1,402 horizons. Soil collection took place during the austral summers between 2002 and 2018, according to criteria established by the Antarctic Permafrost, Periglacial Environments and Soils expert group (ANTPAS) (Bockheim et al., 2006). Selected soils physical and chemical properties (Table 1) were organized in the soil database for subsequent statistical analysis. The database also includes the profiles geographic position and altitude,

parent material, and other characteristics, such as soil depth, color, classification (Soil Taxonomy and WRB/FAO systems), presence of permafrost in the first 200 cm of depth, ornithogenic influence, presence of sulfides, and type of vegetation.

Table 1. Physical and chemical properties used to characterize SSIG and JRIG soils.

Properties of soils	Analysis
<b>Physical</b> <sup>1</sup>	
Sand	Sand content %
Silt	Silt content %
Clay	Clay content %
<b>Chemical</b> <sup>2</sup>	
pH <sub>H2O</sub>	pH in water (soil:solution 1:2.5)
Ca	Calcium (KCl 1 mol L <sup>-1</sup> ) cmol <sub>c</sub> dm <sup>-3</sup>
Mg	Magnesium (KCl 1 mol L <sup>-1</sup> ) cmol <sub>c</sub> dm <sup>-3</sup>
K	Potassium (Mehlich-1) mg dm <sup>-3</sup>
Na	Sodium (Mehlich-1) mg dm <sup>-3</sup>
P	Phosphor (Mehlich-1) mg dm <sup>-3</sup>
Al	Exchangeable aluminum (KCl 1 mol L <sup>-1</sup> ) cmol <sub>c</sub> dm <sup>-3</sup>
H + Al	Potential acidity (Acetate-Ca at pH 7) cmol <sub>c</sub> dm <sup>-3</sup>
BS	Sum of bases [K + Na (Mehlich-1)] + [Ca + Mg (KCl 1 mol L <sup>-1</sup> )] cmol <sub>c</sub> dm <sup>-3</sup>
t	Effective cation exchange capacity (KCl 1 mol L <sup>-1</sup> in soil pH) cmol <sub>c</sub> dm <sup>-3</sup>
T	Total cation exchange capacity (Acetate-NH <sub>4</sub> a pH 7) cmol <sub>c</sub> dm <sup>-3</sup>
V	Base saturation [100 x (BS / T)] %
m	Aluminum saturation [100 x (Al <sup>3+</sup> / t)] %
NaSI	Sodium saturation index [100 x (Na <sup>+</sup> / T)] %
TOC	Total organic carbon (Yeomans e Bremner, 1988) %

<sup>1</sup> According to Ruiz (2005)

<sup>2</sup> According to EMBRAPA (2017)

The descriptive statistical analyses included calculations for mean and median values, coefficient of variation (CV), and maximum and minimum values of the physical and chemical properties of the soils from each island group. Statistical analyses were performed in the R program (R core team, 2018), using the vegan (Oksanen et al., 2018), and stats (R core team, 2018) libraries. The Principal Component Analysis (PCA) was used to better interpretation of the data, for which the ggbiplot package was used (Vincent, 2011). In

addition, the `aqp` (Beaudette et al., 2013), `dplyr` (Wickham et al., 2018), `ggplot2` (Wickham, 2016), and `ggrepel` (Slowikowski, 2018), libraries were used for plotting the graphs. The purpose of the graphs served to visually compare the soil properties of each island group, through the median value of the range of depth between 10 cm and 50 cm by interpolation. The median value was used as it is not influenced by extreme values. . The maximum depth of 50 cm was chosen due to the significant number of samples that go up to this value, which is associated with the possibility of greater transformations in soils characteristics. The graphs also provided information on the dispersion of data between the third and first quartiles (Q3 - Q1).

### **3. Results**

#### **3.1. Physical properties**

The soil profiles from the SSIG and JRIG presented a texture with a great contribution of sand, with mean and median values close to 65.0% (Table 2). The difference in the amounts of sand, silt, and clay between the two island groups is small, with the greatest difference observed for the coarse sand (CS) and fine sand (FS) medians, in which the SSIG presented 47.3% and 14.4%, respectively, whereas the JRIG 11.0% and 47.3%, respectively (Table 2). The highest clay values for the SSIG were observed in Nelson Island (76.0%), while the highest clay values for the JRIG were seen in Seymour Island (58.0%) (Table 2). In general, the median values by the depth of sand, silt, and clay for the two island groups, were homogeneous throughout the profiles (Figs. 2 and 3), due to homogenization by cryoturbation.

Table 2. Descriptive statistical analysis of the physical properties of SSIG and JRIG soils.

	Coarse Sand	Fine Sand	Total Sand	Silt	Clay	Silt + Clay
	%					
<b>SSIG</b>						
Minimum	4.00	0.50	11.00	0.00	0.00	0.70
Maximum	89.50	69.00	99.30	72.00	76.00	89.00
Mean	48.28	15.97	64.10	21.59	14.21	35.83
Median	47.30	14.40	66.00	20.00	13.00	34.00
CV %	17.21	9.91	17.08	12.20	8.95	17.07
<b>JRIG</b>						
Minimum	0.00	2.00	4.31	0.00	0.00	2.00
Maximum	80.00	94.00	98.00	72.12	58.00	95.69
Mean	18.17	47.95	66.12	21.08	12.81	33.89
Median	11.00	49.00	67.80	19.80	12.57	32.20
CV %	19.28	19.87	17.65	13.11	8.24	17.66

CV: coefficient of variation      Coarse Sand (2-0.2 mm Ø); Fine Sand (0.2-0.05 mm Ø); Total Sand (2-0.05 mm Ø); Silt (0.05-0.002 mm Ø); Clay (<0.002 mm Ø); Silt + Clay: sum of silt and clay.

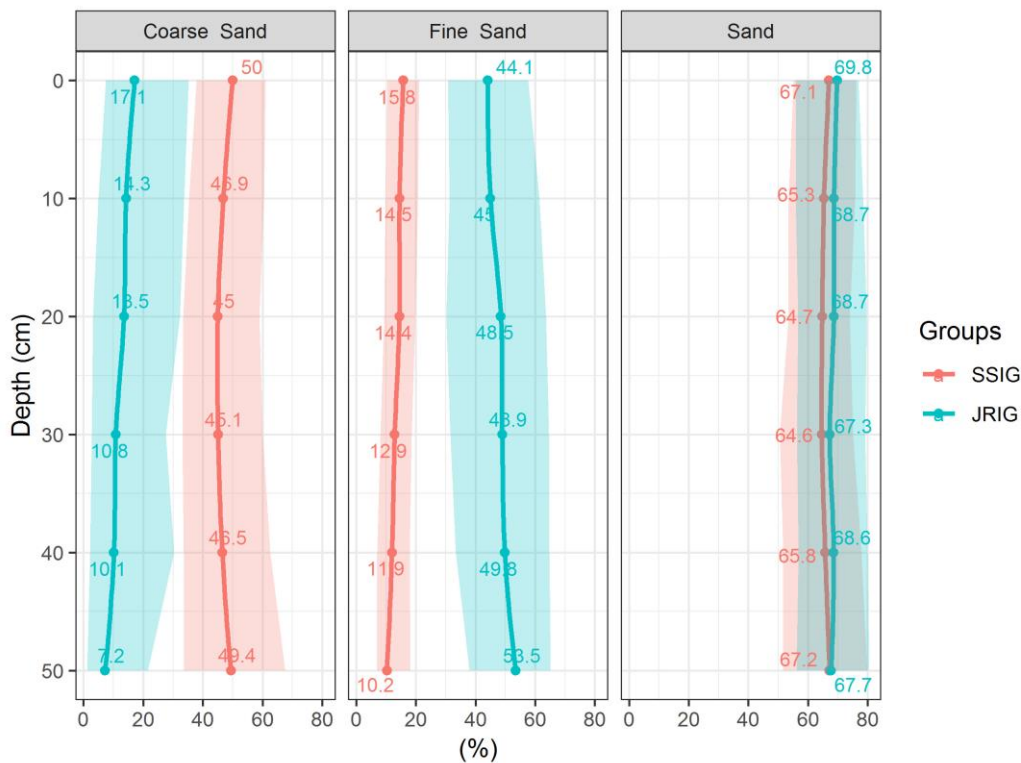


Fig. 2. Median of the texture classes (Coarse Sand, Fine Sand, and Sand) of the SSIG and JRIG soils in depth of 0-50 cm. The shaded areas represent Q1 – Q3.

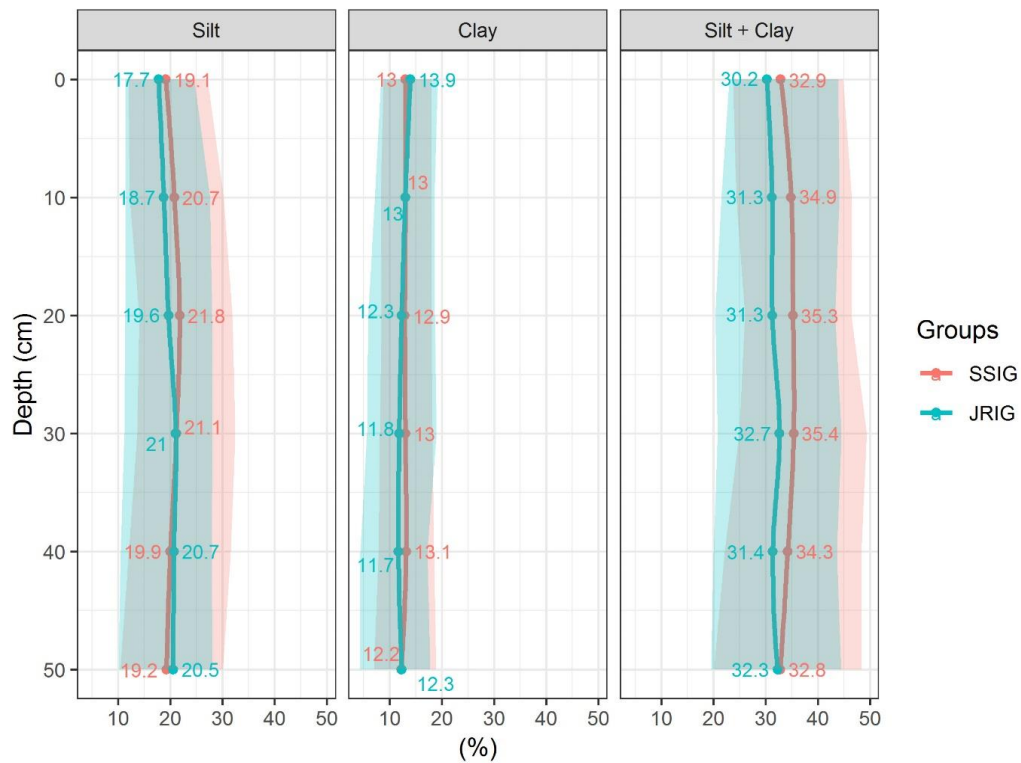


Fig. 3. Median of the texture classes (Silt, Clay and Silt + Clay) of the SSIG and JRIG soils in depth of 0-50 cm. The shaded areas represent Q1 – Q3.

The Principal Component Analysis (PCA) of soil physical properties allowed to explain a total of 46.1% of the variance observed in axis 1 and 37.6% in axis 2 and the two island groups were well-separated in the biplot diagram through PCA (Fig. 4). The first principal component (PC1) had a large negative association with CS and the second principal component (PC2) had a positive association with FS (Table 3).



Fig. 4. Principal component analysis (PCA) indicating the separation of the soils into two different groups (SSIG and JRIG) according to the physical properties of the soil.

Table 3. Results of the principal component analysis (PCA) for the first two principal components (PC) of the all soils (physical properties) of the SSIG and JRIG in depth of 0-50 cm.

Principal components	PC1	PC2	PC3	PC4
CS	-0.709	-0.217	0.025	0.669
FS	0.331	0.722	-0.13	0.591
Silt	0.498	-0.407	0.668	0.371
Clay	0.370	-0.514	-0.730	0.253

CS: Coarse sand; FS: Fine sand

### 3.2. Chemical properties

In the JRIG, most soils have pH values varying from neutral to alkaline (Daher et al., 2019),

resulting in a median pH value of 7.67 (Table 4). Conversely, SSIG soils were acidic, with a median pH value of 5.75. In both groups, the most acidic pH values were 2.90 (Table 4), found on Livingston Island (SSIG), and Seymour Island (JRIG), both sulphide affected and on marine sediments. The median pH values did not vary in depth (Fig. 5).

The median sum of the bases (BS) for the JRIG was 23.11  $\text{cmol}_c \text{dm}^{-3}$ , while the median for SSIG was lower, at 9.60  $\text{cmol}_c \text{dm}^{-3}$  (Table 4). The BS is represented mainly by Ca and Mg in the two regions, where the median Ca, and Mg values for JRIG soils were twice as large as the values for SSIG soils (Table 4). Among the BS medians by depth, the highest values were observed for Ca between 20 and 30 cm of depth, in the JRIG (Fig. 5).

Table 4. Descriptive statistical analysis of the chemical properties of SSIG and JRIG soils.

	pH	Ca	Mg	K	Na	P	Al	H+Al	BS	t	T	V	m	NaSI	TOC
	H <sub>2</sub> O	$\text{cmol}_c \text{dm}^{-3}$		mg $\text{dm}^{-3}$				$\text{cmol}_c \text{dm}^{-3}$				%			
<b>SSIG</b>															
Min.	2.8	0.2	0.0	0.0	0.0	1.6	0.0	0.0	0.4	0.5	2.5	2.1	0.0	0.0	0.0
Max.	9.2	69.0	38.0	3741.0	4927.5	10093.5	36.0	50.6	73.6	73.6	75.4	100.0	94.8	73.3	25.0
Mean	5.9	8.8	5.1	146.6	280.0	613.3	2.1	10.2	15.7	18.1	25.5	57.0	18.8	8.4	2.3
Median	5.8	4.9	2.5	104.0	180.0	232.7	0.5	7.0	9.6	12.2	23.0	58.4	4.6	5.7	0.8
CV %	1.3	10.1	6.3	254.9	468.9	1305.9	3.8	10.2	15.0	14.9	13.8	33.8	24.2	9.3	3.5
<b>JRIG</b>															
Min.	2.8	0.1	0.2	0.0	15.5	0.6	0.0	0.0	1.0	1.2	3.1	32.5	0.0	0.1	0.0
Max.	9.5	150.0	19.8	2150.0	7246.5	2018.9	21.6	35.3	154.7	155.4	163.6	100.0	51.4	78.8	9.8
Mean	7.0	14.2	6.0	331.2	1157.7	129.8	0.8	2.5	26.2	27.0	28.7	90.6	3.2	17.5	0.5
Median	7.7	10.1	5.7	170.0	726.2	57.5	0.0	0.5	23.1	24.1	25.3	97.5	0.0	12.5	0.3
CV %	1.7	14.5	3.7	385.7	1230.5	323.1	2.7	4.7	16.8	17.1	17.8	14.2	8.4	15.9	0.9

CV: coefficient of variation; P, Na and K (Mehlich-1 extractor); Ca, Mg and Al (KCl 1 mol L<sup>-1</sup> extractor); H + Al (Acetate-Ca at pH 7.0); BS: bases sum; t: Effective cation exchange capacity in soil pH; T: Total cation exchange capacity at pH 7.0; V: Base saturation; m: Aluminum saturation; NaSI: Sodium saturation index; TOC: Total organic carbon.

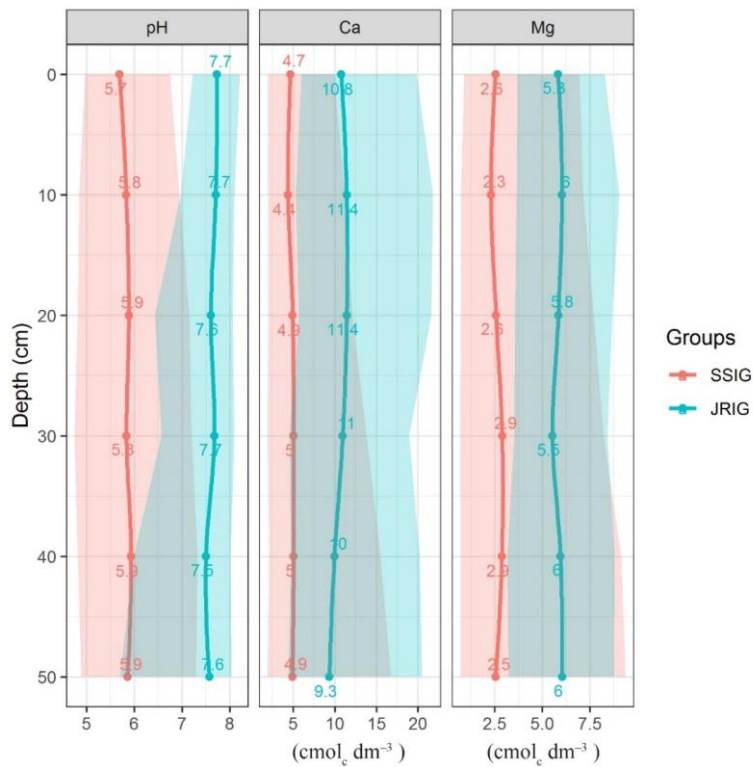


Fig. 5. Median of the pH, Ca and Mg values of the SSIG and JRIG soils in depth of 0-50 cm. The shaded areas represent Q1 – Q3.

The median Na value for the JRIG was high, ranging between 726.20 mg dm<sup>-3</sup>, reaching 7000.00 mg dm<sup>-3</sup> (Table 4) in some places on Seymour Island. The median was lower in the SSIG, with a minimum value of 180.0 mg dm<sup>-3</sup>, and a maximum value of almost 5000.00 mg dm<sup>-3</sup> (Table 4). The same trend was observed for the sodium saturation index (NaSI), which presented higher median values in the JRIG (12.49%), and lower median values in the SSIG (5.69%) (Table 4). Upon comparing the median values for Na and K, the K value was lower in the two study sites (Table 4). In the JRIG, the median Na was higher between 0 cm and 20 cm of depth, and values much higher than the median were observed for both Na and K in the first 10 cm (Fig. 6).

The maximum Mehlich-1 available P content was very high, reaching up to 10,093.5 mg dm<sup>-3</sup> on Elephant Island (SSIG), and 2018.9 mg dm<sup>-3</sup> on Seymour Island (JRIG). The median P



values (Mehlich-1) for the JRIG and SSIG were 57.50 mg dm<sup>-3</sup> and 232.70 mg dm<sup>-3</sup>, respectively (Table 4). The median P values (Mehlich-1) by depth were homogeneous in both groups, being slightly higher at 20 cm in the SSIG (230.3 mg dm<sup>-3</sup>) (Fig. 6).

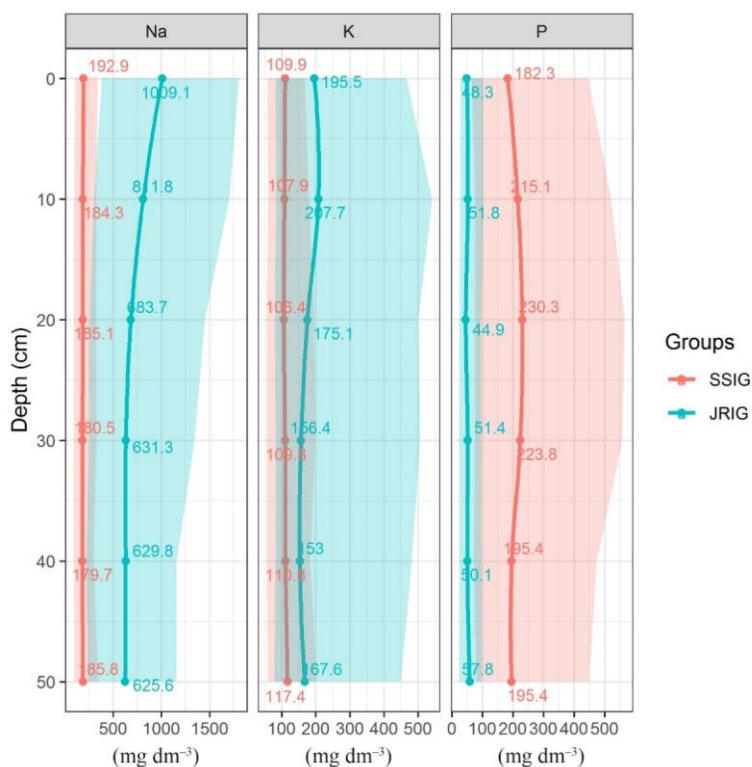


Fig. 6. Median of the Na, K and P values of the SSIG and JRIG soils in depth of 0-50 cm. The shaded areas represent Q1 – Q3.

TOC values were very low in the JRIG, with a median of 0.3%. However, the median in the SSIG was 0.83%, over two times higher (Table 4). The Warszawa Peninsula (King George Island) exhibited the greatest TOC content among all the profiles collected, with 25.02%. The TOC median values were higher in the first 10 cm of SSIG soil, with values higher than the median found mostly in the first 10 cm of depth (Fig. 7).

The median value for Al<sup>3+</sup> in the JRIG was null (ranging from 0.00 to 21.56 cmol<sub>c</sub> dm<sup>-3</sup>), whereas potential acidity (H + Al), was 0.50 cmol<sub>c</sub> dm<sup>-3</sup> (ranging from 0.00 to 35.30 cmol<sub>c</sub> dm<sup>-3</sup>) (Table 4). SSIG median values for both Al<sup>3+</sup> and H+Al were higher, at 0.48 cmol<sub>c</sub> dm<sup>-3</sup>

and  $7.00 \text{ cmol}_c \text{ dm}^{-3}$ , respectively. Values for  $\text{Al}^{3+}$  varied between  $0.00 \text{ cmol}_c \text{ dm}^{-3}$  and  $36.00 \text{ cmol}_c \text{ dm}^{-3}$ , while values for  $\text{H}+\text{Al}$  ranged from  $0.00$  to  $50.60 \text{ cmol}_c \text{ dm}^{-3}$  (Table 4). In both island groups, no discrepancy was found in the median values for  $\text{Al}^{3+}$  at different depths (Fig. 7). However, the median value for  $\text{H}+\text{Al}$  of SSIG soils decreased from  $7.4 \text{ cmol}_c \text{ dm}^{-3}$  to  $5.4 \text{ cmol}_c \text{ dm}^{-3}$  at depth (Fig. 7).

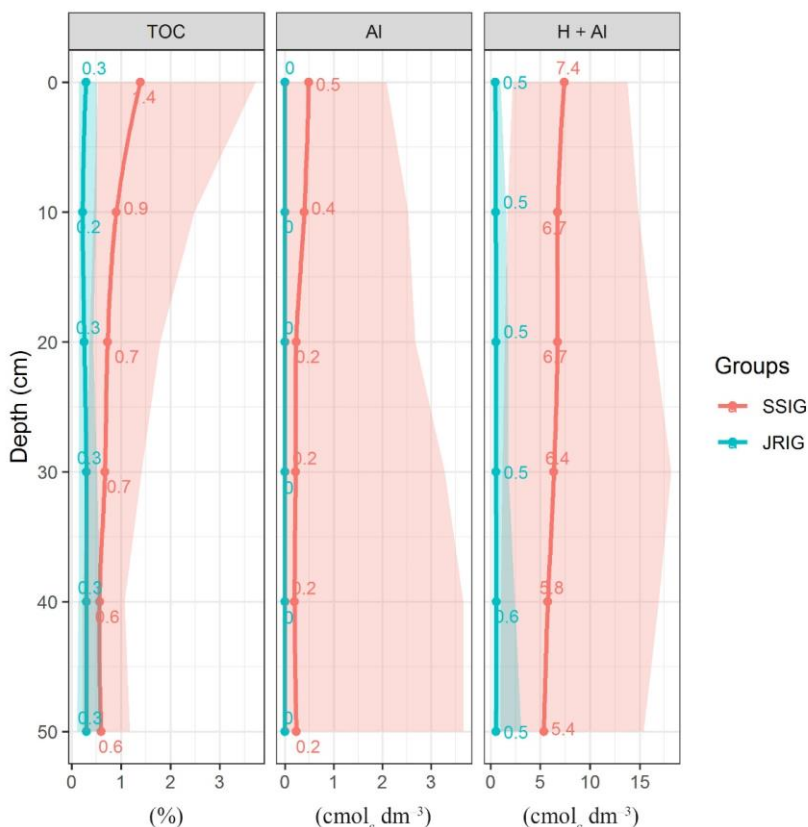


Fig. 7. Median of the TOC, Al and H + Al values of the SSIG and JRIG soils in depth of 0-50 cm. The shaded areas represent Q1 – Q3.

The median value for CTC at pH 7.0 (T) was approximately  $25.00 \text{ cmol}_c \text{ dm}^{-3}$  in both the SSIG and JRIG (Table 4). However, in the SSIG, the median value of effective CTC (t) was reduced by half ( $12.19 \text{ cmol}_c \text{ dm}^{-3}$ ), and in the JRIG, it was close to the CTC value at pH 7.0 (T) ( $24.05 \text{ cmol}_c \text{ dm}^{-3}$ ) (Table 4). There was no great variation in the median values for T and t at different depths (Fig. 8).

In the JRIG, the median value for base saturation (V) was very high (97.50%) (Table 4), and only seven profiles presented dystrophism ( $V < 50\%$ ) on some horizon. In the SSIG, the median value for V fell to 58.40%, and 47% of the horizons exhibited dystrophism. The smallest value was 2.10% (Table 4), found in the soils of Admiralty Bay (King George Island). In the JRIG, the median V values at different depths remained steady, registering 98% between 0 and 10 cm of depth, and 96.9% at 50 cm (Fig. 8). In the SSIG, the median value for V varied with depth, increasing from 57.2% in the first 10 cm to 77.7% at 50 cm (Fig. 8).

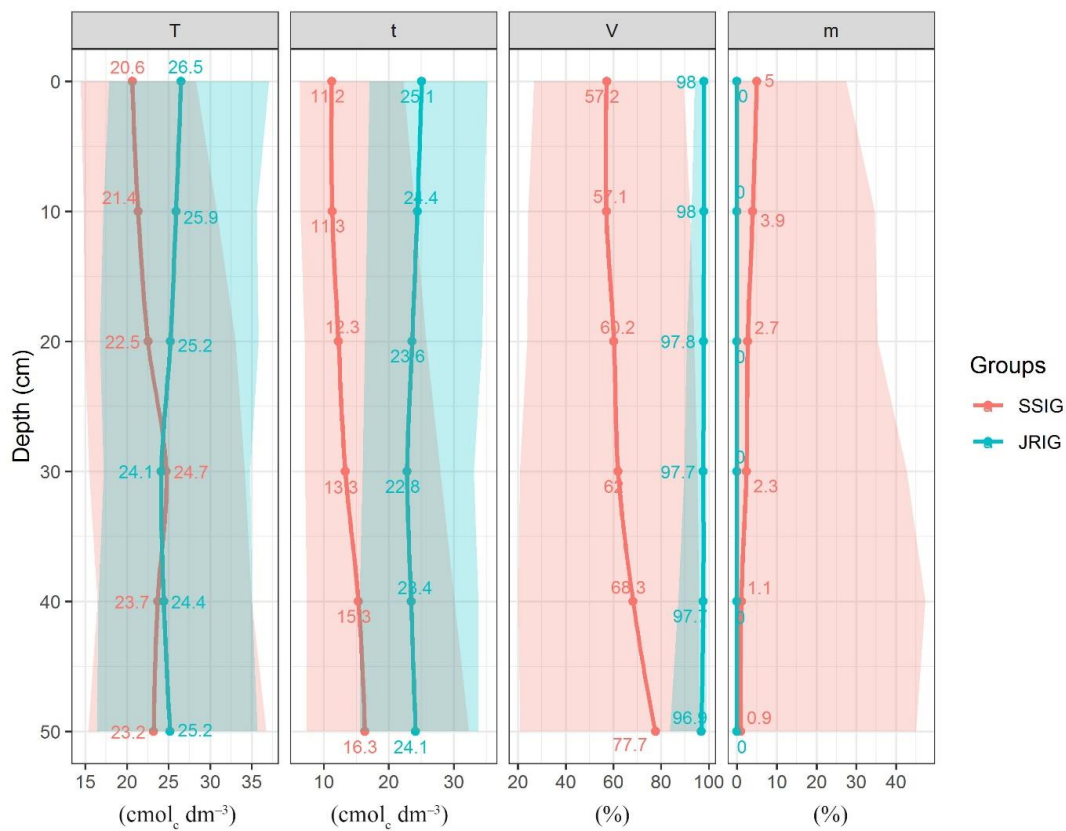


Fig. 8. Median of the T, t and V values of the SSIG and JRIG soils in depth of 0-50 cm. The shaded areas represent Q1 – Q3.

Aluminum saturation values (m) were higher in SSIG soils, with a median of 4.57%, and a maximum value of 94.83% in Barton Peninsula (King George Island). In the JRIG, the median value of m was null, and the maximum value did not exceed 52.0% (Table 4). In the JRIG, the median value for m at different depths was zero throughout the 50 cm. In the SSIG, the

highest value was observed in the first 10 cm (5%) (Fig. 8).

The PCA of soil chemical properties allowed to explain a total of 43.1% of the variance observed in axis 1 and 19.6% in axis 2. The two island groups were well-separated in the biplot diagram through PCA. However it can be verified that in the SSIG there are soils more similar to those of the JRIG (Fig. 9). The PC1 had positive association mainly with BS and in the PC2 had a negative association with pH (Table 5).

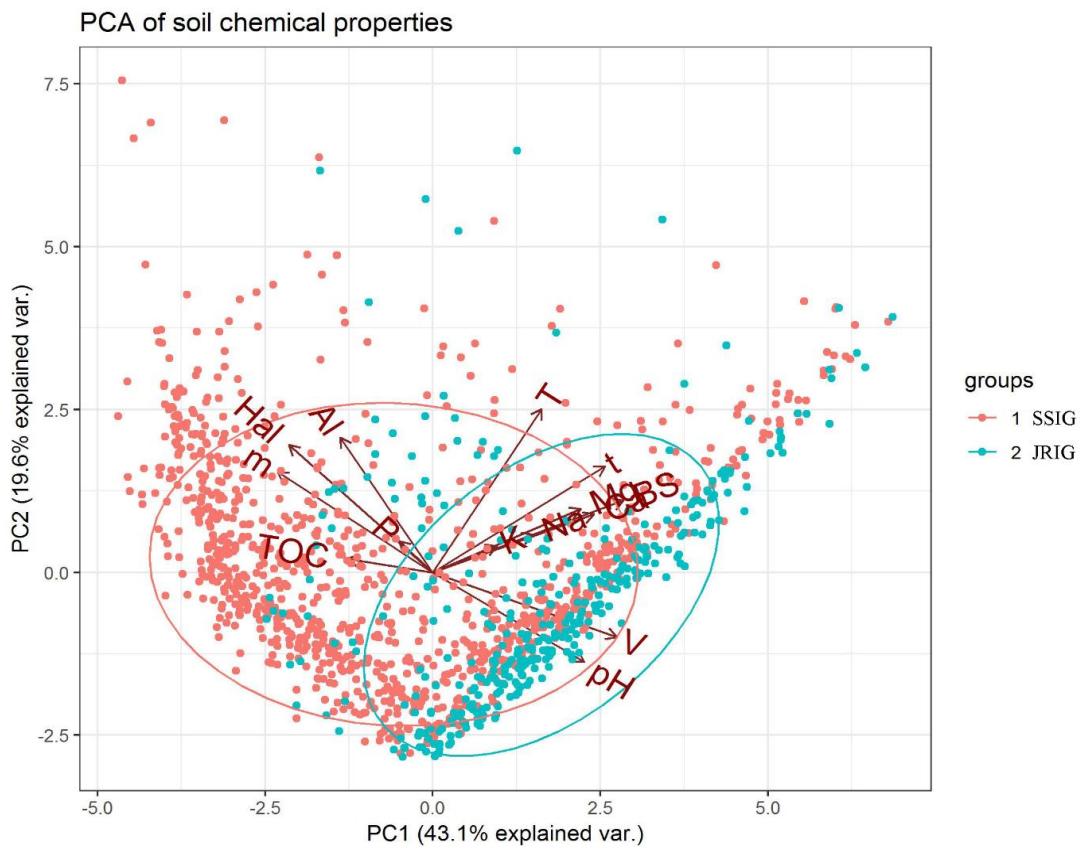


Fig. 9. Principal component analysis (PCA) indicating the separation of the soils into two different groups (SSIG and JRIG) according to the chemical properties of the soil.

Table 5. Results of the principal component analysis (PCA) for the first two principal components (PC) of the all soils (chemical properties) of the SSIG and JRIG in depth of 0-50 cm.

Principal components	PC1	PC2	PC3	PC4	PC5	PC6	PC7
pH	0.298	-0.269	0.010	0.052	0.082	-0.201	0.054
Ca	0.317	0.175	-0.235	-0.267	-0.185	-0.461	-0.068
Mg	0.291	0.191	-0.052	-0.033	0.190	0.734	0.368
K	0.126	0.080	0.627	0.275	-0.053	-0.319	0.612
Na	0.196	0.113	0.480	0.326	0.335	0.069	-0.659
P	-0.066	0.093	0.505	-0.475	-0.581	0.224	-0.172
Al	-0.182	0.406	-0.126	0.337	-0.055	-0.020	0.039
H + Al	-0.283	0.383	0.017	-0.016	-0.023	-0.003	0.045
BS	0.375	0.216	-0.042	-0.098	0.019	-0.049	-0.042
t	0.339	0.319	-0.066	-0.032	0.006	-0.040	-0.031
T	0.214	0.491	-0.039	-0.115	0.021	-0.069	-0.026
V	0.362	-0.194	-0.024	0.074	-0.054	0.028	0.011
m	-0.305	0.302	-0.052	0.160	0.049	-0.128	-0.017
TOC	-0.168	0.041	0.189	-0.590	0.678	-0.160	0.107

BS: bases sum; t: Effective cation exchange capacity in soil pH; T: Total cation exchange capacity at pH 7.0; V:Base saturation; m:Aluminum saturation; TOC: Total organic carbon.

The results of the descriptive statistical analysis of the JRIG and SSIG soil demonstrated a large difference between the maximum and minimum values for all the soil properties. Mean and median values were similar in both island groups for physical properties, besides some chemical properties, such as pH, CTC at pH 7.0 (T), and base saturation (V). In the JRIG, in addition to the above-mentioned properties, the mean and median values were also close for Mg, bases sum (BS), and effective CTC (t). For soil properties where the mean and median values were very different, the median values were always lower, indicating that the maximum values were responsible for the increase in the mean, especially the abnormal values for Na and P (Mehlich-1). As for the coefficient of variation (CV), K, Na, and P (Mehlich-1) record the highest CV (>250%) for both the JRIG and SSIG. The other properties had <24%. In general, the descriptive statistics showed high variability in the soil properties, mainly in the SSIG.

#### **4. Discussion**

In the two island groups, air-dried fine earth fraction (<2 mm Ø) is composed mainly of sand, revealing the predominance of physical weathering of these soils, rather than chemical weathering. Physical weathering in these areas occurs mainly through the freezing and thawing cycles of soils during the summer (Matsuoka, 1995). However, in certain areas, chemical weathering and/or the parent material exert greater influence.

Greater FS content in JRIG soils is related to sedimentary material, which is predominant among this group's profiles. However, the highest clay values among all the profiles of each island group are attributed to chemical weathering. In Seymour Island (JRIG), the greater clay content is due not only to the parent material but also to the sulfurization process (Delpupo et al., 2014). As for Nelson Island (SSIG) (unpublished data), the high clay content is related to the phosphatization process. The acidity generation by sulfurization and ornithogenic activity enhances soil formation. Soil texture is controlled by both the lithology of the parent material, and weathering, as reported in studies by Bockheim (1980) and Ugolini and Jackson (1982) in Continental Antarctica. In the soils of Victoria Land, Ugolini and Jackson (1982) affirmed that the parent material exerted a greater influence on soil texture than the soil's age.

The average pH values for JRIG soils are closer to the values found in Continental Antarctica, where the soils are predominantly alkaline; this is mainly a result of the accumulation of salts due to less precipitation (McCraw, 1960; Ugolini, 1963; Campbell and Claridge 1987). Despite the high pH values, acidic horizons were found in the JRIG because of the influence of sulfides on Seymour Island (Delpupo et al., 2014) and Vega Island (unpublished data).

These acidic soils are formed through the sulfurization process when materials containing sulfide are exposed to oxygen or air, and trigger oxidation and acidification reactions in the medium (Souza et al., 2012; Bigham et al., 1996).

The pH values of SSIG soils are the most acidic in Antarctica (Simas et al., 2008; Michel et al., 2006). This characteristic is related to both the presence of sulfides and ornithogenic influence, associated with the area's greater precipitation and temperature. The ornithogenic condition accelerates microorganism activity, which promotes high rates of guano decomposition over time. This releases acidity into the environment, and pH usually reaches values close to 4.0 (Myrcha and Tatur, 1988, 1991).

Contrary to observations on SSIG phosphatization sites (Michel et al., 2006, 2014; Simas et al., 2007, 2008), the ornithogenic soils of Seymour Island (JRIG) are all alkaline. This indicates that decomposition of organic matter from birds is slow, and acidity has not yet been released into the environment due to the drier and colder climate (Delpupo et al., 2014). This alkalinity can also be observed in the ornithogenic soils of Continental Antarctica examined by Ugolini (1972) and Speir and Cowling (1984).

Although the mean Na value was high in the JRIG, the median value dropped by half. This result is related to the very high Na values in some places, especially in the profiles located in the sea bed, corroborating affirmations by Claridge and Campbell (1977) and Bockheim (1980), who concluded that these salts originate from marine aerosols.

When comparing the median Na values for the profiles of each group, the JRIG still has a much higher Na value due to the region's drier climate. On Seymour Island (JRIG), there was

salt accumulation in the form of superficial crusts, and most of the soils have a sodic character, which indicates salinization as one of the main soil formation processes in this region (Tatur et al., 1993; Delpupo et al., 2014; Schaefer et al., 2015). However, Tatur et al. (1993) asserted that despite the arid conditions of Seymour, there is still sufficient moisture to prevent the accumulation of nitrate salts and chloride, which occurs in the soils within Continental Antarctica.

JRIG soils have a much higher bases sum (BS) than SSIG soils, especially if we compare the median values of these two groups. This is because greater precipitation in the SSIG region favors the greater leaching of the exchangeable bases, mainly Na and K, which are monovalent, thus more mobile in the soil. For this reason, BS values for these islands are influenced mainly by the higher Ca content, followed by Mg content. According to Bockheim (1980), the predominance of Na in Antarctic soils is an additional indication of the extreme aridity of the region. Therefore, we can maintain that although the JRIG is in a drier region than the SSIG, both have sufficient moisture for the leaching of bases. The difference lies in the intensity of leaching.

The highest P values (Mehlich-1) found in the two island groups are due to the influence of birds, mainly penguins. The excretion of these birds is rich in nutrients, such as P and N (Myrcha and Tatur, 1991). The value above 10,000.00 mg dm<sup>-3</sup> for P (Mehlich-1) found on Elephant Island (SSIG) (unpublished data), was the largest ever recorded, substantiating research by Burley (1971) and O'Brien (1979), which highlights the intense colonization of penguins and elephant seals on this island.

However, it is important to consider that despite the expected high P content in ornithogenic



soils, P was quantified by Mehlich-1 extraction. This, according to Novais and Smyth (1999), overestimates P availability in soils with a predominance of P bound to Ca, which is the case of ornithogenic soils, rich in apatites. It is estimated that about 20,000 metric tons of P are deposited annually by penguins on SSIG (Myrcha and Tatur, 1991), which demonstrates the importance of animals in the pedogenesis of this region's soils (Bockheim, 2015). Unlike the SSIG, the nesting of penguins in the JRIG is punctual and limited to a few areas of Seymour Island, as reported by Delpupo et al. (2014).

In both island groups, the soils affected by avifauna activity are those that have the greatest amount of organic material, resulting in high TOC content. In the SSIG, the greater humidity and temperature associated with biological influences, favors the establishment of denser and more complex plant communities, indicating the importance of soil fertilization by these animals, as reported by Tatur (1989). Due to greater vegetation coverage, the concentration of TOC in SSIG soils is the highest in Antarctica, with the formation of a histic horizon with a high content of fibric material, as evidenced by Simas et al. (2015) in the soils of Barton Peninsula (King George Island). In this group (SSIG), the large difference between the mean and median TOC values is related to the highly varied content of organic matter between the islands, and even among the profiles of the same island. According to Øvstedal and Smith (2001) and Schaefer et al. (2004), this is the result of local conditions specific to each area, such as land stability, rock type, and wind activity.

In the JRIG, the drier and colder climate prevents the development of plant communities, with a limited occurrence of lichens in some places. The higher TOC content found in the soils of Seymour Island (JRIG) which is under the ornithogenic influence, is associated with the slow transformation processes of organic components, because of the lower microbial activity and

humification rate, in comparison to SSIG soils. Even the profiles under the ornithogenic influence do not have abundant vegetation, and Delpupo et al. (2014) argue that the wind is one of the factors that limit the establishment of vegetation on the island. Leishman and Wild (2001) indicate that the occurrence of vegetation is more closely related to the abundance of water in the soil than to nutrient enrichment.

The soils of Continental Antarctica (cold desert zone) have a null TOC content and are defined as ahumic (Tedrow and Ugolini, 1966). According to Tedrow and Ugolini (1966), except for sites with penguins and/or areas colonized by mosses and lichens, Antarctic soils are mostly ahumic, just like on the James Ross Island

The median values for  $Al^{3+}$  and aluminum saturation (m) were null in the JRIG because most of the pH values were high in this group, and aluminum is not soluble in alkaline environments. Both JRIG soils and SSIG soils under sulfide influence exhibited the highest  $Al^{3+}$  values. In most ornithogenic soils, there was no significant increase in  $Al^{3+}$  content, which indicates that nesting on these soils did not cause as much acidity as the influence of sulfides. Ornithogenic influence is mainly responsible for the high content of H+Al in the two groups, thereby demonstrating the contribution of organic matter in generating acidity. Therefore, there was a great difference between the medians of the JRIG and SSIG. SSIG registered a much larger median as the influence of birds is greater.

Both groups have high CTC values at pH 7.0 (T) as a consequence of the mineralogy of these soils, rich in 2:1 silicate minerals (Delpupo et al., 2014; Pereira et al., 2013; Simas et al., 2008), typical of poorly developed pedosystems. In the JRIG, the CTC values at pH 7.0 (T) and effective CTC (t) were very close. In the SSIG, this difference was significantly higher,

indicating the presence of not only 2:1 silicate clay minerals, but also of pH-dependent charges from sulfurization and phosphatization processes.

In the sulfurization process, these pH-dependent charges stem from the formation of poorly crystalline iron oxides, such as ferrihydrite, jarosite, and alunite, as observed by Simas et al. (2008) in the acid sulfate soils of Admiralty Bay (King George Island). In the phosphatization process, the dependent loads of pH are related to poorly crystalline secondary phosphates, such as minyulite, leucophosphate, and struvite, and mainly organic matter, since TOC content is much greater in these soils, as previously discussed.

In the JRIG, the base saturation values (V) were very high and even exhibited a hypereutric character according to the IUSS Working Group, 2006. Regarding the seven profiles that presented dystrophism, all had the chemical characteristics of sulfate soils (Delpupo et al., 2014) and were located on Seymour Island. In the SSIG, the much lower V values were related to a higher leaching rate of bases in this environment, conditioned by the more humid climate, greater rainfall, and even the absence of permafrost in the first 100 or 200 cm, allowing for percolation of water. In this environment, the ornithogenic soils are predominantly dystrophic, which corroborates the studies of Schaefer et al. (2004), Michel et al. (2006), and Simas et al. (2008).

## **5. Conclusions**

1. Chemical weathering and the parent material exert influence over the greater content of fine particles in the soils examined. Thus, the increase in fine particle content does not necessarily indicate a greater degree of pedogenetic development, especially for JRIG soils, where the

parent material is mostly sedimentary.

2. Physical weathering is predominant in the two island groups, but chemical weathering is quite significant to the pedogenesis of some of these soils. In the SSIG, through phosphatization and sulfurization processes, the rate of chemical weathering is distinctly higher than in other regions of Antarctica. Sulfurization and salinization carry great importance in the soil formation process in the JRIG, and phosphatization takes on a secondary role due to the greater aridity of the region.

3. Climate is the factor that most influences the development of SSIG soils, because greater precipitation, higher temperatures and avifauna activity greatly increase the organic matter content in these soils, as well as the leaching of bases, and result in a more acidic pH.

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## Conclusões Gerais

O intemperismo físico é predominante tanto nos solos do Grupo de Ilhas James Ross (GIJR), quanto no Grupo de Ilhas Shetland do Sul (GISS), sendo o intemperismo químico representativo em alguns destes solos.

O clima é o fator que mais influência no desenvolvimento dos solos do GISS, pois a maior precipitação, temperaturas mais elevadas e presença de avifauna, fazem com que o conteúdo de matéria orgânica seja maior, bem como a lixiviação de bases. Associados a isso, os processos de fosfatização e sulfurização em alguns destes solos, fazem com que as taxas de intemperismo sejam nitidamente mais elevadas do que em qualquer outra região da Antártica.

Já o clima, juntamente com o material de origem, assume um papel importante na caracterização dos solos do GIJR. Devido à maior aridez da região em relação ao GISS, os solos preservam as características das rochas parentais. Possuem ainda, propriedades intermediárias entre a Antártica Marítima (crioturbação e redoximorfismo) e a Antártica Continental (pavimento desértico e caráter *ahumic*).