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# ANALYSIS OF SHALLOW LAKE SEDIMENTS IN THE FILDES PENINSULA, KING GEORGE ISLAND, MARITIME ANTARCTICA

# ANÁLISE DE SEDIMENTOS LACUSTRES RASOS NA PENÍNSULA FILDES, ILHA REI GEORGE, ANTÁRTICA MARÍTIMA

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**Abstract:**

The work analyzes the deglaciated area of Fildes Peninsula, King George Island, Maritime Antarctica, based upon the interpretation of shallow lacustrine sediment. CAMSIZE analyzer obtained the particle size distribution of sand fractions, and the silt samples were analyzed by the Malvern laser light scattering granulometer. The concentrations of major elements were determined by Energy-dispersive X-ray Spectroscopy, in <0,062 mm particle-size distribution. The mineralogical composition was determined by X-ray diffraction using the Brucker D8 Advance x-ray diffractometer. Chemical Index of Alteration and Plagioclase Index of Alteration were applied. Si was the most abundant chemical element in the samples, followed by Al, Fe, Ca, Mg, Ti and K. Chemical Index of Alteration and Plagioclase Index of Alteration indicated moderates values between 56.0-73.8, and 56.5-68.3, respectively, and increase towards the southern sector of the peninsula, early deglaciated and exposed to the weathering processes. X-ray diffraction reveals the presence of minerals belonging to the volcanic rocks: andesine and olivine. Principal Component Analysis and Cluster Analysis results suggest the sediments are related to the local basaltic rocks. It is also observed the influence of depositional processes on the granulometric and morphoscopic characteristics of the sediments. The climatic and topographic conditions play an important role in the composition and concentration of the elements in the lake sediments since moderate Chemical Index of Alteration and Plagioclase Index of Alteration are indicated.

**Resumo:**

O trabalho analisa a área deglaciarizada da Península Fildes, ilha Rei George, Antártica Marítima, baseada na interpretação de sedimentos lacustres rasos. A distribuição do tamanho das partículas da fração areia foi obtida pelo analisador CAMSIZE e a fração silte foi verificada com o granulômetro a laser Malvern Mastersizer. As concentrações dos principais elementos foram determinadas por Espectroscopia de Raios-X por Dispersão de Energia, em fração granulométrica <0,062 mm. A composição mineralógica foi determinada por difração de raios-X utilizando o difratômetro de Raios-X Brucker D8 Advance. Índice de Alteração Química e Índice de Alteração do Plagioclásio foram aplicados. Si foi o elemento químico mais abundante nas amostras, seguido por Al, Fe, Ca, Mg, Ti e K. IAQ e IAP apresentaram valores moderados entre 56,0-73,8 e 56,5-68,3, respectivamente, e aumentaram em direção sul da península, área deglaciarizada e exposta aos processos de intemperismo por mais tempo. Difração de raios X revela em todas as amostras minerais presentes nas rochas vulcânicas: andesina e olivina. Os resultados da Análise de Componentes Principais e Análise de Agrupamento sugerem que os sedimentos estão relacionados às rochas basálticas locais. Observa-se também a influência dos processos deposicionais nas características granulométricas e morfoscópicas dos sedimentos. As condições climáticas e topográficas desempenham um papel importante na composição e concentração dos elementos nos sedimentos dos lagos, uma vez que valores moderados de Índice de Alteração Química e Índice de Alteração do Plagioclásio são indicados.

## 1. Introduction and background

In the past six decades, the West Antarctic Peninsula and offshore islands region (Maritime Antarctica) has experienced a warming of 3.7 ± 2.1°C per century (VAUGHAN *et al*., 2003; TURNER *et al*., 2014), and it has been accompanied by accelerating glacier mass loss (ABRAM *et al*., 2013). It has been also predicted that warming will continue at 0.34°C per decade until 2100 (PACHAURI *et al*., 2014). The warming has been particularly strong in summer and autumn (MARSHALL *et al*., 2006), suggesting more daily temperatures exceeding 0°C and meltwater increase (ABRAM *et al*., 2013). Torinesi *et al*. (2003) have projected an increase in the number of days with positive air temperature and, consequently, the duration of melt events at a rate of 0.5 ± 0.3d $y^{-1}$ during the 1980–2002 period.

Consequently, lacustrine formations in Maritime Antarctica are particularly important from a physical, chemical, and biological point of view, due to their large abundance in some areas (CORTIZAS *et al.*, 2014). These areas also have some specific characteristics, such as the concentration of sub-, peri-, and proglacial suspended material transported by melting flows (MOLNIEN *et al.*, 2011), and the long duration of the ice-cover isolation from external influences (HEYWOOD, 1984), preserving the sediment.

Geochemical studies on provenance and sedimentary processes in Maritime Antarctica lakes reveal combining of glacial/periglacial and geological agents, like ice, melt-water, and wind activities (PETSCH *et al.*, 2018). Whereas on continental Antarctica chemical weathering is still negligible (HALL *et al.*, 2002; LEE *et al.*, 2004), Maritime Antarctica, under warmer and more humid conditions, weathering processes may have been more significant (MONIEN *et al.*, 2011). For this reason, it is important to identify the source of the sediment, the depositional processes on these lakes, and the degree of alteration that the sediment has been suffering since the more exposition of the landscape to the weathering processes.

South Shetland Islands is located near the northern tip of the Antarctic Peninsula. It is separated from the Peninsula by Bransfield Strait, and from South America by Drake Passage (SIMONOV, 1977). The South Shetland Islands present one of the largest surface melt and runoff of Antarctica (COSTI *et al.*, 2018). The regional subpolar maritime climate is affected by storms generated in the Pacific Ocean, which results in high precipitations, influenced by the low circumpolar pressure action that favors the formation of westerly wind and wet warm air masses (SIMÕES *et al.*, 1999; RASMUSSEN and TURNER, 2003).

King George Island is the largest in the archipelago. During its glacial history, the island had several periods of glaciation and deglaciation from its maximum extension, between 20 ka and 18 ka BP (YOON *et al.*, 2000). Deglaciation process initiated between 11 ka and 9 ka BP (WATCHAM *et al.*, 2011). These changes have been regionally accompanied by the creation of new ice-free areas, favoring soil formation, as well as several lakes and ponds (BRAUN and GOSSMANN, 2002; COOK *et al.*, 2005). Periglacial processes and landforms, and the occurrence of permafrost are among the most relevant geomorphological elements of these ice-free areas (LÓPEZ-MARTINEZ *et al.*, 2012).

The current average temperature of King George Island fluctuates from 1.1 in December to 2.2°C in January, with relative air humidity of 89% (YOON *et al.*, 2000). The precipitation as rain during the summer months produces meltwater (YOON *et al.*, 1997; TURNER *et al.*, 2005). The ice-free Fildes Peninsula lies at the southwestern end of the island (Figure 1). The observed mean annual air temperature at Bellingshausen station is −2.3°C at sea level and daily summer temperatures are usually higher than 0°C. The annual trend (1969−2010) is ±0.259 K decade$^{-1}$± 0.172 K decade$^{-1}$ (RÜCKAMP *et al.*, 2011). The precipitation as rain during the summer months produces high water availability (YOON *et al.*, 1997; TURNER *et al.*, 2005).

This work investigates the sedimentary processes on the deglaciated area of Fildes Peninsula, King George Island, Maritime Antarctica, based upon the morphological, mineralogical composition and chemical characteristics of shallow lacustrine sediment.

## 2. Study area

The low relief of Fildes Peninsula with plateaus and valleys has a total area of 29 km² and elevations below 150 m above sea level (MICHEL *et al.*, 2014), which consists mainly of basaltic rocks, small outcrops of volcanic tufts, sandstones, and conglomerates. The southern sector of the Fildes Peninsula is morphologically marked by structures of basaltic rocks, while the northern sector by basaltic and andesitic rocks (SMELLIE *et al.*, 1984).

The Fildes Peninsula is among the first ice-free areas of Maritime Antarctica after the Last Glacial Maximum (BIRKENMAJER, 1989). According to Tatur and Del Valle (1989) and Hjort *et al.* (1998), using lake sediments, the deglaciation in the Fildes Peninsula area was slow and gradual, between 8.7 ka and 5.5 ka BP. By 5 ka BP, minerogenic components in lake sediments increased, which were interpreted as the result of a new glacial activity that lasted until about 4 ka BP, followed by sea level rise. After that, cooler and drier conditions provided a new re-advance of the glaciers until about 1.5 ka BP (BJÖRCK *et al.*, 1991), consistent with the Neoglacial advance suggested by John and Sugden (1971) and Curl (1980). In this period, a small advance of glaciers occurred on the northern plateaus, producing morainic deposits (SERRANO and LÓPEZ-MARTÍNEZ, 2012). The ice recedes again with the predominance of a slightly warmer climate until the present conditions (INGOLFSSON *et al.*, 1998). According to Mäusbacher *et al.* (1989), the proglacial lakes have formed between 6 and 4 ka BP.

The remaining glacial areas also undergo the action of other agents, such as precipitation, slope activities and meltwater flows, which can rework and alter the original sedimentary characteristics. Fildes Peninsula experiences a paraglacial-periglacial gradient in the north-south direction. The paraglacial features are concentrated in the northern part, influenced by Collins Glacier, where the glacial processes are more evident, with the exposition of a recent set of moraines (HALL, 2007).

The periglacial landforms occupy approximately 70% of the southern sector of the peninsula, which are dominant above 50 m above sea level. Periglacial features predominate between 0 and 20 m, however, they are associated with the snow and gravitational processes. The remaining 30% is constituted by structural reliefs and rocky outcrops shaped by glacial erosion (MICHEL *et al.*, 2014).

## 3. Lakes and wetlands

The climate and topography have influenced the drainage system of the Fildes Peninsula. There is no river valley, but valleys of tectonic and glacial origin are used by present-day water flows (SIMONOV, 1977). There are a large number of lakes and wetlands in the ice-free area and these remain thawed in the short summer period. Most of the lacustrine basins develop in glacial basins and the valleys of the major streams are glacial gullies located along fracture lines (MICHEL *et al.*, 2014). Melting water from Collins Glacier flows to the proglacial lakes in the northern sector (PETSCH, 2018). Nevertheless, lakes and drainage systems are also found in the periglacial zone, without having necessarily glacial origin, but by snowmelt, liquid precipitation and from the melting of the active layer of permafrost (FRENCH, 2007; PETER *et al.*, 2008, PETSCH, 2018). The water level of the lakes is maintained by these factors and is controlled by the variations of the weather conditions during the summer months (BARSCH *et al.*, 1985). The SCAR KGIS database (VOGT *et al.*, 2004) records 109 lakes on Fildes Peninsula, and Peter *et al.* (2008) record 101 lakes, classified into perennial, permanent and temporary lakes. Vieira *et al.* (2015) proposed a lake classification into proglacial, meltwater, temporary, mixed and wetland.

## 4. Methods

Fieldworks were conducted during March/April 2013 in the Fildes Peninsula. Surface sediment (between 10 and 15 cm long) was sampled in water depths ranging from 50 cm to 1 m, along the north-south transect, to assure a spatial variation that can reflect the processes operating on the region. Three replicates were processed for each sample. For this work, nine sediment sampling sites were used: C2, C3, C5, C6, C10, C11, C12, C13 and C14 (Figures 1 and 2).

The samples were stored in plastic bags and frozen at < -4 °C until laboratory analyses. Granulometric, morphoscopic, inorganic geochemical records were used for provenance and weathering of source rocks, and sediment transportation analyses. Before them all samples were freeze-dried for 3 days, subsequently dry-sieved at 0,062 mm, and gently macerated. Each sediment sample was treated with hydrogen peroxide to remove carbonates and organic matter, and with sodium hexa-meth-phosphate (HMP) as a deflocculant.

The particle size distribution of sand fractions was obtained by the CAMSIZE analyzer, and the silt samples were analyzed by the Malvern laser light scattering granulometer. These analyses were performed in the Sedimentology Laboratory, Institute of Geosciences, Federal Fluminense University (UFF). The software Gradistat (BLOTT and PYE, 2001) calculated the statistical analysis. The weight of the granulometric fractions was calculated as weight percentages with a digital scale (instrument error of 0.001 g).

Clast shape analysis at the granule-and-pebble-size fractions (>2 mm) was carried out with the aid of a binocular microscope. Powers (1953) comparison table, modified by Hubbard and Glasser (2005), was used for the estimation of roundness. Roundness classes for each sample were converted into percentages. For the lithological analysis, the adopted sample size was 50 clasts > 0.5mm. Clasts were examined using a binocular microscope, subdivided into classes based upon their lithological properties, and compared to the mineral database available at http://www.webmineral.com, in addition to the works of Klein and Dutrow (2012), and Perkins (2014).

The major chemical elements of the samples were defined by the finer fractions (< 0,062 mm) in Energy

Dispersive X-ray Fluorescence (EDXRF) Spectrometer (SHIMADZU EDX-720). X-ray fluorescence spectrometry is a non-destructive technique that allows identifying the elements present in a sample as well as establishing its concentration.

The percentage of the weight of the chemical elements was used as reference parameters for the analysis. The sediments were prepared in the Sedimentology Laboratory of the Institute of Geosciences (Fluminense Federal University) and analyzed in the Laboratory of Reactors, Kinetics, and Catalysis in the Chemical Engineering Department at UFF.

The X-ray spectrometry does not destroy the sample, so it is possible to use the same aliquot for the mineralogical analysis. The mineralogical composition was determined to ascribe provenance, by X-ray diffraction by a Brucker D8 Advance x-ray diffractometer (XRD) in the X-Ray Diffraction Laboratory, Institute of Physics at UFF. Each sample was scanned from 2° 2θ to 70° 2θ with CuKα radiation (40 kV and 40 mA), using a 0.02° 2θ scanning step and 0.5 s counting time per step, with an LYNXEYE detector. Minerals were identified from their characteristics peaks with DIFRA EVA software, using USGS (United States Geological Survey) mineral database. The crystalline XRD method facilitates the investigation of small structures of the material and the conditions in which they diffract, allowing the knowledge of the crystalline substances and the identification of the main minerals of the sediment (SILVA, 2013).

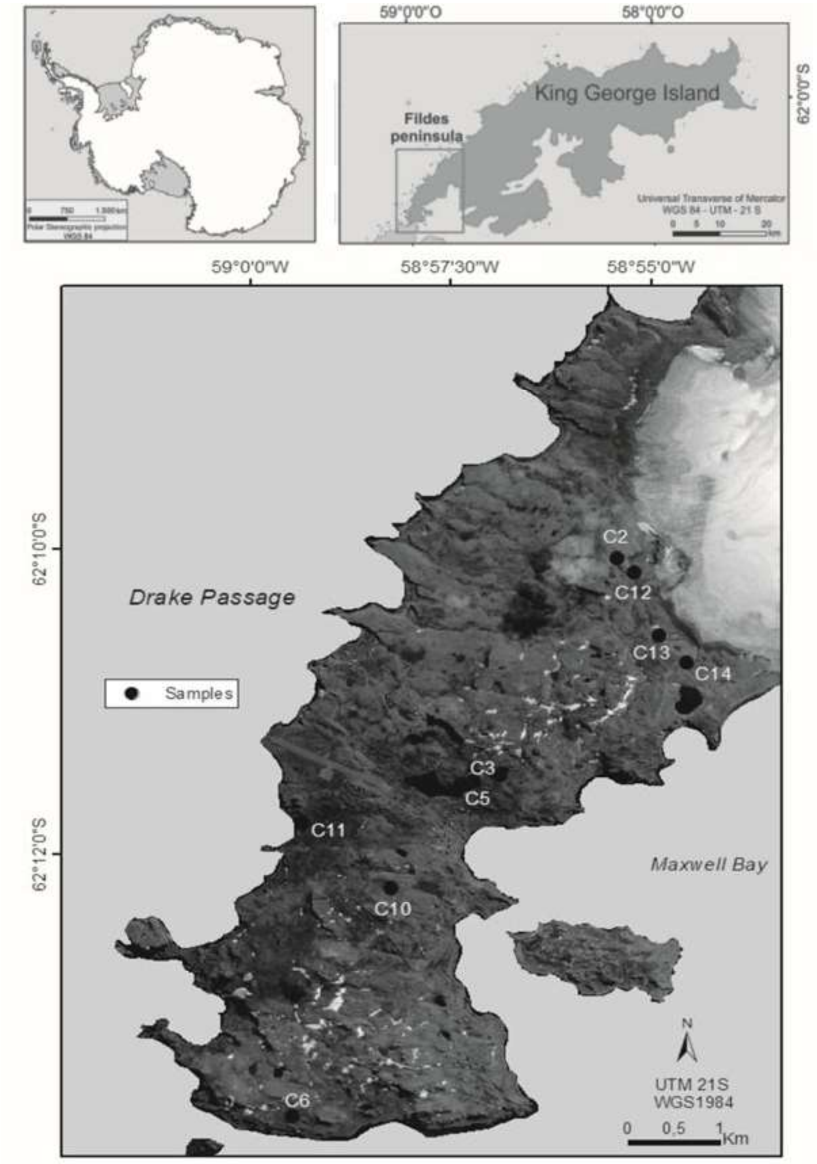


*Figure 1 – Fildes Peninsula and sampling sites. QuickBird imagery, 2012 (USGS).*


*Figure 2 – Photographs showing: (a) C12 sampling site, proglacial lake in the north peninsula; (b) C13 sampling site, proglacial lake in the north peninsula; (c) C14 sampling site, proglacial lake in the north peninsula; (d) C3 sampling site in the central peninsula; (e) C5 sampling site in the central peninsula; (f) C11 sampling site on the coastline; (g) C10 sampling site in the central peninsula; (h) C6 sampling site in the south peninsula.*

One approach to estimate the degree of chemical weathering by Chemical Index of Alteration – CIA (NESBITT and YOUNG, 1982), and Plagioclase Index of Alteration – PIA (FEDO *et al*., 1995) were calculated. Usually, the CIA ranges between 50 for fresh rocks and 100 for highly residual clay. The PIA attains values following the values derived from the CIA formula (NADLONEK and BOJAKOWSKA, 2018). CIA and PIA values were calculated according to the formulas.

$$CIA = [Al_2O_3 / (Al_2O_3 + K_2O + Na_2O + CaO)] \times 100 \quad (1)$$

$$PIA = [Al_2O_3 - K_2O) / (Al_2O_3 + CaO + Na_2O - K_2O)] \times 100: \quad (2)$$

Statistical analyses, including Pearson correlation coefficients and *p*-values (two-tailed test of significance), were conducted. Correlation with $p < 0.05$ were considered. Cluster Analysis and Principal Component Analysis (PCA) were used to access the spatial distribution pattern of the chemical elements. Logarithmic transformation was used before the application of multivariate statistics. In the cluster analysis, Ward, Simple and Paired methods were employed. Euclidean distance was used for the distance measure (ALFONSO *et al*., 2015). For the Principal Component Analysis, the correlation coefficient was used as the initial matrix of similarities, to eliminate the effect of scale. Multivariate analyses were carried out in PAST 3 free software.

## 5. Results

Particle size analysis shows the predominance of sand and silt fractions, distributed in coarse, medium sand and very coarse silt classes (Table 1). Five sites presented a high proportion of sand content (>94%): C2, C3, C5, C6, C11. Sand fractions also dominate in the remaining four samples: C10, C12, C13, and C14, but with a higher percentage of silt content, varying from 20.9 to 32%. The C12, C13 and C14 sampling sites are located near Collins Glacier margin that provides the proglacial lakes fine-grained sediment by the subglacial meltwater flow. Sediments from these three proglacial lakes have the same granulometric characteristics of those sampled in their glaciofluvial channels by Petsch *et al*. (2018). The increasing liquid precipitation and the glacier retreat can generate a greater amount of water and, consequently, increased sediment load to the proglacial areas (BALLANTYNE, 2002; UHLMANN *et al*., 2013; LANE *et al*., 2016).

The particle shape was dominated by rounded (R) and subrounded (SR), being the rounded grains predominant in five of nine sampling sites: C3, C5, C6, C10, and C11. Very angular and well-rounded grains are rare or absent. A higher percentage of angular clasts is present in the central and northern sectors of the peninsula. C11 sampling site, located on the coastline, has the highest percentage of rounded grains, as well as C6 sampling site, in the southernmost lake of the peninsula, an early-deglaciated area. The C12 and C13 sampling sites, close to Collins Glacier margin, have high percentages of rounded grains. The summaries of the particle shape are presented in Table 1 and Table 2.

Using a binocular microscope, olivine is identified in all samples. This mineral is characteristic of basalt and basalt with aphanitic texture. The texture of igneous rock formed entirely or mainly by fine and homogeneous granulometry, which even with the aid of the magnifying glass, the grain distinction is complex (COSTA, 1979). Granite textured diorite (C5 and C6 sampling sites), quartz diorite (C6 and C12 sampling sites), dacite with crystals of plagioclase (C3 sampling site) are also identified. In the sand fraction, plagioclase is highlighted as the main mineral component, with grains altered along the north-south peninsula transect. The presence of plagioclase in the sediments reflects their volcanic origin (BERTRAND and FAGEL, 2008).

Si predominates in the chemical composition of the sediments in all samples, followed by Al, Fe, Ca, Mg, Ti, K, and Mn, respectively (Table 3). Si (43.05–47.68%) composes the major minerals of igneous rocks, like olivine and plagioclase. Basalt contains 45–50 wt% of Si, and Fe, Ca and Mg also are the major components (SMELLIE *et al*., 1984). The samples have moderate to high Al content (19.40–22.48%), probably because of variations in the plagioclase content (MACHADO *et al*., 2005). This distribution is in agreement with the results obtained by Alfonso *et al*. (2015) in the central and southern areas of the peninsula.

Fe/K ratios have been used as an indication of the relative magnitude of the terrestrial contribution and physical/chemical weathering (STUUT *et al*., 2005; GOVIN *et al*., 2012). High Fe/K values suggest a more humid climate, associated with higher chemical weathering compared to physical weathering (STUUT *et al*., 2005). Higher Fe/K ratios observed over southernmost sampling sites indicate a different pattern of chemical weathering acting on the Fildes Peninsula (Figure 3). Although Fe/K values grow towards the south, two situations can be observed: lake C11 is close to the coastline (Figure 2g) and lake C6 (Figure 2i), despite its location in the southernmost peninsula, the sediment has a smaller ratio in comparison with other lakes located in the central part. It is inferred that local topography may influence this result (Table 1 and Figure 2i).

Considering topographic features, the C11 sampling site is the only one located below 40 masl, and the C6 sampling site is set above 120 masl. The other sampling sites are distributed between 40-120 masl. Slope class between 0-10% predominates; the class 10-20% prevails in C11 (Figure 2g) and C14 (Figure 2d) sampling sites, and class 20-30% in the C6 (Figure 2i) and C10 (Figure 2h) sampling sites (Table 1).

**Table 1: Distance to the Collins Glacier and the coastline, and topographic characteristics of the sampling areas.**

| Sampling site | Distance to Collins Glacier (m) | Distance to coastline (m) | Hypsometry (m) | Declivity (%) |
|---|---|---|---|---|
| C2 | 740 | 2700 | 80-120 | 0-10 |
| C3 | 5600 | 1400 | 40-80 | 0-10 |
| C5 | 6900 | 1005 | 40-80 | 0-10 |
| C6 | 15400 | 608 | 120-150 | 20-30 |
| C10 | 8900 | 1250 | 40-80 | 20-30 |
| C11 | 10050 | 120 | 0-40 | 10-20 |
| C12 | 590 | 3810 | 80-120 | 0-10 |
| C13 | 930 | 2560 | 80-120 | 0-10 |
| C14 | 300 | 1488 | 40-80 | 10-20 |

Chemical Alteration Index (CIA) and Plagioclase Index of Alteration (PIA) point to weathering action in the north-south transect (Figure 4). The values above 85 indicate an intense chemical weathering and values between 45 and 55 indicate the absence or incipience of this process. Fresh basalt has values between 30 and 45 (NESBITT and YOUNG, 1982; FEDO *et al*., 1995). High values indicate intensive chemical weathering due to high precipitation and air temperatures, whereas low values may evidence a colder and/or more arid climate where physical weathering prevails. The CIA values in the Fildes Peninsula vary between 56.0 and 73.8 (average – 63), while PIA values range between 56.5 and 68.3 (average – 62.6), which reveal moderate weathered particles. These values approximate the results of Alfonso *et al*. (2015). It is observed that both CIA and PIA values increase towards the south peninsula, early-deglaciated area and more exposed than the northern sector with paraglacial and glacial processes. Some topographic characteristics could also influence these values: C2 (Figure 2a), C12 (Figure 2b) and C13 (Figure 2c) lakes are at 80-120 masl, and have lower CIA and PIA values, compared to C14 lake (Figure 2d), the closest sampling site to Collins glacier margin. C14 lake is localized at a lower altitude, is surrounded by steep slopes, and receives sediment from other proglacial lakes (C13 and C12). C5 (Figure 2f) lake also receives sediment from other lacustrine formations.

Pearson correlation and linear regression were performed between the CIA / PIA values and the approximate distance of the collection points, with respect to the coastline and to the Collins Glacier front (Figures 5 and 6). CIA / PIA show significant ($p$< 0,05) negative linear correlation with coastline distance (r =-0.81 / r = - 0,75; $r^2$ = 0,66 / $r^2$ = 0,57; n = 9), and significant ($p$< 0,05) positive linear correlation with Collins glacier distance (r = 0,88 / r = 0,86; $r^2$ = 0,78 / $r^2$ = 0,74; n = 9).

The values of CIA and PIA are higher in lake C6 (Figure 7a), the southernmost point of the peninsula (15400 m distant from Collins Glacier margin), followed by the C10 site in the central part (8900 m distant from Collins Glacier margin). The lowest values are found for the proglacial lakes C2, C13, and C12, located near to the Collins Glacier margin (Figure 7b).

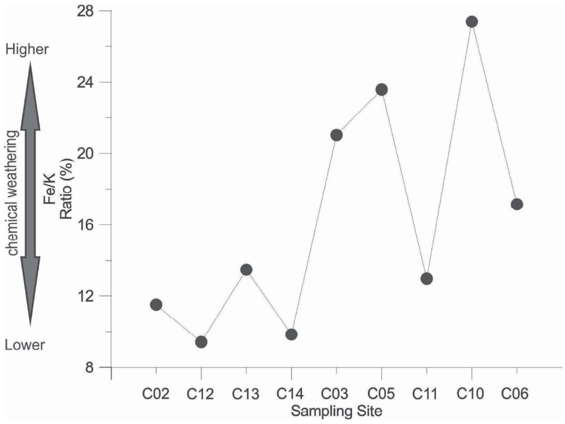


*Figure 3 – Distribution of sampling sites and the Fe/K ratio in the north-south transect.*

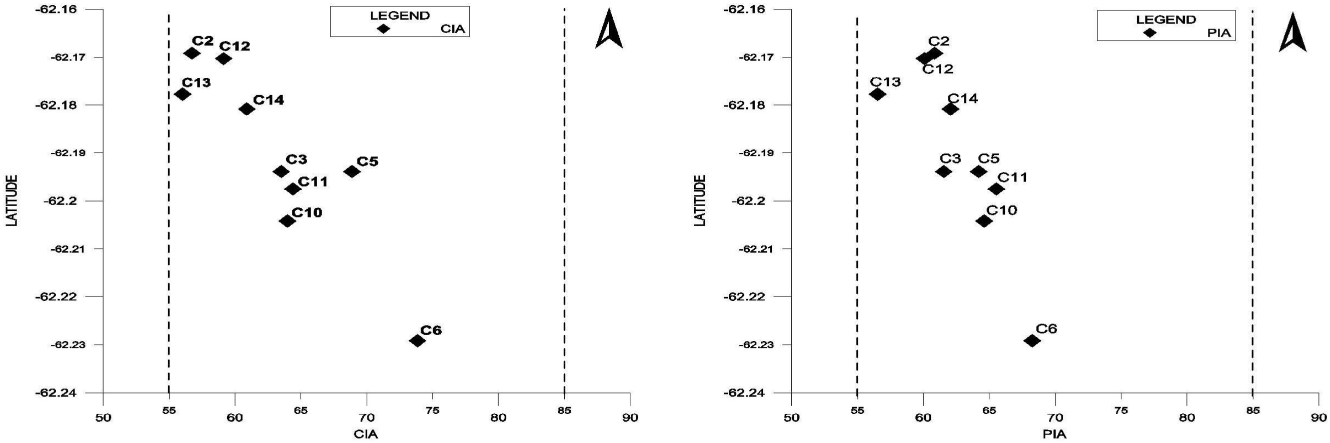


*Figure 4 – Distribution of sampling sites and Chemical Index of Alteration (a) and Plagioclase Index of Alteration (b) in the north-south transect.*

**Table 2: Particle size distribution in lacustrine sediments.**

| Sampling Sites | Coordinates | Altitude (m) | Sand (%) | | | | | Silt (%) | | | | | Textural Group | Roundness* |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Coarse sand | Medium sand | Fine sand | Very fine sand | Total | Very coarse silt | Coarse silt | Medium silt | Fine silt | Total | | |
| C2 | 62°10’13”S 58°55’31”W | 40 | 0.0 | 23.9 | 35.5 | 35.2 | 94.6 | 5.4 | 0.0 | 0.0 | 0.0 | 5.4 | Sand | SA-A |
| C12 | 62°10’40”S 58°55’14”W | 38 | 0.0 | 30.4 | 25.8 | 19.9 | 76.1 | 23.9 | 0.0 | 0.0 | 0.0 | 23.9 | Muddy sand | SR-R |
| C13 | 62°10’9” S 58°55’36”W | 5.5 | 0.0 | 18.8 | 26.0 | 34.0 | 78.7 | 21.3 | 0.0 | 0.0 | 0.0 | 21.3 | Muddy sand | SR-R |
| C14 | 62°10’51”S 58°54’46”W | 38.5 | 0.0 | 16.3 | 4.6 | 47.1 | 68.0 | 32.0 | 0.0 | 0.0 | 0.0 | 32.0 | Muddy sand | SA-A |
| C03 | 62°11’38”S 58°57’39”W | 17.9 | 71.3 | 14.7 | 12.6 | 1.4 | 100.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | Sand | R-SR |
| C05 | 62°11’38”S 58°57’45”W | 17.3 | 0.0 | 59.4 | 22.1 | 18.3 | 99.8 | 0.2 | 0.0 | 0.0 | 0.0 | 0.2 | Sand | R-SR |
| C11 | 62°11’51”S 58°59’41”W | 10.2 | 0.0 | 58.1 | 24.0 | 12.8 | 94.9 | 5.1 | 0.0 | 0.0 | 0.0 | 5.1 | Sand | R-SR |
| C10 | 62°12’15S 58°58’57”W | 43.7 | 0.0 | 22.0 | 27.0 | 20.1 | 79.1 | 20.9 | 0.0 | 0.0 | 0.0 | 20.9 | Muddy sand | R-SR |
| C06 | 62°13’45”S 58°59’56”W | 42,8 | 0.0 | 34.5 | 29.2 | 33.1 | 96.8 | 3.2 | 0.0 | 0.0 | 0.0 | 3,2 | Sand | R-SR |

** SA – Subangular, A – Angular, SR – Subrounded, R – Rounded.*

**Table 3: Chemical composition along the Fildes Peninsula lakes.**

| Sample | Major elements (%) | | | | | | | | | Minor and trace elements (%) | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Si | Al | Fe | Ca | Mg | Ti | Na | K | Mn | S | Ba | Sr | Zr | Zn | P |
| 02 | 43.78 | 19.40 | 17.79 | 8.85 | 5.70 | 1.86 | 3.01 | 1.54 | 0.35 | 0.08 | 0.45 | 0.14 | 0.04 | 0.03 | - |
| 12 | 46.56 | 19.95 | 16.36 | 8.32 | 4.57 | 1.52 | 3.40 | 1.73 | 0.58 | 0.03 | 0.14 | 0.16 | 0.02 | 0.02 | 0.03 |
| 13 | 44.31 | 18.93 | 17.43 | 9.47 | 5.71 | 2.08 | 4.10 | 1.29 | 0.33 | 0.07 | 0.17 | 0.13 | 0.03 | 0.02 | - |
| 14 | 47.30 | 20.07 | 15.81 | 7.97 | 4.76 | 1.52 | 3.32 | 1.60 | 0.36 | 0.01 | 0.31 | 0.13 | 0.03 | 0.01 | 0.10 |
| 03 | 42.67 | 20.61 | 16.84 | 8.99 | 8.20 | 1.02 | 2.06 | 0.80 | 0.32 | 0.07 | 0.17 | 0.15 | - | 0.16 | - |
| 05 | 43.05 | 21.22 | 17.46 | 8.85 | 6.43 | 1.19 | 3.95 | 0,74 | 0.47 | 0.05 | 0.33 | 0.06 | 0.01 | 0.01 | - |
| 11 | 43.89 | 21.75 | 15.48 | 9.17 | 5.71 | 1.21 | 1.65 | 1.19 | 0.19 | 0.77 | 0.26 | 0.18 | 0.01 | 0.01 | 0.02 |
| 10 | 47.68 | 19.77 | 17.53 | 7.20 | 5.01 | 1.43 | 3.28 | 0.64 | 0.38 | 0.11 | 0.57 | 0.11 | 0.03 | - | 0.10 |
| 06 | 45.04 | 22.48 | 17.50 | 6.94 | 4.27 | 1.51 | 3.04 | 1.02 | 0,37 | 0.14 | 0.30 | 0.10 | 0.02 | 0.03 | - |

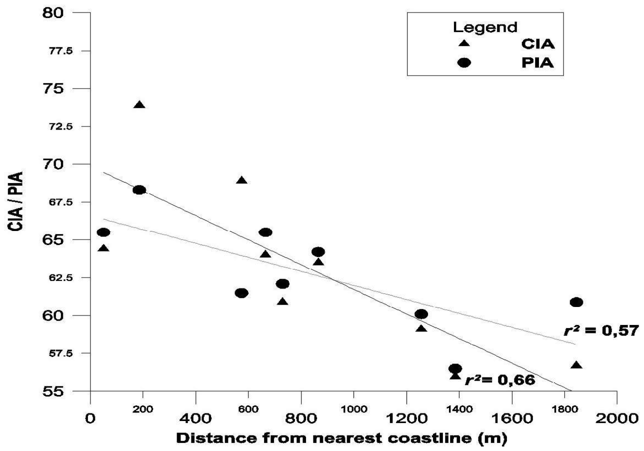


*Figure 5 – CIA and PIA as a function of distance from the coastline. The determination coefficients (r2) apply to power curves fitting through the points. Graph made with Grapher software.*

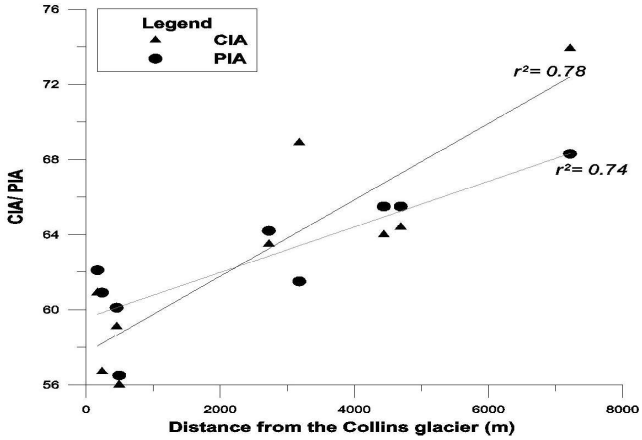


*Figure 6 – CIA and PIA as a function of distance from Collins Glacier. The determination coefficients (r2) apply to power curves fitting through the points. Graph made with Grapher software.*

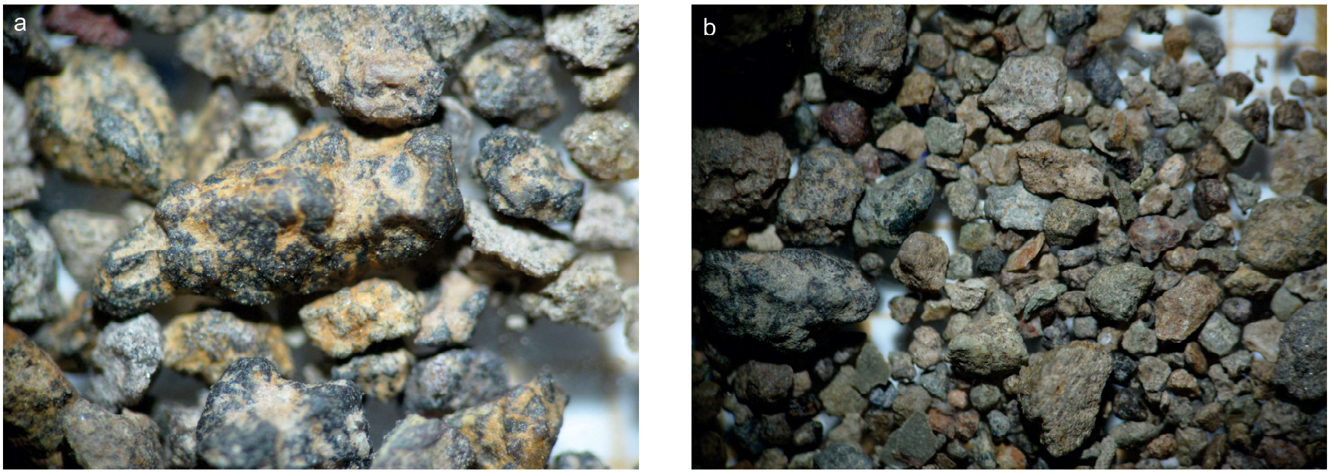


*Figure 7 – View of the sediments (> 500 mμ) in a microscopic magnifying glass. The sample C6 (a), located in the south peninsula, already exhibits signs of alteration, while the C12 sample (b), closest to the Collins Glacier, in the north, contains still preserved sediment. Magnification of photo in 36X.*

X-ray diffraction (XRD - Figures 8a-i) revealed the prevalence of two minerals in all samples: andesine (feldspar group/plagioclase series), and olivine (neso-silicate). Andesine is widespread in igneous rock of intermediate silica content, as andesites. The dominance of these minerals is consistent with the major lithological characteristics of the Fildes Peninsula: weathered olivine-basalt rocks, basalt-andesite or andesite rocks (BIRKENMAJER, 1989; SMELLIE *et al.*, 1984; XIANGSHEN and XIAOHAN, 1990).

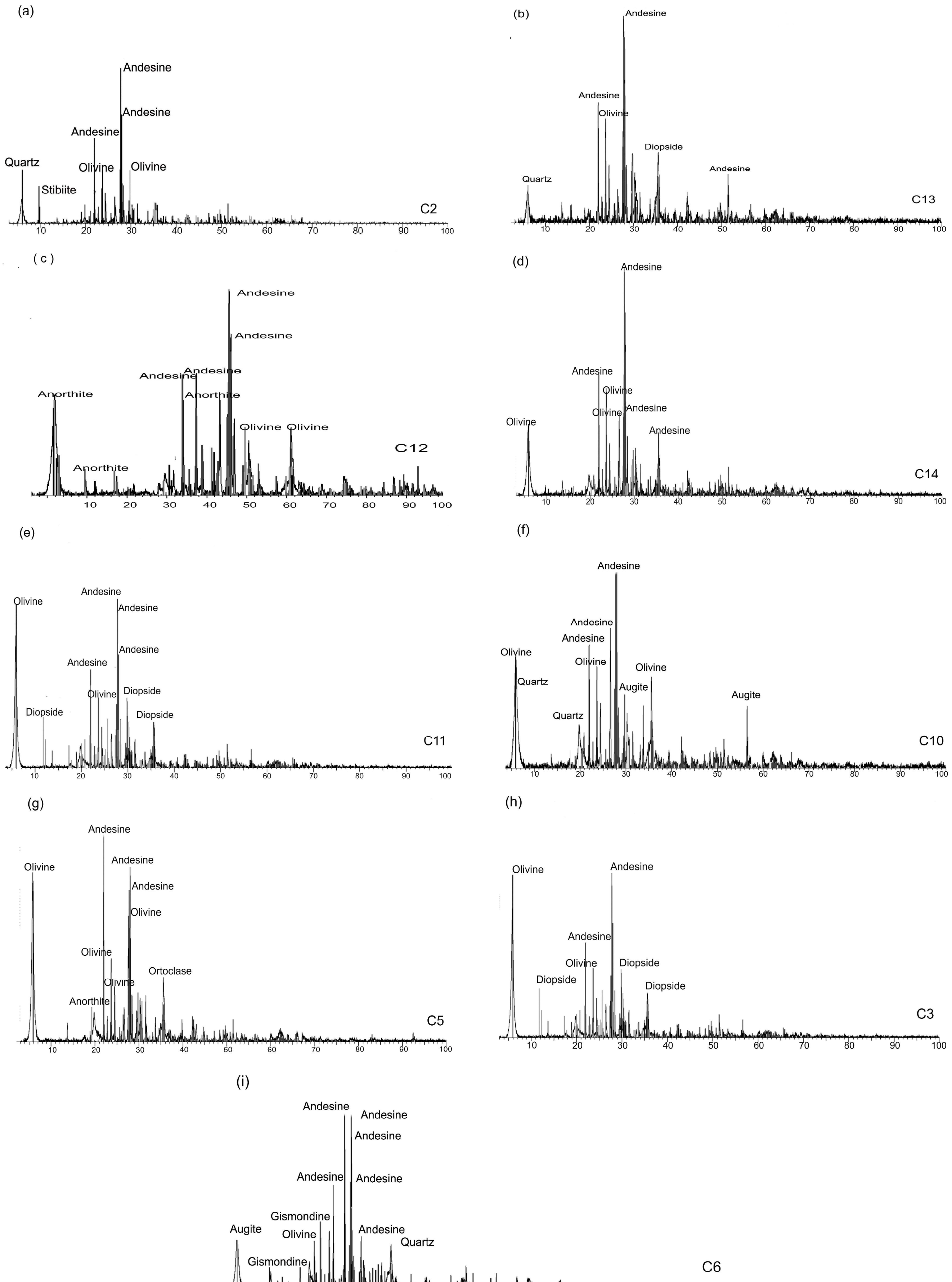


*Figure 8 – Diffratograms of the lacustrine sediments of sample sites: (a) C2; (b) C13; (c) C12; (d) C14; (e) C11; (f) C10; (g) C5; (h) C3; and (i) C6.*

Cluster and Principal Component Analysis (PCA) were applied to obtain similarities and differences between lakes and correlations between chemical elements. The cluster analysis is used in this work as a tool, not as a statistical test. Figures 9a-c show dendrograms with Ward, Simple and Paired methods. The three methods propose the same three groups: (1) lakes C14 and C12 – proglacial lakes; (2) lake C11 - coastline; (3) lakes C10, C5, C3, C13, C2, and C6.

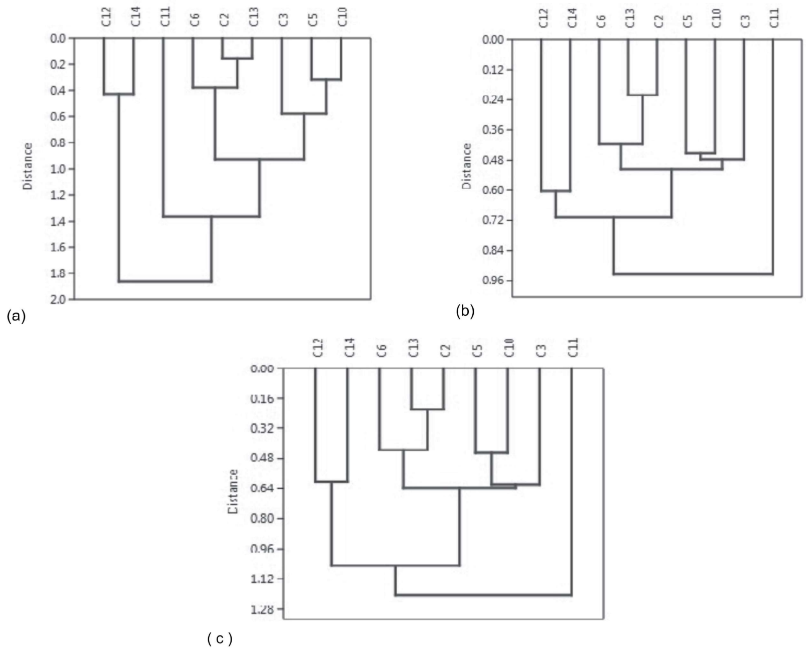


*Figure 9 – Dendrogram elaborated by Ward (a); Simple (b) and Paired (c) methods.*

The lakes of group 1 (C12 and C14) are proglacial and are separated by a narrow channel. Both lakes are near to the Collins Glacier margin (590 m and 300 m distant, respectively), and this suggests that the most sedimentary material is accumulated close to the glacier margin. On the other hand, group 2 (lake C11) is situated on the coastline with marine influence (120 m from the coastline). Group 3 (lakes C6, C2, C13, C3, C5, and C10) corresponds to the lakes of the north, central and south peninsula that receive the sediment load from the surrounding areas, which reveals the influence of the local geology and sedimentary processes.

PCA records are shown in Figure 10. The first two components account for 73.80% of the variance (44.76 and 29.04%, respectively). The Principal Component Analysis biplot shows the same three groups observed in the cluster analysis: (a) lakes 12 and 14; (2) lake 11, and (3) lakes 2, 3, 5, 6, 10 and 13.

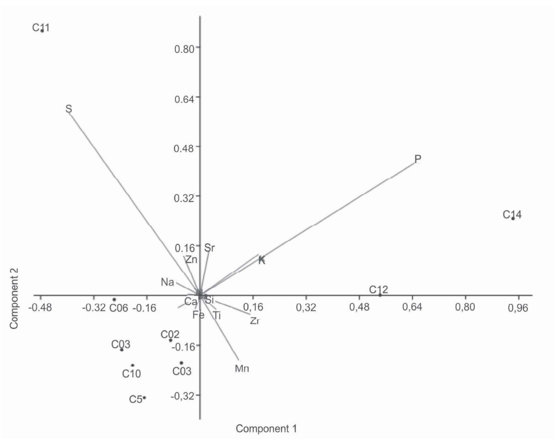


*Figure 10 - Biplot of the first two components of a Principal Components Analysis for the set of chemical elements. 44.76% of the variance is explained by component 1 (horizontal axis) and, 29.04% is explained by component 2 (vertical axis).*

## 6. Discussion

### Particles granulometry and shape

Considering the particle sizes, medium and fine sands are the predominant classes in the shallow lacustrine sediments of the Fildes Peninsula (Table 1). These characteristics may indicate the influence of mechanical weathering, erosive action, and the transport of the sediment from surrounding areas to the lakes, as well as to the period of fusion in the summer season with glaciofluvial and fluvioglacial input. The meltwater flows are intermittent and unable to carry the coarse particles since the relief is not prominent. The superficial sediment samples from the lakes closest to the Collins Glacier, despite the predominance of sands, contain a percentage of fine fraction (< 63 μ) as a function of subglacial transport. The presence of this material is indicative of the wet basal thermal regime of the glacier, also observed by Petsch (2018).

The roundness of the particles shows that the highest amount of angular grains was found in samples located in the north and central parts of the peninsula. The C11 and C6 sampling sites present the highest percentage of rounded sediment (Table 1), the first one situated closest to the sea, and the last one in the south peninsula, which is more exposed to the weathering agents over time. C12 and C13 sampling sites, close to Collins Glacier margin, also present a considerable percentage of rounded and subrounded grains, which could be related to an active transport at the base of the glacier. The angular material of some samples may be related to the fracturing process during transport since it generates new edges and faces (BENN and BALLANTYNE, 1994; LEWIS and MCCONCHIE, 1994). It is relevant to consider the action of physical weathering that operates in the peninsula and produces this type of sediment. On the other hand, the rounded sediment in the southern sector (C6 site) and along the coastline (C11 site) may also be associated with the periglacial and marine actions, respectively.

In the transport of grains, the participation of the wind could be taken into account (LEE *et al*., 2004), since this agent is also capable of producing their rounding. Nevertheless, the influence of glacial, paraglacial and periglacial conditions on the depositional environments is more marked.

### Weathering and source of the sediments

The geochemical analysis exposes a moderate degree of weathering in the superficial lake sediments. However, the degree of weathering increases southwards. In the deglaciated area with sediment exposed for a longer time, the rates of change increase, occurring the opposite towards the Collins Glacier marginal area, recently deglaciated area. The C6 lake, in the southernmost sector of the peninsula, and with the highest chemical changes, has the highest value of Al, which suggests that, with increasing chemical weathering, sediments are gradually enriched with alumina minerals (MACHADO *et al*., 2005; ALFONSO *et al*., 2015).

Although the C14 site is a proglacial lake, it shows moderate rates of CIA and PIA and, even superior to the lakes located in the central part of the peninsula, such as C3, C5, and C11 sites. This could be justified by the role of the chemical composition of the surrounding bedrock. The depth and size of the lake can also influence the weathering processes of the materials on a time scale. Besides, C14 receives water flow from two other lakes (C12 and C13), which can concentrate the reworked material. Lake C11 is the closest sampling site to the coastline and has the highest Si value and the second-largest in Ca values. The other lakes of the peninsula receive the contribution from the surrounding area by the action of the wind, snowmelt flow, and permafrost thaw, due to the increasing depth of the active layer and the water availability (PETER *et al*., 2008).

Major elements, such as Si, Al, and Fe, presented a similar distribution pattern suggesting the same source and similar processes of deposition, controlled by the input of terrigenous material from the catchment area, as can be inferred with the Fe/K ratio (Figure 3). It is observed the constant presence of minerals associated with the basalt rocks in all samples, as olivine phenocrysts, as well as andesine and anorthite, which are in agreement with the geological structure of the area. Therefore, the weathering tendency of the basaltic rocks near the lakes is inferred, which was also recorded by Alfonso *et al*. (2015). The results of the mineralogical composition of the lacustrine sediments are comparable with the soil composition of the area (SIMAS *et al*., 2006; MICHEL *et al*., 2014), but to these authors, chemical weathering is mainly associated with the faunal activity.

According to Srivastava *et al*. (2013), deglaciated areas have long been susceptible to erosive agents. The perception of weathering in cold regions identifies three basic principles: (a) weathering is dominated by mechanical processes; (b) freeze-thaw is the predominant mechanical process; (c) chemical weathering is not a significant element of cold region processes because of low temperatures (HALL *et al*., 2002).

In comparison with continental Antarctica, the Maritime Antarctica region has a higher level of chemical weathering due to its mild oceanic conditions, with temperatures above zero and high summer humidity. In an environment where the temperature is rising the greater availability of water in its liquid state favors the chemical weathering to a greater extent than in other Antarctic areas (SANTOS *et al*., 2007). In King George Island, for instance, chemical weathering is an active process in permafrost areas with the dissolution of primary alumino-silicates and limited leaching of dissolved Al, Fe, and Si. Chemical weathering is enhanced at some sites by the oxidation of sulfides present in the parent material, and by faunal activity (SIMAS *et al*., 2006; MICHEL *et al*., 2006). Some authors, such as Lee *et al*. (2004), and Machado *et al*. (2005) argue that in glacial and periglacial regions chemical weathering is limited or even insignificant, with the predominance of physical processes related to water freezing and thawing. Santos *et al*. (2007) conclude that in ice-free areas of Maritime Antarctica the periglacial erosion prevails in spite of the regional environmental setting, and the physical weathering is likely to be regionally much more important than chemical weathering. Lee *et al*. (2004) suggest that the CIA value of the soils in the Barton Peninsula (King George Island) may not indicate the chemical weathering of the local bedrock, but as a result of mixing with eolian pumice shards from Deception island. Consequently, the measure of chemical weathering degree should be used with caution.

Nevertheless, the chemical weathering north-south gradient observed in the Fildes Peninsula does not match with the major influence of the wind as suggested by Lee *et al*. (2004). Besides, the Fe/K ratios, PCA and the cluster analysis results indicate a substantial influence of local bedrock, as well as of the soils.

In Maritime Antarctica, the summer period is the most important season for chemical, physical and biological processes in ice-free areas (SIMAS *et al*., 2007). In a study on the variability of the size of lakes in the Fildes Peninsula, Petsch (2018) links the rising temperature and precipitation with the thawing of the lakes, once the ice layer breaks and meltwater flow increases from the surrounding areas covered by snow and ice, besides from the active layer of permafrost. Changes in the temperature and precipitation pattern, vegetation and faunal expansion, and the soil formation can influence the chemical weathering intensity, as well as the permafrost degradation can increases thaw and the active layer thickness. Petsch *et al*. (2019) calculated the growth of a vegetated area of 1.5 $km^2$ in the period 1989-2017. Such processes lead to changes in the geomorphological dynamics and the transfer of sediment to the lacustrine areas (BOCKHEIM *et al*., 2013; THOMAZINI *et al*., 2016; De PABLO, 2017).

## 7. Conclusion

Based on the results obtained from shallow lacustrine samples along the north-south transect in the Fildes Peninsula it is suggested the influence of the depositional processes on the granulometric characteristics of the sediment, and the major influence of local basaltic and andesitic volcanic rocks on the sedimentary material. Climatic conditions and local topography have a relevant role in the composition and concentration of the elements in the lacustrine sediments. Weathering of local rocks is considered the major source of sediment. The degree of chemical weathering of sediments varies gradually from north to the south peninsula. Moderate degrees of weathering are found, with increased values towards the southern areas of the peninsula. This sector has been deglaciated earlier, therefore, exposed to the atmospheric phenomena. However, chemical weathering is also present in the northern part, near the glacier margin, which can be justified by the susceptibility of basaltic and andesitic rocks to chemical weathering that promotes the overall presence of minerals associated to these rock-types in the shallow lacustrine sediment, and the local topography. The results are in agreement with other studies that indicate an increase in net precipitation in summer and a greater flow of melting water from the surrounding area of the lakes, the Collins Glacier, and the permafrost soils. Therefore, it is worth that chemical weathering can expand larger than previously thought.

Although some studies argue that in the glacial areas the chemical weathering is limited, with the predominance of physical processes related to the freezing and thawing of the water, the regional and local rising temperature provides more water availability in its liquid state, which favors chemical weathering. Despite the complexity of the environmental and geochemical processes, the further research that includes information on the chemical weathering action in these regions is important for future comparative studies, and, Maritime Antarctic region, sensitive to climate change, must be constantly monitored.

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