An Acad Bras Cienc (2024) 96(Suppl. 2): e20240584 DOI 10.1590/0001-3765202420240584
Anais da Academia Brasileira de Ciências | *Annals of the Brazilian Academy of Sciences*
Printed ISSN 0001-3765 I Online ISSN 1678-2690
www.scielo.br/aabc | www.fb.com/aabcjournal

SOIL SCIENCE

Salt-affected soils in the Lopez de Bertodano Formation, polar semi-desert of Seymour Island, Antarctica: topographic or lithological controls?

DANIEL N. KRUM, CARLOS ERNESTO G.R. SCHAEFER, FÁBIO S. OLIVEIRA, ROBERTO F.M. MICHEL, HEITOR P. PALMA, MARCOS PAULO E. TOMAZ, ANA CAROLINA P. AMARAL, MÁRCIO R. FRANCELINO & GUSTAVO V. VELOSO

Abstract: Salinization is one of the main pedogenetic processes occurring on the semiarid zone of the Weddel sea, like in Seymour Island, where salt-affected soils are widespread. This study aimed to investigate whether topography controls the distribution of salt-affected soils on Seymour Island, particularly with reference to the Lopez de Bertodano Formation. Chemical and physical results from 45 soil profiles were used, where morphometric variables were extracted. Descriptive statistical analysis, extraction of morphometric variables, cluster analysis and principal component analysis were carried out in this database. The separation of soils associated with the López de Bertodano Formation into two groups is explained by topographic atributes, and not by soil properties. Hence, the salts in soils have a geogenic origin, and despite differences in geological units, the uniform mineralogical composition of all Lopez de Bertodano Formation results in the widespread accumulation of salts in soils, influenced by the saline parent material and the semi-desert climate. Despite the lack of topographic control in the distribution of saline soils as a whole, geomorphology play a distinct role in the formation of secondary saline features, such as crusts, efflorescences, and columnar structures, or in salt composition of salts present in the soils.

Key words: Salinity, Antarctica, Lopez de Bertodano Formation.

INTRODUCTION

The Antarctic Peninsula (AP) is a climatic transition region located in the northwest of the Antarctic continent. The west coast, bordered by the Bransfield Strait, has a milder and more humid climate. In contrast, the east coast, facing the Weddell Sea, is characterized by negative temperatures throughout the year and low precipitation (Campbell & Claridge 1987).

The AP and its islands comprise an ice-free area of 14 %, totaling approximately 8,000 km² (Bockheim & Hall 2002). In the southeastern part of the AP lies the James Ross Archipelago, consisting of James Ross, Vega, Cockburn, Snow Hill, and Seymour Islands. In this region, the mean annual air temperature varies between -5.5 and -9.4 °C, with no monthly temperatures above zero and an average annual precipitation of 250 mm (Gutierréz-Elorza et al. 2011).

Pedological studies on Seymour Island have been conducted in central and northern portions (Souza et al. 2014, Schaefer et al. 2015, Gjorup et al. 2020). According to these studies, Seymour's soils are mostly relatively deep (+50 cm) and have a shallower active layer compared to soils in the Maritime Antarctic. These authors observed several predominant pedogenetic processes on the island, such as salinization, sulfuration, and phosphatization. The presence of salt was widely reported on the surface and to a lesser extent in the subsurface, as well as the occurrence of horizons undergoing sulfuration and profiles with pH variation between acidic to basic. Phosphatization was observed in only one location, an extensive penguin colony located in the southeastern portion, which includes active and abandoned areas.

Salinization, according to Bockheim & Gennadiyev (2000), is the process of accumulation of soluble salts of Na, Ca, Mg, and K in the form of chlorides, sulfates, carbonates, and bicarbonates in soils. These accumulations occur through the input of marine aerosols, salt-rich glaciers melting, as well as the action of chemical weathering on marine-origin sediments (Keys & Williams 1981).

In the southwest portion of Seymour Island lies the Lopez de Bertodano Formation, an area with salt-affected soils that remains poorly understood. Studying this formation and the distribution of salts in its soils is crucial, as it may contain the most saline soils on the entire island, or even throughout the Antarctic Peninsula, based on the characteristics described in the literature.

One of the primary areas of interest is understanding the distribution of these salt-affected soils and determining if topography plays a role in controlling the salinization processes. The relief influences water circulation, which, in the Antarctic setting, directly impacts the geochemical soluble salts movement. On Seymour Island, features of salt precipitation, such as crusts and efflorescences, are frequently observed in specific landscape positions, including water channels and snowbanks. However, it remains uncertain whether this phenomenon reflects topographic control of salinization or if saline soils are influenced by other soil-forming factors.

This study aimed to investigate whether topography controls the distribution of salt-affected soils on Seymour Island, particularly in relation to the Lopez de Bertodano Formation. Statistical analyses were conducted, incorporating chemical and physical data from soil profiles along with topographic variables. Our findings have the potential to enhance our understanding of the mechanisms underlying salinization in Antarctic soils and, consequently, contribute to the characterization of environments with unique attributes.

MATERIALS AND METHODS

Study area

Seymour Island covers an area of 77 km^2 and is located off the west coast of the James Ross Archipelago and north/northeast of the Weddell Sea, at latitude 64° 14’S and longitude 56° 43’W (Campbell & Claridge 1987, Nozal et al. 2007) (Figure 1a-c). The island is approximately 20.5 km long in the NE-SW direction and about 9.6 km wide at its widest point (Elliot et al. 1975).

According to Tatur et al. (1993), Seymour Island has unique characteristics compared to neighboring islands, including low temperatures, minimal precipitation, high surface salt content, and sparse vegetation. Reynolds (1981) noted that minimum temperatures occur in June and July, while maximum temperatures are in December and January, with an average annual temperature of -8.3 °C. Annual precipitation typically does not exceed 250 mm, with a maximum of 20 % in liquid form, classifying Seymour Island as having a semi-arid subpolar climate (Gutierréz-Elorza et al. 2011, Reynolds 1981). Similar to continental Antarctica, islands in the Antarctic Peninsula exhibit surface salts, visible as efflorescence on rocks or within the soil profiles (Campbell & Claridge 1987, Claridge & Campbell 1968, 1982). The vegetation is

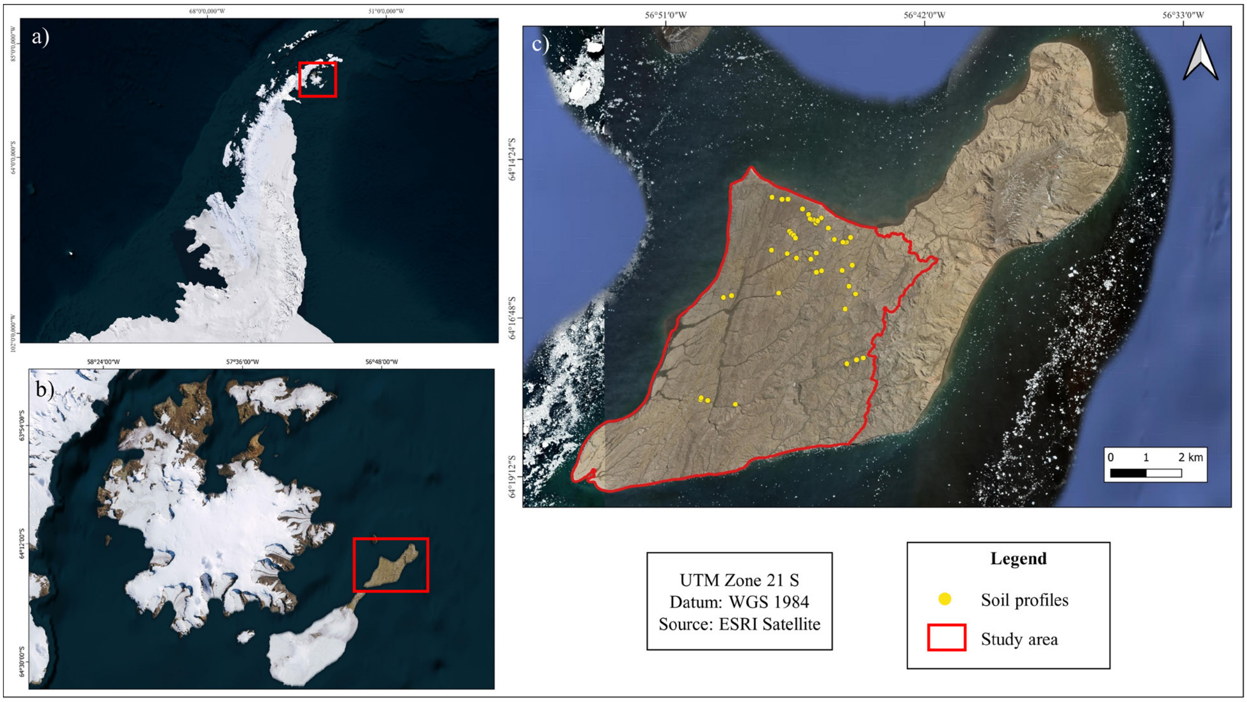

Figure 1. Study area location. a) Location of the James Ross Archipelago on the east coast of the Antarctic Peninsula; b) Location of the James Ross Archipelago and Seymour Island to the east; c) Location of Seymour/Marambio Island, the studied soil profiles, and the study area boundary.

practically absent, limited to small areas within moist fissures in larger rocks (Fretwell et al. 2011, Silva Busso et al. 2000).

The island is predominantly formed by sedimentary rocks developed between the Cretaceous and Neogene periods (Sadler 1988), with the Lopez de Bertodano Formation (FLB) (Cretaceous-Paleocene) being the oldest and occupying the largest area (45 km^2) (Macellari 1988). Specifically, its formation is of marine origin, exhibiting abundant fossil fauna and a low degree of diagenesis. It is largely composed of looser arenosiltaceous sediments, becoming more massive only at the base (Macellari 1988). Overall, these sediments are more homogeneous and denser when weathered, as they have a lower content of bitumen and sulfides (Tatur et al. 1993).

The topography of the area where the Lopez de Bertodano Formation is located is characterized by a succession of cuestas, with structural control of the low-angle dip of the sedimentary layers (Montes et al. 2019). According to Gutiérrez-Elorza et al. (2011), the current morphology of the island is the result of Quaternary erosive processes, such as fluvial and marine morphogenesis, in a periglacial context. Fluvial morphogenesis would be the main shaping agent, along with the snow-periglacial system, being the primary generator of rock frost weathering.

Soil physical and chemical analysis

A total of 45 soil profiles were analyzed, with 31 described and collected in January/December 2019/2020, and 14 in January/December 2022/2023, totaling 171 sampled horizons. The samples were disaggregated and sieved through a 2 mm, composing the Air-Dried Fine Earth (ADFE). Subsequently, physical and chemical analyses were carried out according to Teixeira et al. (2017).

The particle size distribution was determined by the pipette method, using sodium hexametaphosphate as the main reagent (0.058 mol L^{-1}). Electrical conductivity was measured in a 1:5 saturated extract (Richards 1954). EC was corrected based on the equation proposed by Richards (1954), which takes into account soil texture, thus generating the variable ECe.

Soil pH was measured using water and a 1 mol L^{-1} KCl solution in a soil ratio of 1:2.5. The Mehlich-1 method (using 0.05 mol L^{-1} HCl and 0.0125 mol L^{-1} H_2SO_4) was used to extract available cations K and Na. Determination was done by flame photometry (Na and K). Ca^{2+} and Mg^{2+} were extracted using 1 mol L^{-1} and determined by atomic absorption spectroscopy. After that, the sum of cations (K^+, Na^+, Ca^{2+}, and Mg^{2+}) was calculated to generate the variable sum of bases (SB). The analyzed variables studied are: CS, FS, Silt, Clay, pH H2O, pH KCl, SB, Na, and ECe.

Descriptive statistics

Descriptive statistical analyses (mean, median, maximum, minimum, and standard deviation) were conducted on all samples (n = 171). The data were subjected to the Kolmogorov-Smirnov test to check for normal distribution. The Student's "t" test ($p \leq 0.05$) was performed on soil attributes with normal distribution, while the Mann-Whitney U test was applied to those without normal distribution.

Environmental predictors

A set of 42 topographic attributes was generated, involving primary and secondary terrain attributes (Sena et al. 2020), along with terrain-based attribute classifications derived from the Reference Elevation Model of Antarctica (REMA) with a spatial resolution of 10 meters (Table I). The R software (R Core Team 2021) was used for this, employing the "rsaga" (Brenning 2008), "raster" (Robert 2019), and "rgrass7" (Bivand et al. 2018) packages.

The REMA mosaic was built from individual Digital Elevation Models (DEMs) extracted from stereoscopic images of the WorldView-1, WorldView-2, WorldView-3, and GeoEye-1 satellites, mainly collected during the austral summer seasons of 2015 and 2016. The individual DEM was vertically registered to satellite altimetry measurements from Cryosat-2 and ICESat, resulting in absolute uncertainties of less than 1 m over most of the area (Howat et al. 2019).

Cluster analysis

Cluster analysis is a method used to group observations into homogeneous clusters based on their degree of similarity (Hair Junior et al. 1998). For this purpose, the K-means method was employed to group soil profiles with higher similarity based on soil properties and topographic variables. The cluster analysis begins with determining the optimal number of clusters, which was assessed using the PseudoT2 (Duda et al. 2006) and CH (Calinski & Harabasz 1974) methods from the NBClust package in the R software.

Principal component analysis

Principal Component Analysis (PCA) allows similar variables to be grouped into principal dimensions or components, without distinguishing between independent and dependent variables (Borůvka et al. 2005). We used the "FactoMiner" package (Husson et al. 2018) to perform PCA on soil attributes and morphometric parameters (Table I) for each of the soil profiles. This analysis was conducted to understand the relationships between soil attributes and topographic parameters (Abdi & Williams 2010). Essentially, this analysis involves an orthogonal linear transformation of the data,

Table I. Topographic variables derived from the Reference Elevation Model of Antarctica (REMA) of the Lopez de Bertodano Formation.

Terrain atributes	Abreviations	Brief description
Aspect	ASP	Slope orientation
Convergence index	CI	Convergence/divergence index in relation to runoff
Cross sectional curvature	CSC	Measures the curvature perpendicular to the down slope direction
Diurnal anisotropic heating	DAH	Continuous measurement of exposure dependent energy
Effective air flow heights	EAFH	Refers to the effective height above the Earth's surface where the main air transport processes occur.
Flow line curvature	FLC	Represents the projection of a gradient line to a horizontal plane
General curvature	GC	The combination of both plan and profile curvatures
Hillshade	H	Represents the topography of the land.
Longitudinal curvature	LC	Measures the curvature in the down slope direction
Mass balance index	MBI	Balance index between erosion and deposition
Maximal curvature	MAXC	Maximum curvature in local normal section
Digital elevation model	DEM	Represents the elevation in each model cell
Mid-slope position	MSP	Represents the distance from the top to the valley, ranging from 0 to 1
Minimal curvature	MINC	Minimum curvature for local normal section
Multiresolution index of ridge top flatness	MRRTF	Indicates flat positions in high altitude areas
Multiresolution index of valley bottom flatness	MRVBF	Indicates flat surfaces at bottom of valley
Normalized height	NH	Vertical distance between base and ridge of normalized slope
Plan curvature	PLANC	Described as the curvature of the hypothetical contour line passing through a specific cell
Profile curvature	PROC	Describes surface curvature in the direction of the steepest incline
Real surface area	RSA	Actual calculation of cell area
Ridge level	RL	Measure of altitude or elevation along a topographic ridge.
Saga wetness index	SWI	Evaluates the relative humidity of the soil in a given area.
Solar diffuse	SDIF	Refers to diffuse solar radiation, which is a component of solar radiation that reaches the Earth's surface after being dispersed and scattered by the atmosphere.
Solar direct	SDIR	Amount of direct solar radiation that reaches a given area or point on the earth surface.

Table I. Continuation.

Solar ratio	SR	Relationship between the amount of direct solar radiation received by a given area and the total solar radiation available in that area.
Solar total	ST	Total amount of solar radiation that falls on a given area or point on the earth surface during a given period of time.
Sky view factor	SVF	Proportion of ground visibility unobstructed by obstacles from the sky.
Slope degress	SD	Angle of incident sunlight in relation to the plane of the earth equator.
Slope height	SH	Vertical distance between base and ridge of slope
Standardized height	STANH	Vertical distance between base and standardized slope index
Surface specific points	SSP	Indicates differences between specific surface shift points
Tangencial curvature	TANC	Measured in the normal plane in a direction perpendicular to the gradiente
Terrain ruggedness index	TRI	Quantitative index of topography heterogeneity
Terrain surface convexity	TSC	Ratio of the number of cells that have positive curvature to the number of all valid cells within a specified search radius
Terrain surface classification iwahashi	TSCI	Relies on morphometric analyzes to identify patterns in the landscape and assign each region a specific type of terrain.
Terrain surface texture	TST	Refers to the roughness or variation in elevation of the terrain in a given geographic area.
Total curvature	TC	General measure of surface curvature
Topografic openness	TO	Quantifies the exposure or visibility of a given location in relation to its topographic neighborhood.
Topographic position index	TPI	Difference between the an point elevation with surrounding elevation
Valley depth	VD	Calculation of vertical distance at drainage base level
Vector ruggedness measure	VRM	Measures the variation in terrain roughness
Wind exposition	WE	Measure that assesses the degree of exposure of an object to the wind

resulting in a new set of orthogonal data known as Principal Components (PCs), which explain the variation in the data (Jambu 1991).

The 51 parameters (9 soil properties and 42 topographic variables) were employed in reducing the dimensionality of the principal components (PCA). The ideal values of the PCs were determined by examining the contribution values of each variable, which were considered ideal when exceeding 0.7 for Dimension 1, 0.4 for Dimension 2, and 0.2 for Dimension 3. The data used in PCA were normalized using the preProcess function, employing the “center” and “scale” methods available in the caret package of the R software.

RESULTS

Soil groups and their physical and chemical properties

Cluster analysis was performed on the entire data set, allowing to separate two groups. Statistical analysis of soil properties was carried out considering both groups with the aim of understanding whether only soil properties are able of differing from each other. Table II displays the statistical results of the physical and chemical soil properties of the two soil groups. For the variables FS, Silt, Clay, ECe, pH H_2O, pH KCl, and Na, the non-parametric Mann-Whitney test was utilized, as these variables did not exhibit normal distribution according to the Kolmogorov-Smirnov test.

CS and SB exhibited a normal distribution, and thus the parametric t-Student test was conducted. For all soil properties, the only one that showed statistical difference between the groups was CS, which Group 2 presented 0.06 g/kg and Group 1 0.02 g/kg. However, CS values are extremely low and poorly representative of the total constitution of soil granulometric fractions. FS levels were similar for both groups. Clay values showed the same behavior, which Group 1 presented 0.34 g/kg and Group 2 0.35 g/kg. pH values (KCl and H2O), indicate acidity in both groups. Elevated levels of Na were observed in both groups, which Group 1 presented 2414.70 mg/dm³ and Group 2 2377.00 mg/dm³. SB is high in both groups, with values of 28.58 cmolc/dm³ and 31.95 cmolc/dm³ for Group 1 and Group 2, respectively.

Principal component analysis

The PCA analysis corroborates the distinction between the two soil groups identified in the

Table II. **Descriptive statistical analysis of the physical and chemical soil properties related to soil salinity of the Lopez de Bertodano Formation.**

	CS	FS	Silt	Clay	CEc	pH H2O	pH KCl	Na	SB
	Group 1 (n = 104)								
Mean	0,02	0,37	0,27	0,34	10,70	5,55	4,63	2414,70	28,58
Median	0,00	0,36	0,26	0,33	8,56	4,96	3,88	2003,50	25,02
Min	0,00	0,08	0,12	0,15	1,20	3,24	2,71	303,00	15,57
Max	0,40	0,65	0,49	0,53	71,72	8,63	7,24	10621,00	85,41
SD	0,05	0,15	0,09	0,77	9,28	1,78	1,64	2102,86	12,70
	Group 2 (n = 67)								
Mean	0,06	0,36	0,27	0,35	10,65	5,46	4,59	2377,00	31,95
Median	0,00	0,33	0,26	0,34	10,39	4,50	3,65	2231,00	28,67
Min	0,00	0,03	0,14	0,20	0,48	3,17	2,81	181,00	10,52
Max	0,46	0,58	0,45	0,57	27,47	8,67	7,38	7490,00	68,08
SD	0,11	0,13	0,07	0,07	6,62	1,87	1,67	1572,18	14,11
p-value	0,00[1]	0,35[2]	0,82[2]	0,40[2]	0,52[2]	0,33[2]	0,54[2]	0,41[2]	0,11[1]

CS: Coarse sand. FS: Fine Sand. CEc: Corrected electrical conductivity. SB: Sum of bases. SD: Standard deviation. [1]Test t-Student. [2]Test Mann-Whitney.

cluster analysis (Figure 2 and 3). The first three PCs of the PCA were used as they explain the majority of the data variability (57 %). The first PC (PC1) explained 35.7 % of the data, the second (PC2) 13.2 %, and the third (PC3) 8.1 %.

Figure 2 shows that topographic variables are responsible for group separation, while soil physical and chemical properties are less importante for it. FS had the highest contribution (0.14) in Dim2, while Clay (0.13), SB (0.11), and CS (0.09) were the highest values in Dim1. Na (0.05) had a lower contribution in Dim1, along with CEc (0.02). pH H2O (0.01) and pH KCl (0.00) were insignificant in the PCA, as well as Silt (0.00).

Dim3 (Figure 3) follows the same trend as Dim1 and Dim2. However, soil properties pH H2O (0.02) and pH KCl (0.02), which previously had almost no contribution, now begin to have some importance. FS (0.98) remains the most important in Dim3, while CS (0.03) was important in Dim1. The variables CEc, Na, SB, Silt, and Clay showed no relationship with any of the dimensions.

DISCUSSION

The results showed that all soils are very similar to each other. Although topographic attributes separate two distinct groups, there is no significant difference in salt accumulation between them. This indicates that there is no topographic control of salinization, but rather a phenomenon that occurs in the broad spectrum generalized manner.

The high sodium content identified in the soils of Seymour Island is supported by Souza et al. (2014), Gjorup et al. (2020), and Siqueira et al. (2022) in other geological formations of the island. This is initially attributed to the predominant dry

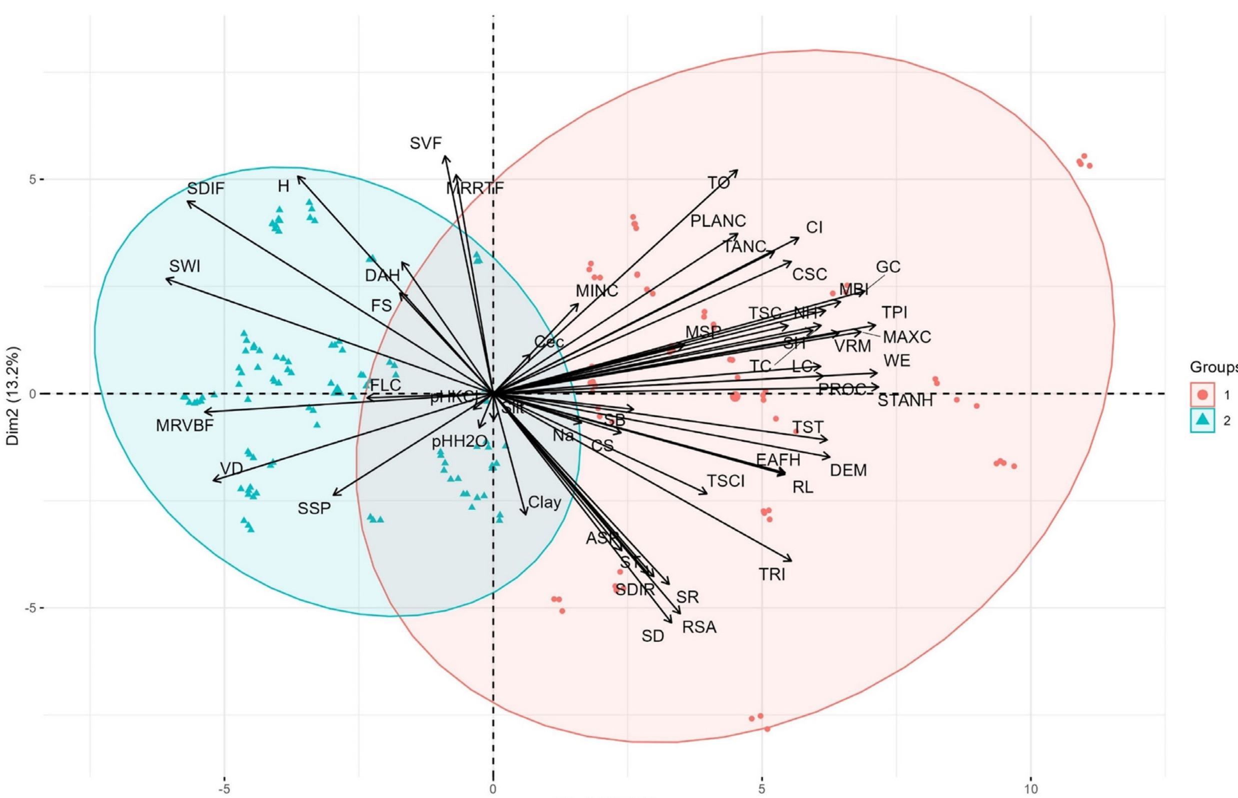

Figure 2. Principal Component Analysis of dimensions 1 and 2 of the Lopez de Bertodano Formation.

climate, favoring salt accumulation irrespective of lithology. Salinization thus emerges as a significant pedogenetic process in local soil formation (Souza et al. 2014). However, these authors indicated that this accumulation is not uniform across the landscape, as relief only promotes salt accumulation in certain areas (Souza at al. 2014, Schaefer at al. 2015, Gjorup et al. 2020).

In the Lopez de Bertodano Formation, topographic variables were found to be the main factors explaining the separation of groups (Figure 4). Regarding Dim1, 14 variables contributed more than 0.7 (GC, LC, MAXC, PROC, TC, MBI, DEM, NH, SWI, STANH, TST, TPI, VRM, and WE); in Dim2, 6 variables contributed more than 0.4 (TO, SD, H, TSA, SVF, and MRRTF); and in Dim3, 5 variables had a contribution greater than 0.2 (RI, SB, MINC, Cec, and Na).

The soils in Group 2 have higher sand content, while those in Group 1 have more clay, sodium, and silt. The other soil properties did not show a strong relationship with either group, meaning they do not follow a pattern and vary randomly in their concentrations. Thus, the position of soil in the landscape and the shape of the terrain where they are located do not determine the increase or decrease in soil properties, including those indicating the salinization process, such as sodium content, pH, and electrical conductivity.

But, why were the soils separated into two groups based on topographic variables? This occurred because, even though topography was not a direct control of salinization, the soils were classified based on two distinct geomorphological characteristics. Group 1 comprises soil profiles found on slopes,

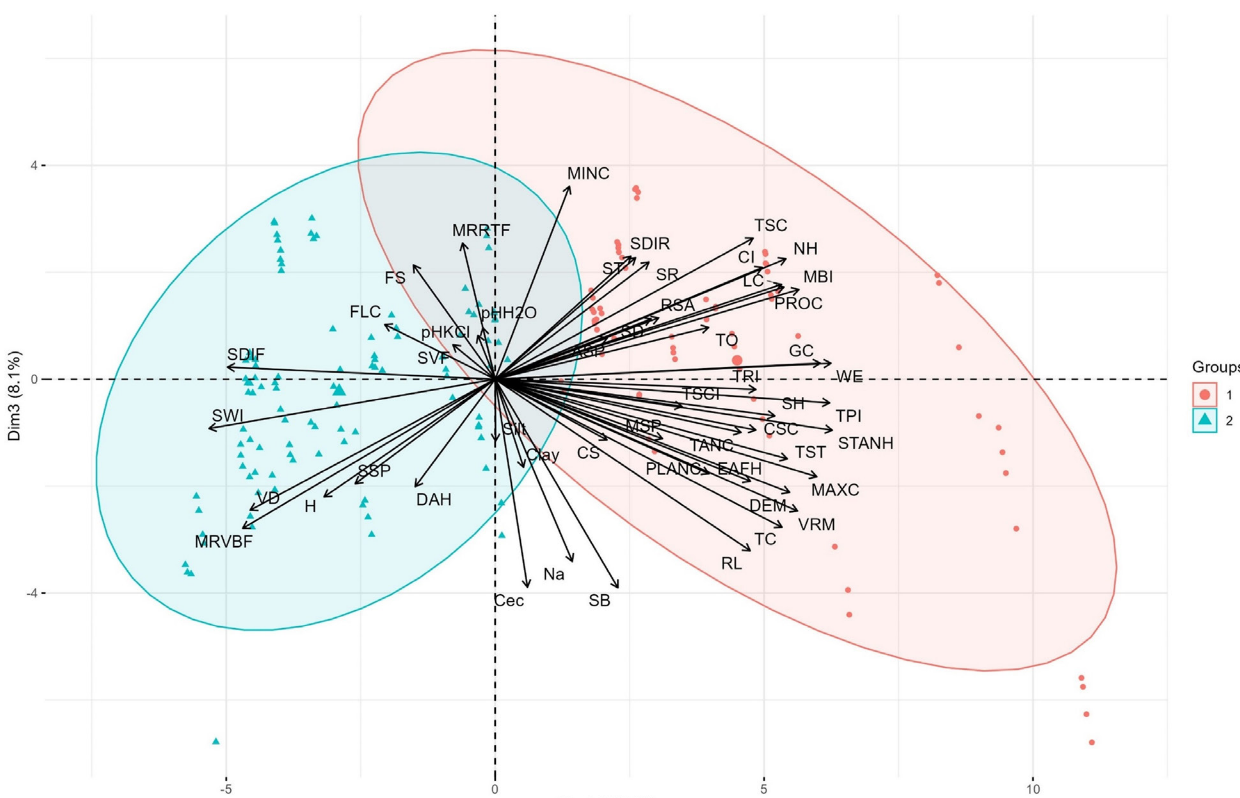

Figure 3. Principal Component Analysis of dimensions 1 and 3 of the Lopez de Bertodano Formation.

characterizing the reverse side of a ridge, with different curvatures and altitudes ranging from the top of the landscape to the bottom of the valleys. On the other hand, Group 2 does not exhibit a defined pattern but tends to have characteristics of soil profiles located in higher and flatter areas.

Soil texture remains relevant in differentiating the groups, even though other properties have higher values as indicated in Figure 4. However, these properties show an opposite trend to that of the groups, meaning they do not significantly contribute to explaining the distinction between them.

And if topography doesn't seem to control salt distribution, what would be the controlling factor? Our results suggest that the widespread occurrence of salt-affected soils in the Lopez de Bertodano Formation, regardless of their position in the landscape, implies that the salt source is related to the parent material, namely, the disseminated presence of salts in the rocks composing this formation.

The Lopez de Bertodano Formation originated from deposition in a transgressive estuarine platform environment, where sedimentation occurred under calm conditions, contributing to a homogeneous lithology (Macellari 1988). Its division into nine units was based on the occurrence of different fossil species (Mollusks from 1 to 6 and Rotularia from 7 to 9), given that the lithological composition

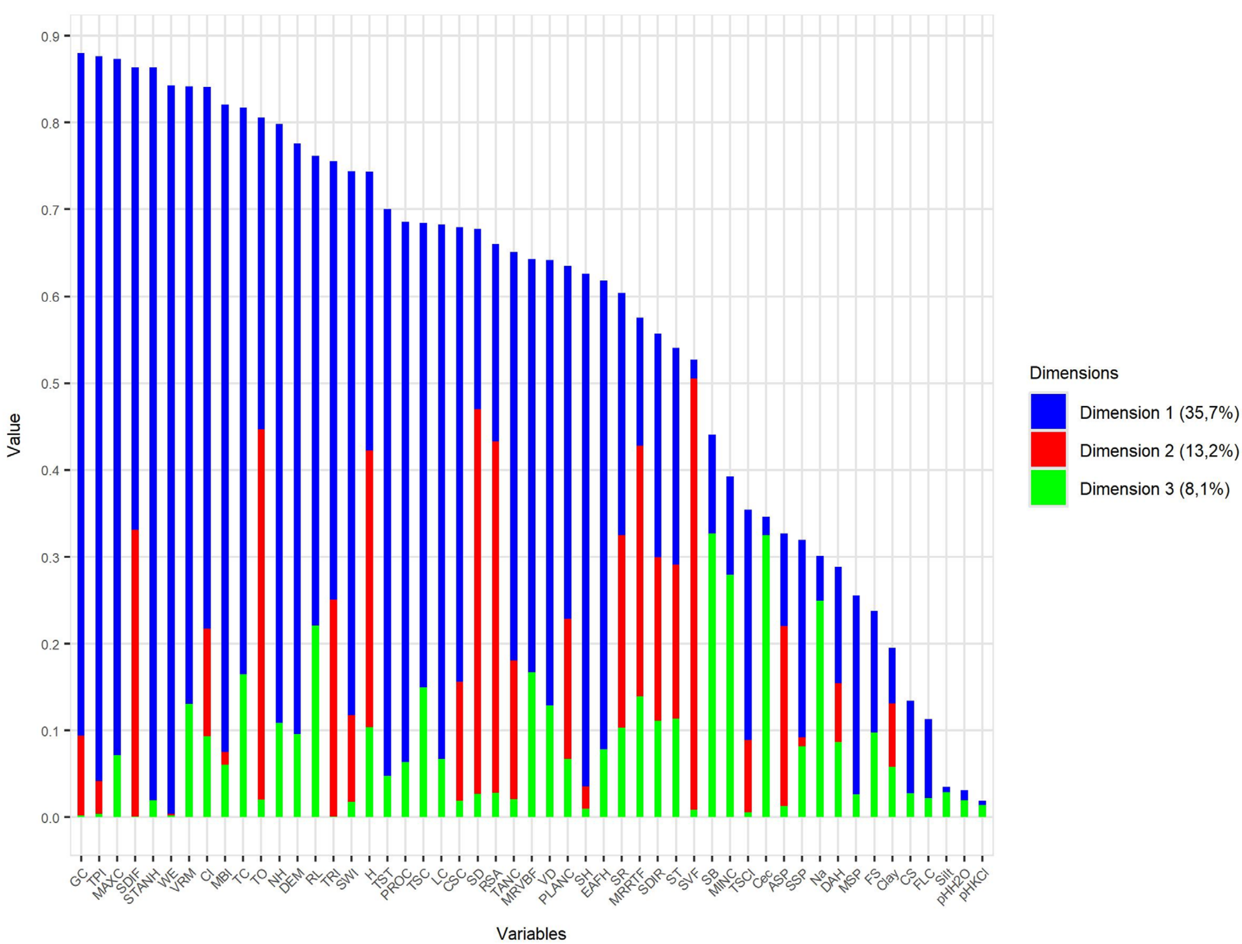

Figure 4. Importance values of the variables in each of the three dimensions of the Principal Component Analysis of the Lopez de Bertodano Formation.

of the material is similar across all units. According to Macellari (1988), the differentiation of species was influenced by factors related to seawater, including salinity. For this reason, the salts in these sediments have a geogenic origin, meaning they were incorporated into the sediments during the platform's formation. The semi-arid conditions of Seymour Island favor the accumulation and concentration of these salts, mainly at the surface. As observed in the results, this is not controlled by topography but by the parent material of the soils.

CONCLUSIONS

- The clustering of soils associated with the López de Bertodano Formation into two groups is explained by topographic attributes, without explaining physical or chemical properties, such as salinization. This shows that topography is not the factor controlling the occurrence of salinization process in the studied area.

- The origin of the salt accumulating in the profiles is geogenic and related to the sedimentary nature of the uplifted Cretaceous marine platform. Although separated into geological units, this formation has a homogeneous composition in mineralogical terms, which makes salt accumulation in soils a widespread process related to the parent material and associated with the preset-day semi-desert climatic conditions.

- However, the absence of topographic control in the distribution of saline soils does not imply na absence of geomorphological importance in the formation of typical secondary saline features, such as crusts, efflorescences, and columnar structures, or even in the composition of salts present in the soils. This needs to be further studied through specific sampling at different landscape positions, including detailed morphological studies and chemical speciation.

Acknowledgments

Part of the funding for this study was provided by the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior (CAPES, Brasil). This work is also a contribution from the TERRANTAR group at the Instituto de Ciência e Tecnologia da Criosfera. For more information about the group, visit the link: https://www.ufrgs.br/inctcriosfera/terrantar.html.

REFERENCES

ABDI H & WILLIAMS LJ. 2010. Principal component analysis. Wiley interdisciplinary reviews: Computational Statistics 2: 433-459.

BIVAND R. 2018. Interface between GRASS 7 Geographical Information System and R [R Package Rgrass7 Version 0.1-12].

BOCKHEIM JG & GENNADIYEV AN. 2000. The role of soil-forming processes in the definition of taxa in Soil Taxonomy and the World Soil Reference Base. Geoderma 95: 53-72.

BOCKHEIM JG & HALL KJ. 2002. Permafrost, active-layer dynamics and periglacial environments of continental Antarctica: periglacial and permafrost research in the Southern Hemisphere. S Afr J 98: 82-90.

BORŮVKA L, VACEKO & JEHLIČKA J. 2005. Principal component analysis as a tool to indicate the origin of potentially toxic elements in soils. Geoderma 128: 289-300.

BRENNING A. 2008. Statistical geocomputing combining R and SAGA: The example of landslide susceptibility analysis with generalized additive models. Hamburger Beiträge zur Physischen Geographie und Landschaftsökologie, 410 p.

CALINSKI RB & HARABASZ J. 1974. A dendrite method for cluster analysis. Communications in Statistics 3: 1-27.

CAMPBELL IB & CLARIDGE GGC. 1987. Antarctica: Soils, weathering processes and environment, Amsterdam: Elsevier, 368 p.

CLARIDGE GGC & CAMPBELL IB. 1968. Some features of Antarctic soils and their relation to other desert soils. Trans. 9th I n f. Congr Soil Sci 4: 541-549.

CLARIDGE GGC & CAMPBELL IB. 1982. A comparison between hot and cold desert soils and soil processes. In: YAALON DH (Ed), Aridic soils and geomorphic processes, Catena supplement: I. Braunschweig, p. 1-28.

DUDA RO & HART PE. 2006. Pattern classification. John Wiley & Sons.

ELLIOT DH, RINALDI CA, ZINSMEISTER W, TRAUTMAN TA, BRYANT WA & DEL VALLE RA. 1975. Geological investigations on Seymour Island, Antarctic Peninsula. Antarct J US 10: 182-186.

FRETWELL PT, CONVEY P, FLEMING AH, PEAT HJ & HUGHES KA. 2011. Detecting and mapping vegetation distribution on the Antarctic Peninsula from remote sensing data. Polar Biology 34: 273-281.

GJORUP DF, SCHAEFER CEGR, SIMAS FNB, FRANCELINO MR, MICHEL RFM & BOCKHEIM JG. 2020. Sulfurization, acid-sulfate soils and active layer monitoring at the semiarid Seymour Island, Antarctica. Geoderma Reg 22: e00305.

GUTIÉRREZ-ELORZA M, NOZAL F & MONTES MJ. 2011. Talus flatirons en la Isla Seymour (Mar de Weddel, Antártida). Consideraciones sobre su génesis. Cuaternario y Geomorfología, 9-19.

HAIR JUNIOR JF, BLACK WC, BABIN BJ & ANDERSON RE. 1998. Multivariate data analysis. Prentice Hall, Upper Saddle River.

HOWAT IM, PORTER C, SMITH BE, NOH MJ & MORIN P. 2019. The reference elevation model of Antarctica. The Cryosphere 13: 665-674.

HUSSON F, JOSSE J, LE S & MAZET J. 2018. FactoMineR: multivariate exploratory data analysis and data mining. R package version 1.4.

JAMBU M. 1991. Exploratory and multivariate data analysis. Elsevier.

KEYS JH & WILLIAMS K. 1981. Origin of crystalline, cold desert salts in the McMurdo region, Antarctica. Geochimica et Cosmochimica Acta 45: 2299-2309.

MACELLARI CE. 1988. Stratigraphy, sedimentology, and paleoecology of Upper Cretaceous/Paleocene shelf-deltaic sediments of Seymour Island. Geological Society of America Memoirs 169: 25-54.

MONTES M, NOZAL F & SANTILLANA S. 2019. Geologia Y Geomorfologia de Isla Marambio (Seymour) (Geology and Geomorphology of Seymour Island (Marambio)). Instituto Geológico y Minero de España.

NOZAL F, MONTES M, SANTILLANA S & MARTÍN-SERRANO A. 2007. Unidades del Relieve de la isla Marambio, Antártida. In VI Argentine and III Latin-American Symposium on Antartic Research (Vol. 10).

R CORE TEAM. 2021. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. URL http://www.R-project.org/.

REYNOLDS M. 1981. The distribution of mean annual temperatures in the Antarctic Peninsula. BAS Bulletins 54: 123-133.

RICHARDS LA. 1954. Diagnosis and Improvement of Saline and alkali Soils. United States Departament of Agriculture: Washington. (Agriculture Handbook No. 60).

ROBERT JH. 2019. Raster: geographic data analysis and Modeling. R package version 2: 8-19.

SADLER PM. 1988. Geometry and stratification of uppermost Cretaceous and Paleogene units on Seymour Island, northern Antarctic Peninsula. Mem Geol Soc 169: 303-320.

SCHAEFER CE, SOUZA KKD, SIMAS FN, GJORUP D & BOCKHEIM JG. 2015. Soils of the Weddell sea sector, Antarctica. The Soils of Antarctica, 332 p.

SENA NC, VELOSO GV, FERNANDES-FILHO EI, FRANCELINO MR & SCHAEFER CEG. 2020. Analysis of terrain attributes in different spatial resolutions for digital soil mapping application in southeastern Brazil. Geoderma Regional 21: e00268.

SILVA BUSSO A, SÁNCHEZ R & FRESINA M. 2000. Caracterización del Comportamiento Hidrogeólogico em la Isla Marambio, Antártida. 1º Conresso Mundial Integrado de Aguas Subterráneas. Abstracts, p. 292. Fortaleza, Brasil.

SIQUEIRA RG, LOPES DV, SOUZA JJLD, SCHAEFER CEG, SOUZA CD, OLIVEIRA FSD & FERNANDES FILHO EI. 2022. Acid sulfate soils from Antarctica: genesis and properties along a climatic gradient. An Acad Bras Cienc 94: e20210625. https://doi.org/10.1590/0001-3765202120210625.

SOUZA KKD, SCHAEFER, CEG, SIMAS FNB, SPINOLA DN & De PAULA MD. 2014. Soil formation in Seymour Island, Weddell Sea, Antarctica. Geomorphology 225: 87-99.

TATUR A, BARCZUK A, DEL VALLE R, SLETTEN R & KICIŃSKA E. 1993. Surface mineralization on Seymour Island, Antarctica. Polish Polar Research 14: 153-168.

TEIXEIRA PC, DONAGEMMA GK, FONTANA A & TEIXEIRA WG. 2017. Manual de métodos de análise de solo.

How to cite

KRUM DN, SCHAEFER CEGR, OLIVEIRA FS, MICHEL RFM, PALMA HP, TOMAZ MPE, AMARAL ACP, FRANCELINO MR & VELOSO GV. 2024. Salt-affected soils in the Lopez de Bertodano Formation, polar semi-desert of Seymour Island, Antarctica: topographic or lithological controls? An Acad Bras Cienc 96: e20240584. DOI 10.1590/0001-3765202420240584.

Manuscript received on June 25, 2024;
accepted for publication on October 22, 2024

DANIEL N. KRUM[1]
https://orcid.org/0009-0007-4171-4383

CARLOS ERNESTO G.R. SCHAEFER[1]
https://orcid.org/0000-0001-7060-1598

FÁBIO S. OLIVEIRA[2]
https://orcid.org/0000-0002-1450-7609

ROBERTO F.M. MICHEL[3]
https://orcid.org/0000-0001-5951-4610

HEITOR P. PALMA[1]
https://orcid.org/0009-0006-2428-365X

MARCOS PAULO E. TOMAZ[1]
https://orcid.org/0009-0005-3874-3648

ANA CAROLINA P. AMARAL[1]
http://orcid.org/0009-0006-5398-7867

MÁRCIO R. FRANCELINO[1]
https://orcid.org/0000-0001-8837-1372

GUSTAVO V. VELOSO[1]
https://orcid.org/0000-0002-9451-2714

[1]Universidade Federal de Viçosa, Departamento de Solos, Av. PH Rolfs, s/n, 36570-900 Viçosa, MG, Brazil

[2]Universidade Federal de Minas Gerais, Departamento de Geografia, Av. Antônio Carlos, 6627, Pampulha, 31270-901 Belo Horizonte, MG, Brazil

[3]Universidade Estadual de Santa Cruz, Departamento de Ciências Agrárias e Ambientais, Rodovia Jorge Amado, Km 1, 45662-900 Ilhéus, BA, Brazil

Correspondence to: **Daniel Nunes Krum**
E-mail: daniel.krum@hotmail.com

Author contributions

Daniel N. Krum - Writing – original draft, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. Carlos Ernesto G. R. Schaefer - Writing – review and editing, Writing – original draft, Formal analysis, Conceptualization, Supervision, Investigation, Methodology. Fábio S. Oliveira - Writing – review and editing, Supervision, Research, Formal analysis. Roberto F. M. Michel – Writing – review and editing, Methodology, Research. Heitor P. Palma and Gustavo V. Veloso – Writing – review and editing, Supervision, Methodology. Marcos Paulo E. Tomaz and Ana Carolina P. Amaral - Methodology, Research. Márcio R. Francelino - Writing – review and editing, Methodology, Research.