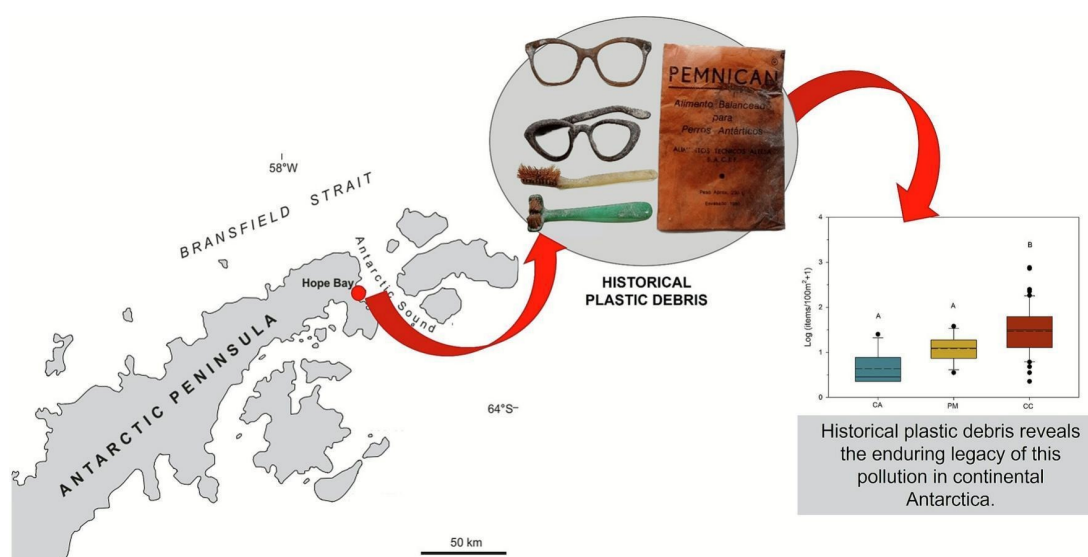


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# Plastic debris on the shores of Bahía Esperanza/Hope Bay: Stranded testimony of the historical occupation in the northern Antarctic Peninsula

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## Abstract

Plastic pollution poses a significant environmental threat in the Antarctic Treaty Area (ATA), raising increasing scientific and management concerns. However, available information on the distribution and composition of plastic debris in the ATA remains limited and is primarily based on opportunistic sampling. Although the human presence in Antarctica has been continuous since World War II, it has grown exponentially in recent decades. Plastic pollution in the region can be attributed to both external sources (marine and atmospheric transport) and local sources, such as scientific, logistical, and tourism activities, including historical waste disposal and management practices. In 2023, we assessed the abundance, morphology, polymeric composition, and spatial distribution of plastic debris along the coast of Esperanza/Hope Bay (north Antarctic Peninsula). Coastal transect surveys (3 people covering a 5-m-wide strip) were conducted, and sampling points (5 m radius) were established based on visual detection of at least one plastic item (>1 cm). All debris within these areas were quantified, measured, weighed, and classified (CCAMLR marine debris guidelines). The chemical composition was analyzed using ATR-FTIR spectroscopy. A total of 3477 items were collected from 85 sampling points, with the highest abundance found near current and historical infrastructure. Notably, some items were identified as long-standing historical plastic debris, including sled dog food containers, eyeglasses, toothbrushes, and electrical devices, and their weathering was analyzed. The persistence of plastics, combined with increasing human activity, underscores the need for long-term, historically informed management strategies. Our study highlights the urgency of sustained monitoring efforts and the strengthening of policies under the Antarctic Treaty System to effectively address and mitigate plastic pollution.

## 1. Introduction

Plastic pollution is a clear environmental threat, even in Antarctica, generating growing scientific and management concerns (Waller et al., 2017). Although Antarctica is often perceived as the last great untouched wilderness on Earth, its connections to the Southern Ocean (Fraser et al., 2018; Suaria et al., 2021) and particularly its socioeconomic teleconnections with human activities north of 60S (Murphy et al., 2021) render its isolation increasingly fragile. As a result, truly pristine areas are becoming increas-

ingly scarce (Tin et al., 2009; Hughes et al., 2011; Convey, 2020; Perterra et al., 2021). Plastic pollution exemplifies this issue, affecting Antarctic ecosystems not only through direct interactions with fauna and flora (entanglement, ingestion) but also indirectly, by acting as a vector for adsorbed organic and inorganic contaminants or facilitating the introduction of non-native species, even at the microbial scale (Rota et al., 2022).

Although the available information on the distribution and composition of plastic debris in Antarctica is still limited and incomplete (Rota et al., 2022), two main sources are currently considered responsible for its presence. The external source is linked to the transport of marine debris into the Southern Ocean and Antarctica from lower latitudes, north of the

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Antarctic Circumpolar Current. In recent years, a growing body of scientific evidence has highlighted the important role of this connection in the marine surface transport of plastics, particularly microplastics (<5 mm) (Lacerda et al., 2019; Lozoya et al., 2022; Jones-Williams et al., 2025). Moreover, there is increasing evidence of another external source with an even more prominent role of atmospheric transport (Brahney et al., 2021; Aves et al., 2022). On the other hand, local sources are linked to scientific, logistical, fishing, and touristic activities in the Antarctic Treaty Area, which are not always carried out, managed, or promoted with the level of care and responsibility appropriate for Antarctica (Braun et al., 2012; Convey, 2020; Hughes et al., 2023). While this might seem unexpected, these local sources are primarily responsible for the presence of marine debris and plastics in Antarctica. This presence persists despite the regulations established by the Antarctic Treaty System and its instruments, including 25 years of the Protocol on Environmental Protection ("Madrid Protocol", in force since 1998) with its Annexes III (Waste Disposal and Waste Management) and IV (Prevention of Marine Pollution), as well as the Convention for the Conservation of Antarctic Marine Living Resources, CCAMLR, adopted in 1980 (Tin et al., 2009; Hughes et al., 2011, Hughes et al., 2023; Rota et al., 2022; Stark et al., 2023).

The increase in human activities in Antarctica over the past few decades (Convey, 2020; Horton and Barnes, 2020), with plastic pollution serving as a testament to this trend (Gurumoorthi and Luis, 2023; De-la-Torre et al., 2024), is further exacerbated by one of the main characteristics of these polymers: their high durability. Designed and produced to last, both macroplastics and the microplastics and nanoplastics derived from them can persist for decades, or even hundreds of years (Horton and Barnes, 2020; Rota et al., 2022). Although Antarctic climatic conditions may affect the integrity of these materials, their long-term persistence necessitates analysis and management on a temporal scale that introduces a "historical" dimension. This need for a historical perspective is particularly relevant in the context of the Madrid Protocol (Hughes et al., 2023; Stark et al., 2023).

Human presence in West Antarctica, particularly on the Antarctic Peninsula, can be traced back to the British top-secret Operation Tabarin (1943–1945) (Tin et al., 2009; Hughes et al., 2011). Although the wintering of the Swedish Antarctic Expedition led by Otto Nordenskiöld in 1902 may be considered the beginning of human presence in the region, it was not until after World War II that it became permanent. In 1945, the British Government established Station D (Ea-

gle House, 13 persons) at Caleta Cabaña/Hut Cove (southeast of Bahía Esperanza/Hope Bay, Figure 1), making it one of the four permanent stations planned under Operation Tabarin and the center for dog-sledge-based fieldwork on the mainland (BAS web; Tin et al., 2009; Hughes et al., 2011). In November 1948 Station D was partially destroyed by fire and in February 1952, a new hut (Trinity House) was established at a new location on the same Trinidad/Trinity Peninsula. Trinity House was closed in 1964 and transferred to Uruguay in December 1997, at which point it was renamed Estación Científica Antártica Uruguay Teniente Ruperto Elichiribehety (ECARE). It remains active as a summer research station to this day.

Meanwhile, in January 1952, the Argentine Navy put into service the Esperanza lighthouse on the largest of the Grunden rocks and built the Esperanza naval detachment, inaugurated in March 1952 (León Wöppke et al., 2021). From this initial site, in November 1953 the Argentine Army began the construction of the Esperanza station at Punta Foca/Seal Point (between Caleta Cabaña/Hut Cove and Caleta Águila/Eagle Cove in Trinidad/Trinity Peninsula, Figure 1), that was formally inaugurated in March 1954. This base, which has remained continuously active, currently comprises 43 buildings covering approximately 374,000 m<sup>2</sup>. It accommodates around 80 people in winter and over 1000 annually in the summer, including scientists and tourists.

## 2. Materials and methods

### 2.1 Study area

Samples were obtained during January 2023 as part of beach surveys conducted in the 2022–2023 Antarctic Summer Campaign of the AntarPLAST Project. The sites analyzed were located in the Bahía Esperanza/Hope Bay area, including different ice-free beaches and rocky shores along the Estrecho Antarctic coast: Costa Papúa (S 63.4025, W 57.0213), Caleta Águila/Eagle Cove (S 63.3997, W 57.0024), Punta Foca/Seal Point (S 63.3937, W 57.0000), Puerto Moro (S 63.3949, W 56.9974), and Caleta Cabaña/Hut Cove (S 63.3995, W 56.9883) (Figure 1).

Bahía Esperanza/Hope Bay is located on the NE coast of the Trinidad/Trinity Peninsula where the Argentinean permanent scientific Esperanza station (90 people) and the Uruguayan summer scientific station Ruperto Elichiribehety (ECARE, 8 people) are located (Figure 1). Also, around 5514 tourists visit Bahía Esperanza/Hope Bay annually, of which only 3% disembark on the peninsula, mainly from cruises and small boats (93%) (IAATO, 2023).

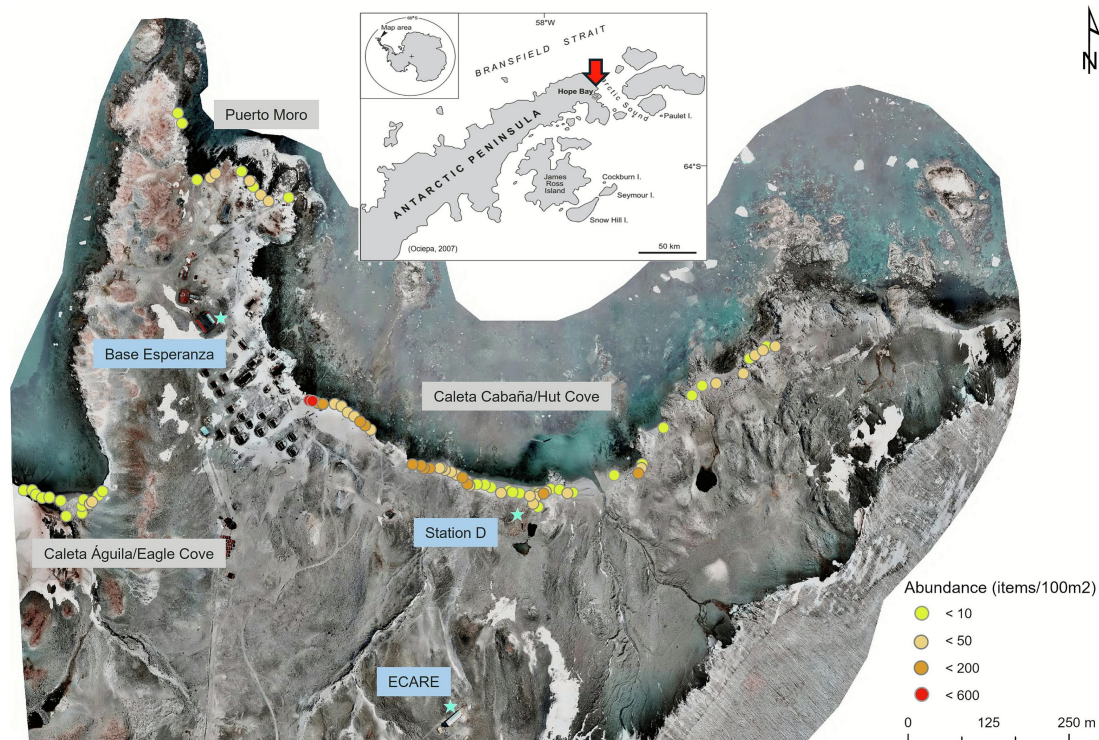


**Figure 1:** Study sites along Bahía Esperanza/Hope Bay area (Trinidad/Trinity Peninsula), highlighting the areas where debris were found: Caleta Águila/Eagle Cove, Puerto Moro, and Caleta Cabaña/Hut Cove. Sampling points are categorized according to their densities (items/100m<sup>2</sup> in legend) (Antarctic peninsula map adapted from Ociepa, 2007 and base map provided by the Uruguayan Military Geographic Institute).

Hope Bay also supports the sixth largest colony of Adélie Penguins (*Pygoscelis adeliae*) in Antarctica, with more than 100,000 breeding pairs (Santos et al., 2018). Other bird species have also been recorded breeding in this area, including the Gentoo Penguin (*Pygoscelis papua*), Brown Skua (*Stercorarius antarcticus lonnbergi*), Antarctic Tern (*Sterna vittata*), Wilson's Storm-petrel (*Oceanites oceanicus*), Kelp Gull (*Larus dominicanus*) and Snowy Sheathbill (*Chionis albus*) (ASPANo. 148 Management Plan, 2002; Ibañez et al., 2020). In addition, the scientific values associated with the high diversity of plant fossils in the area have justified the designation as a Site of Special Scientific Interest (1989), revised and expanded in 2002 in the Management Plan of the Antarctic Specially Protected Area (ASPANo. 148 (ASPANo. 148 Management Plan, 2002, <https://www.ats.aq/devph/en/apadatabase/52>).

## 2.2 Sample collection and plastic analysis

The plastic waste was collected on the beach through transect sampling along the shoreline (three people covering a 5-m-wide strip). Debris were visually identified, focusing on macroplastics and including items as small as 1 cm, considering the area's typical sediment and grain size. Based on the total number

of items found, estimates of abundance per linear meter (items/m) and per square meter (items/m<sup>2</sup>) of surveyed coastline were obtained. These results allowed for comparisons with previous studies reporting stranded beach plastics in Antarctica (Convey et al., 2002; Almela and González Herrero, 2020; Anfuso et al., 2020; Wilkie Johnston et al., 2024; Vesman et al., 2024; Monrás-Riera et al., 2025).

This study also aimed to assess the spatial distribution of debris, identifying areas of potential accumulation along the coastline under the assumption of a non-continuous, patchy distribution. In order to maintain a consistent observation and sampling effort along the transect, circular sampling points (5-m radius; covering 78.5 m<sup>2</sup>) were positioned progressively and georeferenced. Each circular sampling point was associated with the presence of at least one debris item on the shoreline. In cases where only a single item was found within the 78.5 m<sup>2</sup> circle, the abundance was represented solely by that item (i.e., 1 item/78.5 m<sup>2</sup> or 1.27 items/100 m<sup>2</sup>, Figure S1). When more than one item was present, all items located within the circle were collected and included in the abundance estimate for that sampling point. The spatial distribution and aggregation of debris was analyzed based on the cumulative frequency of sampling points as a function of the number of items present in each, as well as the corresponding per-

centage of the total items found (Figure S2). This analysis also allowed us to assess whether the sampling method was effective in identifying both low- and high-density areas. In this context, the potential bias associated with a higher likelihood of detecting additional debris once the first item had been found (and the sampling point established) could be assessed, particularly through the frequency distribution of sampling points with a low number of items. Although individually georeferencing each debris would have offered the most precise characterization of the coastal debris landscape, this method still provided fine spatial detail, allowing for the identification and mapping of potential hotspots along the surveyed shores.

All the collected plastic debris was counted, measured, weighed (dry weight), and classified following criteria based on the categories proposed by the Marine Debris Program of the Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR [www.ccamlr.org/en/data/forms](http://www.ccamlr.org/en/data/forms)). Although the sampling focused on plastic debris (regardless of its original use or activity), items from other categories of the CCAMLR Marine Debris Program were also considered, such as, for example plastic-coated wires (Metal/Wire category), rubber fragments (Rubber/Other rubber category), and fishing gear debris (Fishing Gear/Longline, mono fishing line categories).

This initial analysis of the samples was carried out at the ECARE station, based on precise labeling and separation of the items corresponding to each sampling point. In a second stage, while maintaining both labeling and sample traceability, as well as the necessary conditions to avoid any cross-contamination, a number of debris were selected and prepared for polymer analysis using a category-based criteria. The particles were selected to obtain a representative sample of the debris found across the different CCAMLR categories, allowing the polymer composition of the main debris groups to be determined and assigned. In this selection, priority was given to less common debris rather than to the more abundant, widespread, and easily identifiable items, which were nevertheless analyzed as well (PS, expanded PU, or PVC used in water installations). The chemical composition was spectroscopically analyzed using Fourier Transform Infrared Spectroscopy (FTIR) at the Universidad Autónoma de Madrid and the Universidad de Alcalá. ATR-FTIR spectra were obtained in a Thermo-Scientific Nicolet iS10 apparatus with a Smart iTR-Diamond ATR module. The associate software was OMNIC version 9.1.26 (Thermo Fisher Scientific Inc., Massachusetts, USA). Spectra were taken in the 4000–800

$\text{cm}^{-1}$  range with a resolution of  $4 \text{ cm}^{-1}$  (data spacing of  $0.483 \text{ cm}^{-1}$ ) using 32 scans. Between samples, the ATR-crystal was cleaned with isopropyl and background signal updated. All spectra were compared with the Omnic 9.1.26 (ThermoFisher Scientific Inc., Massachusetts, USA) database and with spectra from our own database. The chemical composition of historical debris was analyzed at the Centro Universitario Regional del Este (Universidad de la República, Uruguay), using an IR SPIRIT-T FTIR Shimadzu with DLATGS detector and QATR-S diamond module. Spectra were taken in the 4000–400  $\text{cm}^{-1}$  range (resolution of  $4 \text{ cm}^{-1}$ ) using 45 scans. Between samples, the ATR-crystal was cleaned with isopropyl and the background signal was updated. All the spectra were compared with the IR Pilot Plastic Analyzer Program with a Standard Library for LabSolutions IR (Shimadzu). As for the other debris, particles were considered as plastics when the match confidence was  $>70\%$  (Villanova-Solano et al., 2022). For four of them, and depending on the polymer, different indexes (carbonyl, carbon-oxygen, hydroxyl, degree of substitution) were calculated to evaluate potential weather-related changes. Depending on the case, they were calculated as the ratio between the peak height of the carbon-oxygen ( $1000\text{--}1200 \text{ cm}^{-1}$ ), carbonyl ( $1550\text{--}1810 \text{ cm}^{-1}$ ), and/or hydroxyl ( $3300\text{--}3400 \text{ cm}^{-1}$ ) functional groups and that of the reference peaks ( $1030 \text{ cm}^{-1}$ ,  $1460 \text{ cm}^{-1}$ ,  $2920 \text{ cm}^{-1}$ ) (Liu and Kazariann, 2022; Tan et al., 2023).

## 2.3 Data analysis

Based on the total number of items collected and the length (meters) and area (in square meters) surveyed, mean abundances were calculated as items/m and items/m<sup>2</sup>, both for the entire Bahía Esperanza/Hope Bay area and for each of the five survey sites. Likewise, a specific abundance and mass per sampling point (items/100m<sup>2</sup> and g/100m<sup>2</sup>) was calculated based on the number of items and mass found at each sampling point (5 m radius, 78.5 m<sup>2</sup>). Additionally, based on these results, an overall mean abundance and mass per sampling point was obtained for each of the five evaluated areas and Bahía Esperanza/Hope Bay. Differences in abundance and mass between areas and possible relationships with both current and historical infrastructures were statistically assessed using ANOVA (with Tukey test for the comparison of sites) and regression analysis (RStudio, version 4.1.2), respectively. Normality was tested using the Shapiro-Wilk test, and homoscedasticity was tested using the Levene test to confirm that the assumptions for ANOVA were satisfied. If needed, data was transformed into  $\log(x+1)$ . Debris characteristics (e.g. use, wear/age, polymeric composition)

were also considered to provide insights into possible origins, pathways, and fates.

### 3. Results

A total of 3477 plastic items were collected along 2437 m of the shore, resulting in an estimated mean abundance for Bahía Esperanza/Hope Bay of 1.43 items/m (ranging from 0 to 3.70 items/m depending on the area) and 0.29 items/m<sup>2</sup> (ranging from 0 to 0.74 items/m<sup>2</sup> depending on the area). Debris was absent in Costa Papúa (CP) and Punta Foca/Seal Point (PF). The highest number of items were recorded near the scientific bases, particularly on the coasts of Caleta Cabaña/Hut Cove (CC). Although this beach was the largest sampled area (CC: 891 m), its average abundance (3.70 items/m and 0.74 items/m<sup>2</sup>) were an order of magnitude larger than those found in Puerto Moro (PM: 424 m, 0.28 items/m and 0.06 items/m<sup>2</sup>) and Caleta Águila/Eagle Cove (CA: 280 m, 0.21 items/m and 0.04 items/m<sup>2</sup>) (Figure 1).

During this campaign, 85 sampling points (5 m radius, 78.5 m<sup>2</sup>) were established, with an average abundance of 52.1 items/100 m<sup>2</sup> (ranging from 1.27 to 760.1 items/100 m<sup>2</sup>). Regarding the distribution and accumulation of debris at the different sampling points, it was observed that, throughout Esperanza Bay, the cumulative frequency up to half of the total sampling points (49%, 42 out of 85 points) accounted for only 6.6% of the total recorded items (230 out of 3477 items), including points that had between 1 and 13 items. These results clearly show that many of the sampling points had few items (e.g., 10.6% had only one item, Figure S2a), while other exhibited markedly higher concentrations (e.g., 60% of the total number of items was concentrated in 7 sampling points, Figure S2a). When analyzed by beach, it was observed that in Caleta Águila/Eagle Cove, 50% of the sampling points (7 out of 14 points) accounted for 11.9% of the total recorded items (7 out of 59 items), all of which contained only one item (Figure S2b). In Caleta Cabaña/Hut Cove, the cumulative frequency of 48% of the sampling points (29 out of 60 points) corresponded to 8.1% of the total recorded items (268 out of 3301 items), including points with between 1 and 22 items (Figure S2c). Finally, in the case of Puerto Moro, 54.5% of the total points (6 out of 11 points) accounted for 28.2% of the total recorded items (33 out of 117 items), including points that contained between 2 and 9 items (Figure S2d). These partial distributions at each beach reinforce an overall pattern, where Caleta Águila shows a large number of points with low densities (50% with only one item), Puerto Moro exhibits intermediate values, and Caleta Cabaña/Hut Cove stands out as the area with the

highest concentrations, including the 7 previously mentioned points that together account for 60% of all debris found in Esperanza Bay.

Caleta Cabaña/Hut Cove also showed the highest number of sampling points and the highest average debris abundance densities per sampling point (CC, 60 sampling points,  $70.0 \pm 138.1$  items/100 m<sup>2</sup>), which were significantly greater than those recorded at Puerto Moro (PM, 11 sampling points,  $13.5 \pm 9.6$  items/100 m<sup>2</sup>) and Caleta Águila/Eagle Cove (CA, 14 sampling points,  $5.4 \pm 6.9$  items/100 m<sup>2</sup>) (ANOVA:  $F = 16.93$ ,  $p < 0.001$ ; Tukey Test, CC-PM:  $p = 0.050$ , CC-AC:  $p < 0.001$  and AC-PM:  $p = 0.075$ ) (Figure 2a). The mean sampling point density in mass ( $\pm$ SD) was also significantly higher in Caleta Cabaña/Hut Cove (CC,  $808 \pm 1428$  g/100 m<sup>2</sup>) than in Caleta Águila/Eagle Cove (CA,  $316 \pm 812$  g/100 m<sup>2</sup>) and Puerto Moro (PM,  $124 \pm 103$  g/100 m<sup>2</sup>) (ANOVA:  $F = 8.40$ ,  $p < 0.001$ ; Tukey Test, CC-PM:  $p = 0.058$ , CC-AC:  $p = 0.001$  and AC-PM:  $p = 0.670$ ) (Figure 2b).

These differences in plastic weight were mainly due to the number of items found in each area, since their sizes (mean  $\pm$  SD) were highest in Puerto Moro (PM,  $28.5 \pm 62.6$  cm), followed by Caleta Águila/Eagle Cove (CA,  $19.8 \pm 27.3$  cm) and Caleta Cabaña/Hut Cove (CC,  $13.4 \pm 22.5$  cm) (Figure 2c). In this sense, the analysis of the debris size structure based on CCAMLR's categories revealed that the two largest class sizes (i.e. Large 10 cm<sup>-1</sup> m and Very Large >1 m) were more prevalent in Puerto Moro (PM, 58.1%, 3.4%) compared to Caleta Águila/Eagle Cove (CA, 45.8%, 1.7%) and Caleta Cabaña/Hut Cove (CC, 36.7%, 0.9%) (Figure 2d).

The most abundant subcategory in terms of the number of items was 'Other plastics' (43.2%), primarily composed of plastic fragments (Table 1 and Figure 3a). This sub-category dominated across all three sites with proportions ranging from 30.8% to 43.8%. Other frequently recorded subcategories included 'Other rubber', 'Wire', and 'Plastic utensils', all ranking among the five most common types. Other subcategories showed site-specific patterns: 'Clothing' was more prevalent in Caleta Águila/Eagle Cove, 'Bags, pieces of bag' in Puerto Moro, and 'Styrofoam' in Caleta Cabaña/Hut Cove, respectively (Table 1).

The polymeric analysis of the subsample of the stranded debris from the three analyzed areas (257 items, 7%) confirmed the dominance of plastics, with over 70% of items matching polymer types (Figure 3b). The most prevalent materials were rubber (24.2%) and polyvinyl chloride (20.4%), followed by polyethylene (8.5%), polyamide (7.1%), acrylonitrile butadiene styrene (ABS, 6.2%), and polypropylene (6.2%). Other polymers, including very conspicuous materials in Antarctica like polystyrene, alkyd resins

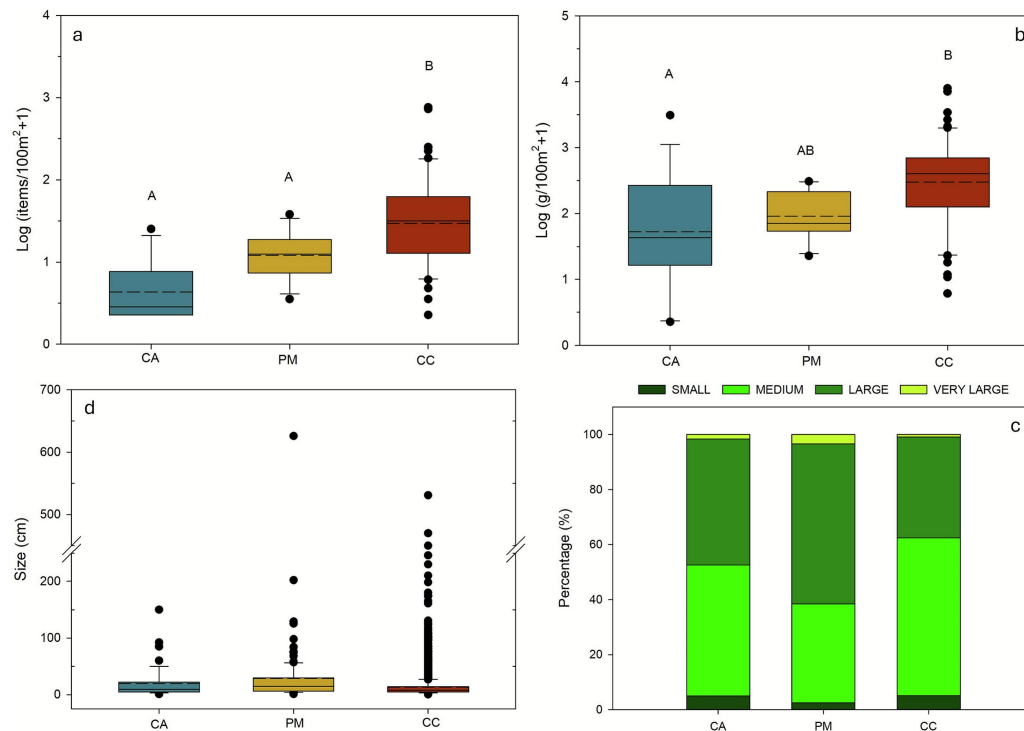


**Figure 2:** Box plots of (a) abundance [ $\text{Log} (\text{items}/100 \text{ m}^2+1)$ ], (b) mass [ $\text{Log} (\text{g}/100 \text{ m}^2+1)$ ], and sizes (c) of plastic debris per sampling point on the three areas analyzed (CA: Caleta Águila/Eagle Cove, PM: Puerto Moro, and CA: Caleta Cabaña/Hut Cove). The median (solid line) and the 10th, 25th, 75th and 90th percentiles are shown, as well as the mean values (dashed line) and the outliers (black dots). Different letters indicate statistically significant differences between sites ( $p < 0.05$ ) according to Tukey's post hoc test. (d) Percentages of the four CCAMLR size categories (Small, Medium, Large, and Very Large) for each of the three areas analyzed.

**Table 1.** Dominant subcategories of debris found in this study along the coast of Bahía Esperanza/Hope Bay, based on the classification proposed by the Marine Debris Program of the Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR, [www.ccamlr.org/en/data/forms](http://www.ccamlr.org/en/data/forms)). Data is presented as a percentage for each area. Values greater than 10% were highlighted.

| CCAMLR Marine Debris Subcategories | Caleta Águila Eagle Cove | Puerto Moro | Caleta Cabaña Hut Cove | All Sites   |
|------------------------------------|--------------------------|-------------|------------------------|-------------|
| Other plastic                      | <b>32.2</b>              | <b>30.8</b> | <b>43.8</b>            | <b>43.2</b> |
| Other rubber                       | <b>15.2</b>              | <b>14.5</b> | <b>23.5</b>            | <b>23.1</b> |
| Wire                               | 8.5                      | <b>21.4</b> | 9.9                    | <b>10.3</b> |
| Plastic utensils                   | 8.5                      | <b>17.1</b> | 6.1                    | 6.5         |
| Styrofoam                          | –                        | –           | 4.5                    | 4.3         |
| Cups, lids, straws                 | 1.7                      | –           | 3.6                    | 3.4         |
| Polyurethane foam                  | –                        | 1.7         | 3.2                    | 3.1         |
| Bags, pieces of bag                | 6.8                      | 3.4         | 2.2                    | 2.3         |
| Longline, mono fishing line        | –                        | 0.8         | 0.8                    | 0.8         |
| Burned plastic                     | 3.4                      | 2.6         | 0.4                    | 0.5         |
| Food wrappers                      | 1.7                      | –           | 0.4                    | 0.4         |
| Open strapping bands               | 1.7                      | 2.6         | 0.2                    | 0.3         |
| Ropes open                         | –                        | 2.6         | 0.3                    | 0.3         |
| Clothing                           | 10.1                     | 0.8         | 0.2                    | 0.3         |
| Sacking                            | 8.5                      | 1.7         | 0.1                    | 0.3         |
| Other wood                         | –                        | –           | 0.2                    | 0.2         |
| Other cloth/fabric                 | –                        | –           | 0.2                    | 0.2         |
| Cigarettes                         | –                        | –           | 0.1                    | 0.1         |
| Bottle                             | –                        | –           | 0.1                    | 0.1         |
| Cigarette lighter                  | 1.7                      | –           | –                      | 0.1         |
| Closed strapping bands             | –                        | –           | 0.1                    | 0.1         |
| Furnishings                        | –                        | –           | 0.1                    | 0.1         |

(paints), and polyurethane, accounted for less than 5% (Figure 3c).

Notably, some items stood out as long-standing debris of historical value. These included eyewear frames, toothbrushes, sledge dog food bags (dated 1980), hard rubber, and pieces or fragments of electrical devices (Figure 4a). Other accompanying non-plastic items were also historical, such as pieces of cotton textiles from charcoal bags and many fragments of ceramic cups (Figure 4a). Except for a single item found in Puerto Moro, all historical debris concentrated in Caleta Cabaña/Hut Cove, with an average abundance of  $17.3 \pm 44.3$  items/100 m<sup>2</sup> (ranging from 1.27 to 188.44 items/100 m<sup>2</sup>) (Figure 4b). This accumulation was particularly evident in the area between Esperanza Station and the former location of Station D. In fact, the relationship between the abundance of historical debris (items/100 m<sup>2</sup>) and distance (m) was statistically significant and, although weak, was exponential when measured from Esperanza Station ( $R^2 = 0.21$ ,  $F = 7.941$ ,  $df: 1-25$ ,  $p = 0.009$ ) (Figure 4c).

When analyzing the polymeric composition of these historical debris, we found that most were plastics, including polyethylene, polyvinyl chloride, and cellulose acetate, showing clear signs of degradation possibly related to weathering processes (Figure 5). In the case of the Antarctic dog food bag, the analysis confirmed an 87% match with PE, particularly with a reference in the library associated with UV irradiation under a super-accelerated weathering process. Furthermore, evaluating the obtained spectrum, the clearly increased hydroxyl group peak (3300–3400 cm<sup>-1</sup>), the carbonyl group peak (1550–1810 cm<sup>-1</sup>), and especially the carbon–oxygen stretching peak (1100–1300 cm<sup>-1</sup>), which do not appear in the reference, indicated degradation (Figure 5a). The analysis of fragments of electrical devices showed an 84% match with PVC and also displayed clear signals of degradation in its spectrum, possibly associated with environmental exposure over the years. Once again, the hydroxyl group peak (3300–3400 cm<sup>-1</sup>) and the carbon–oxygen stretching peak (1100–1300 cm<sup>-1</sup>) were evident, which do not appear in the reference (Figure 5b). Based on these peaks, and by comparing them with the reference band at 1460 cm<sup>-1</sup> (CH<sub>2</sub> deformation), the corresponding indices were calculated for these two historical debris, confirming their degradation (Table S2).

In the case of the toothbrushes and eyeglass frames, a 92% and 86% match, respectively, with cellulose acetate (CA) was confirmed (Figures 5c and 5d). Based on the spectra, the peak corresponding to the C=O double bond stretching of the ester bond (1760 cm<sup>-1</sup>) and the peak of the methyl group of the acetyl (1379

cm<sup>-1</sup>) were evaluated, both of which would lose intensity as AC degrades due to the removal of the acetyl group (Gorassini et al., 2016; Shaikh et al., 2022). In both cases, the intensity of these peaks was lower compared to the library reference, suggesting a possible degradation of these materials (Figure 5c and 5d). However, to confirm this, we calculated the carbonyl index ( $1550-1810 / 2920$  cm<sup>-1</sup>, Tan et al., 2023) and the Degree of substitution (DS,  $3330/1030$  cm<sup>-1</sup>, Liu and Kazariann, 2022). In both cases, the values obtained also suggest that these materials had indeed undergone degradation (Table S2).

## 4. Discussion

This study provides evidence on the presence and distribution of plastic debris in Bahía Esperanza/Hope Bay, highlighting that even in remote Antarctic environments, plastic pollution is detectable and appears to be associated with human activities and infrastructures. During this Antarctic campaign, 3477 plastic items were collected along 2437 m of shores, and the calculated mean abundance per surveyed linear meter for Esperanza/Hope Bay was 1.43 items/m (0–3.70 items/m). The results are comparable to previously reported studies for marine litter in other coastal regions, including the Antarctic Treaty Area. Our results are at least twice as high as the maximum values recorded for the islands of the Scotia Arc and the South Shetland Islands (0.74 items/m for ASPA No. 112 on Robert Island by Wilkie Johnston et al., 2024), and in some cases up to an order of magnitude higher (e.g. 0.1–0.3 items/m by Convey et al., 2002; 0.02 items/m by Sander et al., 2009; 0.05–0.13 items/m by Eriksson et al., 2013; 0.16 items/m by Anfuso et al., 2020; 0.32 items/m by Vesman et al., 2024).

We also estimated an overall mean abundance of 0.29 items/m<sup>2</sup> (0–0.74 items/m<sup>2</sup>) for Bahía Esperanza/Hope Bay, doubling the abundance reported by Vesman et al. (2024) (0.17 items/m<sup>2</sup>) for Fildes Peninsula (King George Island/25 de Mayo), one of the largest ice-free areas of maritime Antarctic and the most important logistic and touristic hub for the Antarctic Peninsula area (Braun et al., 2012; Convey, 2020). However, when analyzing specific areas, our highest estimation (Caleta Cabaña/Hut Cove, 0.74 items/m<sup>2</sup>) was nearly four times greater than the highest abundance reported for Fildes Peninsula (Drake Passage, 0.20 items/m<sup>2</sup>). In this sense, that estimate we obtained for Caleta Cabaña/Hut Cove was quite like the one recently published for Bahía Esperanza/Hope Bay (0.93 items/m<sup>2</sup>) by Monrás-Riera et al. (2025) from samples obtained in a nearby area.

Along the 2437 m of surveyed coastline, we identi-

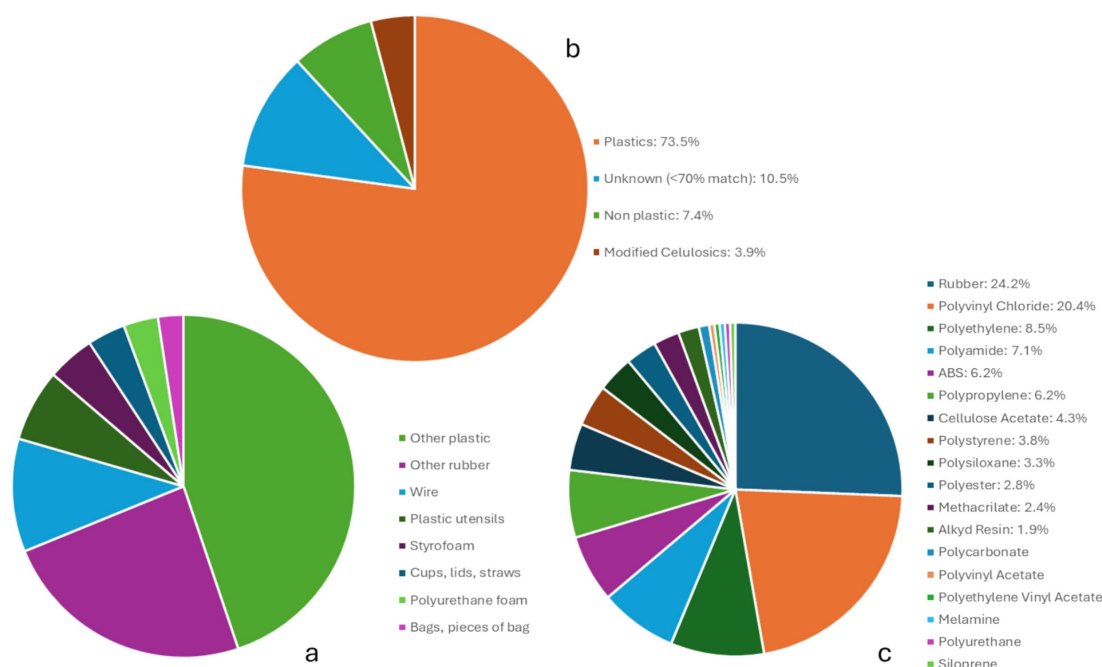


**Figure 3:** Most abundant debris subcategories (CCAMLR Marine Debris Program), highlighting 'Other plastics' (43.2%) which by definition includes any plastic (e.g. fragments) for which a probable origin/use cannot be established. ATR-FTIR analysis confirmed that the majority of the analyzed items (257 items, 7%) were plastics (b), identifying 18 different polymers (match >70%) (c).

fied 85 sampling points containing at least one plastic item. Based on the same sampling effort, which indeed may require a somewhat greater investment of time in terms of walking and collecting, these points (defined by a 5 m radius, 78.5 m<sup>2</sup> and georeferenced) enabled us to achieve a higher level of detail in the analysis of the distribution of these pollutants, improving the characterization of the plastic litter landscape. In general terms, many of these sampling points contained few items (10.6% had only one item), while a small number of them concentrated large amounts of debris (60% of the total items accumulated in just seven points). When analyzed by beach, this pattern was also clear: at Caleta Águila/Eagle Cove, 50% of the points had only one item, while at the other extreme, Caleta Cabaña/Hut Cove showed high concentrations mainly related to these seven hot-spots, each containing between 116 and 597 items. This confirmed that debris distribution is not homogeneous along the coasts of Bahía Esperanza/Hope Bay, with no evidence of any bias of the method used toward high-concentration sites, at least within the a priori established size range (i.e. >1 cm).

Plastic debris presence and abundance appear to be closely linked to areas of human activity on the Trinidad/Trinity Peninsula. While the absence of debris, particularly in Papúa Coast, could also be influenced by tidal effects on that cliffed coastline, both the presence (i.e. number of sampling points) and abundance calculated (items/m and items/m<sup>2</sup>) suggest a strong connection with human activities.

Caleta Cabaña/Hut Cove accounted for 95% of items, more than 70% of the sampling points, and an abundance one order of magnitude higher than those in Puerto Moro and Caleta Águila/Eagle Cove. Furthermore, the average abundance of these 60 sampling points (items/100 m<sup>2</sup> and g/100 m<sup>2</sup>) were significantly greater than in the other two areas. This spatial pattern aligns with the anthropogenic activity zoning proposed by Carlini et al. (2007) for Bahía Esperanza/Hope Bay in their study on Adélie penguins (*Pygoscelis adeliae*), which identified a High Anthropogenic Activity area (HAA, as opposed to Low Anthropogenic Activity Areas: LAA) encompassing the coastal areas where we found plastic debris. This zoning was also confirmed by Ibañez et al. (2020), analyzing interactions between plastic debris and brown skuas (*Stercorarius antarcticus lonnbergi*). Caleta Cabaña/Hut Cove's dominance was reflected in the significantly higher weight of debris per sampling point (g/100 m<sup>2</sup>), regardless of item size or type. This was particularly evident in Puerto Moro, where mean debris sizes were two to three times larger, and 20% corresponded to plastic-coated cables. Yet, the mean weight per sampling point was still significantly lower than in Caleta Cabaña/Hut Cove. Caleta Águila/Eagle Cove, located at the boundary between the HAA and LAA zones also showed debris, but at significantly lower densities compared to the other areas.

The association between plastic debris and proximity to human infrastructure is consistent with the hy-

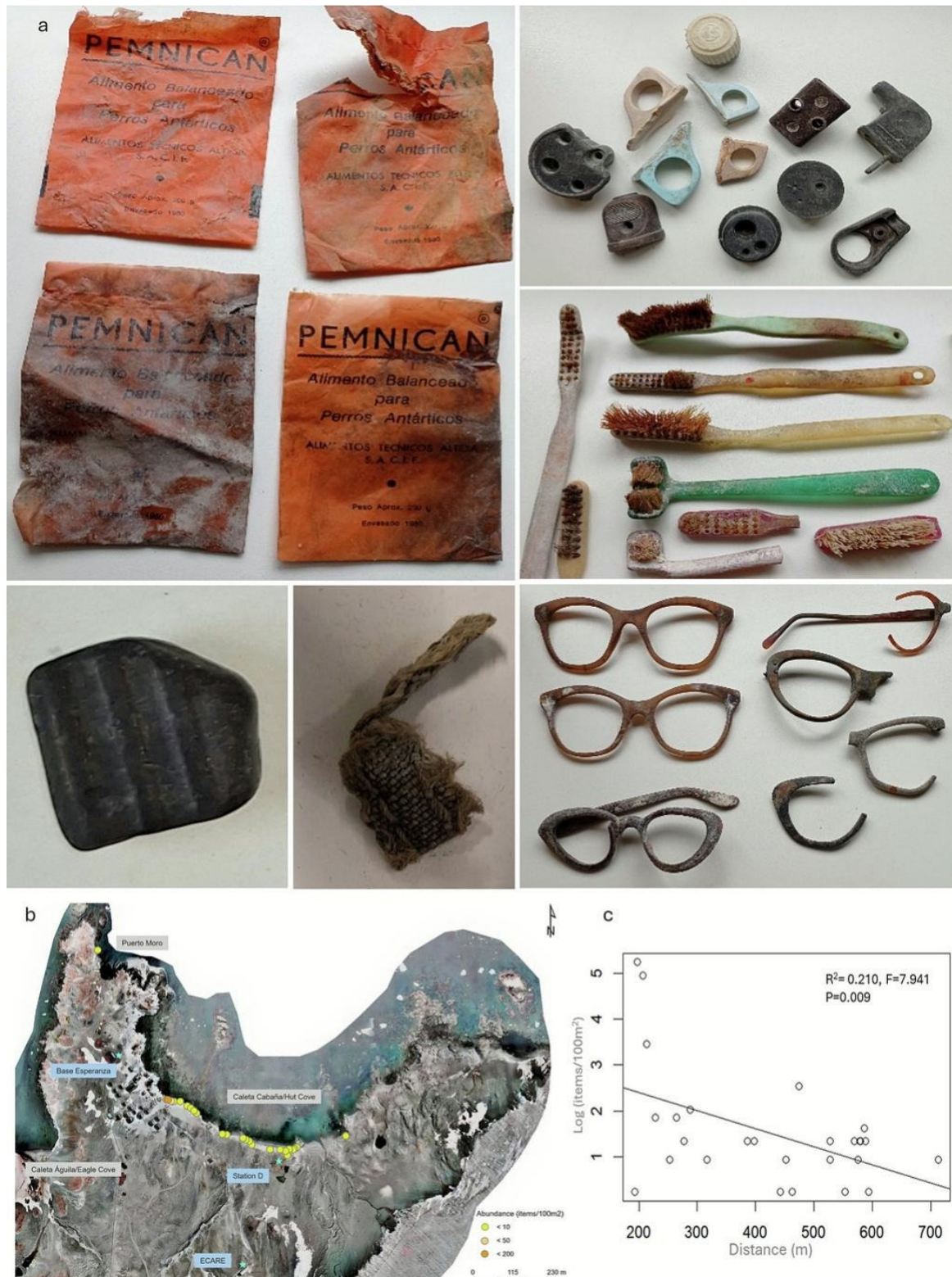


**Figure 4:** (a) Pictures of the historical debris found along the coasts of Caleta Cabaña/Hut Cove, (b) the area between Esperanza station and Station D where these debris were concentrated (higher color intensity indicates higher debris density), and c) results of the significant exponential relationship between the abundance of historical debris and their distance from Esperanza station.

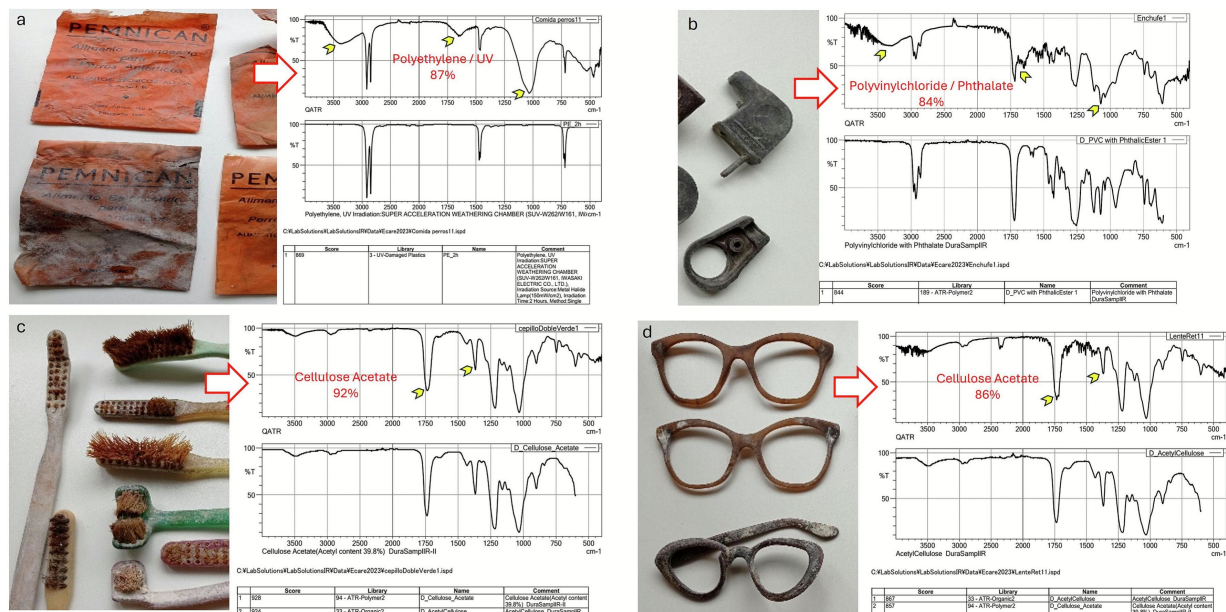


**Figure 5:** Results of the ATR-FTIR analysis of four historical debris, including (a) sledge dog food bags, (b) electrical devices, (c) toothbrushes, and (d) eyewear frames. For all of them, the obtained spectrum is presented, identifying the main degradation features, as well as the reference spectrum with the highest match found in the library, detailing the corresponding percentage.

pothesis that terrestrial sources are the primary contributors. That is further supported by the prevailing and strong N-NW winds in Bahía Esperanza/Hope Bay, which may transport lightweight debris such as bags, polyurethane, and styrofoam. This same wind dynamic may also help explain the accumulation of plastic debris in more enclosed coastal areas, particularly NW-oriented ones like Caleta Águila/Eagle Cove and parts of the central and eastern zone of Caleta Cabaña/Hut Cove.

Ocean currents have been identified as the other main pathway for the arrival and distribution of plastics and marine litter along the Antarctic coastal regions (Lacerda et al., 2019; Gallagher et al., 2024; Wilkie Johnston et al., 2024). Several other studies have attempted to model debris trajectories using oceanography, winds and bathymetry, sometimes incorporating particle-specific characteristics. Despite ongoing challenges due to the vast particle heterogeneity (differences in shapes, polymeric composition, or degrees of aging, weathering and biofouling), these approaches have advanced our understanding of plastic transport in the Antarctica regions (Suaria et al., 2021; Gallagher et al., 2024). In our study area, the hydrography of the Bransfield Strait has been studied since the early 20th century, including surface and shelf circulation of the West Antarctic Peninsula, and particularly around the northern tip of the Antarctic Peninsula. These studies highlight the influence of the cold Antarctic Coastal Current, which carries water from the Weddell Sea as it flows around the tip of the Peninsula and enters the strait, with evidence of flow north of the Antarctic Sound,

between the northeastern tip of the Antarctic Peninsula and Joinville Island (Sangrà et al., 2017; Frey et al., 2023). This suggests that the main contributions of floating plastic debris would not originate from the Bransfield Strait and the South Shetland Islands but rather from areas farther east in the Weddell Sea. In this regard, Gallagher et al. (2024) suggest that debris sources observed in the northern Antarctic Peninsula would be linked to tourism and research activities around the Joinville Islands, and the east along the Weddell Sea coast.

Most of the debris found in our study lacked clear characteristics (geographic information, language, company information, barcode; see Meyer et al., 2023) that would allow us to distinguish between terrestrial or marine sources or whether they were of local or exogenous origins. However, when classified according to CCAMLR categories, a certain predominance emerges of debris associated with local human activities, particularly nearby stations. More than 40% of the debris was categorized as “Other plastics,” and although these were mainly fragments whose origin is not always easy to determine, 40% (605 items) were of PVC pipes. “Other rubber” (23%, 803 items) was the next most abundant category, comprising 19% industrial items (O-rings, hoses, footwear), and 11% hard-rubber fragments likely from tires or snow-vehicle tracks. The third category was “Wires” (10%) due to their plastic coating, and as with the previous cases, these items seem closely related to the operation and maintenance of local infrastructure. The dominance of these categories and types of debris, in turn, determined the relative importance of the

polymers found. As a result, the most common were Rubber (24%) and polyvinyl chloride (20%), relegating those more commonly encountered elsewhere to lower percentages such as polyethylene (8%) and polypropylene (6%).

Historical plastic waste found in Caleta Cabaña/Hut Cove provides clearer evidence of its origin, persistence, and its significant exponential relationship with nearby human settlements. Although not all of them could be dated accurately, the packaging date was identified in the case of sled dogs' food bags (1980). These were likely used until February 1993, when the last 13 Argentine polar dogs left Antarctica, following the recommendation of the Scientific Committee on Antarctic Research (SCAR) under the Madrid Protocol (Maiada, 2015). These findings provide clear evidence of the extreme persistence of plastic waste in these environments (over 30 years) and highlight the long-term footprint of plastic pollution. A detailed analysis of the spectra obtained allowed us not only to confirm the polymeric composition corresponding to each sample based on a robust match (>80%), but also to assess the degradation of these historical debris. For the three identified polymers (polyethylene, polyvinyl chloride and cellulose acetate), both the visual comparison of the spectra and the calculated aging indices enabled us to assess levels of degradation likely caused by exposure to the Antarctic conditions. It has been suggested that, to fully assess the potential risks of this contamination in natural ecosystems, it is essential to understand the "plastic cycle" (Hoellein and Rochman, 2021), which in our case highlights the importance of considering the temporal dimension of these debris given the long-term durability of this material. This is especially relevant considering that larger plastic debris can break down into secondary micro- and nanoplastics due to physical, chemical or biological processes, potentially releasing other chemical components and additives with toxic effects on the environment (Caruso et al., 2022; Lozoya et al., 2024). Despite the challenges posed by spectral analyses, particularly when weathering-related particle degradation further alters the spectra, our results indicate significant degradation of these historical debris. These results are consistent, considering that the extreme environmental conditions in Antarctica have been identified as significant drivers of fragmentation and degradation processes in plastic debris (Tocháček et al., 2019; Caruso et al., 2022). This suggests that such debris may be affecting these environments beyond their direct impacts associated with their size and shape, acting as a sustained source of microplastics over all these

years, with potential contributions of contaminants and plastic additives. This supports evidence of the environmental impacts of human presence in Antarctica, where even localized contamination can lead to long-lasting environmental consequences (Aronson et al., 2011; Pertierra et al., 2021; Hughes et al., 2023; Stark et al., 2023).

Although this issue affects one of the most human-pressured areas in West Antarctica and probably the entire continent (Tin et al., 2009; Pertierra et al., 2021), Bahía Esperanza/Hope Bay remains an iconic location protected within a unique governance framework such as the Antarctic Treaty System (ATS) founded on conservation and peaceful use principles. From our perspective, this makes the Antarctic Treaty Area (ATA) uniquely positioned to uphold these principles, shared by all the parties, and advance collective decisions that may be harder to achieve elsewhere, such as the legally binding Global Plastics Treaty (Cowan et al., 2024). In this regard, the Madrid Protocol was a key in improving waste management in the ATS (Antarctic Treaty, 1991). The historical debris found in Bahía Esperanza/Hope Bay highlights just how necessary such regulations were, even though the current extent of plastic and microplastic pollution was not foreseen at the time. Although the Protocol has undergone updates, it contains only limited references to certain polymers or plastic materials, identifying some as prohibited or highlighting requirements for waste management, which is understandable since plastic was considered a revolutionary material and its potential consequences as hazardous debris were recognized in the 2000s (Rochman et al., 2013). It also appears to lack a comprehensive focus on aspects of plastic pollution that are now better understood, especially microplastics, the majority of which are fibers released through wastewater, or fragments generated by the breakdown of larger plastic debris (secondary microplastics). Moving forward, progress should include reinforcing areas of work related to marine debris and plastics within the ATS (SCAR Expert Group on Plastic in Polar Environment, CCAMLR Marine Debris Monitoring Program) and implementing recommendations from the Antarctic Treaty Consultative Meetings (Resolution 5/ATCM XLII 2019, Secretariat of the Antarctic Treaty, 2019). Key steps involve synchronizing efforts (research and monitoring), harmonizing methodologies to facilitate the collection of comparable data, and improving spatial and temporal data coverage to support evidence-based decision-making (Rota et al., 2022; Lozoya et al., 2024; Monràs-Riera et al., 2025). Annex III of the Protocol on Prevention of Marine Pollution could also be updated with current knowledge to include measures addressing known microplastics sources, such

as wastewater from scientific and touristic infrastructures. Additionally, initiatives should be introduced to recover larger legacy debris, which, in the absence of a clear origin, becomes 'common unmanaged burdens' that continue to release microplastics. Finally, while the ATS can only address local- to regional-scale impacts (Aronson et al., 2011), Antarctica is not isolated from global plastic pollution (Lacerda et al., 2019; Lozoya et al., 2022). Active participation in global negotiations such as the Global Plastics Treaty currently under discussion, is both strategic and urgent, aiming to reduce the flow of plastics and microplastics from lower latitudes into the Antarctic region (Aronson et al., 2011; Meyer et al., 2023).

## 5. Conclusions

The average abundance of plastic debris per linear meter in Bahía Esperanza/Hope Bay was at least two times, and up to ten times, higher than those previously reported for the islands of the Scotia Arc and the South Shetland Islands.

When analyzed per square meter, our overall results doubled those reported for Fildes Peninsula (King George Island/25 de Mayo), one of the main logistical and touristic hubs of the Antarctic Peninsula area. The site with the highest abundance in our study (Caleta Cabaña/Hut Cove) showed values like the only record found for Bahía Esperanza/Hope Bay and was nearly four times higher than the highest value reported for Fildes Peninsula.

Debris in Bahía Esperanza/Hope Bay showed a markedly uneven distribution, with many sampling points containing just one item and only a few accountings for over half of the total. This imbalance was even more apparent when examined by beach, with Caleta Águila/Eagle Cove, where half of the sampling points held a single item, and Caleta Cabaña/Hut Cove, where seven sampling points near Base Esperanza concentrated more than half of the debris recorded.

The concentration of plastic debris was strongly associated with areas near human activity and infrastructures, particularly for historical debris, although environmental drivers such as ocean currents and wind patterns are also known to influence plastic distribution in the region. The discovery of historical debris provides unequivocal evidence of the persistence of plastics in Antarctic environments, whose clear signs of weathering highlight the potential consequences and impacts of the enduring legacy of this pollution.

Continued progress in coordinated research and monitoring efforts is essential to support more effective management of plastic pollution within the

Antarctic Treaty System, reinforcing existing ATCM recommendations, and encouraging further commitments of the member states.

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# Supplementary Materials

## Plastic debris on the shores of Bahía Esperanza/Hope Bay: Stranded testimony of the historical occupation in the northern Antarctic Peninsula

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### Contents:

**Figure S1.** Frequency histograms of the percentage of sampling points (left y-axis, percentage of sampling points) based on the number of items per point (x-axis, items/sampling point). The red lines represent the cumulative frequencies of the total number of items (right y-axis, Total percentage of items), also based on the number of items per point (x-axis, items/sampling point). These relationships are shown for (a) all data from Bahía Esperanza/Hope Bay, (b) Caleta Águila/Eagle Cove, (c) Caleta Cabaña/Hub Cove, and (d) Puerto Moro.

**Figure S2.** Sampling methodology based on linear transects (three people covering a 5-meter-wide strip), focusing on the identification and geolocation of circular sampling points (5-m radius; covering 78.5 m<sup>2</sup>) triggered by the presence of at least one debris (>1cm) on the shoreline. If a single item was found within the 78.5 m<sup>2</sup> circle, abundance was recorded as that item alone (1 item/78.5 m<sup>2</sup>; 1.27 items/100 m<sup>2</sup>). If multiple items were present, all were collected and counted for that sampling point.

**Table S1.** Plastic debris abundances (items/100 m<sup>2</sup>) per sampling point on the three areas analyzed (Caleta Águila/Eagle Cove, Puerto Moro, and Caleta Cabaña/Hut Cove) along the coast of Bahía Esperanza/Hope Bay.

**Table S2.** Results of the indexes (e.g. hydroxyl, carbonyl, carbon–oxygen, and degree of substitution-DS) calculated to evaluate potential weather-related changes in the four historical debris analyzed (see Figure 5). Depending on the polymer (polyethylene-PE, polivinyll chloride-PVC, cellulose acetate-CA) the indexes were calculated as the ratio between the peak height of the functional groups. Wavelengths in cm<sup>-1</sup>. The reference peaks used were 1030 cm<sup>-1</sup>, 1460 cm<sup>-1</sup>, and 2920 cm<sup>-1</sup>.

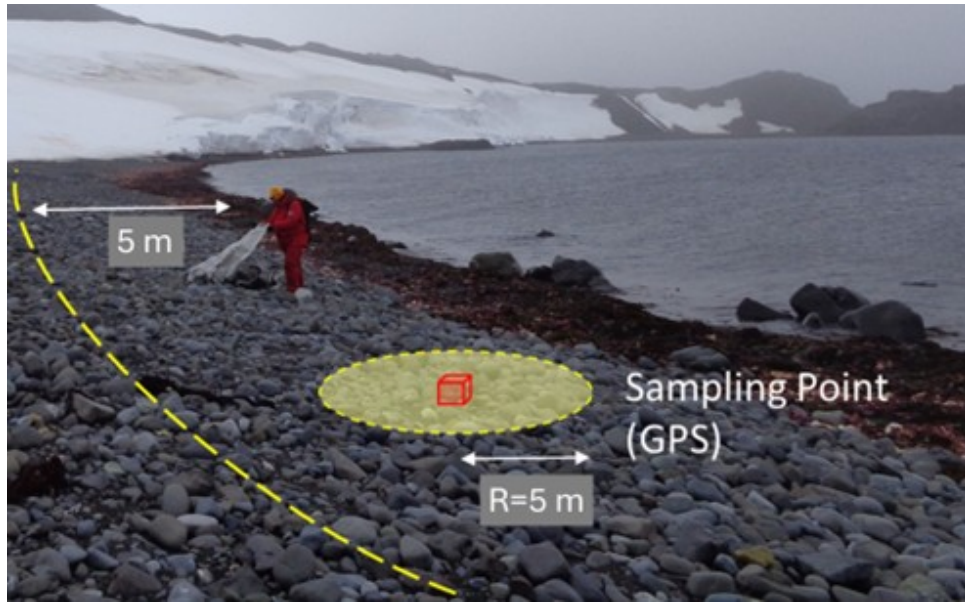


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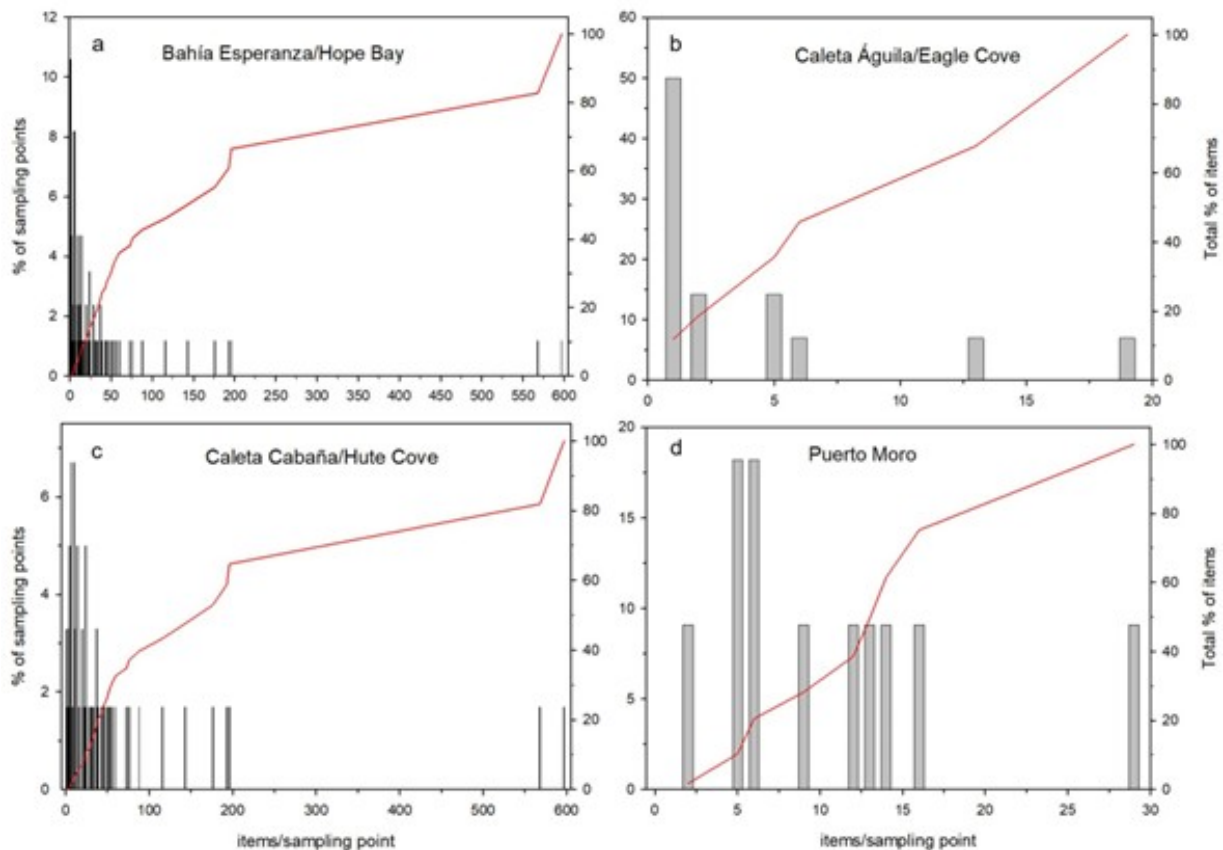


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**Table S1.** Plastic debris abundances (items/100 m<sup>2</sup>) per sampling point on the three areas analyzed (Caleta Águila/Eagle Cove, Puerto Moro, and Caleta Cabaña/Hut Cove) along the coast of Hope Bay.

| Abundance per sampling point (items/100 m <sup>2</sup> ) |             |                          |        |
|----------------------------------------------------------|-------------|--------------------------|--------|
| Caleta Águila<br>(Eagle Cove)                            | Puerto Moro | Caleta Cabaña (Hut Cove) |        |
| 2.55                                                     | 6.37        | 12.73                    | 182.07 |
| 6.37                                                     | 7.64        | 36.92                    | 224.09 |
| 6.37                                                     | 6.37        | 92.95                    | 112.04 |
| 16.55                                                    | 20.37       | 25.46                    | 6.37   |
| 24.19                                                    | 16.55       | 62.39                    | 30.56  |
| 7.64                                                     | 7.64        | 30.56                    | 7.64   |
| 1.27                                                     | 36.92       | 12.73                    | 14.01  |
| 1.27                                                     | 11.46       | 3.82                     | 12.73  |
| 2.55                                                     | 17.83       | 30.56                    | 14.01  |
| 1.27                                                     | 2.55        | 2.55                     | 17.83  |
| 1.27                                                     | 15.28       | 11.46                    | 12.73  |
| 1.27                                                     |             | 19.10                    | 21.65  |
| 1.27                                                     |             | 6.37                     | 760.12 |
| 1.27                                                     |             | 47.11                    | 723.20 |
|                                                          |             | 5.09                     | 249.55 |
|                                                          |             | 7.64                     | 64.94  |
|                                                          |             | 5.09                     | 43.29  |
|                                                          |             | 7.64                     | 17.83  |
|                                                          |             | 38.20                    | 39.47  |
|                                                          |             | 245.73                   | 49.66  |
|                                                          |             | 28.01                    | 96.77  |
|                                                          |             | 71.30                    | 54.75  |
|                                                          |             | 58.57                    | 42.02  |
|                                                          |             | 56.02                    | 47.11  |
|                                                          |             | 48.38                    | 1.27   |
|                                                          |             | 31.83                    | 7.64   |
|                                                          |             | 17.83                    | 6.37   |
|                                                          |             | 67.48                    | 147.70 |
|                                                          |             | 76.39                    | 8.91   |
|                                                          |             | 25.46                    | 1.27   |

**Table S2.** Results of the indexes (e.g. hydroxyl, carbonyl, carbon–oxygen, and degree of substitution-DS) calculated to evaluate potential weather-related changes in the four historical debris analyzed (see Figure 5). Depending on the polymer (polyethylene-PE, polivinyll chloride-PVC, cellulose acetate-CA) the indexes were calculated as the ratio between the peak height of the functional groups. Wavelengths in  $\text{cm}^{-1}$ . The reference peaks used were  $1030\text{ cm}^{-1}$ ,  $1460\text{ cm}^{-1}$ , and  $2920\text{ cm}^{-1}$ .

|               | Peak ( $\text{cm}^{-1}$ ) | %Absorbance | Index |
|---------------|---------------------------|-------------|-------|
| PE            |                           |             |       |
| Reference     | 1460                      | 0.08        | -     |
| Hydroxyl      | 3370                      | 0.07        | 0.88  |
| Carbonyl      | 1655                      | 0.05        | 0.63  |
| Carbon-Oxygen | 1100                      | 0.20        | 2.50  |
| PVC           |                           |             |       |
| Reference     | 1460                      | 76.7        | -     |
| Hydroxyl      | 3310                      | 84.5        | 1.10  |
| Carbonyl      | 1718                      | 64.7        | 0.84  |
| Carbon-Oxygen | 1122                      | 59.6        | 0.78  |
| CA            |                           |             |       |
| Reference     | 2920                      | 95          | -     |
| Carbonyl      | 1735                      | 44.4        | 0.47  |
| Reference     | 1030                      | 25.0        | -     |
| DS            | 3490                      | 92.8        | 3.71  |
| CA            |                           |             |       |
| Reference     | 2920                      | 94.2        | -     |
| Carbonyl      | 1735                      | 59.0        | 0.63  |
| Reference     | 1030                      | 47.0        | -     |
| DS            | 3504                      | 89.4        | 1.90  |