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Living in the cold: Geoarchaeology of sealing sites from Byers Peninsula (Livingston Island, Antarctica)

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ABSTRACT

Few geoarchaeological studies have been conducted in the Antarctic continent. This paper contains the first results of the geoarchaeological research done in two sealing sites dated from the 19th century, located in Byers Peninsula, South Shetland Islands (Antarctica). The research is part of a wider international project that aims at understanding the daily practices of the first anonymous occupants of Antarctica, and the insertion of the continent into the world system. The geoarchaeological study focuses on site formation analyses to provide new data on site function, use of local resources, length of occupation and taphonomy. With this approach, data not attainable through artefact or documentary analyses is provided. The studied sites are Sealer 3 and Sealer 4, two sealing shelters built with piled up boulders on rocky outcrops on the south Beaches of Livingston Island. Two major precincts and annexes were studied by means of multi-element chemical analyses, micromorphology and organic petrology. Although local lithology and cryogenic processes are dominant in the chemical and micromorphological records, respectively, important distinctions could be made, especially on the behavior associated with pyrotechnology and the use of local resources for survival. The effects of humans on the sediments are expressed by higher P_2O_5, CaO and total C concentrations. This is related with the use of seal bones, fat and herbaceous tissue as fuel for the hearths. Shelters with more intense occupation could be differentiated from single-activity sites. Differences are attributed to habitation shelters vs. working spaces for fat processing.

1. Introduction

The history of Antarctica is marked by the feats of adventurous explorers who risked their lives searching for the conquest of the white continent. The stories of the British Captain James Cook, commander of the first crew to cross the Antarctic Polar Circle, were published in 1777 and symbolize the beginning of the history of exploration and exploitation of Antarctica (Senatore and Zarankin, 1999; Senatore, 2002; Zarankin and Senatore, 2007). Key events and few heroes from the early 20th century, like Scott, Amundsen, Shackleton and Mawson, among others, make up the history of the most remote continent on Earth. However, the history of Antarctica is also made from ordinary, anonymous men, who arrived in the 19th century as labor force for the exploitation of natural resources. Their stories are less astonishing, without any heroes or significant events and full of imprecise dates (Zarankin and Senatore, 2005, 2007).

The discovery of the South Shetland Islands in 1819 initiated the seasonal exploitation of sea mammals in Antarctica. This activity was led by sailing companies from Britain and the USA interested in the immense colonies of seals and sea lions, a huge profit in fur and oil. The seal and whale hunters that sporadically occupied the shores of the South Shetland Islands are, in fact, the first inhabitants of the Antarctic continent. These groups of men settled in the coastal beaches for about three months, during hunting seasons for fur extraction (Zarankin and Senatore, 1997, 2005, 2007; Pearson and Stehberg, 2006; Pearson et al., 2009). The daily lives of these sailors are scantly known and most stories are told from the captains of the vessels.

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However, some personal journals illustrate the boredom, exhaustion and difficulties experienced by these men, who even had to struggle with stealing and fights with other sealing crews.

The first archaeological research in the South Shetland Islands, not related with the conservation of historically relevant sites, was made by a Chilean group of researchers lead by Ruben Stehberg. Their aim was to search for evidence of the presence of Fuegian Indians as crew in the sealing vessels (Stehberg, 2003). Currently, archaeological research is being done by an international team in Byers Peninsula (Livingston Island), the largest ice-free area in the South Shetlands Archipelago. The project goal is to investigate the capitalist strategies for integrating the Antarctic land into the world system. This is done by studying the daily practices of seal hunters through their material remains (Zarankin and Senatore, 1997, 2005, 2007; Zarankin et al., 2011a, 2011b). A total of 25 sites have been identified so far in this area and twelve have been already excavated. These sites correspond to sealing shelters built on rocky outcrops along the coast.

In the field season of 2010 two sites were excavated: Sealer 3 and Sealer 4 (Fig. 1). The sites are built on two separate rock

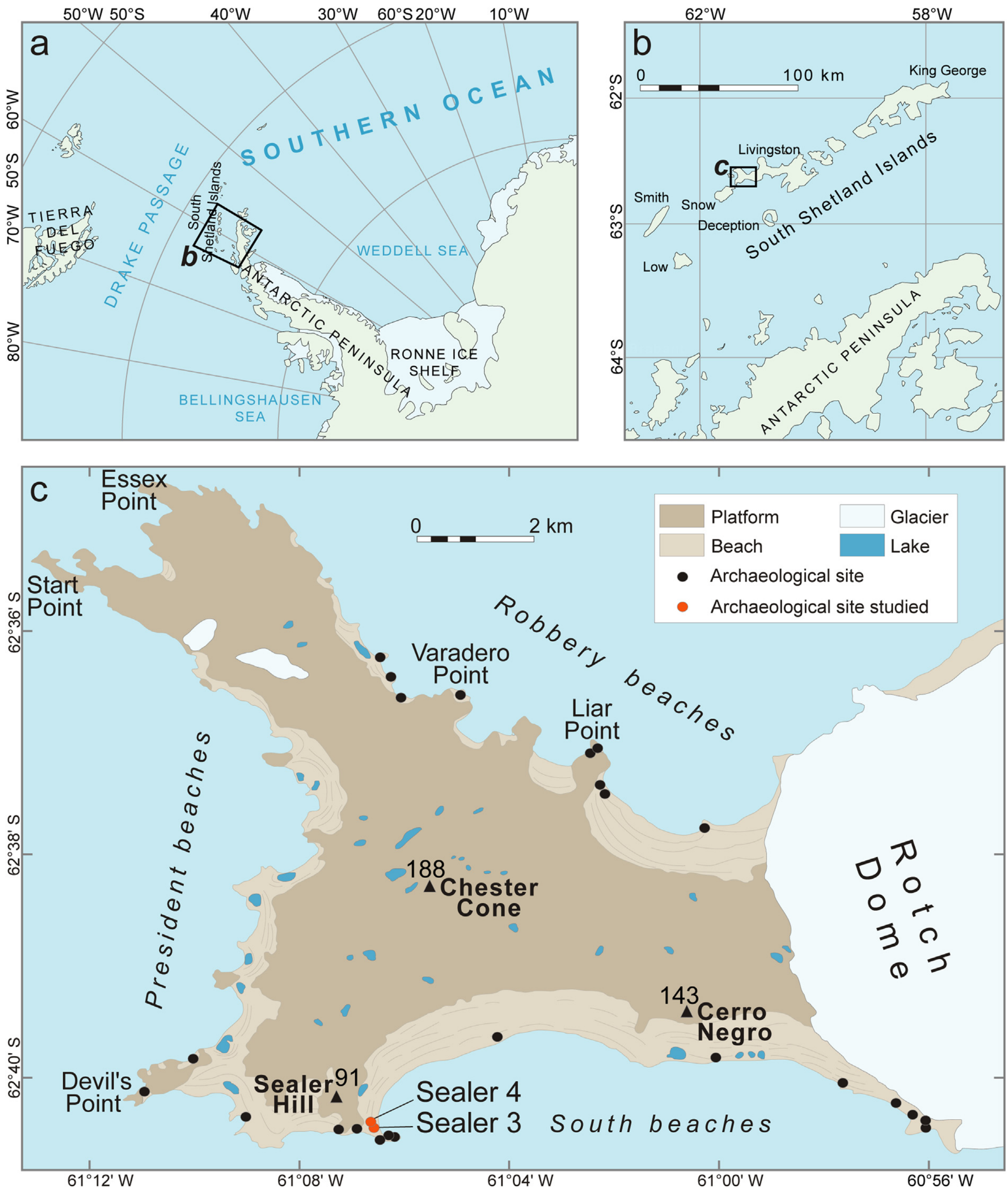

Fig. 1. Location of Byers Peninsula on Livingston Island (South Shetland Islands, Antarctica) (a, b), with the sealing sites studied in this work (c): Sealer 3 and Sealer 4 (maps by Tobias Sprafke).

outcrops and consist of small sheltered areas with walls made of piled boulders (Zarankin and Senatore, 2007; Zarankin et al., 2009, 2011a) (Figs. 2–4). Large combustion features were revealed during excavation. Analyses of the artefactual content of the sites suggest their use as habitation spaces, with possible nearby areas used for storage of animal fur. However, the interpretations derived from the field and artefactual analyses demand also thorough site formation analyses, never done before in sealing sites. In this sense, the incorporation of geoarchaeology to the project is a new line of research intended to provide complementary information on the nature and dynamics of site occupation, use of local resources, pyrotechnology and post-depositional processes affecting the integrity of archaeological remains (Villagran and Schaefer, 2011). This information could further confirm or refute interpretations derived from field and artefactual analyses.

Geoarchaeology of historical sites frequently points at identifying the relations between environmental changes and human occupation, and/or evaluating the large scale geomorphological alterations induced by agriculture, deforestation and development of urban centers etc. (Deagan, 1996; Goldberg and Macphail, 2006). In this work, geoarchaeology is used through a combination of chemical and micromorphological analyses to study the formation processes of two sealing shelters. This type of combined approach has been successfully used in prehistoric (Schaefer et al., 2004; Homsey and Capo, 2006; Arroyo-Kalin, 2008), ethnoarchaeological (Barba and Ortiz, 1992; Parnell et al., 2001; Fernandez et al., 2002) and rural sites (Wilson et al., 2008). We complement the results of chemical and micromorphological analyses with organic petrology, since field observations recurrently mention the presence of coal as a main component in sealing sites. Organic petrology, although still little used together with archaeological micromorphology, is commonly used for the characterization of fossil fuels (peat, brown coals, hard coals) and has recently proved to be useful for the identification and classification of burnt organic material in archaeological sites (Ligouis, 2006; Goldberg et al., 2009; Clark and Ligouis, 2010). The geoarchaeological analyses of sealing sites, through chemical, micromorphological and organic petrology analyses, complement the team's work on characterizing sealing strategies of occupation, identifying different uses of the sites, and the exploitation of local resources.

2. Regional setting

The ice-free area of Byers Peninsula (Livingston Island) is one of the largest in the South Shetland Archipelago (Fig. 1). It is

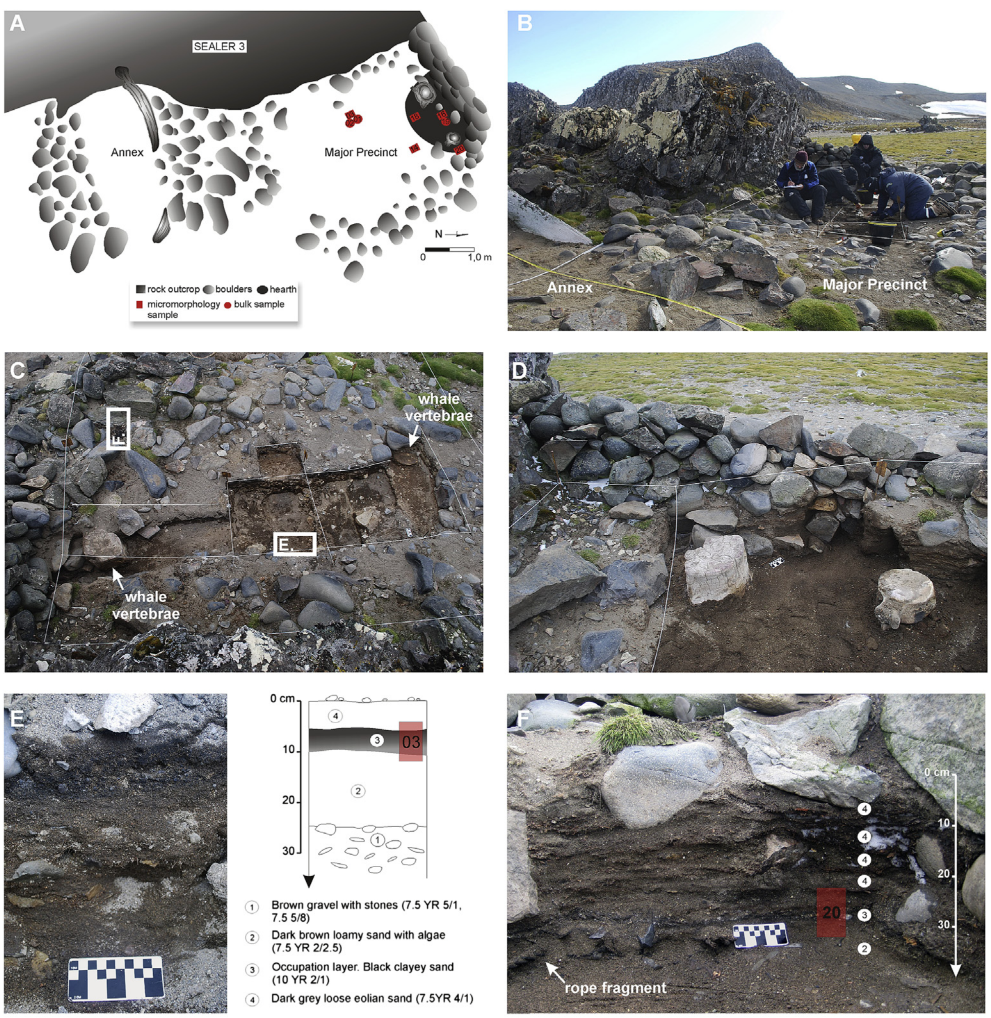

Fig. 2. Sealer 3: schematic view of the major precinct (MP) and annex (A) with location of bulk and micromorphology samples in the major precinct (A); north view of Sealer 3-MP and Sealer 3-A, both located on a rock outcrop over a beach terrace (B); overview of the excavation at Sealer 3-MP (C), note whale vertebrae in the north and south corners of the excavation; detailed view of the walls made of piled up boulders that characterize sealing shelters (D), note two whale vertebrae used as furniture; stratigraphic succession at the center of Sealer 3-MP with description of layers and location of micromorphology sample (E); stratigraphic succession at the north corner or Sealer 3-MP where a large combustion feature was found, with location of layers described in E and micromorphology sample (F), note the rope fragment in the lower left bottom of the image.

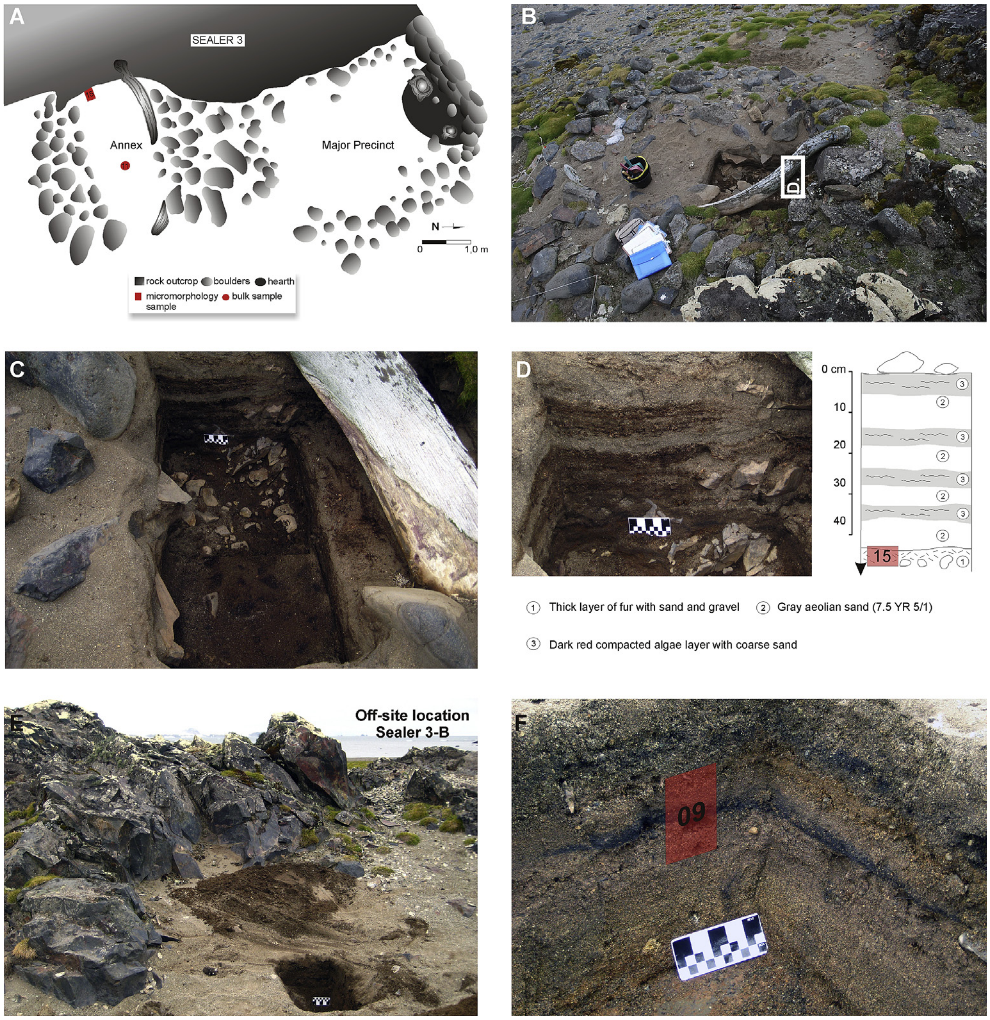

Fig. 3. Sealer 3: schematic view of the major precinct (MP) and annex (A) with location of bulk and micromorphology samples in the annex (A); overview of Sealer 3-A (B), note large whale rib across the site; west view of the excavation at Sealer 3-A (C); stratigraphic succession at the west wall of Sealer 3-A with description of layers and location of micromorphology sample (D); southeast view of the off-site sampling location near Sealer 3 (Sealer 3-B) (E); stratigraphic succession at Sealer 3-B with location of micromorphology sample taken from the black sandy clay layer (F).

considered a key site of Antarctic biodiversity (Quesada et al., 2009). Its unique and delicate ecosystem has granted it a special protection regime, belonging to the Antarctic Specially Protected Area 126 (ASPA-126).

The lithology of Byers Peninsula is made of sedimentary rocks (marine mudstones, sandstones and conglomerates), volcanic and volcanoclastic rocks, and some intruding igneous bodies (Smellie et al., 1984; Hathway and Lomas, 1998; López-Martínez et al., 2012). Deglaciation in the area started approximately between 5000 and 4000 BP (Bjorck et al., 1991). Today, the climate is cold maritime, with annual precipitation of 800 mm and mean annual temperature of about -2 °C. Temperatures rise above 0 only during summer, favoring snow melting and thawing of the surface (Navas et al., 2008; López-Martínez et al., 2012). The geomorphology is characterized by periglacial landforms (e.g. patterned ground, rock glaciers, uplifted marine platforms), especially on higher altitudes, above 20 m a.s.l., where more than 60 lakes have been surveyed.

Sealer 3 and Sealer 4 are located in the western part of the South Beaches of Byers Peninsula, an area that concentrates the highest number of archaeological sites in the region (Zarankin and Senatore, 2007). Both sites are located on rock outcrops over beach terraces, approximately 80–100 m from the present-day coast line (Fig. 1).

The South Beaches of Byers Peninsula are made of Quaternary gravels and alluvium, with poorly developed, shallow soils of high stoniness, low organic matter content and sporadic permafrost development. Vegetation is scarce on the beaches, with only grasses (*Deschampsia* sp.) and mosses, the latter growing on fine grained sediments in depressions (Navas et al., 2008). Studies made on Cryosols from the northern and southern portions of the peninsula show that soil properties are intrinsically related to parent material and its mineralogical composition, except for ornithogenic soils, which derive from decayed bird guano (Navas et al., 2008; Moura et al., 2012).

As in most surveyed sites in Byers Peninsula, Sealer 3 and 4 are formed by two occupation areas delimited by the rocky outcrop and/or the thick walls made of piled up boulders (Figs. 2A–D, 3A and B, 4A and C). Sites also contain whale bones inside, especially vertebrae, used by seal hunters as furniture (Zarankin and Senatore, 2007; Zarankin et al., 2011a) (Figs. 2A, C, D, 3A–C, 4A and F). The same arrangement is also observed in other sealing sites from the South and North Beaches of Livingston Island (Zarankin and Senatore, 2007; Zarankin et al., 2011a) and also on Rugged Island, lying west of Livingston (Pearson and Stehberg, 2006).

The occupation areas in Sealer 3 and 4 were identified as: major precinct (MP); and annex (A). Sealer 3-MP is 16.15 m^2 and contains

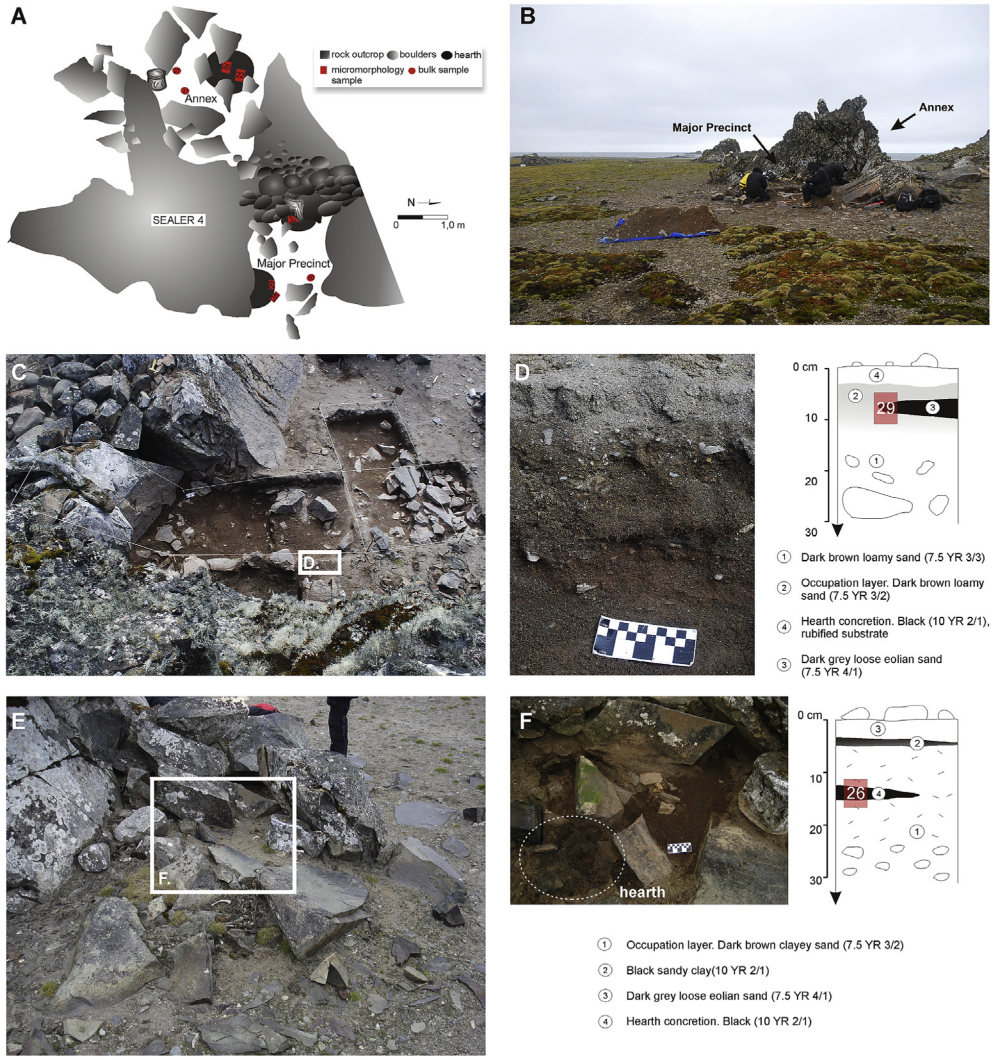

Fig. 4. Sealer 4: schematic view of the major precinct (MP) and annex (A) with location of bulk and micromorphology samples (A); southwest view of Sealer 4-MP and Sealer 4-A located on a rock outcrop over a beach terrace (B); overview of the excavation at Sealer 4-MP (C); stratigraphic succession at the south wall of Sealer 4-MP with description of layers and location of micromorphology sample (D); view of Sealer 4-A before the excavation (E); overview of the excavation at Sealer 4-A with schematic stratigraphic profile, description of layers and location of micromorphology sample (F), note the combustion feature and the whale vertebrae in the left photo.

two whale vertebra close to the walls, while Sealer 3-A is 13.20 m^2 and has one whale rib, already visible in the surface of the site. Sealer 4-MP is 19.25 m^2 and also contains whale bones inside, while Sealer 4-A is 12.25 m^2, contains one whale vertebrae and is delimited by a wall made of large detached rocks from the outcrop (Zarankin and Senatore, 2007; Zarankin et al., 2011a).

3. Methods

Seven bulk samples and twelve undisturbed sediment samples were collected from the major precincts and annexes of Sealer 3 and 4, in the field season of February–March 2010 (Figs. 2A, 3A and 4A). An off-site undisturbed sample was collected in a rocky outcrop located about 50 m south of Sealer 3 (Sealer 3-B) (Fig. 3E, F), to characterize anthropogenic-free sediments. The complete list of samples is detailed in Table 1.

Bulk samples were analyzed for their major, minor and trace element composition by x-ray fluorescence (XRF), with a Phillips PW 24010 equipment. For FRX, pressed pellets and fused beads were prepared from powder samples, previously grinded to silt-size particles (Mori et al., 1999). Total carbon concentrations were

Table 1
Samples collected in field work 2010 from the major precincts (MP), annexes (A) and off-site location (B) of Sealer 3 and 4.

Site	Bulk samples		Undisturbed samples	
	Code	Description	Code	Description
Sealer 3-MP	01	Unit 3 – occupation layer	03	Contact between units 2 and 3
	02	Unit 2 – substrate	14	Contact between units 2 and 3
	19	Hearth	16	Combustion feature – center
			18	Combustion feature – periphery
			20	Combustion feature – periphery
Sealer 3-A	11	Unit 1 – fur	15	Unit 1
Sealer 3-B			09	Dark sandy clay
Sealer 4-MP	30	Unit 2 – occupation layer	28	Combustion feature – periphery
			29	Combustion feature – periphery
			32	Combustion feature with fur
Sealer 4-A	21	Unit 1 – occupation layer	22	Unit 4 – hearth
	27	Unit 2 – black sandy clay	26	Unit 4 – combustion feature

determined on dried samples by combustion with a LECO furnace (CHN-1000) at 1100 °C (Andrade et al., 2009).

The undisturbed samples were collected from the stratigraphic profiles and excavation surfaces, focusing on the contact between layers (natural and modified by human action) and on the combustion features revealed during excavation. In the off-site location (Sealer 3-B), sampling aimed at characterizing the black sandy clay layer, of a few centimeters thick (Fig. 3F), that was also observed in Sealer 4-A at shallow depth (5–10 cm).

Samples were impregnated and sliced up to a thickness of 30 μm at the micromorphology laboratory of the Viçosa Federal University (UFV), with a mixture of polyester resin, catalyst and dilutent. Thin sections were successively polished by nylon disc with diamond paste, from 60 μm, 6 μm, 3 μm down to 1 μm, followed by ultrasonic wash for total removal of polishing residues. Analyses were made with a Zeiss Stemi SV11 stereomicroscope and Olympus DX40 and Zeiss Axioplan 1 optical microscopes, in plane polarized (PPL) and cross polarized light (XPL). Magnifications ranged from ×16 to ×400. Description of thin sections followed the guidelines of Stoops (2003).

Organic petrology studies were made on the polished thin sections after a complementary fine polishing using fine diamond paste and aluminum oxide slurry, down to 0.05 μm. Analyses were made with a Leica DMRX/MPV-SP microscope under white reflected light (WRL) and fluorescent light (UVL) by oil immersion. Magnifications ranged from ×200 to ×500.

To identify possible groups of samples according to their multi-element chemical composition, principal component analyses (PCA) was performed on the basis of variance-covariance matrix, using Minitab15 statistical software. The scatter plots will provide a visual aid in the identification of patterns of activity (Middleton et al., 2010). One scatter plot was made using major and minor elements as variables, and other using trace elements and total C. For the last, only the elements which showed values above the detectable limit in more than half of the samples, were used in the statistical analyses. As suggested by Sawakuchi et al. (2009), all compositional data given in percentages (major and minor elements) were converted to centered log-ratio coefficients (clr). The clr coefficients indicate the proportion of each compositional part in relation to the geometric mean of all parts, and can be interpreted in the same way as the raw proportions.

4. Results

Figs. 2E, 3D and 4D and F contain the description of the stratigraphic profiles at Sealer 3-MP, Sealer 3-A, Sealer 4-MP and Sealer 4-A. In all cases the stratigraphy is quite simple, with only one occupation layer with artifacts and combustion features. Only in Sealer 3-MP the occupation layer (unit 3) was easily identified in the field by its black color (10YR 2/1) and high frequency of artifacts, such as leather shoes, pipes, clothes, bullets, wooden sticks and iron nails, which do not appear in other layers of the site. In the center of the shelter, unit 3 is only 10 cm below the surface and covered by a thin layer of aeolian sand (Fig. 2E). In the north corner of the site, it appears at about 30 cm depth, overlain by a sequence of aeolian sediments and decayed algae layers (Fig. 2F). This shows the uneven surface of the shelter, characterized by a depressed area in the north corner.

In Sealer 4-MP the occupation layer is not black-colored and was defined mostly by its artefactual content, with less diversity and abundance of artifacts than in Sealer 3-MP (Fig. 4D). One combustion feature was identified in the occupation layer of Sealer 3-MP and two in Sealer 4-MP. All combustion features are composed of concreted lenses of 30–40 cm diameter, rich in calcined and carbonized bone fragments over a rubified substrate. For their concreted appearance, carbonized aggregates were described in the field as pieces of coal, although no further analyses until now were done to confirm it.

In the annexes the concentration of artifacts is considerably lower than in the major precincts, with only a few isolated findings. In Sealer 3-A there is an intercalation of centimeter thick layers of aeolian sand with layers of decayed algae, as also seen in the north corner of Sealer 3-MP. This succession overlay a thick layer of what macroscopically looked like fur remains from pinnipeds (marine mammals including seals, sea lions and elephant seals) lying upon the regolith (unit 1) at about 45 cm in depth (Fig. 3C, D). The overlying succession could be explained as several episodes of water saturation in a depressed area (possibly by snow accumulation) with algae growth (unit 3) in between eolian layers (unit 2). Sealer 4-A is a shallow site with a combustion feature in the central area, located in-between a layer of clayey sand with some organic detritus and no artifacts (Fig. 4E, F).

Table 2 contains the concentrations of major, minor and trace elements, together with total C, from the sediments in the four sites studied. Most major and minor elements show little variation between samples; with one exception in sample 19 with highest values of CaO and P_2O_5 (24.49% and 17.45%, respectively) compared to the rest of the samples (mean CaO of 4.24% and P_2O_5 of 1.22%). On the contrary, sample 19 has the lowest SiO and AlO values, almost half of the concentration detected in other samples. Another element with comparable distribution in most samples is total C. In general, the total concentration of C varies between 1 and 2%, except in samples 11 (unit 1 in Sealer 3-A) and 19 (combustion feature in Sealer 3-MP), which show exceptional values of 15.0 and 9.32% total C, respectively. A similar pattern is observed for trace elements, with comparable distributions in most samples. The highest amount of Zn, Cl and F were detected in sample 19, with anomalous S in sample 11, and higher Cu, Sr and V in sample 27. The slight increase in metal concentration seen in sample 27 correlates with the predominance of TiO_2 and Fe_2O_3 in this sample (see Table 2).

Table 2
Chemical composition (major, minor and trace elements) and total C of bulk samples collected from Sealer 3-RM, Sealer 3-A, Sealer 4-RM and Sealer 4-A.

	Sealer 3-MP			Sealer 3-A	Sealer 4-MP	Sealer 4-A	
	01	02	19	11	30	21	27
	%						
SiO_2	57.37	60.40	26.26	44.14	57.39	57.14	49.53
TiO_2	1.229	0.914	0.564	0.726	1.107	1.093	2.401
Al_2O_3	15.12	15.04	6.745	11.27	14.84	14.27	15.37
Fe_2O_3	7.75	6.39	3.64	4.84	7.97	7.41	11.14
MnO	0.111	0.086	0.078	0.064	0.110	0.093	0.133
MgO	2.27	1.62	1.155	1.26	2.15	1.97	2.88
CaO	4.65	3.52	24.83	2.75	4.24	3.93	6.36
Na_2O	3.99	3.89	2.03	2.84	3.89	3.89	4.17
K_2O	1.32	1.55	0.625	1.19	1.37	1.36	0.57
P_2O_5	1.044	1.187	17.676	0.535	1.204	1.223	2.123
Loi	5.36	5.4	15.96	30.81	5.64	7.22	4.72
C	1.5	0.79	9.32	15.0	1.02	2.25	2.01
	ppm						
Ba	237	299	95	233	280	294	116
Ce	47	55	<35	<35	44	<35	57
Co	15	10	9	9	15	13	23
Cr	21	24	13	20	34	34	<13
Cu	41	20	20	36	20	17	57
Ga	17	16	<9	11	17	15	23
La	<28	<28	<28	<28	<28	<28	<28
Nb	<9	<9	<9	<9	<9	<9	<9
Nd	37	28	22	22	41	32	48
Ni	8	5	5	<5	8	8	6
Pb	7	<4	6	<4	<4	<4	<4
Rb	25	32	11	22	28	28	8
Sc	23	19	29	15	23	23	31
Sr	284	276	333	214	284	275	362
Th	<7	<7	7	<7	<7	<7	<7

(*continued on next page*)

Table 2 (*continued*)

	Sealer 3-MP			Sealer 3-A	Sealer 4-MP	Sealer 4-A	
	01	02	19	11	30	21	27
U	3	3	9	6	<3	4	5
V	195	139	84	115	193	177	352
Y	28	26	14	24	27	25	27
Zn	84	71	207	57	81	70	74
Zr	158	147	72	102	139	143	206
Cl	55	<50	363	<50	<50	<50	227
F	606	<500	2129	<500	772	<500	610
S	<550	<550	788	10520	<550	1122	<550

The scatter plot for major and minor elements exhibits one major cluster and three outliers (Fig. 5A, B). The major cluster groups samples from the occupation layers at Sealer 3-MP (samples 1 and 2), Sealer 4-MP (sample 30) and Sealer 4-A (sample 21). Of the three outliers, one corresponds to unit 1 in Sealer 3-A (sample 11), while the other two come from the central combustion feature at Sealer 3-MP and unit 2 in Sealer 4-A (samples 19 and 27, respectively). The scatter plot for trace elements and total C (Fig. 5C, D) shows the same main cluster with the three outliers seen for major and minor elements.

Table 3 contains the micromorphological description of thin sections from Sealer 3 and 4. In Sealer 3-MP micromorphological analyses showed the succession of natural and anthropogenic layers that make up the site. The upper layer (unit 4) is made of aeolian sands, with amorphous volcanic glass and rock fragments, mainly of andesitic basalt (Fig. 6A). The frost-induced granular microstructure (Van Vliet-Lanoë, 1998; Schaefer et al., 2008) is composed of silt-coated grains of diverse mineralogy. All coarse fraction components are rounded and smooth. Grain-size distribution indicates short distance transport and poor selection. In this layer, there are no traces of sub-recent deposition of volcanic ash, only ash material reworked by periglacial erosion and wind.

Below the aeolian sand there is the occupation layer of Sealer 3-MP (unit 3, microfacies 3) (Fig. 6A). The occupation layer shows a dark-colored cryoturbic granular micromass, typical in Antarctic soils (Schaefer et al., 2008) made of burnt organic material mixed with phosphates and clay. Rock fragments and black opaque particles make up the coarse fraction (Fig. 6B). Rock fragments are coated and the larger grains show vertical arrangement due to frost. The black particles are rounded and sub-angular of very fine sand and silt size.

Organic petrological observation done with WRL showed that the black particles are reworked organic combustion residues from bones (Fig. 8A). The organic combustion residues look black and opaque in PPL and XPL, respectively, but have a characteristic bright white color in WRL. Observations made under WRL and UVL also proved the presence of burnt plant material, which occur as fine charcoal pieces (Fig. 8B) and burnt leaf tissue fragments, possibly from grasses. Heterogeneous particles showing strong circular

Table 3
Micromorphological description of thin sections collected from Sealer 3-MP (S3-MP), Sealer 3-A (S3-A), off site location near Sealer 3 (S3-B), Sealer 4-MP (S4-MP) and Sealer 4-Annex (S4-A).

																		Micromass				
	Sp.	mF	Porosity	%	Aggregates	Size (μm)	Microstructure	c/f ratio	c/f rel. distr.	Rock fragments	Burnt bone	Carbonized bone	Char	Charcoal	Tissue	Plant issue	Fung. mycelia	Colour	Limpidity	b-fabric	Composition	PF
S3-MP	03	3	cx-p	5-10	gr	50-100	intergrain microaggregate/ granular	50:50	en	•••••			•••	•		•	•		dt, cl	cry	Clay with char and bone inclusions	co
S3-MP	14	2	cx-p	40	gr	50	granular	90:10	chit en	••••••	•						•		sp	cry	Clay	co
S3-MP	16	-	vs	40	ap	-	bridged, pellicular grain	80:20	chit en	••	••	••••	••••			•	•••		lp	und	Phosphates	-
S3-MP	18	-	vs	50	ap	-	bridged, pellicular grain	90:10	chit gef	•••	•••	••	•••				••		lp	und	Phosphates	-
S3-MP	20	-	s-p cx-p	70	gr	<100	single grain, intergrain microaggregate	95:5	chit en	••••••	••					••			dt	cry	Clay	co
S3-A	15	-	cx-p	60	gr	50-100	granular	90:10	chit en	••••••					•••	•	•••		dt	cry	Clay and phosphates	co
S3-B	09	-	cm-p	35	lt	800	platy	60-40	por	••••••									dt	und	Allophane	-
S4-MP	28	-	cx-p	20	gr	>100	granular to vughy, pellicular	70:30	chit en	••••••	•	••					•		dt, cl lp	cry und	Clay and phosphates	co
S4-MP	29	-	cx-p	20	gr	>100	granular, pellicular grain	70:30	chit en	••••••		••	••			•	•		dt, cl lp	cry und	Clay and phosphates	co
S4-MP	32	-	-	30	-	-	-	-	-	•••			••		••	••	••••		-	-	Phosphates	-
S4-A	22	1	cx-p, vg	40	gr	>100	granular, pellicular grain, bridged	50:50	chit gef en	•••	•	••	•••				•••		lp	und	Char and phosphates	co
		2	cx-p	40	gr	100		70:30		••••••			•				••		dt,cl, lp	cry, und	Clay and phosphates	
S4-A	26	-	-	40	-	-	Bridged, pellicular grain	80:30	chit en	••		••••	••••	••					lp	und	Phosphates	-

Class frequencies after Bullock et al. (1985): • Very few (< 5%); •• Few (5-15%) ; ••• Common (15-30%) ; •••• Frequent (30-50%); ••••• Dominant (50-70%); •••••• Very dominant (>70%). Sp = sample; mF = microfacies; PF = pedofeatures; cx-p = complex packing; cm-p = compound packing; s-p = simple packing; vs = vesicular shaped vughs; vg = vughs; gr = granules; ap = apedal ; lt = lenticular; en = enaulic; chit = chitonic; gef = gefuric; por = porphyric; lp = limpid; sp = speckled; und = undifferentiated; cry = crystallitic; co = coatings.

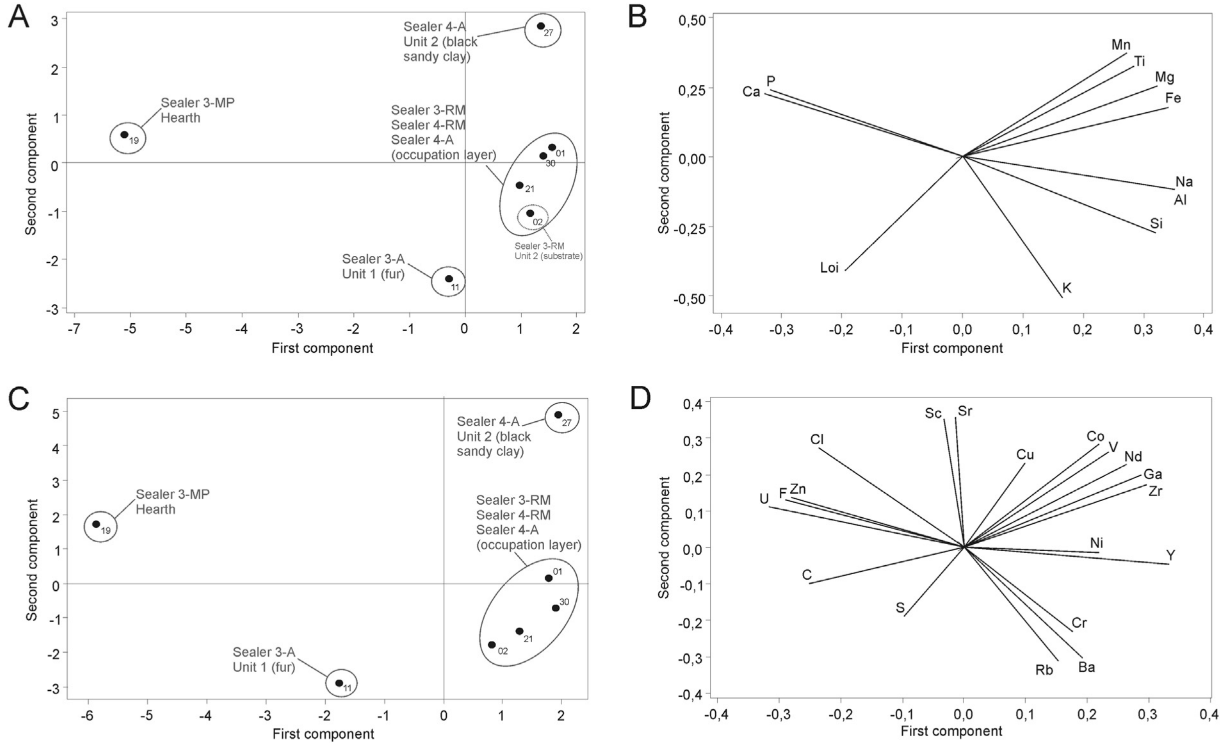

Fig. 5. Principal component analyses (PCA) of major, minor, trace elements and total C: scatter plot of major and minor elements (A) and line diagram with the relative weight of each variable (B); scatter plot for trace elements and total C (C) and line diagram with the relative weight of each variable (D).

anisotropy were also identified. They seem to have a mineral origin, although further analyses are needed for verification.

The sediments underneath the occupation layer of Sealer 3-MP (unit 2, microfacies 2) are mostly free of anthropogenic input. They show the typical microstructure of sandy coastal soils from Antarctica, with rare apatite grains, common in Antarctic sands, and partially decomposed organic residues (Fig. 6C). The same sediments were observed over and below the black sandy clay layer at the off-site location near Sealer 3 (sample 09) (Fig. 6D). At the off-site location, a thin layer of tephra was observed above the beach soils. The micromass is undifferentiated light brown and forms lenticular plates (Fig. 6E) made of volcanic glass and rock fragments (of aeolian input) (Fig. 6F).

Three samples were collected from the combustion feature in Sealer 3-MP. The hearth samples were the only ones to show clearly identified bone fragments of diverse size, sometimes reaching 3 cm in length. Bones in the core of the hearth are completely carbonized (Fig. 6G–I), while bones in the periphery of the hearth show mostly burnt surfaces (Fig. 6J–L). Although no detailed faunal analyses were carried out on this site, archaeofaunsitic studies in sites from the north beaches of Livingston Island (Cueva Lima 1 and 2 and Cutler 1) found pinnipeds as main component, together with cattle and pig bones (Muñoz, 2000).

In the hearth at Sealer 3-MP, bone fragments are mixed with rock fragments, feldspars and volcanic glass (of short distance aeolian transport) (Fig. 6K, L). However, the coarse fraction is mostly made of black, opaque particles with vesicular structure (PPL, XPL), of the same type described for the occupation layer and identified as organic combustion residues under WRL. In this case, the absence of cell structure, as expected in charcoal, the homogeneous texture of the organic combustion residues and the presence of bubbles or vesicles suggest they were originally fluid and have hardened after total release of the volatile gases (see Goldberg et al., 2009). This would be a case of char derived from burning of flesh, bone and/or animal fat (fat-derived char) (Fig. 8C, D). All coarse fraction components are coated with a bright orange, limpid (PPL) and amorphous (XPL) micromass (Fig. 6H, I). This micromass also forms concave meniscus-like bridges between grains, in a chito-gefuric c/f related distribution patter, suggesting water saturation and slow evaporation (see Kuhn et al., 2010). The fluorescence observed under UVL suggests a phosphatic composition for the bright orange micromass (Fig. 8E, D). Burnt plant material is also present in the hearth, mostly tissue remains from grasses (Fig. 8F). No wood charcoal was found.

Fungal mycelia were observed mostly in the periphery of the combustion feature, forming coatings and bridges (Fig. 6L). In the periphery, bones show microscopic focal destructions (Hacket, 1981; Piepenbrink, 1989; Jans, 2004) evidencing microbial attack in the thawing period (see Todisco and Bhiry, 2008; Villagran et al., 2011).

Although sample 15 in Sealer 3-A (unit 1) aimed at characterizing fur remains in thin section, due to the nature of this soft material most of it was lost during polishing (Fig. 7A). The little material that remained in the slide prevented its clear identification (Fig. 7B), although it showed to be invaded by fungal hyphae and mycelia. This tissue is placed between a sand layer made of coated rock fragments, volcanic ash and diatoms. There are also decayed algae tissue fragments in the sample (Fig. 7C) and diatoms.

The combustion feature in the south wall of Sealer 4-MP (Fig. 4A) was sampled in the periphery, thus, the ratio of local sediments (aeolian sand and rock fragments) vs. bone and fat-derived char is higher (Fig. 7D, E). Though the predominant fine fraction is made of clay, it contains the same micromass made of bright orange phosphates seen in Sealer 3-MP, although in less abundance. Both clay and phosphates form compound coatings around grains (Fig. 7F).

Sample 32, from the hearth in the west wall of Sealer 4-MP, was taken to characterize burnt fur under the microscope. However, as in

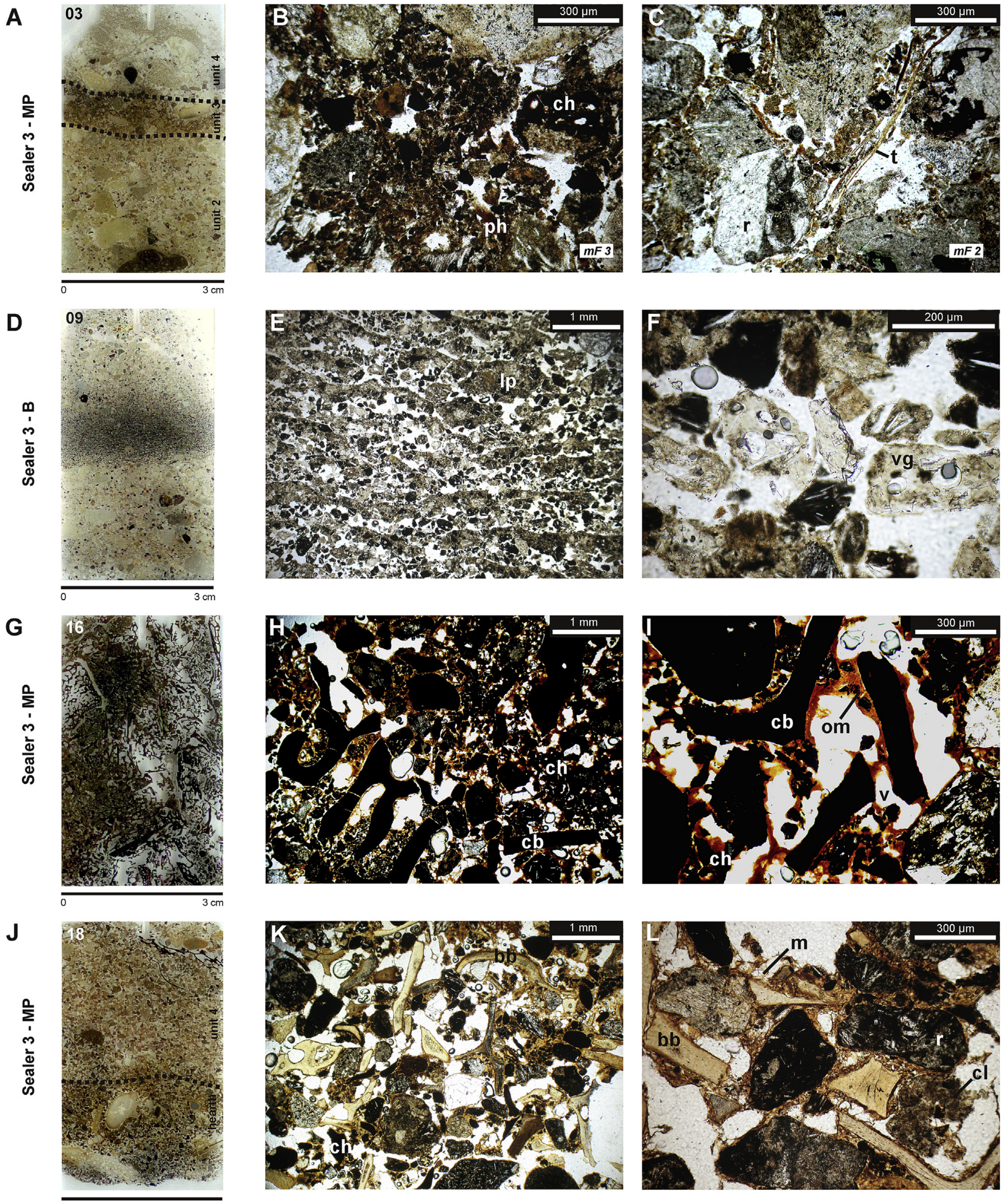

Fig. 6. Photomicrographs (PPL) of Sealer 3-MP and Sealer 3-B: scanned thin section collected from the center of Sealer 3-MP, with identification of units 2, 3 (occupation layer) and 4 (A); groundmass of the occupation layer at Sealer 3-MP (unit 3) with dark-colored cryoturbic granular micromass made of burnt organic material mixed with phosphates (ph) and clay, and coarse fraction made of rock fragments (r) and black opaque particles that proved to be fat-derived char after observations under reflected light (ch). All coarse fraction components show thin undifferentiated orange/yellow coatings possibly related to allophone formation (B); groundmass of unit 2, natural substrate underneath the occupation layer at Sealer 3-MP where no artifacts where found, made of coarse rock fragments (r), granular clay aggregates and long plant tissue remains (t) (C); scanned thin section collected from the off-site sampling location near Sealer 3 (Sealer 3-B) (D); groundmass of the layer of tephra found at about 20 cm below the surface with microstructure made of lenticular plates (lp) (E); volcanic glass (vg) in the coarse fraction of the tephra layer at Sealer 3-B (F); scanned thin section collected from the hearth at Sealer 3-MP (G); groundmass of F made of carbonized bone fragments (cb) and fat-derived char (ch) possibly produced from tossing blubber into the fire, with undifferentiated, bright orange, phosphatic micromass (H); detailed view of the hearth sample with carbonized bone (cb), fat-derived char (ch), vesicle voids (v) and bright orange, phosphatic micromass (om) (I); scanned thin section collected from the periphery of the hearth at Sealer 3-MP with identification of the hearth layer and the overlying aeolian sediments (unit 4) (J); groundmass of the hearth periphery made of burnt bones (bb), fat-derived char (ch) and rock fragments in phosphatic micromass forming coatings and bridges between grains (K); detailed view of K with coatings and bridges around rock and burnt bone fragments (bb) made of phosphatic material and fungal mycelia (m), note clay aggregate (cl) to the right of the image (L). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

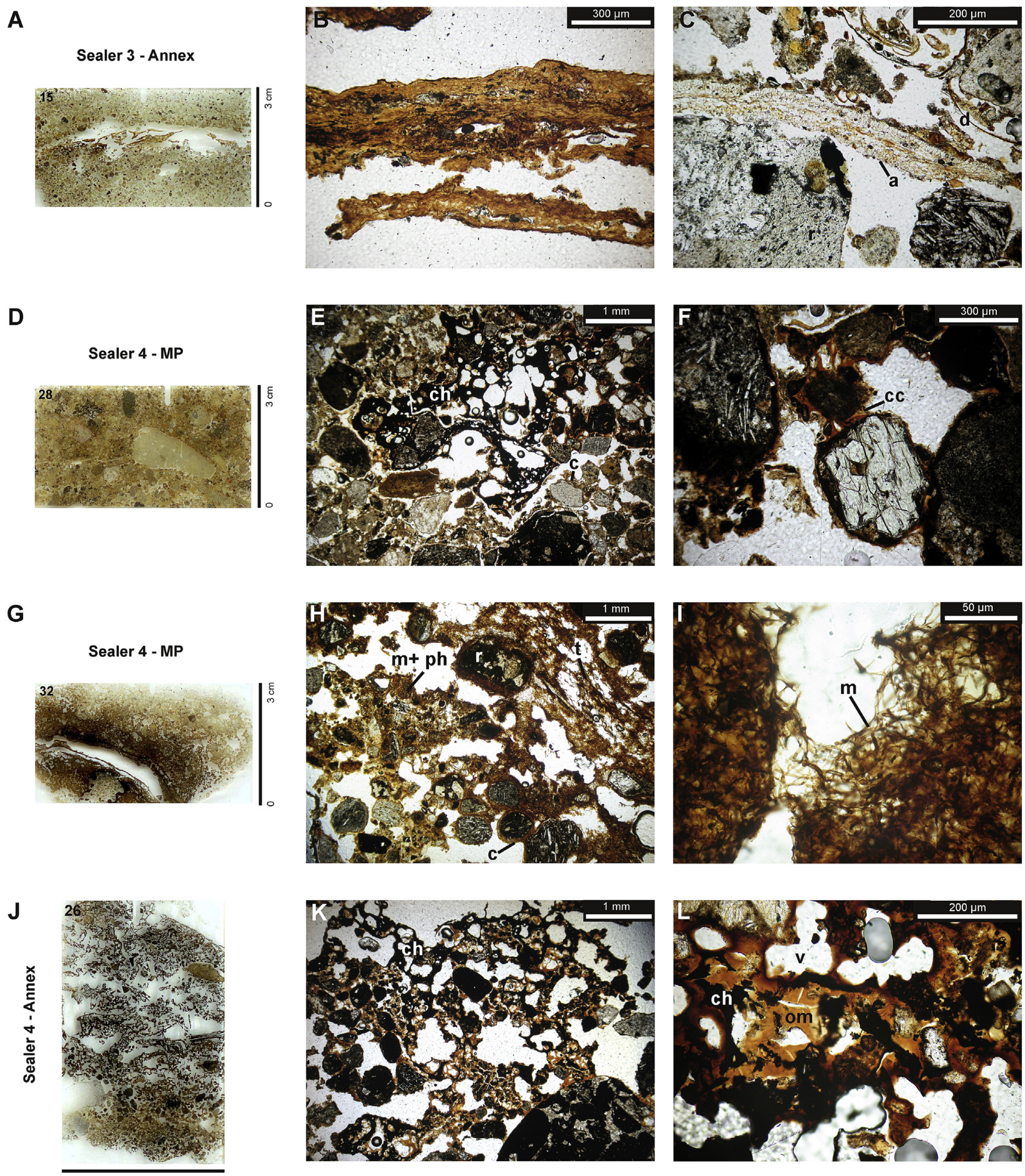

Fig. 7. Photomicrographs (PPL) of Sealer 3-A, Sealer 4-MP and Sealer 4-A: scanned thin section collected from the fur layer (unit 1) at Sealer 3-A, note large, translucide tissue remain across the center of the section (A); compacted, tissue remains seen in A, possibly from pinniped skin according to field observations, though its high compaction hamper clear microscopical identification (B); algae tissue remain (a) in A, there is a concentration of diatoms (d) close to the algae (C); scanned thin section collected from the periphery of the combustion feature at the south wall of Sealer 4-MP (D); groundmass of D made of fat-derived char (ch) and rock fragments with micromass made of clay and undifferentiated, bright orange, phosphatic micromass, forming coatings (c) around the coarse fraction (E); compound coating (cc) and bridges seen in D, made of fat-derived char, secondary phosphates and clay (F); scanned thin section collected from the combustion feature with fur located at the west wall of Sealer 4-MP (G), note detached fur remains in the lower left corner of the section; groundmass of G made of rock fragments (r) and fine char pieces with tissue remains (t) and micromass made of phosphates and fungal mycelia (m + ph), forming coatings around the coarse fraction (c) (H); detailed view of the mass of fungal mycelia (m) associated with the presence of possibly keratinophilic fungi attacking the fur remains (I); scanned thin section collected from the combustion feature at Sealer 4-A (J); groundmass of A made of rock fragments and fat-derived char (ch) with undifferentiated, bright orange, phosphatic micromass coating the rock fragments and fat-derived char (K); detailed view of K with vesicle voids (v), fat-derived char (ch) and the phosphatic micromass (om) (L). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

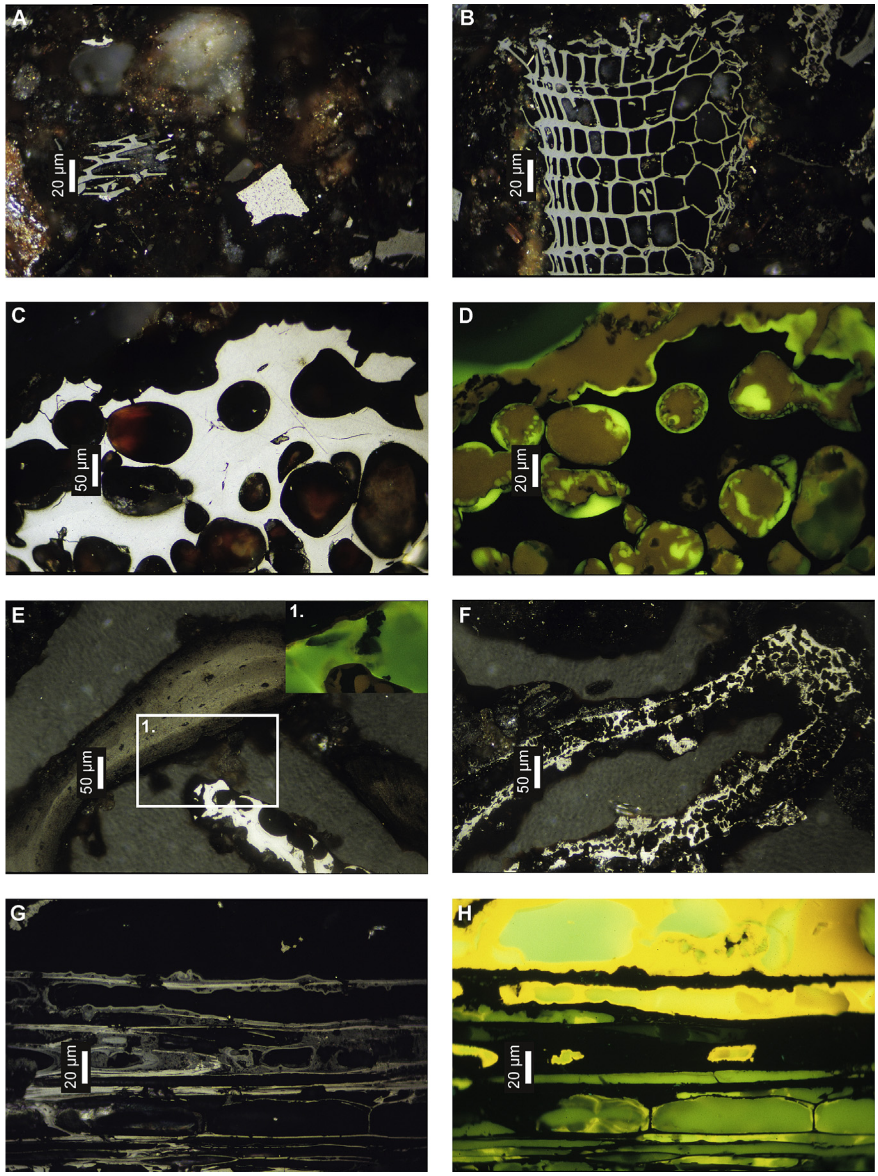

Fig. 8. Photomicrographs made under reflected light (WRL) and fluorescent light (UVL) by oil immersion on polished thin sections from Sealer 3-MP and Sealer 4-A: occupation layer at Sealer 3-MP (unit 3) with charcoal (left) and fat-derived char fragment (right) (WRL) (A); well preserved charcoal fragment in the occupation layer at Sealer 3-MP (unit 3), note fat-derived char in the top right corner (WRL) (B); large body of high reflecting and homogeneous fat-derived char in the hearth of Sealer 3-MP (WRL) (C); C under UVL, note orange fluorescing phosphates coating the body of fat-derived char and filling the pores (D); partially burnt bone fragment (left) and particle of homogeneous and strong reflecting fat-derived-char (right) in the combustion feature of Sealer 3-MP (WRL) (E), with detailed view under UVL of phosphatic coating around bone and fat-derived char (E1); cross-section of permineralized plant tissue (possibly stem) (WRL) in the combustion feature of Sealer 3-MP (F); large wood charcoal fragment in the hearth of Sealer 4-A with signs of mineral replacement seen as grayish cell walls (G); G under UVL showing phosphatic coatings around the charcoal and mineral replacement by phosphates (H). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

sample 15, most of the fur was lost during polishing of the thin section (Fig. 7G). What could be seen in sample 32 are tissue remains with rock fragments, fine fat-derived char particles (50 μm long, identified under WRL), non-burnt plant tissue remains (from leaf epidermis), bright orange phosphates around mineral grains and outstanding concentrations of fungal mycelia, mostly around the area previously occupied by the fur (Fig. 7H, I). As observed in Sealer 3-A, there is a clear association of fur remains with fungal mycelia.

A combustion feature was also sampled in Sealer 4-A (Fig. 4). The combustion feature (unit 4) shows the same micromorphological characteristics seen in Sealer 3-MP. It contains fat-derived char, carbonized bones and rock fragments coated and bridged with bright orange phosphates (Fig. 7J–L). The substrate is rubified with mineral grains and phosphatic coatings with fungal mycelia. The recurrent presence of fungal mycelia in the archaeological sites indicates that saprophytic fungi are active decomposers in these soils, especially in areas enriched with organic residues, like fur layers and hearths. Different from other combustion features, in Sealer 4-A there are large charcoal particles (50–100 μm) (Fig. 8G). Under UVL, some charcoal tissues show evidences of phosphate replacement around the margins (Fig. 8H).

5. Discussion

5.1. Multi-element chemical analyses

Little variation between samples has been detected in the concentration of major, minor and trace elements. This suggests a common parent material for the sediments. Sediments from the South Beaches of Livingston Island have a diverse lithology, derived from the physical weathering and reworking of volcanoclastic rocks, basaltic andesite and sedimentary rocks (mudstones with thin sandstone layers, carbonate concretions and calcite veins) (Smellie et al., 1984; Hathway and Lomas, 1998). Therefore, most of the chemical composition would be reflecting this diversity of sources.

If we consider the mean values for major, minor and trace elements as background related with parent material, abnormally low or high concentrations in any of these may indicate major inputs of anthropic particles in the sediment. For example, the combustion feature from Sealer 3-MP (sample 19) shows the lowest SiO, Al_2O_3, and Fe_2O_3 values of all samples (Table 2). These elements are mostly related with minerals from the natural substrate, thus confirming the higher concentration of anthropogenic particles in the combustion feature, with less local sediments.

Sample 19 also shows the highest concentration of P_2O_5 and CaO, ten to twenty times higher than other samples from the four sites studied (Table 2) and from other soils of the area (see Navas et al., 2008; Moura et al., 2012). This is due to the high content in bone and secondary phosphates in the sample. Also, the level of Zn in sample 19 doubles the values detected in other samples (Table 2). If we consider that seal bones are the main faunal component in sealing shelters (Muñoz, 2000), the high Zn levels could be related with the presence of seal residues, since the soft and hard tissue of seal are particularly rich in Zn (see Yamamoto et al., 1987; Ikemoto et al., 2004; Brunborg et al., 2006). This is even more pronounced in seal species from the Antarctic (Yamamoto et al., 1987; Zeisler et al., 1993; Marcovecchio et al., 1994). The higher levels of Cl also detected in sample 19 (Table 2), could be linked to the residues of soft tissue from marine mammals, like seals (see Mackey et al., 1995).

A similar situation is observed for the C concentration, which is relatively high in all archaeological samples if compared with data from maritime soils of Byers Peninsula and Admiralty Bay (King George Island) (Navas et al., 2008; Simas et al., 2008; Moura et al., 2012). Only unit 2, below the occupation layer of Sealer 3-MP where no artifacts were found, has C values typical of Antarctic soils. The rest of the samples have C values that are comparable with ornithogenic soils or soils of weak ornithogenic character (Simas et al., 2007, 2008; Moura et al., 2012). Since the site is not near a penguin rookery, the C enrichment would be anthropic.

Exceptionally, samples 11 (unit 1 Sealer 3-A) and 19 (combustion feature in Sealer 3-MP) have C values ten times higher than the rest of the samples (see Table 2) and even higher than common ornithogenic soils. In the case of sample 11, the C content is linked to the high S concentration. This would relate to the fact that sample 11 contains fur remains from pinnipeds and that the keratin matrix of hair, and specially of seal hair (Gillespie and Frenkel, 1974), is rich in high-sulfur proteins (Marshall et al., 1991; Bass et al., 2001). The S content also is relatively high in sample 21, where isolated hair remains were seen during excavation. In the case of sample 19, the high C content is related with the abundance of burnt bones and fat-derived char.

The two scatter plots of Fig. 5 showed, in both cases, one major cluster and three outliers. The cluster groups the occupation layer and substrate of Sealer 3-MP, with the occupation layers of Sealer 4-MP and Sealer 4-A. This shows the compositional similarity of sampled sediments that can be interpreted as places where equivalent activities were performed (Cook and Heizer, 1965; Middleton and Price, 1996; Fernandez et al., 2002; Middleton, 2004; Wilson et al., 2008; Middleton et al., 2010). The high C content detected for the occupation layers of Sealer 3-MP, Sealer 4-MP and Sealer 4-A would derive from burnt bones and fat-derived char. Thus, the main cluster in Fig. 5 would be grouping similar lithologies with comparable degrees of anthropogenic influence, derived from the presence of combustion residues in the sediments.

One of the outliers corresponds to the fur layer in Sealer 3-A (sample 11), whose C and S concentrations are related with the presence of hair keratin, as discussed before. The other two outliers correspond to the combustion feature at Sealer 3-MP (sample 19), mainly composed of bone, fat-derived char and phosphates; and the black layer of sandy clay in Sealer 4-A (unit 2, sample 27), not associated with artefactual material.

The black sandy clay layer of Sealer 4-A (unit 2) has higher metal concentrations, mainly Fe and Ti, but also of trace elements like Cu, Sr and V, if compared to other samples (see Table 2). Its C content, although not as elevated as in samples 19 and 11, is comparable to the values seen in the occupation layers of Sealer 3-MP, Sealer 4-MP and Sealer 4-A. The fine thickness, dark color and fine grain-size suggest deposition of sub-recent volcanic ash. In fact, unit 2 in Sealer 4-A is similar to the black sandy clay layer seen at the off-site location near Sealer 3 (Fig. 2F), which was proved to be, after micromorphological analyses, a layer of sub-recent volcanic ash (Fig. 6D–F). The black color could be related to the presence of basaltic tephra and/or organic matter complexed with allophone/imogolite. The high Fe and C also suggest initial stages of andosol development, which involves weathering of the tephra and formation of allophone/imogolite (Ping et al., 1988; Wada et al., 1992; Gérard et al., 2007; Chesworth, 2008). Ash layers in Livingston Island are related with volcanic activity at the neighboring Deception Island; located 18 km southwest of Livingston (see Fig. 1B). Deception Island is an active Quaternary volcanic complex that has been especially active during the 19th and 20th centuries (Roobol, 1973; Baker et al., 1975; Ibañez et al., 2003; Torrecillas et al., 2012).

5.2. Micromorphology and organic petrology

The effects of cryogenic processes are evident in all of the samples, in the form of: 1) granular microstructures; 2) cracking and vertical alignment of large rock fragments and bones; 3) lenticular plates; 4) silty clay coatings; 5) and vesicle vughs (Van Vliet-Lanoë and Coutard, 1984; Van Vliet-Lanoë, 1998, 2010). The granular aggregates would result from the mechanical stress related to frost heave and repeated freeze–thaw cycles (Van Vliet-Lanoë, 1998, 2010). However, the evidences of microbial attack in bones from Sealer 3-MP suggest that biological activity can also be shaping the fine fraction, especially in areas enriched organic waste.

The vertical arrangement of large grains (rock fragments and bones) is produced by the growth of ice lenses on the grains, leading to their rotation and verticalization, while the shattering of rock fragments results from freezing and ice growth on small fissures (Van Vliet-Lanoë, 2010). Lenticular plates were observed only in the tephra layer observed at the off-site location of Sealer 3-B (Fig. 6E). The lenticular microstructure is a common effect of frost action in soils on volcanic ash in cold areas (Stoops, 2007; Van Vliet-Lanoë, 2010).

Freeze–thaw processes are also responsible for the dispersion and eluviation of fine material, a phenomenon seen at shallow depth in the four analyzed locations. Freezing and formation of ice crystals promotes porosity, while ice/snow melting triggers the downwards translocation of fine particles, forming silty clay coatings around grains (Harris and Ellis, 1980; Van Vliet-Lanoë, 1998, 2010). In the subsurface, thin coatings of illuviated fine silt or clay, are also thought to be formed by liquefaction and/or fast percolation of surface runoff after snowmelt (Kuhn et al., 2010; Van Vliet-Lanoë, 2010).

Although most of the coatings are composed of silty clay, the thin coatings that show yellowish brown/orange color and undifferentiated b-fabric could actually be proto-imogolite allophone (Jongmans et al., 1995; Gérard et al., 2007; Stoops, 2007). This is coherent with the prominent presence of reworked volcanic ash in the coarse fraction, since undifferentiated coatings could result from the in situ precipitation of allophone in soils with volcanic ash (Sedov et al., 2010).

Vesicles only appear in the hearths from Sealer 3-MP, Sealer 4-MP and Sealer 4-A, exclusively in the bright orange phosphatic micromass (Figs. 6C and 7L). In cryosols vesicles were first explained as air bubbles trapped within the soil during freezing (Fitzpatrick, 1956; Bunting, 1977; Harris and Ellis, 1980). However, according to Van Vliet-Lanoë (1998), vesicles would be produced in the upper 5–10 cm of the soil during thawing, especially where there is water saturation by snow accumulation.

Since the vesicular microstructure only appears in the combustion features, another possible explanation would be that vesicles formed by rapid cooling of melted material, when gas bubbles produced when heating fat and/or other fluids fail to escape as the hearth cools down (see Canti, 2003). This is consistent with the fat-derived char found in the hearth samples and occupation layers of Sealer 3-MP, Sealer 4-MP and Sealer 4-A, coated with the bright orange phosphatic micromass (Figs. 6I, 7L and 8C, E). The presence of fat-derived char indicates that soft tissue and/or fluids from animals were being tossed into the fire with the bones. Thus, the phosphatic micromass could derive from flesh, viscera, or skins. In fact, seal meat is rich in Ca, P and Zn (Shahidi and Synowiecki, 1993; Brunborg et al., 2006), elements which were also found in high concentrations in the hearth sediments. The use of blood seems less probable since seal blood is rich in Fe (Yamamoto et al., 1987) and chemical analyses show low Fe content in the samples where the phosphatic micromass is predominant.

This discussion leads to a key observation derived from this work, which refers to the complete absence of coal, and coal-derived combustion residues, in all the hearths of Sealer 3 and 4. Previous studies based on field observations point at the recurrent presence of coal in the sealing shelters (see Zarankin and Senatore, 2005, 2007; Pearson and Stehberg, 2006). However, what looked like coal in the field proved to be concretions of fat-derived char. The fat-derived char could be a byproduct of the burning of blubber. Blubber is a subcutaneous fat that serves as insulator, body stream liner and buoyancy adjuster in sea mammals (Brunborg et al., 2006). The oil derived from boiling blubber was commonly used as fuel in the past centuries and the production of oil the blubber from elephant seals was another main task of the sealing crews (Zarankin and Senatore, 2005, 2007; Pearson et al., 2009).

Blubber residues have only been reported in the Point Smellie site, located in the west beaches of Livingston Island, associated to a cast-iron stove (Lewis-Smith and Simpson, 1987), though iron stoves and pots have also been found in other sites of Livingston and close islands (Stehberg, 2003; Pearson and Stehberg, 2006). Philbrick (2000) narrates that during oil production from whale blubber, the fat remains that floated on the boiling oil were removed and tossed into the fire. In this sense, evidences from Sealer 3 and 4 show the use of fat, possibly blubber, as fuel for the fires lit in the sealing shelters. At least in these two sites, analyses prove the use of local resources to feed the fires, like animal bones, fat and local grasses. No evidence was found on the use of coal brought with the sealing crews on the ships.

The common micromorphological characteristics of the hearths from three different locations (Sealer 3-MP, Sealer 4-MP and Sealer 4-A) suggest the same pyrotechnology for all combustions structures. However, there are differences that can serve as indicator of diverse uses for each location. As noticed already in the field, the hearths of Sealer 4-MP and Annex have fewer bones, are more concreted and have sharper boundaries than the hearth in Sealer 3-MP. The wider extension of the hearth in Sealer 3-MP, its higher amount of bones and fat-derived char, suggests the use of more fuel (bones and blubber) and therefore, prolonged use. The occupation layer at Sealer 3-MP is made of reworked components from the hearth nearby. This indicates intense occupation of the site with hearth residues distributed by human trampling inside the shelter. The hearths at Sealer 4-MP and Sealer 4-A were more ephemeral fires with less input of fuel and less redistribution of hearth components in the occupation layer.

Another important difference relates to the complete absence of wood charcoal in the hearth of Sealer 3-MP and the presence of large particles of wood charcoal in the hearth at Sealer 4-A (see Fig. 8G, H). The high concentration of wood charcoal in Sealer 4-A could mean poor combustion, possibly due to humidity conditions. The physical integrity of the wood charcoal particles also suggests low trampling. The absence of charcoal in Sealer 3-MP, but its presence as small fragments in the occupation layer of the site (see Fig. 8B), could be explained by the complete combustion of this material, indicating optimal conditions for burning (good oxygen supply) and possibly a longer use of the hearth. The differential preservation of charcoal could ultimately be related with differences in the temperature reached by the hearths: lower temperature in Sealer 4-A and higher temperature in Sealer 3-MP. This would corroborate the interpretation that Sealer 4-A was less intensively occupied than Sealer 3-MP (see Zarankin et al., 2011a, 2011b). The charcoal would derive from combustion of exogenous wood, like the planks from wrecked ships that commonly appear in the sealing sites and all along the beaches of Livingston Island.

In general terms, the influence of seal hunters on the substrate is mostly evident in the hearth samples, where bones and fat were used as fuel. Outside the combustion features the effects of natural processes are dominant. As in natural soils from the area (see Schaefer et al., 2008), the microfabric development is influenced by local lithology and cryoturbation. An interesting taphonomic process refers to the presence of masses of fungal mycelia in the archaeological sites, possibly keratinophilic due to its frequent association with fur and phosphates derived from soft tissue burning/decay (see Fig. 7I). Keratinophilic fungi are common decomposers of keratin in soils. They have been found in Antarctic soils, especially in areas occupied by mammals (including humans), birds (Mercantini et al., 1989, 1993) and mosses (Del Frate and Caretta, 1990). English (1963) reports the complete destruction of hair by keratinophilic fungi and the replacement of its substance by a compact rope of mycelium forming a “ghost hair”. Thus, the thick masses of mycelium seen in sample 15 and 32, and also seen in the micromass and coatings of samples 3, 14, 16, 18, 22, 28 and 29, could be the eroding mycelium of keratinophilic fungi growing on substrates enriched by fur, skin and other keratinous debris. Fungal activity in the soil would be clearly enhanced in the area influenced by humans, as mycelia and/or hyphae are absent from sample 14 (natural substrate of Sealer 3-MP) and sample 9 (off-site sampling location near Sealer 3). However, more detailed microbiological studies are necessary to confirm this.

6. Conclusion

Temporary settlements of sealing crews from the 18th and 19th centuries characterize the first human occupations in Antarctica. These settlements appear all along the beaches and marine terraces of Byers Peninsula and other protected bays of the South Shetland Islands, where sealing activities were concentrated. The unrestrained exploitations of fur seal lead to the quick devastation of local seal colonies. Between the years of 1821 and 1822, about

320,000 furs were taken by sealing ships out of Antarctica, together with approximately 940 t of elephant seal oil (Lewis-Smith and Simpson, 1987). Despite the large ecological impact of these activities, the shelters that served as home for the sealing crews are small, precarious, single-spaced structures made by piled boulders, whale bones that served as furniture, and large pieces of fabric as roof. Sites would have been occupied by small groups of men who stayed at the hunting spots for a few months during the summer season.

The rough conditions that the sealing crews were subjected to are not only related with the harsh Antarctic weather, but also to the limited supplies brought with them on the ships. Allochthonous materials found in sealing shelters include cattle and pig bones, sugar, coffee, barley, and diverse fabrics. However, the use of local resources was even more fundamental for the survival of these men. The archaeological research of sealing sites indicates the use of local resources for building the shelters and for artifact manufacturing, including leisure artifacts, such as the checkerboard found in the Playa Sur 1 site.

According to the evidence provided by Sealer 3 and Sealer 4, fire, an essential element for living, especially in the cold Antarctic climate, was exclusively obtained by burning local resources and not with the aid of coal combustion. Until now, it was believed that sealing crews were provided with coal for fuel (Zarankin and Senatore, 2005, 2007; Pearson and Stehberg, 2006; Guimarães and Moreira, 2011). However, the evidence provided by Sealer 3 and 4 (the only sites on Byers Peninsula where geoarchaeological analyses have been done) show the complete absence of this material in the sites. As the results of this research show, men had to make use of bones, blubber, local grasses and planks from shipwrecks found on the coast as fuel for the fires that would guarantee their survival. Further geoarchaeological analyses in other sites will confirm if this is a general trend in sealing campsites or just a case-specific scenario.

For the two sites here studied, field work and geoarchaeological analyses allow a closer look at the occupation dynamics of sealing shelters. In Sealer 3-MP, the presence of a black occupation layer enriched with anthropogenic material, artifacts and material derived from reworking of hearth components by human trampling, indicates the intense occupation of this shelter. Sealer 4-MP, located less than 100 m from Sealer 3, showed an occupation layer only identifiable by its scarce artefactual content and two combustion features. However, both sites have similar architectural arrangements and chemical compositions, indicating that analogous activities were done, but with different intensities. The analogous activities refer to the same pyrotechnology, as proved by micromorphological and organic petrology analyses. The differences can be seen in the existence of two hearths at Sealer 4-MP, without evidence of trampling and redistribution of hearth components. This suggests a shorter occupation and probably less inhabitants inside the shelter with more space for fires, which could ultimately be interpreted as a working space, in contrast to the habitation site of Sealer 3-MP.

The annexes of Sealer 3 and 4 are radically different. In Sealer 3-A, there are wall remains and evidence of construction of an architectural space. However, no hearth was found, only a thick layer of fur remains. In Sealer 4-A there is only a hearth surrounded by large stones detached from the outcrop. The micromorphology of this hearth showed its similarity to the hearths in Sealer 3-MP and Sealer 4-MP (bones, fat-derived char, secondary phosphates, fungal mycelia). This suggests that the annexes of Sealer 3 and 4 had different uses. Sealer 3-A was interpreted by the team as being an area for storage of dried fur. There is a similarity in the stratigraphic succession over the layer of fur in Sealer 3-A and the occupation layer in the north corner of Sealer 3-MP. Both are located at similar depths, suggesting contemporaneous occupation of the shelters. However, the anthropic origin of the fur layer is still questionable, as it could also be the remnants of old skin from a molting pinniped (possibly elephant seal).

The annex of Sealer 4 was not used for habitation. It contained a single hearth and no artifacts. As suggested for the annex of Playa Sur 1 (Zarankin and Senatore, 2007), it could have been used for boiling of blubber, as the sediments contain large fragments of charcoal, suggesting low trampling, and high amounts of fat-derived char. During sealing and whaling expeditions, elephant seal blubber was boiled in large iron pots and transported to the ships in wooden barrels. Evidence of these pots has not been found on Livingston Island yet, only the remains of smaller three-legged iron pots. However, some large pots were found on the coasts of the South Shetland Islands and are currently on display at the Scott Polar Research Institute in Cambridge.

Besides the recent chronology of the analyzed sites, the information related with pyrotechnology in sealing shelters has the potential to serve as a reference for other archaeological contexts. Blubber is commonly used as fuel by Inuit (Whitridge, 2004) and its use has been also documented in archaeological contexts from the northern hemisphere since the early Holocene (Bjerck, 2009; Craig et al., 2011). Fat-derived char was characterized by analyzes under WRL and UVL. However, to further reach the complete characterization of this material, more analyses on the composition of this substance need to be done. This will help to identify the use of blubber as fuel in other contexts where, as in Antarctica, there is little or no availability of wood.

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