Experimental Micromorphology in Tierra del Fuego (Argentina)

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Abstract

Now commonly used in archaeological contexts, micromorphology has seen little advance in the field of experimental archaeology. Drawing from early work conducted in the 1990’s on prehistoric ethnographic and experimental sites in the Beagle Channel, we analyze a set of 25 thin sections taken from control features. Control features observed include animal pathways, anthropic structures (hearths) and environmental contexts (beach samples, forest litter, soils from the proximities of archaeological sites). Their micromorphological study constitutes a modern analogue to assist the archaeologists confronted to the archaeological and ethnographical contexts in extreme conditions.

KEYWORDS: Shell middens; Beagle Channel; archaeology; geoarchaeology; ethnoarchaeology; Yamana.
Introduction

Soil micromorphology has progressively become a fundamental tool in geoarchaeological research. It provides valuable information for studies on paleoenvironmental reconstruction and formation processes of archaeological sites. In the past decades this technique has been applied to a variety of cultural contexts that include archaeological cave sediments (Araujo et al., 2008; Courty & Vallverdu, 2001; Goldberg, 2000; Goldberg & Arpin, 1999; Homsey & Capo, 2006; Karkanas, 2002; Karkanas et al., 2007; Mallol et al., 2009; Schiegl et al., 1996), floor deposits (Courty, 2001; Gé et al., 1993; Gebhardt & Langhor, 1999; Goldberg & Whitbread, 1993; Macphail et al., 2004; Matthews et al., 1997; Shahack-Gross et al., 2005), cultivation and manuring practices (Adderley et al., 2006, Guttmann, 2005; Macphail et al., 1990), fish middens (Simpson et al., 1996, 1999, 2005; Villagran et al., 2009), earthen mounds (Cremeens, 2005; Macphail et al., 2003), pastoral sites (Goldberg & Whitbread, 1993; Shahack-Gross et al., 2003, 2004; Shahack-Gross & Finkelstein, 2008), anthropogenic dark earths (Arroyo-Kalin, 2008; Devos et al., 2009; Lima et al., 2002; Schaefer et al., 2004) and open-air paleoindian sites (Macphail et al., 2008).

The small scale data offered by soil micromorphology demands multiple lines of evidence to be put together for straightforward interpretations. Geochemistry, mineralogy, palinology, phytoliths and isotopic analyses are among its inter-complementary techniques. However, the use of experimental approaches in archaeological soil micromorphology has been limited to the experimental earthwork at Wareham (Macphail et al., 2003), the work of Shahack-Gross et al. in pastoral sites (2003, 2004, 2008), Macphail et al. experimental farm deposits in Britain (2004), and Mallol et al. geo-ethnoarchaeological study of Hadza fires (2007).

In many cases, micromorphological analyses use modern soils found in proximity of archaeological sites as control samples to identify anthropic inputs and modifications (see Arroyo-Kalin, 2008; Macphail et al., 2003; Shahack-Gross et al., 2003). However, modern analogues from control features, such as hearths or trampling areas, are also useful to decipher the multiple meanings that characterize archaeological microfacies. In this respect, the experimental collection of thin sections collected for this study in Tierra del Fuego, has no precedent in archaeological micromorphology.
In the 1980’s, a Spanish-Argentinean research team working on prehistoric and historical shell middens from the Beagle Channel, realized the importance of local experimental proxies for the interpretation of archaeological thin sections (Taulé, 1995; Vila et al., 2007). Their excavation method focused on the identification of small-scale shell depositional episodes, activity areas within the sites, and their taphonomic alteration. A reference collection of known anthropic and natural features surrounding of one of the excavated shell middens was constituted. This collection included, among others, samples from a variety of hearths, trampling areas, forest litter and wood ashes, to be used as reference for the microscopic characterization of archaeological thin sections. The original samples were impregnated and kept inside the laboratory closet for over 10 years. It has been only recently that this collection was re-examined keeping in mind some of the original questions in a contemporary perspective (see Balbo et al. in press).

In this paper, we present and examine the collection of experimental samples and evaluate their use as reference data for hunter-gatherer settlement and taphonomy of archaeological sites in the Beagle Channel. Although specific to the natural and anthropic setting of Tierra del Fuego, we hope that experimental proxies from this collection can be useful for archaeological soil micromorphologists working on hunter-gatherer societies at lower latitudes.

Study Area

The Beagle Channel (Tierra del Fuego, Argentina) is about 200 km long and divides Isla Grande de Tierra del Fuego, to the north, from Isla Navarino and smaller islands, to the south (figure 1a). The Beagle Channel consists of a drowned glacial valley that joins the Atlantic and Pacific oceans. Its northern coast presents a system of Late Holocene raised beaches that run almost parallel to the present coastline, believed to be formed by tectonic uplift and/or isostatic recovery following deglaciation (Bujalesky et al., 2004; Gordillo et al., 1992; Rabassa et al., 2000). The oldest reach 10 m above present sea-level (dated ca. 8000 yr BP) and the most recent 1.3 - 3 m (dated after 3000 yr BP).
Present-day climate is cold sub-Antarctic with an average annual temperature of 5ºC and average annual rainfall of 570 mm. Modern vegetation corresponds to subantarctic deciduous beech forest and the evergreen beech forest, represented by several species of *Nothofagus*. Magellanic moorland occurs as patches in the forest and along the windy coast (Heusser, 2003). Paleoenvironmental studies show that the closed forest and the cool and wet climate conditions have remained stable since the Middle Holocene (Candel et al., 2009).

The Beagle Channel has been inhabited by hunter-gatherer populations since ca. 6500 BP. (Orquera & Piana, 1999a). Ethnographically, these groups are known as *Yamana*, canoe people whose subsistence was based on mollusks, fish and sea-mammal consumption (Estevez et al., 2001). *Yamana* archaeological sites are typically ring-shaped shell middens produced by the episodic and recurrent discard of non-edible food remains (mainly shell and fish bones) around the huts (Orquera & Piana, 1995, 2000). These groups have been extensively studied since the 1980´s providing valuable information on human adaptations, social-spatial dynamics and archaeological site preservation in the coldest tip of the Americas (see for example Estevez & Vila, 1998, 2006, 2007; Estevez et al., 2001; Vila & Estevez, 2002; Vila et al., 2005; Zurro et al., 2009).

Figure 1. Study area (a) and photographs of some of the environmental features sampled for the experimental reference collection: *Nothofagus sp.* forest reaching the coast (b), aerial view of the Túnel VII archaeological site (c), cobble beach in front of the shell midden (d), forest litter (e) and soil under the forest (f).
Materials and Methods

A group of experimental samples was collected during the 1995 field season from known environmental and anthropic features that include and animal pathway, samples from the cobble beach, under-forest soil, hearths and combustion of *Drymis winteri* (J.R. et G. Foster) – *canelo* – and *Nothofagus pumilio* ((Poepp. & Endl.) Krasser) – *lenga*. Another set of experimental samples was produced in the laboratory from valves of *Mytilus edulis* (Linnaeus, 1758) burnt at different temperatures in a muffle furnace. For identification, description and context of sampling see table 1.

All samples were oven-dried and impregnated under vacuum with a mixture of polyester resin, catalyst and acetone, following the procedure in Solé (1991). Thin sections on burnt shell were made in the 1990’s at the Jaume Almera Institute of Geology (CSIC), while remaining experimental sections were recently made at Earthslides (Cambridge). Analyses were made under PPL, XPL and OIL using a Leica MZ95 stereomicroscope and an Olympus BX51 optical microscope, following guides by Stoops (2003) and Bullock et al. (1985).

Results

Table 2 summarizes the micromorphological observations of known environmental and anthropic contexts. It includes the description of the types of microstructures, voids, c/f related distribution, c/f ratio, porosity, coarse and fine fraction, b-fabric and some additional observations. In the following section, we present a brief description of each experimental sample.
Table 1. List of experimental samples.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Context</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Animal pathway</td>
<td>Daily used by sheep and cows</td>
</tr>
<tr>
<td>2</td>
<td>High tide beach deposit</td>
<td>Cobble beach near one of the excavated shell middens</td>
</tr>
<tr>
<td>3</td>
<td>Beach deposit</td>
<td>Idem</td>
</tr>
<tr>
<td>4</td>
<td>Forest litter</td>
<td>Collected under the <em>Nathofagus</em> sp. forest</td>
</tr>
<tr>
<td>5</td>
<td>Soil A horizon under trees (a)</td>
<td>Idem</td>
</tr>
<tr>
<td>6</td>
<td>Soil A horizon under trees (b)</td>
<td>Idem</td>
</tr>
<tr>
<td>7</td>
<td>Hearth on prairie grass</td>
<td>Around the <em>Lanasuaia</em> archaeological site</td>
</tr>
<tr>
<td>8</td>
<td>Hearth on cobble beach</td>
<td>Next to the <em>Lanasuaia</em> archaeological site</td>
</tr>
<tr>
<td>9</td>
<td>Hearth from archaeologists campsite (dry)</td>
<td>Used for a month during field season of 1995</td>
</tr>
<tr>
<td>10</td>
<td>Hearth from archaeologists campsite (wet)</td>
<td>Sampled after a heavy rain</td>
</tr>
<tr>
<td>11</td>
<td><em>Drymis winteri</em> ashes</td>
<td>Charcoal and ash from combustion of <em>Canelo</em></td>
</tr>
<tr>
<td>12</td>
<td><em>Nothofagus pumulio</em> ashes</td>
<td>Charcoal and ash from combustion of <em>Lenga</em></td>
</tr>
<tr>
<td>13</td>
<td>Burnt cetaceous bone</td>
<td>Single bone burnt to carbonization</td>
</tr>
<tr>
<td>14</td>
<td>Algae</td>
<td>Seaweed from the cobble beach</td>
</tr>
<tr>
<td>15</td>
<td><em>Mytilus edulis</em></td>
<td>Burnt at 200 °C for 8 hours</td>
</tr>
<tr>
<td>16</td>
<td><em>Mytilus edulis</em></td>
<td>Idem</td>
</tr>
<tr>
<td>17</td>
<td><em>Mytilus edulis</em></td>
<td>Burnt at 300 °C for 8 hours</td>
</tr>
<tr>
<td>18</td>
<td><em>Mytilus edulis</em></td>
<td>Idem</td>
</tr>
<tr>
<td>19</td>
<td><em>Mytilus edulis</em></td>
<td>Burnt at 400 °C for 8 hours</td>
</tr>
<tr>
<td>20</td>
<td><em>Mytilus edulis</em></td>
<td>Idem</td>
</tr>
<tr>
<td>21</td>
<td><em>Mytilus edulis</em></td>
<td>Burnt at 500 °C for 6 hours</td>
</tr>
<tr>
<td>22</td>
<td><em>Mytilus edulis</em></td>
<td>Idem</td>
</tr>
<tr>
<td>23</td>
<td><em>Mytilus edulis</em></td>
<td>Burnt at 600 °C for 5 hours</td>
</tr>
<tr>
<td>24</td>
<td><em>Mytilus edulis</em></td>
<td>Burnt at 700 °C for 5 hours</td>
</tr>
<tr>
<td>25</td>
<td><em>Mytilus edulis</em></td>
<td>Burnt at 800 °C for 4 hours</td>
</tr>
</tbody>
</table>

*Animal pathway.* 1: This thin section shows three successive microfacies, from top to bottom. 1) Surface microfacies: Spongy microstructure with some planar voids formed by rough, organic aggregates composed of fresh plant tissue and fine organic matter with an undifferentiated b-fabric. Coarse fraction consists in angular and subangular rock fragments, moderately sorted (predominantly coarse to very coarse sand sized) and fresh roots (with birefringent cellulose walls). Lenticular platy microstructure at the bottom of the band with partially and non-accommodated voids. 2) Middle microfacies: Linear distribution pattern of organic residues, tissue residues and roots, parallel to the surface. Some planar and partially accommodated voids (100-150 µm width), sub-parallel and perpendicular to the surface. Porous crumbs microstructure with fine fraction composed of a mixture of organic (amorphous) and mineral material of low
birefringence. Coarse fraction is moderately sorted medium sand size and includes less subangular and subrounded rock fragments than top microfacies, as well as many fresh roots and tissue residues. This band shows a linear concentration of fungal spores (200-220 µm each bag of spores) parallel to the surface, as well as a band of rock fragments, of fine to medium sand size, with the same orientation as the fungal spores. 3) Bottom microfacies: Intergrain microaggregate microstructure with mammillated porous crumbs (200-300 µm width) of organic composition, with inclusions of silt sized mineral grains. Coarse fraction increases in rock fragments content and size (many gravel sized fragments), and diminishes in sorting (poorly to moderately sorted). Pedofeatures are observed through the pelletey microstructure and interconnected mammillated crumbs that suggest biological activity.

High tide beach deposit. 2: This slide shows a random distribution of unsorted cetaceous bone fragments and shell with rounded coarse sand and gravel sized rock fragments. Bone fragments are grey at PPL with high birefringence (XPL), have rounded edges and many dissolution marks, especially the enlargement of canals. Shell fragments are angular and subangular with various colorations (violet, gray, light gray, light brown). Crumb microstructure of loose porous organomineral aggregates of various dimensions.

Beach deposit. 3: Same as sample 2. Random distribution of coarse fraction components (cetaceous bone fragments, shell and some rock fragments) with interposed fine, loose, organomineral crumbs.

Forest litter. 4: This sample has an organic groundmass with no mineral components. Coarse fraction is randomly distributed and composed of unsorted fresh roots, wood fragments and tissue residues in reddish organic fine material. Numerous mite excrements can be seen inside wood fragments and preserved cellulose tissue is made explicit by its strong birefringence under XPL.
Table 2. Micromorphological descriptions of the animal pathway (1), high tide beach deposit (2), beach deposit (3), forest litter (4), soil A horizon under trees (5,6), hearth on prairie grass (7), hearth on cobble beach (8), dry hearth from archaeologist camp site (9) and hearth from archaeologist camp site after rain (10).

<table>
<thead>
<tr>
<th>Sample</th>
<th>Microstructure</th>
<th>c/f related distribution</th>
<th>c/f ratio</th>
<th>Porosity (%)</th>
<th>Coarse fraction</th>
<th>Micromass</th>
<th>b-fabric</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>1: top</td>
<td>Spongy with planar voids, partially and non-accommodated</td>
<td>Coarse enaulic</td>
<td>30:70</td>
<td>40</td>
<td>20% coarse to very coarse sand sized rock fragments. 10% fresh roots and plant residues</td>
<td>Reddish organic aggregates</td>
<td>Undifferentiated</td>
<td>Lenticular peds at the base</td>
</tr>
<tr>
<td>1: center</td>
<td>Rough porous crumbs with compound packing voids. Partially accommodated planar voids</td>
<td>Double spaced coarse enaulic</td>
<td>40:60</td>
<td>20-30</td>
<td>10% medium sand sized rock fragments. 20% fresh root and plant residues. 10% moss spores</td>
<td>Dark brown Organic aggregates</td>
<td>Undifferentiated</td>
<td>Linear distribution pattern of plant residues and roots (parallel to the surface)</td>
</tr>
<tr>
<td>1: bottom</td>
<td>Intergrain microaggregate, mammilated crumbs (20-30 µm) with complex packing voids</td>
<td>Single spaced equal enaulic</td>
<td>60:40</td>
<td>50</td>
<td>30% medium sand to coarse sand and gravel sized rock fragments. 5% roots and plant residues</td>
<td>Black, organic aggregates</td>
<td>Undifferentiated</td>
<td>Altered rock fragments. Some pendent and capping organic coatings around rock fragments</td>
</tr>
<tr>
<td>2</td>
<td>Loose porous crumbs with complex packing voids</td>
<td>Double and single spaced fine and equal enaulic</td>
<td>80:20</td>
<td>60-70</td>
<td>30% gravel sized bone fragments. 25% unsorted shell fragments. 2% coarse sand rock fragments</td>
<td>Dark brown organo-mineral, dotted.</td>
<td>Crystallitic</td>
<td>Very altered bones. Shell from a diversity of mollusk species</td>
</tr>
<tr>
<td>Sample</td>
<td>Microstructure</td>
<td>c/f related distribution</td>
<td>c/f ratio</td>
<td>Porosity (%)</td>
<td>Coarse fraction</td>
<td>Micromass</td>
<td>b-fabric</td>
<td>Notes</td>
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</tr>
<tr>
<td>3</td>
<td>Loose fine porous crumbs with complex packing voids</td>
<td>Double and single spaced fine enaulic</td>
<td>95:5</td>
<td>70-80</td>
<td>35% gravel sized bone fragments. 25% shell fragments. 2% gravel sized rock fragments</td>
<td>Dark brown organo-mineral, dotted</td>
<td>Crystallitic</td>
<td>Very altered bones</td>
</tr>
<tr>
<td>4</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>60-70</td>
<td>Wood fragments, fresh roots, tissue residues. reddish fine to very fine sand organic particles</td>
<td>-</td>
<td>-</td>
<td>Decomposing material. Mite excrements inside wood fragments</td>
</tr>
<tr>
<td>5: top</td>
<td>Intergrain microaggregate microstructure. Mammilated crumbs with complex packing voids</td>
<td>Double spaced fine-equal enaulic</td>
<td>20:80</td>
<td>20-80</td>
<td>5% fresh roots. 5% tissue residues. 2% wood fragments</td>
<td>Dark brown organic with some silt sized mineral grains</td>
<td>Undifferentiated</td>
<td>Mammilated excrements</td>
</tr>
<tr>
<td>5: bottom</td>
<td>Spongy to moderately separated granular. Compound packing voids with some sub-parallel accommodated and partially accommodated planes</td>
<td>Open porphyric</td>
<td>30:70</td>
<td>55 Diminishes at the base</td>
<td>10% gravel and sand sized rock fragments. 5% roots (live and dead). 3% medium to fine sand charcoal. Plant residues and some phytoliths</td>
<td>Dotted yellowish brown organo-mineral with some silt sized mineral grains</td>
<td>Speckled</td>
<td>Disorthic Iron (hydr)oxide nodules. Some alteromorphic nodules. Microstructure turns from spongy to chamber at the bottom. Charcoal content increases</td>
</tr>
</tbody>
</table>
Table 2. Cont.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Microstructure</th>
<th>c/f related distribution</th>
<th>c/f ratio</th>
<th>Porosity (%)</th>
<th>Coarse fraction</th>
<th>Micromass</th>
<th>b-fabric</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td>Chamber to moderately separated granular. Compound packing voids, chamber voids and star-shaped vughs. Some sub-parallel partially accommodated planes</td>
<td>Open porphyric</td>
<td>10:80</td>
<td>30-40</td>
<td>5-10% very coarse to coarse sand sized rock fragments, 5% medium to fine sand sized charcoal 3% roots, Organic residues and some phytoliths</td>
<td>Dotted yellowish-brown organo-mineral with some silt sized mineral grains</td>
<td>Speckled</td>
<td>Similar to 10 bottom band. Many iron (hydr)oxide nodules. Some alteromorphic nodules.</td>
</tr>
<tr>
<td>7</td>
<td>Granular</td>
<td>Open porphyric</td>
<td>30:70</td>
<td>50</td>
<td>20% gravel sized charcoal. Some tissue residues and phytoliths</td>
<td>Greyish-brown</td>
<td>Crystallitic</td>
<td>Ash layer and charcoal</td>
</tr>
<tr>
<td>8</td>
<td>Granular</td>
<td>Open porphyric</td>
<td>70:30</td>
<td>30</td>
<td>30% gravel to coarse sand sized bone fragments</td>
<td>Greyish-brown</td>
<td>Crystallitic</td>
<td>Ash layer and bones</td>
</tr>
<tr>
<td>9</td>
<td>Massive</td>
<td>Open porphyric</td>
<td></td>
<td></td>
<td>15 % unsorted charcoal fragments, 5% partially combusted wood, some phytoliths</td>
<td>Greyish with aggregates of rubified clay</td>
<td>Crystallitic</td>
<td>Ash layer. Fauna channels and iron nodules</td>
</tr>
<tr>
<td>10</td>
<td>Blocky microstructure with internal chambers and star-shaped vughs</td>
<td>Open porphyric</td>
<td>15:85</td>
<td>20-30</td>
<td>5-10% charcoal, 5% rock fragments, 5% bone fragments</td>
<td>Grayish with aggregates of rubified clay</td>
<td>Crystallitic</td>
<td>Many iron nodules</td>
</tr>
</tbody>
</table>
Soil humic horizon under trees (a). Thin section shows two different microfacies. The upper is very porous, has a crumb microstructure, composed of organic mammillated crumbs. Organic coarse fraction is composed of fresh roots, tissue residues and wood fragments. The groundmass is equally organic and formed by decomposing plant material with approximately 5% silt sized mineral grains. Some mammillated excrements were also observed. The lower microfacies is progressively less porous and has a spongy to moderately separated granular microstructure. Porosity includes compound packing voids, mainly at the base of thin section, with some unaccommodated and partially accommodated planes, sub-parallel and perpendicular to the surface. Gravel and coarse sand sized rock fragments are abundant, showing many signs of in situ weathering. Some charcoal fragments also appear in the coarse fraction with good sorting, of fine to medium sand size, as well as some phytoliths. Fine fraction is
yellowish-brown (PPL) dotted mixture of clay, organic matter and some silt sized mineral gains, as well as some apparent microcharcoal, with a speckled b-fabric. Pedofeatures include signs of biological activity and iron (hydr)oxide orthic nodules, moderately and strongly impregnated, with some alteromorphic nodules. Within this microfacies, microstructure turns from spongy to chamber downwards. Charcoal fragments increase and porosity diminishes following the same trend.

Soil humic horizon under trees (b). 6: Very similar to the lower microfacies of sample 5. The thin section has a chamber to moderately separated granular microstructure with compound packing voids, some chamber voids, star-shaped vughs and some partially accommodated planes sub-parallel and perpendicular to the surface of thin section. Coarse fraction includes sub-rounded rock fragments, mostly coarse and very coarse sand, with signs of in situ weathering. Some roots are present, phytoliths, organic residues and charcoal fragments, the last being well sorted (mostly fine and medium sand sized). The fine fraction is also yellowish-brown dotted with a speckled b-fabric, composed of a mixture of clay, organic matter, silt sized mineral grains and some apparent microcharcoal. Pedofeatures include faunal and root channels, as well as iron (hydr)oxide orthic nodules, moderately and strongly impregnated and some alteromorphic nodules.

Figure 3. Photomicrographs of the forest litter and soil humic horizon under the Nothofagus sp. forest (PPL). (a) Decay layer of a moder horizon with detail of mite excrements inside a feeding cavity in wood fragment (down, right). (b) Humus substance layer (b), transition from H layer to Aₕ horizon (c) and humic horizon under the forest (d). Note altered rock fragment at the top right of the image and detail of iron nodule formation (down, right).
**Hearth on prairie grass.** 7: The micro-remains of this hearth include a downwards accumulation of centimetric charcoal fragments, a moderately separated granular microstructure with some charcoal, phytoliths and tissue residues in the coarse fraction. The fine fraction is grayish (PPL) with a crystallitic b-fabric of calcite composition. The calcitic fine fraction is associated to wood ashes, which are composed of micro-crystalline aggregates of pseudomorphs of calcium oxalate (POCC). These calcium oxalate cells, naturally present in wood, suffer complete oxidation when burnt at high temperatures (400-600°C) turning into calcite after rehydration and absorption of CO₂ from the atmosphere (see Brochier, 1983a, 1983b, 2002; Courty, 1983; Courty et al., 1989; Courty & Fedoroff, 2002; Canti, 2003). Unfortunately, the pre-existent soil under the prairie hearth was not sampled and we lack information on the alteration induced by surface heating on the substratum.

**Hearth on cobble beach.** 8: This is an ephemeral combustion structure lit for less than an hour and sampled immediately after cooling. Two samples were taken, one from the residue ash layer and the other from the underlying gravel. The ash layer from the upper thin section has a coarse fraction almost exclusively composed of cetaceous bone fragments that show low birefringence (XPL) and many dissolution marks. Some bones are isotropic under XPL and show dark stains of very low birefringence, corresponding to burnt areas. The fine fraction has a moderately separated granular microstructure with a grayish brown speckled mixture of calcite and organic material. The lower thin section has a single grain microstructure exclusively composed of rounded and smooth beach cobbles.

**Hearth from archaeologists camp site (dry).** 9: This combustion structure was active during the whole field season of 1995 (30 days), situated in the center of the camping area. The hearth was used for cooking, lighting and heating. The thin section shows a grayish brown (PPL) massive microstructure in the form of a speckled mixture of clay and calcite with a crystallitic b-fabric. Coarse fraction is composed of unsorted charcoal fragments, some partially combusted wood and phytoliths. Pedofeatures include fauna channels and iron nodules. Interesting to note in this thin section is the in situ distribution of POCC aggregates (see Brochier, 2002; Canti, 2003).

**Hearth from archaeologists camp site (wet).** 10: The hearth described above was sampled after a heavy rain to observe incipient running water taphonomy on
combustion structures. The thin section shows the same open porphyric c/f related distribution pattern observed in sample 9 (dry bonfire), although microstructure presents some massive blocky areas with accommodated planar voids, chambers and star-shaped vughs within the predominant granular microstructure. These blocky peds are made of aggregated wet ashes, while dry or less humid ashes remain loose.

**Figure 4.** Photomicrographs of the three sequential microfacies that compose the animal pathway sample (PPL). (a) top microfacies with platy microstructure and planar voids, (b) center microfacies with concentration of fungal spores and lenticular voids, (c) lower microfacies showing increased mineral components and organic aggregates produced by biological activity.

**Burnt cetaceous bone.** 13: In this slide a bone mostly carbonized shows half-combusted areas around the edges.

**Algae.** 14: In thin section, algae are seen as thin orange to light brown filaments of a birefringent tissue, with undulating edges.

**Drymis wintery (Canelo) combustion.** 11: This slide shows a thin surface layer of loose ashes, tissue residues and charcoal over a band of centimetric charcoal fragments.
Figure 5. Photomicrographs of the four experimental hearths studied: (a) thin millimetric layer of ashes and oxidized plant residues corresponding to the hearth on the prairie grass (PPL), the same image under OIL (down, left); (b) hearth on the beach showing burnt sea-mammal bone fragments with photomicrograph of burnt bone under PPL (down, left) and XPL (down, right); (c) fry hearth from archaeologist camp site composed of ashes, charcoal fragments and rubefied clay under OIL (down, left), note POCC aggregates under PPL (down, right); (d) wet hearth from archaeologist camp site showing ash aggregates with iron nodules inside (PPL), with detail of an aggregate under PPL (down, left) and XPL (down, right).

*Nothofagus pumilio* (*Lenga*) combustion. 12: This sample is composed of a mixture of ashes, unsorted charcoal fragments, oxidized tissue and rubefied clay aggregates. The most remarkable feature observed are numerous charcoal molds composed of ash (POCC aggregates, as defined by Canti, 2003). These elements allow to observe the charcoal to ash transformation process at a detail unattainable in non-experimental contexts. Here charcoal is turning into microcrystalline calcium carbonate crystals, while the shape of the original tissue is still preserved. POCC aggregates are arranged in a fragile structure that reflects the structure of the charcoal from which they originate.
Figure 6. Photomicrographs of carbonized (a), weathered (b) and burnt weathered (c) sea-mammal bone fragments under PPL (top) and XPL (down). Note that the carbonized bone fragment is completely opaque under XPL (a), different from the weathered bone fragment that, in spite of being burnt and charcoal stained, is still birefringent under XPL for its calcite composition.

Figure 7. Photomicrographs of different charcoal pseudomorphs composed of POCC aggregates from combustion of *Nothofagus pumilio* and *Drymis winteri* (a, b, c, d) under PPL). Two examples of this charcoal to ashes transformation processes under PPL and XPL (e,f).

*Mytilus edulis*. (15-25): The shell of this mollusk is formed by two carbonate valves covered by an organic external sheet (the periostracum). The carbonate shell is composed of an outer calcite layer and an inner aragonite nacreous layer, the first being formed by columnar calcite prisms, and the last having a laminated texture of aragonite crystals parallel to the shell interior (Burgoin, 1988). Our analyses of the microscopic
effects of heating of *Mytilus edulis* showed a sequence of alterations from loss of the organic sheet (periostracum), separation of the inner (aragonitic) and outer (calcitic) layers to complete deformation of the valve. Table 3 includes the description of the sequential transformation of shell at increasing temperatures (from 200 to 800 º C), and figure 8 shows photographs and photomicrographs of the burning process.

Table 3. Microscopic alterations of *Mytilus edulis* valves burnt from 200 to 800 º C.

<table>
<thead>
<tr>
<th>Sample N°</th>
<th>Temperature</th>
<th>Description</th>
<th>Figure</th>
</tr>
</thead>
<tbody>
<tr>
<td>15, 16</td>
<td>200 º C</td>
<td>Some parts of the periostracum are still preserved&lt;br&gt;The inner and outer layers are still connected</td>
<td>8.Ae, 8.Ab,c,d</td>
</tr>
<tr>
<td>17, 18</td>
<td>300 º C</td>
<td>Periostracum is completely lost&lt;br&gt;The inner layer starts to fissure along the laminae boundaries, it acquires an oxidized reddish coloration (PPL) and starts to separate from the outer layer</td>
<td>8.Bb, 8.Bb,c,d,e</td>
</tr>
<tr>
<td>19, 20</td>
<td>400 º C</td>
<td>The separation of the inner and outer layers is almost complete&lt;br&gt;The orientation of calcite crystals in the outer layer changes&lt;br&gt;The inner layer shows more fissures and rough texture with dark brown coloration (PPL) in the concave side and reddish color (PPL) at the convex side.&lt;br&gt;Both sides do not extinct under XPL</td>
<td>8.Cb,c, 8.Cd, 8.Ca,e</td>
</tr>
<tr>
<td>21, 22</td>
<td>500 º C</td>
<td>The outer and inner layers have a general shattered appearance&lt;br&gt;Both show many holes and fissures, black stains, rough texture and dark brown to black coloration under PPL</td>
<td>8.Da, 8.Dc,d,e</td>
</tr>
<tr>
<td>23</td>
<td>600 º C</td>
<td>The outer layer turns into a fibrous calcite with dark grayish black coloration (PPL)&lt;br&gt;The inner layer is dark brown (PPL) and heavily fissured</td>
<td>8.Ed,e, 8.Eb,c</td>
</tr>
<tr>
<td>24</td>
<td>700 º C</td>
<td>Sample was over polished and discarded for analyses</td>
<td>-</td>
</tr>
<tr>
<td>25</td>
<td>800 º C</td>
<td>End of the experiment, complete loosening of the shape of the valve with black color under PPL and increased opacity under XPL (dark grayish brown coloration)&lt;br&gt;The inner layer laminae are deformed with formation of pseudo-vacuoles within</td>
<td>8.Fb, 8.Fc,d,e</td>
</tr>
</tbody>
</table>
Figure 8. Transformation process of burnt valves of *Mytilus edulis* from 200 to 800° C, described in table 3.
Discussion

The study of the experimental collection from the Beagle Channel constitutes a valuable corpus of micromorphological observations that can be applied in archaeological and ethnographical contexts. Many elements have never been described before and its analyses offer helpful models for the evaluation of archaeological contexts under these climatic conditions.

The burnt cetaceous bone sample (13) helps identify bones fragments in thin sections from the high tide (2) (figure 2a) and beach deposit (3) (figure 2b and c). In contrast, algae were not identified in any of the remaining thin sections (figure 2d).

The two beach deposits present similar micromorphological characteristics. The coarse fraction of both samples has the same proportion of sea-mammal bones, shell fragments and gravel. The only difference observed was a slightly higher proportion of fine fraction in the high tide deposit. Generally, sea-mammal bones from beaches of the Beagle Channel undergo long-term diagenesis, due to wave action and periodical exposition to sub-aerial conditions. However, physical erosion by water does not seem to be the main cause of bone alteration in the observed thin sections, since the angularity of shell fragments indicate low-energy reworking on the beach.

Bones show wide dissolution areas, through the enlargement of internal canals and trabecular spaces, as well as microscopical focal destructions caused by microbial attack (Hackett, 1981; Jans et al., 2004; Piepenbrink, 1989). They are not composed of hydroxiiapatite, as expected in fresh bone, but of an authigenic mineral possibly calcite or trona, highly birefringent, developed as void fillings in the form of a sparry calcite and as microcrystalline calcite in the dissolved areas around osteons. These minerals gradually disappear towards the periphery and center of the bone that shows areas of first order white (XPL) and opaque lines. The thickest part of bones that showed areas of first order white (XPL) and opaque lines have also lost much of the collagen matrix (see Steiner et al., 1995), but did not suffer yet from this mineral replacement. Mineral replacement has previously been reported from bones exposed over 40 years on soil surfaces in the tropical savannah (Trueman et al., 2004). Along the Beagle Channel, the simultaneous diagenesis of the organic and mineral fraction in bone (Lucas & Prevot, 1991) may be responsible for its mineral replacement. Loss of the collagen matrix may
result from UV influence (Fernandez-Jalvo et al., 2002; Tuross, 1989) and microbial activity (Child, 1995; Hedges, 2002; Jans et al., 2002, 2004) during exposition to sub-aerial conditions and in spite of the low temperatures typical of the region. The loss of the collagen matrix favors acid liberation that triggers the dissolution of the mineral matrix. In this context, the action of water saturated in Ca and/or Na, from bone dissolution and sea-water influence, plus intense wind that promotes evaporitic conditions, could have accelerated the precipitation of this authigenic carbonate.

The forest litter sample (4) (figure 3a) corresponds to the decay layer (F layer) of a moder horizon (Babel, 1975). It has a general reddish brown coloration, associated to tissue containing phlobaphene and oxidation of organic material, and an opaque b-fabric with some areas of first order yellow and orange interference color (XPL), associated to the preservation of cellulose walls. Various plant residues are observed, such as leafs, roots (both dead and living), well preserved droppings and feeding cavities inside wood, aggregates of organic fine substance, and some isolated fungal hyphae.

Many of the components of the forest litter were also observed in sample 5, which contains two microfacies: one corresponding to the humus substance layer (H layer) (figure 3b), and the other to the underlying A\textsubscript{h} horizon (Babel, 1975) developed under the *Nothofagus sp.* forest (figure 3c). The H layer is only a few centimeters thick and darker in coloration than the F layer described for the forest litter sample, and includes a minor percentage of mineral constituents. It shows evidence of intense biological activity, indicated by the mammillated microstructure, roots, channels and excrements. In the A\textsubscript{h} horizon the number of live roots and identifiable plant residues diminishes and the amount of amorphous organic matter increases, forming aggregates of organic fine substance mixed with fine mineral grains and clay. Many altheromorphic nodules are present from *in situ* weathering of rock fragments, with complex and cross-linear alteration. The same characteristics were observed in sample 6 (figure 3d) and, together with evidences of clay contraction, collapse features and formation of iron nodules, indicate waterlog and drying conditions associated to seasonal rains. An interesting feature is the medium to fine sand-sized charcoal fragments, probably wind transported from a nearby fire.

If we sum the evidences offered from the beach (2 and 3) and soil samples (4, 5 and 6) we have many indicators of intense biological activity under the cold climatic
conditions of the Beagle Channel. Usually cold conditions are believed to inhibit the action of microorganisms (Hedges, 2002; Nicholson, 1993), but we have seen in the reference collection under study that microbes are active taphonomic agents both in subareal and sub-surficial contexts. The microscopic focal destructions observed in bones from the beach and the micromorphological properties of the soils samples (microstructure type and pedofeatures) confirm this statement. This means that we can expect to find intense bioturbation in the archaeological sites of the region, contrary to what could be expected due to the climatic context in which they occur.

The experimental sample of the animal pathway (1) (figure 4) allows identifying some of the open-air animal trampling indicators mentioned in Courty et al. (1989) and Shahack-Gross et al. (2003) such as: layered compaction of the grassland mull horizon; development of a platy microstructure near the soil surface; linear and parallel to the surface distribution of plant residues; partially accommodated planar voids (figure 4a); intense fungal activity seen as bands of fungal spores and numerous fungal hyphae (figure 4b). The formation of the lenticular voids and aggregates with massive microstructure could have been enhanced by seasonal freezing of the grassland soil. Such features would not appear in soil samples from the Nothofagus sp. forest where moder prevents frost formation and freezing (see Sveistrup, 2005). Commonly associated to animal trampling (Macphail, 2009: personal communication), dusty clay coatings were not in the surface horizon, rather they appeared around some rock fragments of the lower microfacies. The absence of this textural pedofeature can be associated to strong bioturbation, with abundant opaque micro-aggregates composed of highly humified organic matter dominating the thin section.

Samples from combustion structures (7 to 12), including structured hearths and simple burnt layers, present two main common features. Since they were sampled immediately after cooling, they are in situ combustion structures, or primary facies as defined by Wattez (1992), and have not suffered from post-depositional alterations. This allows extracting relevant information on the preservation of burnt layers in cold climatic conditions, and their taphonomic alteration immediately after abandonment.

The ephemeral hearths, of short duration and moderate intensity (350-450º C), result in a thin millimetric layer of brownish ashes, mixed with oxidized plant residues and microcharcoal over a layer of carbonized material (see Wattez, 1992). This attribute
is independent of the substratum and both the prairie and beach hearth show the same configuration (figure 5a and b). The only difference was observed in the coarse fraction composed of charcoal fragments of *Dymis winteri* in the prairie, and burnt bones from sea-mammals in the beach.

No sample was taken from under the prairie hearth, but the centimetric width of the sample and the presence of only small rubefied clay aggregates, suggests that this burning episode did not induce any major alterations on the pre-existent soil. The sample taken under the beach hearth shows that pebbles did not suffer any structural modification from the fire, while sea-mammal bones within the beach deposit were only oxidized and black stained on the surface (figure 5b). The effects of fire on these highly weathered bones was not so evident, since they had already lost most of their collagen matrix and undergone partial mineral recrystallization prior to burning.

Our experimental samples confirm that long-term diagenesis and instant burning can have the same effects on bone (Nicholson, 1993; Steiner et al., 1995). Had we not been aware that these bones were part of the primary weathered beach deposit, we could easily have mistaken their collagen loss and mineral replacement for carbonization of the organic matrix and calcination from direct contact with fire (figure 6). In this sense, the wide dissolution areas and deep microbial alteration observed in primary beach deposits can help us in avoiding errors in archaeological contexts, such as assuming that a bone had been exposed to high temperatures when in fact it has only been brought to the site from the beach.

The hearth in the archaeologists camp site (9 and 10) remained active for a longer period of time, leading to the formation of a centimetric ash layer that represents a mixture of different burning episodes. This long term exposure can also be identified by the pedofeatures observed in thin section, such as fauna channels and iron nodules. In the dry sample (9), structure is massive and composed of calcium carbonate crystals, very few phytoliths, with minor charcoal and microcharcoal content indicating high burning intensity (> 500º C) and complete combustion of wood used as fuel (Wattez 1992; Mallol et al. 2007) (figure 5c). The wet sample (10) clearly shows the effects of water-log and drying resulting in a blocky microstructure of aggregated clay and ash (figure 5d). Blocky peds have internal star-shaped vughs, produced after the collapse of
fauna channels, and planes from contraction of fine material (clay). In the whole thin section, there is a marked increase in iron nodules.

The *Nothofagus pumilio* (11) and *Drymis winteri* fires (12) include an interesting feature that is almost impossible to find in archaeological hearths. These are the calcite cellular pseudomorphs (Courty et al. 1989) reproducing the shape of the original carbonized tissue. These charcoal pseudomorphs are rare in archaeological deposits because of the high fragility and easy dispersion of ash (figure 7). If these elements are ever to be found in an archaeological context they would be clear indicators of the excellent preservation of a site, related to high rates of sedimentation and low biological activity.

In the coast of the Beagle Channel, the preservation of ash in archaeological contexts would be affected by the hydrological regime, and the high susceptibility to dissolution of this calcitic fine material. In this region, though the average annual rainfall is 500 ml, there is no dry season and rain is constant throughout the year (for information on climatic data of Tierra del Fuego see http://www.cadic.gov.ar/Imagenes/Resumen%20Clima%20Ush.jpg). For this reason, favorable conditions for the preservation of ash would demand either a clayey substrate, to avoid complete leaching, or a calcium saturated soil solution, to avoid dissolution. Likewise, the intense biological activity, whose effects were observed in all samples from diverse environmental contexts (beach, prairie, forest soil), would be an equally important agent of distortion.

Finally, the experimental samples from the sequential burning of *Mytilus edulis* (15 to 25) provide estimates of the temperature of the fire through the coloration, shape, texture and mineralogical characteristic of the valves in thin section (figure 8). The descriptions offered in table 3 will help us interpret ancient *in situ* or reworked hearths in terms of pyrotechnology and formation processes. For example, every time we find a valve of *Mytilus sp.* in an archaeological context, with intense deformation of the laminae, long fissures, black color under PPL and opacity (XPL), we can safely infer its burning above 800º C. If a group of these highly deformed valves is found in association with valves burnt at lower temperatures, we can safely interpret the context as ancient hearth.
The information on burning intensity can also be associated to the function of the combustion structure (see Mallol et al., 2007) that, combined with archaeological evidences, can help us interpret the site as a whole. This is very important for archaeological shell middens of Tierra del Fuego, since *Mytilus edulis* dominates the composition of the sites (Estevez et al., 1995) and any information on their use and management is essential to interpret the site.

**Conclusions**

The analysis of the reference collection of experimental micromorphology samples from the Beagle Channel, offered valuable clues on the preservation potential of archaeological features under cold climates. The group of 25 samples taken from a variety of environmental and anthropic control features demonstrates that bioturbation is a major taphonomic agent in both sub-aerial and sub-surficial contexts, despite the low temperatures that are frequently associated to inhibition of biological activity. The effects of microorganisms are present in all samples from environmental features and even in an experimental hearth sampled after 30 days of continuous burning. This fact is of extreme importance for archaeological research in the area, as we can expect shell middens, usually rich in organic debris, to be deeply affected by bioturbation.

The constant precipitation that characterizes the area is another major source of alteration through dissolution and leaching of fine components, and even the intense coastal winds can enhance evaporation and promote mineral neoformation on material exposed to sub-aerial conditions. All this evidence allow us to construct a model for the expected preservation and meaning of archaeological contexts in Tierra del Fuego: ash layers from hearths would only be preserved if they are situated over a clayey substrate or within a calcium saturated soil solution; rain will promote the aggregation of this material and the formation of iron nodules; if favorable conditions for preservation of ash exist, this material will be reworked by soil microorganisms into an organo-mineral mixture; sea-mammal bones, if collected from dead animals on the beach, will be calcitic and have wide dissolution areas around canals, as well as many microscopic focal destruction; if they were hunted and consumed, therefore brought fresh into the
site and burnt at high temperatures, they would not be as deeply dissolved and bioeroded as naturally weathered beach bones.

Based on this information, we now have a robust set of references that will serve as framework for archaeological interpretations. The next step of our work will be to confront this information with the archaeological evidence from prehistoric and ethnographic shell middens of Tierra del Fuego. In spite of the local character of the reference collection analyzed here, we believe that this empirical and inferential data can be used by researchers working in archaeological contexts under cold climatic conditions.

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