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Oxygen isotopic composition of limpet shells from the Beagle Channel: implications for seasonal studies in shell middens of Tierra del Fuego

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ABSTRACT

Shell middens distributed along the coastal areas of the Beagle Channel (Tierra del Fuego) testify the primary role of marine resources in the successful social dynamic of hunter–gatherer–fisher societies (HGF) in extreme high latitude environmental conditions. Intertidal and subtidal limpet species are frequently identified taxa of these archaeological deposits. We investigated whether shell $\delta^{18}\text{O}$ of the limpet species *Nacella deaurata* is a valuable record of local sea surface temperature (SST) and ambient water $\delta^{18}\text{O}$ ($\delta^{18}\text{Ow}$) fluctuations, and in turn can be used to estimate the season of its exploitation by Holocene HGF. Sequential shell $\delta^{18}\text{O}$ of modern species track seasonal changes of SST and $\delta^{18}\text{Ow}$. The comparison of shell $\delta^{18}\text{O}$ profiles of *N. deaurata* and *Nacella magellanica* (a coexisting species) suggests the occurrence of distinct growth rate and physiological adaptations between species. Shell $\delta^{18}\text{O}$ of zooarchaeological specimens of *N. deaurata* from Lanashuaia II suggests that animals were exploited predominantly in winter and that experienced similar environmental conditions of present day at ~1320 years BP. Results also indicate that *N. deaurata* is a valuable candidate for studying past seasonal changes in SST and $\delta^{18}\text{Ow}$ in this southernmost part of South America.

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1. Introduction

The earliest evidence of human occupation of the coastal areas of the Beagle Channel (Isla Grande de Tierra del Fuego) is dated to ~6.9 ka BP (Orquera and Piana, 1999). From ~6.5 ka BP to the end of the 19th century, hunter–gatherer–fisher (HGF) groups developed economic strategies addressed primarily to the exploitation of littoral environments, as attested by numerous shell middens in the region (Orquera and Piana, 2009; Orquera et al., 2011), composed by marine and terrestrial mammals, fish, shellfish, sea birds remains (Yesner et al., 2003; Estévez and Vila, 2007; Orquera and Piana, 2009; Zangrando, 2009; Tivoli and Zangrando,

2011; Briz et al., 2011). Recent studies suggest that the economic and social scenarios behind this littoral specialized system were more dynamic than previously proposed and that they likely changed from the earliest expression of littoral specialization to the end of the 19th century (Yesner et al., 2003; Yesner, 2004; Álvarez and Briz, 2006; Álvarez, 2009; Briz et al., 2009a; Zangrando, 2009; Tivoli and Zangrando, 2011).

Assessing past seasons of resource exploitation is imperative to corroborate or reject ethnographic and archaeological models and to improve our understanding of socio-economic dynamics in these societies. Within this trend, our aim is to explore and to disentangle the role of the processes of social aggregation, in HGF societies, in order to shed light on their social organization to the extent that temporary concentrations promote economic cooperation, information exchange, and constitutes an arena for social interaction (e.g., Conkey, 1980; Kelly, 1995; Hofman, 1994; Jerardino, 2010).

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For that reason we have been carrying out an ethno-archaeological project (Briz et al., 2009b) addressed to unveil the mechanisms of social aggregation and cooperation of HFG groups who lived at the Beagle Channel region. To accomplish this aim, we develop a multidisciplinary approach that includes extensive excavations, detailed stratigraphic studies, *ad hoc* sampling strategies and a comprehensive array of laboratory analytical methods (Álvarez et al., 2009; Zurro et al., 2010). From our concern, one of the main factors in archaeology of aggregation processes is to explore the contemporaneity of the occupations supposedly produced by the development of the aggregation event. Apart from radiocarbon data, isotope analysis can provide indirect indicators of simultaneous occupations.

Because shells of intertidal molluscs are prevailing components of shell middens in the region (e.g., Vila et al., 2009; Verdún, 2010; Orquera et al., 2011), they have significant potential as archive of seasonal use of coastal environments and resources therein, and of palaeoenvironmental conditions at the time of resource exploitation in this region. Shell $\delta^{18}\text{O}$ is a function of the ambient water $\delta^{18}\text{O}$ ($\delta^{18}\text{Ow}$) and the temperature at which the carbonate secretion takes place (e.g., Wefer and Berger, 1991). Thus, by determining the seasonal variations of shell $\delta^{18}\text{O}$ relative to seawater temperature and $\delta^{18}\text{O}$, the season in which the mollusc was harvested can be estimated (e.g., Kennett and Voorhies, 1996; Quitmyer et al., 1997; Jones et al., 2008; Culleton et al., 2009; Colonese et al., 2009, 2011; Mannino et al., 2011).

This paper discusses oxygen isotopic data of shells of *Nacella deaurata* (Gmelin 1791) in order to 1) establish if this species may provide suitable information about local sea surface temperature (SST) and $\delta^{18}\text{Ow}$, and 2) in turn be used to investigate its seasonal exploitation pattern by Holocene HGF. Recent isotopic studies on modern shells of *Nacella magellanica* (Gmelin 1791) from the Beagle Channel, a coexisting species, revealed consistent correlation between shell $\delta^{18}\text{O}$ and SST, demonstrating the potential of this species to investigate seasonal of resource procurement by HGF groups in this region (Colonese et al., 2011). Both species are commonly found in coastal shell middens of Tierra del Fuego (Orquera and Piana, 2001, 2002; Verdún et al., 2010), thus advances in their isotope ecology would benefit investigations at large scale. In this paper we first compare isotopic signature of modern shells of both species to investigate potential differences. We then analyze the $\delta^{18}\text{O}$ of archaeological shells of *N. deaurata* retrieved at Lanashuaia II (a Late Holocene coastal shell midden) in order to establish the season of its exploitation.

2. Environmental and archaeological setting

2.1. The study area

The Beagle Channel is located in the south side of the Isla Grande de Tierra del Fuego (politically divided between Chile and Argentina), and separates this island from other southernmost islands (Fig. 1A–B). The channel is a drowned glacial valley about 5 km wide and 180 km long with an estuarine dynamic. River discharges from precipitation and glaciers partially influence water circulation, along with semidiurnal microtidal oscillations (mean tidal range is ~ 1.1 m) (e.g., Iturraspe et al., 1989; Isla et al., 1999; Bujalesky, 2007, Servicio de Información Ambiental y Geográfica – SIAG, CADIC). Two more pronounced tides occur during the year, in winter and summer respectively (<http://www.hidro.gov.ar/SHNhome.asp>). Larger-scale surface circulation is also influenced by the Antarctic Circumpolar Current (Gordillo et al., 2008) and summer meltwater discharge into the channel is the main responsible for decreasing SSS.

2.2. The site

Lanashuaia II is a shell midden archaeological site, placed on the northern coast of the Beagle Channel, at ~ 60 km east from Ushuaia Bay (Tierra del Fuego, Argentina; Fig. 1A–E). The Lanashuaia locality host a series of ring-shape shell middens evenly spaced on a linear distribution along the isthmus that separates inner (CI) and outer (CE) Cambaceres bays. The series of ring-shape shell middens is placed near the Cambaceres Interior (CI) beach (Piana et al., 2000; Briz et al., 2009b). It has been excavated over three seasons between 2009 and 2011 over a surface of 55 m². Shell midden deposits were superimposed forming a ring structure around a central depression, placed next to the inner bay shoreline. The ongoing stratigraphic studies reveals that Lanashuaia II had an initial deposition stage on the northern part of the site that formed a little dome; subsequently, the accumulation of anthropic residues produced an annular structure that attained the maximum thickness on the eastern boundary (>1 m), in which several hearths were also discovered.

In this paper we present seasonal isotopic results of archaeological shells recovered in the little dome (Layer C20), which provided a ¹⁴C age on charcoal of 1320 ± 20 Cal BP (uncal 1385 ± 25 ; CNA 590; ¹⁴C calibration performed with the updated CALPAL-A; Weninger and Jöris, 2010). Although archaeozoological and technological studies are still in progress, preliminary results depict an economic scenario composed by a broad range of exploited animals, such as sea lions (*Arctocephalus australis* and *Otaria flavescens*), guanacos (*Lama guanicoe*), whales, sea birds, fishes and shellfish, suggesting an articulated subsistence system. Intertidal and subtidal molluscs are the most abundant faunal remains and are mostly represented by rocky-shore taxa, among which mussels (e.g., *Mytilus edulis*) and limpets (e.g., *N. deaurata* and *N. magellanica*, ongoing study) dominate assemblages. Lithic assemblages comprise flakes, cores and retouched artefacts made on local raw materials. Bone tools such as harpoons, chisels and awls were also recovered. Regarding archaeobotanical remains, hundreds of charcoals have been found within the shell midden layers as the result of maintenance processes of the hearths inside the dwellings.

3. Materials and methods

3.1. Water chemistry and property

Monthly mean SST records at Ushuaia Bay (port of Ushuaia, ~ 60 km from the study area) from 1994 to 2001 were used to generate an intra-annual picture of SST oscillation in the study area (data source: Servicio de Información Ambiental y Geográfica, CADIC). Monthly mean SSS were instead generated from data collecting from 1971 to 1987 (Obelic et al., 1998) and from 1987 to 1989 (G. Lovrich, *personal communication*). To obtain the first local picture of seasonal water chemistry ($\delta^{18}\text{Ow}$) and property (SSS, SST) for the study area, 100 ml of water were collected on the shore in different months between 2009 and 2010 ($N = 18$) for oxygen isotope analysis, along a spatial gradient between freshwater and marine sources which characterize the study area (i.e., outer Cambaceres Bay (CE), inner Cambaceres Bay (CI) and Varela river (VRL); Fig. 1C). SSS and SST were also measured on the field at the moment of water sampling (Table 1).

3.2. Selected species: *N. deaurata* and *N. magellanica*

N. deaurata and *N. magellanica* are subantarctic limpets, very common on rocky-shores of the Beagle Channel (Morriconi, 1999; Malanga et al., 2004) and in archaeological sites of this region

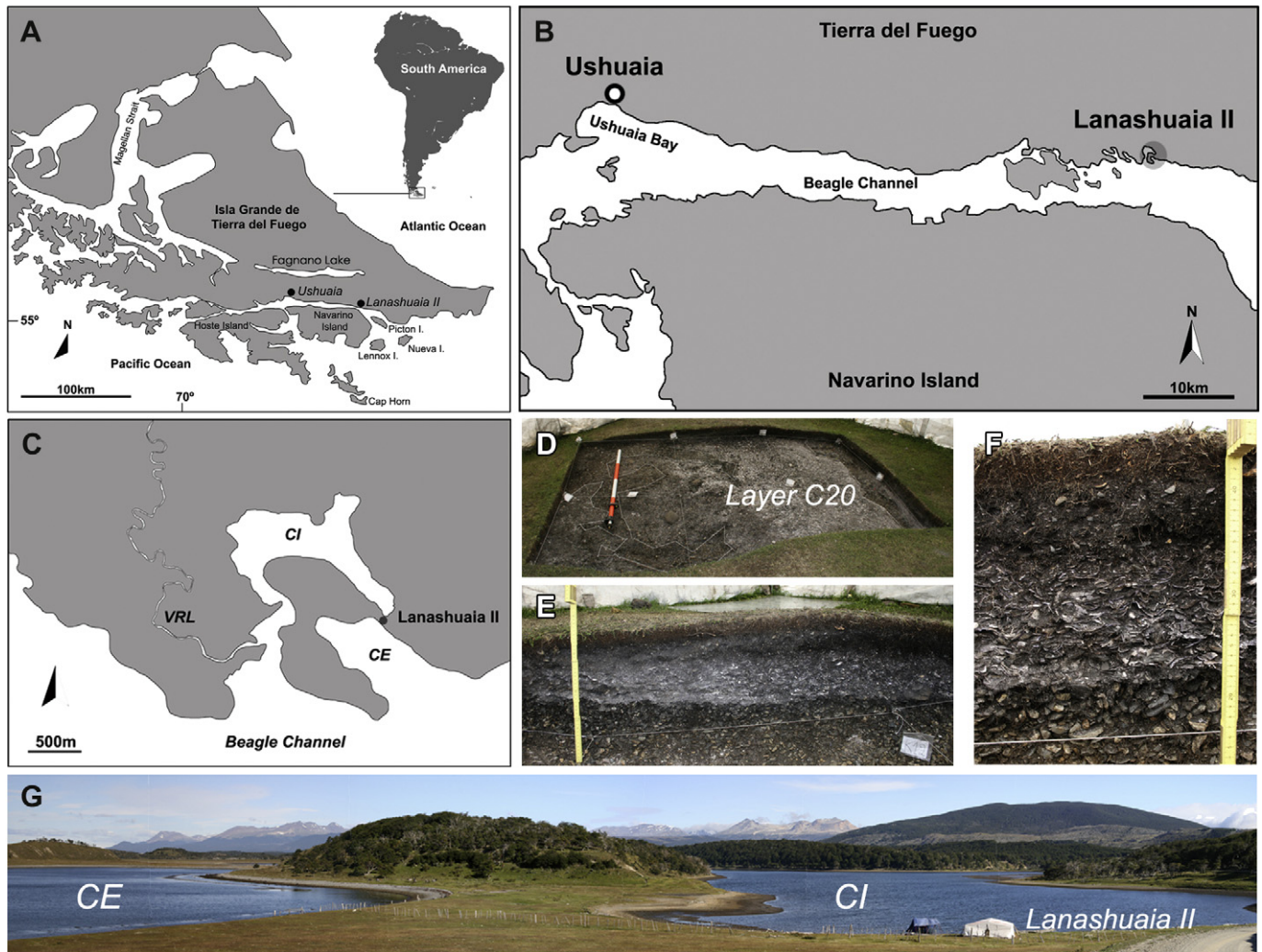


Fig. 1. A) Map of Isla Grande de Tierra del Fuego showing geographic position of the Beagle Channel, including the archaeological shell midden Lanashuaia II; B) Position of Lanashuaia II in the Beagle Channel, also reported the location of Ushuaia Bay; C) Map of Lanashuaia II shell and water collection sites (CI, CE, VRL). Lanashuaia II, view of layer C20 (D) and profile showing its thickness (E–F). Environmental setting of the study area, note the site between the outer (CE) and inner (CI) Cambaceres Bay.

Table 1
Temperature, salinity and $\delta^{18}\text{Ow}$ measured at Varela River (VRL), inner Cambaceres Bay (CI) and outer Cambaceres Bay (CE) between 2009 and 2010.

Site	Data	SST ($^{\circ}\text{C}$)	SSS (ppt)	$\delta^{18}\text{Ow}_{\text{‰}}$ (V-SMOW)
VRL	November (2009)	ND	0	-10.71 ± 0.08
	February (2010)	7	0	-10.73 ± 0.07
	June (2010)	0	0	-11.11 ± 0.04
	August (2010)	6	0	-10.92 ± 0.06
	October (2010)	5	0	-10.85 ± 0.07
CI	December (2009)	12	34	-1.71 ± 0.11
	January (2010)	11	26	-3.46 ± 0.04
	February (2010)	9	15	-6.13 ± 0.04
	June (2010)	3	19	-5.93 ± 0.05
	August (2010)	3	35	-1.35 ± 0.02
CE	October (2010)	7	30	-1.92 ± 0.09
	December (2009)	11	35	-1.32 ± 0.07
	January (2010)	9	30	-1.55 ± 0.10
	February (2010)	9	35	-1.44 ± 0.11
	April (2010)	5	36	-1.20 ± 0.06
	June (2010)	5	35	-1.25 ± 0.05
	August (2010)	3	35	-0.79 ± 0.06
	October (2010)	7	35	-1.18 ± 0.12

(Orquera and Piana, 2001, 2002; Verdún, 2010; Verdún et al., 2010), including Lanashuaia II. *N. deaurata* lives in the lower intertidal and the sublittoral, while *N. magellanica* occur mostly in the high and middle intertidal zones (Morriconi, 1999; Gonzáles-Wevar et al., 2011, and references therein). Their distinct shore line occupations also reflect in different aerial and thermal exposure. For instance, *N. deaurata* may be daily exposed to air for 3 h only during spring tides. In contrast *N. magellanica* may experience daily exposure twice for 3–5 h each time. As a consequence, the former may experience seasonal SST from $\sim 3^{\circ}\text{C}$ in winter to $\sim 11^{\circ}\text{C}$ in summer, whereas the later is exposed to winter and summer atmospheric temperature from $<0^{\circ}\text{C}$ to $>20^{\circ}\text{C}$ respectively (Malanga et al., 2004; Gonzáles-Wevar et al., 2011, and references therein).

Previous studies revealed that the metabolic activity of *N. magellanica* is strongly influenced by seasonal environmental conditions, such as SST and phytoplankton productivity (Malanga et al., 2005, 2007). Its metabolism increases progressively from the early spring and throughout the warmer seasons, decreasing during the winter (e.g., Malanga et al., 2005, 2007). The effect of temperature might reasonably be expected also for *N. deaurata*. For instance both species spawn in spring–summer, synchronously with the rise in SST and primary production (Morriconi, 1999).

Reproduction of *N. magellanica* has been observed in September, with a peak at the end of spring (Malanga et al., 2007). In *N. deaurata* reproduction has been documented from July to January, with variable periodicity during this interval as possible response to environmental factors (Morriconi, 1999).

N. deaurata and *N. magellanica* specimens were collected live on 9 December 2005 in the intertidal – subtidal rock shore located in the exterior sector of Cambaceres Bay (CE), in front of Lanashuaia II (Fig. 1C). One shell of *N. deaurata* (catalogue number M8-13, 50 mm length) and *N. magellanica* (M8-26, 50 mm length) were selected for stable isotopic analysis. M8-13 was collected in the lower intertidal zone while M8-26 was gathered in the upper one, at short distance between each other. Medium-large shells were selected in order to evaluate the effect of ontogenic growth rate on the shell isotopic signature (Fig. 2A–B). After collection, animals were removed from the shells in the field. In the lab shells were rinsed with distilled water and partially embedded in an epoxy resin. Shells were then sectioned along the axis of maximum growth, polished, and cleaned with distilled-water. By using a manual microdrill with a 0.3 mm bit, sequential carbonate microsamples (~150 µg) were obtained along the axis of maximum growth from the inner calcitic layer (e.g. $m + 2$ in shells of *Patella vulgata*; Fenger et al., 2007; Ferguson et al., 2011). Samples were obtained from the shell-edge towards the umbo, and parallel to visible growth increments (Fig. 2C–E).

Archaeological specimens from Lanashuaia II ($N = 10$) were recovered during archaeological excavation in 2009. Shells derive from the layer C20 (1320 ± 20 Cal BP), which is, at the moment, the earliest midden deposit of the site. Sample preparation of zooarchaeological shells follows that of modern counterparts. After sectioned and rinsed with distilled water, four continuous carbonate samples starting from the shell-edge were obtained from

the inner calcitic layer. The shell-edge $\delta^{18}\text{O}$ value is representative of the period (season) when molluscs were collected. In the case of harvesting during intermediate seasons (i.e., spring and autumn) the further three samples behind the shell-edge would provide indications of SST trend (cooling or warming). Three archaeological shells (C20-12, C20-13, C20-14) were sampled sequentially with the same manual microdrill (0.3 mm bit). These sequential samples would record the intra-annual shell $\delta^{18}\text{O}$ variability, which is representative of seasonal SST and $\delta^{18}\text{O}$ variations at the time of shell collection (e.g. Mannino et al., 2007; Colonese et al., 2009, 2011).

Isotopic analyses were performed at Vrije University in Amsterdam. Carbonate samples were analyzed using a Finnigan MAT 252 equipped with an automated preparation line (Kiel II type). The reproducibility of a routinely analyzed carbonate standard (NBS 19) is better than 0.09‰ for both $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$. Water samples were analyzed using Gas Bench II equipped with a Delta + mass spectrometer. The reproducibility of a routinely analyzed lab water standard is better than 0.1‰. The isotopic composition is expressed using the δ (‰) notation. Shell carbonate isotopic signatures are related to V-PDB standard (Vienna Pee Dee Belemnite) and water values to V-SMOW (Vienna Standard Mean Ocean Water). X-ray diffraction on powder carbonate revealed that the sampled shell layer was entirely composed of calcite.

4. Results and discussion

4.1. SST, SSS and $\delta^{18}\text{O}$ in the study area

Both SST and $\delta^{18}\text{O}$ of ambient water are expected to control the shell $\delta^{18}\text{O}$ signature (e.g. Wefer and Berger, 1991), therefore understanding these parameters is mandatory before environmental interpretations of shell $\delta^{18}\text{O}$ are carried out. Mean monthly SST for the years 1994–2001 from Ushuaia Bay ranged from 9 ± 0.4 °C to 4.5 ± 0.4 °C in summer and in winter respectively ($\Delta\text{SST} = \sim 4.5$ °C). The intra-annual average SST was 6.6 ± 1.7 °C. Mean monthly SSS in the area ranged from ~ 26 to ~ 31 PSU ($\Delta\text{SSS} = \sim 5$ PSU), with substantial differences between SSS1 and SSS2 (Fig. 3A). SSS1 shows an irregular trend throughout the year, while SSS2 variations are consistent with the model of summer meltwater discharge into the channel (e.g. Iturraspe et al., 1989; Bujalesky, 2007).

On overall measured SST data during water sampling are consistent with long-term records reported above (Fig. 3B). The average SST differs between sampled areas, with lowest and highest values recorded at VRL (from 0 °C to 7 °C; mean = 3.8 °C) and CI (from 3 °C to 12 °C; mean = 7.5 °C) respectively. SSTs at CE (mean = 7.1 °C) range from 3 °C (August) to 11 °C (December) and are in good agreement with values recorded at Ushuaia Bay. Our SSS data also vary notably between sampled areas, due to the strong gradient from freshwater (VRL), through mixed water (CI) to seawater (CE) (Fig. 3C). SSS at VRL is constant with a mean value of 0 ppt, by contrast SSS at CI oscillates from 30 to 35 ppt (August–October) to 15–19 ppt (February–June), with an average value of 26.5 ppt. SSS changes at CI are compatible with the record represented by SSS2 and again reflects seasonal variations in freshwater discharge. Finally SSS at CE is nearly constant, with a mean value of 34.4 ppt. Minor oscillations are represented by higher (36 ppt) and lower (30 ppt) values in autumn (April) and summer (January) respectively due to the same mechanism described above (changes in freshwater discharge). As expected the $\delta^{18}\text{O}$ tracks the strong SSS gradient of the study area (Fig. 3D). Mean $\delta^{18}\text{O}$ values range from -11 ‰ at VRL, through -3.4 ‰ at CI, to -1.2 ‰ at CE. The $\delta^{18}\text{O}$ exhibit a strong positive linear relation with SSS (for SSS range of 0–36 ppt; Fig. 4, Table 1):

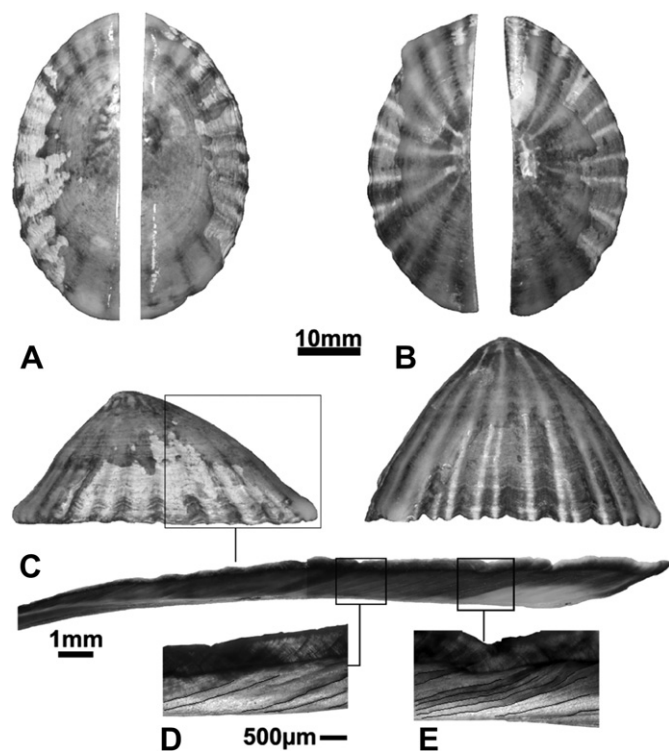


Fig. 2. A–B) Sectioned shells of *Nacella deaurata* (M8-13) and *Nacella magellanica* (M8-26). C) Shell section of M8-13 along the axis of maximum growth; major growth lines were also recognized (D–E). Closely spaced lines (E) coincide with more positive $\delta^{18}\text{O}$ values, suggesting reduced growth at lower SST.

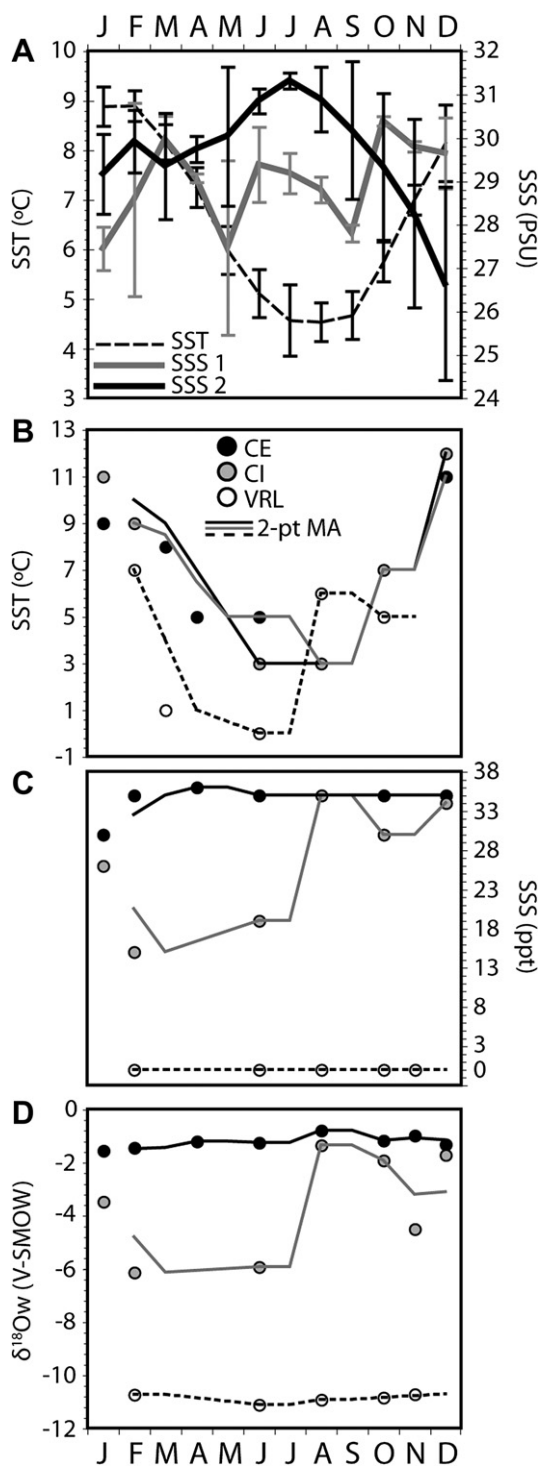


Fig. 3. A) Sea surface temperature (SST) and salinity (SSS) from the Beagle Channel. SSTs result from measurements in Ushuaia Bay (port of Ushuaia) during 1994–2001 (data from Colonese et al., 2011). SSS1 refers to the interval from 1987 to 1989 (Lovrich, personal communication), and SSS2 to the period between 1971 and 1987 (Obelice et al., 1998). B–D) Measured SST, SSS and $\delta^{18}\text{Ow}$ over nearly one year at the outer Cambaceres Bay (CE), inner Cambaceres Bay (CI) and Varela river (VRL), 2pt-MA = 2-point moving average.

$$\delta^{18}\text{Ow}_{(\text{SMOW})} = 0.28 * \text{SSS} (\text{ppt}) - 10.79 \quad (1)$$

$(R^2 = 0.99; N = 18; p < 0.001)$

The amplitude of $\delta^{18}\text{Ow}$ ($\Delta\delta^{18}\text{Ow}$) also varies between sampled areas as a function of seasonal SSS change. The $\Delta\delta^{18}\text{Ow}$ is

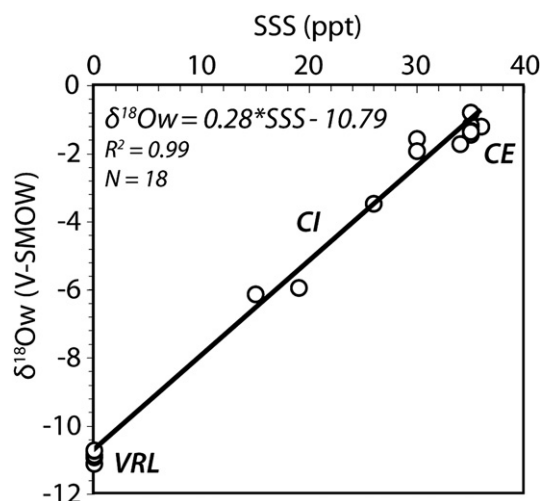


Fig. 4. $\delta^{18}\text{Ow}$ versus SSS samples taken over nearly one year at the outer Cambaceres Bay (CE), inner Cambaceres Bay (CI) and Varela river (VRL).

narrow at VRL (0.4‰) and at CE (0.8‰), but increase considerably at CI (4.8‰).

4.2. Intra-shell $\delta^{18}\text{O}$ variations in modern *N. deaurata* and *N. magellanica*

Sequential shell $\delta^{18}\text{O}$ of *N. deaurata* (M8-13) and *N. magellanica* (M8-26) depict a quite sinusoidal pattern similar to oscillations of SST (Fig. 5A–B; Table 2). $\delta^{18}\text{O}$ values of M8-13 range from $+2.4\text{‰}$ to -0.1‰ and provide a mean $\delta^{18}\text{O}$ of $+0.9 \pm 0.7\text{‰}$. $\delta^{18}\text{O}$ values of M8-26 range from $+1.9\text{‰}$ to -0.8‰ and show an average $\delta^{18}\text{O}$ of $+0.8 \pm 0.7\text{‰}$. Intra-shell $\delta^{18}\text{O}$ variability ($\Delta\delta^{18}\text{O}$) is 2.5‰ and 2.7‰ for M8-13 and M8-26 respectively. Mean $\delta^{18}\text{O}$ values of both shells are consistent with average isotopic values (i.e., -0.2‰ to $+1.4\text{‰}$) of other modern mollusc shells from the Beagle Channel (Panarello, 1987; Obelice et al., 1998; Lomovasky et al., 2002, 2007; Gordillo et al., 2010, 2011; Colonese et al., 2011).

In order to test if shells precipitated in (or near) isotopic equilibrium with ambient water, we used the following paleotemperature equation for biogenic calcite precipitated at similar SSS and SST of the study area (Wanamaker et al., 2007):

$$T (\text{°C}) = 16.33 - 4.48 * (\delta^{18}\text{O}_{(\text{V-PDB})} - \delta^{18}\text{Ow}_{(\text{SMOW})}) \quad (2)$$

According to Eq. (2) both SST and $\delta^{18}\text{Ow}$ fluctuations account for $\Delta\delta^{18}\text{O}$ in M8-13 (2.5‰) and M8-26 (2.7‰), but the extent of their contribution may be different. Using a constant $\delta^{18}\text{Ow}$ value of -1.2‰ (average $\delta^{18}\text{Ow}$ at CE), we estimate that the amplitude of measured SST in the study area (ΔSST at CE = 8°C) would explain $\sim 70\%$ of intra-shell $\delta^{18}\text{O}$ variability in both specimens (i.e. predicted shell $\Delta\delta^{18}\text{O} = 1.8\text{‰}$). The residual $\sim 30\%$ (i.e. predicted shell $\Delta\delta^{18}\text{O} = 0.8\text{‰}$) would be in turn associated with the effect of the seasonal oscillation of $\delta^{18}\text{Ow}$ ($\Delta\delta^{18}\text{Ow} = 0.8\text{‰}$), when a constant SST of 7.1°C is computed. However, erroneous estimations may derive from local SST and $\delta^{18}\text{Ow}$ data because based on few spot measurements. Thus the theoretical contribution of SST and $\delta^{18}\text{Ow}$ to shell $\delta^{18}\text{O}$ was also calculated according to data from Ushuaia Bay. Using the ΔSST ($\sim 4.5\text{°C}$) and $\Delta\delta^{18}\text{Ow}$ (1.3‰ ; using Eq. (1) on SSS2) from mean monthly values, the temperature would explain $\sim 38\%$ of intra-shell $\delta^{18}\text{O}$ variability in both specimens (i.e. predicted shell $\Delta\delta^{18}\text{O} = 1\text{‰}$), while $\sim 50\%$ would be associated with the effect of $\delta^{18}\text{Ow}$ (i.e. predicted shell $\Delta\delta^{18}\text{O} = 1.3\text{‰}$) at constant

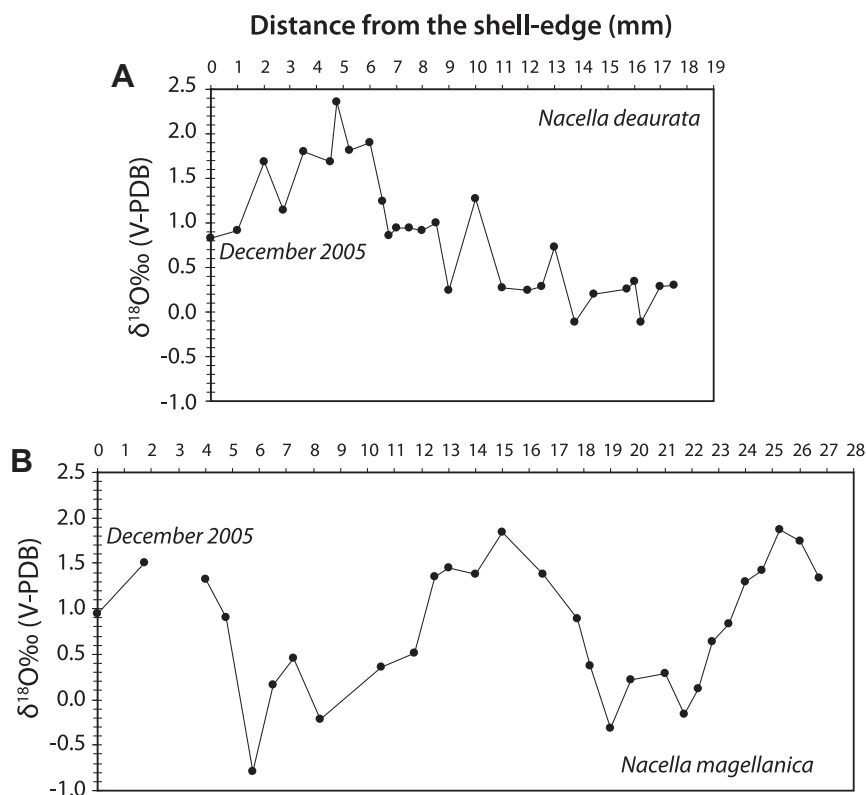


Fig. 5. Sequential shell $\delta^{18}\text{O}$ of *N. deaurata* (M8-13) (A) and *N. magellanica* (M8-26) (B) plotted versus distance from the shell-edge (mm). Note the cyclical $\delta^{18}\text{O}$ pattern recording mainly seasonal SST fluctuations. Shell-edge values of both specimens are in good agreement and refer to collections on December 2005.

SST of 6.6 °C. The predicted shell $\Delta\delta^{18}\text{O}$ (2.3‰) approaches the measured counterparts, but a remained 12% of shell $\delta^{18}\text{O}$ variability ($\sim 0.3\%$) suggest that specimens experienced additional oscillations of SST and/or $\delta^{18}\text{Ow}$. Nevertheless, at seasonal scale, both SST and $\delta^{18}\text{Ow}$ move shell $\delta^{18}\text{O}$ signature in the same direction because increasing SST is accompanied by decreasing SSS due to enhanced freshwater input and *mutatis mutandis* (Fig. 3).

Using Eq. (1) on $\Delta\delta^{18}\text{Ow}$ reported above (0.8‰ and 1.3‰), we calculate that both *N. magellanica* and *N. deaurata* experienced SSS oscillations of ~ 3 to ~ 5 ppt. Those values are in good agreement with that inferred by Colonese et al. (2011) using shell oxygen isotopic composition of *N. magellanica* from the Beagle Channel (~ 3 ppt). In conclusion, isotopic data suggest that both specimens experienced limited salinity oscillations, within values of local seawater. Field observations would be in support of this hypothesis; both species were indeed absent from the CI area, where SSS oscillated up to 20 ppt. These finds reveal the advantage of these species over others present in the study area (e.g. *M. edulis*; Obelic et al., 1998) when reconstructing isotopic-derived paleotemperature, because the limited imprinting of SSS changes in their shell isotopic signature.

Although incomplete, intra-annual SST oscillations at CE show higher amplitude (8 °C) compared with those from Ushuaia Bay (4.5 °C), thus only the former is used in the follow discussion. SST and $\delta^{18}\text{Ow}$ data from CE predict shell $\delta^{18}\text{O}$ values ranging from -0.1% to $+2.2\%$, and an average of $+0.9\%$. These values are consistent with those measured in M8-13 and in M8-26 (Fig. 6). Using the range of $\delta^{18}\text{Ow}$ at CE (from -0.8% to -1.6%), we estimate average SSTs for M8-13 (6.4 °C) and M8-26 (6.7 °C) that broadly agree with mean annual data recorded at Ushuaia Bay (6.6 ± 1.7 °C) and in the study area (7.1 °C). Small offsets may to some degree be an artifact of incomplete SST and $\delta^{18}\text{Ow}$

records (Fig. 7). Results thus indicate that intra-shell $\delta^{18}\text{O}$ signatures from both specimens record seasonal changes in SST and $\delta^{18}\text{Ow}$, suggesting oxygen isotopic equilibrium during shell formation.

The Fig. 6 also depicts an offset of $\sim 0.6\%$ between the minimum (summer) and maximum (winter) shell $\delta^{18}\text{O}$ of *N. magellanica* and *N. deaurata*. A detailed understanding of this isotopic discrepancy is complicated by the limited amount of specimens. However it is worth noting that these species inhabit different shore levels and display different physiological strategies to survive to thermal stress and air exposure during tidal emersion (e.g. Malanga et al., 2004; Pöhlmann et al., 2011). In particular, it has been demonstrated that *N. magellanica* has a more efficient response to short periods of tidal exposure and enhanced temperatures compared with *N. deaurata* (Pöhlmann et al., 2011). Therefore, aforementioned differences could to some extent reflect different specie-specific physiological responses to environmental stress. For instance, isotopic data could suggest a reduced physiological activity of *N. deaurata* during summer warmer temperatures compared with *N. magellanica*. By contrast, isotopic data may indicate that *N. magellanica* reduces (or interrupts) its shell secretion in winter. This could be reasonable given that this species may experience very low winter temperatures at low tide. However, higher winter $\delta^{18}\text{O}$ in *N. deaurata* may also be induced by more saline conditions (higher $\delta^{18}\text{Ow}$), not recorded in *N. magellanica* shell.

Fenger et al. (2007) and Ferguson et al. (2011) observed positive offsets ($\sim 0.7\%$ to $\sim 1\%$) in shell $\delta^{18}\text{O}$ from isotopic equilibrium in limpet species from the Mediterranean and North Atlantic coasts. Although predicted shell $\delta^{18}\text{O}$ values do not reveal a similar isotopic behaviour in *Nacella* species, the magnitude our offset ($\sim 0.6\%$) between *N. magellanica* and *N. deaurata* is intriguingly close to

Table 2

Sequential shell $\delta^{18}\text{O}$ of modern specimens of *N. deaurata* (M8-13) and *N. magellanica* (M8-26).

Samples	Modern shells	
	$\delta^{18}\text{O}_{\text{‰}}$ (V-PDB)	
	<i>Nacella deaurata</i> (M8-13)	<i>Nacella magellanica</i> (M8-26)
1	+0.83	+0.94
2	+0.92	+1.51
3	+1.69	ND
4	+1.14	+1.32
5	+1.80	+0.91
6	+1.68	-0.79
7	+2.36	+0.16
8	+1.81	+0.45
9	+1.91	-0.22
10	+1.24	+0.35
11	+0.85	+0.51
12	+0.94	+1.35
13	+0.94	+1.44
14	+0.91	+1.38
15	+0.99	+1.84
16	+0.24	+1.38
17	+1.27	+0.89
18	+0.28	+0.37
19	+0.24	-0.32
20	+0.29	+0.22
21	+0.73	+0.29
22	-0.11	-0.16
23	+0.21	+0.11
24	+0.26	+0.63
25	+0.35	+0.83
26	-0.11	+1.29
27	+0.29	+1.42
28	+0.30	+1.87
29		+1.75
Max	+2.36	+1.87
Min	-0.11	-0.79
Mean	+0.87	+0.80
$\Delta\delta^{18}\text{O}_{\text{‰}}$	2.47	2.66

those reported in these previous studies. Thus we cannot rule out the possibility that this offset may exist within the errors of the study.

In both shells the correspondence between more positive $\delta^{18}\text{O}$ values with closely spaced growth increments (Fig. 2D–E; ongoing study), and *mutatis mutandis*, is consistent with reduced growth

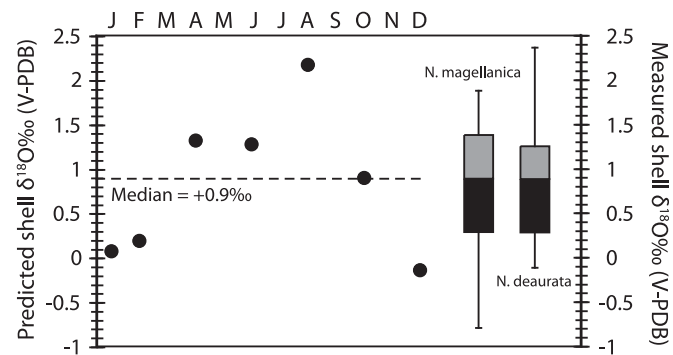


Fig. 6. Monthly predicted shell $\delta^{18}\text{O}$ according to measured SST and $\delta^{18}\text{O}_{\text{w}}$ at CE plotted against the quartile distribution of sequential shell $\delta^{18}\text{O}$ of *N. deaurata* (M8-13) and *N. magellanica* (M8-26). Intra-shell $\delta^{18}\text{O}$ fluctuations are distributed into four different groups of equal parts consisting with 1/4th of the data set. Lowest $\delta^{18}\text{O}$ values corresponding to warmer months are grouped in the lower quartile (lowest 25% of data). Highest $\delta^{18}\text{O}$ values associated to colder months are grouped into the upper quartile (upper 25%). Intermediate $\delta^{18}\text{O}$ values representing environmental conditions between the two above are grouped into the interquartile range (>25% and <75%), with the 50% of the $\delta^{18}\text{O}$ data set. The dotted line indicates the median predicted shell $\delta^{18}\text{O}$ (+0.9‰). Results are in broad agreement with the average and amplitude of measured shell $\delta^{18}\text{O}$ in M8-13 and M8-26.

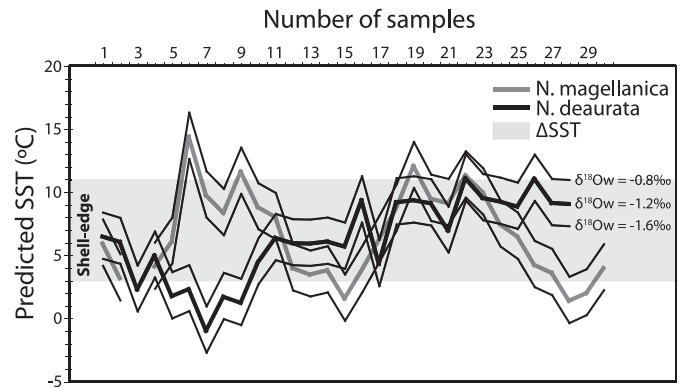


Fig. 7. Estimated SSTs from shell $\delta^{18}\text{O}$ of *N. deaurata* (M8-13) and *N. magellanica* (M8-26). SSTs were computed using maximum (-0.8‰), minimum (-1.6‰) and average (-1.2‰) $\delta^{18}\text{O}_{\text{w}}$ from CE. Estimated SSTs fall into the range of measured SST at CE (grey band).

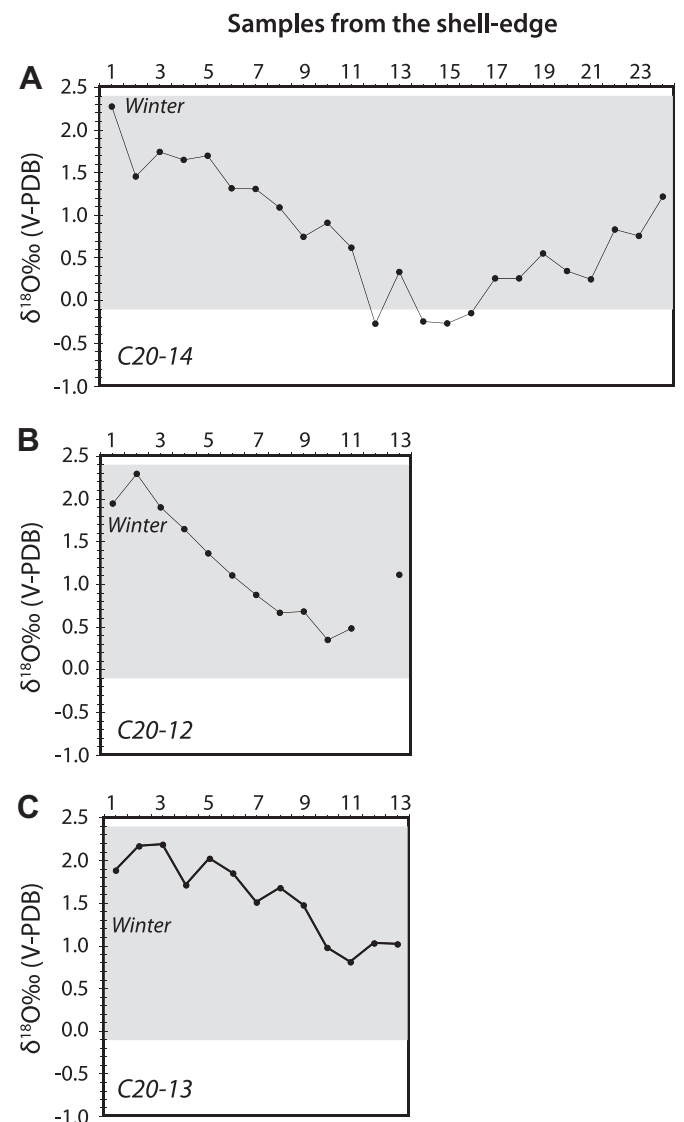


Fig. 8. Sequential shell $\delta^{18}\text{O}$ of archaeological specimens of *N. deaurata* C20-14 (A), C20-12 (B) and C20-13 (C), plotted versus samples from the shell-edge. The grey bands indicate the amplitude of shell $\delta^{18}\text{O}$ of the modern specimen (M8-13).

rate during winter (e.g. Fenger et al., 2007; Schöne, 2008). Integration of isotopic data with observed increments suggests that mayor growth checks in both species might represent fortnightly growth breaks, but further studies are required.

The $\delta^{18}\text{O}$ profiles suggest distinct specie-specific growth rate between analyzed species. Sequential $\delta^{18}\text{O}$ samples of *N. deaurata* spanning approximately only 1 year of growth. By contrast *N. magellanica* exhibits a $\delta^{18}\text{O}$ profile consistent with a little bit more than 2 years. Using relations between shell length and distance of carbonate samples, we estimate for M8-13 an overall growth rate of ~ 18 mm/yr. By contrast the growth rate of M8-26 can be estimated to be ~ 9 mm/yr and ~ 13 mm/yr in the early and later year respectively. To some extent, previous isotopic results support our observations (Colonese et al., 2011). Sequential isotopic profile on a *N. magellanica* shell from the study area also revealed two years of animal growth, but the overall secretion rate was ~ 5 mm/yr. Differences between *N. magellanica* shells may arise from intra-specific variability in growth rate (Colonese et al., 2011).

Finally limpets may be subjected to shell erosion by contact with the substrate (e.g., Day et al., 2000). In our case isotopic results suggest that shell erosion, if occurring, was negligible and likely have not affected $\delta^{18}\text{O}$ profiles of both specimens. Additional evidence in support of shell preservation is the broad agreement between shell-edge isotopic signatures of the two specimens collected contemporaneously on 9 December 2005 in the same intertidal area ($+0.8\text{‰}$ and $+0.9\text{‰}$ in M8-13 and M8-26 respectively).

4.3. Seasonality of exploitation of *N. deaurata* at Lanashuaia II

Our results suggest that shell $\delta^{18}\text{O}$ of *N. deaurata* record most of the intra-annual SST and $\delta^{18}\text{Ow}$ variability in the study area and thus has a great potential as an archive of past seasonal SST and $\delta^{18}\text{Ow}$ variability. The annual growth rates of *N. deaurata* also provide a more extensive record of environmental conditions compared with *N. magellanica*, thus it would be more suitable for paleoclimate reconstruction or in determining season of harvest than *N. magellanica*. Nevertheless, intra-shell $\delta^{18}\text{O}$ variability in modern specimens may differ from archaeological counterparts due to potential changes in SST, SSS and $\delta^{18}\text{Ow}$. Thus sequentially shell $\delta^{18}\text{O}$ were measured in three archaeological specimens and used as reference for the shell-edge $\delta^{18}\text{O}$ values of other archaeological specimens (Fig. 8A–C; Table 3). The largest specimen C20-14 displays $\delta^{18}\text{O}$ values ranging from $+2.3\text{‰}$ to -0.8‰ ($\Delta\delta^{18}\text{O} = 2.5\text{‰}$), providing an average of $+0.8 \pm 0.7\text{‰}$. The $\delta^{18}\text{O}$ profile of C20-14 is composed by decreasing and increasing values, which form a curve coherent with a little bit less than one year of SST and $\delta^{18}\text{Ow}$ fluctuations. The overall growth rate (~ 16 mm/yr) is close to that estimate in M8-13 (~ 18 mm/yr), and both the range and the average $\delta^{18}\text{O}$ are similar to those measured in the modern specimen, suggesting comparable environmental conditions at the time of shell precipitation. By contrast C20-12 and C20-13 exhibit $\delta^{18}\text{O}$ values ranging from $+2.2\text{‰}$ to $+0.8\text{‰}$ ($\Delta\delta^{18}\text{O} = 1.4\text{‰}$) and $+2.3\text{‰}$ to $+0.3\text{‰}$ ($\Delta\delta^{18}\text{O} = 1.9\text{‰}$), with averages of $+1.6 \pm 0.5\text{‰}$ and $+1.2 \pm 0.6\text{‰}$ respectively. Both specimens depict a $\delta^{18}\text{O}$ profile characterized by increasing values toward the shell-edge, which appear consistent with approximately a half a year of shell formation. The reduced portion of shell sampled (9.5 mm and 7.4 mm in C20-12 and C20-13 respectively) probably explains the lack of lower $\delta^{18}\text{O}$ values compared with C20-14 (16 mm). Shell-edge $\delta^{18}\text{O}$ values of C20-12 and C20-13 (1.8‰ and 1.9‰ respectively) are substantially close to that measured in C20-14 (2.3‰), and according to modern observations they are indicative of animals collected in winter.

Table 3
Sequential shell $\delta^{18}\text{O}$ of archaeological specimens of *N. deaurata*.

Samples	Archaeological shells		
	$\delta^{18}\text{O}\text{‰}$ (V-PDB)		
	C20-12	C20-13	C20-14
1	+1.88	+1.95	+2.28
2	+2.17	+2.29	+1.46
3	+2.18	+1.90	+1.75
4	+1.71	+1.65	+1.65
5	+2.02	+1.36	+1.70
6	+1.85	+1.11	+1.32
7	+1.51	+0.88	+1.31
8	+1.68	+0.67	+1.09
9	+1.47	+0.68	+0.75
10	+0.98	+0.35	+0.91
11	+0.81	+0.49	+0.62
12	+1.03		-0.27
13	+1.02		+0.34
14			-0.24
15			-0.26
16			-0.14
17			+0.26
18			+0.26
19			+0.55
20			+0.35
21			+0.25
22			+0.83
23			+0.76
24			+1.22
Max	+2.18	+2.29	+2.28
Min	+0.81	+0.35	-0.27
Mean	+1.56	+1.20	+0.78
$\Delta\delta^{18}\text{O}\text{‰}$	1.38	1.94	2.55

The $\delta^{18}\text{O}$ profile of C20-14 is the most complete and comparable with modern counterpart (M8-13), thus it has been used as references against which to compare $\delta^{18}\text{O}$ values of shells used for seasonal determinations (four sequential samples; Table 4). Along with isotopic data from the modern shell M8-13, $\delta^{18}\text{O}$ values from C20-14 is represented into quartiles (Fig. 9A), which organizes intra-shell $\delta^{18}\text{O}$ fluctuations into four different groups of equal parts consisting with 1/4th of the data set. Lowest $\delta^{18}\text{O}$ values corresponding to warmer months (also generally characterized by lower $\delta^{18}\text{Ow}$) are grouped in the lower quartile (lowest 25% of data). Highest $\delta^{18}\text{O}$ values associated to colder months (with generally higher $\delta^{18}\text{Ow}$) are grouped into the upper quartile (upper

Table 4
 $\delta^{18}\text{O}$ results of shells selected for seasonal analysis. Shell-edge $\delta^{18}\text{O}$ is indicative of the season of collection. The further three samples behind the shell-edge provide indications of SST trend (cooling or warming).

Lanashuaia II	$\delta^{18}\text{O}\text{‰}$ (V-PDB)			
	1st sample (shell-edge)	2nd sample	3rd sample	4th sample
C20	+1.3	+1.9	+1.5	+1.5
C20	+2.1	+1.9	+1.2	+1.1
C20	+1.6	+1.8	+1.2	+0.7
C20	+1.8	+1.6	+0.8	+1.0
C20	+0.7	+1.5	+1.8	+1.9
C20	+1.3	+2.1	+1.6	+1.5
C20	+1.6	+1.6	+1.1	+0.6
C20	+2.3	+1.5	+1.7	+1.6
C20	+1.9	+2.3	+1.9	+1.6
C20	+1.9	+2.2	+2.2	+1.7
Max	+2.3			
Min	+0.7			
Mean	+1.7			
$\Delta\delta^{18}\text{O}$	1.6			

25%). Intermediate $\delta^{18}\text{O}$ values representing environmental conditions between the two above are grouped into the inter-quartile range (>25% and <75%), with the 50% of the $\delta^{18}\text{O}$ data set. This approach allows seasonal discriminations devoid of subjective attributions of shell-edge $\delta^{18}\text{O}$ to specific seasons (Mannino et al., 2007; Colonese et al., 2009, 2011).

Shell-edge $\delta^{18}\text{O}$ values of archaeological specimens from Lanashuaia II ($N = 10$) range from +2.3‰ to +0.7‰, with an average $\delta^{18}\text{O}$ of $+1.7 \pm 0.5\text{‰}$ ($\Delta\delta^{18}\text{O} = 1.6\text{‰}$). Quartile distributions of $\delta^{18}\text{O}$ vary from the upper (90% of data, from +1.3‰ to +2.3‰) to the inter-quartile range (10% of data, +0.7‰). Such division is indicative of a prevalent animal collection during cold months, with only a single shell recording intermediary values (e.g. decreasing $\delta^{18}\text{O}$ trend, Table 4). If we exclude this shell, the $\Delta\delta^{18}\text{O}$ becomes quite narrow (1‰) compared with those measured in both M8-13 ($\Delta\delta^{18}\text{O} = 2.5\text{‰}$) and C20-14 ($\Delta\delta^{18}\text{O} = 2.5\text{‰}$; Fig. 9B). Using Eq. (2) the $\Delta\delta^{18}\text{O}$ can be converted in a ΔSST of $\sim 4.5\text{ }^\circ\text{C}$. The influence of $\delta^{18}\text{O}_{\text{w}}$ may be excluded from the $\Delta\delta^{18}\text{O}$ given that only small oscillations of $\delta^{18}\text{O}_{\text{w}}$ are reasonably expected during winter due to reduced snow-melt (Fig. 3A). As consequence we estimate that exploitation of *N. deaurata* during the initial stage of shell midden formation at Lanashuaia II (layer C20) occurred prevalently during winter, with perhaps sporadic collection in spring. Shellfish collection and site formation were frequently connected (shells were used as building material for dwelling structures; e.g., Verdún, 2010). Our results suggest a relative rapid (seasonal) formation rate of shell deposit in the study area.

It is worth noting that seasonal limpet collection (*N. magellanica*) prevalently during cold and intermediary seasons has been

recently reported for recent Yamana shell midden sites of the Beagle Channel (Colonese et al., 2011). At Lanashuaia, another shell midden in the same beach, (Piana et al., 2000; Colonese et al., 2011; Tivoli and Zangrando, 2011), also named Lanashuaia I in recent works to avoid any confusion with Lanashuaia II or Lanashuaia site (Zurro et al., 2010), *N. magellanica* was collected during autumn and beginning of winter and the same pattern has been detected for the occupation G of Túnel VII (Piana and Orquera, 1995; Orquera and Piana, 1999; Estévez and Vila, 2007). However *N. magellanica* has been also exploited in spring and autumn at Túnel VII, during occupations H and J respectively. In both sites other faunal remains appear to support the periodicity of shellfish exploitation (Colonese et al., 2011).

The most striking feature in this study is the additional evidence of shell $\delta^{18}\text{O}$ of limpet species as archive of seasonal SST and $\delta^{18}\text{O}_{\text{w}}$ oscillations in coastal environments (e.g., Fenger et al., 2007; Ferguson et al., 2011). The possibility to access seasonal environmental changes using shells from archaeological sites in the Beagle Channel may offer new perspectives to the understanding of social dynamics in high latitude environments, such as strategies designed by hunter–gatherer–fisher groups to face with environmental fluctuations and to what extent these fluctuations affected the different productive spheres of these societies, along the entire occupation of the region.

The results presented here open a fruitful avenue of research providing indirect material markers to assess periodicity of resource exploitation and site occupation in the Beagle Channel. To establish contemporaneity, between dwelling units or adjacent shell midden structures, is a key step to identify people temporary concentrations (Hofman, 1994). Contemporaneity has been usually inferred in Archaeology employing different methods such as radiocarbon dating and/or bone and lithic refitting (Morin et al., 2005; Cooper and Qiu, 2006). The recognition of seasonality of site occupations can also address the question of contemporaneity to the extent that, if the two (or more) dwelling units correspond to a concentration episode, the limpets contained in these midden layers should have been gathered during the same season. In this respect, it is important to remark that this indicator is not a self-sufficient data for identifying an aggregation site; but the integration with multiple lines of evidence (which includes the determination of site occupation season) leads to recognize transitory banding together of groups otherwise dispersed. These results are the first step of ongoing analysis addressed to accomplish this objective.

5. Conclusions

Intertidal and subtidal limpet species *N. deaurata* and *N. magellanica* are frequently identified taxa in shell middens distributed along the coastal areas of the Beagle Channel. Sequential shell $\delta^{18}\text{O}$ of both species track seasonal changes of SST and $\delta^{18}\text{O}_{\text{w}}$, which in combination move shell $\delta^{18}\text{O}$ in the same direction. Shell $\delta^{18}\text{O}$ profiles also suggest distinct growth rate and possible physiological adaptations between species, therefore care must be taken in identifying the species of *Nacella* prior isotopic studies. However the sample size in this research is not large enough or geographically diverse enough, thus observed differences between the two species should be considered with caution. Results indicate that *N. deaurata* is a valuable candidate for studying past seasonal changes in SST and $\delta^{18}\text{O}_{\text{w}}$ in this southernmost part of South America.

Shell $\delta^{18}\text{O}$ of archaeological specimens of *N. deaurata* from the initial stage of Lanashuaia II suggests that animals experienced similar environmental conditions of present day at ~ 1320 years ago. Seasonal analysis of *N. deaurata* collections also revealed that specimens were exploited predominantly in winter, with perhaps

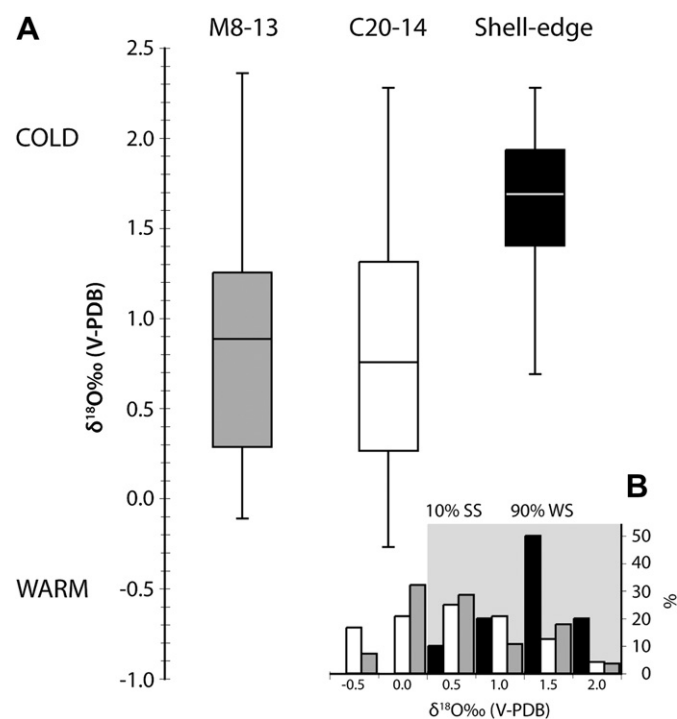


Fig. 9. A) Quartile distribution of shell-edge $\delta^{18}\text{O}$ values of *N. deaurata* ($N = 10$) recovered at Lanashuaia II. Sequential shell $\delta^{18}\text{O}$ of modern (M8-13) and archaeological (C20-14) *N. deaurata* specimens are reported for comparison. Note that shell-edge $\delta^{18}\text{O}$ values are mainly distributed in the upper quartile of sequential $\delta^{18}\text{O}$ values of both modern and archaeological shells. B) Frequency distribution of shell-edge $\delta^{18}\text{O}$ values and sequential values of modern and archaeological specimens. The grey band marks the range of shell-edge $\delta^{18}\text{O}$ values. Comparisons with sequential data indicate that 90% of shell-edge $\delta^{18}\text{O}$ values ($N = 9$) have a winter signal (WS) and only 10% ($N = 1$) show a spring signature (SS).

exploitation also occurring in spring. In the light of these preliminary results, future research will lead to a better understanding of periodicity as well as occupation length at Lanashuaia II. Both variables, in conjunction with other archaeological signatures, will allow us to establish if the formation of Lanashuaia II and adjacent shell middens represents a pre-contact evidence of aggregation events in the Beagle Channel.

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