Seasonal Shellfishing across the East Adriatic Mesolithic-Neolithic Transition: Oxygen Isotope Analysis of *Phorcus turbinatus* from Vela Spila (Croatia)

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The Mesolithic-Neolithic transition is a classic topic of archaeological discussion, and the East Adriatic is of particular interest as a gateway region for agriculture entering Europe from the Near East. Neolithisation along the East Adriatic coast has been characterised as a two-wave process of leap-frog demographic replacement along the Dalmatian coast, followed by a longer process of acculturation further inland. Research on this transition primarily addresses the arrival of Neolithic technology and domesticates, but the view from 'traditionally Mesolithic' activities can provide an alternative perspective. This pilot study highlights one such practice, identifying changes in the seasonality of shellfish gathering over the Neolithic transition using material from Vela Spila, Korčula (Croatia). Specimens of the gastropod *Phorcus turbinatus* from across this transition were assessed using oxygen isotope analysis. Results showed a focus on summer and autumn collection during the Mesolithic, which then shifted to autumn and winter in the Neolithic. These results indicate differences in shellfish gathering and exploitation across the Neolithic transition, and implications for the demographic transition and human-environment interactions are discussed. Shellfishing in the East Adriatic is identified as an area of Neolithisation rather than Mesolithic continuity.

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Keywords: Shellfish exploitation, Seasonality, Stable Isotopes, Mesolithic, Neolithic, Croatia

Introduction

Investigation of seasonality in mollusc gathering and subsistence is a key element to archaeological understanding of prehistoric diet. Molluscs have often been ethnographically recorded as a winter dietary supplement (Claassen 1998), leading to

the suggestion that molluscs are ‘nutritionally poor’ (Richards and Schulting 2006, pg. 445) and only play a role in human diet when other resources are depleted. Indeed, when the calorific content of molluscs is compared to other food sources (e.g. Bailey 1978) molluscs do not appear as a particularly energy-efficient resource. However, this downplays the potentially important micronutritional role of molluscs. For example, shellfish are listed by Hockett and Haws (2003) as one of the five main Palaeolithic food groups and can be an important source of vitamins (e.g. B12, D, and E), iodine, iron and fatty acids (Cunnane and Crawford 2014; Haws and Hockett 2004; Jerardino 2016; Kyriacou et al. 2014; Lindeberg 2009). While these micronutrients can be sourced elsewhere, their abundance in molluscs may lead to nutritional significance. It is even suggested that shellfishing and aquatic diet may have played an evolutionary role in hominin encephalisation (e.g. Jerardino 2016; Parkington 2010).

Beyond the famine season, seasonal mollusc use at other times of the year may indicate gathering preferences and patterns of environmental interaction, while year-round exploitation could suggest the importance of molluscs as a dietary staple. As such, study of gathering season can help determine the function of molluscs within diet, and may provide further insight into their nutritional and cultural status. For example, Mannino and Sineo (2012) interpret the clustered winter collection of shellfish at Grotta d’Oriente as evidence of periodic occupation for funerary rituals.

This pilot study explores seasonality through stable isotope analysis of *Phorcus (Osilinus) turbinatus*. This well-established technique relies on both the isotopic composition of the water and the sea surface temperature, which incorporate into the shells of marine molluscs, allowing the reconstruction of collection season through stable isotope mass spectrometry. The oxygen isotope ratio of shell aragonite precipitates in equilibrium with ambient sea water, which is in turn regulated by

temperature (Epstein et al. 1951; Shackleton 1973). This creates an inverse correlation between shell $\delta^{18}O$ and sea surface temperature (SST).

Prehistoric archaeological sites from coastal Croatia provide large assemblages of marine and terrestrial molluscs suitable to such seasonality analysis (e.g. Diedrich 2011; Klindžic Šošić et al. 2015; Lubell 2004; P. Miracle 2003). In this region, the Neolithic transition is thought to have begun at around 6000 BC, marked by the emergence of pottery and domesticates (Stašo Forenbaher, Kaiser, and Miracle 2013). This is relatively early in the larger picture of the European Mesolithic-Neolithic transition, and the Balkan peninsula is one of the key routes for the spread of the Neolithic from Anatolia into central Europe (Lightfoot et al. 2011).

Discussion of East Adriatic Neolithisation focuses primarily on ceramic styles, with the abrupt arrival of Impressed Ware pottery used as an indicator of demographic expansion by Neolithic people into the region. This demic view persists to some extent, although more recent models have emphasised that this probably only holds true for a first wave of rapid leapfrog colonisation, with slower subsequent infilling of the karstic hinterland likely involving elements of indigenous acculturation (Stašo Forenbaher and Miracle 2006). The site of Vela Spila (Korčula, Croatia) provides archaeological remains dating to either side of this transition, as well as some deposits considered transitional between the two. This material includes a large assemblage of marine and terrestrial molluscs (alongside other faunal remains) which represent a good opportunity for the use of oxygen isotope analysis to reconstruct gathering season over the Neolithic transition in the East Adriatic.

Such research aids understanding of changing human diet between the Mesolithic and Neolithic by identifying changes in subsistence activities beyond species selection. This is a particularly useful perspective on the Neolithic transition. The

definition and identification of this process have relied heavily on the introduction of agricultural diet, with the majority of research focusing on plant and animal domesticates (e.g. Larson et al. 2007; Scheu et al. 2012; Tresset 2003; Zeder 2008). Evidence of non-agricultural fauna/flora in the Neolithic is generally viewed as evidence of Mesolithic continuity (e.g. Bishop 2013; N. J. Milner and Craig 2009; Stiner et al. 2003). However, there is no singular way to hunt or gather food, so continued gathering of wild resourced in the Neolithic can also represent a further locus for behavioural change and development.

Case Study: Vela Spila, Korčula

Vela Spila is a cave site on the Dalmatian island of Korčula, in the East Adriatic region. It is a large, well-stratified site which provides archaeological material documenting a long history of human use between at least the Upper Palaeolithic to Bronze Age (~17000 BC to ~2000 BC). The cave is situated above the modern town of Vela Luka (see Figure 1). The cave is cretaceous limestone, and consists of one large chamber measuring 50 m long, 30 m wide and 17 m high. It is close to the coast (c. 400m in a straight line), and is located on a hillside 120 m above modern sea level. While regional modelling shows rising sea level over the period in question (Surić et al. 2005), the bathymetry of the local coastline suggests that the Vela Luka bay has remained largely unchanged since the beginning of Mesolithic occupation (S. Forenbaher 2002; Rainsford, O'Connor, and Miracle 2014).

The site has been known archaeologically since the 19th century, but has only been systematically excavated since the mid-20th century. Recent excavations were directed by Čečuk (1974–1995), Radić (1996–2006), and Radić, Miracle and Forenbaher (2010–12, 2015–18). Figure 2 shows a site plan of the cave, as well as the

105 locations of excavated trenches. The material chosen for isotopic analysis came from
106 some of the recent field seasons in 2010 and 2011, which was excavated using modern
107 techniques (including wet sieving), is well-preserved and shows good stratigraphic
108 provenience.

109 Vela Spila has contributed much of the dating and material culture evidence for
110 the broader East Adriatic region (e.g Lightfoot et al., 2011; Forenbaher et al., 2013;
111 Rainsford et al., 2014). As such, the picture from Vela Spila during the Mesolithic-
112 Neolithic transition is not far removed from that already outlined. Within Forenbaher
113 and Miracle's (2006) two-stage model, the Mesolithic-Neolithic transition of Vela Spila
114 fits well into the first stage as a coastal site which saw rapid demographic expansion by
115 incoming farmers, leading to major shifts in site use and subsistence strategy.

116 The possibility of changing site use is discussed by Rainsford et al. (2014), who
117 suggests a move from occupation and food processing in the Mesolithic, to livestock
118 penning in the Neolithic. Nevertheless, the Mesolithic and Neolithic and transitional
119 deposits from the site all contain material considered subsistence-related, and
120 comparison between them allows for chronological examination of palaeodiet.

121 The mollusc assemblage from Vela Spila is the focus for isotopic analysis, in
122 particular the species *Phorcus turbinatus*. This is one of 4 main mollusc genera
123 identified from the site, the others being the marine gastropods *Patella caerulea, Patella*
124 *ulyssiponensis* and *Cerithium vulgatum*, and the terrestrial gastropod *Helix sp*. Of the
125 marine genera, most are present within the rocky intertidal zone which is thought to be
126 the primary foraging locale targeted for prehistoric mollusc collection in this area
127 (Branscombe 2017). Chronological study of the assemblage size and composition
128 showed that overall abundance of mollusc species decreased significantly in the
129 Neolithic compared to the Mesolithic (Branscombe 2017). It is hoped that isotopic study

of this material may shed further light on how gathering practices may have changed alongside gathering intensity.

Methods & Materials

Scientific Background

Oxygen isotope analysis as a method for reconstructing past sea surface temperature (SST) was introduced by Emiliani et al. (1964). Shortly afterwards, Shackleton (1973) pioneered the use of the same technique to determine season of collection using archaeological limpets (*Patella tabularis*). Since then, similar techniques have been used successfully, and on a wide variety of different species including marine bivalves and gastropods (e.g. Colonese et al. 2012; Deith 1983; Fenger et al. 2007; Gutiérrez-Zugasti et al. 2016; Mannino et al. 2007; Prendergast et al. 2013; Surge et al. 2013).

The process of $\delta^{18}O$ incorporation occurs in marine molluscs as animals use carbon, oxygen and calcium from the surrounding water to precipitate their calcareous shell (Epstein et al. 1951, 1953). This precipitation is usually regular, producing incremental shell growth, and occurs in equilibrium with the $\delta^{18}O$ of the surrounding. In turn, $\delta^{18}O$ of the water correlates negatively to its ambient temperature. Therefore, in a perfectly preserved (non diagenetically-altered) marine mollusc, the $\delta^{18}O$ of its shell carbonate should be predominantly a function of the surrounding water's $\delta^{18}O$, and the sea surface temperature (SST) (Leng and Lewis, 2014). Unless there are also seasonal changes in $\delta^{18}O_{seawater}$, this results in seasonally resolved sinusoidal $\delta^{18}O$ curves. Accordingly, analysis of shell aragonite using mass spectrometry provides a proxy for SST across the individual shell's lifespan. The remaining small variation in $\delta^{18}O$ incorporation relates to foraging by the shellfish, trace amounts from their substrate and

a variety of possible kinetic effects (Fenger et al., 2007; Schöne et al., 2007; Schöne, 2008).

Changes in shell growth due to suboptimal environmental conditions and growth stoppages can affect the consistency of growth record available from marine shell (Prendergast 2013; Schöne 2008). Cessations of growth render palaeoenvironmental reconstructions incomplete. The species used here (*Phorcus turbinatus*) can show such stoppages, but this problem can be circumvented by careful sample selection. Furthermore, this species tends to avoid higher intertidal rockpools and sites with freshwater input, which may otherwise affect $\delta^{18}O$/ $\delta^{13}C$ values (Menzies et al. 1992).

Modern and archaeological test cases using this species in Italy, Malta and Libya have shown that *P. turbinatus* is a good candidate for isotopic investigation (Colonese et al. 2009; Mannino et al. 2008; Prendergast 2013; Prendergast et al. 2013). While the intertidal conditions (including salinity and temperature ranges) present in Korčula may vary from these test cases, it was not possible to undertake modern reference samples as part of this study. Without local references, we are relying on the SST- $\delta^{18}O$ relationship outlined for this species elsewhere in the Mediterranean, which is a potential shortcoming that will be further discussed later in this paper.

Sample Selection

The species *P. turbinatus* was identified in the 2010–12 Vela Spila assemblage using Boulajfene and Tlig-zouari (2016). *P. turbinatus* is abundant within the assemblage, providing a large dataset from which to select suitable individuals.

Several criteria were used to select sampled individuals. Firstly, medium-sized shells (relative to the rest of the assemblage) were preferred. Smaller shells are harder to sample and may not preserve a full seasonal sequence, while larger shells are more

liable to growth cessations (Colonese et al. 2009; Mannino et al. 2007; Mannino, Spiro, and Thomas 2003). Shells were also checked to show no edge damage, as the full preservation of edge aragonite is essential for accurately estimating seasonality, with the edge sample representing the final pre-collection growth. Similarly, all selections showed a translucent and nacreous (not too dull or white) aragonite layer, indicating that no significant diagenesis had occurred. Finally, irrespective of shell size, the body whorl was checked to ensure that no major cessations of growth were visible. These are generally easy to recognise as slightly indented bands running perpendicular to the whorl.

Three chronological periods were chosen during sampling; the Mesolithic (~7500 BC), Mesolithic-Neolithic transition (~6000 BC) and the early Neolithic (~5900 BC). Within each period, shells were chosen from a single stratigraphic layer to make sure each set was as closely chronologically constrained as possible. The Mesolithic sample comes from trench 2 layer 51 (one of the two earliest Mesolithic layers) the transitional sample comes from trench 2 layer 39 (the layer with the most evidence for mixed foraging and farming economy) and the Early Neolithic sample comes from trench 1 layer 49 (the sole Early Neolithic layer from this trench with diagnostic pottery). Five radiocarbon dates from the transitional layers of the site place it between 6190–5660 cal. BC (Miracle et al. In Press). Based on material from comparable sites nearby, it's estimated that the transition occurred closer to 6000 cal. BC. Of all of the *P. turbinatus* identified in these layers, a subsample of 9 Neolithic shells, 9 transitional and 10 Mesolithic shells were selected. This brought the total sample size to 28 archaeological shells.

Drilling

Sampling methodology for drilling was adapted from Mannino et al. (2007,

2008), and unlike the technique of Prendergast et al. (2016) does not use sectioning or require the samples to be embedded in resin. A Kemet base unit and Argofile hand piece were used, with 3 mm-shank drill bits. A groove was drilled around the body whorl to expose the aragonite in the direction of growth. This was done on the periphery of the whorl, where growth increments are largest. Samples were then drilled sequentially from the growth edge, at approximately 1 mm intervals (Figure 3). Powdered samples weighed 0.25–0.5 mg. The outer edge of the shell, the sampling holes and drilling equipment were all cleaned with acetone between each sample to remove loose powder.

The best-preserved shell from each layer was chosen to represent the full annual cycle of isotopic values. These provide the full seasonal signal required for period-specific seasonal estimates using edge samples. For each full sequence shell, 30 samples were initially drilled from the whorl. This number was chosen by reference to the literature on *P. turbinatus* sampling, where continuous sampling of 24–29 samples appears to show a full annual growth cycle (Bosch et al. 2018; Colonese et al. 2009; Mannino et al. 2008; Prendergast et al. 2013). However for the Mesolithic and Neolithic shells used here, 30 samples was insufficient to show the full annual range. These long sequences were therefore extended (to 41 and 42 samples, respectively). Figure 3 shows an example of long sequence sampling.

For the remaining 25 shells, short sequences of three samples were taken from the shell edge. These could be compared to the long sequences to identify season of collection. The range ($\delta^{18}O_{max}$ - $\delta^{18}O_{min}$) from the long sequences was divided by 4, with the highest quarter of values representing winter, the lowest summer and the two middle quarters spring/autumn. These quarters will be referred to as ‘quartiles’,

although it should be noted that they are not true statistical quartiles as they are based on the overall amplitude rather than the distribution of samples within that range (which is more easily biased by seasonally-focused collection and sampling strategy). The edge sample from each shell was matched to the appropriate seasonal quartile. If it fell into spring/autumn then the upwards or downwards trend would determine whether the climate was cooling or warming to distinguish between the seasons. If these short sequences did not provide conclusive results up to 3 further samples were analysed per shell (Figure 3).

Diagenetic testing

As per Loftus et al. (2015), FTIR-ATR was used to test for diagenetic alteration of the shell aragonite. This was done using a Thermo Nicolet iS5 spectrometer and an iD7 ATR accessory in the Charles McBurney laboratory for Geoarchaeology, University of Cambridge. All specimens (n= 28) were tested at $4cm^{-1}$ resolution. These were run sequentially, taking a background reading every 2 hours. Equipment was cleaned with hydrochloric acid and water between each sample to prevent cross-contamination.

Loftus et al. (2015) suggest that an advantage of FTIR-ATR analysis is that it can be undertaken on the same powdered sample as mass spectrometry. During this project however, the powdered samples taken for isotopic analysis were too small to use in the FTIR-ATR analysis, given the potential loss of sample powder during transfer to and from the instrument. Therefore, a separate FTIR-ATR sample was drilled from each shell after the mass spectroscopy samples. In the short sequence shells, these were taken from the area between the 2nd and 3rd samples. In the long sequence shells, these were taken from the middle of the long sequence.

FTIR-ATR spectra indicate that the shells are not diagenetically altered. As can be seen in Figure 4, absorbance peaks at 1443 cm^{-1}, 1083 cm^{-1}, 855 cm^{-1}, 712 cm^{-1} and 700 cm^{-1} are clearly distinguishable. These are very similar to the aragonite peaks described by Loftus et al. (2015), which occur at 1454 cm^{-1}, 1082 cm^{-1}, 856 cm^{-1}, 711 cm^{-1} and 700 cm^{-1}. The slight inconsistences with the 1454 cm^{-1} peak (an 11 cm^{-1} difference and slight shoulder to left of the peak) still fit within expected variance for shell carbonate, and the shoulder visible sits in the wrong direction to indicate a mixed aragonite-calcite sample (Andersen et al. 1991). Furthermore, the double peak at 700/711 cm^{-1} is a defining trait of aragonite compared to calcite (which has only a single peak at 711 cm^{-1}) (Loftus et al., 2015).

Mass spectrometry

Mass spectrometry was undertaken in the Godwin Laboratory, University of Cambridge, using a Gasbench device attached to a Thermo DELTA V ADV isotopic ratio mass spectrometer. Powdered samples were flushed with CP grade helium and acidified with 104% orthophosphoric acid, left to react for 1 hour at 70 degrees Celsius and then analysed using the mass spectrometer in continuous flow mode. Each run of samples also included 12 reference carbonated (Carrara Z) and 2 control samples (Fletton Clay). The degree of precision is ±0.06‰ for $^{13}C/^{12}C$, and ±0.08‰ for $^{18}O/^{16}O$. Results are reported by reference to the international Vienna Pee Dee Belemnite standard.

To minimise expense, only every other sample in each long sequence (after the three edge samples) was sent for analysis. This approach provided a general picture of annual $\delta^{18}O$/temperature range, with the option of additional analysis.

Results

Full sequence samples

Results for the full sequences from each period are charted in Figure 5, showing the $\delta^{18}O$ and $\delta^{13}C$ for each sampled shell. In each shell, all samples returned usable results. Descriptive statistics are compiled in Table 1.

Both the Mesolithic and transitional shells show an annual cycle of $\delta^{18}O$, with distinct peaks and troughs showing winter and summer values (respectively). The Neolithic sample does show a summer trough at sample 35, but even after extending the sequence as far as possible around the shell whorl (to 42 samples), the winter peak cannot be definitively identified. Since the highest $\delta^{18}O$ value (sample 1) falls at the edge of the sequence, it may not capture the true maximum annual $\delta^{18}O$.

To try and combat this issue, a long sequence was also sampled from a second Neolithic shell (VSNEO3). Unfortunately the same issue was encountered in this shell, with the maximum $\delta^{18}O$ values falling at the limits of sampling. Moreover, the range in this shell (2.26) was less than the original full sequence (3.41), indicating either that less of the annual cycle is visible, or this shell grew in a year of restricted seasonality. As such, when interpretation was made from full sequences only VSNEO3 was excluded in favour of VSNEO1.

Comparison with the more-complete transitional sequence shows that the $\delta^{18}O$ range is similar in all three (Table 1) and is actually smallest in the transitional sequence. This is a good indicator that the Neolithic sequence can be interpreted as at least a near-full annual range, further supported by the fact that none of the short sequence results fall out of the full sequence range (Figure 6). Nevertheless, the winter values for the Neolithic period should be considered with some uncertainty, as indicated

by the open ended maximum range in Figure 5. There are short sequence outliers in the Mesolithic and transitional sequences, but these all fall below clear $\delta^{18}O$ minima in the long sequences. This means that they precipitated their shells in warmer conditions than the long sequence specimens. This could be caused by measurement error (unlikely, as most outliers are more than 0.08 beyond the full sequence), cooler-than-average recorder summers, or the presence of shells which lived in different environmental conditions, for example due to time averaging within the stratigraphic unit.

To gauge the effect of outliers in the Mesolithic and transitional samples, seasonal quartiles were calculated first using only the long sequence values[1], and then again including the short sequence values. Seasonal attributions made using both sets of quartiles were then compared (Table 2).

For the Mesolithic, calculation of the quartiles including short sequence outliers resulted in a change of seasonal attribution for two shells: two (VSMESO2, VSMESO4) went from summer to autumn. For the transitional period, two (VSTRANS6, VSTRANS8) went from summer to autumn and one (VSTRANS7) from autumn to winter. Given these shifts, results are displayed using histograms (Figure 6) which show seasonal clustering according to temperature, as well as rose diagrams (Figure 7) where shells that shift are labelled as late spring/early summer, late summer/autumn etc..

Short Sequence Samples

Edge sample $\delta^{18}O$ values were compared to the relevant seasonal ranges. If the edge sample fell within the summer or winter quartiles, the shell was assigned to that season.

[1] When using quartiles based on the long sequences alone, outliers were assigned seasons dependant on whether they were high (winter) or low (summer).

In order to be allocated a particular season, the edge $\delta^{18}O$ value had to be greater than 0.16‰ (double the measurement error) away from the quartiles boundary. For sequences whose edge samples fell into the middle spring/autumn quartiles, short sequences were charted to determine the trend in values.

From these charts, the trend was judged to be rising (autumn collection), falling (spring collection) or inconclusive (no clear trend). The full $\delta^{18}O$ results for these short sequences samples can be seen in Table 3. In some cases a rising/falling trend was consistent across all three samples. In others the trend was estimated by comparing the 1st (edge) and 3rd samples. In these cases, differences between values were only considered large enough to warrant a trend if they were greater than 0.16‰ (double the measurement error), as per Mannino et al. (2007).

From the total of 28 shells analysed, 27 produced gathering season estimates. The remaining shell produced an edge sample that fell into the middle spring/autumn quartiles, and a sequence that showed no clear trend which could not be explained by measurement error. The results of seasonal attribution are displayed in Table 2 and Figures 6 and 7.

Discussion

The results presented here show a clear chronological trend in *Phorcus* exploitation. Although seasonality work on other species would be required to confirm this, it is a reasonable assumption that the signal from *Phorcus* can be extrapolated to wider marine mollusc exploitation at Vela Spila. This is especially likely given that the most abundant species share similar year-round habitats, and so were probably collected during the same foraging trips.

During the Mesolithic, gathering appears focused in the summer and autumn, while in the Neolithic this shifts to autumn and winter collection. The transitional period is more difficult to interpret, as seasonal attributions vary more depending on the inclusion/exclusion of outliers in quartile calculations (Table 2). In Figure 6, we can see that gathering is still predominantly focused on the warmer half of the year during the transitional period, which suggests more Mesolithic-style gathering practices.

Gathering in both the Mesolithic and Neolithic was seasonally-focused rather than year-round, with the most significant difference being decreasing summer exploitation over time. As outlined by Waselkov (1987) the year-round availability of shellfish indicates that such changes in scheduling are more likely explained by human factors or mobility, preference and/or ease of gathering.

Seasonality evidence is often discussed as a method for assessing occupation season in archaeological contexts (e.g. N. Milner 2005; Shackleton 1973), so it is worth considering whether gathering patterns seen at Vela Spila may reflect changing seasons of occupation. Zooarchaeological analysis of the assemblage shows year-round occupation throughout this period (Miracle et al. in press), with spring/summer use of small game, spring to autumn use of roe deer and winter/autumn use of red deer. In the Neolithic the cave was likely used across all seasons to retain proximity to crops and livestock (Forenbaher et al. in press). In other words, although people were present at the site throughout the year shellfish were only consumed in the colder half of the year during the Neolithic. This suggests a restricted gathering strategy rather than on opportunistic one.

Seasonal variations in nutrient content and taste may also be important, but are at present under-researched fields. Erlandson (1988) discusses this possibility, suggesting that for certain (unspecified) shellfish, carbohydrate and protein content may

peak in the spring, prior to their reproductive season. Claassen (1986) also touches upon the potential significance of seasonal nutrition to archaeological gathering, but consensus on this topic has not yet been reached. It is likely that there is large inter- and intra-species variation for different nutrients (Claassen, 1986). The majority of research undertaken on this matter refers to marine bivalves – likely due to their more significant role in modern cuisine – with little mention of the gastropods found commonly at prehistoric sites such as Vela Spila. This matter certainly warrants further consideration. but currently little information is available to determine whether changing foraging habits relate to shellfish nutrition or taste.

Instead, we can consider the seasonality of shellfish exploitation as an indication of wider resource abundance. A shift in mollusc gathering season could indicate changes in the availability of higher ranked resources (e.g. Clark and Kandel 2013; Langejans et al. 2012). For example, in this case the reduction in summer gathering over time could indicate the availability of other foods in that season which were preferred over shellfish. In this scenario, it is assumed that molluscs are a similarly low-ranked seasonal supplement in both the Mesolithic and Neolithic (albeit required during different seasons). However, further work at Vela Spila (Branscombe 2017) showed that this shift in exploitation coincides with significant/substantial decreases in overall mollusc abundance from the early Neolithic.

This shift in both the timing *and* intensity of exploitation suggests that changes in shellfish use not only reflect the availability of other resources, but also the relative importance of shellfish as a resource. More intense seasonal utilisation during the Mesolithic, as well as its use during times of relative nutritional abundance (summer) indicates that molluscs were not a foodstuff reserved for times of scarcity. By contrast, the Neolithic signal for winter/autumn collection suggests shellfish may have been used

392 to supplement an otherwise scant winter resource base, for example as suggested by
393 Prendergast et al. (2016) at Haua Fteah, Libya. Therefore, the seasonality results can be
394 interpreted to show shellfish as a summer-autumn staple in the Mesolithic, a year-round
395 supplement in the transitional period, and an autumn-winter supplement during the
396 Neolithic.
397 This fits well with an optimal-foraging view, in which Neolithic domesticates
398 become a higher-ranked resources and are prioritised over molluscs where available.
399 Furthermore, increased focus on the maintenance of terrestrial domesticates may have
400 reduced human interaction with the littoral environment, resulting in decreased
401 opportunistic mollusc gathering and the drop in mollusc remains visible at Vela Spila.
402 In order to explore coastal habitat exploitation as a whole it would be interesting to
403 draw comparisons with the ornamental species (*Columbella* sp.) here, but the small
404 number found during this period from the site (n=31) shows no coherent trend.
405 The topic of increasingly terrestrially-focused economy was also discussed by
406 Rainsford (2014), showing that exploitation intensity of fish also decreased in the
407 Neolithic at Vela Spila. As with shellfish collecting, it is likely that this subsistence
408 resource was largely replaced by agriculture. It is possible that shellfish gathering
409 occurred opportunistically alongside fishing, and so the reduction in fishing may be an
410 important related factor in decreasing mollusc exploitation.
411 The shellfish exploitation results may also provide insights into the effects of
412 this narrower Neolithic subsistence strategy, which largely abandoned broad spectrum
413 shellfishing, fishing and hunting diet (Rainsford, O'Connor, and Miracle 2014;
414 Forenbaher et al. in press). The presence of shellfish as a winter-collected resource
415 suggests that there may have been a seasonal dietary shortfall in the Neolithic. This idea
416 reflects the work of other authors investigating the effect of Neolithic lifeways on health

and diet, which argues that homogenised diets, sedentism and high population density resulted in poor health and osteologically visible stress (e.g. Jovanović 2017; Krenz-niedbała 2014). In the case of Vela Spila, shellfish evidence can be interpreted to show seasonal shortages in agricultural production, resulting in reversion to low-ranked but reliable resources.

Even so, given the current data it would be extreme to deem molluscs a true 'famine food' at Neolithic Vela Spila. This would imply hardship not necessarily evidenced by these results. It is of course possible that cold-season food shortages, combined with the vulnerability of an agriculturally-reliant resource base, may have occasionally resulted in famine. However, the picture visible through the seasonality results presented here is more likely one of regular and predictable shortfalls, which had similarly predictable end-points. In this case, a more suitable phrase to describe the Neolithic use of shellfish might be as a 'stopover' or 'stopgap' resource.

Finally, these results also provide a new line of evidence for understanding the nature of the Mesolithic-Neolithic transition in Croatia. The prevailing view of Neolithic expansion in this region involves rapid demographic advance along the Dalmatian coast, followed by slower inland acculturation (Stašo Forenbaher and Miracle 2006). At the coastal site of Vela Spila, we would expect a relatively sharp shift in subsistence strategy occurring over this transition as a result of Mesolithic population replacement. According to the gathering season estimates present here, a relatively sharp change in gathering behaviour can indeed be supported, with distinctly Neolithicised practices seen in the early Neolithic. The signal from the transitional period further suggests that this change in behaviour primarily happened towards the end of the transition, and had not substantially taken place at the time of this layer's

deposition. More detailed dating of the sampled transitional and early Neolithic layers would be useful to constrict the absolute date for this behavioural change.

It would be remiss to finish this discussion without highlighting shortcomings of this pilot study, and directions for future work on this topic. Firstly, it would be of great benefit to analyse modern reference shells from the local area. As previously mentioned, we rely here on the relationship between SST and $\delta^{18}O$ as published for other regions of the Mediterranean, but there may be local variability in SST, $\delta^{18}O_{sewater}$ and salinity which can only be understood through comparison to modern known-age shells. In particular, this may help elucidate the relationship between $\delta^{18}O$ and $\delta^{13}C$, as Figure 5 shows that there was inconsistency between these measures in our results. Furthermore, the samples size used in this study were small which can lead to issues in interpreting behavioural and climatic trends (Hausmann and Meredith-Williams 2017; Thomas 2015; West, Burchell, and Andrus 2018). In order to validate and increase the statistical significance of the results from this pilot study, further work is required to extend the sample size.

Conclusion

The results presented here show the utility of seasonality estimates in the East Adriatic archaeological record. Shellfish gathering was identified predominantly during summer and autumn in the Mesolithic and transitional periods, and autumn and winter in the Neolithic. The seasonal focus for mollusc gathering shifted towards cooler seasons in the Neolithic, and quantification evidence shows a significant concurrent reduction in exploitation intensity. These results suggest marine molluscs were more of a summer dietary staple in the Mesolithic, versus a winter supplement in the Neolithic.

This shift in gathering practices likely relates to incoming terrestrial agricultural

practices, which became dominant over broad-spectrum Mesolithic diet and decreased opportunity for interaction with marine resources. As has been inferred from ceramic and faunal evidence (Stašo Forenbaher et al. in press; Stašo Forenbaher and Miracle 2006), these results support a two-wave process of Neolithisation in the East Adriatic by indicating a relatively rapid and distinct change in gathering practices on the Dalmatian coast.

The changes in Mollusc exploitation seen over the Neolithic transition of Vela Spila illustrate the pitfalls in viewing mollusc exploitation as merely residual Mesolithic continuity. While it is true that shellfishing decreased after the Mesolithic in this region, it did not only persist in the Neolithic, but was itself a locus for Neolithisation. Therefore, by investigating the changing nature of shellfishing, we can gain more nuanced insights into subsistence and human-environment interactions across the transition. Similar work on other perceived 'Mesolithic continuities', e.g. terrestrial hunting practices and plant use, may also prove fruitful in distinguishing between true Mesolithic versus 'Neolithicised' behaviours.

Acknowledgements

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members of the Godwin Laboratory (Department of Earth Sciences, University of Cambridge).

Disclosure Statement

No potential conflict of interest is reported by the authors.

References

Andersen, F. A., Brečević, L., Beuter, G., Dell'Amico, D. B., Calderazzo, F., Bjerrum, N. J., and Underhill, A. E. 1991. "Infrared Spectra of Amorphous and Crystalline Calcium Carbonate." Acta Chemica Scandinavica 45: 1018–1024.

Bailey, G. N. 1978. "Shell Middens as Indicators of Postglacial Economies: A Territorial Perspective." In The Early Postglacial Settlement of Northern Europe: An Ecological Perspective, ed. Paul Mellars. Pittsburgh: University of Pittsburgh Press.

Bosch, Marjolein D., Mannino, Marcello A., Prendergast, Amy L., Wesselingh, Frank P., and O'Connell, Tamsin C. 2018. "Year-Round Shellfish Exploitation in the Levant and Implications for Upper Palaeolithic Hunter-Gatherer Subsistence." Journal of Archaeological Science: Reports 21(October): 1198–1214.

Boulajfene, Wafa, and Sabiha Tlig-zouari. 2016. "Shell Morphological Comparison of Two Species of *Phorcus* Genus (Risso , 1826) along the Rocky Coasts of Tunisia." : 261–70.

Branscombe, T. L. 2017. "Mollusc Diet and the Mesolithic to Neolithic Transition: A Case Study from Vela Spila, Korcula (Croatia)." Unpublished MPhil thesis, University of Cambridge.

Claassen, Cheryl. 1998. Shells. Cambridge University Press.

Clark, Jamie L., and Andrew W. Kandel. 2013. "The Evolutionary Implications of Variation in Human Hunting Strategies and Diet Breadth during the Middle Stone Age of Southern Africa." Current Anthropology 54(S8): S269–87.

Colonese, André Carlo et al. 2009. "Mesolithic Shellfish Exploitation in SW Italy: Seasonal Evidence from the Oxygen Isotopic Composition of *Osilinus Turbinatus* Shells." Journal of Archaeological Science 36(9): 1935–44.

Colonese, A. C., Verdún-Castelló, E., Álvarez, M., Briz i Godino, I., Zurro, D., and Salvatelli, L. 2012. “Oxygen Isotopic Composition of Limpet Shells from the Beagle Channel: Implications for Seasonal Studies in Shell Middens of Tierra Del Fuego.” Journal of Archaeological Science 39(6): 1738–48.

Cunnane, Stephen C., and Michael A. Crawford. 2014. “Energetic and Nutritional Constraints on Infant Brain Development: Implications for Brain Expansion during Human Evolution.” Journal of Human Evolution 77: 88–98.

Deith, Margaret R. 1983. “Molluscan Calendars: The Use of Growth-Line Analysis to Establish Seasonality of Shellfish Collection at the Mesolithic Site of Morton, Fife.” Journal of Archaeological Science 10(5): 423–40.

Emiliani, C. et al. 1964. “Palaeotemperature Analysis of Marine Molluscs (Food Refuse) from the Site of Arene Candide Cave, Italy and the Haua Fteah Cave, Cyrenaica.” In Isotopic and Cosmic Chemistry, eds. H. Craig, S. Miller, and G Wasserburg. Amsterdam: North-Holland Publishing Company.

Epstein, Samuel, R Buchsbaum, H a Lowenstam, and H C Urey. 1953. “Revised Carbonate-Water Isotopic Temperature Scale.” Geological Society of America Bulletin.

Epstein, Samuel, Ralph Buchsbaum, Heinz Lowenstam, and Harold C. Urey. 1951. “Carbonate-Water Isotopic Temperature Scale.” Bulletin of the Geological Society of America.

Fenger, Tracy, Donna Surge, Bernd Schöne, and Nicky Milner. 2007. “Sclerochronology and Geochemical Variation in Limpet Shells (*Patella vulgata*): A New Archive to Reconstruct Coastal Sea Surface Temperature.” Geochemistry, Geophysics, Geosystems 8(7).

Forenbaher, S. 2002. “Prehistoric Populations of the Island of Hvar - An Overview of Archaeological Evidence.” Collegium antropologicum 26(1): 361–78.

Forenbaher, Stašo et al. in press. “The Adoption of Food Production, Trans-Adriatic Navigation, and Prehistoric Shepherds and Farmers 6,000-2,000 BC.” In Hunters and Herders in Southern Dalmatia: The Palaeolithic, Mesolithic, and Neolithic of Vela Spila (Korcula, Croatia), eds. Preston T. Miracle and Dinko Radić. Oxford: Archaeopress.

Forenbaher, Stašo, Timothy Kaiser, and Preston T Miracle. 2013. “Dating the East Adriatic Neolithic.” European Journal of Archaeology 16(April): 589–609.

553 Forenbaher, Stašo, and Preston T Miracle. 2006. “The Spread of Farming in the Eastern
554 Adriatic.” Documenta Praehistorica 33(May 2004): 89–100.
555 Gutiérrez-Zugasti, Igor, David Cuenca-Solana, André Carlo Colonese, and Javier
556 Fernández-López de Pablo. 2016. “Time for the Tide. New Perspectives on
557 Hunter-Fisher-Gatherer Exploitation of Intertidal Resources in Atlantic Europe
558 and Mediterranean Regions.” Quaternary International 407: 2–5.
559 Haws, Jonathan, and Bryan Hockett. 2004. “Theoretical Perspectives on the Dietary
560 Role of Small Animals in Human Evolution.” In Petits Animaux et Sociétés
561 Humaines: Du Complément Alimentaire Aux Ressources Utilitaires, Actes.
562 Actes Des XXIVe Rencontres Internationales d’archéologie et d’histoire
563 d’Antibes, 23-25 Octobre 2003 ., eds. Jean-Philip Brugal and Jean Desse.
564 Antibes: Éditions APDCA, 173–84.
565 Hockett, Bryan, and Jonathan Haws. 2003. “Nutritional Ecology and Diachronic Trends
566 in Paleolithic Diet and Health.” Evolutionary Anthropology 12(5): 211–16.
567 Jerardino, Antonieta. 2016. “On the Origins and Significance of Pleistocene Coastal
568 Resource Use in Southern Africa with Particular Reference to Shellfish
569 Gathering.” Journal of Anthropological Archaeology 41: 213–30.
570 Jovanović, Jelena D. 2017. “The Diet and Health Status of the Early Neolithic
571 Communities of the Central Balkans (6200-5200 Bc).” Univeristy of Belgrade.
572 Krenz-niedbała, Marta. 2014. “A Biocultural Perspective on the Transition to
573 Agriculture in Central Europe.” Anthropologie 2(2): 115–32.
574 Kyriacou, Katharine, John E. Parkington, Adrian D. Marais, and David R. Braun. 2014.
575 “Nutrition, Modernity and the Archaeological Record: Coastal Resources and
576 Nutrition among Middle Stone Age Hunter-Gatherers on the Western Cape
577 Coast of South Africa.” Journal of Human Evolution 77: 64–73.
578 Langejans, Geeske H.J., Karen L. van Niekerk, Gerrit L. Dusseldorp, and J. Francis
579 Thackeray. 2012. “Middle Stone Age Shellfish Exploitation: Potential
580 Indications for Mass Collecting and Resource Intensification at Blombos Cave
581 and Klasies River, South Africa.” Quaternary International 270: 80–94.
582 Lightfoot, E. et al. 2011. “Exploring the Mesolithic and Neolithic Transition in Croatia
583 through Isotopic Investigations.” Antiquity 85(327): 73–86.
584 Lindeberg, Staffan. 2009. “Modern Human Physiology with Respect to Evolutionary
585 Adaptations That Relate to Diet in the Past.” In The Evolution of Hominin
586 Diets: Integrating Approaches to the Study of Palaeolithic Subsistence, eds.

Jean-Jacques Hublin and Michael P Richards. Dordrecht: Springer Netherlands, 43–57.

Loftus, Emma, Keith Rogers, and Julia Lee-Thorp. 2015. “A Simple Method to Establish Calcite: Aragonite Ratios in Archaeological Mollusc Shells.” Journal of Quaternary Science 30(8): 731–35.

Mannino, Marcello A. et al. 2007. “Marine Resources in the Mesolithic and Neolithic at the Grotta Dell’Uzzo (Sicily): Evidence from Isotope Analyses of Marine Shells.” Archaeometry 49(1): 117–33.

Mannino, Marcello A., and Luca Sineo. 2012. “Le Sepolture Della Grotta d’Oriente (Favignana).” In Atti Della XLI Riunione Scientifica, Firenze: Istituo Italiano di Preistoria e Protostoria, 342–51.

Mannino, Marcello A., Baruch F. Spiro, and Kenneth D. Thomas. 2003. “Sampling Shells for Seasonality: Oxygen Isotope Analysis on Shell Carbonates of the Inter-Tidal Gastropod *Monodonta Lineata* (Da Costa) from Populations across Its Modern Range and from a Mesolithic Site in Southern Britain.” Journal of Archaeological Science 30(6): 667–79.

Mannino, Marcello A., Kenneth D. Thomas, Melanie J. Leng, and Hilary J. Sloane. 2008. “Shell Growth and Oxygen Isotopes in the Topshell *Osilinus Turbinatus*: Resolving Past Inshore Sea Surface Temperatures.” Geo-Marine Letters 28(5–6): 309–25.

Menzies, R., Cohen, Y., Lavie, B., and Nevo, E. 1992. “Niche adaptation in two marine gastropods, *monodonta turbiformis* and *m. Turbinata*.” Bolletino Di Zoologia 59(3): 297–302.

Milner, Nicky. 2005. “Seasonal Consumption Practices in the Mesolithic: Economic, Environmental, Social or Ritual?” In Mesolithic Studies at the Beginning of the 21st Century, eds. Nicky Milner and Peter C. Woodman. Oxbow Books, 56–68.

Miracle, Preston T. et al. in press. “Korčula – from Peninsula to Island: Fishers, Hunters, Trappers, and Gatherers 7,500–6,000 BC.” In Hunters and Herders in Southern Dalmatia: The Palaeolithic, Mesolithic, and Neolithic of Vela Spila (Korcula, Croatia), eds. Preston T. Miracle and Dinko Radić. Oxford: Archaeopress.

Nigst, Philip R. and Bosch, Marjolein D. 2019. R Script Rose Diagram Seasonality, version 1. doi:10.5281/zenodo.3246766

620 Parkington, John. 2010. “Coastal Diet, Encephalization, and Innovative Behaviors in the
621 Late Middle Stone Age of Southern Africa.” Human Brain Evolution: The
622 Influence of Freshwater and Marine Food Resources: 189–202.
623 Prendergast, Amy L. 2013. “Late Pleistocene to Holocene Human-Environment
624 Interaction in the Southeastern Mediterranean: Stable Isotope Analysis of
625 Mollusc Shells from Haua Fteah , Libya and Ksar Akil, Lebanon.” University of
626 Cambridge.

627 Prendergast, A. L., Azzopardi, M., O’Connell, T. C., Hunt, C., Barker, G., and Stevens,
628 R. E. 2013. “Oxygen isotopes from *Phorcus (Osilinus) turbinatus* shells as a
629 proxy for sea surface temperature in the central Mediterranean: A case study
630 from Malta.” Chemical Geology 345: 77–86.

631 Prendergast, A. L., Stevens, R. E., O’Connell, T. C., Fadlalak, A., Touati, M., Al-
632 Mzeine, A., Schöne, B. R., Hunt, C. O., and Barker, G. 2016. “Changing
633 Patterns of Eastern Mediterranean Shellfish Exploitation in the Late Glacial and
634 Early Holocene: Oxygen Isotope Evidence from Gastropods in Epipaleolithic to
635 Neolithic Human Occupation Layers at the Haua Fteah Cave, Libya.”
636 Quaternary International 407: 80–93.

637 Rainsford, Clare, Terry O’Connor, and Preston Miracle. 2014. “Fishing in the
638 Adriatic at the Mesolithic–Neolithic Transition: Evidence from Vela Spila,
639 Croatia.” Environmental Archaeology 19(3): 311–20.
640 Richards, M P, and Rick J. Schulting. 2006. “Touch Not the Fish: The Mesolithic-
641 Neolithic Change of Diet and Its Significance.” Antiquity 80(308): 444–58.
642 Schöne, Bernd R. 2008. “The Curse of Physiology - Challenges and Opportunities in
643 the Interpretation of Geochemical Data from Mollusk Shells.” Geo-Marine
644 Letters 28(5–6): 269–85.
645 Shackleton, N J. 1973. “Oxygen Isotope Analysis as a Means of Determining Season
646 of Occupation of Prehistoric Midden Sites.” Archaeometry 15(1): 133–41.
647 Surge, D., T. Wand, Gutierrez-Zugasti I., and P. H. Kelley. 2013. “Isotope
648 Sclerochronology and Season of Annual Growth Line Formation in Limpet
649 Shells (*Patella vulgata*) From Warm- and Cold-Temperate Zones in the
650 Eastern North Atlantic.” Palaios 28(6): 386–93.

Surić, Maša, Mladen Juračić, Nada Horvatinčić, and Ines Krajcar Bronić. 2005. “Late Pleistocene-Holocene Sea-Level Rise and the Pattern of Coastal Karst Inundation: Records from Submerged Speleothems along the Eastern Adriatic Coast (Croatia).” Marine Geology 214(1–3): 163–75.

Waselkov, Gregory A. 1987. “Shellfish Gathering and Shell Midden Archaeology.” Advances in Archaeological Method and Theory 10(1987): 93–210.

	Full Sequences					All Samples				
Shell ID	Min	Max	Range	Summer Quartile	Winter Quartile	Min	Max	Range	Summer Quartile	Winter Quartile
VSMESO2	-0.66	2.93	3.59	<0.24	>2.03	-1.06	2.93	3.98	<-0.06	>1.93
VSTRANS1	-0.64	2.28	2.92	<0.09	>1.54	-1.37	2.28	3.65	<0.45	>1.37
VSNEO1	-1.5	1.91	3.41	<-0.65	>1.06	-1.5	1.91	3.41	<-0.65	>1.06
VSNEO3	-0.92	1.34	2.26	<-0.36	>0.78	-1.5	1.91	3.41	<-0.65	>1.06

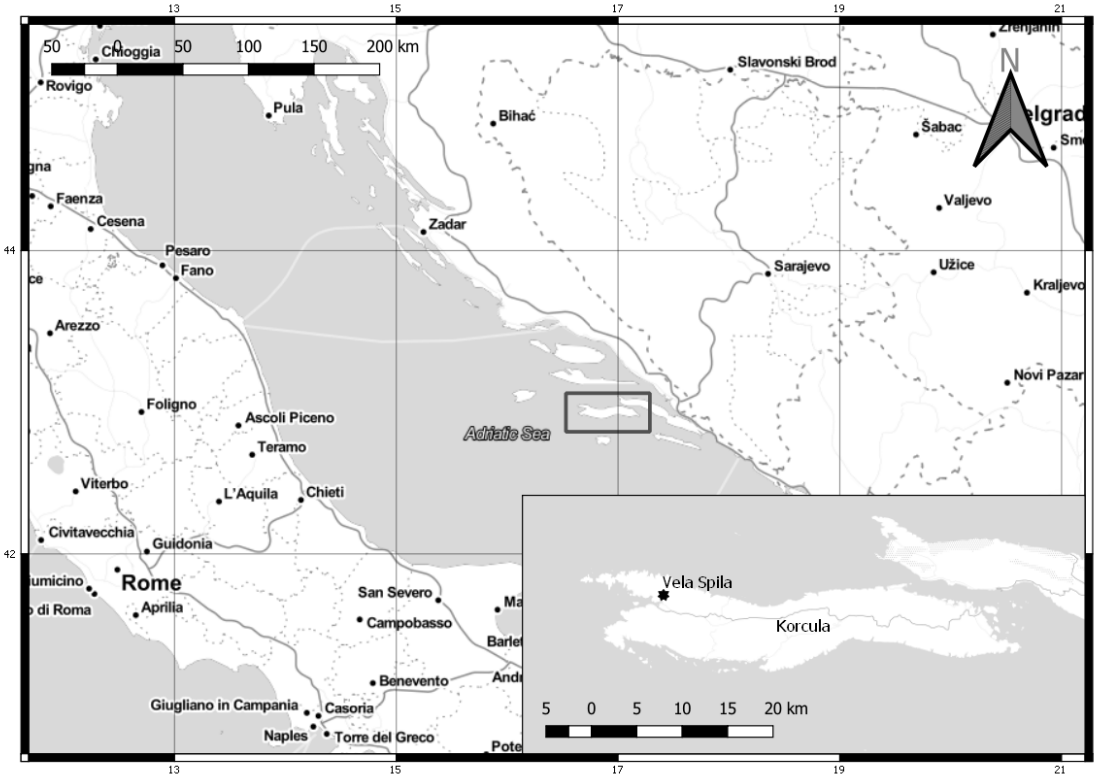
658 Table 1. Descriptive statistics for long $\delta^{18}O$ sequence values compared to combined
659 long and short sequences (all samples). Showing min, max, range and seasonal quartiles
660 for each long sequence shell.

Period	Shell ID	Type	Sample 6 $\delta^{18}O$	Sample 5 $\delta^{18}O$	Sample 4 $\delta^{18}O$	Sample 3 $\delta^{18}O$	Sample 2 $\delta^{18}O$	Edge $\delta^{18}O$	Trend	Season (full sequence)	Season (all samples)
Mesolithic	VSMESO2	Long	-	0.1	-	-0.14	-0.23	0.11	Rising	**Summer**	**Autumn**
	VSMESO3	Short	-	-	-	-0.40	-0.52	-1.06	Falling	Summer	Summer
	VSMESO4	Short	-	-	-	-0.53	-0.01	0.23	Rising	**Summer**	**Autumn**
	VSMESO5	Short	-0.87	-0.67	0.09	0.47	1.13	0.70	Rising	Autumn	Autumn
	VSMESO6	Short	-	-	--	-0.18	-0.30	-0.45	Falling	Summer	Summer
	VSMESO7	Short	-	-	-	-0.55	-1.05	-0.72	Rising	Summer	Summer
	VSMESO8	Short	-	-	-	0.11	-0.01	-0.56	Falling	Summer	Summer
	VSMESO11	Short	-	0.67	1.12	1.19	1.17	1.62	Rising	Autumn	Autumn
	VSMESO12	Short	-	1.51	1.35	1.14	0.65	0.28	Falling	Spring	Spring
	VSMESO13	Short	-	0.79	0.56	-0.04	-0.47	-0.64	Falling	Summer	Summer
Transitional	VSTRANS1	Long	-	-0.64	-	0.37	0.37	0.18	Rising*	Autumn	Autumn
	VSTRANS2	Short	1.74	2.04	0.60	0.19	-0.48	0.29	Falling	Spring	Spring
	VSTRANS3	Short	-	-	-	-0.01	0.37	0.20	Rising	Autumn	Autumn
	VSTRANS4	Short	-	-	-	-0.91	-0.83	-0.81	?	Summer	Summer
	VSTRANS5	Short	-	-	-	1.03	1.29	1.17	?	?	?
	VSTRANS6	Short	-	-	-	-0.89	-1.34	-0.19	Rising	**Summer**	**Autumn**
	VSTRANS7	Short	-	-	-	0.50	0.87	1.48	Rising	**Autumn**	**Winter**
	VSTRANS8	Short	-	0.01	-0.66	-1.37	-0.95	0.07	Rising	**Summer**	**Autumn**
	VSTRANS9	Short	-	1.35	-0.08	-0.45	0.11	0.36	Rising	Autumn	Autumn
Neolithic	VSNEO1	Long	-	1.28	-	1.58	1.82	1.91	Rising	Winter	Winter
	VSNEO2	Short	-	-	-	0.69	0.79	1.48	Rising	Winter	Winter
	VSNEO3	Long	0.30	-	0.94	1.27	0.64	1.25	?	Winter	Winter
	VSNEO4	Short	-	-	-	-0.52	0.47	0.85	Rising	Autumn	Autumn
	VSNEO6	Short	-	-	-	0.32	0.76	1.04	Rising	Autumn	Autumn
	VSNEO7	Short	-	-	-	-0.27	-0.17	0.10	Rising	Autumn	Autumn
	VSNEO8	Short	-	-	-	0.26	0.38	0.76	Rising	Autumn	Autumn
	VSNEO9	Short	-	-	-	1.27	1.68	1.51	Rising	Winter	Winter
	VSNEO11	Short	-	0.43	-0.03	-0.17	0.19	0.83	Rising	Autumn	Autumn

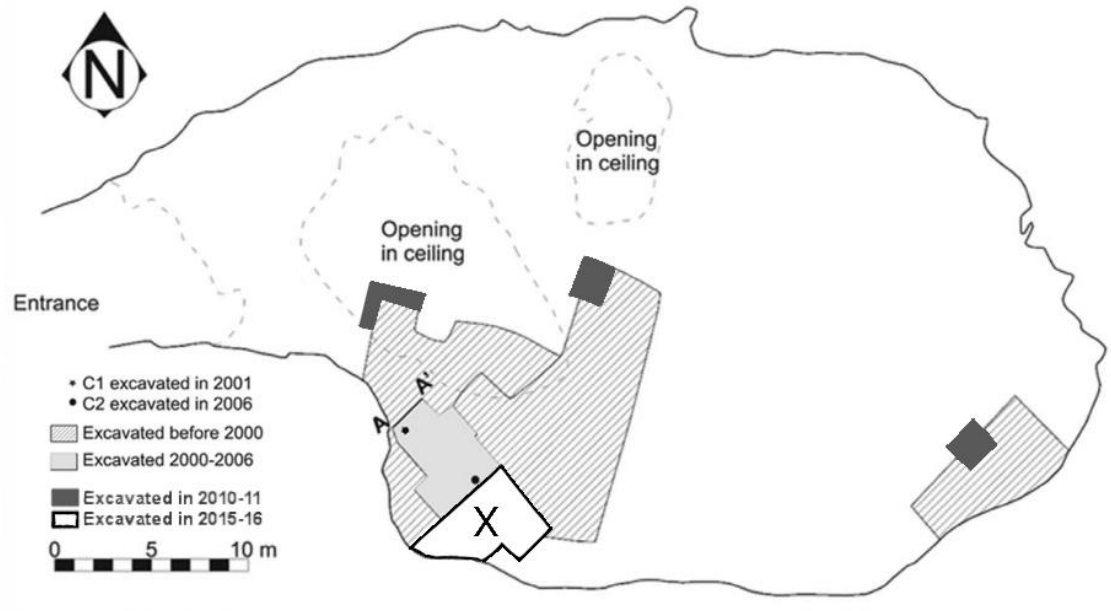
Table 2. Short sequence results (up to 6 samples) for each shell by period, showing $\delta^{18}O$ trend and seasonal collection estimate. Bold shows shells where seasonal attribution changed depending on the use of full sequences only or all samples to calculate quartiles. *Trend from first three samples appears to be falling, but shell places in autumn based on long sequence.

667 **Figure Captions**

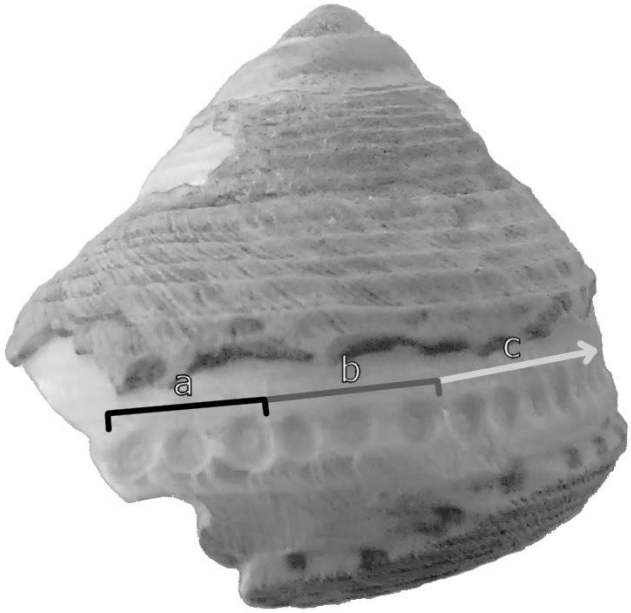
668 Figure 1. Map showing the location of Vela Spila within Korčula and the wider East
669 Adriatic. Map tiles by Stamen Design, under CC BY 3.0. Data by OpenStreetMap,
670 under ODbL.



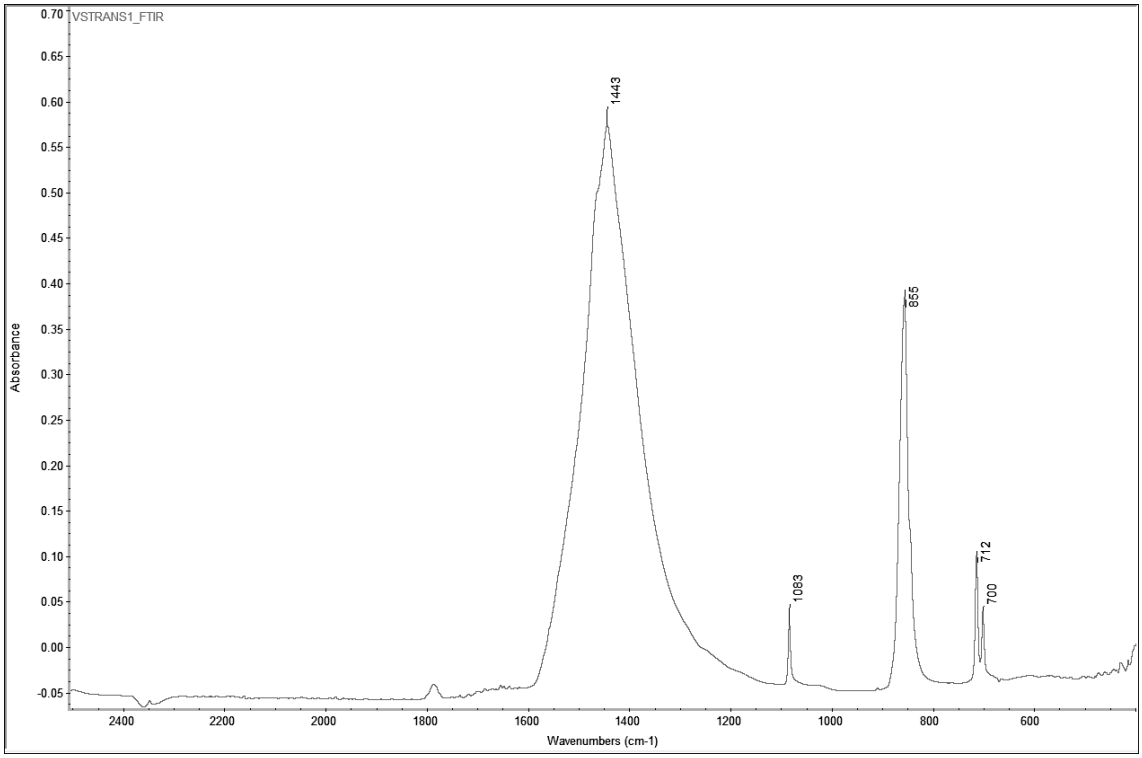
671 Figure 2. Vela Spila site plan showing location of excavated trenches. Image courtesy of
672 Dinko Radić, Vela Luka Cultural Centre.



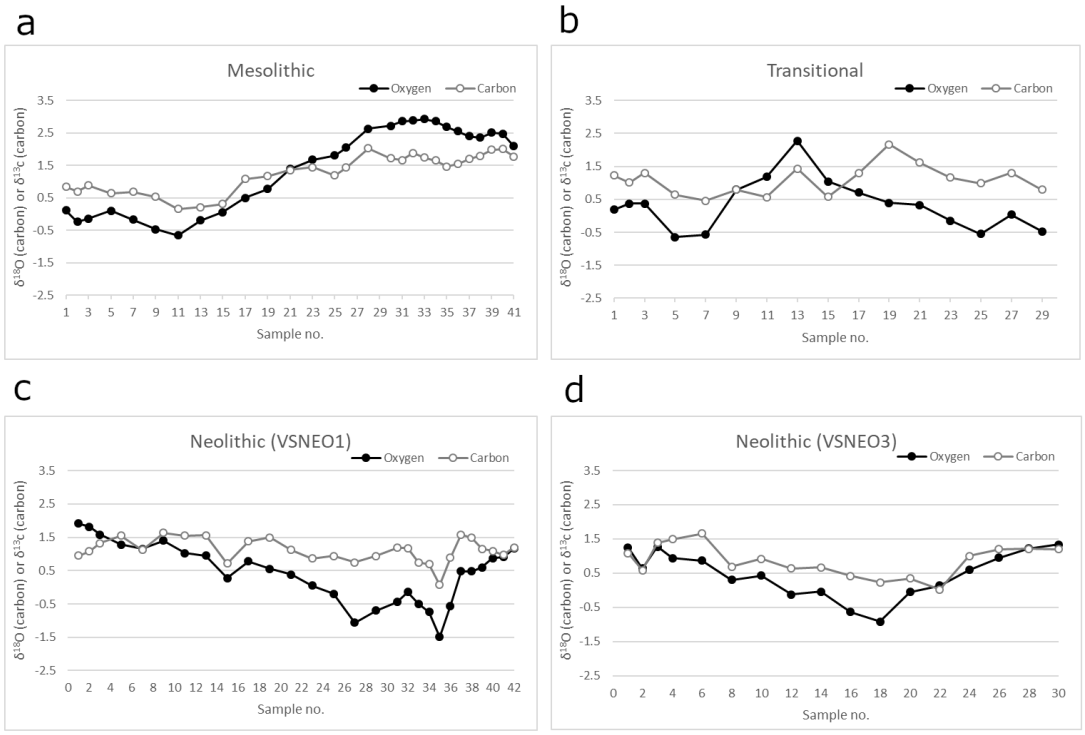
673 Figure 3. Example *P. turbinatus* (VSMESO2) after long sequence drilling. a = short
674 sequence, b = extended short sequence if three samples was inconclusive, c = long
675 sequence.



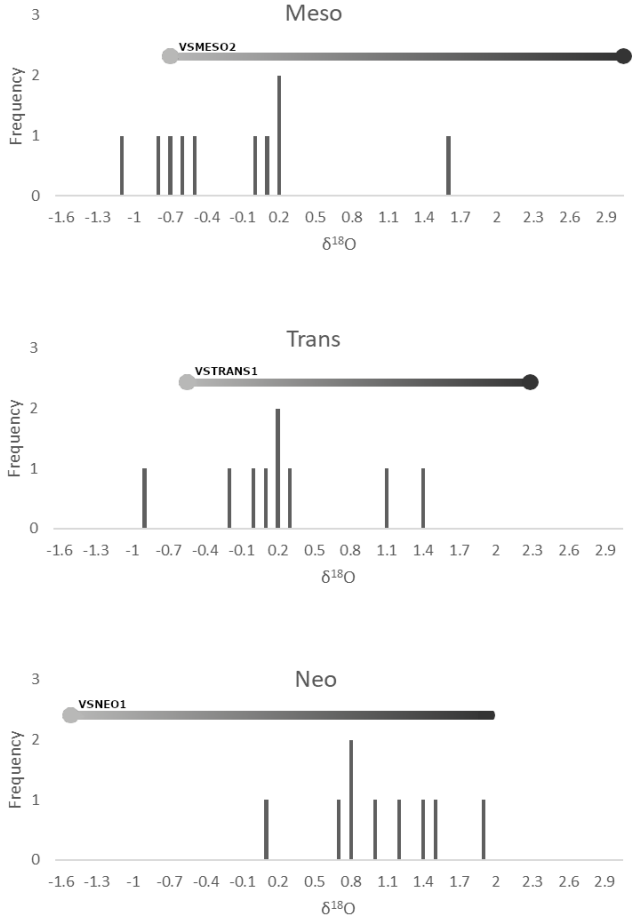
676 Figure 4. FTIR-ATR spectrum from *P. turbinatus* (VSTRANS1) showing characteristic
677 aragonite absorbance peaks.



678 Figure 5. Full sequences of $\delta^{18}O$ and $\delta^{13}C$ for the Mesolithic (a), transitional (b) and
679 Neolithic (c, d) periods. Sample no. 1 = edge sample.



680 Figure 6. Histogram showing $\delta^{18}O$ edge samples compared to annual range. Lower $\delta^{18}O$
681 = higher temperatures. The Neolithic range is left open ended to indicated the uncertain
682 maximum $\delta^{18}O$.



683 Figure 7. Rose diagrams showing the numbers of shells by season for the Mesolithic,
684 transitional and Neolithic periods. R code: Nigst and Bosch 2019.

