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Deciphering late Quaternary land snail shell $\delta^{18}O$ and $\delta^{13}C$ from Franchthi Cave (Argolid, Greece)

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ABSTRACT

This paper investigates the stable isotopic composition from late Pleistocene–Holocene (~13 to ~10.5 cal ka BP) shells of the land snail *Helix figulina*, from Franchthi Cave (Greece). It explores the palaeoclimatic and palaeoenvironmental implications of the isotope palaeoecology of archaeological shells at the time of human occupation of the cave. Modern shells from around the cave were also analysed and their isotopic signatures compared with those of the archaeological shells. The carbon isotope composition of modern shells depicts the consumption of C_3 vegetation. Shell oxygen isotopic values are consistent with other Mediterranean snail shells from coastal areas. Combining empirical linear regression and an evaporative model, the $\delta^{18}Os$ suggest that modern snails in the study area are active during periods of higher relative humidity and lower rainfall $\delta^{18}O$, probably at night. Late glacial and early Holocene $\delta^{18}Os$ show lower values compared to modern ones. Early Holocene $\delta^{18}Os$ values likely track enhanced moisture and isotopic changes in the precipitation source. By contrast, lower late glacial $\delta^{18}O$ could reflect lower temperatures and $\delta^{18}Op$, compared to the present day. Shell carbon isotope values indicate the presence of C_3 vegetation as main source of carbon to late glacial and early Holocene snails.

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Introduction

Land snail shells are a frequent faunal component in archaeological deposits from Mediterranean regions (Lubell and Barton, 2011). Advances in their isotopic ecology reveal that the great potential of shell remains from archaeological sequences in this region as a source of palaeoclimatic and palaeoenvironmental information by means of their $^{18}O/^{16}O$ and $^{13}C/^{12}C$ ratios (e.g., Goodfriend, 1991; Colonese et al., 2007, 2010a,b, 2011; Yanes et al., 2011). The oxygen isotope composition of shells is mostly related to the isotopic composition of environmental waters (water vapour, dew, local meteoric precipitation; e.g., Lécolle, 1985; Zanchetta et al., 2005; Baldini et al., 2007; Zaarur et al., 2011), temperature (Lécolle, 1985) and relative

humidity (Balakrishnan and Yapp, 2004) experienced by the snails during periods of activity. In addition, it has been recently suggested that snails build their shells during periods of higher temperature compared to mean environmental temperatures (Zaarur et al., 2011), and that this would occur in isotopic equilibrium with the ^{18}O-enriched body fluids affected by evaporation (Balakrishnan and Yapp, 2004; Zaarur et al., 2011). However, in moist environments, the isotopic composition of other sources of oxygen (plants, carbonates) has been also proposed in order to explain shell ^{18}O-enrichment (Stevens et al., 2012).

In contrast, shell carbon isotope composition has been more readily associated with the isotopic composition of food (Stott, 2002, and reference therein). Most land snails are herbivorous and detritivorous (Speiser, 2001), thus their shell $\delta^{13}C$ has a great potential to be an indicator of distinct photosynthetic pathways of the consumed plants (C_3, C_4, CAM [crassulacean acid metabolism]), physiological strategies (e.g., distinct water use efficiency) and the possible effect of environmental conditions on plant carbon isotope fractionation. Ingested foreign carbonates may additionally contribute to the carbon isotope signature of some species, depending on their feeding

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behaviour (Goodfriend and Hood, 1983; Yanes et al., 2008; Colonese et al., 2010b), but potentially also seasonal weather conditions (Mensink and Henry, 2011). These empirical and theoretical models converge on the general assumption that shell $\delta^{18}O$ and $\delta^{13}C$ reflect conditions experienced by snails during periods of activity, which in turn are controlled by prevailing weather conditions (such as intervals of high humidity and mild temperatures) and endogenous mechanisms (e.g., circadian rhythms, nutritional, reproductive and osmotic status; Prior, 1985; Cook, 2001, and references therein). Therefore, palaeoecological interpretations of snail shell isotopic composition rely considerably upon complex activity cycles (periods and durations) and other behavioural factors (e.g., feeding behaviours, activity areas).

This paper presents the $\delta^{18}O$ and $\delta^{13}C$ variations in the shells of the land snail *Helix figulina* (Pulmonata, Stylommatophora) from the archaeological site of Franchthi Cave (Argolid, Greece; Fig. 1). The isotopic signature of modern and fossil snail shells (~13 to ~10.5 cal ka BP) from this region is investigated for the first time. Franchthi Cave preserves one of the most remarkable late Pleistocene–Holocene archaeological sequences of the Mediterranean basin, and is a key site for the understanding of human–environment interactions in the eastern Mediterranean during the late Quaternary (Shackleton, 1988; Hansen, 1991; Farrand, 2000; Perlès, 2010; Stiner and Munro, 2011), but also the spread of the earliest farming communities into eastern European regions (Perlès, 2001).

The late Pleistocene and early Holocene deposits have yielded vast quantities of land snails. The present study aims to improve the understanding of climatic-environmental mechanisms controlling shell $\delta^{18}O$ and $\delta^{13}C$ in Mediterranean regions and to explore the potential of snail shell isotope ecology in dry environments. The available palaeoclimatic records from the Aegean Sea enable us to test the hypothesis that shell oxygen and carbon isotope composition capture regional changes in past atmospheric and vegetation conditions during the interval covered by this study.

Environmental and archaeological setting

The study area

Franchthi Cave (henceforth FRC; Fig. 1) is located in the southwestern Argolid Peninsula (Peloponnese, Greece). The region has a typical Mediterranean climate, characterized by hot dry summers and wet winters. At a seasonal scale, precipitation occurs predominantly in autumn–winter and is mainly of frontal origin. Frontal depressions from the Atlantic Ocean or the western and central Mediterranean move eastwards and promote south-westerly air masses over the Ionian Sea and southern Greece. Summer precipitation, on the other hand, is predominantly convective due to enhanced evaporation from the Aegean Sea. Precipitation also originates from Saharan depressions moving north–northeastwards (Flocas and Giles, 1991; Dotsika et al., 2010).

Mean monthly temperature at Nafplio (~25 km north of FRC) for the period 1975–1988 ranges from 10.5°C in winter to 28°C in summer, while the corresponding mean monthly precipitation ranges from 85.8 mm to 6.7 mm, with a mean annual rainfall amount of ~538 mm (Kornaros, 1999; Fig. 2). Mean monthly relative humidity (RH) shows highest values in autumn–winter (66.5%) and lowest in summer (45%). Mean annual oxygen-isotope composition of precipitation ($\delta^{18}O_p$) over the study area is ~−4‰ (Matiatos and Alexopoulus, 2011). The aforementioned seasonal atmospheric conditions are responsible for prevalent ^{18}O-depleted and ^{18}O-enriched precipitation in winter and summer respectively (Argiriou and Lykoudis, 2005, 2006; Dotsika et al., 2010). Natural vegetation in the southern Argolid Peninsula includes pine forest (*Pinus halepensis*), phrygana, maquis and grassland, interspersed with cultivated fields (Gavrielides, 1976).

However, maquis and phrygana are the dominant vegetation types in the area, with *Juniperus communis* as the dominant species, but also including *Quercus coccifera*, *Pistacia lentiscus*, *Coridothymus* sp. (van Andel and Sutton, 1987).
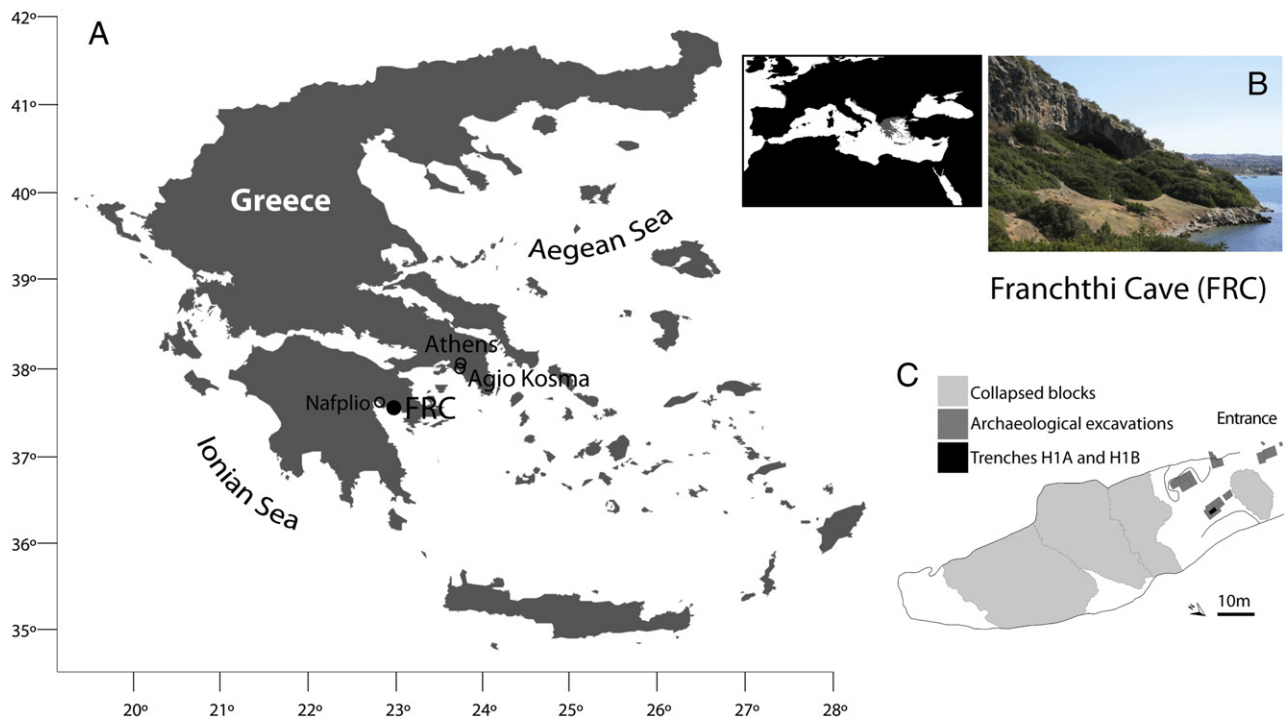

Figure 1. (A) Geographic position of Franchthi Cave (FRC; Argolid, Greece) in the borderlands of the Aegean Sea. The Agios Kosmas meteorological station is located close to Athens. Also shown is a snapshot of the environment (B) and a plan of the cave (C), including excavated areas (Archaeological excavations) and trenches from where analysed shells have been selected. After Jacobsen and Farrand (1987).
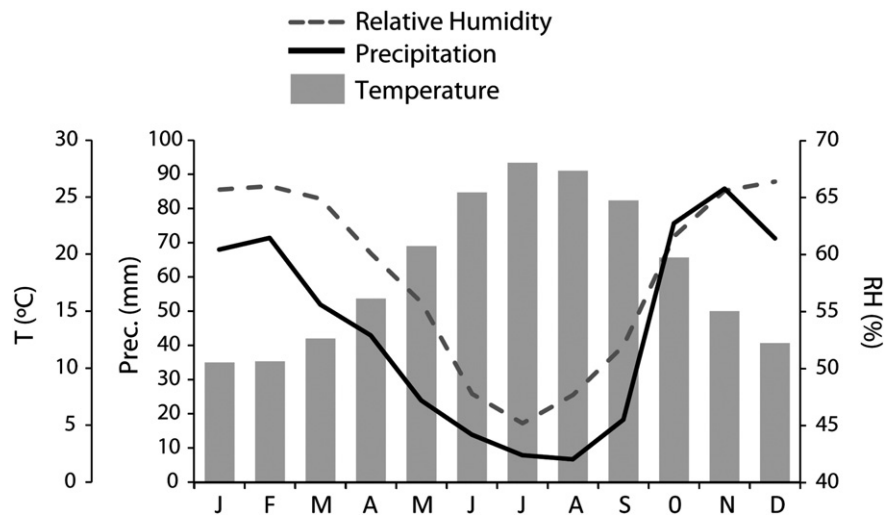
Figure 2. Atmospheric data from Nafplio, including monthly amount of precipitation (mm), mean monthly relative humidity (RH) and mean monthly temperature (°C).

Franchthi Cave

Franchthi Cave was excavated between 1967 and 1979 under the supervision of T. W. Jacobsen of Indiana University (Jacobsen and Farrand, 1987). This vast cavity (NW–SE), a few metres above sea level (~10 m above sea level), overlooks the now-submerged coastal plain of Koiladha Bay, in southwestern Argolid (Fig. 1). The cave is developed in a Cenomanian (lower Cretaceous) limestone, which is the dominant rock type of the area (Farrand, 2000).

The occupational sequence (excavated in different trenches) is exceptionally long and spans the late Pleistocene (Upper Palaeolithic) to the middle Holocene (Mesolithic and Neolithic). Environmental studies were a prime focus of the excavations, and pioneering research, based on systematic water-sieving, retrieved a wide variety of remains, including, for the first time in Greece, land snails. The combination of ^{14}C ages, along with biostratigraphic (seeds, molluscs, vertebrates) and archaeological (chipped stone tools) remains has been used to establish the cave's chronology and the phases of human occupation from the late Pleistocene (Upper Palaeolithic) to the early Holocene (Mesolithic) (Jacobsen and Farrand, 1987; Perlès and Vanhaeren, 2010, and references therein). These are represented by excavation units, embedded in distinct sedimentary episodes (stratum Z to P) with eventual further subdivisions (followed by a number; e.g., T3). In the two deepest archaeological trenches (trenches FAS and H1B), excavations reached levels that pre-date a tephra layer corresponding to the Campanian Ignimbrite (Stratum Q; Farrand, 2000), deposited at ~40 cal ka BP (Hajdas et al., 2011).

Land snail shells (mainly composed of *H. figulina*) are frequent from late Epigravettian deposits dated to 12,950 cal yr BP (stratum T, phase 5), where most of the snails were broken, very often burnt (Perlès and Vanhaeren, 2010), and intimately mixed with animal bones, carbonized seeds, sea shells, charcoal, etc., suggesting intensive collections of the snails as a food resource. At the very end of the Pleistocene (phase 6, stratum U and V), land snails became rare again, only to reappear in abundance in the lower Mesolithic deposits (stratum W, phase 7; Perlès, 2003). Here again, they are mixed with stone tools, ornaments, animal bones, sea shells (Shackleton, 1988), and, especially, a very rich array of carbonized seeds (Hansen, 1991). Although their density decreased clearly in the Late Mesolithic (phase 8), they are frequently present until the Neolithic.

Materials and methods

Prehistoric shells of *H. figulina* were selected for isotopic analysis from distinct units of trenches H1A and H1B (for details, see: Jacobsen

and Farrand, 1987; Farrand, 2000). Trenches H1A and H1B are a subdivision of trench H1, located ~15 m inside the drip line of the cave. Trench H1 (3 × 4 m) was excavated in 1969 down to ~3.5 m and then subdivided in four quadrants of unequal size, labelled H1A, H1B, H1C and H1D. Trenches H1A and H1B were excavated down to −9.2 and −9.7 m respectively (Fig. 3). In situ deposits from these trenches cover the period from ~39 to ~9.10 cal ka BP (Table 1). As with all other remains from trenches H1A and H1B, land snails were hand-picked during excavation, and then systematically retrieved through a water sieve with meshes of 10 mm, 5 mm, and 2.8 mm. The residues from the smallest sieve (1.5 mm), on the other hand, were only sorted on certain subsamples. For the present study, only well-preserved shells from the trench bag and the >10-mm residues were selected, comprising excavation units spanning the late Pleistocene and the early Holocene (~13 to ~10.5 cal ka BP). Analysed late glacial deposits preserve evidence of human occupation dated to just before (stratum T1 and T3) and during (stratum U and V) the Younger Dryas cold interval in the North Hemisphere (YD; Björck et al., 1998). Early Holocene deposits from Stratum W were also analysed.

Modern shells were collected from the ground surface surrounding the cave and near the town of Nafplio, in order to compare their isotopic signature with their archaeological counterparts. No live specimens of *H. figulina* were found, but only some well-preserved empty shells very similar to archaeological *H. figulina*. This medium-sized helicid (shell length from 22.5 to 29 mm, but see also Kotsakiozi et al., 2012 for body mass) has been reported for the southern Balkan Peninsula and islands (e.g., Greece, Bulgaria, western Turkey) and western Asia Minor (e.g., Georgia), inhabiting dry open fields with herbaceous vegetation (Gittenberger and Goodfriend, 1993; Mumladze et al., 2008; Triantis et al., 2008; Georgiev and Stoycheva, 2010; see also http://www.faunaeur.org/). It has a limited distribution to these regions, but in the past this species had a much broader distribution, at least in the Aegean region, including islands (Kotsakiozi et al., 2012, and references therein). Along with *H. figulina* shells of other helicid species, exhibit similar habitat preferences, were also collected (e.g., *Eobania vermiculata* and *Cornu aspersum*). *E. vermiculata* has a wide distribution around the western Mediterranean (Giusti et al., 1995). It is a rather thermophilic and herbivorous species, very common in coastal areas and in inland sites at low altitude, on all kinds of soils (Giusti et al., 1995). *E. vermiculata* has a moderate degree of adaptation to open environments, such as shrublands and anthropogenic habitats (Giusti and Castagnolo, 1982). *C. aspersum* is an herbivorous species with a Western European and Holomediterranean distribution, occurring from coastal regions up to altitudes of ~1000 m, in many different kinds of biotopes (Giusti et al., 1995). A recent study on Greek
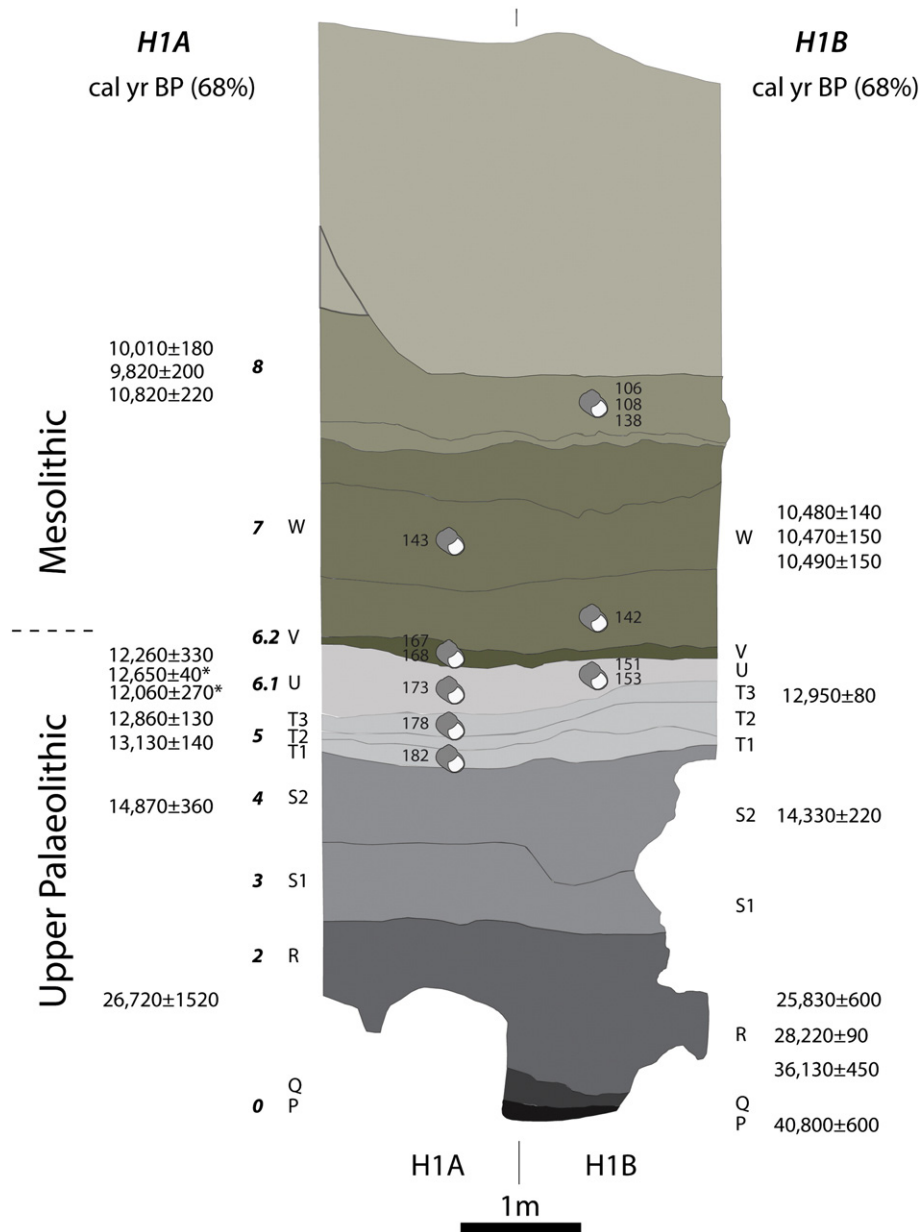
Figure 3. Schematic profile, radiocarbon calendar ages (1 sigma, 68%) by cultural attributions and lithostratigraphy in trenches H1A and H1B (*[14]C ages from trench FAS); the provenance of archaeological land snail shells for each archaeological phase (0–8), stratigraphic unit (106–182) and stratum (P–W) is also reported (from Farrand, 2000; Perlès and Vanhaeren, 2010, modified). Radiocarbon dates (Farrand, 2000; Douka et al., 2011) were calibrated using the curve CalPal 2007 Hulu (Weninger and Jöris, 2008; Weninger et al., 2010).

populations of *H. figulina* and *C. aspersum* revealed that the active season starts at the onset of autumn rains and ends with the beginning of the dry season; *H. figulina*, in particular, is only active from autumn to spring, following rain (Kotsakiozi et al., 2012). All modern shells were entire and well-preserved (e.g., still preserving the periostracum), and some of them (e.g., *E. vermiculata* and *C. aspersum*) contained residues of decomposing fresh tissue and thus were presumed to have died recently.

Modern shell organic matter was removed by immersing them in a solution of 5% NaClO for 48 h. Archaeological shells were cleaned in 30% H_2O_2 for 24 h to disaggregate all sediment by oxidizing organic materials. Following this treatment, the shells were placed in an ultrasonic bath for 30 min, rinsed in deionised water and dried in an oven at 60°C. Each shell was then powdered and homogenized and subsampled for isotopic analysis (~1 mg). Evidence of diagenetic alteration of archaeological shells was investigated on random samples using X-ray diffraction (XRD). According to calibration with a

mixture of calcite standards and shell aragonite, the results indicate that the fossil shells were composed almost entirely of aragonite (>99%). Some shells contained an amount of calcite from ~4% to ~15%. However, their isotopic compositions do not appear different from pure aragonite shells, indicating that this change in mineralogy was not accompanied by detectable changes in isotopic composition.

Shell stable isotope ($\delta^{18}O$ and $\delta^{13}C$) measurements (N = 64) were mainly performed at the School of Environmental and Life Sciences at the University of Newcastle (Australia). Samples were digested in 105% phosphoric acid at 70°C and analyses were made on the evolved CO_2 gas using a GV Instruments GV2003 mass spectrometry. Results were normalized to the Vienna Pee Dee Belemnite (V-PDB) scale using internal working standards, which were cross-checked against the international standards NBS18 and NBS19. Mean analytical precision (1σ) for both $\delta^{18}O$ and $\delta^{13}C$ was ≤0.1‰, based on multiple measurements of an internal standard of Carrara Marble (NEW1). Some modern shells (N = 10) were also analysed at the Institute of

Table 1
Radiocarbon data from trenches H1A and H1B based on charcoal measurements. [14]C ages from stratum U in trench FAS were also included given their good lithostratigraphic correlation with H1A and H1B. [14]C ages are reported as conventional and calibrated yr BP. 1 sigma ^{14}C ages (68% probability) are reported as weighted mean values along with standard deviations; 2 sigma ^{14}C ages (95% probability) are also shown. Calibration was performed with CalPal 2007 Hulu in CALPAL_A (advanced) (http://www.calpal.de; Weninger et al., 2010).

Trench	Strata	Phase	Units	[14]C yr BP	cal yr BP (68%)	cal yr BP (95%)	Cultural attribution	Lab code
H1A		8	101[*]	8940 ± 120	10,010 ± 180	10,370–9650	Upper Meso.	P − 1664
		8	117P[*]	9480 ± 130	10,820 ± 220	11,260–10,380	Upper Meso.	P − 1665
		8	117R[*]	8740 ± 110	9820 ± 200	10,220–9420	Upper Meso.	P − 1666
	U	6.1	173[*]	10,460 ± 210	12,260 ± 330	12,920–11,600	Final U.P.	I − 6139
	T3	5	175[*]	10,880 ± 160	12,860 ± 130	13,120–12,600	Late U.P.	I − 6129
	T2	5	181[*]	11,240 ± 140	13,130 ± 140	13,410–12,850	Late U.P.	P−1923
	S2	4	199[*]	12,540 ± 180	14,870 ± 360	15,590–14,150	Late U.P.	P − 1827
	R	2	219[*]	22,330 ± 1270	26,720 ± 1520	29,760–23,680	Early U.P.	I − 6140
H1B	W	7	126[*]	9290 ± 100	10,480 ± 140	10,760–10,200	Lower Meso.	P − 2102
		7	139[*]	9300 ± 100	10,490 ± 150	10,790–10,190	Lower Meso.	P − 2103
		7	139[*]	9270 ± 110	10,470 ± 150	10,770–10,170	Lower meso.	P − 2104
	T3	5	155	11,045 ± 50	12,950 ± 80	13,110–12,790	Late U.P.	GifA 80050
	S2	4	166	12,230 ± 60	14,330 ± 220	14,770–13,890	Late U.P.	GifA 80051
	R	2	191–192[*]	21,480 ± 350	25,830 ± 600	26,660–24,660	Early U.P.	P − 2233
	R	2	203[**]	23,510 ± 90	28,220 ± 90	28,400–28,040	Early U.P.	OxA 21060
	R	2	210[**]	32,110 ± 200	36,130 ± 450	36,900–35,260	Early U.P.	OxA 241173
	P	0	215[**]	35,600 ± 350	40,800 ± 600	42,000–39,600	Undiagnostic	OxA 20616
FAS	U	6.1	204[*]	10,260 ± 110	12,060 ± 270	12,600–11,520	Final U.P.	P − 2231
	U	6.1	205	10,605 ± 50	12,650 ± 40	12,730–12,570	Final U.P.	GifA 80102

[*]Unpublished dates from Gif. [**]Data from Douka et al. (2011); all other dates from Jacobsen and Farrand (1987). Cultural phases (numbers) and cultural attribution are also reported (Perlès and Vanhaeren, 2010). Lab codes: P (University of Pennsylvania, USA), I (Teledyne Isotopes, USA), OxA (Oxford Radiocarbon Accelerator Unit, UK), GifA (Gif sur Yvette and Orsay, France).

Geosciences and Earth Resources (IGG) of the CNR at Pisa (Italy). The samples were analysed by reaction with 100% phosphoric acid using the inverted y-tube technique at 70°C under vacuum. The released carbon dioxide was cryogenically-cleaned in a vacuum line and analysed using a Varian Mat 252 mass spectrometer. The results were normalized to the Vienna Pee Dee Belemnite using internal working standards of carbonate − MS, MAB (Carrara Marble) and MOM, which were calibrated against the international standards NBS18, NBS19 and NBS 20. Mean analytical precision (1σ) for both $\delta^{18}O$ and $\delta^{13}C$ was ≤0.1‰.

Decomposing bulk vegetation litter (small fragments of leaves, roots) preserved within some modern shells was combined and analysed in order to estimate the $\delta^{13}C$ of related vegetation (e.g., Wedin et al., 1995). The litter was rinsed with deionised water, dehydrated in an oven at 40°C, then homogenized using a mortar and pestle, and converted to powder for isotopic analysis. Litter was analysed at the Cornell Stable Isotope Laboratory (USA) using a ThermoFinnigan Delta V IRMS, introduced via a Carlo Erba NC2500 Elemental Analyzer. Results were normalized to the V-PDB scale using internal working standards calibrated against the international standards (IAEA). The $\delta^{18}O$ of waters is quoted relative to V-SMOW. Mean analytical precision (1σ) for $\delta^{13}C$ was better than 0.1‰.

Comparisons of $\delta^{18}O$ and $\delta^{13}C$ values among modern and archaeological shells and between shells of different units were performed using the non-parametric Kruskal–Wallis test in the software PAST 2.13 (Hammer et al., 2001), using a statistical significance probability threshold of $\alpha = 0.05$. Radiocarbon ages, carried out mainly on charcoal, were calibrated with CalPal-2007 Hulu calibration curve (Weninger and Jöris, 2008; Weninger et al., 2010).

The steady-state flux balance model (FBM; Balakrishnan and Yapp, 2004) was tested on the modern shells using meteorological data from Nafplio (from 1975 to 1988) and from Agios Kosmas near Athens (year 2006; at ~80 km NE from FRC and ~5 m a.s.l.; http://hoa.ntua.gr/; Fig. 1). The use of the two meteorological stations is justified because data from Nafplio (Fig. 2) only provide mean monthly atmospheric conditions, whereas mean daily conditions are available from Agios Kosmas. Monthly $\delta^{18}O$ data of precipitation ($\delta^{18}Op$) from Athens was also used (year 2006, Mount Pendeli, 498 m; International Atomic Energy Agency, IAEA, http://www.iaea.org/), after correction for the mean altitudinal gradient in $\delta^{18}Op$ observed in Argolis Peninsula (~−0.45‰/100 m) by Matiatos and Alexopoulus (2011). It was assumed that all of the water incorporated by snails was lost via evaporation and that the environmental vapour was in isotopic equilibrium with $\delta^{18}Op$ (see Balakrishnan and Yapp, 2004).

Results

Modern shells and decomposed litter

Shell oxygen ($\delta^{18}Os$) and carbon ($\delta^{13}Cs$) isotope values of modern specimens are reported in Table 2. Modern *H. figulina*, *E. vermiculata* and *C. aspersum* exhibit median $\delta^{18}Os$ of $0.0 \pm 0.4‰$ (n = 3), $+0.1 \pm 1.2‰$ (n = 7), and $-0.2 \pm 0.2‰$ (n = 4) respectively. For carbon isotopes, the same species yielded median $\delta^{13}Cs$ values of $-10.9 \pm 0.7‰$, $-10.5 \pm 0.7‰$ and $-10.6 \pm 0.9‰$ respectively. No correlation ($R^2 = 0.006$) and no significant difference were detected for both $\delta^{18}Os$ ($P = 0.622$) and $\delta^{13}Cs$ ($P = 0.870$) between species (Fig. 4). Therefore, the median $\delta^{18}Os$ ($0.0 \pm 0.8‰$) and $\delta^{13}Cs$ ($-10.6 \pm 0.7‰$) of all species were used for comparison with archaeological counterparts.

The $\delta^{13}C$ of the decomposed litter are $-21‰$. Taking into account that some Mediterranean shrubs may have leaf $\delta^{13}C$ values up to $-23‰$ (Filella and Peñuelas, 2003) and that a ^{13}C-enrichment up to 0.7‰ has been reported for bulk C3-derived decomposed litter (Wedin et al., 1995), a value of $-21‰$ may derive mostly from C_3 vegetation.

Archaeological shells

Late glacial–Holocene shells of *H. figulina* (n = 60) have median $\delta^{18}O$ values ranging from $-1.0 \pm 0.3‰$ to $-1.5 \pm 0.5‰$ at ~13 and ~10.5 cal ka BP, respectively. The median $\delta^{13}Cs$ show values from $-9.4 \pm 0.2‰$ at ~13 cal ka BP to $-9.8 \pm 0.3‰$ at ~10.5 cal ka BP (Table 3). Results thus indicate that archaeological shells are significantly ^{18}O-depleted ($P < 0.001$) compared to modern counterparts, from 1.0‰ (~13 cal ka BP) to 1.5‰ (~10.5 cal ka BP). By contrast, late Pleistocene–Holocene shells are significantly ^{13}C-enriched compared to modern ones ($P < 0.001$), within median differences ranging from 1.2‰ (~13 cal ka BP) to 0.8‰ (~10.5 cal ka BP).

Significant differences have been observed also between some chronological intervals for $\delta^{13}Cs$. Shells dated to ~13 and ~12.3 cal ka BP are slightly ^{13}C-enriched (0.4‰) compared with shells dated to ~10.5 cal ka BP ($P < 0.05$ and $P < 0.001$ respectively).

Table 2
Oxygen and carbon isotope composition, median, standard deviation (sd) and range values of modern shells from FRC.

Species	δ^{18}Os‰	Median	sd	Δδ^{18}Os‰	δ^{13}Cs‰	Median	sd	Δδ^{13}Cs‰
H. cf. *figulina*	+0.3	0.0	0.4	0.7	−11.3	−10.9	0.7	1.3
	0.0				−10.9			
	−0.4				−10.0			
C. aspersum	−0.4	−0.2	0.2	0.5	−10.6	−10.6	0.9	1.9
	−0.3				−10.6			
	+0.1				−10.4			
	−0.1				−12.2			
E. vermiculata	+0.1	+0.1	1.2	3.4	−10.5	−10.5	0.7	2.1
	+1.3				−11.1			
	+2.1				−10.5			
	−0.1				−10.2			
	−1.3				−11.3			
	+0.1				−9.2			
	−0.3				−11.1			

Discussion

Modern shells

In spite of the different species involved, modern shells exhibit similar δ^{18}Os signatures (p = 0.622), with a median value (0.0 ± 0.8‰) falling within the range of other shells from Mediterranean and European regions, which are characterized by mean δ^{18}Op ranging from ~ −5.5‰ to ~ −6.0‰ (Lécolle, 1985; Goodfriend et al., 1989; Zanchetta et al., 2005; Colonese et al., 2010a, 2011). Since no empirical δ^{18}Os–δ^{18}Op relationships exist for the study area, we estimate the mean δ^{18}Op used by snails according to the relationship obtained by Lécolle (1985) and Zanchetta et al. (2005) on extant shells from Euro-Mediterranean areas (Eq. (1)) and the Italian Peninsula (Eq. (2)), respectively:

$$\delta^{18}Op = 1.17 * \delta^{18}Os - 5.91 \tag{1}$$

$$\delta^{18}Op = 0.65 * \delta^{18}Os - 5.44. \tag{2}$$

Eqs. (1) and (2) express positive relationships between δ^{18}Os and δ^{18}Op, implying that shell ^{18}O-depletion (^{18}O-enrichment) is a function of lower (higher) δ^{18}Op. Seasonal variations of δ^{18}Op over the study area are modulated by changes in atmospheric temperature, amount of rainfall, and source and trajectory of air masses (Argiriou and Lykoudis, 2005, 2006; Dotsika et al., 2010; Lykoudis et al., 2010). Using both Eqs. (1) and (2) on median δ^{18}O we predict a mean δ^{18}Op of −5.9‰ and −5.4‰ respectively, which are lower than the estimated mean annual δ^{18}Op for the study area (~ −4‰). Similar, and even lower values have been reported during wetter months, at lower temperatures and according to synoptic circulation patterns (Argiriou and Lykoudis, 2006; Lykoudis et al., 2010). These values therefore confirm that the snails do not form their shells through the year but likely capture the ^{18}O-depleted rainfall of the wettest period of the year. Indeed, previous studies on modern helicids from Greece have demonstrated that snails aestivate in summer, when water availability is drastically reduced (e.g., Kotsakiozi et al., 2012).

Additional factors may influence δ^{18}Os, such as differences in the extent of evaporation of body fluids and surface soil water (Lécolle, 1985; Goodfriend and Magaritz, 1987; Balakrishnan and Yapp, 2004; Zanchetta et al., 2005; Zaarur et al., 2011), but also different snail physiological responses to regional environmental conditions (Kotsakiozi et al., 2012). Theoretical models (Balakrishnan and Yapp, 2004) and recent clumped isotopic studies (Δ$_{47}$, Zaarur et al., 2011) emphasize the role played by evaporation on snail body fluids, from which shell precipitation take place. The role played by RH is discussed in detail by Balakrishnan and Yapp (2004) and its effect on our snail dataset can be explored using an evaporative steady-state flux balance model (FBM) proposed by the same authors. The model predicts that land snails secrete their shells in oxygen isotopic equilibrium with body fluids that undergo isotopic fractionation through evaporation (^{18}O-enrichment). Evaporation increases with decreasing RH, promoting a coefficient of ~ +0.4‰ in the shell for every 0.01 reduction (expressed as a decimal fraction). Previous papers have demonstrated that the

Figure 4. δ^{18}Os and δ^{13}Cs of modern land snails. Most δ^{18}Os values overlap, suggesting no significant species-specific fractionation between *H. figulina* (HF), *E. vermiculata* (Ev) and *C. aspersum* (Ca). Also no significant variability has been observed between the δ^{13}Cs distribution of different species. Box and whiskers represent the quartile distribution of δ^{18}Os and δ^{13}Cs data.

Table 3
Median oxygen and carbon isotope composition, standard deviation (sd) and range values of sampled (n) archaeological shells from FRC. Also reported the estimated radiocarbon age ranges for each unit based on data in Table 1. Age ranges were estimated using the max and min dates expressed in cal yr BP (95%) from combined strata: 10,790–10,170 (H1B-W), 12,920–11,520 (FAS-U, H1A-U), 13,410–12,600 (H1A-T3, -T2). Cultural attributions are reported as M (Mesolithic) and UP (Upper Palaeolithic).

Estimated ^{14}C age ranges (cal yr BP)	Culture	Median δ^{18}Os‰	sd	Δδ^{18}Os ‰	Median δ^{13}Cs‰	sd	Δδ^{13}Cs ‰	n
10,790–10,170	M	−1.5	0.46	2.05	−9.8	0.34	1.42	30
12,920–11,520	M-UP	−1.2	0.45	1.68	−9.4	0.51	1.93	20
13,410–12,600	UP	−1.0	0.30	0.93	−9.4	0.21	0.67	10

evaporative model is a suitable approach to explain oxygen isotopic variability in modern land snail shells also in some Mediterranean environments (Balakrishnan and Yapp, 2004; Colonese et al., 2011), encouraging its application in other Mediterranean areas.

Using RHs and temperatures from Nafplio and Agios Kosmas, two different sets of input variables were initially used for predicting shell oxygen isotopic response to hydrological and atmospheric conditions (case A and B) according to the FBM (Eq. 7 in Balakrishnan and Yapp, 2004). Meteorological data from Nafplio (from 1975 to 1988) only enabled $\delta^{18}Os$ estimates using mean monthly atmospheric conditions (case A). Thus, mean daily meteorological (T and RH) information from Agios Kosmas (year 2006) was used (case B). For case A, only months with a mean RH $\geq 60\%$ and T (°C) ≥ 10 °C and ≤ 27°C were introduced (see Fig. 2). The average $\delta^{18}Op$ from these months was -4.9‰. In case B, only days with a RH $\geq 70\%$ and T (°C) ≥ 10 °C and ≤ 27°C were selected along with an equivalent $\delta^{18}Op$ of -4.5‰. In case A, the assumed RH is far too low and thus unsuitable for snail activity, but it is reported here to elucidate the effect of mean monthly conditions on the model calculation. Contrarily, atmospheric conditions in B appear reasonable because they embrace the minimal requirement for snail activity (Balakrishnan and Yapp, 2004). In so doing, case A differs considerably from B in terms of the amount of suitable days for snail activity (Table 4), but all cases indicate that the autumn-to-spring months are the most suitable period for shell formation.

Predicted $\delta^{18}Os$ values according to the variables in A and B are compared with measured $\delta^{18}Os$ ($\Delta\delta^{18}Op$-m; Fig. 5). The $\Delta\delta^{18}Op$-m values at zero (dotted line) represent an exact agreement between predicted and measured $\delta^{18}Os$. Our results show neither a perfect relationship, nor even close agreement, between measured $\delta^{18}Os$ and the prediction from the evaporative model based on the aforementioned meteorological variables. In both cases A and B predicted $\delta^{18}Os$ appear notably overestimated. Above discrepancies are possibly explained by snail activities during periods of higher RH and lower $\delta^{18}Op$.

Given the limited hydrological regime it could indeed be expected that the snails are prevalently active at night, intercepting dew and fog (Örstan, 2010). Large differences have been observed between day and night in the RH of Mediterranean coastal areas, and in contrast to diurnal conditions, nocturnal RH may display values $\geq 85\%$ (e.g., Colonese et al., 2011). Furthermore, both Eqs. (1) and (2) attest that snails form their shells at lower $\delta^{18}Op$ than those used in both cases A and B. Equation (2), however, is likely to better represent the $\delta^{18}Os$ response to $\delta^{18}Op$ because it incorporates a greater influence of Mediterranean vapour water (Zanchetta et al., 2005).

These new conditions are tested again here with the FBM. In the case of B, using a $\delta^{18}Op$ of -5.4‰ (Eq. (2)) and an average RH of 87%, the predicted $\delta^{18}Os$ ($+0.2$‰) finally approach the measured median $\delta^{18}Os$ ($+0.1$; Fig. 5, case C). This result confirms that modern snails were active during wetter months of the year, but prevalently at night, recording higher RH and lower $\delta^{18}Op$. The results are in good agreement with predicted $\delta^{18}Os$ values from other snails in Mediterranean coastal areas (Colonese et al., 2011) and emphasize the suitability of both approaches for understanding the $\delta^{18}Os$ response to atmospheric conditions in the study area. Mean monthly
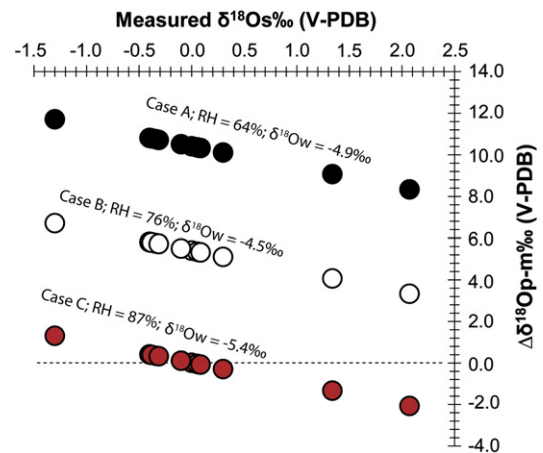

Figure 5. FBM-derived $\delta^{18}Os$ estimates of modern snail activity according to cases A, B and C in the study area. The exact agreement between predicted and measured $\delta^{18}Os$ ($\Delta\delta^{18}Op$-m) is represented by a value of zero (dotted line) on the $\Delta\delta^{18}Op$-m axis. The substantial difference between cases A–B and C indicates that snails experienced more humid conditions (higher RH) and environmental waters depleted in ^{18}O (case C) than predicted according to average monthly (A) and daily (B) conditions.

(case A) and daily (case B) atmospheric conditions may not represent the mean environmental conditions at the moment of snail activity.

By contrast, the $\delta^{13}Cs$ can primarily be associated with the carbon isotope signature of the digested food (e.g., Stott, 2002), even if other sources of carbon and snail feeding behaviour are likely responsible for the observed variability (e.g., Yanes et al., 2008; Colonese et al., 2010b). The $\delta^{13}C$ of food may be estimated using empirical relations between the $\delta^{13}C$ of vegetation with different photosynthetic pathways (C$_3$, C$_4$) and $\delta^{13}Cs$, such as that proposed by Stott (2002) on cultured *C. aspersum* fed with isotopically controlled food:

$$\delta^{13}Cs = 8.7 + 0.74\delta^{13}C_{diet}. \tag{3}$$

According to Stott's equation, the median $\delta^{13}Cs$ of modern specimens (-10.6‰) can be readily converted to a $\delta^{13}C_{diet}$ of -26‰, which is clearly indicative of C3 vegetation type. The narrow $\Delta\delta^{13}Cs$ between specimens imply that all individuals fed on isotopically similar food. The estimated $\delta^{13}C_{diet}$ may suggest a negligible (if any) contribution of soil carbonate to the $\delta^{13}Cs$ of all these three species.

Archaeological shells

Late glacial–Holocene shells are ^{18}O-depleted and ^{13}C-enriched compared to their modern counterparts, respectively, suggesting different hydrological and atmospheric conditions over the region at the time. Both $\delta^{18}Os$ and $\delta^{13}Cs$ values, however, do not provide evidence of substantial climate changes between ~13 and ~10.5 cal ka BP (Fig. 6).

According to Eq. (2) and the FBM, changes in $\delta^{18}Os$ can be associated with variations in RH, $\delta^{18}Op$ and temperature. Therefore, lower early Holocene $\delta^{18}Os$ at FRC seem to reflect wetter conditions recorded in synchronous palaeoclimatic records from the eastern Mediterranean (Bar-Matthews et al., 2000; Geraga et al., 2005; Kotthoff et al., 2008a, b; Roberts et al., 2008; Dormoy et al., 2009; Leng et al., 2010; Peyron et al., 2011), including previous snail shell isotopic data (Goodfriend, 1991). Lower $\delta^{18}O$ values are also chronologically consistent with the substantial ^{18}O-depletion of eastern Mediterranean seawater (~-1.3‰) in response to the injection of isotopically light freshwater from African margin (Marino et al., 2009). The decrease of $\delta^{18}O$ in Mediterranean seawater, with the consequent reduction of the $\delta^{18}O$ in precipitation over the regions, accounted for much of lower $\delta^{18}O$ values in regional continental isotopic proxies at that time (Kolodny et al.,

Table 4
Environmental parameters used in the estimation of $\delta^{18}Os$ values of individuals active in the study area according to the steady-state flux balance model (FBM) on three different cases (A, B and C). Also reported are the differences between predicted and measured $\delta^{18}Os$ ($\Delta\delta^{18}Os$) for the three cases. The days of activity refer to daylight only and are here reported only for comparison between cases. Nocturnal activities would enhance the number of days in the case C.

Cases	Mean T (°C)	RH (decimal fraction)	Mean $\delta^{18}Op$‰	Days of activity	Predicted $\delta^{18}Os$‰
A	13.8	0.64	-4.9	~210	$+10.4$
B	16.8	0.76	-4.5	58	$+5.4$
C	16.8	0.87	-5.4	58	$+0.2$

2005; Roberts et al., 2008; Marino et al., 2009) and could also have induced early Holocene shell [18]O depletions at FRC.

On the other hand, taking into account that the Mediterranean seawater was ^{18}O-enriched at ~13 and ~12.3 cal ka BP compared to the present day (Rohling, 1999), it is surprising that the late glacial $\delta^{18}O_s$ values are considerably lower than their modern counterparts. A potential explanation is that vapour sourced directly from the Mediterranean had little or no contribution to precipitation over the study area and that warmer and wetter conditions started much earlier in southern Greece than recorded in other continental isotopic proxies from the eastern Mediterranean (e.g., Roberts et al., 2008). However, there is no clear evidence in support of such a climatic scenario, in particular of wetter conditions compared to present day. Furthermore, some of the late glacial shells were recovered in archaeological units synchronous with the Younger Dryas stadial (YD, Björck et al., 1998), which in the northern and southern Aegean Sea has been associated with increased aridity and lower temperatures (Rossignol-Strick, 1995; Geraga et al., 2000, 2005; Kotthoff et al., 2008a, b, 2011), although faunal and archaeobotanical remains from FRC give no clear indication that this event radically transformed the local environment (Perlès, 2010).

The isotopic composition of precipitation in the eastern Mediterranean is strongly influenced by the trajectory and source of air masses. Winter air masses originating from northeastern Europe usually promote precipitation substantially ^{18}O-depleted over Greece (Griffiths et al., 2002). This circulation pattern was probably more intense over the northern and southern Aegean Sea during late glacial and Holocene cold intervals (Rohling et al., 2002; Gogou et al., 2007; Kotthoff et al., 2011). A more frequent incursion of northerly air masses may have reduced local temperatures and the overall $\delta^{18}O_p$ over the study area at ~13 and ~12.3 cal ka BP compared to the present day. Therefore, rather than wetter conditions, lower $\delta^{18}O$ values may reflect ^{18}O-depleted precipitation forced by lower temperatures and changes in the atmospheric circulation. This circulation pattern would have also reduced the seasonal contribution of Mediterranean seawater, specifically during spring and autumn. According to our results, such atmospheric conditions should have been active just before the YD, during the Allerød interstadial (~13 cal ka BP). It is worth noting that the northern Aegean Sea at this time interval was also marked by unstable conditions, and a rapid transition towards a cold climate is detected from 13.2 cal ka BP (Dormoy et al., 2009; Kotthoff et al., 2011). Similar shell oxygen isotopic response to changes in $\delta^{18}O_p$ has been also observed in other central European (Kehrwald et al., 2010) and Mediterranean regions during the late Pleistocene (Colonese et al., 2007), but further studies are required in order to better understand the $\delta^{18}O$ behaviour over the study area at that time.

The $\delta^{13}C_s$ are positively correlated with the carbon isotope composition of vegetation. Therefore, the ingestion of plants with a higher (lower) carbon isotope composition moves $\delta^{13}C_s$ to higher (lower) values (Stott, 2002). Higher late glacial and early Holocene $\delta^{13}C$ values at FRC compared with modern counterparts (~1‰) imply that snails consumed plants with invariably higher ^{13}C/^{12}C ratios from ~13 and ~10.5 cal ka BP. Calculations using Eq. (3) show that the median $\delta^{13}C$ values of vegetation ranged from −24.5‰ (late glacial) to −25‰ (early Holocene). These values are only slightly ^{13}C-enriched compared to present day $\delta^{13}C_s$-derived vegetation (−26‰) and indicate that snails fed prevalently, or exclusively, on C_3 vegetation type. Higher values compared with the present day may in addition indicate that drought-adapted plants were present near the site. Indeed, similar $\delta^{13}C$ values have been observed in Mediterranean woody shrubs during dry seasons (e.g., Filella and Peñuelas, 2003), in response to reduced water availability. These results are supported by the archaeobotanical remains. The composition of the carbonized seed assemblages at FRC, for example, is also rather uniform and does not reflect much in the way of environmental change, with *Prunus amygdalus*, *Pyrus amygdaliformis*, *P.* cf. *lentiscus*, predominant throughout, followed by the species of *Lens*, *Avena* and Liliaceae family (Hansen, 1991).

Conclusion

Land snail shells are a common component in the late glacial and Holocene deposits of Franchthi Cave (Argolis, Greece). In order to interpret palaeoclimatic and palaeoenvironmental signals imprinted in the snail shell stable isotopic composition, both modern and archaeological shells were analysed. Results indicate that modern shell oxygen isotope signals match with those of other Mediterranean snails living in coastal areas. The evaporative model (FBM) suggests that modern specimens may have been active at high RH and lower $\delta^{18}O_p$ than daily and monthly average condition over the study area. Thus far we confirm that snails are most likely active in the wetter months of the year, and particularly at night. Carbon isotopes of modern shells reflect the composition of the consumed vegetation, predominantly or exclusively of the C3 type.

Late glacial and early Holocene shells show almost invariably lower ^{18}O/^{16}O ratios compared with their modern counterparts. Lower early Holocene $\delta^{18}O_s$ values are consistent with wetter conditions recorded in other palaeoclimatic records in eastern Mediterranean. By contrast lower temperatures and $\delta^{18}O_p$ may have caused ^{18}O-depletions in late glacial shells. Our results suggest that atmospheric circulation and hydrological regime may affect $\delta^{18}O_s$ to varying degrees. At the same time, carbon isotope results indicate the presence of C3 vegetation

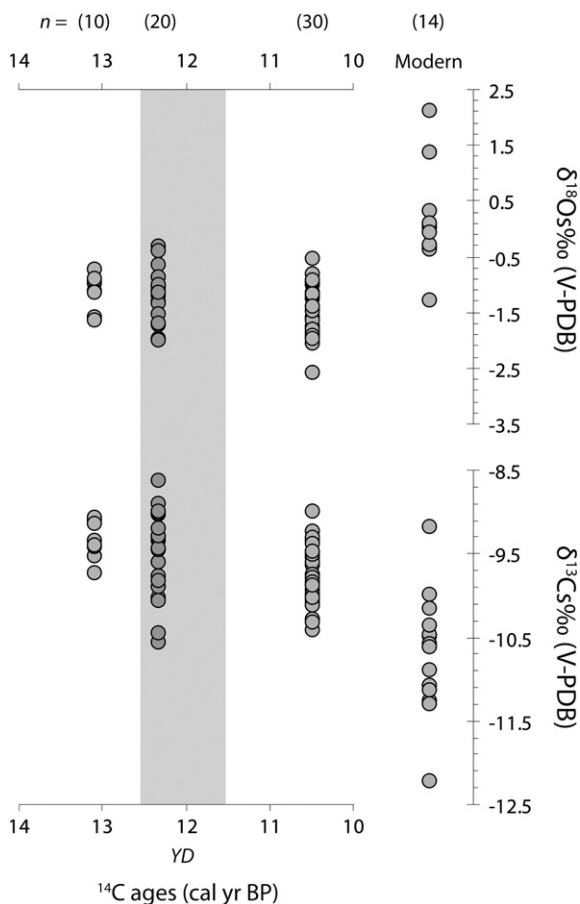**Figure 6.** Late glacial, early Holocene and modern $\delta^{18}O_s$ and $\delta^{13}C_s$ values from FRC. The time scale was elaborated using mean calendar ages (68% probability) from different strata, but in the case of strata T1 and V (no available ^{14}C ages) we used data from T2 + T3 and U respectively (Table 1). The time and duration of the Younger Dryas stadial (YD) are also reported (Björck et al., 1998).

type, with $\delta^{13}C$ values similar to those observed in some Mediterranean woody shrub species adapted to drought.

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