



Stable isotopic signatures of the modern land snail *Eremina desertorum* from a low-latitude (hot) dry desert—A study from the Petrified Forest, New Cairo, Egypt



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ABSTRACT

This study was conducted on recent desert samples—including (1) soils, (2) plants, (3) the shell, and (4) organic matter from modern specimens of the land snail *Eremina desertorum*—which were collected at several altitudes (316–360 m above sea level) from a site in the New Cairo Petrified Forest. The soils and shell *E. desertorum* were analyzed for carbonate composition and isotopic composition ($\delta^{18}\text{O}$, $\delta^{13}\text{C}$). The plants and organic matter *E. desertorum* were analyzed for organic carbon content and $\delta^{13}\text{C}$. The soil carbonate, consisting of calcite plus minor dolomite, has $\delta^{18}\text{O}$ values from -3.19 to -1.78‰ and $\delta^{13}\text{C}$ values -1.79 to -0.27‰ ; covariance between the two values accords with arid climatic conditions. The local plants include C3 and C4 types, with the latter being dominant. Each type has distinctive bulk organic carbon $\delta^{13}\text{C}$ values: -26.51 to -25.36‰ for C3-type, and -13.74 to -12.43‰ for C4-type plants.

The carbonate of the shell *E. desertorum* is composed of aragonite plus minor calcite, with relatively homogenous isotopic compositions ($\delta^{18}\text{O}_{\text{mean}} = -0.28 \pm 0.22\text{‰}$; $\delta^{13}\text{C}_{\text{mean}} = -4.46 \pm 0.58\text{‰}$). Most of the $\delta^{18}\text{O}$ values (based on a model for oxygen isotope fractionation in an aragonite-water system) are consistent with evaporated water signatures. The organic matter *E. desertorum* varies only slightly in bulk organic carbon $\delta^{13}\text{C}$ values ($-21.78 \pm 1.20\text{‰}$) and these values suggest that the snail consumed more of C3-type than C4-type plants. The overall offset in $\delta^{13}\text{C}$ values (-17.32‰) observed between shell *E. desertorum* carbonate and organic matter *E. desertorum* exceeds the value expected for vegetation input, and implies that 30% of carbon in the shell *E. desertorum* carbonate comes from the consumption of limestone material.

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1. Introduction

Land snails are gastropod mollusks with carbonate shells; their lifespan according to Heller (1990) varies from one species to another, with the majority of species living to around 1–2 years. The snails contain geochemical sensors of environmental change, mainly in the form of isotopic signatures. These organisms are susceptible to dehydration in arid or semi-arid regions by losing water via evaporation from body fluid. The amount of water loss depends on the relative humidity of the ambient environment, which in turn, is controlled by the temperature and pressure of the system. Because land snails are active during night and following rains (generally at temperatures between 10 and 27 °C and relative humidities above 70%), it has been assumed that snails' growth (i.e. secretion of the shell) takes place during times of relatively moist conditions when snails tend to be active (see Balakrishnan

and Yapp, 2004, for references). Consequently, the oxygen isotopic compositions of their shell carbonate may potentially record that of meteoric water at the time of shell precipitation, and should reflect conditions under a comparatively narrow range of moderate temperatures and high relative humidities. While some efforts from semi-arid and arid areas to relate the oxygen isotopic compositions of snail shells and local precipitation have failed (e.g. Goodfriend and Magaritz, 1987; Goodfriend et al., 1989; Colonese et al., 2007), several others studies have shown a relationship between local meteoric waters and $\delta^{18}\text{O}$ values of snail shells (e.g. Yapp, 1979; Bonadonna et al., 1999; Goodfriend and Ellis, 2002; Zanchetta et al., 2005; Yanes et al., 2008).

The values of $\delta^{13}\text{C}$ of the snail shells, on the other hand, are related to the isotopic composition of respiratory CO_2 derived from the assimilation of vegetation-based food resources (McConnaughey et al., 1997; McConnaughey and Gillikin, 2008) and to the isotopic composition of carbonates ingested by the snails (e.g. Goodfriend, 1987; Yanes et al., 2008). In contrast, the $\delta^{13}\text{C}$ values of the shell-bound organic carbon are primarily related to the isotopic composition of the vegetation diet (e.g. C3 vs. C4

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of the snails (Stott, 2002). In short, the $\delta^{13}\text{C}$ values of land snail records should reflect the $\delta^{13}\text{C}$ compositions of carbon sources that the organism consumed (e.g., Goodfriend and Magaritz, 1987; Goodfriend, 1988, 1990, 1992; Goodfriend and Ellis, 2000, 2002; Balakrishnan et al., 2005a,b; Yanes et al., 2008, 2009). These compositions are a reflection of the climatic conditions such as humidity or aridity of an environment.

There still remain large uncertainties in the feeding behavior and physiology of land snails, and consequently the isotopic compositions of snail carbonate and organic matter. Thus, the $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ components in the snail paleorecord are not precise indicators of the environments of snail-shell formation, but are most usefully reviewed along with other evidence of snail ecosystem conditions. Here, the author has integrated stable isotope data from recent desert communities at the New Cairo Petrified Forest, including soils, plants, as well as shell carbonate and organic matter of the land snail *E. desertorum*. The objective is to assess stable-O and C isotope signatures extracted from the carbonate and organic matter of the snail in relation to environmental variables characterizing their ecosystem. This, in turn, should allow us to better interpret the isotopic signals contained in the modern and fossil records of this snail, a species also occurring in fair abundances in other locations in Egypt (Biggs, 1959; FMNH, 2013; VBG, 2013) and Palestine (Mienis, 2004).

2. Materials and methods

The study area (Fig. 1), a natural reserve desert covering $\sim 6\text{ km}^2$ is located in New Cairo, about 20 km east of Old Cairo, Egypt. Low altitude predominates, with elevations from 290 to 375 m above sea level (masl). The exposed rock unit in the area known as the late Eocene Maadi Formation is made up of sand, gravel and calcareous shale (Hermina and Lindenberg, 1989), with a large number of silicified tree trunks (El-Saadawi et al., 2011). The soils there are dry, consisting of sand plus minor amounts of clay and carbonate, with minimal organic matter. Vegetation is limited to a few species of dry grasses and small shrubs. There are numerous well-preserved snail shells of variable sizes lying on the ground or buried partially by sand and gravel (Fig. 2) where no living population is present at the moment. These shells, identified as individuals of *Eremina desertorum*, were seen on slopes, open sites and, to a lesser extent, in direct association with vegetation and broken pieces of fossilized tree trunk. They appear of recent age where organic matter—a dry brown/dark substance—is occasionally found inside the upper whorls, which is mainly derived from decompositions of snail body tissues.

For this study 37 samples were selected from several sites (between 316 and 360 masl; Fig. 1): (1) 5 samples of soils, (2) 10 samples of plants, (3) 12 samples of shell *E. desertorum*, with very similar sizes and shapes, and (4) 10 samples of organic matter *E. desertorum* that had been trapped in the upper whorls of snail shells and was then removed after the shells were chopped into sections. The soil and shell *E. desertorum* samples were dried at room temperature and then were ground and converted to powder, so each analyzed aliquot represents a homogenized specimen. Powder samples were analyzed by X-ray diffraction (XRD) using a Philips X'Pert diffractometer (Cu-radiation) and were analyzed for magnesium (Mg) and calcium (Ca) contents by titration against EDTA after acid digestion at the Central Laboratory Sector of the Egyptian Mineral Resources Authority, Cairo.

Aliquots of the shell *E. desertorum* for determinations of their CaCO_3 content and isotopic composition were reacted in 105% phosphoric acid in vacuo at 90°C with an individual sample Multicarb device attached to a GVI IsoPrime isotope ratio mass spectrometry (IRMS). The resulting CO_2 was cryogenically purified of H_2O vapor at -94°C , concentrated on a cold finger at -180°C , and introduced directly into the IRMS inlet at the Stable Isotope Laboratory, University of California, Davis, USA. Bulk soil samples were processed similarly, but analyzed using a common acid bath autocarbonate device attached to a Fisons Optima isotope IRMS. Multiple samples of a laboratory marble standard (UCD-SM92) which was previously calibrated against NBS-19 (limestone), were weighed and analyzed with the samples in order to standardize the stable isotope data to V-PDB (Vienna Pee Dee Belemnite) and to compute wt% CaCO_3 content of the samples through a regression comparison of the standard mass to mass 44 beam intensity. Isotopic data are expressed in per mil (‰) values using standard delta (δ) notation: where $\delta^{13}\text{C}$ or $\delta^{18}\text{O}$ (‰) = $[(R_{\text{sample}})/(R_{\text{standard}}) - 1] \times 1000$ and R is a $^{18}\text{O}/^{16}\text{O}$ or $^{13}\text{C}/^{12}\text{C}$ ratio. Precision is $\pm 0.07\text{‰}$ for $\delta^{13}\text{C}$ and $\pm 0.04\text{‰}$ for $\delta^{18}\text{O}$ ($\pm 1\sigma$). The analytical precision of the measured CaCO_3 content is $\pm 0.14\text{ wt\%}$ for soil and $\pm 0.1\text{--}5.6\text{ wt\%}$ for shell *E. desertorum* samples.

Samples of the plants and organic matter *E. desertorum* to be measured for their organic carbon content and isotope composition were reacted with HCl to dissolve carbonates and then water washed. The samples were dehydrated in an oven at about 80°C , and then ground. Subsamples of 1–4 mg were weighted into tin

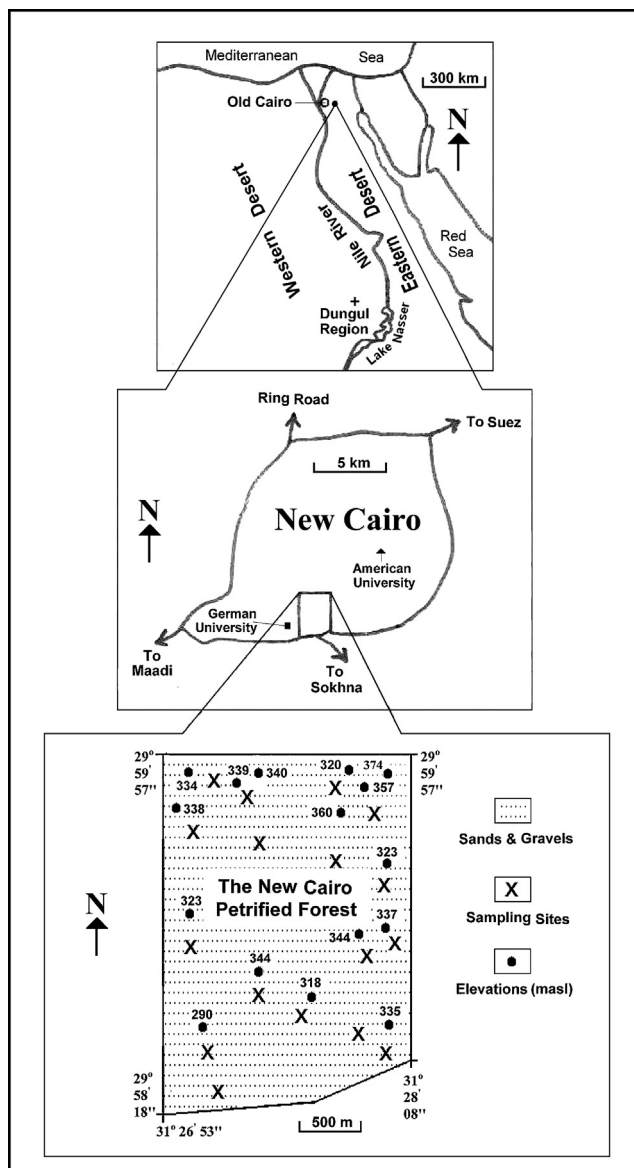


Fig. 1. Geographical location of the study area, with sampling sites and elevations.

capsules and analyzed for weight percent of organic carbon in a Vario EL Cube elemental analyzer (EA), where combustion of the samples occurred at 1000°C . The CO_2 produced after combustion was analyzed on a PDZ Europa 20–20 IRMS attached to the analyzer (the Stable Isotope Facility, University of California, Davis, USA) and the carbon isotope results are reported in δ notation, as ‰, with respect to the V-PDB standard. EA-IRMS precision (standard deviation determined from duplicate samples, using G-7 Peach leaves, G-18 Nylon and USGS-41 as the reference materials) was $\pm 1.4\text{ wt\%}$ for organic carbon analysis and of $\pm 0.2\text{‰}$ V-PDB for $\delta^{13}\text{C}$ ($\pm 1\sigma$) in the samples.

3. Results

The powder X-ray diffractograms with identifications of minerals are shown in Fig. 3. In the samples of the shell *E. desertorum*, aragonite was identified as the main component with a minor amount of calcite. In the soils hosting these shell samples, on the other hand, in addition to the major mineral quartz, amphibole, plagioclase, kaolinite, and calcite low in magnesium were identified by XRD analysis as minor components; they were associated with minor amounts of dolomite.

The CaCO_3 contents of the shell *E. desertorum* samples ranged from 94.7 to 99 wt%, while the CaO ranged from 53 to 53.5 wt% and the



Fig. 2. Field photographs from the New Cairo Petrified Forest showing fossil shells of the desert snail *Eremina desertorum* (Forsskål, 1775): Helicidae (family), Helicinae Rafinesque, 1815 (subfamily), Gastropoda Pulmonata (class), Mollusca (phylum); the shells are of unequal size (scale bar = 30 mm). Shell diameters from ~1.2 to 2.4 cm.

MgO from 0.06 to 0.071 wt%. For the soils, contents of CaCO₃, CaO, and MgO ranged from 5.6 to 11.25, 1.05 to 6.12, and 0.54 to 3.68 wt%, respectively.

Results of oxygen and carbon isotope analyses of carbonate from shell *E. desertorum* and soil samples from the study area are given in Table 1, along with the CaCO₃, CaO and MgO contents. The $\delta^{18}\text{O}$ values of the shell *E. desertorum* carbonate range from -0.65

to $+0.01\%$ with a mean of $-0.28 \pm 0.22\%$, while the $\delta^{13}\text{C}$ values range from -5.01 to -3.00% , with a mean of $-4.46 \pm 0.58\%$. For the soil carbonate, $\delta^{18}\text{O}$ values range from -3.19 to -1.78% with an average of $-2.55 \pm 0.57\%$ and the $\delta^{13}\text{C}$ values from -1.79 to -0.27% and averaging $-0.98 \pm 0.61\%$. The differences in $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ values observed between the shell *E. desertorum* carbonate (mainly aragonite) and soil carbonate (mainly calcite) are not

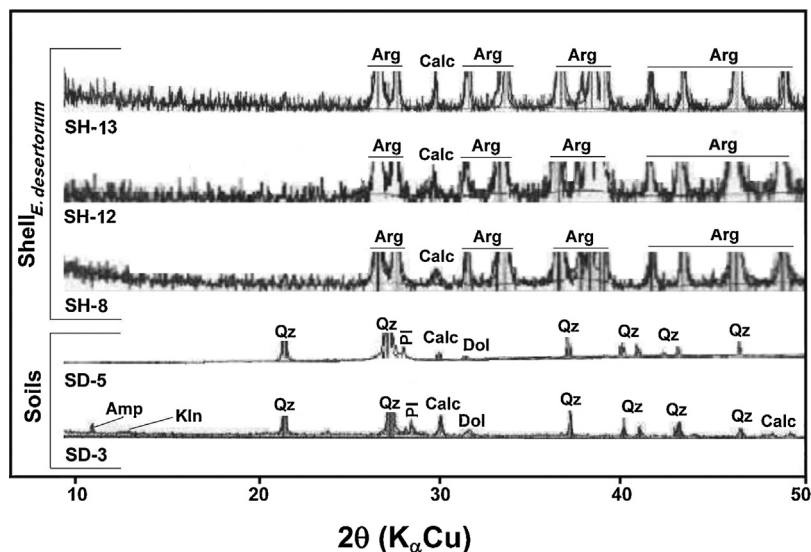


Fig. 3. X-ray powder diffractograms from selected soil and shell *E. desertorum* samples from the New Cairo Petrified Forest, Egypt. Mineral abbreviations in alphabetical order: Amp (amphibole), Arg (aragonite), Calc (calcite), Dol (dolomite), Kln (kaolinite), Pl (plagioclase), Qz (quartz).

Table 1
Carbonate compositions and isotopic values of samples from the New Cairo Petrified Forest, Egypt.

Sample	CaO wt%	MgO wt%	CaCO ₃ wt%	Carbonate, $\delta^{13}\text{C}$ ‰ V-PDB	$\delta^{18}\text{O}$ ‰ V-PDB
Soils					
SD-1	5.76	1.84	9.7	-0.27	-1.78
SD-2	-	-	9.0	-1.37	-2.61
SD-3	6.12	3.68	11.25	-1.79	-3.19
SD-4	-	-	9.65	-0.88	-2.97
SD-5	1.05	0.54	5.6	-0.60	-2.18
Mean	4.31	2.02	9.04	-0.98	-2.55
(S.D.) ^a	2.83	1.58	2.09	0.61	0.57
Fauna					
<i>Eremina desertorum</i>					
Shells					
SH-6	-	-	-	-4.54	-0.65
SH-7	-	-	99	-4.69	-0.42
SH-8	-	-	97	-3.80	-0.38
SH-9	-	-	-	-4.95	-0.20
SH-10	-	-	-	-4.91	-0.14
SH-11	-	-	-	-4.67	-0.42
SH-12	53.36	0.06	95.29 ^b	-4.59	0.00
SH-13	-	-	-	-4.06	-0.44
SH-14	53.5	0.071	95.55 ^b	-4.40	-0.51
SH-15	-	-	95	-4.85	-0.16
SH-16	-	-	99	-3.00	+0.01
SH-17	53.0	0.071	94.66 ^b	-5.01	-0.02
Mean	53.29	0.067	96.5	-4.46	-0.28
(S.D.) ^a	0.26	0.006	1.86	0.58	0.22

-, not analyzed.

^a Standard deviation ($\pm 1\sigma$).

^b Calculated from the CaO contents.

comparable with the oxygen (0.6‰) and carbon isotopic offsets (1.7‰) expected between aragonite and calcite precipitated in equilibrium (Grossman and Ku, 1986; Romanek et al., 1992); this is consistent with two different carbonate systems.

The contents of organic carbon and isotope composition from plants and organic matter *E. desertorum* from the study area are listed in Table 2. The organic carbon contents of the plants varied from 32.83 to 44.5 wt%, while the $\delta^{13}\text{C}$ values varied from -26.51 up to -12.43‰. This clear difference in $\delta^{13}\text{C}$ implies heterogeneous vegetation (e.g. Smith and Epstein, 1971). For the organic matter *E. desertorum*, organic carbon contents varied from 24.25 to 47.94 wt%, and $\delta^{13}\text{C}$ values from -19.86 to -23.38‰, comparable to those reported for recent land snail body tissues from arid-to-semi-arid areas in the eastern Canary Islands (Yanes et al., 2008).

4. Discussion

The New Cairo Petrified Forest is a low-latitude arid desert that is warm and dry in the summer and moderate with limited rainfall increasing in the winter. The isotopic compositions of rain water from ~15 km north of this area were monitored from 1987–1991 to 2000–2003 by the International Atomic Energy Agency (IAEA, 2013). The results show wide ranges of isotopic values: -8.18 to +5‰ V-SMOW for $\delta^{18}\text{O}$ and -56.9 to +40‰ V-SMOW for H^2/H^1 or $\delta^2\text{H}$ (Fig. 4). The isotopic values lie on trajectories having a slope of 6.78, a deviation from the global meteoric water line (Craig, 1961) that may reflect atmospheric circulation patterns, water vapor sources and evaporation modes. The weighted average values of $\delta^{18}\text{O}$ and δD for the rain water in the area for hydrologic years 1987/1988, 1989/1990, 1991, 2001 and 2003, calculated from the data presented here using normalized mean monthly rainfall from WMO (2014), are also given in Fig. 4. The calculated $\delta^{18}\text{O}$ values range from -5.39 to -0.61‰ V-SMOW. This range of $\delta^{18}\text{O}$ values is considered to be representative of the oxygen isotope variation of the rain water at the time of snail formation within the study

area. The weighted average value of $\delta^{18}\text{O}$ for present-day rain here, derived from the OIPC data base, is -4.6‰ V-SMOW (Bowen, 2008).

In the New Cairo Petrified Forest, vegetation is scarce and is represented by four different species: (1) *Haloxylon salicornicum* (Moq.) Bunge ex Boiss., (2) *Anabasis setifera* Moq., (3) *Zilla spinosa* (Turra) Prantl, and (4) *Centurea calcitrapa* L. The first two species belong to a family of flowering plants known as Chenopodiaceae and are classified as C3 plants (Calvin-Benson photosynthetic pathway), with $\delta^{13}\text{C}$ values of bulk organic carbon ranging from -26.51 to -25.36‰. The third and fourth species belong to the Cruciferae and Compositae, respectively, and are C4 plants (Hatch-Slack photosynthetic pathway), with bulk organic carbon $\delta^{13}\text{C}$ values ranging from -13.74 to -12.43‰. The clear difference in $\delta^{13}\text{C}$ values observed here between C3-type and C4-type plants is mainly metabolism-related (e.g. Smith and Epstein, 1971). Plants following the C3 photosynthetic pathway are known to dominate during wetter/colder conditions while those of the C4 pathway tend to respond well to life in stress and, hence, dominate during drier/warmer conditions (as in the Cairo Petrified Forest). The presence of both C3 and C4 plants translates biochemically into the vegetative landscape, providing land snails with a highly heterogeneous carbon isotope diet.

Before the $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ values of carbonates (shell and inorganic) are used for paleoenvironmental analysis, it is necessary to evaluate the degree of diagenesis which might have altered the samples. Most land snail shells are composed of aragonite, a metastable calcium carbonate (CaCO₃), and any diagenetic change will lead to either total dissolution or recrystallization, in the form of calcite, the stable form of CaCO₃, under these conditions. This implies that the carbonate of the shell *E. desertorum* samples collected at the study site, which are still composed of aragonite plus minor calcite (Fig. 3), has escaped diagenetic alteration for the most part. The soils in which these shells were found contain low-magnesium calcite plus a lesser amount of dolomite (Fig. 3). Low-Mg calcite indicates primary precipitation and therefore has been used to assess the chemistry of deposition (e.g.

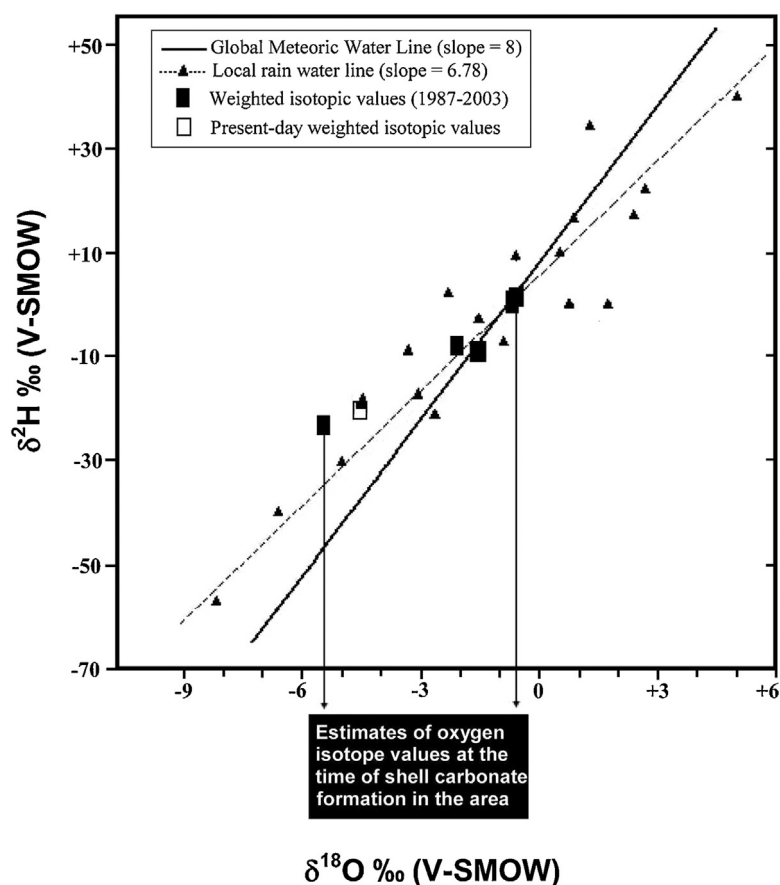


Fig. 4. Comparative plot of stable isotopic compositions of rain waters from New Cairo, Egypt (see text).

Hassan, 2014a,b). Collectively, the carbonates of the studied samples appear well-preserved and presumably record their initial environments.

Plots of $\delta^{18}\text{O}$ vs. $\delta^{13}\text{C}$ values for the shell *E. desertorum* and soil carbonates (Table 1) are shown in Fig. 5 along with those values from Hassan (2006) for carbonates from recent snail shells (*Z. insularis*) and their hosting tufas in the Dungul region, Egypt (Fig. 1). Correlation between $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ in shell *E. desertorum* carbonate does not exist ($r = +0.03$). There is, however, a significant correlation ($r = +0.85$) between the soil carbonate $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ values. This positive correlation could be linked to climatic factors such as aridity. In arid regions where evaporation rates are high, isotopically depleted H_2O and CO_2 molecules are lost from the surfaces of soils to the atmosphere, which causes simultaneous isotopic enrichments in the residual solutions in the soils; there should be a positive correlation between the $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ values of carbonates formed under these conditions. However, Cerling (1984) indicated that sometimes a covarying trend between $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ in soil carbonates is found; this is due to the fact that the oxygen and carbon isotopic composition of carbonates in soils is related to the isotopic composition of meteoric water and to the proportion of C3 biomass present, which in turn, both are temperature dependent.

The stable isotopic compositions of carbonate in the shell *E. desertorum* ($\delta^{18}\text{O}_{\text{mean}} = -0.28 \pm 0.22\%$; $\delta^{13}\text{C}_{\text{mean}} = -4.46 \pm 0.58\%$) are heavy in comparison to those of the carbonate shell of the desert land snail *Z. insularis* in Egypt/the Dungul Region, which ranged from -9.17 to -7.68% $\delta^{18}\text{O}$ and -8.12 to -5.77% $\delta^{13}\text{C}$ (Fig. 5). A wide range of isotopic compositions have been reported globally for land snail shell carbonate from natural settings: $\delta^{18}\text{O}$ values ranging from -11.7 to $+4.5\%$ and $\delta^{13}\text{C}$ values ranging from

-13% (see Balakrishnan et al., 2005a for references) to $+1.7\%$ (Yanes et al., 2008). Reported $\delta^{13}\text{C}$ values for snail carbonate from experimentally cultured *H. aspersa* fed with a controlled diet ranged from -24.3 to $+2.5\%$ (Stott, 2002).

In land snails, the water consumed by the snail mainly controls $\delta^{18}\text{O}$. However, because of variations in the isotopic composition of the environmental water that a snail may consume, there is no universal correlation between land snail shell $\delta^{18}\text{O}$ and a particular environmental factor: in humid regions meteoric water or precipitation tend to dominate the signal (e.g. Zanchetta et al., 2005), while at more temperate climates, temperature and humidity are the primary factors (e.g. Balakrishnan and Yapp, 2004).

The oxygen isotope composition of snail carbonate (aragonite) in oxygen isotopic equilibrium with water ($\text{CaCO}_3^{16} + \text{H}_2\text{O}^{18} \rightleftharpoons \text{CaCO}_3^{18} + \text{H}_2\text{O}^{16}$) is directly related to that of the water plus a temperature effect. If, for simplicity, it is assumed that the shell *E. desertorum* (mainly aragonite) was formed in isotopic equilibrium, from rain waters at a temperature range similar to the one observed for Cairo City (Open Source, 2014), then the oxygen isotopic composition of the waters of formation can be predicted using the following equation (modified from Grossman and Ku, 1986):

$$\delta^{18}\text{O}_{\text{water}} \text{‰ (V-SMOW)} = 4.54 - \delta^{18}\text{O}_{\text{shell } E. \text{desertorum}} - \text{Temperature}(T)$$

where $\delta^{18}\text{O}_{\text{shell } E. \text{desertorum}}$ is listed in Table 1 and $T = 16\text{--}28^\circ\text{C}$. The $\delta^{18}\text{O}$ values predicted for waters at the time when the *E. desertorum* precipitated their carbonate shell range from -1.9 to $+1.5\%$. These values are partly overlapping with the values estimated for

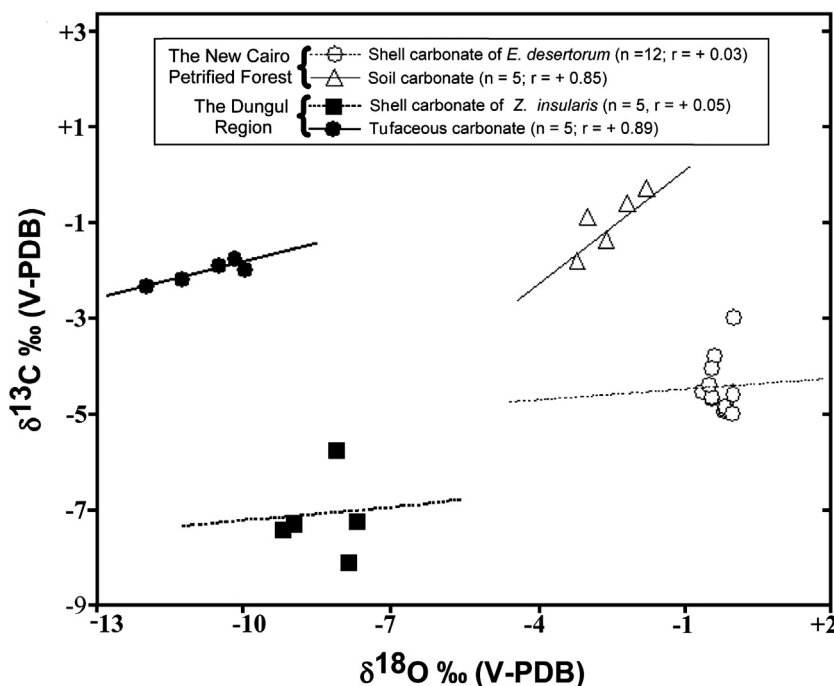


Fig. 5. Comparative plots of stable isotopic compositions of carbonate samples from Egypt (see text); n = number of samples; r = correlation coefficient.

rain water at the time of snail shell carbonate formation within the study area (black rectangular along the x-axis of Fig. 4). In particular, the predicted $\delta^{18}\text{O}$ values were higher than the observed values by up to $\sim 6.89\%$. This is consistent with data by other authors who have indicated that the $\delta^{18}\text{O}$ values of the shell carbonate of land snails from semi-arid to arid areas in Israel and in the Canary Islands show a notable enrichment, between 2 and 8‰ (Goodfriend and Magaritz, 1987; Yanes et al., 2008). This may have resulted from evaporation, but metabolic effects on body water (e.g. lower activity producing greater enrichment) cannot be ruled out. This interpretation of oxygen isotope fractionation cannot be made directly from this model which is limited by several prerequisite conditions. Hence, the assumptions that the mineralizing waters are identical to present-day rains and the shells analyzed formed under isotopic equilibrium conditions are difficult to prove. In addition, land snails utilize the ambient water vapor. Temperature might have a dominating effect on evaporation and the magnitude of the equilibrium oxygen isotope factor for the shell samples; however, other factors such humidity, wind action and aridity may significantly impact the evaporative signature in this hyperarid region. In the study area the relative humidity varies from 47 to 61%, with an annual average of 55.8%; storms, marked by wind with little or no precipitation, are frequent during the months of March and April (Open Source, 2014). Wind activity, a factor influencing evaporation rates and evaporation, is less known.

Attempts to use $\delta^{13}\text{C}$ values of land snails to estimate distribution patterns of C4- and C3-type plants have relied on several assumptions such as that the isotopic compositions of inorganic and organic carbon in fossilized shells and those of the former organisms are similar (Goodfriend and Hood, 1983; Goodfriend and Magaritz, 1987; Goodfriend, 1988, 1990). It has also been assumed that land snails consume C4- and C3-type plants indiscriminately and in amounts relative to the abundances of these plants in the environment. Another assumption that must be made is that there is a constant $\delta^{13}\text{C}$ difference between the two-plant types; further, that there is no significant fractionation between the diet and the body tissue of a snail. Notwithstanding, some updated

assumptions are used to construct a mass balance equation to account for the contribution of $\delta^{13}\text{C}$ from C3- and from C4-type plants. This equation is written as follows:

$$\delta^{13}\text{C}_{\text{snail organic carbon}} = \delta^{13}\text{C}_{\text{C3plant}} * (X) + \delta^{13}\text{C}_{\text{C4plant}}(1 - X) + 1 \text{‰} \quad (1)$$

where X = the fraction of C3-type plants consumed by the snail = amount of C3-type plants present in the snail environment; $\delta^{13}\text{C}_{\text{C3plant}}$ = the isotopic composition of C3-type plants; $\delta^{13}\text{C}_{\text{C4plant}}$ = isotopic composition of C4-type plants; and 1‰ = isotopic offset between the snail and its plant diet (Stott, 2002).

Applying Eq. (1) to results from Table 2 requires $56.7 \pm 9.2\%$ of the carbon in the snail's plant diet to be from the incorporation of C3 plants and the remaining portion from C4-type plants. This inference implies relative abundances of C3-type over C4-type plants in the study environment, which is at odds with the present-day dominance of C4-type plants which is in accordance with dry climatic conditions. It may be that individuals of the snail *Eremina desertorum* did not eat C3 and C4 plants indiscriminately or in proportion to their abundances in the environment, a possibility consistent with land snail *Helix aspersa* that was regularly fed with mixed plants and showed a preference for C3 food (Metref et al., 2003).

Experimental laboratory studies showed that the $\delta^{13}\text{C}$ of shell carbonate of the snail *H. aspersa* differs from the shell-bound organic carbon by only 12.3% (due to fractionation associated with the production of metabolic CO_2 and to the fractionation of this CO_2 with respect to the bicarbonate pool from which the carbonate precipitates), and was not influenced by the consumption of carbonate or by the diffusion of atmospheric CO_2 into the hemolymph (Stott, 2002). Therefore, the relatively large $\delta^{13}\text{C}$ offset (17.32%), from -4.64% in the shell *E. desertorum* (Table 1) to -21.78% in the organic matter *E. desertorum* (Table 2) suggests the snail may have also ingested inorganic or organic carbonates from local substrate. The

Table 2
Contents of organic carbon and isotopic values from the New Cairo Petrified Forest, Egypt.

Sample	Organic carbon, wt%	$\delta^{13}\text{C} \text{‰ V-PDB}$
Vegetation		
C4-type plants		
Chenopodiaceae		
<i>Haloxylon salicornicum</i> (Moq.) Bunge ex Boiss.		
C4-18	42.79	−13.32
C4-19	44.50	−13.54
C4-20	32.83	−12.43
<i>Anabasis setifera</i> Moq.		
C4-21	34.36	−12.60
C4-22	37.70	−13.74
Mean	38.44	−13.13
(S.D.) ^a	5.11	0.58
C3-type plants		
Cruciferae		
<i>Zilla spinose</i> (Turra) Prantl		
C3-23	39.28	−25.36
C3-24	43.10	−26.10
C3-25	44.24	−26.51
Compositae		
<i>Centurea calcitrapa</i> L.		
C3-26	34.17	−26.20
C3-27	35.93	−26.41
Mean	39.34	−26.12
(S.D.) ^a	4.37	0.45
Fauna		
<i>Eremina desertorum</i>		
Organic matter		
OM-28	24.25	−19.86
OM-29	24.33	−20.39
OM-30	40.43	−21.39
OM-31	41.31	−21.68
OM-32	24.33	−23.53
OM-33	30.07	−21.53
OM-34	34.16	−21.48
OM-35	25.17	−22.92
OM-36	31.33	−21.64
OM-37	47.94	−23.38
Mean	32.33	−21.78
(S.D.) ^a	8.46	1.20

^a Standard deviation ($\pm 1\sigma$).

$\delta^{13}\text{C}$ effect of possible carbonate ingestion in the study area can be calculated using the following expression:

$$\delta^{13}\text{C}_{\text{shell}} = \delta^{13}\text{C}_{\text{shell from plants}} * (X) + \delta^{13}\text{C}_{\text{soil carbonate}}(1 - X) + 1.7 \text{‰} \quad (2)$$

where $\delta^{13}\text{C}_{\text{shell}}$ = the measured value of the shell carbonate (which is mainly aragonite) = -4.64‰ (Table 1); $\delta^{13}\text{C}_{\text{shell from plants}}$ = the hypothetical value of the shell carbonate derived exclusively from the consumed vegetation, using the Stott (2002) equation ($\delta^{13}\text{C}_{\text{shell}} = \delta^{13}\text{C}_{\text{plant diet}} * 0.94847 + 12.278$; $r^2 = +0.98$) = -8.38‰ ; X = the fraction of vegetation consumed by the snail; $\delta^{13}\text{C}_{\text{soil carbonate}}$ = the value of the soil carbonate = $-0.98 \pm 0.60\text{‰}$ (Table 1); $1 - X$ = the fraction of soil carbonate ingested by the snail; and 1.7‰ = isotopic offset between aragonite and calcite when formed in isotopic equilibrium (Grossman and Ku, 1986).

Applying the values of $\delta^{13}\text{C}_{\text{shell}}$, $\delta^{13}\text{C}_{\text{shell from plants}}$, and $\delta^{13}\text{C}_{\text{soil carbonate}}$ to Equation 2 above suggests 30% of the snail carbon coming from ingestion of limestone carbonates from the local soils. This estimate appears reasonable given (1) similar estimates ($\sim 33\%$) previously published based on radiocarbon analysis from semi-arid areas in Israel and the West Bank (Goodfriend, 1987), (2) the predicted values for carbonate ingestion (20–40%) by snails

in arid-to-semi-arid areas in the eastern Canary Islands (Yanes et al., 2008), (3) the scarcity of vegetation in the study area, and (4) the presence of reasonable amounts of limestone carbonate in the soil and sediments of the study area. Consequently, $\delta^{13}\text{C}$ values of the carbonate shells from the Petrified Forest cannot be used as proxies of paleovegetation unless corrected for carbonate ingestion. Because the contributions of carbon from carbonates into snail shells, particularly in arid or carbonate-rich regions, mask dietary effects on $\delta^{13}\text{C}$, the plant diet should be identified using the carbon isotopic compositions of both shell carbonate and of the shell-bound organic matter of the snail. Whenever organic data are not available for fossil snails, it may be difficult to argue what the proportion of C4 (or C3) in the snail diet was.

5. Conclusions

The stable oxygen and carbon isotope compositions of shell carbonate and the carbon isotope composition of the organic matter from the modern land snail *E. desertorum* from the Cairo Petrified Forest are varying only slightly. Minimal isotopic variations are consistent with the isotopic patterns observed for the local soils and vegetation, which are also common generally for low-latitude deserts. The $\delta^{18}\text{O}$ values of the shell carbonate indicate evaporation-induced signatures. The $\delta^{13}\text{C}$ values of the organic matter, on the other hand, suggest a higher proportion of C3 than C4 plants in the diet of the *E. desertorum*. The difference in $\delta^{13}\text{C}$ values observed between shell *E. desertorum* carbonate and organic matter *E. desertorum* exceeds the expected value for snails regularly fed with a plant diet. A mass balance model—based on the $\delta^{13}\text{C}$ of shell *E. desertorum* and soil carbonates and the hypothetical $\delta^{13}\text{C}$ value of the shell *E. desertorum* carbonate derived exclusively from the ingested vegetation—indicates that the former snail in the environment of study ingested notable amounts (30% on an average basis) of limestone carbonate.

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