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Vermetid reefs in the Mediterranean Sea as archives of sea-level and surface temperature changes

Renato Chemello[a]* and Sergio Silenzi[b,c]

[a]*Dipartimento di Ecologia, Università di Palermo, Palermo, Italy;* [b]*ISPRA – Istituto Superiore per la Protezione e la Ricerca Ambientale, Rome, Italy;* [c]*Dipartimento di Scienze della Terra, Università di Roma La Sapienza, Rome, Italy*

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Vermetid reefs are among the most important bioconstructions in the Mediterranean Sea, with a distribution restricted to the warmest part of the basin. Their structure, and vertical and geographical distribution make them good biological indicators of changes in sea level and sea-surface temperature over the last two millennia.

Keywords: vermetid reef; sea-level change; sea-surface temperature; Mediterranean Sea

1. Introduction

In marine ecosystems, a bioconstruction is any structure built by living organisms that rises from the bottom towards the surface and is able to modify the local environment both physically and ecologically [1]. All bioconstructions increase in volume or thickness through progressive stratification by generations of successive organisms. However, they can be eroded or destroyed by other organisms and by physical factors, following a cycle of bioconstruction/bioerosion [2].

Whatever their origin, all bioconstructions share unique features, such as structural complexity and rigidity. Structural complexity varies with building species, and depends on their growth forms, the geology and morphology of the seabed, exposure and water depth. Structural rigidity is due to the deposition of calcium carbonate in the form of skeletons or shells which, by providing great resistance to breaking and eroding agents, also contribute to longer habitat stability [3]. Furthermore, all bioconstructions have a positive topographic relief due to the physiological response of the habitat builders to sedimentation, and the need for better nourishment and favourable conditions for the associated symbionts. As a consequence, high growth rates are needed to cope with marine erosion and borers (which account for the high production of sediments associated with bioconstructions). In these systems, deposition and erosion are opposite processes, the balance tilting toward deposition in growing buildups. This balance can be influenced by the growth habit of the structure which can, at times, undergo a kind of ‘suicide’, leading to its destruction by catastrophic events [4].

*Corresponding author. Email: chemello@unipa.it

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Vermetid reefs are bioconstructions commonly found in the southern Mediterranean Sea. They have proved to be excellent natural archives to reconstruct both the paleosea level and sea-surface temperature fluctuations. Moreover, up- or down-lifted fossil reefs may provide information on the vertical displacement of coastal areas at the local scale (see Antonioli et al. [4] and Pirazzoli et al. [5] for a complete list of references).

Vermetids precipitate an aragonite shell that is considered to be in isotopic equilibrium with the ambient seawater. Although it has not yet been established whether vermetids have an important effect on the isotopic composition of their shells, or whether seasonality affects this isotopic composition, a preliminary study [6] showed that coeval and living vermetid shells, sampled in different portions of Sicilian reefs, have the same isotopic signature (<0.01‰ variation in $\delta^{18}O$). A later, more exhaustive article [7] established that the vermetid isotopic signature is in equilibrium with the environment. Oxygen isotopes obtained from analysis of fossil remains can be converted into temperature records by using the biogenic aragonite vs. temperature fractionation equation [8] and AMS ^{14}C dating for the age model.

Here, we provide a short review of the main results obtained to date on vermetid reefs as potential archives for paleoclimatic reconstructions in the Mediterranean region.

2. Description of a vermetid reef

A typical vermetid reef is the outcome of complex synergistic building activity by the vermetid mollusc *Dendropoma* (*Novastoa*) *petraeum* (Monterosato, 1892) and the encrusting red alga *Neogoniolithon brassica-florida* (Harvey) Setchell & Mason (1943) [9]. Other species, namely the vermetid *Vermetus* (*V.*) *triquetrus* A. Bivona, 1832, and red algae *Lithophyllum byssoides* (Lamarck) Foslie (1900), *Lithophyllum incrustans* Philippi (1837) and *Neogoniolithon mamillosum* (Hauck) Setchell & Mason (1943) may also support *D. petraeum* and *N. brassica-florida* in the process of bioconstruction.

In a recent article, Calvo et al. [10] genetically characterised *D. petraeum* throughout its entire distribution range in the Mediterranean Sea. Data from different sites indicate the existence of a cryptic species complex within *D. petraeum*, comprising at least four species. According to the authors, such diversification processes were mainly the result of a series of vicariant partitions by the ancestor of the *D. petraeum* complex. The history of the distribution of *Dendropoma* populations includes fragmentation processes resulting from past isolation of water masses followed by restricted gene flow among sub-basins.

Using literature data, a general model of a vermetid reef can be described (Figure 1(a),(b)), following a hypothetical transect from shore to open sea [9]. (1) A small encrustation, a few centimetres thick, built by the two encrusting red algae *N. brassica-florida* and *L. byssoides*. This formation is widely distributed along the Mediterranean basin, where it often substitutes the vermetid reef under sciaphilic conditions or in the absence of *Dendropoma*. (2) An inner margin, formed by *D. petraeum*, a few centimetres thick and ∼5–50 cm wide, depending on local exposure. (3) One or more small pools, called cuvettes, ∼10–200 cm (or more) in size and generally <50 cm deep. Cuvettes can be compared to small retrorecifal lagoons. (4) An outer margin, consisting of a very thick formation by *Dendropoma*, occasionally over 40 cm wide and 50 cm thick. This portion, which is typically quite complex and rich in crevices, is the active part of the vermetid platform, growing outwards and upwards. (5) An upper infralittoral belt made by the brown alga *Cystoseira amentacea* var. *stricta* and developed below the outer margin of the platform. Given the peculiar environmental conditions, groups of small structures (called islands or atolls) can occur externally to the reef, due to the different erosion rate between the coast and the reef itself.

Vermetid reefs develop in the lower mesolittoral and upper infralittoral, on rocky coasts only. Their size depends on the type of substrate, decreasing with the series: sandstone, limestone,

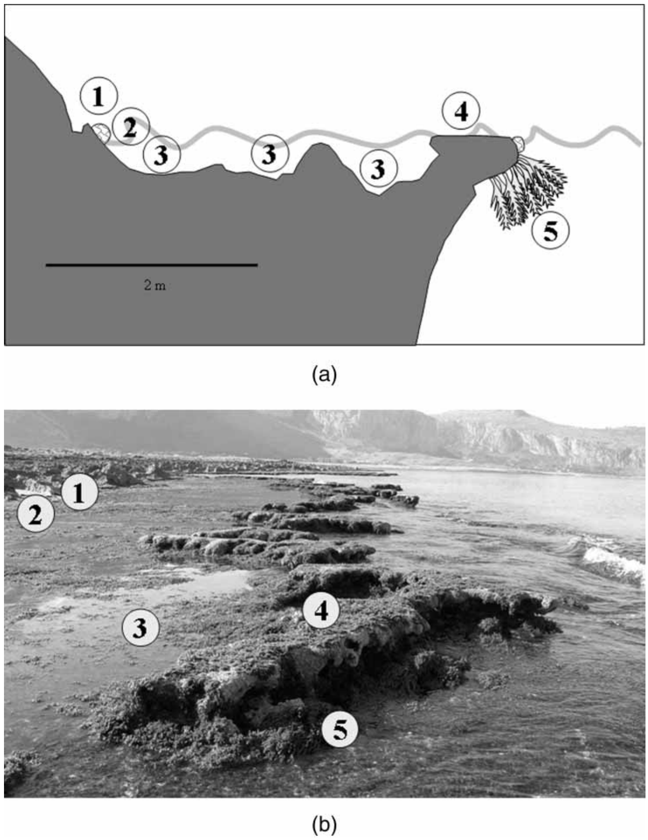

Figure 1. (a) A simplified model of a vermetid reef along a hypothetical transect from shore to open sea. (b) A vermetid reef from a field study along the Sicilian coast. The numbers refer to the different parts of the reef described in section 2 of the text.

dolomite and flysch [9]. The presence of an abrasion platform is the essential condition for a true reef. However, Schiaparelli et al. [11] observed that *D. petraeum* preferentially colonises granite, rather than limestone, along the coasts of Sardinia. This may be explained by competition processes acting during the settlement phase, as vermetid larvae may prefer substrata where the algal cover is reduced.

A second environmental feature influencing the distribution and size of these structures on a small scale is the hydrodynamism of shallow water layers, because vermetid platforms are rare along sheltered coasts. Accordingly, large vermetid reefs are present in Sicily along the entire coast facing north/northwest, whereas only smaller reefs are found along northeast coasts [12].

Finally, the slope of the shore also plays a role in determining the size and shape of bioconstructions: larger reefs develop where the slope is between 15° and 40° on the horizon line. By contrast, vermetid formations growing on flat shores (0–15°) show reduced thickness and width, and appear as ledges or thin crusts. Where slopes exceed 40° (cliffs), formations rapidly decrease in size, being completely absent from 50° onwards [12].

3. Distribution of vermetid reefs in the Mediterranean Sea

Mediterranean vermetid reefs are found where the temperature of surface coastal waters is no lower than 14°C (in winter). The upper latitudinal limit for these formations is around 38°N,

Figure 2. Mediterranean distribution of the main vermetid reefs cited in the text. The light grey stripe indicates the megatransect described in section 4 of the text. Dot size is proportional to reef surface length. White dots indicate sites sampled along the megatransect.

although Laborel [13] recorded them in the north of Corsica, though further confirmation by direct observation is needed.

The present-day distribution of vermetid reefs includes the central-southern Mediterranean Sea, although they are more frequently found in eastern areas of the basin (Figure 2). The largest structures, developed as reefs or atolls, were described along the Israeli coasts [14–16], although living vermetid reefs are progressively disappearing in this region (G. Rilov, pers. comm.). A similar situation occurs in Lebanon, where vermetid formations are evenly distributed along the coast [17], but living reefs are present in only a few locations (Sidon, Tyre). This may be linked to oil spills and cleaning operations following the 2006 war (S. Silenzi, pers. obs.). Reefs have also been reported in southern Turkey and Crete [13]. Along Maltese shores, vermetids developed mainly as crusts and ledges [18], although the presence of some true reefs is acknowledged [19]. Vermetid platforms have been observed at Tipaza and Fouka-Marine in Algeria [20] and small formations have been found along Mediterranean Moroccan coasts (Gofas S.) [21]. In Spain, vermetid formations are mainly distributed between Cap de la Nao (near Alicante) and Cabo de Gata (Almeria) in the southeast Iberian Peninsula [21,22]. Some well-developed bioconstructions have also been described in Ibiza and Formentera in the Balearic Islands [21,22]. Along the continental shores of Italy there are no published studies on the distribution of vermetids, although some structures are known on the Island of Licosa (Campania; G.F. Russo, pers. comm.), in Campomarino (Taranto – Apulia; S. Silenzi, pers. comm.), and in Capo Rizzuto (Calabria; S. Silenzi, pers. comm.). *Dendropoma petraeum* has been reported on the island of Ischia, in the Gulf of Naples [23], and on northwest coasts of Sardinia, between Capo Figari and Tavolara Island, with a ledge morphology [11]. Large reefs are found in northern Sicily, between Milazzo Cape and the coast of Trapani with the Egadi Islands. Some small reefs, shaped as ledges and encrustations, are also found around Taormina and Syracuse, on the eastern coast of Sicily, and on the islands of Lampedusa and Ustica [9,12].

4. Vermetid reefs as natural archives of past climatic variations

Vermetid reefs have only recently been recognised as natural archives for reconstructing past sea-surface temperature variations and sea-level changes [4,6,7,24]. Vermetid bioconstructions are widely distributed in the Mediterranean basin, located between the lower mesolittoral and the upper infralittoral, and are mostly found in place (and not reworked by marine erosion). Because of their continuous growth and the possibility of dating the fossil portion using AMS ^{14}C, vermetids represent unique archives which retain palaeoclimatic information at high-resolution, spanning the last ∼2000 years. All these reasons make them ideal biological sea-level indicators [25].

In the central Mediterranean region, for example, the study of vermetids can provide an accurate reconstruction of the sea level of the late Holocene, based on precise knowledge of the vertical position of the living portion with respect to reef mean sea level and longevity [26]. Along Levantine coasts, tectonic vertical displacement values were extracted from tens of sites using *D. petraeum* as a bioindicator of past sea level [27].

Current knowledge of past sea-level variations in the Mediterranean Sea results mainly from beachrock deposits [28], submerged speleothems [29,30], and archaeological remains [31,32] and other biological markers [33] which, however, do not cover the last 2000 years. The interval between the fifteenth and nineteenth centuries, which includes the end of the Medieval Warm Period and the Little Ice Age (LIA) is crucial to understanding the link between sea-level changes and rapid climatic fluctuations, and can only be studied using fossil vermetid reefs.

A portion of vermetid reef collected in a tectonically stable area in northwest Sicily and radiocarbon dated at 430 ± 30 yr cal BP revealed that the sea level was -40 ± 8 cm below present mean sea level [4]. The same portion was analysed for stable isotopes ($\delta^{18}O$) by Silenzi et al. [6], who identified a colder phase during the LIA (between the seventeenth and nineteenth centuries), with a sea-surface temperature 1.99 ± 0.37°C lower than today, consistent with literature data [34]. Recently, data by Silenzi et al. [5] have been revised based on the aragonitic structure of *D. petraeum* [26], by applying the fractionation equation of biogenic aragonite and sea-surface temperature [$T = 20.6 - 4.34 \times (\delta^{18}O_{aragonite} - \delta^{18}O_{seawater})$]. Conversion of the $\delta^{18}O$ time series into temperature resulted in an average annual temperature for the LIA ranging from 17.6 to 21.1°C. The period after the LIA is characterised by a warming trend which is briefly interrupted by a colder phase between 1930 and 1940, which lasted until the mid-1990s (Figure 3(a)).

Following these promising results, Sisma-Ventura et al. [7] reconstructed the sea-surface temperature, hydrology and productivity along the Israeli coast using the $\delta^{18}O$ and $\delta^{13}C$ signatures of seven cores. The isotopic data span the last 500 years with an average resolution of 6 years. The authors showed that the $\delta^{18}O$ signature of the living *D. petraeum* corresponds precisely to the range of values for inorganic carbonates precipitated at equilibrium with seawater for a temperature range of 23–28°C (Figure 3(b)).

The LIA in the Israeli coast is characterised by two cold anomalies (around 1590 and 1700 yr cal BP) separated by an intermediate warm period (∼1580–1680 yr cal BP). According to the authors, the Levantine Basin was probably 1°C colder than the present during the LIA maximum. However, due to the poor chronological constrain, based on only a single ^{14}C dating obtained by Antonioli et al. [4] in Sicily, care should be taken in interpreting the results presented by Sisma-Venturi et al. [7].

Recently, Silenzi et al. [26] presented new data on sea-level variation in the western Mediterranean, covering two specific time periods (between 2380 ± 40 and 1520 ± 45 yr cal BP, and over the last three centuries). These data were obtained from two tectonically quasistable areas: S. Vito Lo Capo (northern Sicily) and Cabo de Gata (southeast Spain). Preliminary results show that the sea level in Sicily rose from -27.5 ± 1.6 cm (2385 ± 40 yr cal BP) to -10.5 ± 1.6 cm (1520 ± 40 yr cal BP), with an average rate of 0.20 ± 0.02 mm $\cdot$ yr^{-1}.

New studies are currently being performed along a west–east megatransect in the Mediterranean Sea: ^{14}C AMS dating, $\delta^{18}O$ and trace element ratios on 16 new cores from southeast Spain, northwest Sicily, west Apulia, north Tunisia and several locations on the coasts of Lebanon and Crete. All these data will be combined with the aim of reconstructing the Mediterranean sea-level and sea-surface temperature variations during the last two millennia.

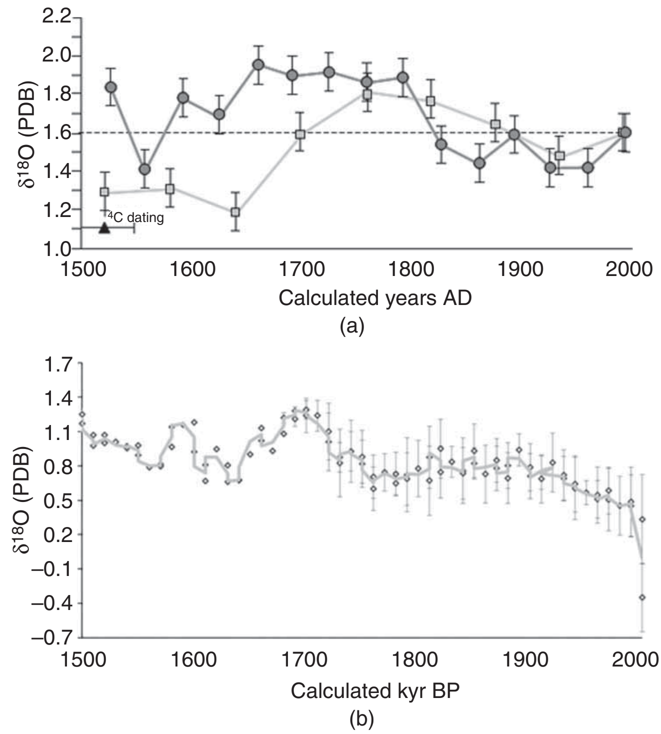

Figure 3. The $\delta 1^{18}$O (‰ PDB) composition of two different transects of the Sicilian Vermetid colonies (a) (modifed from Silenzi et al. [6]) compared with the mean δ^{18}O (‰ VPDB) recorded from the Israeli Mediterranean coast (b) (modified from Sisma-Ventura et al. [7]). The black triangle in (a) represents the calibrated ^{14}C date on which the chronological models of all the three records are based. The dashed lines in the Sicilian records indicate the δ^{18}O value of each section for actual living Vermetids.

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