Biodiversity and geodiversity in the mud volcano field of the Spanish margin (Gulf of Cádiz)

Biodiversidad y geodiversidad en el campo de volcanes de fango del margen Español (Golfo de Cádiz)

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Cold seeps and mud volcanoes represent heterogeneous seafloor structures that promote a wide variety of geological features, habitat types and associated biota. In Spanish waters of the Gulf of Cádiz, a total of 11 mud volcanoes have been found so far, containing more than 15 habitat types (according to EUNIS and LPRE) and around 850 species. Some of these species (~ 20 spp.) are included in local, national or international conservation lists of threatened species, others represent first records for this area and more than 50 are of commercial value. The biodiversity found in the mud volcano field of the Spanish margin of the Gulf of Cádiz is influenced by its biogeographical location (with Atlantic, Mediterranean, African, amphiatlantic and endemic species), its wide bathymetric range (from 300 to 1100 m depth), the singular biogeochemical and sedimentological characteristics of each mud volcano and the combination of different sampling methods targeting different faunistic components. According to the new directives (Habitats directive, Marine Strategy Framework directive) and the anthropogenic impacts occurring in the area (especially trawling fisheries), conservational measures should be carried out for a balanced and sustainable extraction of the natural resources and the conservation of the Spanish and European Natural heritage regarding these singular deep-sea ecosystems.

Palabras clave: surgencias frías, corales de aguas frías, quimiosíntesis, carbonatos autigénicos, hábitat.
Keywords: *cold seeps, cold-water corals, chemosynthesis, authigenic carbonates, habitat.*

INTRODUCTION

Cold seeps were discovered in 1983 in the Gulf of Mexico and, since then, further studies have demonstrated their presence in the margins of every continent of the world (Milkov, 2000; Van Dover et al., 2002). In these systems, hydrogen sulfide, methane and other hydrocarbon-rich fluid seepage occurs, influencing the mobilization of subsurficial sediment and, in some cases, the formation of mud volcanoes. Chemosynthetic bacteria promote the formation of authigenic carbonates (chimneys and slabs) due to the anaerobic oxidation of methane. This process increases the sedimentary and habitat complexity and influences differences with the surrounding bottoms or between mud volcanoes in different stages of their development (Díaz-del-Río et al., 2003; León et al., 2007; Fernández-Zambrano et al., 2012). In European waters, mud volcanoes are included in the Habitats Directive (Habitat 1180, Submarine structures made by leaking gases) and, therefore, deserve protection. For such reason, it is of importance to increase the knowledge on different aspects of their distribution, functioning and dynamics, faunistic assemblages and natural resources, among others.

The Gulf of Cádiz represents an important area of seepage activity with the presence of ca. 50 mud volcanoes, of which ca. 20 are located in European waters (Spain and Portugal) (Medialdea *et al.*, 2009; León *et al.,* 2012). Fluid venting structures in the Gulf of Cádiz are related to salt tectonics and diapirism developed in a compressional system linked to Africa-Eurasia plate convergence (Medialdea *et al.,* 2009). There is a high variety of geomorphic features widespread along the sea floor associated with fluid venting, being mud volcanoes the most common one and consisting in a cone-shaped edifice built up by successive episodes of mud flows as a result of degassing processes in deep diapiric marls bodies. Previous projects and sampling expeditions have resulted on a large amount of information on different aspects of mud volcanoes of the Moroccan margin, which seem to have a higher seepage activity than those of the Iberian margin. Previous studies mainly focused on their geological characteristics, whereas others offered novel information on their associated biota, especially the endosymbiont-bearing invertebrates as well as non-previously described species (reviewed in Vanreusel *et al.*, 2009). On the other hand, information on those located in the Spanish margin of the Gulf of Cádiz was mostly restricted to geological topics until the project INDEMARES/Chimeneas de Cádiz (Díaz-del-Río *et al.*, 2003; León *et al.,* 2007; Medialdea *et al.,* 2009; Rueda *et al.,* 2011). This project is nowadays studying habitats and associated biodiversity in order to identify areas that deserve protection within the Gulf of Cádiz, representing an opportunity for increasing the knowledge on these cold seeps that enrich the local and European natural heritage.

MATERIAL AND METHODS

Samples were collected in different areas (summit, flanks, seafloor depression, adjacent bottoms) of eleven mud volcanoes located within Spanish waters (Albolote, Gazul, Anastasya, Tarsis, Pipoca, Chica 1 & 2, Hespérides, Almazán, St Petersburg and Aveiro), from 300 to 1,100 m water depth, during the INDEMARES/CHICA 0610, 0211 and 0412 surveys (Fig. 1). This mud volcano field is exposed to the highly saline (36.1-36.9 psu) and warm (ca. 13°C) Mediterranean Outflow Water (MOW) that forms a strong bottom current flowing towards the W and NW above the less saline (34.9-35.2 psu) and cold (3-8°C) North Atlantic Deep Water (NADW) (Nelson *et al.*, 1999). Sampling was carried out using different methods such as box-corer (BC) (ca. 0.09 m^2 of sampling area, n=82), benthic dredge (DA) (ca. 300 m^2, n=56) and beam-trawl (BT) (ca. 2000 m^2, n=40) on board R/V Emma Bardan, Cornide de Saavedra and Ramón Margalef. Sediments collected with the box-corer (generally up to 0.20 meters below seafloor) were sectioned at 5 cm intervals and sieved (0.5 mm) in order to study the vertical distribution of species. Material collected with the benthic dredge was sieved on a sieve column of 10, 5 and 1 mm mesh sizes. Large specimens were generally sorted just after sampling on board and small size individuals were separated from the sediment in the laboratory using stereo microscopes. Individuals were preserved in 70% Ethanol, 10% Formaldehyde, 2.5% Glutaraldehyde or dry for the case of shell remains. Moreover, some areas have also been explored with ROV LIROPUS 2000 and VOR APHIA 2012, obtaining images of species that were not collected by the traditional sampling methods.

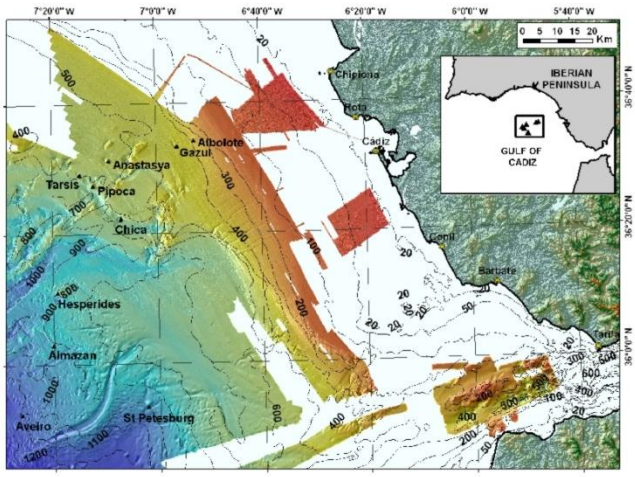

Fig. 1. Location of mud volcanoes in the Spanish margin of the Gulf of Cádiz.

Environmental variables from the water column (current speed, temperature, salinity and oxygen content), the sediment (pH, Eh, grain size distribution, % organic matter, % carbonates) and the human activity (vessel monitoring systems) were also studied in the sampled areas.

RESULTS

More than 850 species have been found in the mud volcano field of the Spanish margin, with molluscs displaying the highest number of species (~200 spp.), followed by fishes (~120 spp.), annelids (~110 spp.), crustaceans (~100 spp.), cnidarians (~80 spp.), sponges (~80 spp.) and echinoderms (~50 spp.), among other groups that display a lower representation (brachiopods, sipunculids, bryozoans, etc.).

Around 20 species are included in local, national and international lists of threatened or vulnerable species, such as the cnidarians (*Madrepora oculata, Dendrophyllia cornigera, Lophelia pertusa*), echinoderms (*Centrostephanus longispinus*), molluscs (*Charonia lampas*) and fishes (*Centrophorus granulosus*) (Fig. 2).

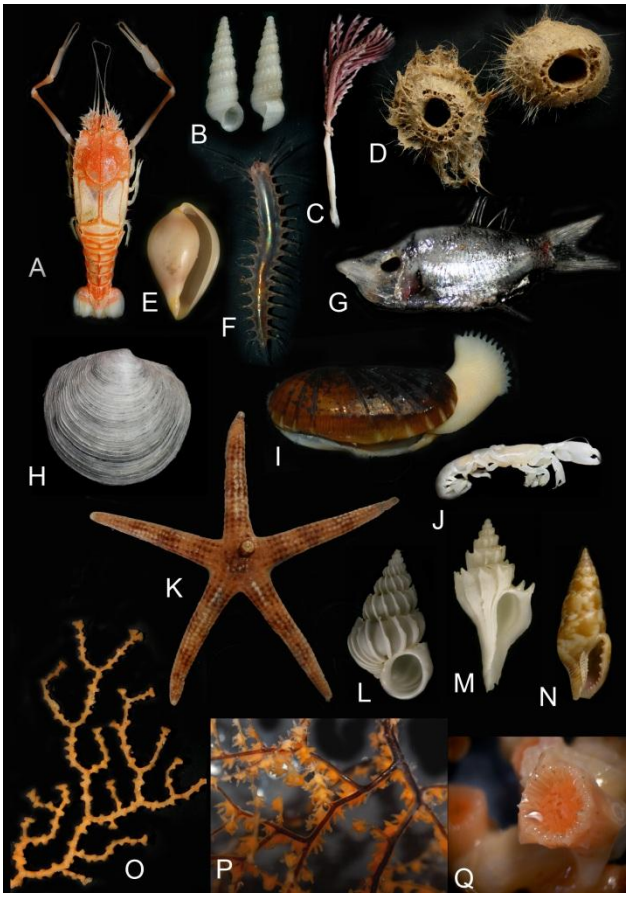

Fig. 2. Some species found in mud volcanoes with different bio-geochemical and sedimentological characteristics within Spanish waters of the Gulf of Cádiz: (A) Stereomastis sculpta; (B) Bittium watsoni; (C) Pennatula aculeata; (D) Pheronema carpenteri; (E) Pseudosimnia flava; (F) Leocrates atlanticus; (G) Opisthoproctus grimaldii; (H) Lucinoma asapheus; (I) Solemya elarraichensis; (I) Calliax sp.; (K) Hacelia superba; (L) Epitonium celesti; (M) Pagodula echinata; (N) Mitrella pallaryi; (O) Chelidonisis aurantiaca; (P) Leiopathes glaberrima; (Q) Madrepora oculata.

Other species are new records for the area (Hacelia superba, Acharax gadirae, Pseudosimnia flava, Neopycnodonte zibrowii, Solemya elarraichensis, Lucinoma asapheus, Zenion hololepis, Opisthoproctus grimaldii). Around 60 spp. are of commercial interest, being mostly decapods (Nephrops norvegicus, Palinurus mauritanicus, Parapenaeus longirostris) and fishes (Lophius spp., Helicolenus dactylopterus, Merluccius merluccius, Phycis blennoides), and representing an

important natural resource that is permanently exploited by the large trawling fleet (128 vessels, mainly from Sanlucar de Barrameda and Isla Cristina). This fishing activity is high in Albolote and Anastasya mud volcanoes, representing an important threat to their habitats and biological communities.

The endosymbiont bearing chemosynthetic fauna occurs at the summits of most mud volcanoes (except Albolote and Chica), displaying higher densities and number of species in Anastasya, Hespérides, Aveiro and Almazán. The most common species are the frenulate polychaetes (*Siboglinum* spp.) and some infaunal bivalves (*A. gadirae, S. elarraichensis, L. asapheus*). Other typical cold seep species are only represented by shell remains (*Bathymodiolus* sp., *Isorropodon* sp.) in some mud volcanoes, indicating stronger seepage conditions in the past or their occurrence in restricted areas that have not been sampled yet. Underwater images showed the presence of several filamentous bacterial mats at the summit of Anastasya, suggesting a high fluid expulsion, but also the presence of a large number of trawling marks due to the high trawling activity.

Non-symbiont bearing fauna represents by far the most diverse group, being present in every mud volcano with different sedimentological characteristics and habitat types. Poriferans are widely distributed on soft bottoms (*Pheronema carpenteri*, *Thenea muricata*) (San Petersburg, Tarsis) and hard bottoms generated by the authigenic carbonates (*Phakellia* spp., *Asconema setubalense, Petrosia* cf. *crassa, Geodia* sp.) (Pipoca, Gazul). Cnidarians are very well represented in most mud volcanoes, including species that are widely distributed in those with sandy (*Flabellum chunii*) (Chica, seafloor depression of Gazul), muddy (*Funiculina quadrangularis, Kophobelemnon stelliferum, Isidella elongata*) (Tarsis, Anastasya, Almazán, seafloor depression of San Petersburgo) or hard bottoms (*Acanthogorgia, Leiopathes*) (Gazul, Almazán, Pipoca, Hespérides), as well as others that are more restricted to few mud volcanoes (*M. oculata* in Gazul, *Stichopathes gravieri* in Almazán, *Chelidonisis aurantiaca, Anthothela* sp.). Some hidrozoa occur in the area and are not common in other parts of Europe such as *Cladocarpus sinuosus, Nemertesia falcicula* or *Plicathoteca anitae*. Molluscs are one of the most diverse phyla, with species occurring on authigenic carbonates (*Asperarca nodulosa, Bathyarca philippiana, Limopsis angusta*) or soft bottoms (*Abra longicallus, Yoldiella* spp., *Bittium watsoni, Galeodea rugosa, Neomenia carinata*) of several mud volcanoes. Nevertheless, other molluscs seem to be less common in the mud volcano field (*Mitrella pallaryi, Danilia tinei* and *Epitonium celesti* in Gazul, *Neopycnodonte* zibrowii and *Lima marioni* in Hespérides,). Polychaetous annelids display a similar pattern with species widely distributed in different mud volcanoes (*Vermiliopsis* spp., *Serpula* spp., *Eunice vittata, Laetmonice filicornis, Notomastus latericeus, Haplosyllis spongicola*) and others that are restricted to one or two mud volcanoes (*Poecilochaetus fauchaldi, Eunice norvegica, Tetreres varians, Pseudexogone dineti, Pionosyllis enigmatica*). The most widespread crustacean decapods are *Pagurus alatus, Ergasticus clouei, Plesionika martia, Bathynectes maravigna* and *Monodaeus couchii*, but other species displayed a very low frequency of presence in the studied area (*Pasiphaea hoplocerca, Pandalina profunda, Gennadas valens, Nephropsis atlantica, Dorhynchus thomsoni*). It is noteworthy to highlight the presence of thalassinid decapods (*Calliax* sp.) in mud breccia bottoms of Anastasia, Pipoca and Tarsis mud volcanoes together with endosymbiont bearing fauna. Echinoderms are also represented by species that are abundant and frequent in some mud volcanoes (*Leptometra phalangium, Gracilechinus acutus, Hymenodiscus coronata, Cidaris cidaris, Neocomatella europaea*) and also some that are restricted to particular ones (*Chaetaster longipes*, *Coronaster* sp., *Sclerasterias* spp., *Ophiomyces* cf. *grandis*, *Conocrinus* cf. *cherbonnieri*). Finally, the most common fishes are *Helicolenus dactylopterus* (Gazul, Chica, Pipoca), *Nezumia aequalis* (Aveiro, Hespérides, Anastasya, Gazul), *Galeus atlanticus* (Gazul, Anastasya), *G. melastomus* (Tarsis, Pipoca, Hespérides), *Etmopterus spinax* or *Chimaera monstrosa* (Pipoca, Chica, Almazán). Other fishes such as *Bathypterois dubius, Chaunax pictus* and *Lampanyctus crocodilus* were only found in one or two mud volcanoes.

The mud volcanoes Gazul, Pipoca and Chica displayed the highest species richness values, but Anastasya displayed low ones due to its extremophile sedimentary conditions with chemosynthetic-based communities and also the high trawling activity. The role of cold seeps for increasing biodiversity when compared to adjacent soft bottoms was noticeable in Gazul, Anastasya and Chica.

Regarding habitats, more than 15 habitat types included in EUNIS and LPRE (Lista Patrón de Hábitats de España) lists have been found in this mud volcano field. These mainly belongs to the categories of Deep-sea bed rock (*Callogorgia verticillata* on deep sea rock in Chica and Pipoca, "Roca limpia batial con grandes esponjas hexactinélidas *Asconema setubalense"* - Bathyal rocky bottoms with large hexactinelid sponges *Asconema setubalense* in Pipoca and Gazul), Deep-sea mixed substrata ("Fondos detríticos batiales con campos de *Leptometra phalangium*" - Bathyal detritic bottoms with *Leptometra phalangium* in Pipoca, Hespérides and Tarsis), Deep-sea sand ("Fondos sedimentarios batiales no fangosos con cidaroideos"- Bathyal sedimentary bottoms with cidaroids and without mud), Deep-sea mud (Facies of sandy muds with *Thenea muricata* in Almazán and Tarsis, Facies of compact muds with *Isidella elongata* in Almazán, Tarsis and Anastasya), Deep-sea bioherms (Communities of deep-sea corals in Gazul) and Vents, seeps, hypoxic and anoxic habitats of the deep sea (Seeps in the deep sea bed) (all mud volcanoes).

There is also a wide diversity of geological features and structures spread out over the sea floor, illustrating the geodiversity of this high geodynamically active area. León *et al.* (2006) distinguished three morphological types of mud volcanoes in the Gulf of Cádiz, but a more complete classification is proposed according to the main features and deposits as well as the new fluid-flow spots discovered: (1) Circular cones (Gazul, Anastasya, Pipoca, Tarsis and St Petersburg), (2) Oval cones (Almazán), (3) Multicone (Hespérides, Aveiro and Chica) and (4) Irregularly shaped (Albolote) (Fig. 3). Maximum diameter of mud volcanoes ranges from ca.

400 (Albolote) to 3000 m (Hespérides), and height from ca. 40 (Tarsis) to 150-200 m (St Petersburg).

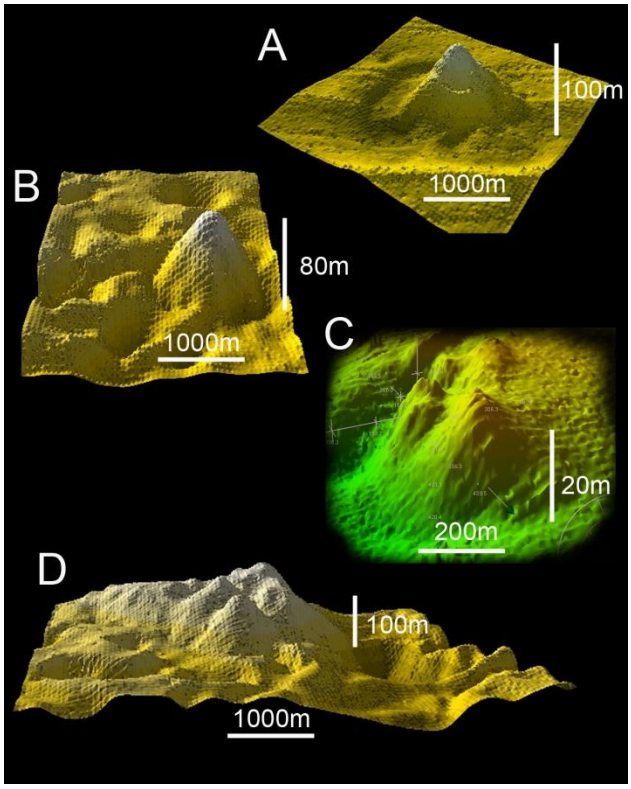

Fig. 3. Some mud volcanoes of the Spanish margin of the Gulf of Cádiz displaying different geomorphological shapes: (A) Circular cone (Anastasya, a single subrounded MV with summit at 461 m depth and maximum diameter 1.5 km); (B) Oval cone (Almazán, a single rounded MV with summit at 870 depth and maximum diameter of 1.5 km); (C) Irregular cone (Albolote, multicone shaped with asymmetric flanks and main summit at 340m depth) and (D) Multicone (Hespérides, six single cones over an oval plateau covering a maximum diameter of 1.5 km with the main summit at 682 depth)(Somoza et al., 2003)

All mud volcanoes were confirmed with gravity cores that recovered greyish mud breccia sediment. Since most of them are not presently active, surficial sediment is mainly hemipelagic foraminifera-rich sandy mud of different thickness that increases with the distance down-slope from the top. In many cases some polymictic gravel-sized clasts are observed in these sediments, probably as result of mixing with the mud breccia underneath. Only at the summit of Anastasya and Aveiro, the hemipelagic sediment is almost absent indicating recent activity. Sediments of the associated mud volcanoes depression and adjacent areas usually range from bioclastic sandy mud to relatively compacted mud. Abundant coral rubble occurs in Gazul, Albolote, Almazán and Hespérides, whereas authigenic carbonates (chimneys and slabs) were mainly collected in Gazul, Chica and Hespérides.

4. DISCUSSION

A high number of species have been recorded in the mud volcano field of the Spanish margin of the Gulf of Cádiz, as a result of the geological, geochemical, oceanographic and habitat heterogeneity of this area. This is a general feature of other cold seep areas of the world, promoting high levels of beta diversity across areas with differential fluid emissions (Cordes *et al.*, 2009) and suggesting that the studied mud volcanoes are in different development stages (León *et al.,* 2007). The faunistic list for mud volcanoes of the Spanish margin have increased considerably in three years from 30 spp. (Díaz-del-Río *et al.,* 2009) to more than 800 spp. (this study) due to a higher sampling effort using different techniques targeting the infaunal, epifaunal and demersal species, new multidisciplinary sampling expeditions on recently discovered mud volcanoes or different areas within those that were already sampled in the past as well as the contribution of experienced taxonomists on different phyla, among other factors. Further studies on the faunistic material collected could result in a higher number of species or even the description of new species, especially of faunistic groups with small size.

The geographical location of the Gulf of Cádiz represents an important factor influencing high number of species, due to the confluence of fauna with different biogeographical affinities as found in infralittoral and circalittoral communities of southern Spain. In this study, species with different geographical ranges have also been found, including those with a wide distribution (*Funiculina quadrangularis, Eusergestes arcticus, Plesionika narval*), with a distribution that is mainly Atlantic and considered rare in the Mediterranean Sea (*Asconema setubalense, Flabellum chunii, Penaeopsis serrata*) or mainly Mediterranean but rare in the Atlantic Ocean (*Plesionika gigliolii*). Other species do not generally reach northern Europe (*Isidella elongata, Etmopterus pusillus, Gnathophis mystax, Symphurus nigrescens*), including this group amphiatlantic species (*Hymenopenaeus debilis, Centrostephanus longispinus, Hacelia superba*) or species that are widely distributed along western Africa (*Tethyaster subinermis, Plesionika antigai*). In these communities it is possible to find endemic species from the Gulf of Cádiz and Alborán Sea such as the bivalve *Limopsis angusta* or the Atlantic sawtail cat shark *Galeus atlanticus* as well as some of the chemosymbiotic species that have been only found on mud volcanoes of the Gulf of Cádiz.

Different types of habitats occur in the mud volcano field due to the high geomorphological and sedimentological variability. This results in a good representation of different bathyal habitats from the Mediterranean and Atlantic basin, and with some of them having a protection status under OSPAR (sea pen communities, cold water corals, sponge aggregations) or Habitats Directive (Submarine structures made by leaking gases 1180, Reefs 1170). The habitat heterogeneity, together with the presence of threatened species, rare species that are not found in other parts of Europe, chemosymbiotic species that are endemic of cold seeps of the Gulf of Cádiz and the singular geological features of mud volcanoes may represent important factors to be considered for providing a protection status to these singular ecosystems. This is of importance because some of them are located in areas with high trawling activity (Anastasya) or exposed to future human impacts (fisheries, non-renewable resource extraction, deployment of submarine infrastructures).

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