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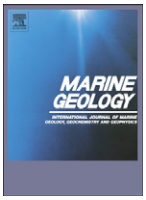

# Tectonics and mud volcano development in the Gulf of Cádiz

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ABSTRACT

Many structures associated with fluid escape, including mud volcanoes, mud-carbonate mounds, pockmarks and slides, have been identified and characterized in the Gulf of Cádiz. Most of the mud volcanoes following NE–SW and NW–SE main trends are found at 350–2000 m depth in the eastern domain of the Gulf of Cádiz, which corresponds to the Betic–Rifean Margin. Scattered mud volcanoes have also been recognized on the lower slope at 2300–3900 m depth. The major tectonic structures are thrust faults, extensional faults, strike-slip faults and diapirs. All these tectonic structures have provided escape pathways for overpressured material and fluids or have favoured upward fluid movement along the sedimentary column and eventually the build up of mud volcanoes. In this work we present images of the mud volcano plumbing systems and the relationship between regional tectonics and mud volcano development. Seismic profiles acquired during the TASYO 2000 and MVSEIS/TTR-15 cruises are used to image and interpret the link between the mud volcano edifices and the subsurface tectonic structures.

## 1. Introduction

Data collected in the last few years have revealed the importance of sea-floor structures related to hydrocarbon fluid venting on the continental slope of the Gulf of Cádiz. Major fluid venting features in the Gulf of Cádiz have sizes ranging from kilometres to hundreds of metres and have been grouped into three main types: 1) pockmarks (Baraza and Ercilla, 1996; Casas et al., 2003; León et al., 2006); 2) mud volcanoes, some bearing gas hydrates in both the Iberian (Somoza et al., 2002; Pinheiro et al., 2003) and the Moroccan margins (Ivanov et al., 2000; Gardner, 2001; Kopf et al., 2004; Van Rensbergen et al., 2005); and 3) carbonate-mud mounds bearing carbonate chimneys, crusts and slabs (Díaz-del-Río et al., 2003; Magalhães et al., 2004; Fernández-Puga et al., 2007).

Three main relationships have been identified between mud volcano development and geological environments (Dimitrov, 2002): (1) the occurrence of a close relationship between mud volcanism and tectonics (Kopf, 2002; Huguen et al., 2004; Panahi, 2005), especially in compressional settings (Milkov, 2000); (2) the existence of deep potential source layers in the sedimentary succession (Feyzullayev et al., 2005); and (3) the location of mud volcanoes where hydrocarbons have been or are actively being generated (Guliyev and Feizullayev, 1997; Yusifov and Rabinowitz, 2004). The Gulf of Cádiz fulfils all these interrelations (Somoza et al., 1999, 2001; García Mojonero and Martínez del Olmo, 2001; Ovsyannikov et al., 2003; Van Rensbergen et al., 2005; Pinheiro et al., 2006; León et al., 2007; Fernández-Puga et al., 2007).

To date, most of the published work on mud volcanism has been aimed at studying the fluid venting structures, the morphology and geometry of the edifices and the geochemistry and origin of the fluids. Little attention has been paid to mud volcano occurrence in relation to tectonics, which is still poorly constrained. The large number of mud volcanoes identified in the Gulf of Cádiz, their distribution along different sectors of the margin and their location in different tectonic settings provides the possibility of studying the development of mud volcanism in a tectonically active area under a compressive/transpressional regime with a high level of seismicity. In this work we image and document the relationship between tectonics and mud volcano development on the Betic–Rifean margin and lower slope. With this aim we use seismic profiles acquired during the TASYO Project and the MVSEIS/TTR-15 cruises to analyze the "mud volcano system" structure and the relationship between its genesis and tectonics. The images presented correspond to "mud volcano systems" located in different sectors of the continental slope, where the tectonic structure varies.

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We use the term “mud volcano system” in the sense given by Stewart and Davis (2006): “a set of structures associated with a constructional edifice (mud volcano) and the feeder complex that connects the volcano to its source stratigraphic unit”.

## 2. Geological background

The present geological structure of the Gulf of Cádiz is the result of the European–African plate convergence motion, dextral strike-slip along the Azores–Gibraltar Plate Boundary and the westwards migration of the Betic–Rifean Arc. This plate convergence lasted from Mid-Oligocene up to Late Miocene times and then continued with slow Late Miocene to Recent NW convergence (Dewey et al., 1989; Vázquez and Vegas, 2000; Rosenbaum et al., 2002). Westward drift and collision of the Alborán Domain with the North African and southern Iberian margins in the Early–Middle Miocene caused the development of the Betic–Rifean Belt (Figs. 1 and 2) and as a consequence the radial emplacement of huge allochthonous masses (the so-called “Olistostrome Unit”), here named the Allochthonous Unit of the Gulf of Cádiz (AUGC), on the Guadalquivir Basin (Iberian foreland), the Rharb Basin (North African foreland) and the Gulf of Cádiz (Torelli et al., 1997; Maldonado et al., 1999; Medialdea et al., 2004).

This complex geodynamic evolution is recorded in the architecture and tectonic structure of the continental margin of the Gulf of Cádiz, which has a series of physiographic, morphological and geological features and a geodynamic framework that have focused the attention of many researchers. Among these features, the following stand out: 1) an irregular physiography, with an outstanding development of a broad continental slope; 2) the emplacement of a chaotic body, the AUGC, which occupies the central part of the Gulf of Cádiz; 3) complex tectonics with large-scale diapiric processes throughout the entire continental margin; 4) the occurrence of gas and gas hydrates, and eventually 5) the formation of sea-floor features related to hydrocarbon seepage, including many mud volcanoes (Fig. 1). All these geological features are in a close relationship.

The continental slope extends from 140 m depth to the Horseshoe and Seine abyssal plains, reaching a width of about 300 km (Hernández-Molina et al., 2003). The sedimentary cover of the slope consists of Triassic to Quaternary materials (Maldonado et al., 1999), and ranges in thickness from: 2–2.5 s Two-Way Travel Time (TWTT) on the middle continental slope to 2–3.5 s (TWTT) on the lower slope, and again to 2–2.5 s (TWTT) on the abyssal plains (Medialdea et al., 2004). The AUGC mentioned above represents the thickest unit of the sedimentary cover (Fig. 1B). It is a wedge-shaped unit which extends from the Iberian Peninsula and Morocco to the Horseshoe and Seine Abyssal Plains. The structure consists of low-angle thrust sheets affected by later gravitational collapse and reactivated thrusting (Torelli et al., 1997; Maldonado et al., 1999; Medialdea et al., 2004). The AUGC consists of a mixture of Triassic, Cretaceous, Paleogene and Neogene sedimentary units, overlying a Palaeozoic basement (Maldonado et al., 1999). It involves a huge volume of mud and salt diapirism of Triassic salt units and undercompacted Early–Middle Miocene plastic marls (Maestro et al., 2003). The origin of this chaotic body is highly controversial. It has been interpreted as a complex of olistostromes caused by gravitational sliding and thrust tectonics (Torelli et al., 1997; Medialdea et al., 2004). Its emplacement on the Atlantic realm has been related to the western migration of the Alborán terrain as a consequence of an once active subduction zone (Royden, 1993; Lonergan and White, 1997; Rosenbaum et al., 2002; Medialdea et al., 2004; Iribarren et al., 2007). Alternatively, Gutscher et al. (2002) proposed that this subduction is still active beneath Gibraltar. There is a general agreement on the age of emplacement of this unit, which has been established as Late Tortonian in the Gulf of Cádiz (Torelli et al., 1997; Maldonado et al., 1999; Somoza et al., 1999; Medialdea et al., 2004), although the AUGC was later reactivated in the Late Miocene to Present as the result of the NW compression. This feature appears as a chaotic, highly diffractive body on the seismic profiles. The chaotic character attributed to the AUGC is due to its heterogeneous composition and internal deformation produced by diapirs, strike-slip faults, extensional faults, thrust faults, slides and fluid venting structures (Figs. 1 and 2). Extensive mud diapirism has been reported throughout the Gulf of Cádiz margin, especially on the slope (Somoza et al., 1999; Maldonado et al., 1999; Lowrie et al., 1999; Maestro et al., 2003; Somoza et al., 2003; Fernández-Puga et al., 2007).

Along the Gulf of Cádiz continental margin, the origin of hydrocarbon-related fluid venting structures is related to the occurrence of both thermogenic and biogenic gas within the AUGC (Maldonado et al., 1999; Mazurenko et al., 2003). The 50 mud volcanoes confirmed by coring so far are cone-shaped sea-floor edifices ranging from 800 to 3500 m in diameter, which can tower in places up to 300 m above the seabed. They are produced by mud and fluid (water, brine, gas, oil) eruptions as the result of degassing processes in deeper reservoirs (Hensen et al., 2007), intercalated with periods of inactivity. Most mud volcanoes are built up of episodes of mud-breccia flows (Somoza et al., 2003; Van Rensbergen et al., 2005) with evident indications of gas saturation: degassing structures, a strong $H_2S$ smell and chemosynthetic fauna (e.g. Pinheiro et al., 2003; Somoza et al., 2003).

## 3. Methodology and data sources

The results of this work are mainly based on the interpretation of multichannel seismic profiles collected during the TASYO 2000 cruise along the Iberian margin and in deep waters on the lower slope (Fig. 3) in the framework of the MVSEIS Project and the UNESCO IOC TTR Programme. Data related to new mud volcano discoveries obtained recently on the MVSEIS08 Cruise have also been added. This work would not have been possible without the results obtained from the extensive dataset acquired during several surveys carried out aboard the *Prof. Logachev*, *Hespérides* and *Cornide de Saavedra* research vessels, which allowed discovering and investigating the diverse sea-floor structures related to fluid venting along the Gulf of Cádiz. An important contribution was also provided by the side scan sonar mosaic of Dr. Joan Gardner from the Naval Research Laboratory, Washington DC (Gardner, 2001). During these cruises, in addition to swath bathymetry data obtained with a multibeam echosounder (Simrad EM-12), the geophysical data acquired include multichannel and single-channel seismic reflection profiles, surface (12 kHz) and high resolution deep-towed (30–100 kHz) side scan sonar and underwater video profiles. Targets of interest previously selected on multibeam bathymetric maps, backscatter maps and seismic profiles were sampled with dredges, TV-controlled grabs and gravity cores.

The seismic dataset presented in this work includes high- to medium-resolution seismic profiles that were obtained with a Topographic Parametric Echosounder (TOPAS) with a maximum penetration of 100 m and a Sparker system with an energy source of 3500–7000 J and a recording length of 2 s. The seismic data were recorded using Delph2 Triton Elics-software. Furthermore, 1728 km of multichannel seismic profiles were obtained during the TASYO 2000 cruise (Fig. 3). The multichannel seismic data were acquired with a five BOLT airgun array of 22.45 and 34.8 l capacity and a TELEDYNE 96-channel streamer of 2.5 km length, and were recorded for 10 s at a 2 ms sampling rate. The shot interval was 50 m. Seismic data were poststack time-migrated at the Instituto Andaluz de Ciencias de la Tierra. Fledermouse software was used to analyze the multibeam data, and Kingdom Suite software was used to produce the seismic images.

## 4. Results

### 4.1. Tectonics and diapirism

The NW to WNW-directed compressional regime is responsible for the development of NE–SW, ENE–WSW, NW–SE and WNW–ESE tectonic structures on the lower slope and abyssal plains, where either the sedimentary cover or the continental and oceanic basement are involved (Fig. 1). Compressional structures consist of thrust faults and