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ORIGINAL

New discoveries of mud volcanoes on the Moroccan Atlantic continental margin (Gulf of Cádiz): morpho-structural characterization

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Abstract During the MVSEIS-08 cruise of 2008, ten new mud volcanoes (MVs) were discovered on the offshore Moroccan continental margin (Gulf of Cádiz) at water depths between 750 and 1,600 m, using multibeam bathymetry, backscatter imagery, high-resolution seismic and gravity core data. Mud breccias were recovered in all cases, attesting to the nature of extrusion of these cones. The mud volcanoes are located in two fields: the MVSEIS, Moundforce, Pixie, Las Negras, Madrid, Guadix, Almanzor and El Cid MVs in the western Moroccan field, where mud volcanoes have long been suspected but to date not identified, and the Boabdil and Al Gacel MVs in the middle Moroccan field. Three main morphologies were observed: asymmetric, sub-circular and flat-topped cone-shaped types, this being the first report of asymmetric morphologies in the Gulf of Cádiz. Based on morpho-structural analysis, the features are interpreted to result from (1) repeated constructive (expulsion of fluid mud mixtures) and destructive (gravity-induced collapse and submarine landsliding) episodes and (2) interaction with bottom currents.

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Introduction

Mud volcanoes (MVs) are defined as conic edifices constructed by surface extrusion of cold fluids containing mud, saline water and/or gases expelled from a pressurized deep source upwards through structurally controlled conduits (e.g. Brown 1990; Milkov 2000; Dimitrov 2002; Kopf 2002). A more constrained definition would consider that gas and water are related to hydrocarbon diagenetic and catagenetic production and accumulation processes: predominantly methane and subordinately other alkanes (mainly ethane and propane) and non-hydrocarbon gases such as CO_2, nitrogen, argon and helium. In this sense, the definition of a mud volcano has been recently extended in order to consider the whole "mud volcano system" (Stewart and Davies 2006), defined as a set of structures associated with a constructional edifice (mud volcano) and the feeder complex which connects it to its source stratigraphic unit. Therefore, the morpho-structure of these edifices provides an important record of their eruptive history, as well as of the processes of migration and extrusion of fluid mud mixtures.

MVs have been described worldwide at active and passive continental margins, both onshore and offshore, where fluid extrusion gives rise to a variety of morphological features including also pockmarks, brine lakes and hydrocarbon-derived authigenic carbonates (HDACs; see overview by Judd and Hovland 2007). These are areas of intensive geological, geochemical, thermal and biological activities (e.g. Dando and Hovland 1992; Judd and Hovland 2007; Foucher et al. 2009). For this reason, the scientific community has long focused on the widespread occurrence of seabed fluid flow in ocean sub-bottom sediments, and its importance in relation to global carbon fluxes, climate change, geohazards and, increasingly, as a potential energy resource (e.g. Hovland and Judd 1988; Paull and Dillon 2001). In the Gulf of Cádiz offshore the Iberian Peninsula, various seabed fluid flow features indicative of intense hydrocarbon-seep activity have been reported along the continental slope of both the Iberian and African margins (Medialdea et al. 2009): pockmarks (e.g. Baraza and Ercilla 1996; Casas et al. 2003; León et al. 2006, 2010), mud volcanoes (e.g. Ivanov et al. 2000; Gardner 2001; Pinheiro et al. 2003; Somoza et al. 2003), HDAC chimneys, crusts and slabs (Díaz-del-Río et al. 2003), and ferromanganese nodules (González et al. 2009).

The first MVs discovered in the Gulf of Cádiz were those offshore the Moroccan margin, in an area named the Moroccan field (Fig. 1; Ginsburg and Yuma MVs; Ivanov et al. 2000; Gardner 2001), and offshore the Spanish-Portuguese margin in the so-called Tasyo field (e.g. the Hespérides and Faro MVs; Somoza et al. 2003). Deepwater mud volcanoes have also been observed at the front of the allochthonous wedge in an area named the deep south Portuguese field (Fig. 1; e.g. the Ribeiro MV; Pinheiro et al. 2003). Later, a cluster of mud volcanoes was discovered at the eastern boundary of the Moroccan field, in the El Arraiche field (Fig. 2; e.g. the Mercator and Al Idrisi MVs; Van Rensbergen et al. 2005).

The aim of this article is to characterize ten new mud volcanoes discovered during the MVSEIS-08 cruise to the Moroccan field onboard the R/V *Hespérides* in 2008, including the hitherto poorly explored western sector (cf. below; Fig. 2). The acquired dataset comprises high-resolution bathymetric profiles, backscatter images, TOPAS profiles, dredge hauls and sediment gravity cores. This formed a solid basis to define the morpho-sedimentary features and to interpret the sedimentary processes characterizing the edifices within the framework of a proposed evolutionary model for this mud volcano system.

Geological and oceanographic setting

The Gulf of Cádiz is located along the African-Eurasian plate boundary (Zitellini et al. 2009; Fig. 1). The geodynamic evolution of the Betic-Rifean orogenic belt results from the N to

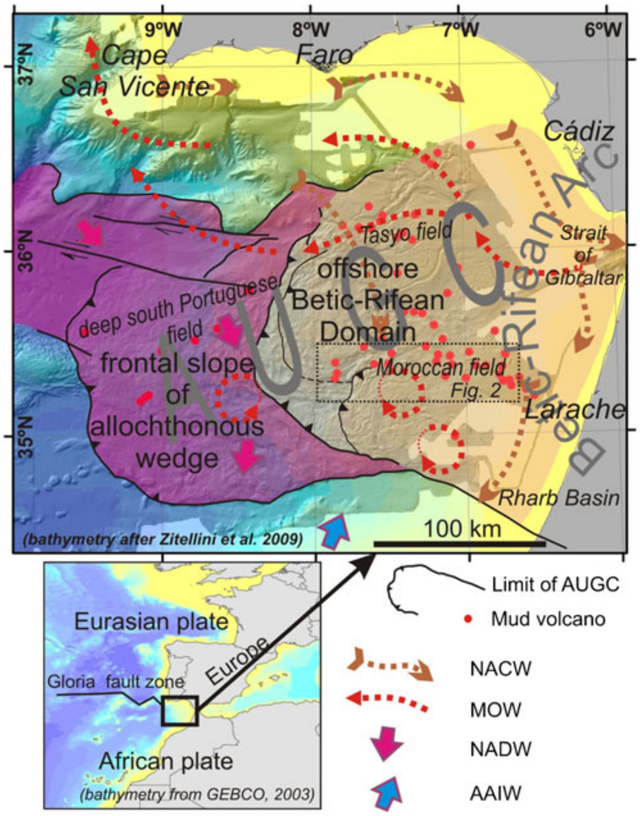

Fig. 1 Geological setting of the Gulf of Cádiz (modified from Medialdea et al. 2004, 2009; bathymetry from SWIM compilation of Zitellini et al. 2009), with *dotted rectangle* showing the study area (Fig. 2): *AUGC* allochthonous unit of the Gulf of Cádiz, *AAIW* Antarctic Intermediate Water, *MOW* Mediterranean Outflow Water, *NACW* North Atlantic Central water, *NADW* North Atlantic Deep water

NW convergence between Africa and Eurasia-Iberia. The thrust belt formed mainly from 19 Ma until 6 Ma, as a result of the westward relative drift of the Alboran Domain between the converging Iberian and African plates (Platt 2007). This had two main consequences: the formation of the Betic-Rifean Arc, and the westward emplacement of huge chaotic masses named the allochthonous unit of the Gulf of Cádiz (AUGC; Medialdea et al. 2004). The Miocene M1 unit and the AUGC are the source rocks that feed the widespread mud and salt diapirism (Maldonado et al. 1999; Medialdea et al. 2004, 2009). Diapirs are controlled by major tectonic structures comprising thrust faults, extensional faults and strike-slip faults which appear to be in close relation with the intense seabed fluid flow recorded along both the Iberian and African margins (Fernández-Puga et al. 2007; Medialdea et al. 2009). In the Gulf of Cádiz, hydrocarbon fluid flow is both of thermogenic and biogenic origin (Ivanov et al. 2000; Stadnitskaia et al. 2006). About 60 mud volcanoes have been confirmed by coring in the Tasyo field, the Moroccan field and the deep south Portuguese field, comprising cone-shaped seafloor edifices of 400 to 4,800 m diameter resulting from episodic flows of mud breccias.

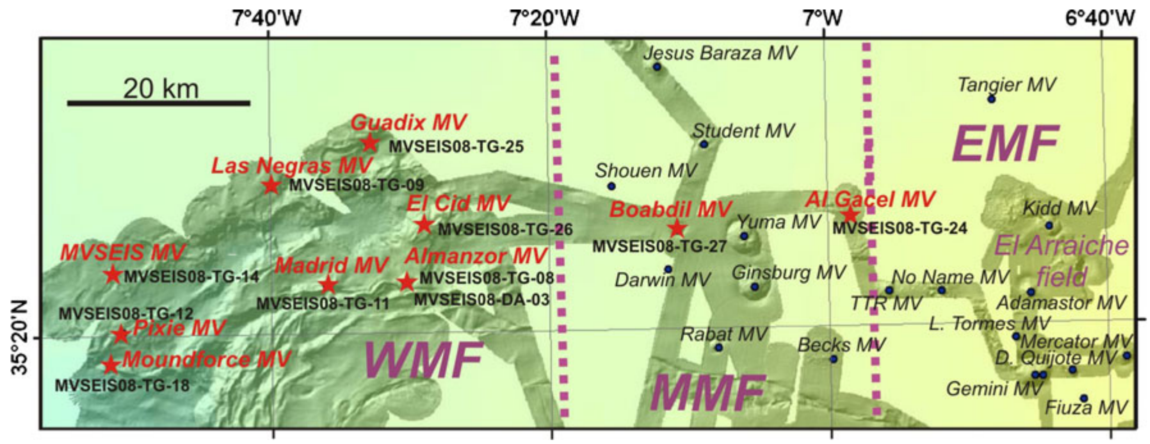

Fig. 2 Location of the newly discovered mud volcanoes along the Moroccan margin (bathymetry compilation from MVSEIS-08 cruise): *WMF* western Moroccan field, *MMF* middle Moroccan field, *EMF* eastern Moroccan field (based on Fig. 50 of Kenyon et al. 2000). *Circles* Known mud volcanoes, *stars* new mud volcanoes, with names of gravity cores and dredge material recovered

The *Moroccan field* is located in the offshore extension of the Rharb Basin along the middle and upper slope of the Moroccan margin. It was discovered during the TTR-9 cruise of 1999, and has been subdivided into three main sectors (Ivanov et al. 2000): the *eastern Moroccan field* (EMF), the *middle Moroccan field* (MMF) and the *western Moroccan field* (WMF). The first MVs identified in the EMF were the TTR, Adamastor and Kidd MVs. Later, Van Rensbergen et al. (2005) identified a new cluster of eight MVs in this sector (the El Arraiche field), where the Al Idrisi MV is the largest. During the TTR-9 cruise, the first MVs bearing hydrates (the Yuma and Ginsburg MVs) were discovered in the MMF. Mud volcanoes belonging to the EMF and MMF are surrounded by contourite drifts and moats (Casas et al. 2010; Van Rooij et al. 2011), and form a continuous cluster of cone-shaped morphologies bearing cold-water corals (CWCs) possibly related to the Mediterranean Outflow Water (MOW) bottom current (Foubert et al. 2008). In contrast to the other two sectors, MVs have long been suspected in the WMF but to date not identified.

In the Gulf of Cádiz, oceanographic circulation follows an anti-cyclonic gyre (Pelegrí et al. 2005), and is controlled by the exchange of water masses through the Strait of Gibraltar and by the interaction of MOW with the Atlantic circulation. In the study area, the upper thermocline water mass is the North Atlantic Central Water (NACW) located at 300–600 m water depth (Machín et al. 2006). Two intermediate water masses are found between 600 and 1,500 m: the low-salinity Antarctic Intermediate Water (AAIW) and the MOW. Below 1,500 m occurs the North Atlantic Deep Water (NADW). MOW circulation is poorly constrained and flows in three main branches: an intermediate branch towards the northwest, a principal branch towards the west, and a southern branch which plunges as far as the Canary Islands. The latter has been reported at 800 m along the Moroccan margin (Pelegrí et al. 2005), possibly transported through meddies (Ambar et al. 1999).

Materials and methods

Multibeam echo-sounder (MBES) data were acquired using a hull-mounted Simrad EM-120 during the MVSEIS-08 cruise onboard the R/V *Hespérides*, enabling simultaneous collection of high-resolution seafloor bathymetric and backscatter data (Fig. 2). The Simrad EM-120 was operated at a frequency of 13 kHz with 191 beams, triggering at pulse lengths of 2–15 ms and with a vertical resolution of 0.1–0.4 m. Transducer opening was 1°, so that the footprint range was from 11 m (at 600 m water depth) to 35 m (at 2,000 m water depth). MBES data were processed with Simrad Neptune and Caraibes software.

Digital terrain models (bathymetry and backscatter) were generated with FLEDERMAUS and post-processed with ArcGIS. Cell sizes of the bathymetric and backscatter grids were at a resolution of 14 and 10 m respectively. Backscatter values ranged from −2 to −47 dB.

The ultrahigh-resolution topographic parametric sounder (TOPAS) used in the present study operated with a CHIRP wavelet at two simultaneous primary frequencies of 15 and 18 kHz. This provided a maximum penetration of 100 m with a resolution of 0.5–1 m.

One benthic dredge haul and ten gravity sediment cores with a maximum length of 190 cm were taken on the summits and/or slopes of the mud volcanoes (Table 1). The cores were photographed and a litho-stratigraphic visual description made in each case.

Results

Western Moroccan field

In all, eight MVs were discovered in the WMF: these have been named the MVSEIS, Moundforce, Pixie, Las Negras,

Table 1 Locations, morphological characteristics and gravity core codes for the mud volcanoes presented in this paper. *Dp* (m) Water depth at top of mud volcano, *H* (m) maximum height, *D* (m) maximum diameter, *S* (°) average slope on flanks of mud volcano

Name	Latitude	Longitude	Field	Dp (m)	H (m)	D (m)	S (°)	Core
MVSEIS	35°23.64′N	7°51.42′W	WMF	1,594	68	889	4.0	MVSEIS08-TG-14
Moundforce	35°18.30′N	7°51.66′W	WMF	1,800	51	641	2.8	MVSEIS08-TG-18
Pixie	35°20.22′N	7°50.70′W	WMF	1,633	81	577	5.0	MVSEIS08-TG-12
Las Negras	35°28.74′N	7°39.96′W	WMF	1,362	98	905	9.0	MVSEIS08-TG-09
Madrid	35°22.92′N	7°36.06′W	WMF	1,361	205	1,087	10.0	MVSEIS08-TG-11
Guadix	35°31.14′N	7°32.88′W	WMF	1,399	184	1,679	7.0	MVSEIS08-TG-25
Almanzor	35°22.98′N	7°30.36′W	WMF	1,235	175	1,984	8.0	MVSEIS08-TG-08
El Cid	35°24.48′N	7°26.37′W	WMF	1,230	337	2,853	8.0	MVSEIS08-TG-26
Boabdil	35°25.82′N	7°10.74′W	MMF	1,102	88	1,390	5.2	MVSEIS08-TG-27
Al Gacel	35°23.64′N	6°58.39′W	MMF	763	107	944	8.3	MVSEIS08-TG-24

Madrid, Guadix, Almanzor and El Cid MVs (Fig. 2, Table 1). Most (except Pixie and Moundforce) have an asymmetrical profile, with flanks of different lengths. Asymmetrical MVs were identified only in the WMF, on escarpments where mud extrusions flow downslope in only one direction. The largest of these edifices are the El Cid, Guadix and Madrid MVs, with reliefs of up to 200 m. Their emission centres have a high eccentricity, associated with mud flows extending up to 2,500 m from the central cones. The asymmetrical MVs often are terraced and several mud-flow events can be distinguished morphologically on their undulated surfaces. Some (e.g. the MVSEIS and El Cid MVs) have a flat-topped summit with a depressed central area forming a crater. By contrast, the Pixie and Moundforce MVs are sub-circular, cone-shaped features with symmetrical profiles up to 120 m high and 1,000–1,500 m wide (Fig. 3). Their summits lie between 1,360 and 1,500 m water depth.

MVSEIS MV

The MVSEIS MV is located at the extreme NE of a 2,000-m-long diapiric crest (Fig. 3). It is a NW-elongated structure composed of two partially merged cones. The smaller of these is 40 m high, 446 m in diameter and has a central dome. The main cone (NW) has an oval plan shape with an asymmetrical profile, is 68 m high (1,594 m water depth at the top) and has a maximum diameter of 889 m. It has a flat top with a central depression characterized by high backscatter values (−18 to −20 dB; Fig. 3d) and surrounded by a ring-shaped irregular relief (Fig. 3b). A 2-m-high mound was detected in the central depression. At least two outflow episodes were identified. Episode 1 formed the main cone, which is characterized by low backscatter (−29 to −34 dB). Episode 2 is represented by an outflow lobe of moderate backscatter (−23 to −25 dB) which is situated on the flank of the main cone, enlarging the latter in a north-westerly direction.

The slopes show three terraced sectors outlined by scarps of 5.8–7.9° and 4.8–4.2°. The base of the cone has more pronounced slopes (12.3–17.1°) and is surrounded by a rimmed depression of 8–10 m depth.

The gravity core from the top of the MVSEIS MV at 1,611 m water depth (MVSEIS08-TG-14, Fig. 4) yielded mud breccias at 123–157 cm below seafloor, overlain by a 94-cm interval comprising at least 16 layers of reduced grey mud interbedded with brown oxidised sediments. These intercalations can be interpreted as events of ejection of low-viscosity material from the crater, alternating with periods of inactivity with predominance of hemipelagic deposits. The upper 30 cm are composed of yellowish brown massive mud with abundant foraminifers, indicating hemipelagic sedimentation.

Moundforce MV

The Moundforce MV (1,800 m water depth at the top) outcrops in a dome structure over an E-W-elongated ridge located at the south of the Pixie-Dixie group (cf. below; Fig. 3). It has an irregular lobate perimeter of 641 m maximum diameter. The flanks show a terraced profile delineating two main sectors: a base and a central dome. The base has very low backscatter (−31 to −35 dB). The steep slopes have gradients of 8–10°, increasing to maximum values of 15–20° on the south flank. The central dome has a sub-circular perimeter and is located in the NE sector of the cone. The top is smooth and mounded with slopes of about 1–3°, associated with low backscatter (−28 to −33 dB). Rimmed depressions were not observed.

A gravity core recovered from the top of this mud volcano at 1,810 m water depth (MVSEIS08-TG-18) comprises, from top to bottom, a ca. 20-cm-thick layer of yellowish brown mud containing foraminifers, which grades

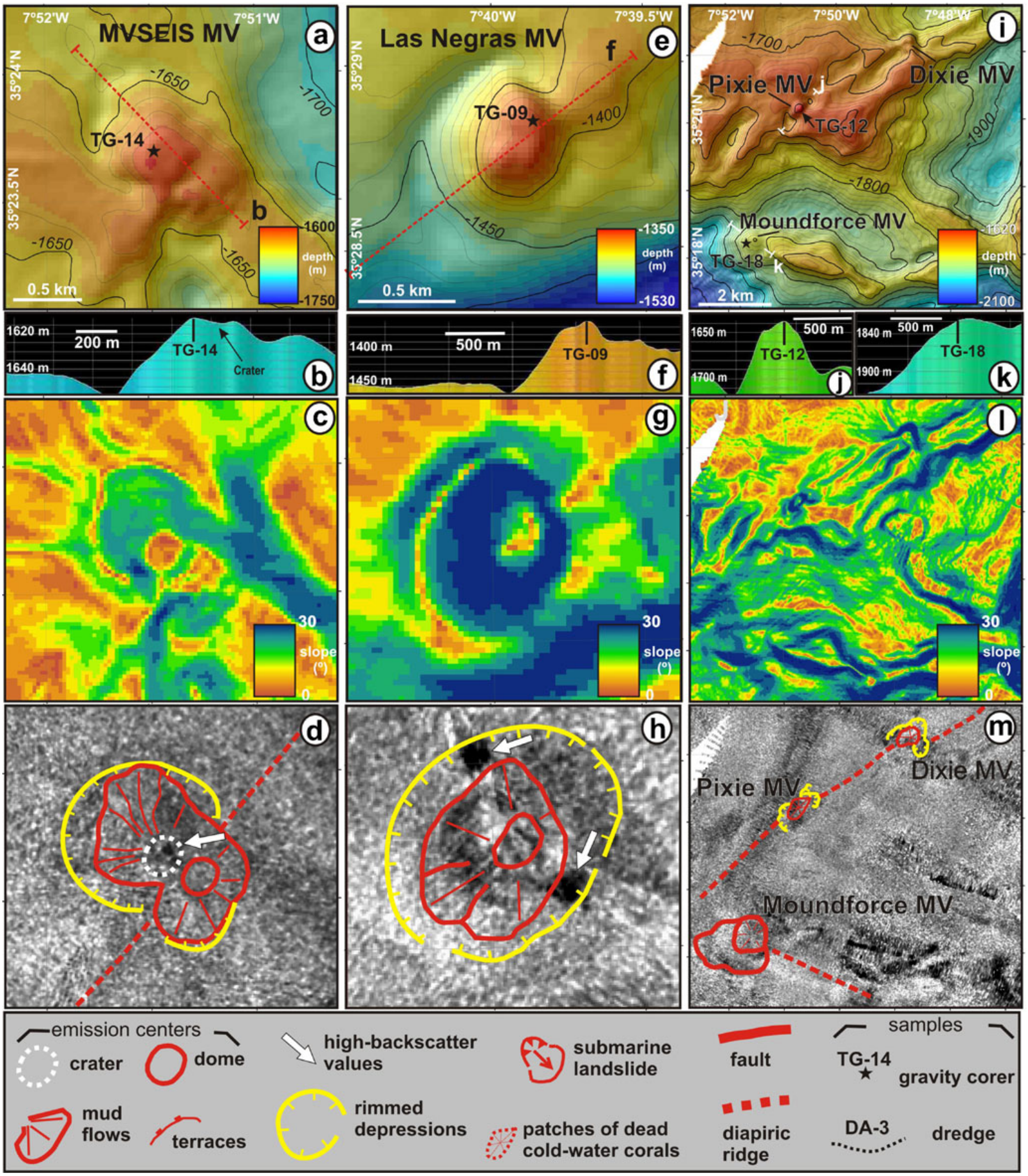

Fig. 3 Western Moroccan field: **a**–**d** MVSEIS MV, **e**–**h** Las Negras MV, **i**–**m** Pixie, Dixie and Moundforce MVs, and corresponding **a**, **e**, **i** bathymetric maps, as well as locations of gravity cores and cross sections (*red dashed lines*), **b**, **f**, **j**, **k** cross sections, **c**, **g**, **l** gradient maps, and **d**, **h**, **m** geological interpretations overlain on backscatter mosaics

into a chaotically bedded olive grey mud containing sub-angular clasts (0.3–3.5 cm in diameter) composed of lutitic material, showing a sharp erosive base at 33 cm below the seafloor (Fig. 4). This is followed downwards by a complex, 160-cm-thick sequence of olive grey sandy mud with high abundances of

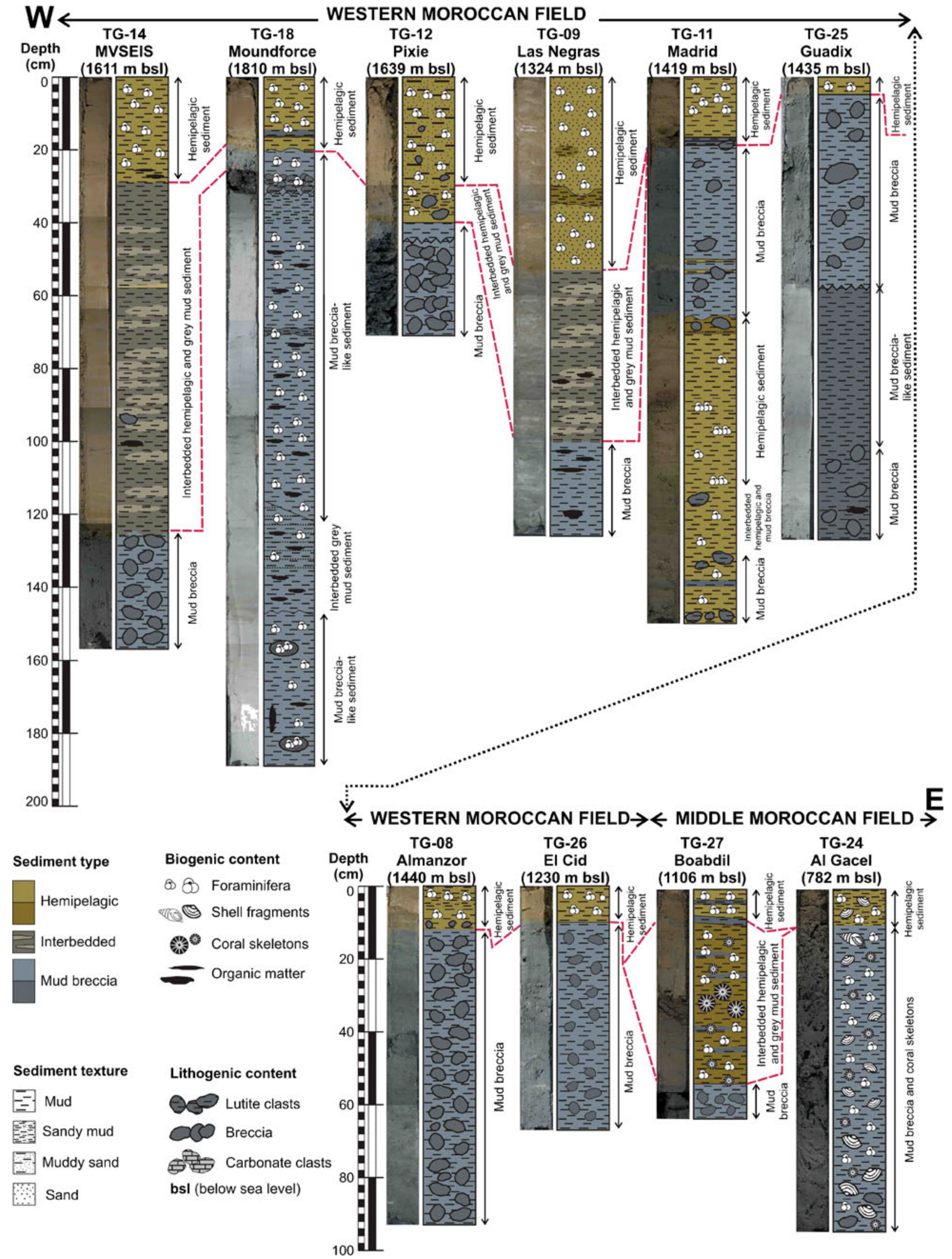

Fig. 4 Photographs and descriptions of gravity cores recovered over the mud volcanoes located along the Moroccan margin in the western Moroccan field and the middle Moroccan field

foraminifers and interbedded with laminated greyish olive mud with a strong H_2S smell. This lower unit contains low-viscosity fluids derived from the mud volcano.

Pixie-Dixie group

Pixie and Dixie (Fig. 3) are two small cones located at the extremities of ridges in the southwest sector of the WMF (Fig. 2). Pixie (1,633 m water depth at its top) is a simple mud volcano with an elongated shape, 81 m high and 577 m in maximum diameter. It shows variably steep slopes with high backscatter (−17 to −23 dB), 5–7° at the top and 19–26° on the flanks. Outflows or mud-extrusion episodes were not detected. Two irregularly oval-rimmed depressions 25 m deep can be distinguished on the NE and SW flanks. The core taken from the Pixie MV at 1,639 m water depth (MVSEIS08-TG-12) comprises darkish blue green mud breccias at ca. 40–70 cm below seafloor. This is overlain by an upper 40-cm layer of greyish orange sandy mud with foraminifers, containing abundant mud breccia clasts at its base (Fig. 4).

The Dixie mound (1,702 m water depth at the top) is a sub-circular cone-shaped feature 92 m high, 527 m in maximum diameter, and with steep slopes of 17–23° with moderate backscatter (−22 to −28 dB). It is surrounded by a rimmed depression 10 m deep. A gravity core taken from this mound at 1,762 m water depth (MVSEIS08-TG-13) comprises chaotic olive grey mud with scattered foraminifers at 116–198 cm below seafloor, overlain by yellowish brown mud with abundant foraminifers and bioclasts. Although typical mud breccias were not identified at this site, its morphological similarities with the Pixie MV suggest a mud volcano edifice.

Las Negras MV

The Las Negras MV (1,362 m water depth at the top) has a single cone, 98 m high and 905 m in diameter (Fig. 3). The top shows an irregular flat surface with slopes varying in the range 1.5–4°. The flanks have steep slopes of 8–15° and moderate backscatter (−20 to −28 dB); they are quite homogeneous and only one outflow episode can be distinguished at the SW side. The steepest slopes reach values of 21–23°. There is an offset of 26 m between the NW and SE sides of the edifice (ca. 25% of the total height). The base is surrounded by a rimmed depression 32 m deep. This depression shows two areas of very high backscatter (−4 to −12 dB).

A gravity core from this mud volcano (MVSEIS08-TG-09) yielded ca. 53 cm of yellowish brown sand overlying olive grey sandy mud (Fig. 4). Similarly to the MVSEIS MV (cf. above), these layers provide evidence of multiple mud-flow events interbedded with foraminifer-rich sands. Below, darkish blue green mud with clasts and a strong H_2S smell occurs from ca. 100 cm below seafloor to the core base.

Madrid MV

The Madrid MV is a single cone with its summit at 1,361 m water depth, 202 m high and of 1,927 m maximum diameter (Figs. 5, and 6a, b). Mud extrusions flow towards the northwest, resulting in a sub-elliptical morphology. The transverse profile is clearly asymmetric, with a ca. 186-m difference in water depth between the NW and SE sides of the base of the cone. Thus, the cone can be differentiated into two distinct parts. The upper part is situated at the top of a ridge, in the form of a circular conic dome 20 m high with slopes ranging from 12–17° and reaching 22° at the SW side. The lower part is located to the NW side of the upper part.

At least four terraces can be distinguished along the flanks, and these can be related to four episodes of mud flows (MFs in Fig. 6a, b). On TOPAS seismic profiles, these terraces appear as distinct smooth hyperbolic diffractions (Fig. 6b). The basal terrace (MF-1) has very steep slopes (20–31°) relative to the surrounding flat seafloor, and low backscatter values (−28 to −36 dB). The upper terraces (MF-2, MF-3, MF-4) have moderate backscatter (−25 to −28 dB). The downslope terminations of the mud flows show ramps with slopes of 10–14°; by contrast, their upper surfaces have values of 4–7° (Fig. 5c). A shallow (4 m deep), smooth-rimmed depression was detected on the SE flank of this mud volcano. The base does not show evidence of any ring-shaped depression, the outflows onlapping directly over the seafloor.

The occurrence of several outflow episodes can be inferred also from information gained from gravity cores. Two cores were taken from this mud volcano, at its top and from the upper flows along its flanks. The top core (1,359 m water depth, MVSEIS08-TG-10) yielded about 1 m of massive greyish olive mud breccias with a strong H_2S smell, and containing abundant sub-angular clasts between 0.5 and 3 cm in diameter and composed of lutitic material. The mud breccia layer is overlain by only 6 cm of yellowish brown sandy mud with foraminifers, interpreted as hemipelagic sediments.

On the upper flows observed along the flanks, the other core (1,419 m water depth, MVSEIS08-TG-11) yielded two layers of matrix-supported mud breccias separated by a layer of brown mud with foraminifers (Fig. 4). The upper mud breccia layer is found at 20–66 cm below seafloor, the lower mud breccia near the base of the core from about 139 cm below seafloor. The upper layer can be related to the latest ejection event (MF-4 in Fig. 6b) which formed the uppermost lobe observed on the multibeam bathymetry, and is overlain by 20-cm-thick hemipelagic sediments. The lower mud

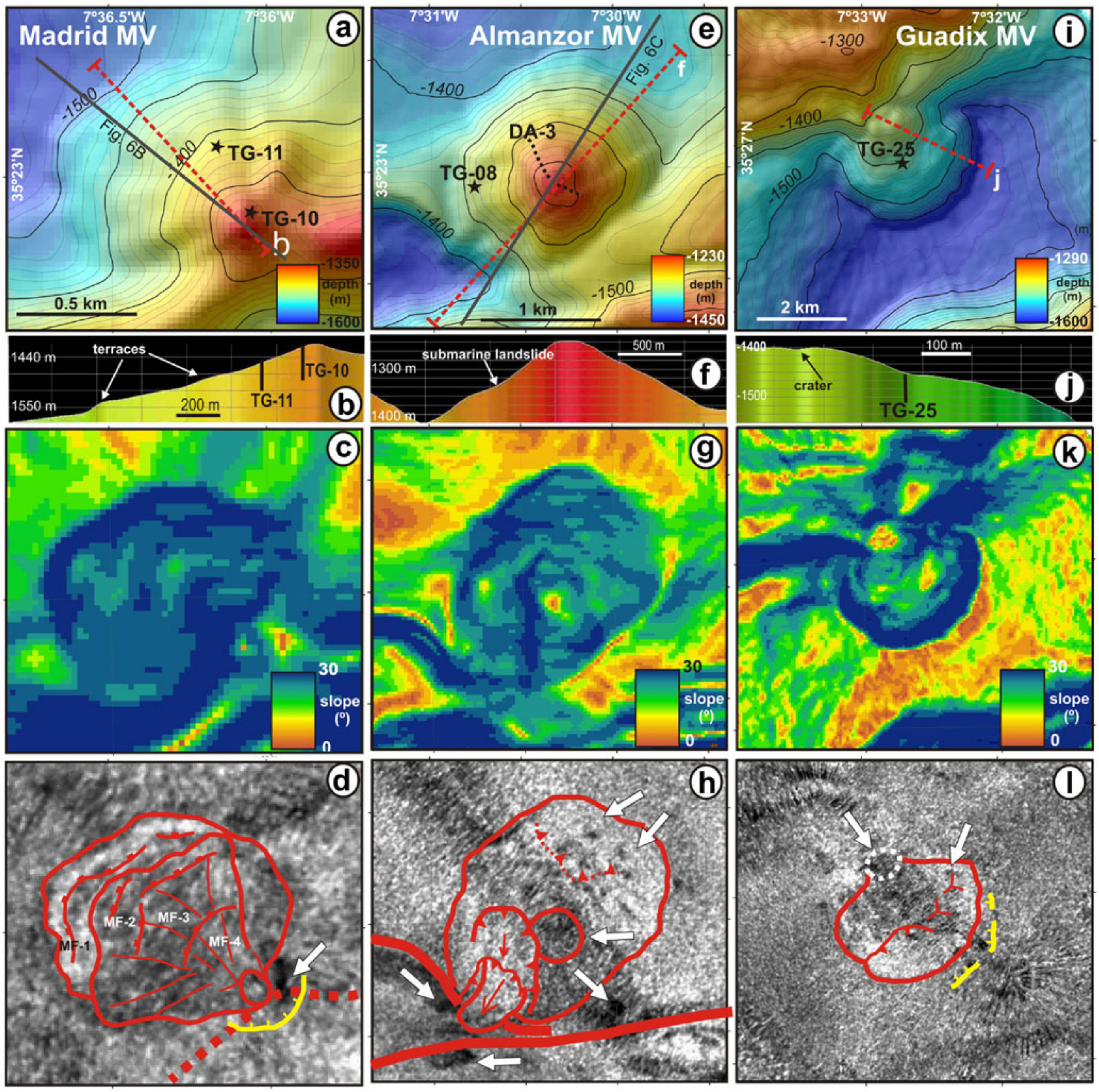

Fig. 5 Western Moroccan field: **a**–**d** Madrid MV, **e**–**h** Almanzor MV, **i**–**l** Guadix MV, and corresponding **a**, **e**, **i** bathymetric maps, as well as locations of gravity cores and cross sections (*red dashed lines*), **b**, **f**, **j** cross sections, **c**, **g**, **k** gradient maps, and **d**, **h**, **l** geological interpretations overlain on backscatter mosaics. *Dark grey lines* on bathymetric maps Locations of TOPAS seismic profiles in Fig. 6, *MF* mud flow (see legend in Fig. 3)

breccia layer can be associated with the penultimate MF-3 event identified on the TOPAS seismic profile (Fig. 6b).

Guadix MV

The Guadix MV (1,399 m water depth at the top) consists of a single, 184-m-high lobate cone which has a maximum diameter of 1,679 m (Fig. 5). The main emission point (top of cone) is located in the extreme NW, the mud extrusions flowing to the SE. As a result, the cone is strongly asymmetrical, the eccentricity ratio being 0.077. At the top of the cone is a small, 2-m-high central dome which has a small, 7-m-deep depression (crater) with a maximum diameter of 320 m and slope gradients of 2–4°.

The cone flanks have an irregular relief. Two major morphological elements, separated by a NE–SW lineation, characterize the flanks of the cone. One is located in the higher NW sector and shows moderate backscatter (−20 to

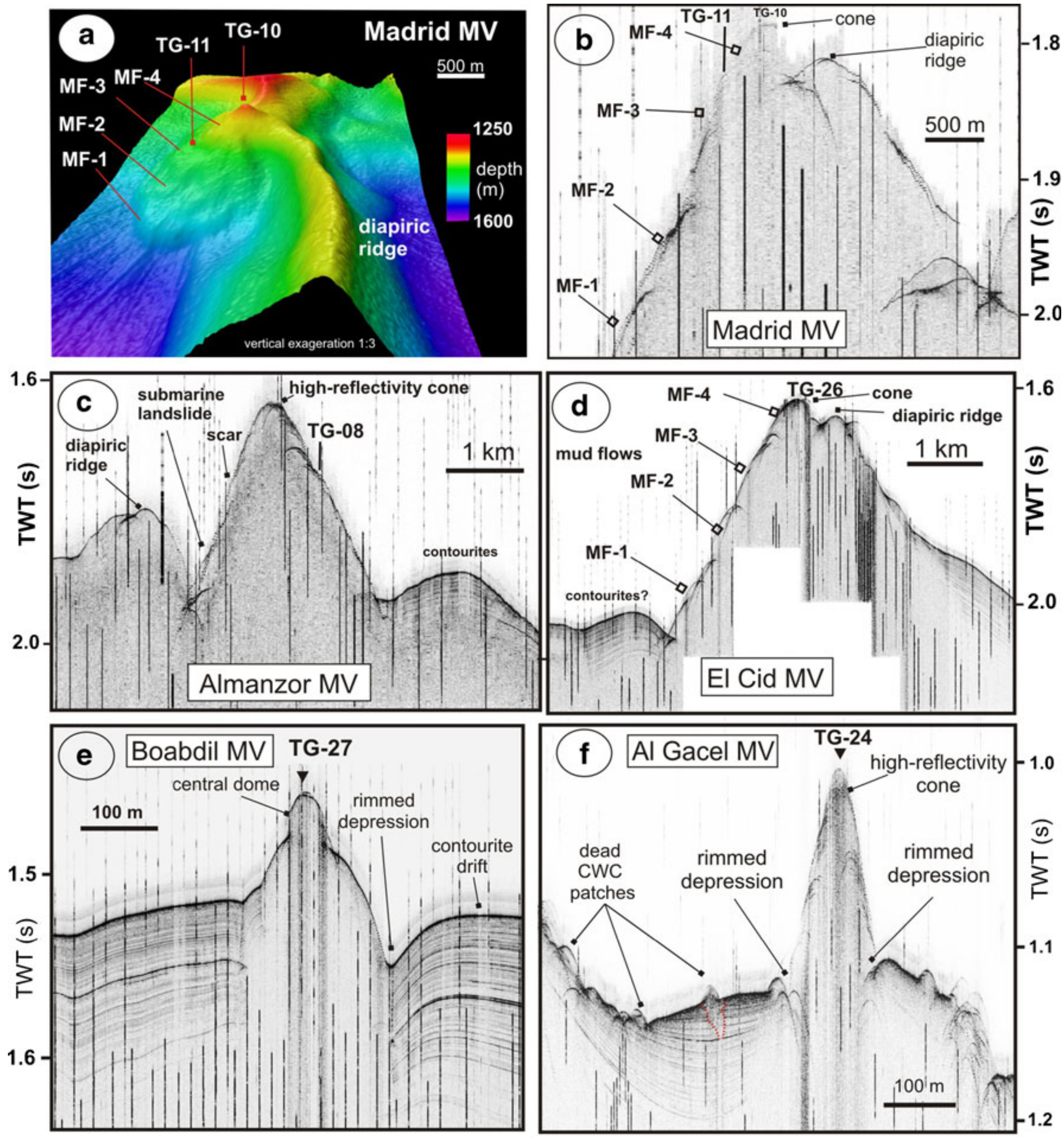

Fig. 6 **a** Three-dimensional model of the Madrid MV, and TOPAS seismic profiles of the **b** Madrid MV, **c** Almanzor MV, **d** El Cid MV, **e** Boabdil MV and **f** Al Gacel MV. *MF* Mud flow

−28 dB; Fig. 5l) and quite variable slopes of 0.7–14°. The other is located at the lower SE side. This is a mounded area of irregular relief consisting of at least three domes of 200 m diameter. The base of the cone has very low backscatter values (−30 to −37 dB) and very steep slopes (19–30°). In the south, a smooth-topped irregular relief possibly represents a gravitational slump or slide.

A gravity core taken from the Guadix MV at 1,435 m water depth (MVSEIS08-TG-25) yielded at least two layers of mud breccia flow deposits (Fig. 4). The lower one, located at 60–130 cm below seafloor, is composed of greenish grey mud with abundant lutitic clasts at its base. The upper layer of mud breccias, at 5–60 cm below seafloor, is bound at its base by a sharp erosional contact and is composed of greyish olive mud containing sub-angular clasts up to 3 cm in diameter made of lutite and carbonate. The upper mud breccia deposit is overlain by only 5 cm of oxidised yellowish brown mud with foraminifers (Fig. 4).

Almanzor MV

The Almanzor MV is a round, cone-like structure 175 m high with its summit at 1,235 m water depth, a maximum diameter of 1,984 m and an average slope of 5° on its flanks (Figs. 5 and 6c). At least two extrusion episodes can be distinguished, the main episode forming the major part of the cone. It has a homogeneous relief of very low backscatter (−32 to −35 dB). At the top, a central dome of moderate backscatter (−21 to −26 dB) may represent a younger mudflow episode.

The SW flank is affected by submarine landslides. At least two slide scars have been identified along the trace of a fault interpreted from the swath bathymetry (Fig. 5d). The submarine landslides appear as hyperbolic diffractions on a TOPAS seismic profile (Fig. 6c). A dredge haul and a gravity core were taken from the top of this mud volcano. The 81-cm-long core recovered at 1,440 m water depth (MVSEIS08-TG-08) consists mainly of mud breccias supported by a chaotic greyish olive matrix containing abundant lutitic sub-angular clasts. The mud breccia is topped by 12 cm of hemipelagic sediments comprising yellowish brown sandy foraminiferal mud (Fig. 4). The dredge haul (MVSEIS08-DA3) recovered abundant silty-sandy, brown hemipelagic sediments with centimetre-size fragments of HDACs, dead CWCs (*Madrepora oculata*), bivalves, gastropods and sponges.

El Cid MV

The El Cid MV (1,230 m water depth at the top) consists of a single lobate, 337-m-high cone with a maximum diameter of 2,853 m. Due to the NW-directed flow of the mud extrusions, the mud volcano has an asymmetrical profile (Figs. 6d, and 7). The difference in elevation between the NW and SE base of the cone is 35 m. Thus, two different parts can be distinguished. The higher part (MF-4 in Figs. 6d, and 7d) is elliptical (460×710 m) with a flat-topped, 35-m-high dome characterized by very high backscatter values (−18 to −22 dB). The lower part is located at the NW side of the edifice and shows at least three major mud-flow events which have formed a terraced morphology (Fig. 7b, c).

The outflows form several concentric, semi-circular structures of different backscatter which correlate with hyperbolic diffraction patterns on TOPAS seismic profiles (Fig. 6d). The basal mud-flow event (MF-1) is associated with slopes of 2–6° and with two sectors of different backscatter values. The western sector (MF-1a) shows very low backscatter (−31 to −35 dB), whereas that of the eastern sector (MF-1b) is moderate (−27 to −31 dB). The western basal terrace slopes very steeply (17–30°) down to the adjacent basin floor. MF-2 ends downslope in a marked ramp which has a maximum height of about 50 m and slopes ranging from 12–17°. MF-2 and MF-3 have moderate backscatter (−23 to −28 dB) and a mounded relief. Their upper slopes are 5–10° (Fig. 7c). A 10-m-deep rimmed depression can be recognized along the SE flank. The NW side, by contrast, does not display a rimmed depression but merges with the adjacent seafloor by a marked change in slope.

A 66-cm-long gravity core recovered from the El Cid MV at a depth of 1,230 m (MVSEIS08-TG-26) consists mainly of greyish olive mud breccias with abundant clasts grading at the top into a 10-cm-thick layer of oxidised yellowish foraminiferal mud (Fig. 4).

Middle Moroccan field

Two new mud volcanoes, named Boabdil and Al Gacel, were discovered in the MMF (Fig. 2). These are isolated, circular, cone-shaped edifices about 1 km in diameter with central domes and narrow depressions displaying collapsed rims. The surrounding area consists of dead CWC patches.

Boabdil MV

The Boabdil MV is a single, 88-m-high circular cone-like structure with a diameter of 1,390 m, its summit being located at a water depth of 1,102 m (Figs. 6e, and 7). It has a central dome and a terraced morphology (Fig. 7j, k), comprising two terrace levels which are possibly related to different outflow episodes. The upper terrace shows moderate backscatter (−25 to −27 dB), contrasting with the lower values of the basal terrace (−31 to −28 dB). The slopes are gentle at the top of the terraces (1–2.5°) but steep at the base of the cone and across the scarp of the terraces (9–15°). The central dome, which is characterized by high backscatter (−15 to −18 dB), is cone-shaped with slopes ranging from 7–10°. A seismic profile reveals a rimmed, 24-m-deep depression which has been modified by contourite deposits (Fig. 6e).

A 64-cm-long gravity core recovered from the top of the mud volcano (MVSEIS08-TG-27; Fig. 4) at a water depth of 1,106 m has a lower 10-cm layer consisting of mud breccias with a strong H_2S smell. These are overlain by 54 cm of foraminifer-rich mud containing abundant coral fragments.

Al Gacel MV

The Al Gacel MV is a single, cone-shaped structure with its summit at 763 m water depth, 107 m high and 944 m in diameter (Figs. 6f, and 7). The flanks are homogeneous and continuous with slopes ranging from 7–13°. The upper part of the cone shows moderate backscatter (−20 to −26 dB), contrasting with the lower values (−24 to −29 dB) of the middle and basal parts of the flanks. The maximum slope value is 23° at the foot of the cone. At the SW and NE sides, two smooth-topped irregular reliefs could represent gravitational slump structures. On the corresponding TOPAS seismic profile (Fig. 6f), the submarine landslides are characterized by high-reflectivity hyperbolic diffraction patterns. An 11-m-deep rimmed depression surrounds the mud volcano. It has an irregular lobate shape with patches of

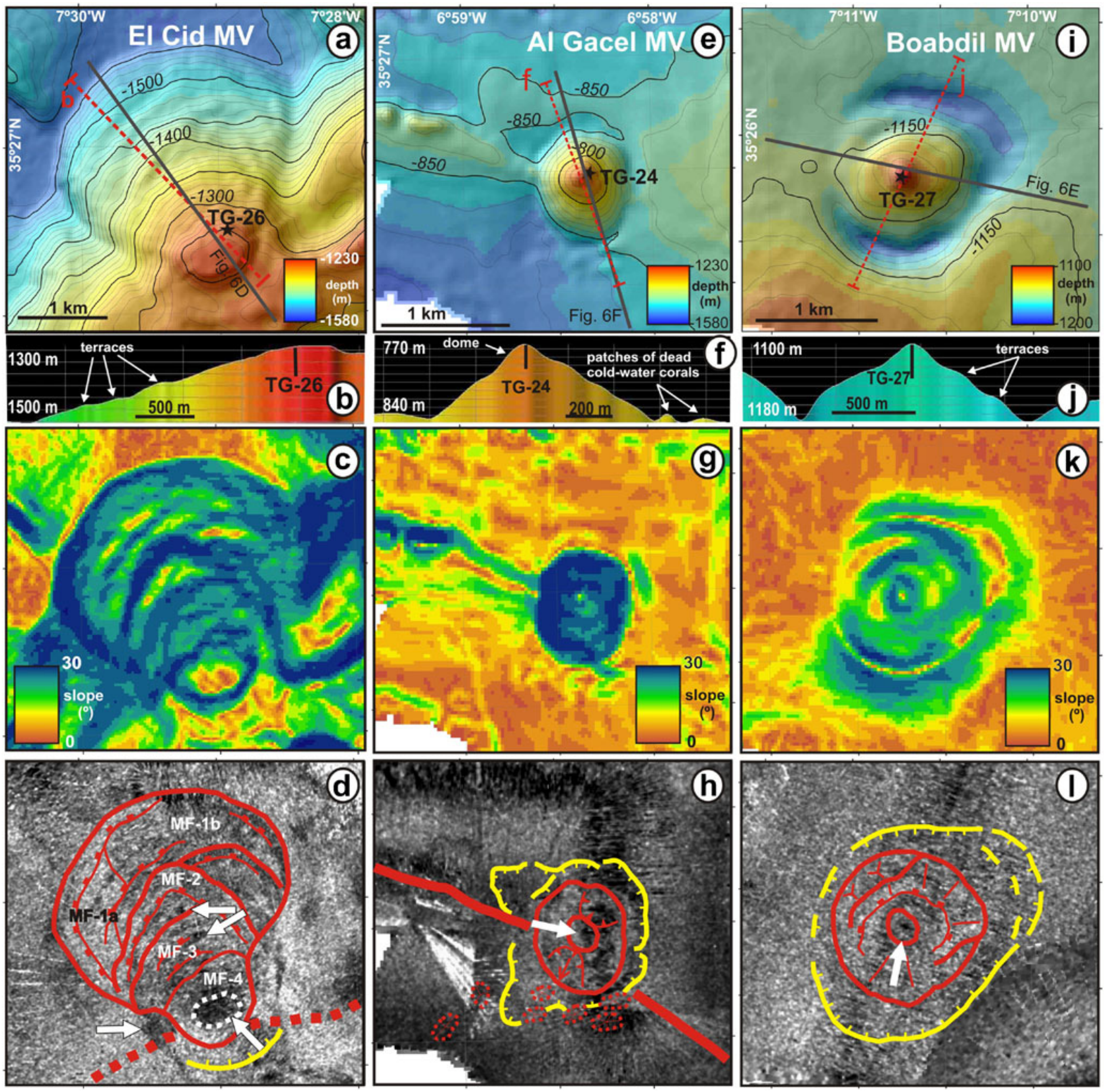

Fig. 7 Western Moroccan field: **a**–**d** El Cid MV, middle Moroccan Field: **e**–**h** Al Gacel MV, **i**–**l** Boabdil MV, and corresponding **a**, **e**, **i** bathymetric maps, as well as locations of gravity cores and cross sections (*red dashed lines*), **b**, **f**, **j** cross sections, **c**, **g**, **k** gradient maps, and **d**, **h**, **l** geological interpretations overlain on backscatter mosaics. *Dark grey lines* on bathymetric maps Locations of TOPAS seismic profiles in Fig. 6, *MF* mud flow (see legend in Fig. 3)

positive relief composed of dead CWCs which have high backscatter (−16 to −20 dB). The TOPAS seismic profile (Fig. 6f) reveals a highly reflective cone with a central dome. Patches of dead CWCs characterized by high-reflectivity hyperbolic patterns can be recognized in the surrounding areas. On the backscatter mosaic, these patches have high backscatter values.

An 84-cm-long gravity core recovered from the top of the Al Gacel MV (MVSEIS08-TG-24) at a water depth of 782 m has a lower 74-cm layer consisting of ejected mud breccias with a strong H_2S smell (Fig. 4). They contain abundant coral fragments and bioclasts, which may be interpreted as erosional entrainments of mud flows crossing coral patches. The mud breccia layer is overlain by 10 cm of yellowish brown sandy mud containing abundant foraminifers and bioclastic fragments. Several patches of dead CWCs (*Lophelia pertusa*) were recorded in the western and southern sectors of this region.

Discussion

Morphology of episodically active mud volcanoes

The results presented above show a high variety of morphological characteristics which define specific geological processes and provide information about the nature and dynamics of mud extrusions. Mud volcanism is inherently episodic, with long periods of dormancy separating eruptions (e.g. Dimitrov 2002; Kopf 2002). Theoretical discharge rates from conduits suggest that periods of quiescence account for over 95% of the life of a mud volcano (Kopf 2002). Mud-flow extrusions reflect active periods of degassing and are considered to be catastrophic events interspersed with periods of inactivity (e.g. Guliyiev and Feizullayev 1997).

In the present study, stacking of recent mud breccia flows, suggesting cyclicity, has been revealed by gravity coring combined with multibeam bathymetry and backscatter data for the slopes of terraced asymmetric mud volcanoes. This is consistent with the cyclic activity reported for other mud volcanoes in the Gulf of Cádiz (Van Rensbergen et al. 2005; Perez-Garcia et al. 2011). Eventually, the phase of quiescence is characterized by hemipelagic sedimentation and, indeed, hemipelagic sediment thickness has been used as an indicator of mud volcano inactivity (Van Rensbergen et al. 2005). Mud volcanoes such as Madrid and El Cid have at least two stacked layers of mud breccia extrusions each only 0.5 m thick, intercalated between hemipelagic layers. Evidence of both low- and high-viscosity mud flows (cf. below) is consistent with mud flows of different shear strengths driven by the evolving dynamics of mud chambers, as proposed by Praeg et al. (2009).

The rimmed depressions of the Las Negras and Madrid MVs, the area surrounding the Almanzor MV, and the summits of the flat-topped MVs such as MVSEIS and El Cid show high and very high values of backscatter compared to other parts of the edifices. Moreover, gravity cores from these flat-topped mud volcanoes revealed mud breccia deposits overlain by multi-layer sequences of hemipelagic sediments interbedded with cohesive grey muds up to 1–2 cm thick. It is suggested that these thin layers correspond to low-viscosity mud flows similar to those observed in onshore mud volcanoes in the form of “pools” or “salsas” (Yakubov et al. 1971; Hovland et al. 1997). The very high backscatter values documented in the Las Negras, Madrid and Almanzor MVs could be related to sites of focused fluid flow and the occurrence of HDAC precipitates. The high backscatter values at the summits of flat-topped MVs could be related to the absence of hemipelagic sediments (or their occurrence in very thin layers) on hard substrates such as cold-water corals, HDACs and polymetallic precipitates (sulphides, ferromanganese concretions). As Magalhães et al. (2011) suggest, these could include pavements of aragonite-lithified mud volcano breccias.

Flat-topped edifices are absent along the Iberian margin of the Gulf of Cádiz and, in this study, have been detected only in the western Moroccan field. The Las Negras and MVSEIS MVs, for example, are morphologically similar to the Meknes and Al Idrisi MVs of the eastern Moroccan field (Kenyon et al. 2003; Van Rensbergen et al. 2005), the latter considered to have formed during periods of higher fluid flow activity. Thus, both along the Mediterranean Ridge and in the Black Sea, the formation of flat-topped mud volcanoes seems to be related to enhanced fluid flow associated with the extrusion of mud of lower shear strengths (Ivanov et al. 1996; Lykousis et al. 2004).

Asymmetrical MVs crop out on the slope scarps and mud extrusions flow downslope to the deep seafloor, resulting in very long outflows with strongly displaced mud emission centres relative to the geographic centres of the cones. The length of an outflow is a function of, among others, its viscosity, the seafloor roughness, and the energy and duration of the mud extrusion event. As these all change in the course of a given active phase, it is very rare that outflows have the same length, especially in the case of asymmetrical MV types. As a consequence, terraced profiles are more common on the flanks of asymmetrical oval morphologies. In this sense, terraced flanks with lobate shapes are suggestive for the existence of an active phase. The majority of analysed asymmetrical cones clearly have more than one episode of mud-extrusion flow, each giving rise to a terraced lobe.

Backscatter mud-flow signatures show different values for older (basal) and younger (upper) events, plausibly explained by variations in hemipelagic sediment thickness over outflows and the presence/absence of HDAC precipitates (e.g. cores MVSEIS08-TG-10 and MVSEIS08-TG-11 of the Madrid MV). Compared with the upper terraces, increased hemipelagic sediment thickness and low backscatter for the basal terraces would be related with older outflow episodes.

The central domes and associated outflows of single-cone mud volcanoes such as Al Gacel and Boabdil can be related to younger episodes of mud-extrusion activity. These dome-like features are morphologically very similar to others less commonly observed onshore such as “gryphons” (Yakubov et al. 1971), resulting from high-viscosity extrusions (Hovland et al. 1997; Mazzini et al. 2009). Thus, it is possible that the central domes were generated during a late phase characterized by higher-viscosity extrusions. This evolution from less to more viscous outflows with time could be related to variations in sediment pore pressure during periods of tectonic reactivation. Degasification caused by overpressure would evolve from an initial energetic stage to an end stage, when tensional sediment conditions would tend to normalize. Thus, decreasing shear stress at the end of an active phase would generate late, higher-viscosity mud ejections. Indeed, deep thermal maturation of clay minerals promotes the diagenetic transformation of smectite to illite with supply of water by dewatering, contributing to overpressure in the sedimentary pile (Brown et al. 2001). This important supply of water would favour low-viscosity outflows in the initial stages of mud volcanism.

Depressions commonly occur in two main parts of such edifices: at the top (e.g. the Mercator and Al Idrisi MVs; Van Rensbergen et al. 2005) and at the periphery (e.g. the Hespérides and Pipoca MVs; Somoza et al. 2003). Both types of depressions are related to a mass defect below the edifice and/or relaxation of the compressional stress field due to the expulsion of sediment and fluids from the mud chamber. It is argued here that, in the phase of reduced seepage activity, the mud chamber is depleted and the loss of volume at depth generates a localized basin or rim syncline of sagged strata which will eventually collapse. The restriction of rimmed depressions to the SE sides of the asymmetrical MVs, such as the Madrid and El Cid MVs, can be explained by the preferential NW flow of their mud extrusions. Their rimmed depressions are constrained by their feeder channels and then related to the diapiric crest. The NW flow would fill and bury any depression which may have been present on this side.

Submarine landslides occur mainly on the flanks of three sub-circular, cone-shaped edifices, the Almanzor, Al Gacel and Moundforce MVs. The emission centres of these MVs are located over the tracks of faults and other tectonic lineaments. At the Moundforce MV (core MVSEIS08-18), thin layers of low-viscosity fluids expelled from the mud volcano are separated by layers preliminarily interpreted as being generated by instability of slope deposits.

The Almanzor MV has steep slopes and collapse structures have not been observed. Thus, submarine landslides are associated with steep slopes and possibly triggered by the activity of neighbouring faults. The presence of gastropods, Foraminifera and cold-water coral skeletons inside the mud breccias of the Al Gacel MV might result from two processes: remobilization and mixing at the seafloor and/or submarine landsliding on the flanks of the mud volcano. The scars identified on the MBES and seismic profiles, as well as the higher seabed roughness over the flanks of the Al Gacel MV associated with hyperbolic seismic reflections suggest that the presence of this type of bioclast material is related to submarine landslide processes. In summary, it is argued here that submarine landslides on the mud volcano flanks are related to (1) the activity of tectonic or diapiric lineaments; (2) lateral extension of sediments affected by progressive subsidence or collapse of the edifice; (3) slope failure due to oversteepening of the flanks; (4) a combination of all these factors.

The Al Gacel and Boabdil MVs are morphologically similar to the previously reported Student and Rabat MVs (Kenyon et al. 2001; Pinheiro et al. 2003) in the middle Moroccan field. These structures are about 1–1.5 km in maximum diameter, with smooth rimmed depressions. Their morphology resembles that of single cones observed on top of complex mud volcanoes in this field, such as the Yuma and Ginsburg MVs (Kenyon et al. 2000; Gardner 2001). Rimmed depressions are a common feature in all the mud volcanoes surveyed in the MMF (Kenyon et al. 2000; Pinheiro et al. 2003; Van Rensbergen et al. 2005). In the present case, the seismic data show that the rimmed depressions of, for example, the Boabdil and Al Gacel MVs seem to be modified by contourite moats and sediments (Casas et al. 2010) related to strong deep bottom currents. Thus, the rimmed depression of the Boabdil MV would correspond to a contourite moat generated by interaction of the deep bottom current with the positive relief of the mud volcano.

Role of deep bottom currents

The occurrence of patches of dead cold-water corals around (about 5 km) the Al Gacel MV is not an isolated case. Along the Atlantic Moroccan margin, mounded patches of dead and buried CWCs surrounding MVs and seepage areas are very common (Foubert et al. 2008; Wienberg et al. 2009; Van Rooij et al. 2011) from the upper to the lower slope (Wienberg et al. 2009). Most deep CWC patches observed during the MVSEIS-08 cruise were found up to 1,250 m water depth in contourite drifts of the Moroccan Atlantic margin (Casas et al. 2010). Although dead CWCs have been recovered in the western Moroccan field—e.g. the Almanzor MV (1,235 m water depth)—and on the adjoining lower slope (Wienberg et al. 2009), CWC patches were not observed in multibeam mosaics below 1,200 m water depth. Seeing that the diameter of patches identified in the middle Moroccan field ranges from 100 to 300 m, and that the MBES footprint at 2,000 m water depth is 35 m, it is highly unlikely that any WMF patches would have remained undetected.

As discussed above, high backscatter values observed at the summits of the MVSEIS, Almanzor, Madrid and El Cid MVs (from 1,230 to 1,594 m water depth) can be related to the presence of hardgrounds (HDACs and polymetallic crusts and nodules) and/or cold-water corals. This partial "lithification" of mud volcanoes takes place in two phases. An initial, latent phase is characterized by reduced micro-seepage activity and the possible occurrence of diffuse methane flow (León et al. 2007). Anaerobic oxidation of methane generates vast amounts of HDAC chimneys, crusts and pavements and, as suggested by González et al. (2009), ferromanganese-carbonate nodules and crusts. This is followed by a quiescent phase with colonization by non-chemosynthetic organisms such as CWCs (e.g. *L. pertusa*, *M. oculata*) on hard substrates like HDAC pavements and ferromanganese-oxide nodules, exhumed by deep bottom currents such as inferred for the contourite deposits and moats of the middle and eastern Moroccan fields (Casas et al. 2010; Van Rooij et al. 2011).

Thus, it is possible that the contrasting patterns of cold-water coral occurrence in the vicinity of mud volcanoes in the three Moroccan fields are due to different oceanographic constraints. As proposed by Wienberg et al. (2010), upwelling processes during the Younger Dryas event could have promoted the growth of solitary CWCs below 1,200 m water depth. On the other hand, strong deep bottom currents related to contourite drifts and moats of the Moroccan Atlantic margin could have promoted coral growth at shallower depths in the middle and eastern Moroccan fields. The origin of these bottom currents is controversial. Van Rooij et al. (2011) suggest relationships with either the present-day interface between the AAIW and NACW, creating several intermediate nepheloid layers, or an intensified MOW arising during colder periods (glacials/stadial) due to an enhanced meddy activity, as suggested also by Foubert et al. (2008) and Casas et al. (2010). However, evidence of MOW in the middle Moroccan field remains to be reported.

Based on the arguments presented above, the main characteristics which define the structure and morphology of mud volcanoes in the Gulf of Cádiz can be combined in the following evolutionary model, whereby at least three stages may be differentiated (cf. León et al. 2007): (1) an active phase of mud-flow extrusion and mud volcano formation, (2) a latent phase with reduced activity and diffuse fluid flow, leading to the formation of HDACs, and (3) a quiescent phase characterized by bottom current erosion and colonization by non-chemosynthetic organisms such as deep cold-water corals on hard substrates.

Conclusions

For the ten newly discovered MVs in the western and middle Moroccan fields on the Moroccan Atlantic continental margin, gravity core-based evidence of mud breccia deposits attests to the nature of extrusion of these cones and enabled assessment of the use of the term “mud volcanoes” (e.g. Dimitrov 2002). The typical asymmetric cone morphology of the Las Negras, MVSEIS, Madrid, Guadix and El Cid MVs has not been reported hitherto for the Gulf of Cádiz, and asymmetric MVs were observed only in the western Moroccan field. Characterized by a high eccentricity of their outflows with respect to the emission centres, their morphology is probably due to the location of the edifices along diapiric crests. Of these, the MVSEIS, Las Negras, Guadix and El Cid MVs display flat-topped summits with distinct depressed central areas interpreted as craters.

The Moundforce, Pixie, Boabdil, Al Gacel and Almanzor MVs are sub-circular cone-shaped edifices located over tectonic lineaments. Large submarine landslides identified on the flanks of the Moundforce, Al Gacel and Almanzor MVs are interpreted to have been caused either by recent tectonic activity along the diapiric lineaments or by progressive subsidence or collapse of the edifices, causing lateral extension of mud breccia sediments.

High to very high backscatter values concentrated in sub-circular patches in distinct sectors of the mud volcanoes are interpreted as signals of recent seabed fluid flow. These occur in the rimmed depressions of, for example, the Las Negras, Almanzor and Madrid MVs, as well as in the craters of the flat-topped summits of, for example, the El Cid and MVSEIS MVs.

Patches of dead cold-water corals have been observed at water depths reaching 1,200 m in the vicinity of mud volcanoes in the middle Moroccan (present study) and eastern Moroccan fields but not below this water depth, where only solitary dead specimens have been recorded. This could be a sign of different oceanographic constraints involving upwelling processes during the Younger Dryas event and strong deep bottom currents associated with contourite drifts and moats along the Moroccan Atlantic margin.

Supported by core-based information, the morpho-structural analysis of the mud volcanoes suggests episodic mud-extrusion events separated by periods of quiescence. Evidence of this episodic activity includes identification of (1) layers of mud breccias separated by hemipelagic sediments, (2) terraced and lobe-shaped flanks, and (3) abrupt changes in the slopes and relief of the edifices—e. g. flat tops and central domes with high backscatter values.

Quiescent periods act in different ways on the morphology of mud volcano edifices, depending on the tectonic setting and oceanographic conditions. Subsidence, bottom current erosion, landsliding, and colonization by cold-water corals are some key processes affecting the morphology of mud volcanoes during quiescence.

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