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Distribution and geological control of mud volcanoes and other fluid/free gas seepage features in the Mediterranean Sea and nearby Gulf of Cadiz

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Abstract:

Existing knowledge on the distribution of mud volcanoes (MVs) and other significant fluid/free gas-venting features (mud cones, mud pies, mud-brine pools, mud carbonate cones, gas chimneys and, in some cases, pockmark fields) discovered on the seafloor of the Mediterranean Sea and in the nearby Gulf of Cadiz has been compiled using regional geophysical information (including multibeam coverage of most deepwater areas). The resulting dataset comprises both features proven from geological sampling, or in situ observations, and many previously unrecognized MVs inferred from geophysical evidence. The synthesis reveals that MVs clearly have non-random distributions that correspond to two main geodynamic settings: (1) the vast majority occur along the various tectono-sedimentary accretionary wedges of the Africa-Eurasia subduction zone, particularly in the central and eastern Mediterranean basins (external Calabrian Arc, Mediterranean Ridge, Florence Rise) but also along its westernmost boundary in the Gulf of Cadiz; (2) other MVs characterize thick depocentres along parts of the Mesozoic passive continental margins that border Africa from eastern Tunisia to the Levantine coasts, particularly off Egypt and, locally, within some areas of the western Mediterranean back-arc basins. Meaningfully accounting for MV distribution necessitates evidence of overpressured fluids and mud-rich layers. In addition, cross-correlations between MVs and other GIS-based data, such as maps of the Messinian evaporite basins and/or active (or recently active) tectonic trends, stress the importance of assessing geological control in terms of the presence, or not, of thick seals and potential conduits. It is contended that new MV discoveries may be expected in the study region, particularly along the southern Ionian Sea continental margins.

1. Introduction

Since the pioneering work of Hovland and Judd (1988), expanded by Judd and Hovland (2007), a considerable amount of work has been published on cold fluid seepages on continental margins, and their impacts on various aspects of the marine environment. A worldwide estimate of submarine mud volcano (MV) distribution was first proposed by Milkov (2000) and, soon thereafter, Dimitrov (2002) compiled 270 confirmed and 572 suspected MVs in offshore domains, including about 30 proven and 80 inferred in the Mediterranean Sea. Mazurenko and Soloviev (2003) published a global distribution of deep-water fluid venting indicating about 2,000 occurrences, with 11 proven MV fields in the vicinity of the Mediterranean. Kopf (2003), using a similar MV distribution, tentatively estimated the impact of MV degassing on the accumulation of greenhouse gases in the atmosphere. More recently, Tinivella and Giustiniani (2012) provided a worldwide overview of MVs associated with gas hydrate systems, including the related Mediterranean Sea datasets compiled by Milkov (2000) and Dimitrov (2002).

This paper presents a state-of-the-art synthesis of proven and inferred submarine MVs at the scale of the entire Mediterranean Sea, including information on the nearby Gulf of Cadiz, an area geodynamically related to the evolution of the Mediterranean. Incorporating the most recently published datasets, this is the first complete review of MVs in this world region. Moreover, GIS tools have served to cross-correlate MV occurrences with other main geological characteristics²only such a systematic approach may enable better assessment of key factors controlling MV distribution.

2. Overview of previous work

In the Mediterranean Sea, the first mud volcano ever discovered is the Prometheus mud breccia dome, first described as a mud diapir by Cita et al. (1981). Located in the Ionian Basin along the north-western inner branch of the Mediterranean Ridge, Prometheus dome was suggested to originate from diapiric processes of deeply buried Mesozoic décollement levels of the Mediterranean accretionary prism (Ryan et al. 1982). It remained the only known such feature until the discovery in the late 1980s/early 1990s, also by Italian scientists, of new mud breccia domes on top of the central Mediterranean Ridge, interpreted to record processes of intrusion and extrusion over at least 300 ka (Cita et al. 1989; Camerlenghi et al. 1992, 1995). Scientific drilling of two of these features during ODP leg 160, the Napoli and Milano MVs, showed them to record extrusion of mud breccias over at least the last 1.2 Ma (Robertson and Ocean Drilling Program Leg 160 Scientific Party 1996; Emeis et al. 1996).

At the same time, discoveries of such features increased dramatically through the use of sidescan sonar data, including a reassessment of GLORIA long-range imagery acquired in the 1970s (Fusi and Kenyon 1996), and new higher-resolution data collected during expeditions conducted mostly in the eastern Mediterranean chiefly, but not only, under the flag of the Russian/UNESCO TTR project headed by the late M. Ivanov (see In Memoriam by Suzyumov 2012). This led to a rich variety of publications concerning characteristics such as the acoustic signatures, geochemical signals, sedimentological and lithological typologies, and structural fabrics of these seafloor-specific morphologies, by then generally interpreted as mud volcanoes (e.g. Cita et al. 1994). Two areas in particular were investigated: (1) south of Crete, the now well-known Olympi MV group, including the Napoli and Milano MVs (Limonov et al. 1994, 1996; Galindo-Zaldivar et al. 1996; Hieke et al. 1996; Ivanov et al.

1996; Cronin et al. 1997), and (2) south of Turkey, the Anaximander Mountains area and particularly the large Amsterdam MV (Woodside et al. 1998; s et al. 2004, 2009).

From 1995 to 1998 French scientists (from Ifremer, ENS-Géologie Paris and Géoazur-Villefranche) conducted systematic swath mapping of the western (Ionian), central and eastern domains of the Mediterranean Ridge (Mascle et al. 1999, 2006; Chamot-Rooke et al. 2005). These surveys resulted in an almost 100% bathymetric coverage of wide areas of the deep eastern Mediterranean basins between the foot of the northern African (Libyan) continental margins and the southern borders of the Aegean microplate, approx. from Kephalonia to Rhodes. The huge and detailed bathymetric and backscatter datasets, together with 3.5 kHz profiles and six-channel seismic data, provided for the first time an opportunity to not only discover many new features interpreted as probable massive fluid/mud emissions directly on the seafloor, but to also locate these with respect to the main Mediterranean Ridge structural domains and particularly its backstop. This information was then progressively completed by results from several surveys conducted along the eastern branch of the Mediterranean Ridge and the Anaximander Mountains (EEC-Anaximander project in 2003, e.g. Lykousis et al. 2009; Simed survey by Géoazur/Ifremer in 2004), as well as over the eastern Cyprus Arc (Blac survey in 2003, e.g. Benkhelil et al. 2005; Hübscher et al. 2009; Maillard et al. 2011), all of which provided new geophysical evidence of features interpreted as probable fluid/mud emission centres on the seafloor.

While a few MVs were already indicated off southeast Sicily (Holland et al. 2003), swath mapping of the eastern Mediterranean accretionary systems was completed by surveys made in 2005 by OGS Trieste (Ceramicola et al. 2006) on the external Calabrian Arc which evolved as a result of the Ionian/Calabria convergence (Rossi and Sartori 1981; Sartori 2003). Cores of mud breccia were obtained from distinctive morphological structures at two sites, the Madonna dello Ionio and Pythagoras MVs, which seismic profiles showed to be the tops of buried extrusive edifices >1 km thick inferred to have been episodically active since the mid-Pliocene (Praeg et al. 2009). The two sites were subsequently investigated using ROVs (remotely operated vehicles) and found to be seeping warm fluids that host chemosynthetic ecosystems (Foucher et al. 2009). Integration of multibeam morpho-bathymetric with backscatter data indicates the presence of many additional proven and inferred MVs across the inner to central arc, inferred to have been active over the last 56 ka (Ceramicola et al., this volume).

One of the most spectacular occurrences of fluid/mud expulsion structures on the Mediterranean seafloor has been documented on the Nile deep-sea fan along the Egyptian passive continental margin, where multibeam imagery acquired in the late 1990s to early 2000s revealed mud volcanoes, gas chimneys and dozens of small mud cones (Mascle et al. 2002) as well as larger fields of pockmarks (Coleman and Ballard 2001; Loncke 2002; Loncke and Mascle 2004). Some of these features were studied later in more detail by means of near-bottom geophysical and sampling systems and found to be active cold seeps emitting gas-rich fluids and brines to the seabed, and hosting chemosynthetic ecosystems (e.g. Dupré et al. 2007; Mastalerz et al. 2007; Bayon et al. 2009; Feseker et al. 2009, 2010; Huguen et al. 2009; Giresse et al. 2010).

In the western Mediterranean Sea, a small province of mud volcanoes has been recognized, along with several pockmark fields, within the westernmost area of the Alboran Sea, a back-arc setting containing a thick Neogene sedimentary succession (Comas et al. 2000a, 2000b; Sautkin et al. 2003; Blinova et al. 2011). First recognized on seismic profiles as seabed features developed above deeply rooted mud diapirs (Pérez-Belzuz et al. 1997; Talkuder et al. 2003), recent studies have revealed small seabed cones on tops of extrusive edifices interfingering with the sediments of the Cueta Drift and inferred to record mud extrusion since the mid-Pliocene (Somoza et al. 2012). Almost no other such features have been recognized in the western Mediterranean Sea, although possible mud diapirs and mudflows have been found in the southeastern Tyrrhenian Sea on the continental slope of Calabria (Gamberi and Rovere 2010). It has also been suggested that a field of small abyssal hills in the Balearic Sea may include features that could be mud volcanoes, based on their morphology (Camerlenghi et al. 2009), but this interpretation remains untested by coring. Clusters of rather small mud diapirs have also been recognized within the central Adriatic (Martinelli and Judd 2004); these features seem to originate from very shallow levels (Hovland and Curzi 1989) and cannot be considered as typical MVs.

Finally, at the western exit of the Mediterranean Sea, the Gulf of Cadiz is another probable accretionary wedge thought to result from the eastward subduction of the oldest central Atlantic oceanic crust beneath the Alboran Sea (Gutscher et al. 2002). Following an initial discovery of large pockmarks (Baraza and Ercilla 1996), numerous swath bathymetric and backscatter data collected from 1999±2002 led to the discovery of dozens of sub-circular features interpreted as MVs, many proven by coring (e.g. Somoza et al. 2000, 2001, 2002, 2003; Gardner 2001; León et al. 2001, 2007, 2012; Mazurenko et al. 2002; Pinheiro et al. 2003; Sautkin et al. 2003; Van Rensbergen et al. 2005).

3. Criteria for identification of MVs and fluid seeps

Ivanov et al. (1996) and Limonov et al. (1996) have argued that the identification of mud volcanoes requires geological evidence: only features that have been observed *in situ* or sampled, and shown to have typical sedimentological and/or geochemical characteristics (such as for the Anaximander and Olympi clusters) can be interpreted as being mud volcanoes. By contrast, the authors of the present article contend that the identification of fluid-releasing features (mud volcanoes, gas chimneys, mud and brine cones, pockmarks and mounds) may also be based, with a good degree of confidence, on characteristics derived from geophysical evidence.

Mud volcanoes that have been sampled and observed *in situ* typically display strong similarities between different geophysical signatures in terms of, for example, morpho-bathymetry, backscatter, seismic facies character and, in some cases, hydroacoustic flares; this justifies many as yet unsampled features being interpreted as active or recently active fluid/mud-releasing structures. Based on this approach, it has been possible to map a wide variety of MVs and other fluid/mud expulsion centres such as mud cones, mud pies, mud-brine pools and even fields of pockmarks at a regional scale. For the sake of convenience in this paper, the term mud volcano refers to all seafloor features potentially resulting from recently active or active fluid releases, irrespective of the nature and the origin of the fluid and the specific morphology. This compilation is based on the following geophysical criteria: morphologies, backscatter signatures and seismic images; geophysical mapping has been completed by MVs identified from geological samples and in situ observations (submersibles, ROVs).

3.1. Morphological characteristics

As indicated above, considerable amounts of swath bathymetric data have been made available for the Mediterranean Sea since the mid-1990s. This includes information from hull-mounted systems, providing deep-water resolution of 25±100 m (over wide areas), as well as systems mounted on AUVs (autonomous underwater vehicles) and ROVs that provide imagery of individual structures at resolutions as high as 1 m, approaching those of *in situ* observation. Comparisons of these different datasets illustrate the scale-dependent morphologies of mud volcanoes.

Regional multibeam datasets acquired by European research institutes active in the Mediterranean Sea have been digitally compiled in a series of large-scale maps under the auspices of CIESM (Commission Internationale pour l'Exploration Scientifique de la Méditerranée), with a grid resolution of ca. 500 m (Medimap Group 2005, 2007). The latest version of this compilation has recently been completed to generate the most precise morphological map of the Mediterranean Sea available to date (DTM at 500 m; Brosolo et al. 2012; Fig. 1). This map chiefly highlights the dramatic differences between the shallower (up to 3,000 m deep) and tectonically less deformed western Mediterranean and the deeper (up to 5,000 m) eastern Mediterranean Sea characterized by (from west to east) a series of broad, arc-shaped reliefs corresponding to the accretionary prisms of the external Calabrian, Mediterranean and Florence-Hecatus ridges. Even at regional scale, inspection of these seafloor features, and particularly of the Mediterranean Ridge, reveals the presence of numerous small cone-shaped morphologies, many already known to be MVs.

A close up of the central part of the Mediterranean Ridge using more detailed mapping (DTM at 100 m; Fig. 2) shows the well-known Olympi MV group characterized by several circular to lens-like features 1±2 km in diameter, proven to be active mud volcanoes (Limonov et al. 1994; Robertson and Ocean Drilling Program Leg 160 Scientific Party 1996; Kopf et al. 1998; Huguen et al. 2005). Of these, the Napoli mud volcano (Fig. 3a) has been studied during three successive multibeam surveys, including near-bottom swath mapping and *in situ* sampling using a ROV. Near-bottom data reaching 2 m resolution display a much more complex morphology than that obtained from the sea surface, including the occurrence of numerous small-scale depressions and mud/brine flows (Fig. 3b).

Similar multi-scale comparisons are available for four mud volcanoes, or gas chimneys, investigated in detail during the past years on the Nile deep-sea fan (Dupré et al. 2007, 2008, 2010; Huguen et al. 2009), considerably expanding our understanding of fluid-releasing features on the Egyptian continental margin. Figure 4a illustrates a cluster of small mud cones and a caldera-like depression at the foot of the north-western Egyptian margin, in an area also affected by intense disruption due to salt tectonics; Fig. 4b shows two small twin mud cones mapped using near-bottom swath bathymetry tools within the caldera; one of these is now inactive, whereas the other contains a brine/mud/fluid lake up to 250 m deep (Dupré et al., this volume). Finally, Fig. 5 illustrates a sector of the seabed comprising numerous pockmark and authigenic carbonate pavement fields on the middle continental slope of the Nile margin.

Such datasets support interpretations of many other sub-circular mound-like features detected on the seabed of the Mediterranean Ridge and in other areas as active, or recently active, mud/fluid expulsion centres. An interesting example of the discovery of mud volcanoes based solely on distinctive morphologies is provided by the Madonna dello Ionio MVs on the Calabrian Arc, comprising twin cones and a caldera (together resemble a reclining woman, hence the name) that all yielded cores of mud breccia (Ceramicola et al. 2006; Praeg et al. 2009). Morphology alone does not provide conclusive evidence, however, and the identification of mud volcanoes is greatly strengthened by additional geophysical characteristics, notably backscatter (e.g. Ceramicola et al., this volume).

3.2. Backscatter signatures

One key characteristic of mud volcanoes, and other fluid/mud expulsion centres, is that they often coincide with patches of high acoustic backscatter, as observed throughout the Mediterranean Sea and the Gulf of Cadiz (e.g. Fusi and Kenyon 1996; Volgin and Woodside 1996; Sautkin et al. 2003; Huguen et al. 2004; Rabaute and Chamot-Rooke 2007; Lykousis et al. 2009; Dupré et al. 2010). Backscatter of energy to high frequency (10±100s kHz) swath sonar systems (sidescan and multibeam) takes place both from the water±sediment interface and from a subbottom sediment volume, to some limit of penetration that depends on source frequencies and can reach metres or even tens of metres for deep-water systems (e.g. Mitchell 1993).

Backscatter is influenced by sediment properties including composition and micro-relief, and work in the Mediterranean Sea has shown that mud breccias are highly effective backscatterers due to characteristics such as clast content, gas bubbles, irregular mudflows and bioactivity (e.g. Volgin and Woodside 1996; Zitter et al. 2005; Dupré et al. 2010). Backscatter strength also depends on the depth of burial, such that it is possible to distinguish older from younger mudflows (e.g. Zitter et al. 2005; Rabaute and Chamot-Rooke 2007; Lykousis et al. 2009). Moreover, frequency-dependent penetration of up to several meters can be used together with sedimentation rates to constrain the age of eruptive activity (e.g. Rabaute and Chamot-Rooke 2007; Ceramicola et al., this volume). Indeed, high-backscatter signatures observed on sidescan or multibeam imagery have played an important role in the identification and investigation of mud diapirs, mud volcanoes, brine lakes and pools, as well as pockmark fields throughout the Mediterranean Sea (e.g. Cita et al. 1981; Fusi and Kenyon 1996; Woodside and Volgin 1996; Huguen et al. 2001a, 2004; Loncke and Mascle 2004; Gamberi and Rovere 2010); in addition, quantitative analyses have been used to tentatively evaluate the volume of expelled mud and the mechanisms of extrusion (Rabaute and Chamot-Rooke 2007).

In the present article, characteristic backscatter signatures have served to extend regional mapping of inferred expelling mud/fluid centres to areas where no direct sampling or *in situ* observations were available. The results are presented in Figs. 6 ,7a and b.

3.3. Seismic reflection data

Where available, and as illustrated on Fig. 8, seismic reflection records may constitute particularly efficient tools facilitating the identification of mud volcanoes and cones. Commonly, the seismic profiles show the seabed mud structures to be the tops of buried extrusive edifices extending as much as 1±2 km into the subsurface (e.g. Loncke and Mascle 2004; Deville et al. 2006; Rabaute and Chamot-Rooke 2007; Praeg et al. 2009). The mud cones and subbottom edifices are usually characterized by a mainly unstratified seismic facies that in many cases fills subsidence depressions bounded by inward-dipping and well-layered reflectors, and which may find surface expression in seabed moats (e.g. Rabaute and Chamot-Rooke 2007; Praeg et al. 2009). The nearly reflection-free seismic signature, which can also be observed on 3D seismic slices (e.g. Loncke 2002), may be due to a high gas content of the extruded mud, although it has also been suggested that it could reflect reworking of successively deposited mudflows by the action of mud chambers developed within the subsiding extrusive edifice (Praeg et al. 2009).

In many cases seismic data illustrate a typical *Christmas tree* geometry, such as the one shown on Fig. 8d, indicating successive episodes of mud extrusion interbedded within normal marine sedimentation (Dupré et al. 2010); such cyclic functioning has been supported by the results of shallow drilling made on Milano MV during ODP leg 160 (Kopf et al. 1998). In the Alboran Sea, seismic profiles indicate interfingering extrusive edifices underlain by unstratified downward-tapering cones interpreted as intrusive feeder complexes, as observed in other settings (Somoza et al. 2012). In some specific cases seismic data may help to image, and understand, the relationships between mud cones and subjacent tectonic features; this is well illustrated on Fig. 8c, which shows, near the backstop of the Mediterranean Ridge, a small mud cone located on a thrust fault that has likely acted as a conduit for mud extrusion.

3.4. In situ observations and sampling

In the Mediterranean Sea and in the Gulf of Cadiz, geological ground-truth is now available for several active, or recently active, fluid-releasing features in the form of core or grab samples (and, in two cases, deep-sea drilling results); in some cases seabed observations have been made using video cameras attached to grab samplers (e.g. Volgin and Woodside 1996) or to ROVs equipped with sampling arms, or directly from submersibles (e.g. Bayon et al. 2009; Foucher et al. 2009). In addition, hydroacoustic evidence of gas flares rising from seabed features has been used as a form of geophysical ground-truthing of seepage activity to guide more detailed investigations (e.g. Dupré et al. 2010; Praeg et al. 2014). The relatively small population of MVs in the Gulf of Cadiz and the western area of the Alboran Sea has been extensively sampled by coring and grab sampling (e.g. Pinheiro et al. 2003; Sautkin et al. 2003; Blinova et al. 2011). In the Gulf of Cadiz the various products resulting from MVs activities, such as methane-derived authigenic carbonates, carbonate chimneys, gas hydrates, and nodules, have been tentatively linked to MV evolutionary stages (León et al. 2006, 2007; Magalhães et al. 2012).

In the eastern Mediterranean Sea, mud volcanoes were first identified from cores of mud breccia from the Mediterranean Ridge (Cita et al. 1981, 1996a, 1996b; Camerlenghi et al. 1992), which led to scientific drilling of the Milano and Napoli MVs yielding geochemical evidence of ongoing fluid and gas seepage (Dählmann and de Lange 2003; Charlou et al. 2003). Mud breccias have since been cored from many additional mud volcanoes along the eastern Mediterranean accretionary systems (e.g. Woodside et al. 1998; Chamot-Rooke et al. 2005; Zitter et al. 2005; Lykousis et al. 2009; Praeg et al. 2009), and the Olympi MV group (central Mediterranean Ridge) and Anaximander Mountains MVs have on several occasions been targets for direct *in situ* observations and measurements during deep dive operations using submersibles and ROVs (Limonov et al. 1996; Huguen et al. 2004, 2005; Zitter et al. 2005). These observations have shown that at most features the past eruption of mud breccias, now buried beneath hemipelagic sediments, has given way to localized seepage of muds and fluids, including hydrocarbon gases that support chemosynthetic life-forms. Gas seepage has also resulted in the formation of gas hydrates at four MVs in the Anaximander Mountains (Woodside et al. 1998; Lykousis et al. 2009; Pape et al. 2010); these are the only proven occurrences known to date in the Mediterranean Sea, although gas hydrates are argued to be present from pore water data in a MV from the western Alboran Sea (Blinova et al. 2011).

So far the most spectacular data from *in situ* studies of fluid escape features in the Mediterranean Sea have been obtained for a series of mud volcanoes, pockmarks and brine lakes on the Egyptian continental margin, investigated during several expeditions between 2003 and 2007 (Dupré et al. 2007; Pierre et al. 2008; Bayon et al. 2009; Foucher et al. 2009; Huguen et al. 2009; Dupré et al., this volume). On the western Nile fan, submersible and ROV dives within the Menes caldera have enabled the observation and sampling of mud volcanoes associated with lakes, ponds and flows of mixed brines, fluids and muds, often associated with bacterial mats and filaments, and carbonate pavements associated with chemosynthetic communities. Similarly, submersible and ROV dives made on pockmarks of the central Nile fan have enabled observations and sampling of many authigenic carbonate pavements and chimneys (Bayon et al. 2009; Pierre et al., this volume; Fig. 9).

4. Results

Using categories of proven (sampled and/or observed *in situ*) or inferred MVs (from geophysical data) in combination with ArcGis software, MVs and other fluid-releasing features detected on the seafloor have been mapped at a regional scale encompassing the entire Mediterranean Sea and adjoining Gulf of Cadiz.

4.1. The western Mediterranean Sea and Gulf of Cadiz

The resulting synthesis for the western Mediterranean Sea and Gulf of Cadiz is illustrated in Fig. 10. Major MV fields can be detected within the sedimentary cover of the Gulf of Cadiz, which consists of a thick pile of deformed sediments resulting from the convergence/subduction of the central Atlantic oceanic crust (and its sedimentary cover) beneath the Gibraltar region.

Another well-identified MV field characterizes the western domain of the Alboran Sea, a back-arc basin setting where a thick Early Miocene over-pressured shale is suspected to have generated mud diapirism and mud volcanism, including several MVs inferred to have been active since the mid-Pliocene and that continue to seep hydrocarbon-rich fluids (Blinova et al. 2011; Somoza et al. 2012). Outside of this main area, no significant MV field has been described to date within the western Mediterranean basin, with the exception of potential deep-water mudflows and mud expulsion centres on the western Calabrian margin of the Tyrrhenian Sea within the Marsili back-arc basin (Gamberi and Rovere 2010).

4.2. The eastern Mediterranean Sea

The eastern basins of the Mediterranean Sea are the sectors where MVs and related fluid expulsion features are the most abundant. The observations summarized in Fig. 11 show that the vast majority of features occur along the accretionary piles resulting from the convergence/subduction of the African and Eurasian plates. A smaller but nevertheless important association of features occurs on the North African passive margin within the Nile deep-sea fan.

MV distributions can be distinguished in terms of four main structural domains:

1. The most recently discovered mud volcano province of the Mediterranean Sea lies on the inner to central Calabrian accretionary prism, and includes three main features proven by coring (Madonna, Pythagoras and Sartori MVs) and numerous features inferred from geophysical data (Praeg et al. 2009; Ceramicola et al., this volume); two of these have been sampled and observed during ROV dives (Foucher et al. 2009).

2. Numerous mud domes and volcanoes are observed on the Mediterranean Ridge and particularly within its western (Ionian) and central domains. Many of these structures are proven by geological samples; the Olympi cluster in particular has been the target of scientific drilling as well as several near-bottom investigations using submersibles and ROVs. Proven and inferred MVs delineate two main belts, one along the inner border of the accretionary wedge, another running more or less along its axis. The eastern branch of the Mediterranean Ridge shows only a few, inferred MVs (chiefly along its backstop).

3. A cluster of proven MVs characterizes the Anaximander Mountains area (south of Turkey), a tectonic relay between the still active Mediterranean Ridge and the now apparently inactive, or less active, sedimentary wedge that runs northwest and east of Cyprus (Florence and Hecateus rises respectively) where only a few, inferred mud volcano-type features have been imaged.

4. Several large-scale mud volcanoes overlying inferred gas chimneys are observed along the upper continental slope of the passive Nile continental margin, while a broad cluster of smaller mud cones including larger caldera-like structures occurs in its northwestern deep corner.

5. Discussion and conclusions

5.1. Regional distribution

Proven and inferred MVs are abundant in the Mediterranean Sea, particularly in its eastern basins. The MVs occur in three main geologic settings: (1) within thick accretionary wedges on convergent margins: the Gulf of Cadiz, the external Calabrian Arc, the western and central Mediterranean Ridge and, to a lesser extent, the tectono-sedimentary wedge running from the Anaximander Mountains to offshore western Syria, which is likely to be inactive; (2) along parts of the Mesozoic passive continental margin of northern Africa, particularly off Egypt where MVs seem closely related to the thick sedimentary cone built by the river Nile since the Early Miocene; (3) finally, albeit to a lesser extent, within thick sedimentary basins created in back-arc settings such as the western Alboran Sea, and the south-eastern Tyrrhenian margin of Calabria.

5.2. Origin of fluids and mud breccias

Mud volcanoes form in response to overpressure of deep fluids characteristically including hydrocarbons, and the process of mud volcanism is thought to be driven by the fluid fraction that rises to liquefy mud-rich units, incorporate solid clasts and shallow (biogenic) fluids/gases, and expel material to the seabed and into the water column (Dimitrov 2002; Kopf 2002, 2003; Deville et al. 2003; Planke et al. 2003). While the abundance of MVs within the Mediterranean Sea supports the presence of petroleum systems at depth, and thus of various potential source rocks and reservoirs, there are no reliable data on the nature, ages and depths of the sedimentary layers from which fluids may originate. Within the Gulf of Cadiz (Maldonado et al. 1999) as well as along the Egyptian continental margin (Dolson et al. 2005; Tari et al. 2012), Mesozoic source rocks have been hypothesized, chiefly from comparison with known oil fields from nearby onshore areas. Cretaceous rocks have been documented among the various clasts collected in cores of mud breccia from the external Calabrian Arc (Rossi and Sartori 1981; Morlotti et al. 1982), the Mediterranean Ridge (Akhmanov 1996; Cita et al. 1996a, 1996b; Huguen et al. 2001b) and the Anaximander Mountains (Huguen et al. 2001b; Lykousis et al. 2009). While their analysis has brought pertinent information on the stratigraphy of the Mediterranean deep basins and margins (Akhmanov 1996), it is unrealistic to conclude that, in such active tectono-sedimentary wedge, all these clasts are directly originating from deep-seated layers; rather, they may correspond to older sediments eroded and re-deposited by tectonic and erosional processes and transported to the seafloor by ascending fluids (e.g. Rabaute and Chamot-Rooke 2007).

On the central Mediterranean Ridge and on the Nile continental margin, some clasts are of Late Cretaceous to Eocene ages but most of Middle to Late Miocene age (Akhmanov 1996; Huguen et al. 2001a; Rabaute and Chamot-Rooke 2007; Giresse et al. 2010). This is in good agreement with a relatively low maturity of organic matter in mud breccias (Kopf et al. 2000), and the presence of associated brines that in turn may directly result from percolation and remobilization of thin Messinian salt-bearing deposits; the clast age data are also consistent with the presence of known source rocks of Cainozoic age in the surrounding onshore. The presence of biogenic gases within mud breccias, often mixed with thermogenic fluids (Prinzhofer and Deville 2013), indicates that recent and relatively shallow sediments (sapropelic layers?) may contribute to degassing processes on the seabed of the Nile continental slope (Bayon et al. 2013). Gas hydrate dissociation during Quaternary glacial± interglacial cycles has also been considered as a possible source for fluids directly released at the seabed of the Nile margin, particularly in pockmark-rich areas (Praeg et al. 2008); however, no information is yet available on the composition of the gas seen to be venting from such features (Dupré et al. 2010; Praeg et al. 2014).

5.3. Geological control

5.3.1. MV distribution and Messinian deep basins

Using a GIS-based compilation of the main geological characteristics of the Mediterranean domain (Mascle and Mascle 2012), it has been possible to cross-correlate MV distribution and the main deep evaporite Messinian basins mapped from seismic data. Inspection of Fig. 12 yields interesting observations:

1. Most of the MV provinces in the eastern Mediterranean Sea, including the main fields on the Calabrian Arc, the Mediterranean Ridge and the upper Egyptian continental margin, occur where Messinian evaporites are thin or absent, or perhaps simply undetectable on seismic reflection data; this strongly suggests that thick evaporite covers act as traps for deep fluids and thereby prevent leakages to the seabed, a phenomenon well known in the oil industry.

2. A cluster of mud cones and active fluid seeps exists, however, in the north-western corner of the Nile deep sea fan, underlain by thick Messinian evaporites; it is suspected that this anomalous occurrence is due to the presence of specific source rocks at depth (palaeo-Nile organic matter-rich sediments?), their fluids having been trapped beneath an evaporite seal that has been ruptured as a consequence of gravity tectonics. Figure 4a illustrates particularly well the presence in this area of a dense fault system generated by downslope salt tectonics. Based on *in situ* temperature measurements and seismic data analysis, Dupré et al. (this volume) propose that the fluids expelled in this area originate from at least 2.7 km below the seafloor, i.e. below the top of Messinian evaporites.

3. No MV has yet been observed (at least to the knowledge of the authors) within the deep western Mediterranean Sea; this may be explained by the presence of a thick, almost unruptured layer of Messinian evaporites acting as a regional and continuous cap-rock or, alternatively (considering the probably effects of loading by the Rhone Fan), by the absence of any significant and mature source rocks in this quite recent basin (less than 20 Ma).

4. The young western Calabrian and western Alboran Sea back-arc basin margins, as well as the much older Gulf of Cadiz domain do not contain Messinian evaporites; therefore, MVs develop when and where source rocks, reservoirs and conduits to the seabed exist.

5.3.2. MV distribution and active tectonics

The relationship between MVs and active tectonic structures is well evidenced on Fig. 13, also extracted from the GIS compilation of the Mediterranean Sea by Mascle and Mascle (2012). In the Gulf of Cadiz, almost all MVs appear effectively located on active transcurrent or normal faults, as well illustrated by data from Pinheiro et al. (2003) and Medialdea et al. (2009). Such a relationship has also been documented in the eastern Mediterranean Sea, particularly on the western branch of the Mediterranean Ridge where Chamot-Rooke et al. (2005) have established that MVs are preferentially located along belts in close relation with thrust faults along the ridge backstop and/or along transcurrent lineaments partitioning the pre-Messinian accretionary wedge; Rabaute and Chamot-Rooke (2007) have even proposed a link with a regional kinematic plate reorganization in the area around 1±2 Ma. A similar arrangement can be observed in the central domain of the Mediterranean Ridge (Huguen et al. 2004), where incipient continental collision between the European and African plates has been postulated (Mascle et al. 1999). The various MVs discovered on the Anaximander Mountains appear similarly tectonically controlled (Zitter et al. 2006; Lykousis et al. 2009). As underlined above, the Egyptian margin represents a specific case. Here, MV locations are controlled either by tectonic pathways created by the apparent remobilization of former regional fault trends, particularly along the upper continental slope, or by growth faults related to salt-induced gravity tectonics, particularly at the foot of the north-western Nile cone lower slope (Loncke and Mascle 2004; Loncke et al. 2006).

Strong differences in fluid systems between the western and eastern basins of the Mediterranean Sea emerge from all these observations. The latter is the remnant of an old, Mesozoic oceanic basin bounded to the south by passive continental margins containing (at depth) thick sedimentary piles also of Mesozoic age, including several organic matter-rich sedimentary layers. The western basin is much younger (<20 Ma for its central domain); moreover, it has opened by back-arc extension of previously thickened continental crusts involved in former collisions, a setting not favourable for organic matter preservation and maturation. Furthermore, even if the Messinian salinity crisis resulted in the deposition of massive salt layers (over 1 km thick) in the deep sectors of the western and eastern Mediterranean domains, this event evidently did not leave a similar imprint on both domains: a wide, apparently unruptured Messinian salt-rich cap >1 km thick covers the western deep Mediterranean basin, preventing major (if any) fluid leakages; by contrast, the eastern Mediterranean Sea shows a rather discontinuous pattern of variably thick evaporitic basins that, combined with strong ongoing deformation, may have facilitated fluid migration and seepage from several potential sources.

Based on these interpretations, it is unlikely that many new seepage features will be discovered within the western Mediterranean basin. The old passive continental margins bordering the southern shores of the eastern Mediterranean Sea, however, may well harbour as yet unknown fields of mud volcanoes and other fluid seepage structures, an aspect deserving more complete and detailed swath mapping.

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Figures

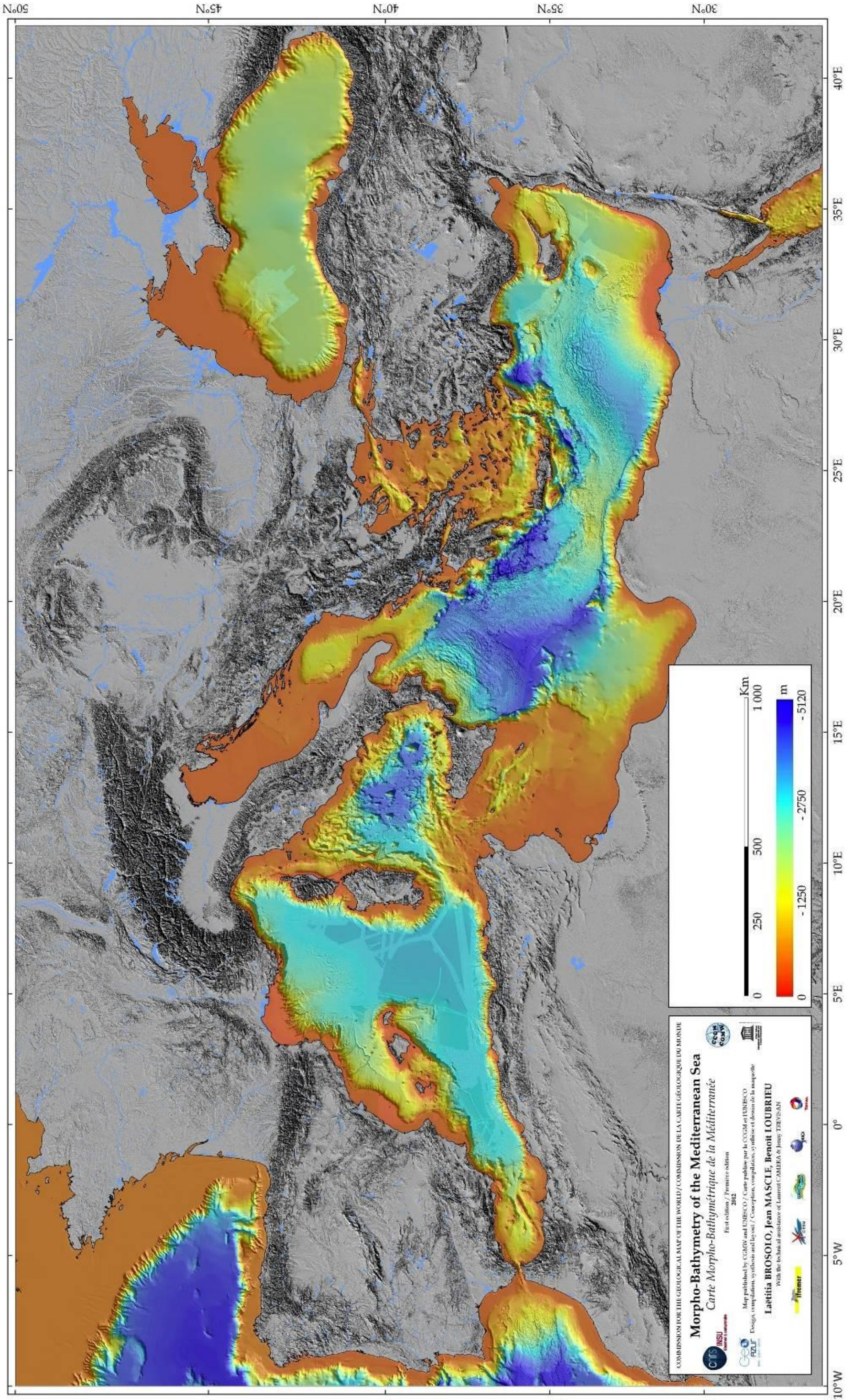

Fig. 1 Morphology of the Mediterranean Sea region: synthesis (DTM at 500 m) from available swath bathymetric data (extracted from Brosolo et al. 2012).

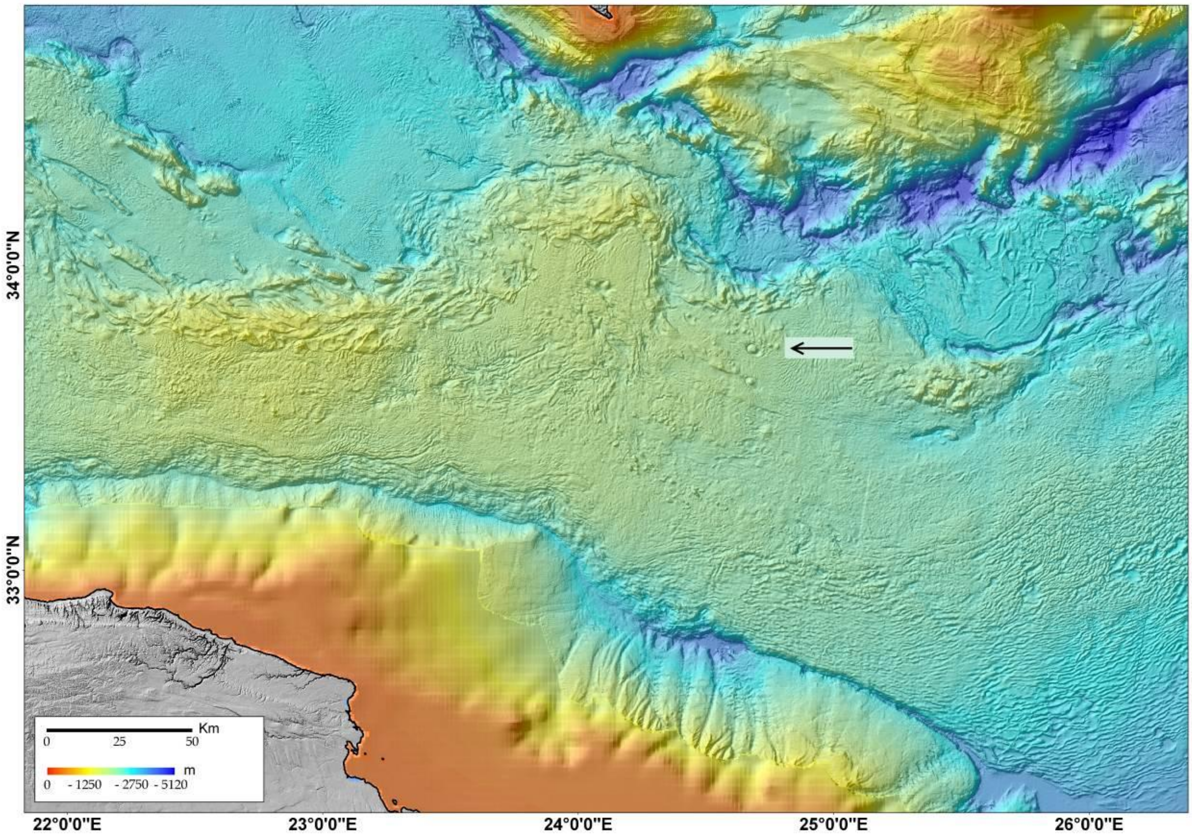

Fig. 2 Morphologies of mud volcanoes on the central Mediterranean Ridge accretionary prism between Crete to the north and the passive continental margin of Libya to the south, from surface swath bathymetric data (DTM at 100 m; extracted from Brosolo et al. 2012). Arrow shows the Olympi MV group, including the Napoli MV (see Fig. 3).

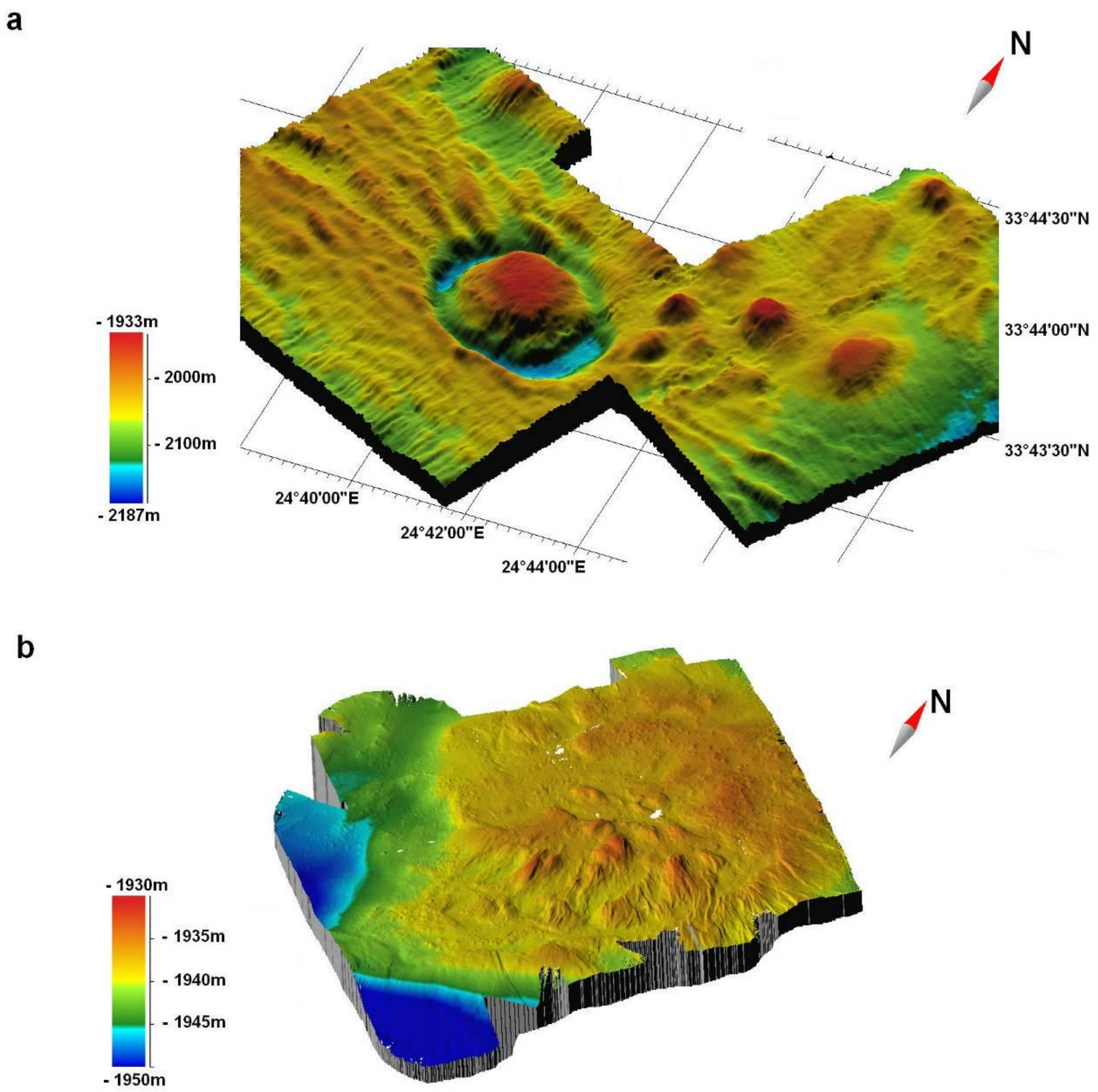

Fig. 3 a) 3D view of Napoli MV from surface swath bathymetric data (DTM 50 m); this lens-shaped feature is about 50 m high and 1 km in diameter. b) Top of Napoli MV from near-bottom swath data recorded with a ROV (DTM at 2 m), showing a rather rough topography characterized by small depressions (some fed by brines), small mounds and mudflows.

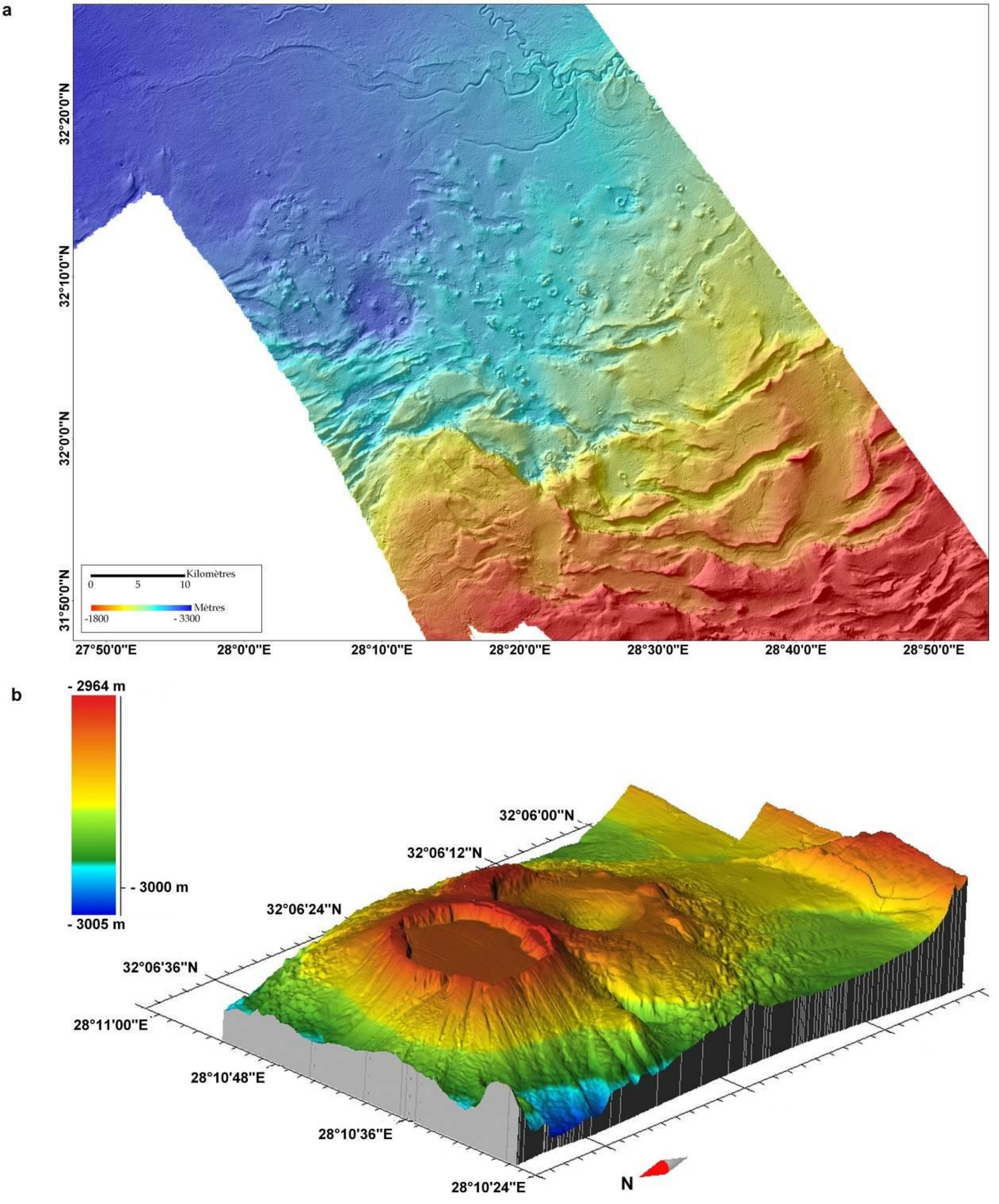

Fig. 4 Morphologies of various fluid seepage features on the Egyptian continental margin. a) At a regional scale: the wide caldera-like Menes depression (Huguen et al. 2009; Dupré et al., this volume), and numerous mud cones at the foot of the continental slope (DTM at 50 m, surface swath bathymetry). b) At a local scale: two *twin* mud cones within the Menes caldera (DTM at 2 m; see Dupré et al., this volume).

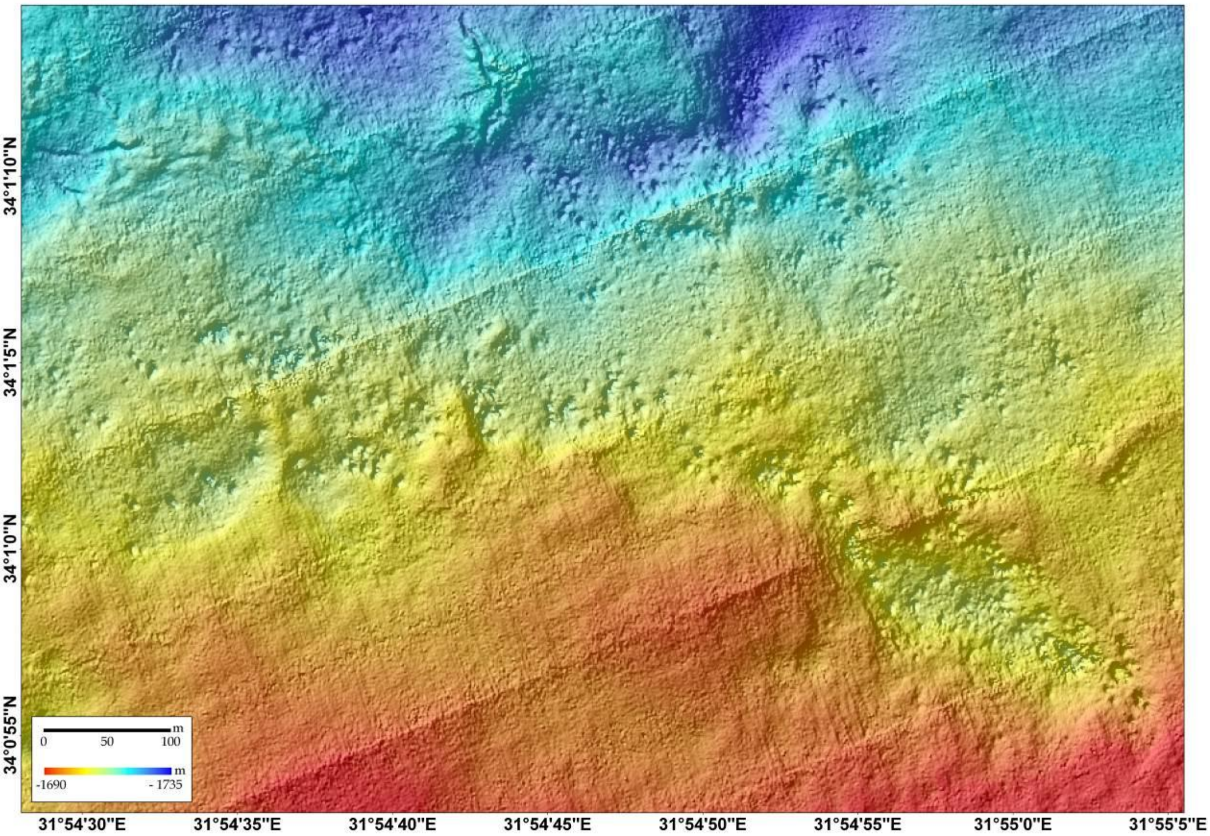

Fig. 5 Fields of pockmarks on the Egyptian continental slope (DTM at 2 m, near-bottom swath bathymetry).

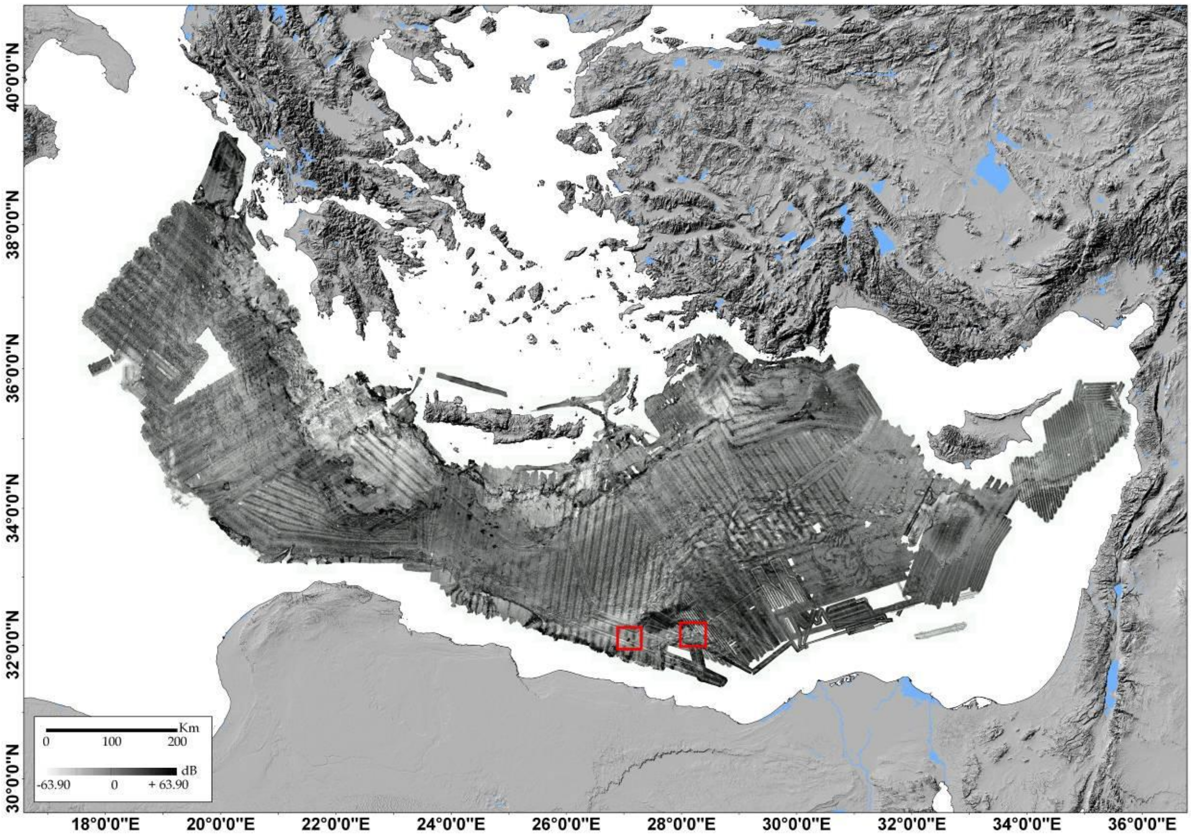

Fig. 6 Backscatter signatures of various fluid seepage features on the seabed of the eastern Mediterranean Sea (backscatter scale in decibels). At a regional scale, the Mediterranean Ridge is characterized by numerous high-backscatter (dark grey to black) patches often associated with mud/fluid expulsion, particularly along the western branch and central domain (Olympi field) of the Mediterranean Ridge. Rectangles indicate locations of features shown on.

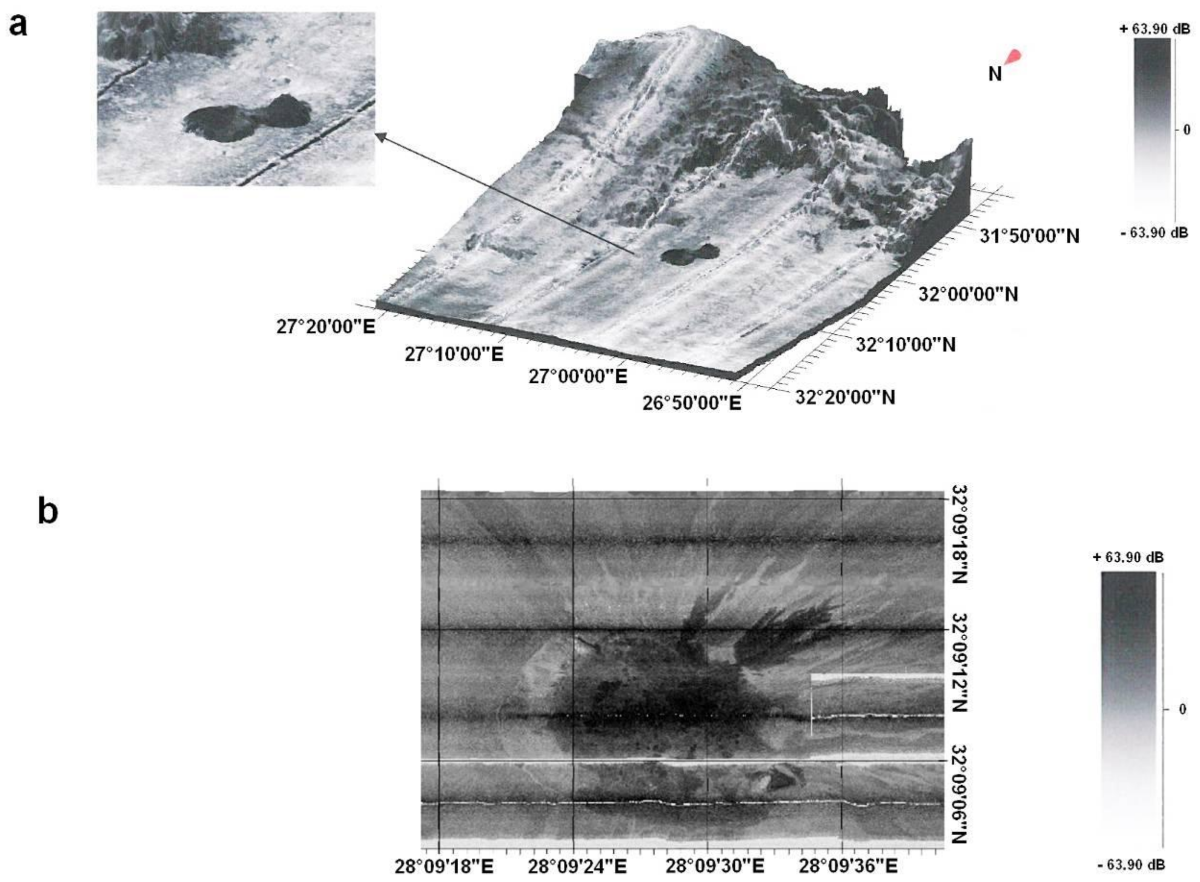

Fig. 7 More detailed backscatter signatures of fluid seepage features in the eastern Mediterranean. a) At a local scale, 3D view of high-backscatter records over inferred mud volcanoes at the foot of the Western Desert´ Egyptian continental margin; the features are approx. 2 km in diameter (extracted from Tari et al. 2012). b) At a near-bottom scale, backscatter records (near-bottom swath data) over Chefren mud cone (3,000 m water depth, central area of the Menes caldera; see Fig. 4a); note the mud/brine flows associated with this ca. 150-m-wide feature (see also Dupré et al., this volume); backscatter scale in decibels.

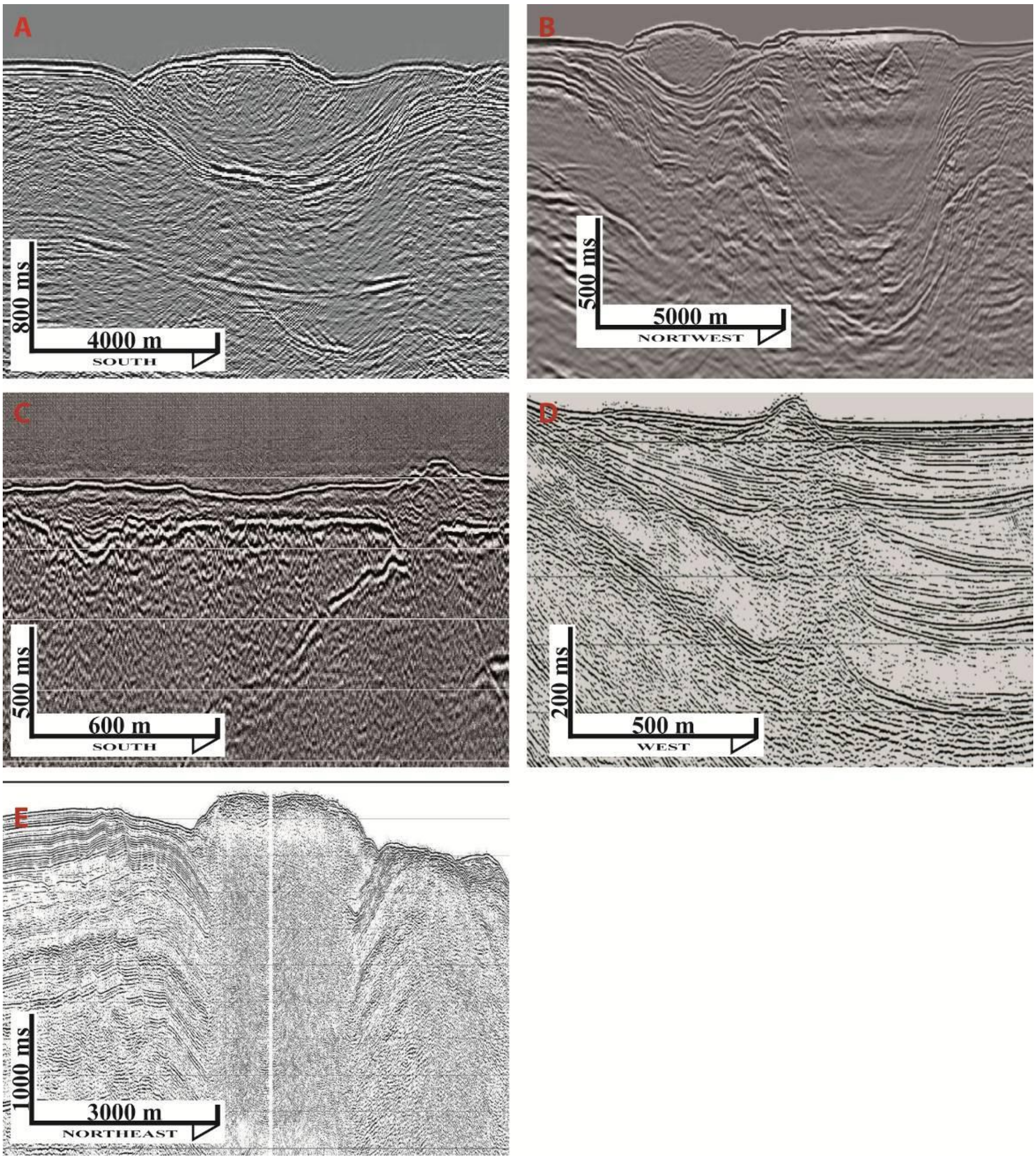

Fig. 8 Examples of seismic reflection profiles across various mud volcanoes in the eastern Mediterranean Sea. a) Napoli MV, Olympi MV group, central Mediterranean Ridge. b) Two MVs at the foot of the Western Desert Egyptian margin. c) Mud cone on the central Mediterranean Ridge, associated with a probable thrust fault. d) Mud cone in the Menes caldera (see Fig. 4a; see also Dupré et al., this volume). e) Seismic line across a gas chimney on the Egyptian upper continental margin (extracted from Loncke 2002)

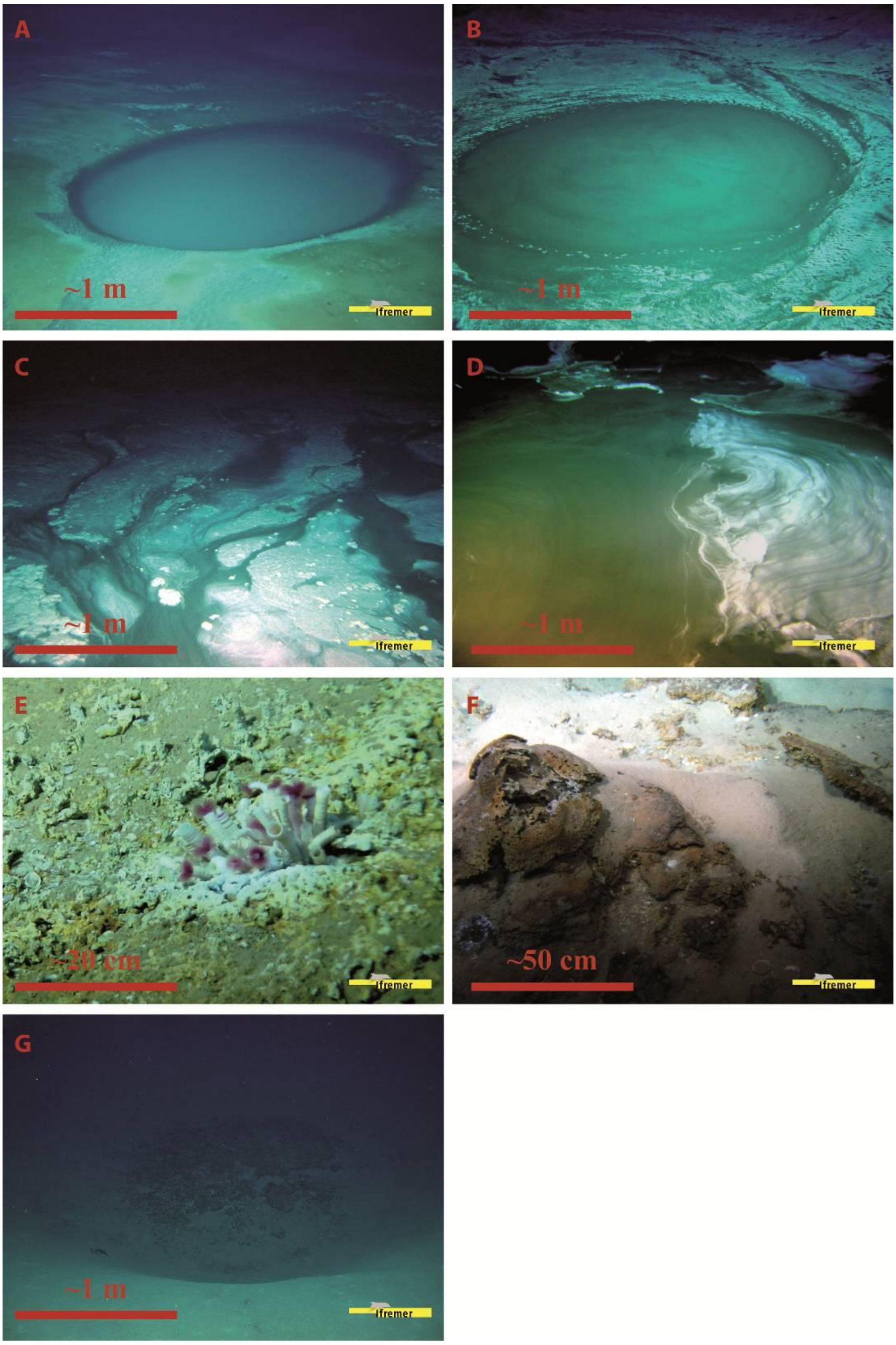

Fig. 9 Seabed photographs showing various details of mud volcanoes in the eastern Mediterranean Sea. a) Brine/fluid pool on top of Napoli MV south of Crete; b-g Egyptian continental margin. b) Brine/fluid pool on Chefren mud cone (Menes caldera); c, d) brine lake (with bacterial filaments) and brine stream on a mud cone (Menes caldera); e, f) carbonate pavements (and live worms) and carbonate chimneys; g) a pockmark (and fragments of authigenic carbonate crusts).

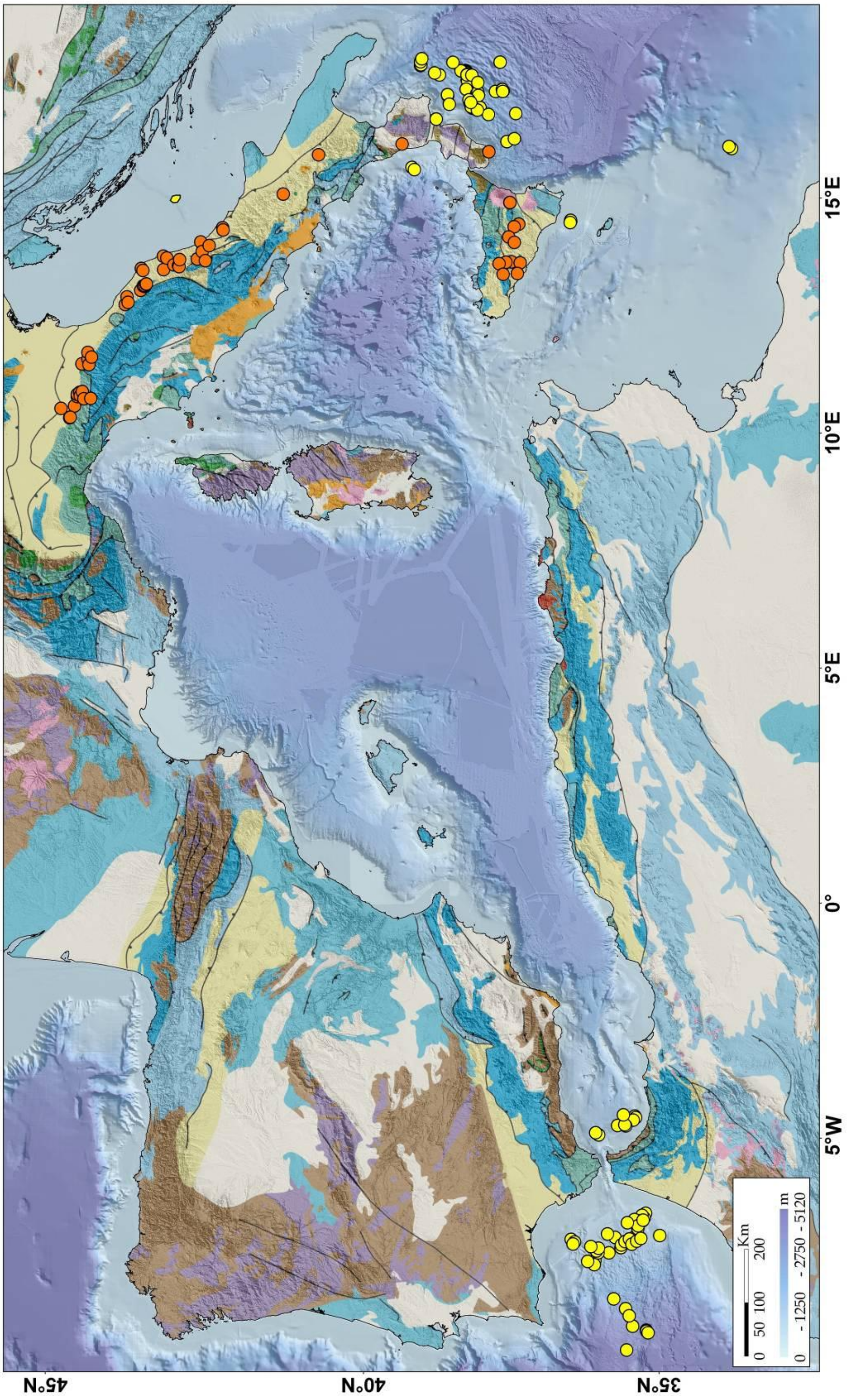

Fig. 10 Distribution of mud volcanoes and other fluid/mud-releasing structures (yellow dots) in the western Mediterranean Sea and Gulf of Cadiz, including MVs in the western sector of the Alboran Sea and potentially some areas of the Calabria margin (Tyrrhenian side). Red dots MVs known on mainland Italy and Sicily (based on Martinelli and Judd 2004).

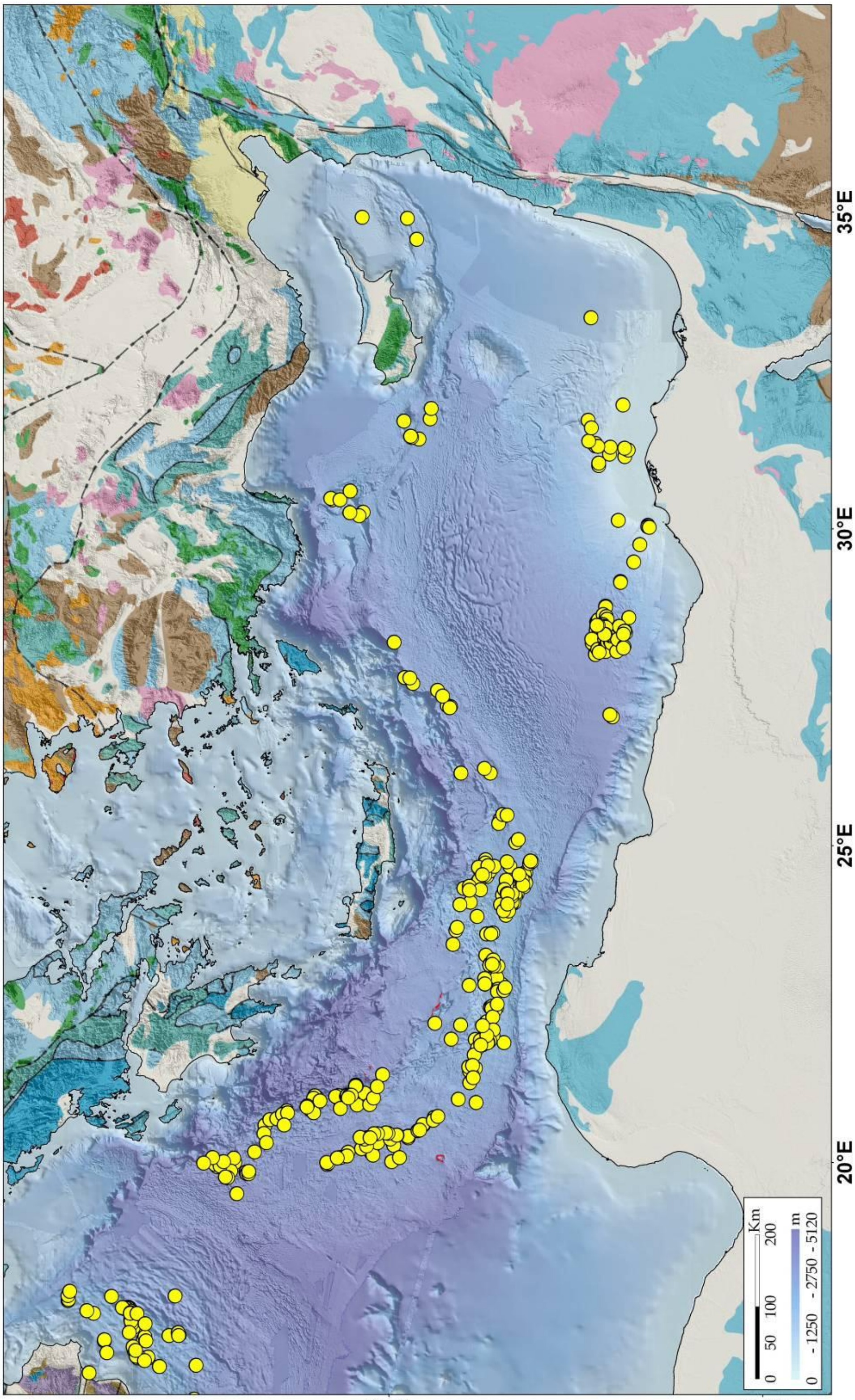

Fig. 11 Distribution of mud volcanoes and other fluid/mud-releasing structures (yellow dots) in the eastern Mediterranean Sea. MVs are widely distributed, particularly within the inner domains of the Calabrian and Mediterranean accretionary prisms, south of Turkey, in the vicinity of the Anaximander Mountains, and on the Egyptian passive continental margin; extinct MVs have been detected on the Hecateus ridge east of Cyprus. Some fluid/mud-releasing features occur also along the Florence Rise. Red main brine lakes.

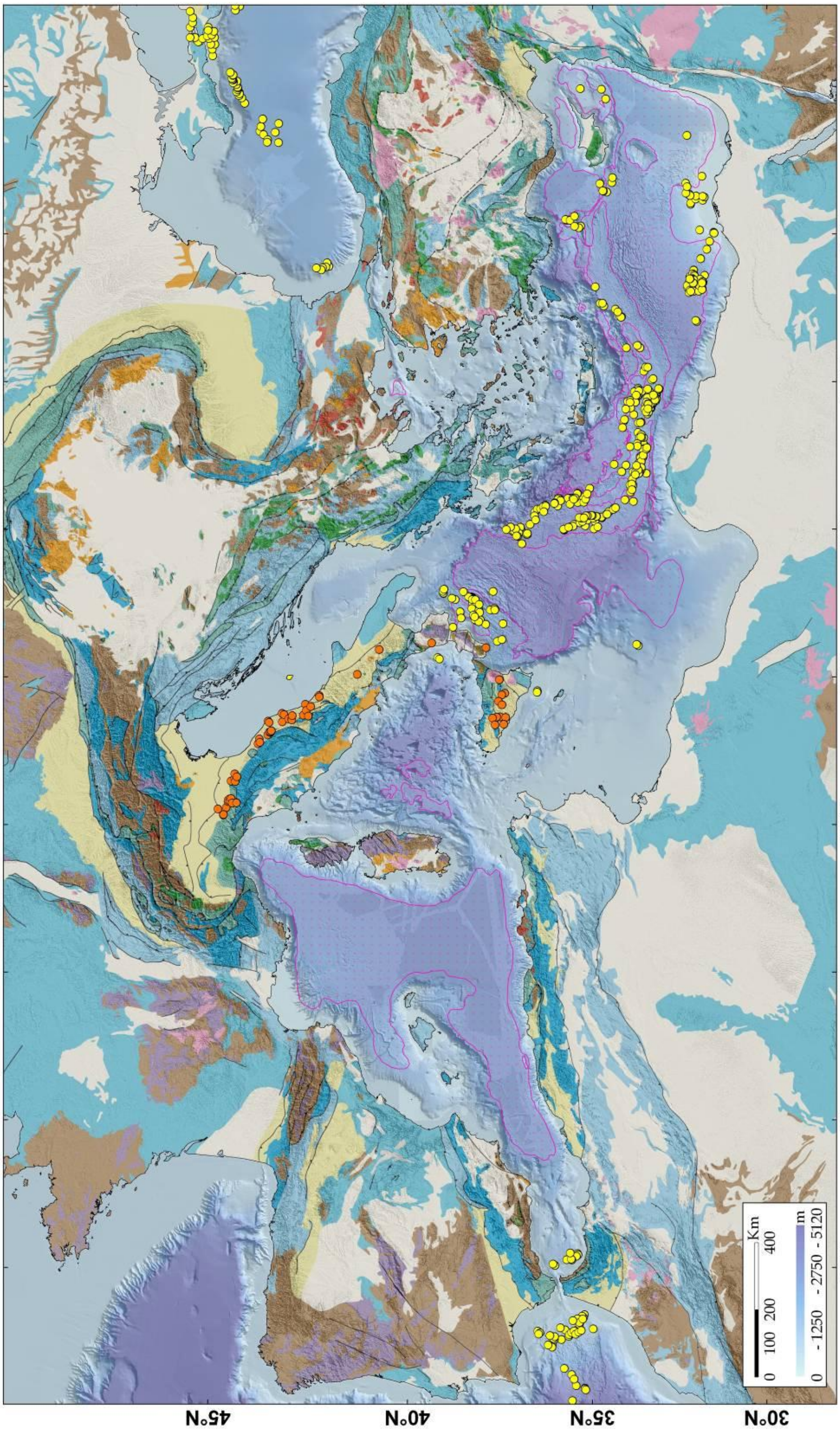

Fig.12 Large-scale distributions of MVs (yellow dots) and deep Messinian evaporitic basins (pink lines) in the Mediterranean Sea and Gulf of Cadiz. The majority of mud volcanoes are seen in areas where no thick Messinian evaporite cover exists, with the exception of the North-Western Egyptian continental margin (see text)

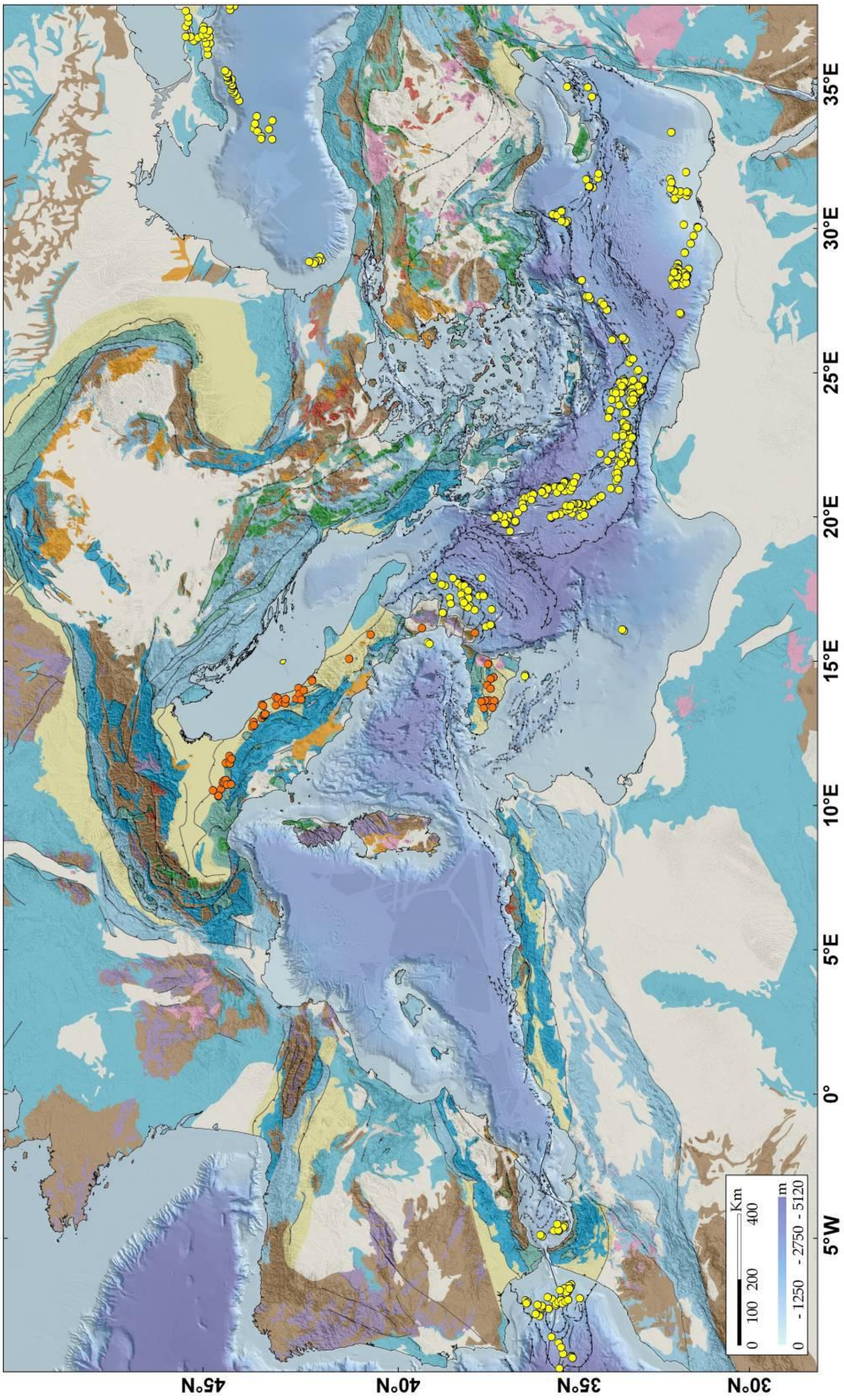

Fig. 13 Large-scale distributions of MVs (dots) and tectonic features (dotted lines) in the Mediterranean Sea and Gulf of Cadiz. Most MVs are closely associated with active faults and thrusts serving as conduits for fluid/mud release. Along the Nile continental margin, overpressured mud and fluid release is facilitated by previously active fault systems likely reactivated by differential sedimentary loading (upper continental slope), and by growth faults resulting from Messinian evaporite gravity tectonics that cut across post-Messinian deposits.