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Gouge marks on deep-sea mud volcanoes in the eastern Mediterranean: Caused by Cuvier's beaked whales?

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Abstract

Enigmatic seafloor gouge marks at depths of 1700–2100 m have been observed from submersible during geological survey work studying mud volcanoes in the eastern Mediterranean Sea. The marks consist of a central groove (about 10 cm deep and 1–2 m long), superimposed on a broader bowl-shaped depression (1–2 m long by about 50 cm wide) with raised rims (up to 10 cm high) to either side of the central groove. We discuss the potential biological causes of these marks, and conclude that they are probably created by Cuvier's beaked whales (*Ziphius cavirostris*) during foraging dives to these depths. The mud volcanoes have a comparatively rich and diverse benthic ecology associated with methane-rich fluid seeps and thus could be the base of food chains that reach top predators like the deep-diving whales. The characteristic high acoustic backscatter of the mud volcanoes would facilitate their detection by the echolocation system of these whales.

Keywords: Seafloor seeps and mud volcanoes; Marine mammals; Deep water; Foraging behaviour; Marine geology; Eastern Mediterranean; (33–36°N; 24–31°E)

1. Introduction

The seafloor of the deep ocean and the ecosystems that it sustains are largely unknown because of the difficulties of studying them. Great progress has been made in deep sea research during the past 30 yr or so through the use of research submersibles and remotely operated vehicles (ROVs) with cameras and sampling equipment (Sibuet and Olu, 1998; Van Dover, 2000). However, the ecology and biological interactions in the deep sea are still largely unknown. Opportunistic observations during marine geological survey work can therefore be of great interest to biologists, as are the observations of biologists to geologists where interests overlap. In 1998 gouge marks were observed directly from the French submersible *Nautile* on the seafloor of the eastern Mediterranean Sea at depths of around 2000 m.

Seafloor modification caused by marine mammals has been observed in relatively shallow water for several species and at several locations (Visser, 1999, Weitkamp et al., 1992; Darling et al., 1998, Hain et al., 1995, Rossbach and Herzing, 1997; Avery and

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Hawkinson, 1992). The interest by marine geologists in this has been both direct—for example, studying seafloor modification and re-suspension of sedimentary material by whales (Nelson et al., 1987)—as well as indirect, in cases where the seafloor modification has been inferred to have been caused by marine mammals (Hein and Syvitski, 1989).

Shallow-water foraging by cetaceans is relatively easy to observe in comparison to deep-water foraging. However, in recent years major research advances have allowed the collection of timed-depth data from deep-diving marine mammals (Hooker and Baird, 1999; Baird et al., 2002, 2006; Amano and Yoshioka, 2003; Zimmer et al., 2003; Johnson et al., 2004; Tyack et al., 2005; Watwood et al., 2006). Dive data collected from Cuvier's beaked whales (*Ziphius cavirostris*) suggest that they forage at depths as great as 1950 m (Tyack et al., 2005); and the first dive data collected for a beaked whale species, the northern bottlenose whale (*Hyperoodon ampullatus*) in this case, recorded it foraging at or near the seafloor at 1500 m depth (Hooker and Baird, 1999).

After considering several different explanations for gouge marks observed in 1998 from *Nautile*, it seemed most likely that they were caused by a large animal; and, despite the great depth, it was thought, on the basis of comparisons with marks made by cetaceans elsewhere on the seafloor, that whales could be responsible for them. The purpose of this short paper is to describe these unusual sea floor features, to evaluate potential causes, and to discuss the possible relationship of deep-water cetacean foraging to the rich and diverse ecology related to cold gas seeps associated with these mud volcanoes.

2. The seafloor observations

Seafloor observations were conducted during the multidisciplinary Dutch–French MEDINAUT project to investigate mud volcanism and fluid seepage, including both the geological processes and the unique cold seep ecology (MEDINAUT/MEDINETH Shipboard Scientific Parties, 2000; Olu-Le Roy et al., 2004; Zitter et al., 2005; Heijs, 2005). Gouge marks were observed on mud volcanoes or in areas of fluid seeps in several parts of the eastern Mediterranean at depths between about 1700 and 2100 m, the full depth range in which the MEDINAUT work took place (Fig. 1). Few mud volcanoes at shallower or deeper depths than this have been surveyed, so it is unknown whether this represents the full range at which such marks are made.

Gouge marks were distinctive, and all showed the same basic topography (Fig. 2). Dimensions of gouge marks were estimated during direct observation at the seafloor using the distance above the sea floor of the *Nautile* and the submersible's manipulator arm for scale. These gouge marks have a central part consisting of a narrow groove about 5–10 cm deep and perhaps the same width. The wider part of the gouge in which the groove is found is in the form of an elongate (oval) and gently rounded bowl, about 1–2 m long and about 0.5–1 m wide. It is formed in part by ridges of sediment that are extruded to the sides of the gouge. Small grooves are frequently observed to the sides of the ridges and lying parallel to them. Clumps of mud are commonly found nearby, but usually along the projected axis of the feature. Occasionally there may be two or even three gouge marks in a row, about 5–10 m apart (e.g., Fig. 3(e)). The marks appear to be randomly positioned on the flanks of the mud volcanoes, with a possible slight tendency to be vertical (i.e., up and down the flanks rather than tangential to the circumference).

Numerous gouge marks have been observed on Kula Mud Volcano (35°43.7′N—30°27.5′E, 1683 m, in the Anaximander Mountains south of southwestern Turkey), many of which seem to be fresh in contrast to older ones observed on Napoli Mud Volcano (33°43.5′N—24°41.0′E; 1950 m, in the Olimpi Mud Diapir Field south of Crete; see Cita et al., 1996) (Fig. 1). The relative ages of the gouge marks can be roughly estimated on the basis of the degree of subsequent sedimentation (Fig. 3(a)–(g)) and slow reprocessing by bioturbation (Fig. 2(b)). The gouge marks in Fig. 2(a) and (c) are relatively fresh according to these criteria because the edges are sharp rather than smooth, there is no overlying sediment, and no bioturbation has occurred in the mark despite plenty of examples of bioturbation in the surrounding sediment. Sedimentation rates in this area range from about 2 to about 12 cm/kyr but are mainly closer to 4 or 5 cm/kyr. Assuming a sedimentation rate even as large as 5 cm/kyr, these gouge marks could not be older than about 100 yr because there appears to be at most a dusting of 5 mm of overlying sediment. On the other hand there are plenty of examples of older gouge marks (possibly hundreds of years old) which have very rounded and subdued relief, with still recognisable

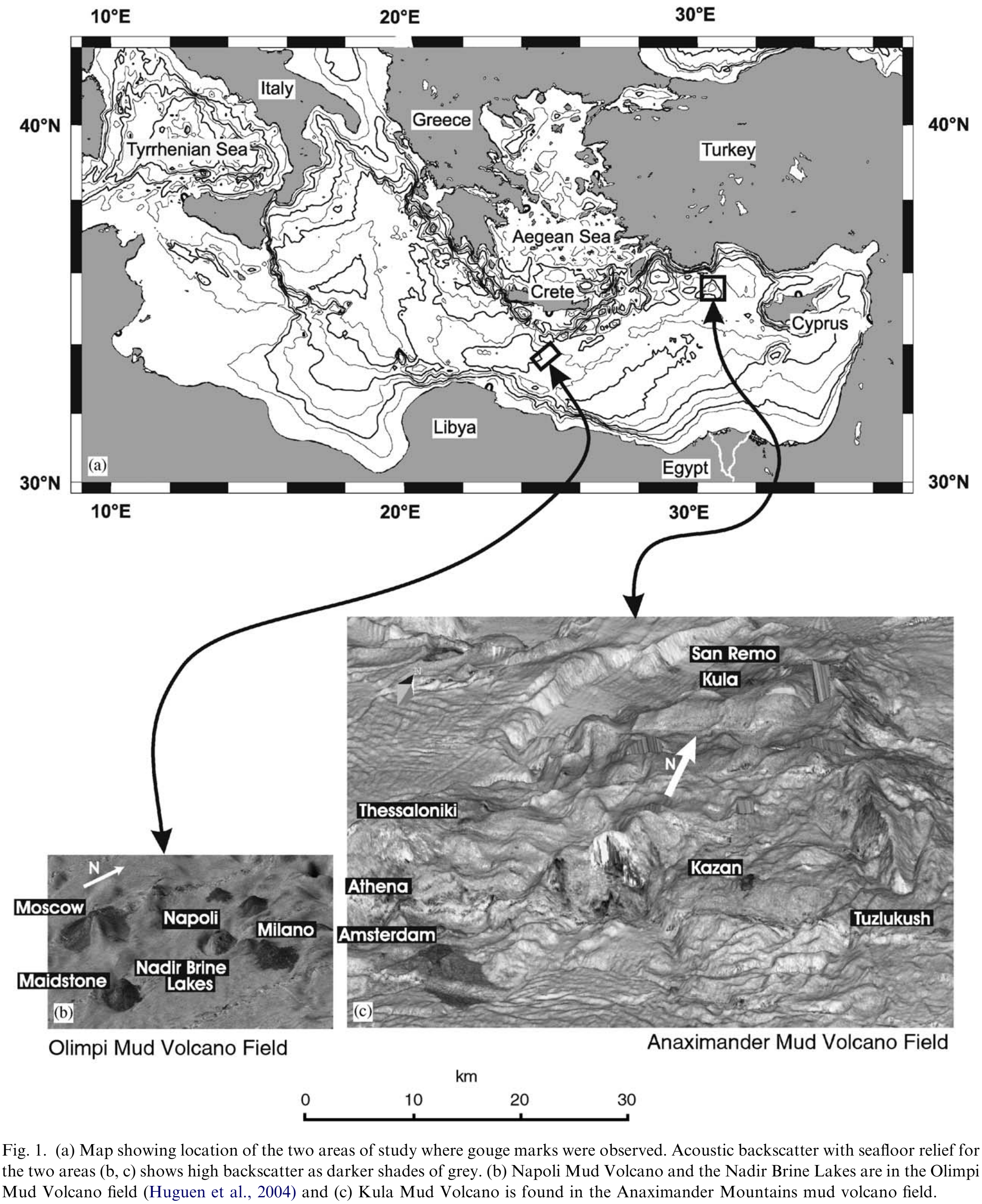

Fig. 1. (a) Map showing location of the two areas of study where gouge marks were observed. Acoustic backscatter with seafloor relief for the two areas (b, c) shows high backscatter as darker shades of grey. (b) Napoli Mud Volcano and the Nadir Brine Lakes are in the Olimpi Mud Volcano field (Huguen et al., 2004) and (c) Kula Mud Volcano is found in the Anaximander Mountains mud volcano field.

morphology, and high levels of bioturbation (see Fig. 3). Most of the gouge marks on Napoli Mud Volcano (Fig. 3(c)–(f)) are relatively old (possibly thousands of years), since a change in activity of this mud volcano, with less mud and more fluids emitted, may have left them relatively unmodified.

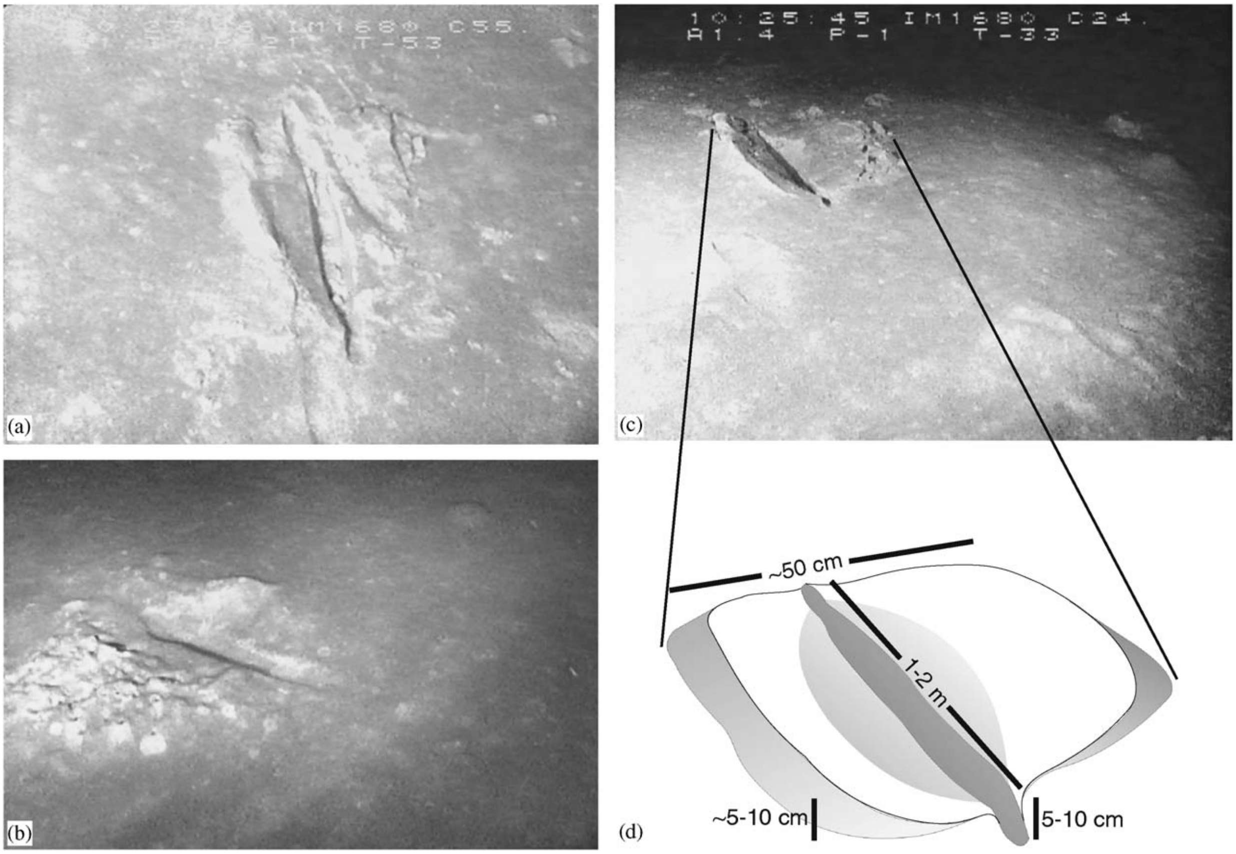

Fig. 2. Examples of relatively fresh gouge marks (a, c) from Kula Mud Volcano and (b) one considered relatively old because of later seafloor bioturbation and overlying sedimentation from Napoli Mud Volcano. The rough dimensions of a typical gouge mark (c) are shown in (d).

3. Geological environment

Mud volcanoes are similar in appearance to normal volcanoes but are smaller (100–200 m high and 1–5 km across in general) and erupt a mixture of overpressured mud and fluids with rock fragments—a so-called mud breccia (Cita et al., 1981). They are found worldwide, especially on continental margins and inland seas, and they are estimated to number at least as many as 200 in the eastern Mediterranean alone (Dimitrov, 2003; Fusi and Kenyon, 1996; Loncke et al., 2004). Mud volcanoes along the Mediterranean Ridge lie on faults within the compressed and deforming sediment. The build up of pressure in wet gassy sediments below these faults can periodically release, forming mud volcanoes (Huguen et al., 2004; Kopf, 2002; Zitter et al., 2005). In their dormant phase they continue to emit fluids at cold seeps. The fluids are usually very rich in gases, predominantly methane, which are the energy source for a rich ecology based on microbial processing of the gases and chemosynthesis (Boetius et al., 2000; Pancost et al., 2000; Werne et al., 2004; Heijs, 2005). The associated fauna ranges from microbes of various types, such as methane-oxidising archaea and sulphate-reducing bacteria, through bivalves, gastropods and polychaetes to rays and other fish (Olu-Le Roy et al., 2004; Sibuet and Olu, 1998). Mud volcanoes normally have a high acoustic backscatter (Fig. 1) because they often present a rough microtopography with embedded rock clasts in the mud matrix of the mud flows forming them, authigenic carbonate crusts precipitated during the anaerobic oxidation of methane via sulphate reduction (Aloisi et al., 2000), and high gas content (Charlou et al., 2003).

Observations of gouge marks were made during geological reconnaissance of mud volcanoes and fluid seeps, and they were thus incidental to the objectives of the research. Quantification and

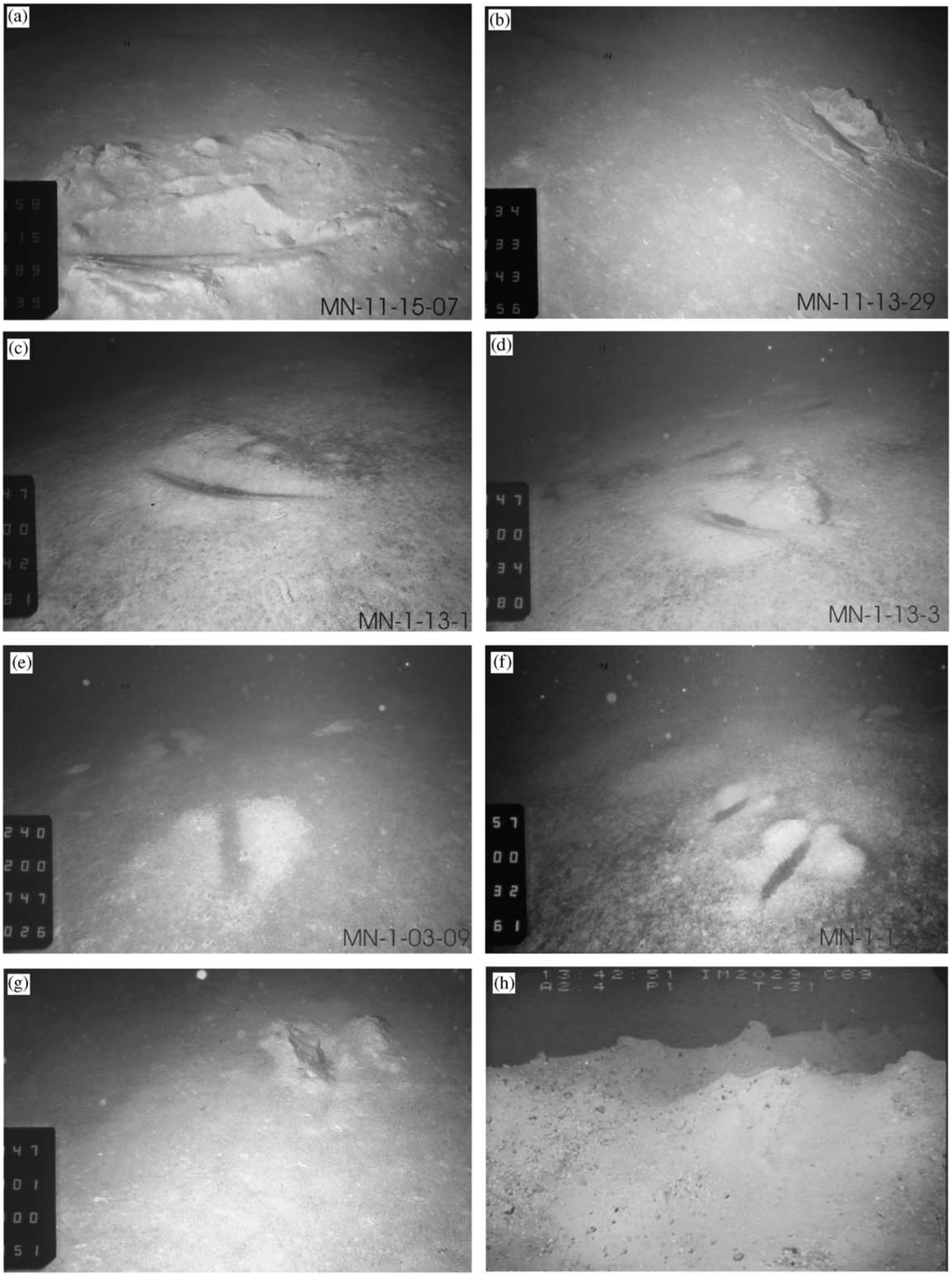

Fig. 3. Seafloor gouge marks from Kula Mud Volcano (south of Turkey in the Anaximander Mountains) at depths of about 1700 m (a, b), Napoli Mud Volcano (c–f) and the Nadir Brine Lakes areas (g), both south of Crete on the Mediterranean Ridge at depths of 1950 and 2050 m, respectively. Gradations in age from relatively recent to older (b, g, a, c, d, f, e) are inferred from the degree of bioturbation, smoothness of the relief, and infill from phytodetritus. The surface of a fresh mud flow is shown in (h).

statistical analysis is therefore not possible with the current data set. Gouge marks were found in the Olimpi Mud Diapir Field on the Mediterranean Ridge (an accretionary prism) south of Crete and the Anaximander Mountains south of southwest Turkey; both areas are quite different environments geologically, but both have mud volcanoes and fluid seeps. The gouge marks were visible only in inactive or dormant areas of mud volcanism and fluid seeps, where there had been no recent mud flows (from eruptions). The simple reason for this is that gouge marks would not be easily noticeable in areas where mud flows form a chaotic body of sediment with a rough surface relief (Fig. 3(h)). Since the majority of our research focused on areas of recent eruption, our results are biased toward areas where a record of gouge marks was less likely to survive, and our observations may therefore have underestimated their total number and frequency in general.

On both Napoli (Olimpi Field) and Kula (Anaximander field) mud volcanoes the gouge marks were observed on the upper flanks of the structure, just off the summit. This region consisted of smooth and undisturbed sediment in comparison to the rough surface of fresh mud flows found at the summit. Gouge marks would be more difficult to distinguish in such fresh mud breccia (Fig. 3(h)). Gouges seemed to be concentrated to some degree in patches. It was estimated that during one dive on Napoli and one on Kula there were approximately 30–40 gouge marks observed in total. Although these gouge marks appear to be relatively common, since they may be up to hundreds of years old, they may not be created frequently. A number of gouge marks were also noticed in the vicinity of the Nadir Brine Lakes area of the Olimpi Mud Diapir Field (33°38.8′N—24°38.5′E, 2070 m; Fig. 3(g)), presumably because this is also an area of active seafloor seeps even though without the presence of mud volcanoes.

4. Possible source of seafloor marks

Several possible causes could be proposed for the creation of gouge marks on mud volcanoes, but most of them do not withstand close examination. Because of their large number and characteristic shape, it is highly improbable that these features at depths of 2000 m are man made (e.g., submarines bumping into the mud volcanoes or fishermen dragging nets over them)—in fact the scientists of the MEDINAUT expedition were the first to actually visit these mud volcanoes. Likewise it is also improbable that they originate by some sort of previously unknown seafloor modification by benthic organisms, as pockmarks formed by fluid emissions (which normally have an obvious vent in the centre and are bowl shaped and symmetrical), or that may originate from a previously unknown sedimentary or hydrological process. It therefore seems more likely that they are produced from above by a large marine predator. Marks similar to these have been observed made in sand or mud by large cetaceans (Rossbach and Herzing, 1997; Darling et al., 1998).

Consideration of the distribution, depth of deepest dives, size, rostrum shape and diet of several large predators suggests that most would not be likely to produce these marks for one or more reasons (Table 1). The only animals large enough and anatomically capable of producing large gouge marks of this size at this depth are predatory cetaceans. Risso's dolphin (*Grampus griseus*) and long-finned pilot whales (*Globicephala melas*) have not been observed to dive deep enough to produce these marks, and neither have a prominent rostrum or lower jaw. Sperm whales (*Physeter macrocephalus*) dive deeply but have not been recorded at these depths in the Mediterranean or elsewhere (Amano and Yoshioka, 2003; Zimmer et al., 2003; Watwood et al., 2006). Furthermore, their underslung and relatively long lower jaw could not easily be envisaged to create these marks requiring a ploughing action with both lower jaw and belly grazing the substrate. Sperm whales are generally about 1.6–2.2 m in width (calculation based on Bolognari, 1949) and would presumably make too broad a mark.

The most likely candidate appears to be the beaked whale species frequently found in these locations: the Cuvier's beaked whale (*Z. cavirostris*). This species has been shown to dive to depths of 1950 m (Tyack et al., 2005), is widely distributed in the Mediterranean (Notarbartolo di Sciara, 2002), and has a pronounced rostrum (beak). Its size (average length of about 5.5 m) and shape (maximum girth approximately 2.5 m, i.e. width under 1 m, Heyning, 1989) seem to be suitable to create the seafloor impressions observed.

5. Discussion

The gouge marks observed on mud volcanoes are considered by us to be caused by the glancing

Table 1
Predatory large cetaceans with a Mediterranean presence that are potential sources of gouge marks

	Distribution	Depths	Length (m)	Rostrum shape	Diet
Risso's dolphin (*Grampus griseus*)	Relatively common from Gibraltar to Aegean (Notarbartolo di Sciara, 2002)	Diving behaviour unknown	2.5–3.5	Bulbous head	Crustaceans, cephalopods
Long-finned pilot whale (*Globicephala melas*)	Presence in eastern Mediterranean doubtful (Notarbartolo di Sciara, 2002)	Mediterranean: max. 648 m (Baird et al., 2002)	5–6.5	Bulbous head	Primarily squid eaters, also take fish
Sperm whale (*Physeter macrocephalus*)	Widely distributed in the Mediterranean Sea (Notarbartolo di Sciara, 2002). Abundant along the Hellenic Trench, eastern Mediterranean (Gannier et al., 2002; Frantzis et al., 2003).	Japan: max. 1200 m (Amano and Yoshioka, 2003). Mediterranean: feeding between 550 and 900 m (Zimmer et al., 2003; Watwood et al., 2006)	10–15	Underslung jaw	Primarily cephalopods
Cuvier's beaked whale (*Ziphius cavirostris*)	Found throughout Mediterranean (Notarbartolo di Sciara, 2002). Comparatively abundant along the Hellenic Trench, eastern Mediterranean (Frantzis et al., 2003)	Mediterranean: max. 1950 m (Tyack et al., 2005)	5–7.5	Beak	Suction-feeding on fish and squid

Length is given as a general reference for the size of these animals and as an indicator of relative size for other dimensions due to similarities in body shape.

contact of a large predator such as those indicated in Table 1. We envisage the elongated general depression of around 1 m wide and 2 m long as the impression of the belly of the animal and the central groove of around 10 cm deep and wide caused by its rostrum. In some cases where grooves were observed parallel to the central axis of the main groove but outside the general oval depression, we presume these were caused by flipper movements. The animal would most likely have been right side up because an inverted contact with the seafloor would result in a deeper more irregular groove if it were caused by the dorsal fin.

The eastern Mediterranean Sea is known to be one of the most oligotrophic areas of the world (Tselepides and Lampadariou, 2004); yet it also harbours a rich and abundant fauna related specifically to mud volcanoes and cold seeps (Olu-Le Roy et al., 2004). Two benthic 'hot spots' have previously been noted in the eastern Mediterranean, in the Hellenic and Pliny trenches (Tselepides and Lampadariou, 2004) which may similarly be better explained as related to fluid seeps known in this geological setting than as related to anomalies in the source of food—organic matter originating from primary production—from above: i.e., chemosynthetic rather than photosynthetic sources (see Sibuet and Olu, 1998; Van Dover, 2000).

We hypothesise that the gouge marks observed are related to the abundant benthic fauna associated with these mud volcanoes and cold seeps (Olu-Le Roy et al., 2004), and that the marks are caused by cetacean predators, most likely the Cuvier's beaked whale. This species is common in the eastern Mediterranean and particularly along the Hellenic Trench (Frantzis et al., 2003); the only other common deep-diving whale species (sperm whales) probably have too broad a girth and too large a jaw to produce a general elongated seafloor indentation no more than a metre or so wide with a central groove of around 5–10 cm deep and wide (Table 1). There are several possibilities as to why these beaked whales could cause such indentations: (1) they may be feeding on benthic organisms found in high abundance at these locations (Olu-Le Roy et al., 2004); (2) they may be trying to catch squid attracted by the high prey abundance associated with these features—such squid may be "hiding" at the seafloor, or the whale may catch them by squeezing them against the seafloor; (3) they may be ingesting sediment for an unknown, potentially digestive, reason. For any of these, a low angle approach of the whale would result in a grazing contact with the seafloor causing marks of the type described here. It can be noted that other species of beaked whales are known to plough through the mud with their beaks during benthic foraging (e.g., the northern bottlenose whale (*H. ampullatus*), as inferred from sea-stars in its stomach and a thin yellow covering of mud on its beak; Ohlin, 1893). The suction-feeding mechanism of beaked whales would allow the selection of prey within mud and then expulsion of mud as water held in the forestomach is released past prey secured against the rugose palate (Heyning and Mead, 1996).

Cuvier's beaked whales are known to frequent offshore areas where water is deep (i.e., over 2000 m) and to dive to depths of over 1500 m in order to feed (Johnson et al., 2004). The maximum recorded published dive depth is at least 1950 m, and whales may dive for as long as 85 min (Tyack et al., 2005). They have also been shown to echolocate (Zimmer et al., 2005; Johnson et al., 2004, Frantzis et al., 2002), and thus would presumably be able to detect sea-floor features like the mud volcanoes, a great advantage in finding these ecologically diverse oases in 2 km ocean depths. Their diet consists almost exclusively of cephalopods, although deep demersal fish and crustaceans have occasionally been found in their stomach contents (Heyning, 1989; Santos et al., 2001; MacLeod et al., 2003). The presence of crabs (probably leucosiid) and pebbles in the stomach of a Cuvier's beaked whale from the central Pacific coast of Japan allowed Ohizumi and Kishiro (2003) to suggest that the whale had been foraging on the seafloor. Stomach contents from eight individuals that stranded in Kyparissiakos Gulf (Greece, eastern Mediterranean) contained only squid remains (squid flesh, beaks, eye lenses) from one, two or all of the following species: *Histioteuthis bonnelli*, *H. reversa* and *Octopoteuthis sicula* (Lefkaditou and Poulopoulos, 1998; Frantzis and Lefkaditou, unpublished data). In one of those animals one shrimp (probably *Aristaeomorpha foliacea*) has been found among the squid remains.

The rich benthic ecology of mud volcanoes and fluid seeps studied in the eastern Mediterranean by Olu-Le Roy et al. (2004) includes bivalves, snails, sponges, anemones, worms, crustaceans and echinoderms. It is unknown whether any of these animals would be attractive as food for Cuvier's beaked whale or whether their more common squid prey (or deep-water fish) are also present in association with this faunal abundance. No squid were observed during the Nautile dives. On the other hand, if the creation of gouge marks is the infrequent event that it seems to be, then it is also possible that random examination of stomach contents might not show the results of such foraging on mud volcanoes.

The relative abundance of the Cuvier's beaked whale in the eastern Mediterranean together with its extreme deep-water foraging abilities suggest that it could take advantage of the rich fauna associated with mud volcanoes and fluid seeps. Furthermore, by echolocation the whale could easily find mud volcanoes by their characteristic high backscatter. We identified mud volcanoes using Simrad EM12D multibeam bathymetry and acoustic imagery (frequency roughly 15 kHz), before checking by direct sampling (Zitter et al., 2005; Volgin and Woodside, 1996). These mud volcanoes appear as acoustic bright spots on an otherwise dimmer and acoustically less significant seafloor in the multibeam echosounder or sidescan sonar (Fig. 1). Presumably they would be equally apparent to whale sonar.

6. Conclusions

Characteristic gouge marks found on eastern Mediterranean mud volcanoes are hypothesised to be formed by Cuvier's beaked whales during long deep dives to feed on the comparatively rich biomass associated with the methane seeps on mud volcanoes. The observations of these marks at depths up to 2100 m indicate that such depths can be reached by these animals and that the food supply is sufficiently good to warrant such extreme dives. Sperm whales are a potential alternative cause but they are larger, less common, and have not been observed to dive to the equivalent depths of these features so would appear less likely to cause these than Cuvier's beaked whales.

It is worth examining chemosynthetic communities forming 'benthic hot spots' in the eastern Mediterranean as important sources of biomass in an otherwise impoverished environment. These observations could provide a simpler explanation of high values of meiofaunal abundance in some areas of deep water there.

Although the type of observations reported here are not directly of importance to the marine scientists studying mud volcanism and fluid seeps on the seafloor, they do illustrate that observations made by one community of scientists can have potential value to another part of the scientific community. So little is known of biological interactions in the deep sea that observations such as these can provide biologists with potential insights linking records of near-seafloor diving behaviour, and possible feeding events taking place there. Such interdisciplinary collaborations are clearly of great importance.

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