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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