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Comprehensive global inventory of submarine mud volcanoes

Simone Napoli[1], Daniele Spatola[1]✉, Daniele Casalbore[1,2], Luigi Lombardo[3], Hakan Tanyas[3] & Francesco Latino Chiocci[1,2]

Systematic morphometric studies of submarine potential geohazard elements such as mud volcanism are still limited in the scientific literature. To fill this gap and contribute to the global geohazard databases, we present a comprehensive inventory of submarine mud volcanoes (MVs) considering their spatial location and characteristics. The "Global inventory of submarine mud volcanoes" database here presented includes a large dataset, providing an overview of the morphometric analyses we performed as well as the considerations that arose from them. These cover basic marine geological and applied geohazard aspects. We explored frequency-area distribution patterns within this dataset, as typical of other geoscientific branches. This effort is a first step towards a shared and open knowledge of MVs, through which the marine geology community would further investigate the genesis of such phenomena and contribute to society in making informed decisions on related submarine geohazards.

Background & Summary

State of the art of mud volcanoes. Mud volcanoes (MVs, Fig. 1) are positive morphologies of variable size formed by vertical migration of overpressured fluids (gas, mainly CH_4 and CO_2, and water) together with fine-grained sediments, commonly known as "argille scagliose"[1,2], "diapiric mélange"[3], "mud slurry"[4] or "mud breccia"[5–7].

MVs usually have a subcircular diagnostic shape and sometimes show a gas plume escaping from the seabed[8]. They can be found in irregular or scattered clusters over a wide water depth range[9,10]. More than 1100 mud volcanoes are documented onshore and on continental shelves (less than 200 m) and at least 10^3–10^6 mud volcanoes are expected on continental slopes and abyssal plains[11]. Knowledge of the activity and morphology of the deep-sea mud volcanoes is still rather limited as at depth bathy-morphological data are usually at low resolution[12].

Submarine MVs are found in different geological environments (e.g. active continental margins, open seas) (Fig. 2), especially where compressional tectonic settings facilitate the development of high pore pressures[6], and in areas with high sedimentation rates such as deltas and confined sedimentary basins[13,14].

Mud volcanoes morphologies (with distinctive features such as gryphons and bubbling mud pools) depend on a multitude of variables, including characters and viscosity of the extruded mud breccia, the state of activity of the mud volcano, and the frequency of the eruptive events[6,15,16]. *Conical mud volcanoes* are typically produced by the progressive superimposition of mud flows from a central vent, while the development of *mud pies* or *plateau-like mud volcanoes* is usually associated with increased water content in the mud breccia[14,17,18].

A thick mud breccia with low water content generates a conical mud volcano with steep slopes and a thin mud breccia with high water content results in a low-elevation structure with a flatter top. Alternatively, the different morphologies depend on the size of the pipe-like feeder channel: a small conduit provides significantly less mud breccia volume generating conical mud volcanoes[19]. The occurrence of MVs appears to be linked to various geological predisposing factors such as tectonic activity, sedimentary load, existence within the stratigraphic succession of thick fine-grained plastic sedimentary units and the presence of hydrocarbons[13,20–23].

Recently, Dimitrov[24] suggested pore-fluid pressure, buoyancy contrasts and tectonic force as the three driving mechanisms for the genesis of MVs. To date, two formation models have been proposed in the scientific literature:

[1]Department of Earth Sciences, Sapienza University, Rome, Italy. [2]Institute of Environmental Geology and Geo-Engineering (IGAG), Consiglio Nazionale delle Ricerche (CNR), Rome, Italy. [3]University of Twente, Faculty of Geo-Information Science and Earth Observation (ITC), PO Box 217, Enschede, AE, 7500, the Netherlands. ✉e-mail: daniele.spatola@uniroma1.it

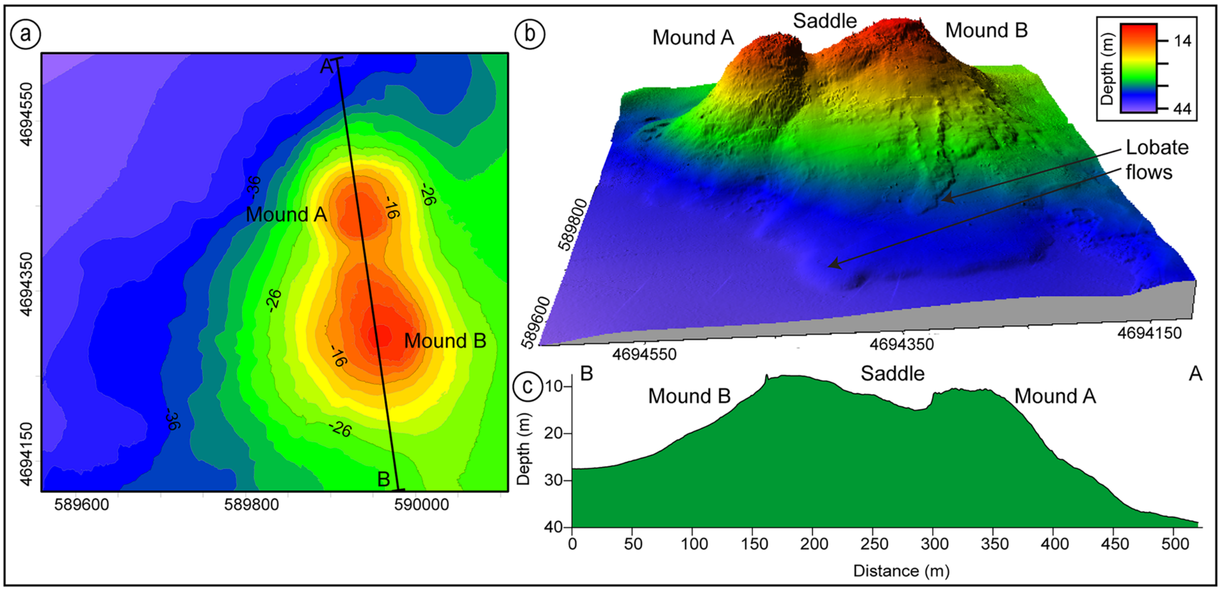

Fig. 1 (**a**) Bathymetric map showing the occurrence of a submarine mud volcano complex composed by two mounds (A and B) mapped in the Scoglio d'Affrica offshore (northern Tyrrhenian Sea). (**b**) 3D view of the mud volcano complex. (**c**) Bathymetric profile A-B (modified from Spatola *et al.*[78]).

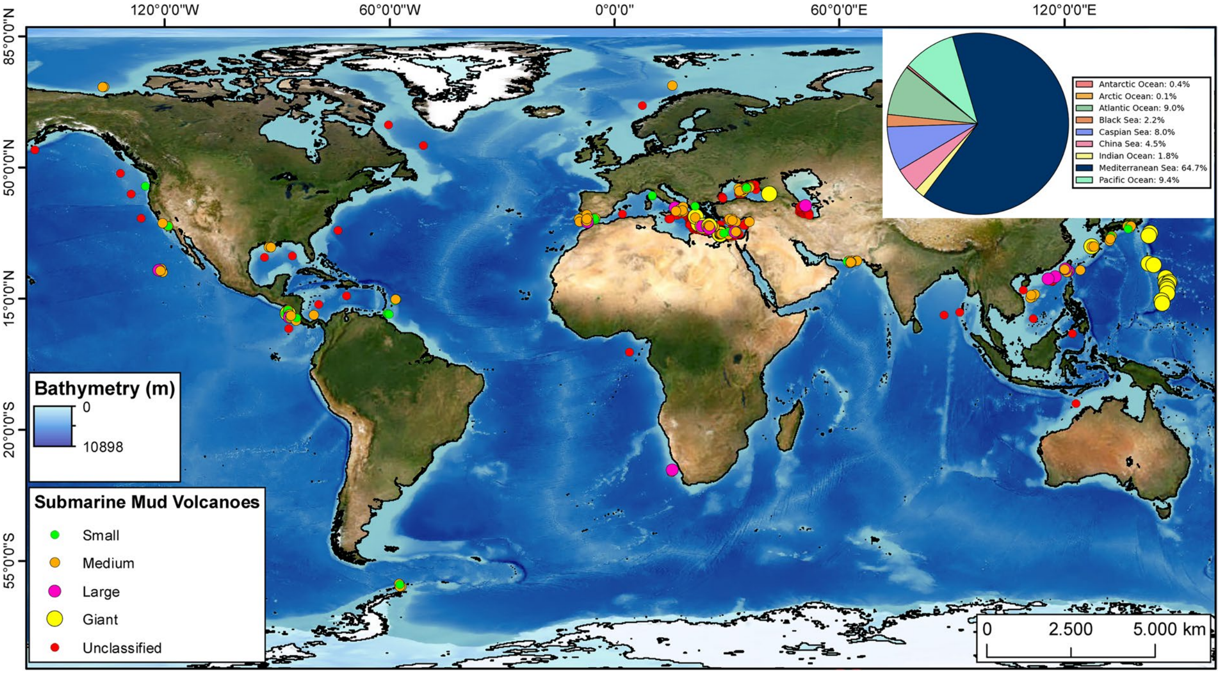

Fig. 2 Location and size of submarine mud volcanoes (N = 1003). Background bathymetry from General Bathymetric Chart of the Oceans (GEBCO; https://www.gebco.net/data_and_products/gridded_bathymetry_data/). Inset top right: percentages of submarine MVs locations. Inset bottom left: submarine MVs divided by size (small, medium, large or giant). Unclassified submarine MVs (i.e. those lacking morphometric parameters; see Table S3 in the supplementary information) are showed as red points[7,9,14,79–81].

1) the "*solid model*" proposes the genesis of the mud volcano on the crest of the diapiric structure affected by the fluid migration[9,21,25];
2) the "*fluid model*" proposes the genesis of the mud volcano as a pure consequence of the ascent of fluidified mud along faults and fractures, providing migration paths in a variety of geodynamic settings (intracontinental, continent–ocean, intraoceanic)[26–30]. In both models, the fluid migration is crucial for the formation of these positive features[9,31–33].

Numerous studies suggest that MVs are important geohazard elements for submarine infrastructures (e.g. oil rigs, telecommunications cables, pipelines, windfarms, etc.) since they are unstable sedimentary structures[34,35] often associated with cyclical explosive eruptions[24,36], with highly variable intervals of years or decades, involving the release of large amounts of hydrocarbons (mainly methane) and mud into the hydrosphere/atmosphere[37–41]. Hence the importance of assessing their worldwide spatial distribution (Fig. 2). It is estimated that onshore and shallow water mud volcanoes release 2.2 and 6 Tg yr^{-1} of methane to the atmosphere[42,43] and that at least 27 Tg yr^{-1} of methane may escape from deep water mud volcanoes with significant implications for the balance of atmospheric greenhouse gases[9,44]. The flux of carbon from submarine MVs plays a key role in biogeochemical processes near the seabed (e.g. anaerobic oxidation of methane, AOM)[45,46].

The underestimation of the mud volcanic hazard (both marine and onshore) is due to their episodic activity; for instance in Italy, it is demonstrated by two recent such as the paroxysmal in the last decade one off the Scoglio d'Affrica (northern Tyrrhenian Sea)[47,48] and another, with causalities, that occurred on 27 September 2014 at the *Macalube di Aragona* in southern Sicily[49,50].

Classification of mud volcanoes. The increasing resolution accuracy, spatial resolution, and accessibility of multibeam digital elevation models (DEMs), quantitative hosted surface analysis, and geomorphometry, have become fundamental in the field of submarine geomorphology[51–53]. The morphometry of certain volcano types has been widely discussed[54]. Specifically, these include cinder cones[55–57], oceanic shields[58,59], subglacial volcanoes[60,61], seamounts[2,62–64], and extraterrestrial volcanoes ranging from Martian volcanoes to pancake domes on Venus[65–67]. Conversely, systematic morphometric studies on submarine mud volcanoes are still relatively few[6,68,69] due to the limited amount of available data.

In the recent scientific literature, various classifications of mud volcanoes have been proposed based on different criteria, including period time and intensity of the eruption[42] or the activity of mud volcanoes[70]. The following morphological classifications of mud volcanoes have been suggested:

1. Etiope and Milkov[11] proposed a dimensional classification of mud volcanoes based on a collection of data from 120 MVs (marine and onshore) scattered around the world. They classified mud volcanoes in small-size (<0.5 km^2), medium-size (0.5–9 km^2), large-size (>9 km^2) and giant-size mud volcanoes (>20 km^2) (classification used in this paper and reported in Fig. 2 and in Tables S1, S2 in the supplementary information).
2. Kopf[6] and later Authors such as Omrani and Raghimi[71] classified mud volcanoes on the basis of the mean slope values into mud cones (>5°) and mud pies (<5°).
3. Bonini and Mazzarini[72] using the maximum diameter D_{max} and the mud volcano shape index (or axis ratio) D_{max}/D_{min}, defined four main morphological classes (A, B, C and D) of onshore mud volcanoes.
4. Komatsu *et al.*[73] for Martian mud volcanoes defined the following morphological types: cones with typical H/D ratios of 0.071–0.1 (T1), shield-shaped features or cakes with H/D ratios of 0.003–0.044 (T2) and round mounds or domes with H/D ratios of 0.075–0.143 (T3).

Objectives and organization. To date, the scientific literature includes only one available geodatabase of submarine mud volcanoes, compiled by Kioka and Ashi[68]. In terms of reviews, the most comprehensive is likely the one prepared by Kopf *et al.*[6]. Building on these existing scientific publications, this study aims to create a more complete, though not entirely exhaustive, morphometric inventory of submarine mud volcanoes. The inventory is based on both published data (e.g. location, height, diameter, and, when available, water depth and mean slope) and derived data (e.g. inferred locations of submarine mud volcanoes not explicitly reported by authors, perimeter, area, volume, aspect ratio, and height/radius ratio). The primary novelty of this study lies in the development of a comprehensive and detailed dataset of submarine mud volcanoes, which includes valuable information such as morphological classifications. Notably, this represents the first complete dataset on mud volcanoes, addressing a significant gap in previous research. For instance, the earlier database by Kioka and Ashi[68] included a limited set of dimensional characteristics (e.g. height and diameter) for 258 MVs against 700 MVs of our dataset[74]. In contrast, we have calculated the key morphometric parameters commonly employed in recent marine geomorphological studies[54]. This dataset serves as a crucial resource for the scientific community, facilitating deeper insights into the dynamic genesis and evolutionary models of submarine mud volcanoes.

Methods

Morphometric parameters of submarine MVs. The following section reports the description of the main morphometric parameters adopted in the present study for the characterization of submarine MVs. We recall that some of the information presented in Tables S1–S3 is derived from a thorough literature review. These data were supplemented with morphometric parameters calculated using a semi-automatic method to extract key parameters, following recent literature on submarine volcanic settings in the Tyrrhenian Sea[63], the Canary Islands[75], and the Sicily Channel[64].

1. *Size parameters*: the mean radius of each mud volcano R is defined as $R = (D_{mean})/2$, where the mean basal diameter $D_{mean} = (D_{max} + D_{min})/2$[76], or it is taken as the representative diameter available in the scientific literature. The basic perimeters are respectively calculated as $2\pi(\sqrt{(D_{max}{}^2 + D_{min}{}^2)/2})$ or $2\pi R$, the basic areas as $\pi D_{max} D_{min}/4$ or $\pi D_{mean}{}^2/4$ and the volumes as $\pi D_{max} D_{min} H/12$ or $\pi D_{mean}{}^2 H/12$.
2. *Shape parameters*: we calculate shape parameters such as aspect/basal ratio (bsr, D_{min}/D_{max}), mud volcano shape index commonly known as elongation or axis ratio (D_{max}/D_{min}), height versus radius of the mud volcano's body (H/R), vertical relief to area ratio (Height/Area), compactness factor

(comf = Perimeter/(√4* π* Area)), ellipticity index (ei = (π*(D_{max} /2)²)/Area), dissection index (di = (Perimeter/2*Area)*(√(Area/π)), and eccentricity (e = (√(D_{max} /2)² − (D_{min} /2)²/ D_{max} /2)[75,77].
3. *Slope parameter*: the mean surface slope of the analysed submarine mud volcanoes, if not reported in the scientific literature, is given by arctan(H/R), with H as the maximum height.

Data Record

The dataset is available at "Global inventory of submarine mud volcanoes" (https://zenodo.org/records/13120956)[74]. This dataset includes a file.KMZ named "Geodatabase" including different types of information such as name, geographic coordinates, water depth (and associated hydrostatic pressures), height (H), diameter (D_{mean}, D_{max} and/or D_{min}), slope, shape, size of 700 submarine MVs (Table S1 in supplementary information). The data has been formatted as a.KML file to ensure compatibility with all GIS platforms.

Technical Validation

All data were manually entered and cross-checked by multiple authors. Comprehensive validation procedures were conducted to ensure data accuracy, including thorough checks of the published metadata. To identify and exclude potential outliers and/or duplicates, we analysed the distributions and characteristics of each MVs by georeferencing all occurrence points. However, we encourage users to report any errors or submit additional records to the corresponding author to help maintain the dataset's accuracy and relevance. All updates will be subjected to the same rigorous technical validation process outlined earlier.

Usage Notes

Future geodatabase development. The geodatabase we realised has intrinsic limitations, being partly based on published data. Future development of the geodatabase primary includes the addition of missing information, the implementation with newly discovered submarine mud volcanoes and the incorporation of geophysical, geotechnical, geochemical, and biological data. The geodatabase will also be extended to terrestrial onshore mud volcanoes and/or fluid escape structures. These developments need the researchers to participate in the continuous evolution and improvement of the geodatabase and possibly in launching an international initiative to collect and compare MVs characters, involving research groups that study these landforms. Consequently, the geodatabase should be a dynamic platform, receptive to feedback from the scientific community. If this goal will be achieved, the geodatabase gradually will transform into a nexus for collaborative research initiatives, with topics and interests ranging from geology to ecology to engineering.

Code availability

No customized code was produced to create or analyse this dataset. Specifically, we used ArcGIS software to create the dataset, however our inventory can be opened with any GIS software (open-sourced or licensed).

Received: 11 December 2024; Accepted: 27 February 2025;
Published: xx xx xxxx

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Author contributions

Simone Napoli: Writing – review & editing, Writing – original draft, Methodology, Investigation, Data curation, Conceptualization. Daniele Spatola: Writing – review & editing, Writing – original draft, Supervision, Methodology, Investigation, Data curation, Conceptualization. Daniele Casalbore: Review & editing, Supervision. Luigi Lombardo: Review & editing. Hakan Tanyas: Review & editing. Francesco Latino Chiocci: Review & editing.

Competing interests

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Additional information

Supplementary information The online version contains supplementary material available at https://doi.org/10.1038/s41597-025-04726-1.

Correspondence and requests for materials should be addressed to D.S.

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