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Pockmarks of the Mediterranean region seas: A Comprehensive Geodatabase for Marine Geomorphological Analysis

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We present a high-resolution georeferenced database of pockmarks documented on the Mediterranean region seas by using different geophysical technologies (e.g. multibeam, seismic reflection) carried out during oceanographic expeditions. Pockmarks are probably the most ubiquitous morphologies linked to the fluid flow processes at the seafloor with a density up to 3.4 features per km^2. They vary from sub-circular to elongated in plan-view and have U- or V-shape in cross section. Through georeferencing over 7,516 pockmarks from the recent literature, we have built an active and systematic database with the aim of incorporating significant data on these seafloor morphologies. The database can have a number of applications: it can be used to assist submarine infrastructure planning (e.g. pipelines, offshore wind farms), ecological study (e.g. pockmarks are habitat for sensitive benthic communities), and natural resource appraisal (e.g. hydrocarbon reservoirs, gas hydrates, offshore groundwater). Moreover, it can serve as a significant tool of scientific investigation, allowing to understand fluid flow processes and marine geosystems.

Background & Summary

Pockmarks definition and origin of the gas. Fluids within marine sediments are lighter than the solid particles and, therefore, rise up to the seafloor due to buoyancy[1]. These processes are called "fluid flow"[2,3] and give rise to diverse types of seafloor morphologies[3]. The most common morphologies linked to the fluid flow processes are sub-circular depressions, known as pockmarks. King and MacLean[4] introduced the term "pockmark" when they for the first time recognised and mapped these depressions through the Nova Scotian shelf by using echo-sounder records[4]. In the recent literature, pockmarks can have diameters and depths up to a few km and 150 m respectively and show circular to elliptical planform shapes[5,6] (Fig. 1). They display U- and V- cross section and flat to cone-shaped bottoms; their internal walls have slope gradients of 6°–18°[7], on average less than 10° (Fig. 1b).

More recently, in the scientific literature, the term "Pockform" was introduced to indicate "Pockmark-like seafloor features" with a genesis possibly linked to fluid escape from the seafloor[8]. These authors describe pockforms as seafloor morphologies associated with tectonically or dissolution-induced collapse structures and erosional features such as scours or remnants of channel courses.

Pockmarks are typically described as cold seeps, where the emitted fluids are primarily composed of methane (CH_4), and may also include hydrogen sulfide (H_2S), carbon dioxide (CO_2), or nitrogen (N_2), either as gas bubbles or dissolved gases[9]. Methane generally originates from the bacterial degradation of organic matter at low temperatures (microbial gas)[10,11], or from thermogenic processes involving the breakdown of organic precursors at high temperatures and pressures[12,13]. CO_2 and N_2 are associated with hydrocarbon systems that develop near subducting slabs or during the final stages of thermogenic gas generation[14], and can also be found in mixed sedimentary-volcanic basins[15–18]. When methane is accompanied by hydrogen sulfide, exposure can be toxic or even fatal under certain conditions[19].

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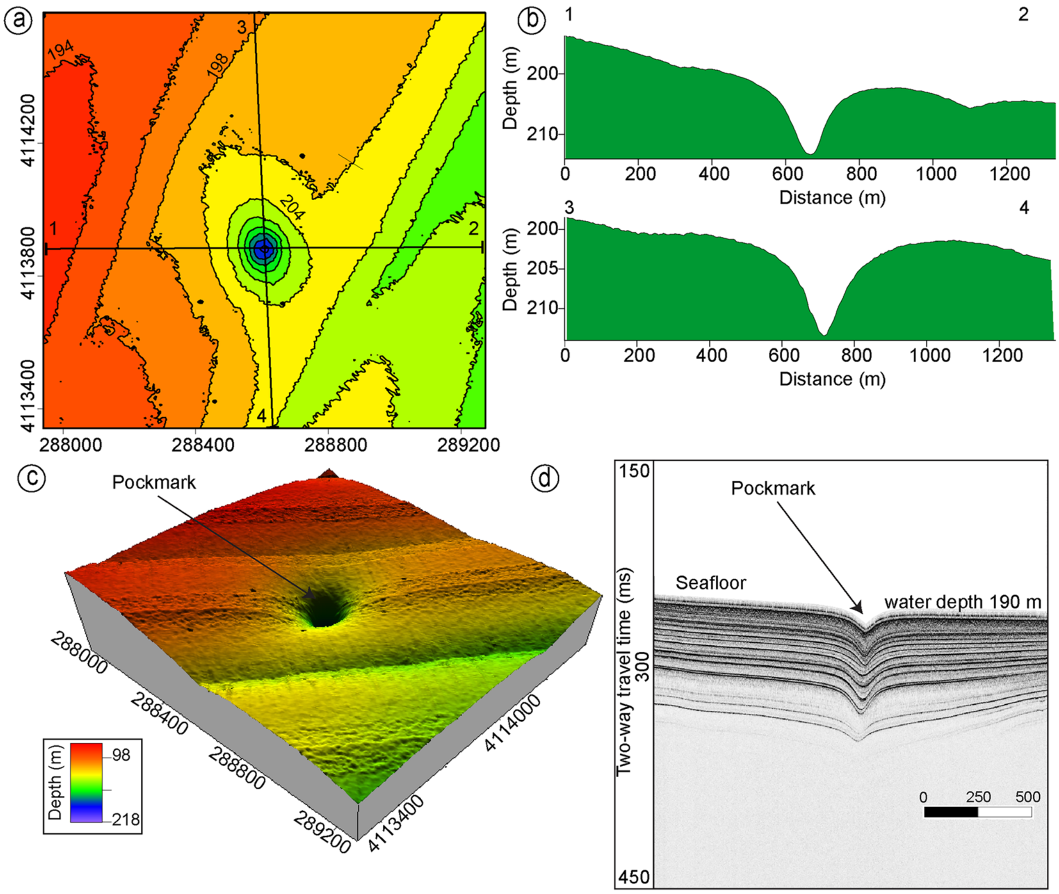

Fig. 1 (**a**) Bathymetric map showing the occurrence of a circular pockmark mapped on the Graham Bank (Sicily Channel, southern Mediterranean Sea). (**b**) Bathymetric profiles crossing the center of the pockmark. (**c**) 3D bathymetric model of the pockmark. (**d**) Sub bottom profile Chirp crossing the pockmark showing the internal seismic character of the pockmark. It approximately aligns with bathymetric profile 3–4 shown in (**b**). Note that (**a,c**) are realized using the projected coordinate system UTM 33 N (WGS 84).

Classification of pockmarks. Pockmarks have been subdivided in different classes on the basis of their morphological characters[20]. The term "*Unit*" pockmark was coined by Hovland *et al.*[20] during a comparative study of pockmark-associated features on both sides of the Atlantic Ocean to indicate very small (1–10 m in diameter, and up to 0.6 m deep) seafloor depressions which are found isolated or organised in groups, as well as in association with larger pockmarks. "*Normal*" pockmarks are bigger, with diameters of 10–250 m and depths up to 45 m deep. Both unit and/or normal pockmarks are usually found arranged in strings that may be few km in length. These strings can be linked to near-vertical faults, fractures or flexures in weakness zones affecting the upper sedimentary layer[5,18]. Pockmarks bigger than 250 m in diameter are known as "G*iant*" pockmarks[20]. They were described for the first time on the Californian margin[21] and successively were mapped in several continental margins, e.g. in the Gulf of Cadiz. Pockmarks typically appear oval or nearly circular in in planform and vary widely in size, ranging from 125 to 850 m in diameter, most commonly between 300 and 500 m with internal depths ranging from 1 to 16 m, and more frequently between 3 and 12 m[22]. Giant Pockmarks can be organised as cluster or random[23,24], or more generally associated with underlying geological structures (e.g. system faults)[25,26]. Kilometers-wide circular depressions by fluid flow were called in the recent literature as "*Mega*". Most of mega-pockmarks were observed in northern South China Sea, reaching a diameter of 3,210 m and an internal depth of ~ 126 m based on multibeam data and seismic reflection data so far[27].

Pockmarks activity. In the scientific literature, pockmarks have been interpreted as active in case fluid or gas flux as bubbles have been observed[28] in the water column or as inactive/dormient whether no flares were detected in the water column[29] and seepage is not directly visible near the seafloor in sub-bottom data[30]. Differentiating between active pockmarks and dormant or inactive ones proves quite challenging and is not always achievable. The only way is to identify evidence of active outgassing in the water column (gas bubbles) emanating from the pockmarks and identified by image/video[30] (Fig. 2a). Marine geophysical explorations using high and very high-resolution seismic reflection (e.g. sub bottom profiler) and backscatter data in the water column have allowed to record the occurrence of fluid/gas seepage from shallow to deep water environments[31–35] (Fig. 2b). The most common acoustic water column anomalies (i.e. gas flares) consist of straight or inclined high-amplitude acoustic scattering that extend upwards from the seafloor towards the sea level, due to the presence of gas bubbles

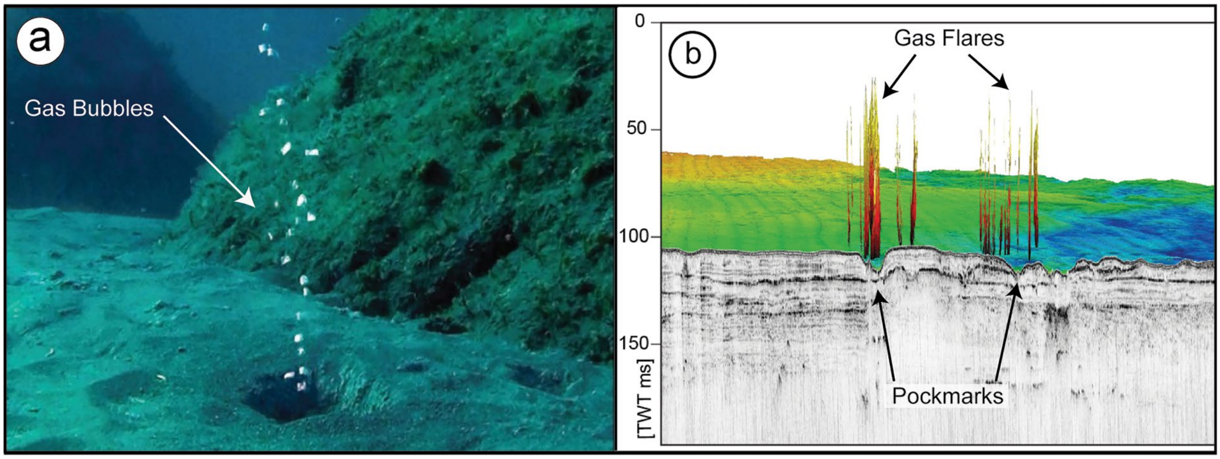

Fig. 2 (**a**) Gas bubbles from a ROV image collected across the Pianosa Ridge; (**b**) Sub-bottom seismic profile collected in the Adriatic Sea with superimposed gas flares detected with multibeam EM2040 in 2018 (modified from Rovere *et al.*[37]).

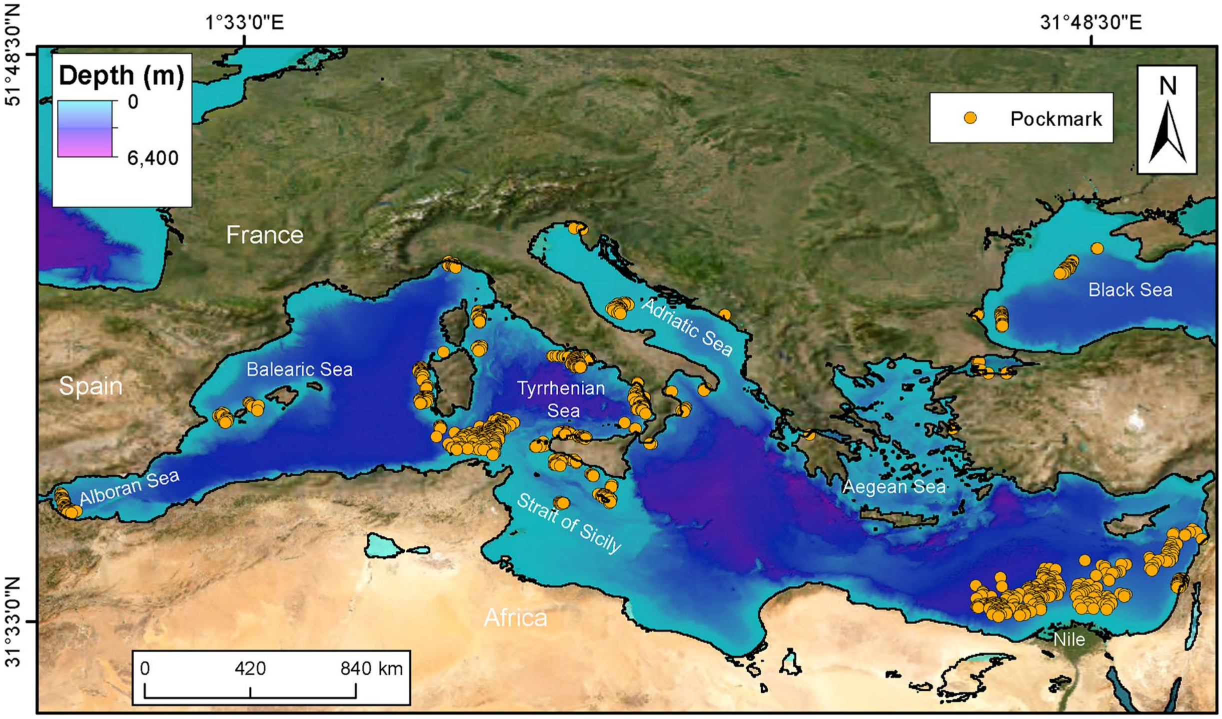

Fig. 3 Map of pockmarks documented on the seafloor along the Mediterranean region seas. Source of depth data: EMODnet Bathymetry.

in the water column and the acoustic impedance contrast with the surrounding seawater[36]. On high resolution seismic reflection sections, they appear as hyperbolas and columns ascending from the seafloor sometimes up to the sea surface[15,37]. However, it is noteworthy that similar hydro-acoustic signature may also be produced by fish shoals[30], suspended sediment concentrations, or even metallic and/or plastic litter on the seafloor.

Objectives. All over the world, fluid flow processes produce a large variety of seabed pockmarks, with diameters ranging from mm to km. Pockmarks in the Mediterranean region are probably the most common fluid flow morphology characterising the continental margins[38]. In this paper, we geo-referenced 7,516 pockmarks from the recent literature (Fig. 3), including ~1,500 with just spatial location coming from vectorization of thematic maps produced inside two Italian projects: Magic (Marine Geohazards along the Italian Coasts)[39] and METIQ (*Modello Evolutivo del Territorio Italiano nel Quaternario*).

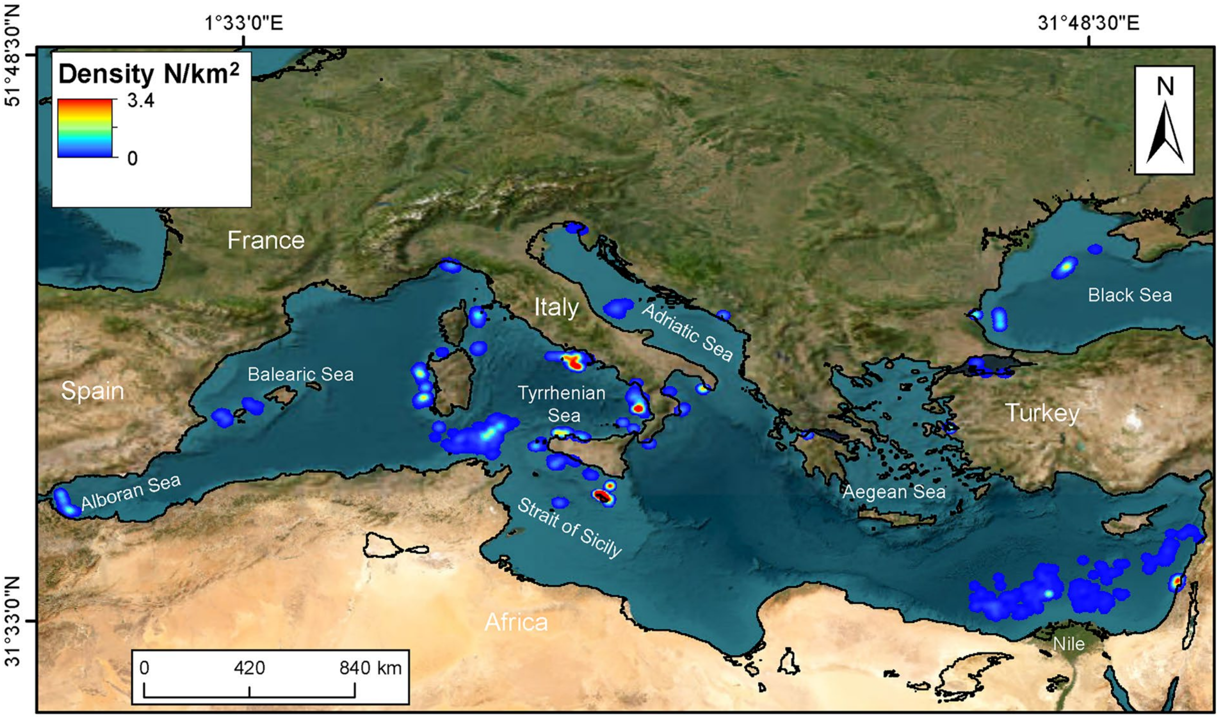

Fig. 4 Density map distribution of pockmarks on the seafloor along the Mediterranean region seas.

The development of a georeferenced database is required to systematically collect, structure, and disseminate the available information on the most common geomorphic features associated with fluid flow processes (i.e. pockmarks). With this database, we would like to support the readers in multiple domains of application as the following one: (i) submarine infrastructure planning and development (e.g. pipelines, telecommunication cables, and offshore wind farms); (ii) ecological aspect since pockmarks are habitats with high ecologically significant and sensitive benthic communities; (iii) natural resource evaluation since pockmarks can provide valuable insights into the presence of subsurface hydrocarbon accumulations, gas hydrates, and mineral resources as well as offshore groundwater; (iv) scientific motivations, the database can easily be an important baseline tool for interdisciplinary researches with the aim of better understanding active marine geosystems. The primary novelty of this study lies in the development of comprehensive and detailed information on pockmarks. Notably, it presents a first dataset on pockmarks[40], addressing a significant gap in previous research. This repository is as complete as possible at the time of the paper's submission, and its open structure will allow for the incorporation of new data as it becomes available. We chose to focus on the Mediterranean region due to its well-documented high concentration of pockmarks, reaching up to 3.4 per km^2 (Fig. 4).

The Mediterranean Sea is an important hot-spot of biodiversity[41] and pockmarks are well knew to be characterised by dense accumulations of chemosynthetic-based and benthic communities and usually affect the ecology of the seafloor by sustaining unique oasis-type ecosystems[42,43]. Furthermore, the Mediterranean Sea, being a semi-enclosed basin, serves as an important natural laboratory for better understanding global and climate change[44]. Finally, coastal areas in the Mediterranean region are characterized by high population densities and increasing human pressure, making this paper and its associated database valuable tools for planning the installation of new offshore infrastructures, such as offshore wind farms or pipelines.

Study Area

The geology of the Mediterranean region is shaped by the evolution of the Tethys Ocean, which began in the late Palaeozoic, reached its peak in the Mesozoic, and closed in the Cenozoic[45]. The convergence of the Eurasian and African plates played a crucial role in forming circum-Mediterranean thrust belts and back-arc basins, leading to significant geological complexities, volcanism, and seismic activity. Remnants of the Tethys Ocean remain in the Ionian Sea and Eastern Mediterranean[46]. The Mediterranean is divided into three main basins, but in the study due to the large quantity of pockmarks, we also include the Black Sea as study area:

1. Western Mediterranean: formed by the extensional collapse of an orogen after the collision of a lithospheric fragment with the Eurasian margins during the Eocene[47]. Key sectors include the Gulf of Lion, Southeast Iberian margins, Balearic Promontory, and the tectonically active Alboran Sea[48].
2. Central Mediterranean: shaped by a combination of tectonic, sedimentary, and erosional processes. Important areas include the back-arc Tyrrhenian Sea[49], the Adriatic basin[50], the deep Ionian Sea[51], and the Sicily Channel[52].
3. Eastern Mediterranean: a remnant of the Neotethys Ocean, marked by tectonic processes and significant

hydrocarbon potential. Key sectors include the Nile Delta deep-sea[53], the Aegean Sea[54]. The Eastern Mediterranean basin is widely recognized for its abundant hydrocarbon resources[55].

4. Black Sea: a semi-enclosed basin formed as the result of back-arc extension, with the development of two basin that coalesced in a single depocenter during their post-rift phase in the Pliocene[56].

Methods

A bibliometric analysis carried out using the main scientific platforms (e.g. Scopus, Web of Sciences or Google Scholar) reveals a significant increase in the worldwide research interest and very high number publications related to pockmarks, underscoring their scientific importance. From 1970 to date, ~ 6,000 scientific documents indexed in the Scopus were published as original articles, case reports, technical notes, pictorial essays, commentaries, and editorials. Our geodatabase was constructed by methodically extracting all the data present in the scientific literature, such as the geographical positions of pockmarks. In populating the geodatabase, we gave greater weight to articles that provided high resolution morpho bathymetric maps with coordinates. This allowed for more accurate georeferencing and ensured that the data incorporated into the database were as reliable as possible. In fact, where authors do not share the exact coordinates of the features, location data were derived by digitizing and georeferencing maps within original papers. This was carried out by using ArcMap, from which a corresponding shapefile was created. The bathymetric background used in this study was the ~ 100 m resolution DEM available in EMODnet Bathymetry (https://emodnet.ec.europa.eu/geoviewer/).

Data Record

The dataset described in this paper is available ZENODO with the title "Pockmarks of the Mediterranean region seas"[40]. We decide to share the geodatabase in different format (e.g. KML, shapefile) to be used with different open-source GIS Platforms, such as QGis or Google Earth. The database includes two different sets of information. The first set has been calculated in this study: FID (i.e. field contains the Object ID), Geographic coordinates in Latitude and Longitude, Geographic Sea, Location, Depth (m), Slope (°), Fault Dist. (m), Seafloor Lithology, Thickness of Pre-Messinian sediments (m), Thickness of Plio-Quaternary sediments (m), Thickness up to the Messinian base (m). To calculate the thickness information we used the georeferenced raster data provided by Sampietro *et al.*[57], and by using the tool "Extract Multi Values to Points" in ArcMap (https://desktop.arcgis.com/en/arcmap/latest/tools/spatial-analyst-toolbox/extract-multi-values-to-points.htm). We included these latter two parameters because Spatola *et al.*[38] have recently demonstrated a significant spatial correlation between the occurrence of pockmarks and the thickness of the Plio-Quaternary sediments, in a subset region of the Mediterranean Sea. The scientific literature lacks strong evidence of a meaningful relationship between pockmarks and evaporites, despite the widespread presence of Messinian evaporites along the Italian continental margins[58].

For fault and seafloor lithology distribution layers, we used data from EMODnet Geology (https://emodnet.ec.europa.eu/geoviewer/) as background information. While these public databases are valuable, they are significantly limited by their low resolution. To reduce this weakness, we implemented them with additional data from other scientific sources, such as the *Modello Strutturale d'Italia*[59]. To estimate the distance between pockmarks and faults we used the tool "Euclidean Distance" in ArcMap (https://desktop.arcgis.com/en/arcmap/latest/tools/spatial-analyst-toolbox/euclidean-distance.htm). This tool calculates the shortest straight-line distance from each cell in a raster to the nearest source feature.

The second set includes information coming from the scientific papers: Mean axis (m), Internal depth (m), Mean water depth (m), Cross-section shape, Planar shape, Bearing, Kind of fluid/gas, Type of Multibeam, Type of seismic reflection data, Water column data, State of activity, Seafloor lithology, Year of acquisition, Name of the research vessel, Notes, References, and DOI/URL. Morphometric analyses of pockmarks are not always conducted by researchers, often due to time constraints associated with data processing and analysis. Because of this bias, the second group of information often does not refer to individual pockmarks but rather to all mapped morphologies within the area of interest. However, for scientific manuscripts including morphometric analysis of individual pockmarks, we added this information to the "Notes" layer of our database.

Technical Validation

All pockmark information were manually tabulated in the database and independently verified by authors consulting all the references (indicated in the database). Comprehensive validation procedures were implemented to ensure the reliability of the dataset, including meticulous examination of published metadata in public repository of meta data (i.e. EMODnet Bathymetry). To identify and eliminate potential outliers and/or duplicates, we analysed the spatial distribution and morphological characteristics of each pockmark by georeferencing all recorded occurrences. Any future updates will undergo the same rigorous technical validation protocol described above.

Usage Notes

Future geodatabase development. The geodatabase produced within this work is designed to be an active and evolving entity, open to contributions and feedback from the scientific community. While it is based at its core on published data previously existent that are necessarily of restricted detail at the scale of individual pockmarks, its value resides within the scale-averaged build-up of data within pockmark clusters. As outlined in the "Objectives" section, such a database has various uses, some of which include offshore infrastructure planning and risk evaluation, as well as offshore groundwater reservoir exploration, which is an increasingly important target in regions such as the Mediterranean, where freshwater resources are dwindling. Despite its initial limitations, the geodatabase provides a structural framework which can be useful to applied and scientific research.

Future developments will aim to include missing (e.g. morphometric analysis) or underrepresented data, add newly found pockmarks, and expand the data set to encompass geophysical, geotechnical, geochemical, and biological data. Development of this tool will continue to depend on active participation of the scientific community through sharing data and collaborative research.

Code availability

No customized code was produced to create or analyse this dataset[40]. Specifically, we used ArcGIS software to create the dataset, however our inventory can be opened with any GIS software (open-sourced or licensed).

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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.

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