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A model-estimation of gas overpressure in gas saturated layers in a volcanic setting: a case study from the Banco della Montagna (Naples Bay, Italy)

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***Abstract* – The 5 km wide Banco della Montagna (BdM) morphological high is located on the seafloor of Naples Bay (Tyrrhenian Sea, Italy) and is characterized by a hummocky surface. Oceanographic surveys revealed active fluid vents at BdM. High-resolution mono-channel seismic and multibeam bathymetry allow us to define the detailed morphology and the inner geometry of BdM, which consists of a complex set of dome-like structures (pagodas) affecting the present-day seabed. We suggest that a gas-water-sand sediment mixture upraises from a gas saturated layer pushing up the overlying marine deposits and forming mounds, folds, and faults. According to a thin-plate elastic model, we estimate the fluid (gas) pressure Pdef required to form BdM and obtain Pdef = 0.3 Pa, a value consistent with that for doming processes in gas-hydrate settings. At BdM, the pressure ΔP required to break the seabed is in the order of 2-3 MPa, while the gas column height is about 240 m.**

I. INTRODUCTION

Deep-sea hydrothermal fluid (thermal waters and gases) discharges are a common feature of mid-ocean ridges and convergent plate margins, whereas cold emissions of gas hydrates (chlatrates) generally characterize continental shelves and passive margins [1]. The less common occurrence of submarine hydrothermal discharges in coastal areas implies a heat source (magma reservoir) within the continental crust and/or the mantle. These discharges may be due to shallow intrusion and/or precede magma upraising through the uppermost level of the crust and, ultimately, eruptions and emplacement of volcanic seamounts[2]. Therefore, the recognition of (a) morphologies related to active deformation of the seabed and (b) hydrothermal emissions near inhabited coastal areas is of primary importance for an evaluation of the hazard related to possible volcanic activity at shallow depth.

Here, we present bathymetric, seismic, water column and geochemical data on a submerged, morphologically and structurally complex area affected by gas emissions located in the Gulf of Naples (southern Italy), about 5 km offshore from Naples (about 1 million inhabitants). We describe and interpret the seafloor morphology and subsurface structures where the hydrothermal gas discharges occur, discuss the origin of the discharged fluids, and identify and parameterize the mechanisms that regulate the gas upraising and the associated deformations.

II. GEOLOGICAL SETTING

The Gulf of Naples forms part of the western margin of the Plio-Quaternary, NW-SE elongated Campanian Plain structural depression[3]. The gulf is confined to the north by the E-W arranged, active volcanoes of Ischia Island (from about 150 ka to 1302 AD), Campi Flegrei caldera (from about 300 ka to 1538 AD), to the east by the Somma-Vesuvius volcano (from < 360 ka to 1944 AD) [3 and reference therein], while to the south it is bordered by the Sorrento Peninsula, made of sedimentary bedrock (Fig. 1). The Gulf of Naples is affected by prevailing NE-SW and second-order NW-SE striking faults. Ischia, Campi Flegrei and Somma-Vesuvius are characterized by hydrothermal manifestations, ground deformations, and shallow seismicity. The volcanic activity in the last 36 ka at Campi Flegrei and 18 ka at Somma Vesuvius, and the sea level oscillations have controlled the depositional system in the Gulf of Naples[4]. A lowstand of the sea level during the last

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glacial maximum (18 ka) produced a seaward shift of the paralic-shallow water depositional systems, while during the Late Pleistocene-Holocene sea-level rise the gulf was filled by transgressive sediments. Submarine gas emissions were recognized around Ischia Island and offshore near the coast of Campi Flegrei and Somma-Vesuvius.

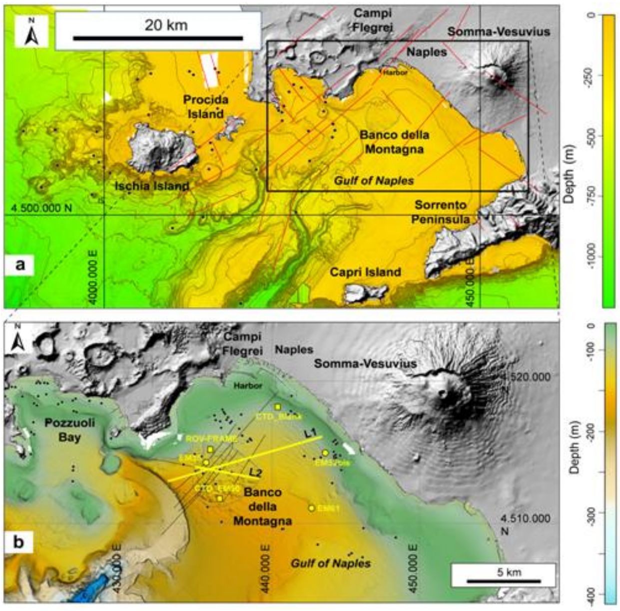

Fig. 1. a) Morphological and structural arrangement of the continental shelf and Gulf of Naples. Dots are the main submarine eruptive centers; the red lines represent the main faults. b) Bathymetry of the Gulf of Naples with the detected fluid vents (dots) and the trace of the seismic lines (black lines). Yellow lines are the traces of the seismic lines L1 and L2 reported in Fig. 6. The boundary of the Banco della Montagna (BdM) dome-like structure is marked by a bleu dashed line in a) and b). Yellow squares mark the location of the acoustic water column profile, CTD-EMBlank, CTD-EM50, and ROV frame reported in Fig. 5. Yellow circles mark the location of the sampled gas discharges, whose composition is reported in Table 1.

III. DATA AND RESULTS

The Gulf of Naples Digital Terrain Model (DTM) shows that the seafloor south of the harbor of Naples is characterized by a southward facing, gently dipping (slope < 3°) surface interrupted by a 5.0 x 5.3 km dome-like structure, locally known as Banco della Montagna (BdM). BdM develops between about 100 and 170 m depth and it is 15-20 m higher than the surrounding seafloor. BdM dome shows a hummocky morphology due to 280 sub-circular to elliptical mounds, 665 cones, and 30 pockmarks (Figs. 2 and 3). The maximum height and perimeter of the mounds is 22 m and 1,800 m, respectively. The circularity of the mounds decreases as the perimeter increases (Fig. 2b). The axial ratio of the mounds ranges between 1 and 6.5, with 15%) < 2 (Fig.2c). Those mounds with axial ratio > 2 show a preferred N45°E$\pm$15° strike and a second-order, more dispersed, N105°E to N145°E strike (Fig. 2c). Single or aligned cones occur on the BdM flat surface and on the top of mounds. The spatial density of the cones and pockmarks evidences major NE-SW alignments and less extended NW-SE alignments.

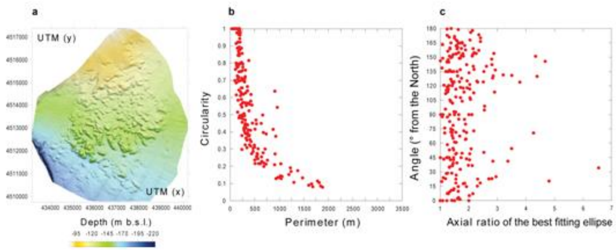

Fig. 2. a) Digital Terrain Model (1 m cell size) of the Banco della Montagna (BdM) dome. b) Perimeter vs. Circularity of the BdM mounds. C) Axial ratio vs. angle (orientation) of the major axis of the best fitting ellipses encircling the mounds.

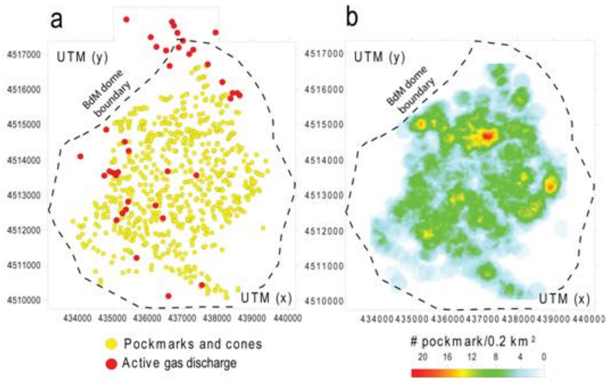

Fig. 3. a) Spatial distribution of the detected craters, pockmarks and active gas discharges on the BdM (boundary reported from the DTM of Fig. 2). b) Spatial density (number/0.2 km^2) of the craters and pockmarks reported in a).

We recognize 37 gas emissions in the BdM area from echo-sounder images of the water column and direct observations on the sea bottom with ROV (Fig. 4b). The observed streams are highly variable: from a continuous, dense bubble-flux to short-lived phenomena. The pH values in the water column just above the discharge sites show a significant drop indicating local more acidic conditions (Fig. 4c). Significant variations of the seawater temperature and salinity between the BdM emissions and other sites in the Gulf of Naples are not recorded (Figs 4c, 4d).

The gas samples collected from the study area show a similar composition, largely dominated by CO_2 (934-945 mmol/mol). Light hydrocarbons, whose sum ranges from 0.24 to 0.30 mmol/mol, consist of C2-C4 alkanes, aromatics (mainly benzene), propene and S-bearing compounds (thiophenes). Seismic profiles show the transition between BdM and the distal stratigraphic sequences of Somma-Vesuvius and Campi Flegrei volcanic areas (Fig. 5).

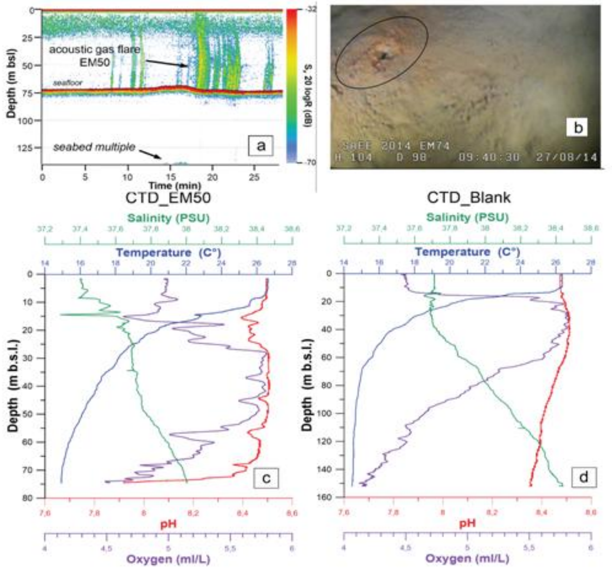

Fig. 4. a) Acquisition window of an acoustic water column profile (echosounder Simrad EK60). Vertical green bands corresponding to gas flares detected on the EM50 fluid emission (ca 75 m below sea level) located in the BdM area; seabed multiple signal on the bottom and seafloor are also shown. b) Single photo collected with a Remote Operated Vehicle in the BdM area showing a small crater surrounded by red to orange sediments (black circle). c) and d) Multi-parameters probe CTD data processed with the SBED-Win32 software (Seasave, version 7.23.2). Patterns of selected parameters (Salinity, Temperature, pH and Oxygen) of the water column above the fluid emission EM50 (panel c) and outside the Bdm discharge area (panel d).

BdM is characterized by the presence of two main seismo-stratigraphic units (MS and PS; Fig. 5b). The uppermost one (MS) shows sub-parallel reflectors of high to medium amplitude and lateral continuity. This unit includes the post-Last Glacial Maximum systems tract marine deposits, which consist of sands and clays[5,6]. The underlying PS layer is characterized by a chaotic to transparent facies and shows a columnar or hourglass shape. The PS apical tips occasionally correspond to the seabed mounds. These diapir-like geometries testify the rising up of the PS transparent material across the superjacent MS deposits. This upraising locally produces folds and faults in the MS deposits. Gravity cores collected at the top of BdM in correspondence of the transparent seismic layer show that the uppermost 40 cm of the sea-floor sub-bottom consist of recent to presently depositing sands, and the underlying succession is made up of these sands chaotically mixed with pumice fragments ascribable to the 11.9 to 14.8 ka old pumices form explosive eruptions of Campi Flegrei [6].

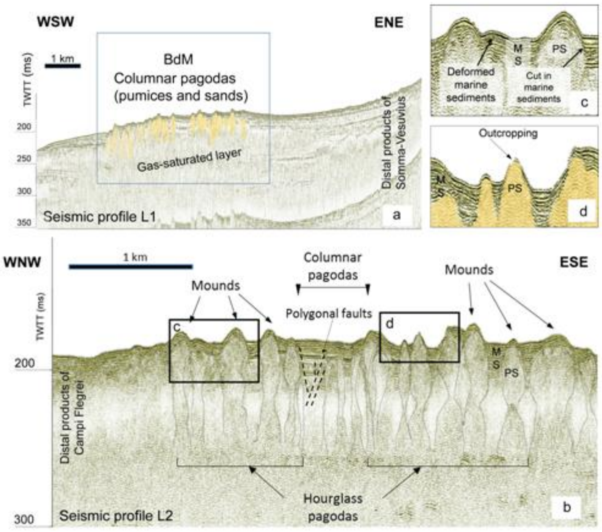

Fig. 5. a) Mono-channel seismic profile L1 (navigation track in Fig. 1b) showing the spatial arrangement of columnar shapes (pagodas). Pagodas are made up of chaotic sediments constituted, as revealed by gravity coring, by pumices and sands. The presence of a gas-saturated layer below the pagodas obliterates the continuity of the deeper stratigraphic layers. b) Mono-channel seismic profile L2 (navigation track in Fig. 1b) with highlighted seafloor mounds, offset and folding of the marine (MS) and pumice-sand sediments (PS). (c) Detail of the deformations in MS and PS are reported in c) and d).

IV. DISCUSSION

The morphological and structural features of BdM are similar to those of other submarine hydrothermal and gas hydrate fields worldwide[7] and commonly associated with the upraising (doming and mounds) and discharge (cones, pockmarks) of fluids. The spatial arrangement of the mounds, pockmarks, and active vents indicate that their emplacement is partly controlled by NW-SE and NE-SW striking fractures. These are the preferred strikes of the fault systems affecting the Campi Flegrei and Somma-Vesuvius volcanic areas and the Gulf of Naples. Therefore, we conclude that the faults and fractures of the Gulf of Naples represent the preferred pathway for the fluid migration to the surface.

The three collected gas discharges show chemical features typically recognized in hydrothermal fluids, i.e. predominance of CO_2 and significant concentrations of reduced gases and light hydrocarbons. According to the above reported data and to the results of experimental models on dome-like structures associated with submarine fluid-rich areas, fluid pressurization at depth is likely responsible for the formation of the km-scale BdM dome. In order to provide an estimate of the overpressure P_{def} responsible for the BdM doming, we applied a thin-plate mechanical model assuming that the dome is a sub-circular thin plate with a radius a larger than the vertical maximum displacement w and thickness h of the deformed soft cohesive sediments. P_{def} represents the differences between the total pressure and the lithostatic pressure plus the pressure of the water column. At BdM, the radius is about 2,500 m, w is 20 m, and the maximum value of h estimated from the seismic profiles is in the order of 100 m. We calculate P_{def} from the relation $P_{def} = w\ 64\ D/a^4$, where D is the flexural rigidity; D is given by $(E\ h^3)/[12(1 - \nu^2)]$, where E is the Young's modulus of the sediments and ν is Poisson's ratio (~0.5). Since measurements of the mechanical properties on the BdM sediments are not available, we set E= 140 kPa, which is a reasonable value for coastal sediments. We obtain P_{def} = 0.3 Pa, a value consistent with that estimated for seafloor doming processes in gas-hydrate basin settings. At BdM, a possible decrease in stiffness due to localized gas saturation of the sediments and/or the occurrence of pre-existing fractures could also promote failure and consequent gas release, thus allowing the formation of the observed venting structures. The collected seismic profiles (Fig. 5) show that PS sediments upraise from a gas-saturated layer (GSL) pushing up the overlain MS marine deposits, thus generating mounds, folding and sedimentary cuts. This suggests that the 14.8 to 12 ka old pumices intrude the younger, MS layers by upward gas migration process. The morphological features of the BdM structures can be regarded as the result of the overpressure generated by fluid emissions arising from the GSL. The upward migration of gas within the sediments has also the effect to scrub the materials included in MS, thus explaining the presence of chaotic sediments in the gravity cores sampled over BdM25. In addition, a complex fracture system is spawned from the overpressure in GSL. Overall, this morphological, structural and stratigraphic settlement is known as 'pagoda' [8]. Therefore, the growth mechanism of the BdM pagodas is likely governed by the gas upraising and accumulation within the sediment, and the pagoda formation is controlled by a decrease in the density of the soft sediments as gas enters from below. The vertical extent of the pagodas is, on average, 70-100 m. Owing to the presence of MS undulations, and taking into account the stratigraphy of the BdM gravity cores, we infer that the rising of pagoda structures was younger than about 14-12 ka and it is still active. The pagodas not crossing the present-day seabed suggest that (a) the gas upraising and/or gas-sediment mixing locally stops, and/or (b) a lateral flow of the gas-sediment mixture does not allow local overpressurization processes. According to theoretical models of diapirism, a lateral flow testifies a negative balance between the sediment-gas mixture supply rate from below and the rate of the upward movement of the pagoda. A decrease of the supply rate could be associated with an increase in the density of the mixture due to vanishing gas supply. The above-summarized results, and the buoyancy-controlled uprising of pagodas allow us to estimate the gas column height hg. The buoyancy is given by $\Delta P = hg\ g\ (\rho w - \rho g)$, where g is the gravity (9.8 m/s^2), and ρw and ρg are the water and gas densities, respectively. ΔP is the sum of the previously calculated P_{def} and the lithostatic pressure P_{lith} of the sediment plate, which is $\rho s\ g\ h$, with ρs the sediment density. In this context, the value of hg needed for the required buoyancy is given by $hg = (P_{def} + P_{lith})/[g\ (\rho w - \rho g)]$. At BdM, we set P_{def} = 0.3 Pa and h=100 m (see above), ρw = 1,030 kg/m^3, ρs = 2,500 kg/m^3, A negligible ρg because $\rho w >> \rho g$. Using these values, hg is 245 m. At BdM, ΔP is in the order of 2.4 MPa. This value is, on average, one order of magnitude higher than that required to generate gas-hydrated dome-like structures; it accounts for the overpressure required to break the BdM seafloor and form degassing vents.

V. CONCLUSIONS

A 25 km^2 wide dome-like structure affected by active degassing occurs in Gulf of Naples few kilometers offshore from the city of Naples. The gas composition is consistent with a mantle source modified by the addition of crustal fluids. The rough E-W alignment of the BdM dome and of the active volcanoes of Ischia, Campi Flegrei, and Somma-Vesuvius, along with the composition of the discharged gases, suggests that a unique long-lived magma pool occurs beneath the whole Neapolitan area. At present, the BdM features are indicative of a non-magmatic unrest potentially foregoing embryonic volcanism, i.e. the early emission of magma and/or hot fluids. A monitoring activity should be implemented with the aim to analyze the evolution of the phenomena with time and evaluate the hazard related to possible hydrothermal explosions or shallow-water volcanic eruptions.

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