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Pockmark morphology and turbulent buoyant plumes at a submarine spring

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ABSTRACT

The input flow of groundwater from the seabed to the coastal ocean, known as Submarine Groundwater Discharge (SGD), has been only recently recognized as an important component of continental margin systems. It potentially impacts physical, chemical and biological marine dynamics. Independently of its specific nature (seepage, submarine springs, etc.) or fluid chemical composition, a SGD is generally characterized by low flow rates, hence making its detection and quantification very difficult, and explaining why it has been somewhat neglected by the scientific community for a long time. Along with the growing interest for SGDs emerged the need for in-situ observations in order to characterize in details how these SGDs behave. In this work, we describe the morphology of a pockmark field, detected in the Southern Tyrrhenian Sea (Mediterranean Sea), and provide observational evidences of the presence of active submarine springs over the coastal shelf area. We describe the effect of the fluid seeps on the water column stratification close to the main plumes and in the neighbouring areas, providing quantitative estimates of the intensity of the turbulent mixing and discussing their potential impact on the seabed morphology and pockmark formation in the context of turbulent buoyant plumes analytical modelling.

1. Introduction

The existence of submarine sources of groundwater has been documented for centuries, recognizing their potential relevance for freshwater management issues (e.g. Moore, 2010). However, information on submarine springs were never collected and organized consistently and, for a long time, the scientific community has almost neglected their eventual effects on the coastal environment and potential impacts on coastal dynamics. While this was mainly due to the difficulty in identifying and measuring submarine sources of water of terrestrial origins, a number of studies have highlighted their importance in coastal hydrology, based on modern technologies and/or modelling (e.g. Taniguchi et al., 2003; Lambert and Burnett, 2003; Moore, 1996, 2003; Oberdorfer, 2003; Smith and Zawadzki, 2003; Destouni and Prieto, 2003).

Despite the fact that Submarine Groundwater Discharge (SGD) is estimated to account only for a few percent of the total freshwater flux in the global oceans, mainly occurring through river input and precipitations, springs and diffuse seepage through the sea floor can still represent important contributions to the coastal ecosystem (Zhang and Mandal, 2012). Indeed, SGD not only brings fresh (or less saline) waters through usually undetected pathways, but it can also affect chemical composition of sea water, due to both anthropogenic land use and natural interactions with aquifer and sediments. Coastal SGD can also be contaminated by fertilizers, pesticides or industrial wastes, as well as by sewage and other pathogen substances, potentially diffusing pollution to the ocean, with potentially devastating effects on local ecosystems and related economies (e.g. Laroche et al., 1997; Gobler and Sanudo-Wilhelmy, 2001). SGD can also modify the nutrient availability along the water column (e.g. Slomp and Van Cappellen, 2004) as well as benthic habitats, and low-salinity input may create particular habitats on the sea floor, especially for fishery stock. Besides, Rodellas et al. (2015) have highlighted the importance of SGD as a source of nutrients to the Mediterranean Sea, demonstrating that SGD involve a large volume of freshwater, actually larger in magnitude than riverine discharge. They indicate that SGD represents a major source of dissolved inorganic nitrogen, phosphorous, and silica to the oligotrophic Mediterranean Sea, with relevant impact on the Mediterranean primary productivity.

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Despite a growing recognition of the importance of SGD (UNESCO, 2004; Moore, 2010), only a partial quantification and chemical characterization of known SGD has been carried out (e.g. Burnett et al., 2006), and a complete identification of SGD areas along with an evaluation of their impacts on local ecosystems, water stratification and coastal dynamics, as well as on seabed morphology, are still lacking.

Several indirect potential indicators of SGD have been suggested, based on water colour, temperature, salinity or some other geochemical fingerprint, but not yet routinely applied (see also Bokuniewicz et al., 2003 and references therein). Salinity anomalies, in particular, have been used to detect submarine freshwater seeps looking either at regional water budgets or vertical profiles at specific locations (e.g., Johannes and Hearn, 1985; Valiela et al., 1990).

Pockmarks are among the most common manifestations of fluid flow from the subsurface to the seafloor and may occur also in the subsurface as buried and stacked features, in presence of persisting fluid migration through preferential pathways (Andresen and Huuse, 2010). They consist of concave, crater-like depressions in the seabed, almost ubiquitous along continental margins and in lakes (Judd and Hovland, 2007; Moss et al., 2012; Loher et al., 2016). Generally, pockmarks are associated with fast buoyant fluid flows (fresh-water submarine springs or fluid seeps) typically found in submerged areas constrained by karst topography or by a fractured limestones bedrock (Roxburgh, 1985; Fleury et al., 2007), along continental margins in presence of gas-hydrates decomposition, hydrocarbons (Solheim and Elverhøi, 1985; Pau et al., 2014) or pore-fluid expulsion (Harrington, 1985; Lafuerza et al., 2009;), and in volcanic areas with residual hydrothermal activity (Passaro et al., 2014; Tudino et al., 2014; Ingrassia et al., 2015). Understanding their formation and morphodynamical behaviour has been a major challenge since their first discovery (King and MacLean, 1970), in particular for the hazard-related concerns, for their relevant role in hydrocarbons exploitation issues, and for being indicators of methane release to the oceans (e.g. Judd and Hovland, 2007). A variety of mechanisms have been proposed, which involve either continuous processes (seeps) or rapid and sudden events of episodic releases and blowout (vents) of fluids (e.g. Marcon et al., 2014; Loher et al., 2016). These include:

- suspension of fine-grained sediment with low sediment/water ratio, by ascending fluid drags and formation of a coarse-grained lag deposits, ensuing removal of fines from the pockmark rims through bottom water currents (Cartwright et al., 2007; Cathles et al., 2010);
- localized collapse after emptying of a fluid reservoir in the subsurface, even by discrete blowout events (Cartwright et al., 2007), with a volume loss (Leon et al., 2010; Wessels et al., 2010, Cartwright and Santamarina, 2015),
- sediment fluidization (liquefaction) and ensuing volume compaction of particles, induced by fluid seeps or vents (Draganits and Janda, 2003);
- development of a syn-sedimentary, self-regulated process, growing vertically during prolonged fluid seeps, between particles settlement and fluid pressure drag, that promote the coarser grains to deposit in the space above the plume site;
- decrease of the shear strength of the matrix by ascending fluid flow through sediments and preferential erosion caused by strong bottom currents, including episodic storm surges (Schlüter et al., 2004).

Pockmark maintenance is thus generally accompanied by significant sediment redistribution in the surrounding seabed. Observations (Draganits and Janda, 2003; Schlüter et al., 2004) and numerical models (Hammer et al., 2009; Brothers et al., 2011) suggest that pockmarks can be maintained and reshaped through vertical flow and seabed currents, in stormy- or tidally-controlled conditions (Fandel et al., 2017). Simulations in scaled laboratory tests, indeed, have proved that seabed currents are deflected by pockmarks depression and have a role in modifying pockmarks' original shape through time (Pau et al., 2014). Loher et al. (2016) assert that sediment remobilization and spill over the rims of the pockmarks is accounted for by the switch from 'quiescent' to 'eruptive' activity mode of rising fluids. In any case, a fine-grained sediments medium (clayey silt or silty clays) is needed to support their structure and long-time existence (Papatheodorou et al., 1993).

Pockmarks are often clustered around two main dimensional classes within the same field (Hustoft et al., 2010; Wessels et al., 2010; Moss et al., 2012), possibly reflecting different hydrodynamic regimes and mechanisms behind the initial stage of pockmark development (Riboulot et al., 2016). The smaller elements are generally composed by unit pockmarks whose diameters average around 18–20 m, normally not exceeding 40 m, and depths attains around 3.5–5 m, with flanking slopes 3° to > 6° steep; their geometry is near circular and aspect ratio of 1:1.5. The wider elements cluster around 350 m in diameter within a dimensional range of 100–700 m and 10–50 m deep, with planform geometries ranging between circular to highly-elliptical and average aspect ratio up to 1:3.7 (Moss et al., 2012). The pockmarks density and spatial distribution appears to be attributable to differences in shallow fluids availability and deeper geology controlling fluid migration pathways (Gafeira et al., 2012).

In this work, we investigated the presence and effect of submarine springs in a coastal shelf area initially surveyed during CARG CMS03 (CARtografia Geologica, GeoMare Sud −2003) campaign and successively monitored during the ARCOSE (Age and Recurrence of Campania Offshore Slide Events) cruise, both carried out by the Istituto per l'Ambiente Marino Costiero (IAMC) of the Research National Council of Italy (CNR). ARCOSE survey was carried out in September 2010 in the Southern Tyrrhenian Sea (Mediterranean Sea) and was mainly devoted to the acquisition of geophysical data and hydrographic profiles. The observations revealed the presence of characteristic pockmarks in the Gulf of Policastro (Figs. 1–3). Conductivity Temperature Depth (CTD) profiles were collected in correspondence of each of these pockmarks and in the area close to Punta Infreschi (Fig. 1). Unfortunately, a more regular and wider mapping of the hydrographic parameters in the area was not possible due to a combination of adverse weather conditions and time constraints. Available data allowed to identify which submarine springs were effectively active and made it possible to characterize the dynamics governing the mixing of groundwater with surrounding marine waters. Satellite data showed that the area considered is characterized by very low mean surface currents with low variance (Rinaldi et al., 2010), so that preferential erosion due to strong currents along the shelf can be reasonably excluded. As a consequence, a consistent scenario for the mechanisms creating and maintaining the pockmarks has been proposed by comparing the observations with the results of an analytical model describing the evolution of turbulent buoyant plumes in a stably stratified environment with a distinct vertical structure in the background salinity and temperature field.

2. Geographical and geological setting

The study area is located off the Cilento coast (Southern Italy), a mountainous region belonging to the fold and thrust belt of the Southern Apennines (Mostardini and Merlini, 1986), with a mean elevation of 450 m asl and mean annual precipitations exceeding 1800 mm, in 1951–1980 time span (Desiato et al., 2014).

The wide outcrops of carbonate deposits, part of the Bulgheria-Verbicaro and Albuno-Cervati Units, and clayey-marly flysch succession belonging to the Liguride Unit (Bonardi et al., 2009; Ciarcia et al., 2009), constitute the ideal ground for the development of large karst aquifers along the coast (Cotecchia et al., 1990). Indeed, the peculiar geology of the subsurface (high permeability due to karstic cavities and tectonic fracturation) and the position of watershed seem to favour the dispersion at sea of large amount of underground water towards two preferential coastal sectors (Fig. 1). Besides, the hydrogeological balances of the phreatic aquifers document the loss at sea (Allocca et al., 2007).