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Methane fluxes and carbonate deposits at a cold seep area of the Central Nile Deep Sea Fan, Eastern Mediterranean Sea

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ABSTRACT

High acoustic seafloor-backscatter signals characterize hundreds of patches of methane-derived authigenic carbonates and chemosynthetic communities associated with hydrocarbon seepage on the Nile Deep Sea Fan (NDSF) in the Eastern Mediterranean Sea. During a high-resolution ship-based multibeam survey covering a ~225 km^2 large seafloor area in the Central Province of the NDSF we identified 163 high-backscatter patches at water depths between 1500 and 1800 m, and investigated the source, composition, turnover, flux and fate of emitted hydrocarbons. Systematic Parasound single beam echosounder surveys of the water column showed hydroacoustic anomalies (flares), indicative of gas bubble streams, above 8% of the high-backscatter patches. In echosounder records flares disappeared in the water column close to the upper limit of the gas hydrate stability zone located at about 1350 m water depth due to decomposition of gas hydrate skins and subsequent gas dissolution. Visual inspection of three high-backscatter patches demonstrated that sediment cementation has led to the formation of continuous flat pavements of authigenic carbonates typically 100 to 300 m in diameter. Volume estimates, considering results from high-resolution autonomous underwater vehicle (AUV)-based multibeam mapping, were used to calculate the amount of carbonate-bound carbon stored in these slabs. Additionally, the flux of methane bubbles emitted at one high-backscatter patch was estimated (0.23 to 2.3 × 10^6 mol a^{-1}) by combined AUV flare mapping with visual observations by remotely operated vehicle (ROV). Another high-backscatter patch characterized by single carbonate pieces, which were widely distributed and interspaced with sediments inhabited by thiotrophic, chemosynthetic organisms, was investigated using in situ measurements with a benthic chamber and ex situ sediment core incubation and allowed for estimates of the methane consumption (0.1 to 1 × 10^6 mol a^{-1}) and dissolved methane flux (2 to 48 × 10^6 mol a^{-1}). Our comparison of dissolved and gaseous methane fluxes as well as methane-derived carbonate reservoirs demonstrates the need for quantitative assessment of these different methane escape routes and their interaction with the geo-, bio-, and hydrosphere at cold seeps.

1. Introduction

Seafloor hydrocarbon seeps characterized either by release of bubble-forming free gas or by diffusive fluid flow are widespread on continental margins. They are known from diverse geological settings and morphological structures and may be restricted to individual structures such as mud volcanoes (e.g. Dimitrov, 2002; Etiope and Milkov, 2004; Greinert et al., 2006), or widely distributed over large areas as at a paleo-fan system in the Black Sea (e.g. Naudts et al., 2008; Greinert et al., 2010). However, quantitative data allowing to evaluate their role in the carbon cycling and partitioning between the geo-, bio-, and hydrosphere is rare. In particular, flux estimates for methane discharge from deep-water seeps are lacking (mainly due to their low accessibility). In addition, most flux-related studies were focused on single fluid pathways, such as gaseous methane emissions (e.g. Leifer and MacDonald, 2003; Sahling et al., 2009; Römer et al., 2012a,b) or dissolved fluid flows (e.g. Linke et al., 2005; Felden et al., 2010; Lichtschlag et al., 2010; Sommer et al., 2010). To our knowledge only few studies comparing both pathways are available, so far. For instance, Sauter et al. (2006) calculated gas fluxes from the Håkon Mosby mud volcano on the Barents Sea slope and Torres et al. (2002) reported fluxes from Hydrate Ridge at Cascadia Margin, both representing very different seep sites with regard to geological setting and areal extent.

Numerous fluid seepage-related seafloor features, including mud volcanoes, pockmarks and mounds, brine lakes and authigenic methane-derived carbonates, are known from the Nile Deep Sea Fan (NDSF, Fig. 1) (e.g. Loncke et al., 2004, 2006; Dupré et al., 2007, 2010; Gontharet et al., 2007; Bayon et al., 2009b). Several of them have been

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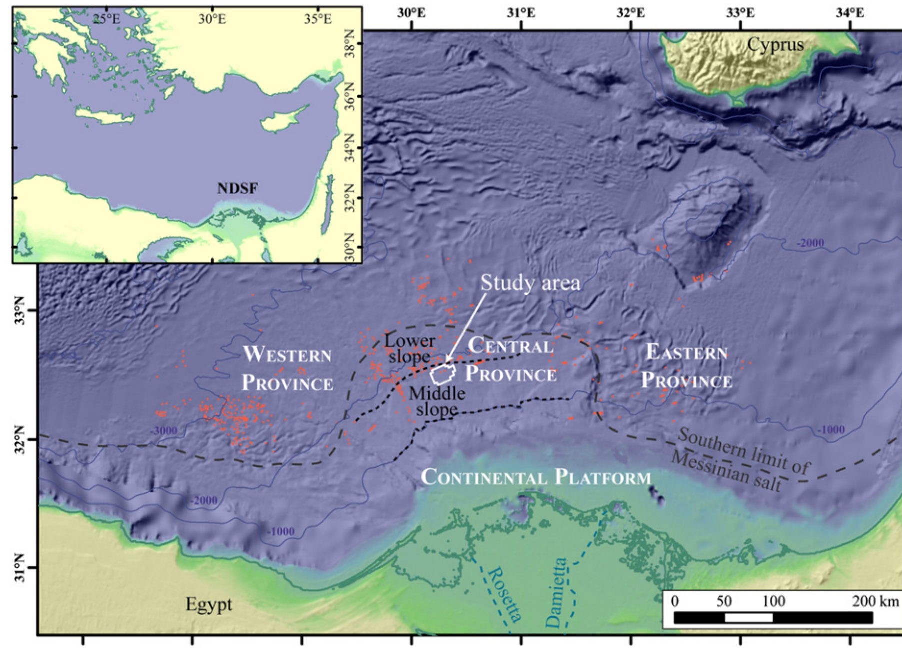

Fig. 1. Shaded bathymetry of the Nile Deep Sea Fan (NDSF), and the Egyptian continental platform from a compilation of GEBCO-data and ship-based swath echosounder data of several cruises (courtesy of Ifremer). The fan is divided into the Western, Central, and Eastern Provinces according to their morphological characteristics (Loncke et al., 2004). The study area is located at the middle slope landward of the southern limit of Messinian salt depicted by the dashed line (Loncke et al., 2009). Red dots represent areas showing high-seafloor backscatter (depicted from Loncke et al., 2004).

shown to emit methane into the hydrosphere, and to support benthic chemosynthetic life and biodiversity hotspots (Girnth et al., 2011; Grünke et al., 2011; Ritt et al., 2011; Felden et al., 2013). The present study concentrates on a particular type of seepage-related seafloor features that are characterized by high amplitudes in hydroacoustic backscatter maps, in the following termed 'high-backscatter patches'. Compared to the mud volcanoes of the NDSF such as Cheops, North Alex, Osiris, Isis, or Amon (e.g. Dupré et al., 2008; Feseker et al., 2008; Huguen et al., 2009; Feseker et al., 2010; Felden et al., 2013; Bayon et al., 2013) high-backscatter patches on flat seafloor areas of the NDSF have gained less attention. However, from precise bathymetric and backscatter maps, hundreds if not thousands of high-backscatter patches have been identified of extensive parts of the NDSF (Loncke et al., 2004, red dots in Fig. 1). Submersible investigations in different NDSF provinces have demonstrated that high backscatter is caused by the dense occurrence of methane-derived authigenic carbonates, which are regarded as manifestations of former and current fluid seepage (Loncke et al., 2004; Zitter et al., 2005; Bayon et al., 2009b; Dupré et al., 2010). A strong relation between high seafloor-backscatter and presence of authigenic carbonates was also observed at other hydrocarbon seep areas, e.g. off California (Orange et al., 2002), at Hydrate Ridge (Johnson et al., 2003), in the lower Congo Basin (Gay et al., 2007), at the Hikurangi margin off New Zealand (Klaucke et al., 2010) as well as in the northwestern (Naudts et al., 2008) and eastern Black Sea (Klaucke et al., 2006). However, the sizes, shapes, and abundances of high-backscatter patches in the different (sub-) provinces of the NDSF vary considerably, suggesting that their genesis is controlled by differences in the tectonic and sedimentological regimes influencing the fluid flow processes (Loncke et al., 2006; Bayon et al., 2009b; Dupré et al., 2010). Previous deep-towed sidescan sonar surveys at two sub-regions within our study area (Dupré et al., 2010, their Figs. 12 and 13) showed rising gas bubbles into the water column from high-backscatter patches indicative for intense hydrocarbon seepage. Stable carbon isotopic compositions and lipid biomarker distribution patterns of carbonate crusts collected from the seafloor at one high-backscatter patch (Gontharet et al., 2007, 2009; Bayon et al., 2009a) showed that the carbonates have formed via the anaerobic oxidation of methane (AOM).

A major objective of our study was to quantify hydrocarbon fluxes associated with high-backscatter patches at the middle slope of the Central Province of the NDSF (Fig. 1). In addition, we studied the source and composition of hydrocarbons by sampling gas emissions at the seafloor. At most cold seep systems a substantial amount of the hydrocarbon fluxes is consumed already in the sediments in the process of AOM (Hoehler et al., 1994; Boetius et al., 2000). AOM increases the alkalinity in the pore space eventually leading to precipitation of authigenic carbonates (Ritger et al., 1987). It also produces hydrogen sulfide providing the energy for chemosynthesis-based organisms thriving at the seeps such as sulfur-oxidizing filamentous bacterial mats, clams, and vestimentiferan tubeworms (Sibuet and Olu, 1998; Sahling et al., 2002; Sommer et al., 2006). Combining different biogeochemical methods we compared the amounts of methane consumed microbially in the seafloor to the total methane efflux occurring as free bubble-forming gas or dissolved in seeping fluids.

2. Regional setting

The NDSF is an extensive sedimentary wedge in the Southeastern Mediterranean Sea (Fig. 1). The sedimentary fan sequence formed since the Late Miocene (Salem, 1976) and is mainly composed of terrigenous sediments delivered from the Nile River. The modern drainage is dominated by two main fluviatile transport pathways: the Rosetta branch in the western part and the Damietta branch in the eastern part of the continental platform (Loncke et al., 2009; Fig. 1). At the foot of the deltaic platform a capacious deep-sea fan has been formed.

The morphology of the NDSF is mainly controlled by the interaction of various sediment deposition and relocation processes, such as turbidites, slumps, debris flows, and of salt tectonics (Gaullier et al., 2000; Mascle et al., 2000; Loncke et al., 2002, 2006), involving large quantities of evaporites that precipitated during the Messinian salinity crisis (Hsu et al., 1977; Ryan, 1978). Gravity-induced gliding of salt and sliding of