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Deflection of natural oil droplets through the water column in deep-water environments: The case of the Lower Congo Basin

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A B S T R A C T

Numerous recurrent seep sites were identified in the deep-water environment of the Lower Congo Basin from the analysis of an extensive dataset of satellite-based synthetic-aperture radar images. The integration of current data was used to link natural oil slicks with active seep-related seafloor features. Acoustic Doppler current profiler measurements across the water column provided an efficient means to evaluate the horizontal deflection of oil droplets rising through the water column. Eulerian propagation model based on a range of potential ascension velocities helped to approximate the path for rising oil plume through the water column using two complementary methods. The first method consisted in simulating the reversed trajectory of oil droplets between sea-surface oil slick locations observed during current measurements and seep-related seafloor features while considering a range of ascension velocities. The second method compared the spatial spreading of natural oil slicks from 21 years of satellite monitoring observations for water depths ranging from 1200 to 2700 m against the modeled deflections during the current measurement period. The mapped oil slick origins are restricted to a 2.5 km radius circle from associated seep-related seafloor features. The two methods converge towards a range of ascension velocities for oil droplets through the water column, estimated between 3 and 8 $cm\,s^{-1}$. The low deflection values validate that the sub-vertical projection of the average surface area of oil slicks at the sea surface can be used to identify the origin of expelled hydrocarbon from the seafloor, which expresses as specific seafloor disturbances (i.e. pockmarks or mounds) known to expel fluids.

1. Introduction

Natural hydrocarbon seeps occur along most continental margins (Wilson et al., 1973; Levy and Ehrhardt, 1981; MacLean et al., 1981; Becker and Manen, 1988; Kvenvolden and Cooper, 2003; Zatyagalova et al., 2007; Jauer and Budkewitsch, 2010; Körber et al., 2014; Suresh, 2015; Jatiault et al., 2017).

For environmental purposes, understanding the dynamic behavior of the oil plume is crucial for emergency response to oil spills (Spaulding, 1988; Reed et al., 1999; Price et al., 2006; Leifer et al., 2006, 2012; Chen et al., 2007; MacFadyen et al., 2011; Fingas and Brown, 2014; MacDonald et al., 2015). Defining the rise path of the oil helps to target probable areas affected by environmental damage due to anthropogenic spills (Chen et al., 2015; Korotenko, 2016). For scientific expeditions and exploration campaigns, understanding the rise paths of the oil plume is of prime importance to link sea surface natural oil slicks to their origin on the seafloor (Crooke et al., 2014). The targeting and inventorying of seafloor areas accommodated by deep-sea communities is facilitated by identifying seepage areas (MacDonald et al., 1996; Garcia-Pineda et al., 2010; Lessard-Pilon et al., 2010; Jones et al., 2014). In petroleum exploration, the identification of seafloor seeps is used as a first-order tool to identify active petroleum systems and confirms the presence of matured source rocks (e.g. Abrams, 2005). Combined with geophysical sub-seafloor datasets, locating active seafloor thermogenic seeps provides significant evidence for understanding the hydrocarbon plumbing system (Serié et al., 2016). Pockmarks, which are local depressions on the seafloor associated with contemporary focused fluid flow (e.g. King and MacLean, 1970; Hovland and Judd, 1988), are widely recognized as the seafloor outlet of expelled fluids. Even if hydrocarbon migration across the water

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Table 1
Compilation of reported values of hydrocarbon ascension velocities through the water column.

Reference	Hydrocarbon type	Minimum value ($cm\,s^{-1}$)	Maximum value ($cm\,s^{-1}$)	Type of study
Rehder et al. (2002)	Methane	26	27	Laboratory
Leifer and Patro (2002)	Methane	5	15	Laboratory
Greinert et al. (2006)	Methane	12	22	In-situ measurement (Black Sea)
De Moustier et al. (2013)	Methane	17	23	In-situ measurement (Gulf of Mexico)
Leifer and MacDonald (2003)	Methane, oily bubbles	2	20	Laboratory
Crooke et al. (2015)	Oil and gas mixture	5	50	In-situ measurement (Gulf of Mexico)
Van Ganse et al. (2013)	Oil and gas mixture	2	18	Laboratory
Körber et al. (2014)	Oil and gas mixture	13	15	In-situ measurements (Black Sea)

column presents strong and varied implications, the phenomenon remains strongly under-evaluated.

The fate of oil droplets either sinking to the seafloor or rising through the water column depends on the buoyancy of the expelled hydrocarbons. Lighter components rise through the water column (De Beukelear et al., 2003; Körber et al., 2014; Garcia-Pineda et al., 2015) until reaching the sea surface (e.g. MacDonald et al., 2002; Greinert et al., 2006; Rollet et al., 2006; Smith et al., 2014).

During the ascent through the water column, oceanic currents affect the deflection of the plume by advecting the oil droplets during their rise from the seafloor to the surface (Crooke et al., 2015). The lateral deflection distance is controlled by the current strength and the transit time of the oil droplets in the water column. The transit time is controlled by both the water depth and the ascension velocity and can be affected by horizontal and vertical turbulent dispersion. Estimating the ascension velocity is therefore compulsory for quantifying the range of the deflection (Table 1).

The few case studies documenting the ascension velocity of oil droplets are exclusively based on laboratory experiments or measured in a few marine settings (e.g. Gulf of Mexico and Black Sea). The reported ascension velocities range from 2 to 50 $cm\,s^{-1}$. While most studies focused on the vertical ascent of oil droplets in the water column (MacDonald et al., 2002; Greinert et al., 2006; Crooke et al., 2015; Chen et al., 2015; Korotenko, 2016), only a handful have addressed the horizontal deflection associated with currents in natural systems. In the Gulf of Mexico, the lateral deflection of oil droplets was estimated using an affine deflection function based on water depths (Garcia-Pineda et al., 2010).

Quantitative models approximate the ascension velocity of hydrocarbon droplets based on characteristics such as bubble shape and diameter (Clift et al., 1978; Perry and Green, 1984; Korotenko, 2016). Depending on the oil type and environmental conditions, the shape of the oil droplets can range from spherical, ellipsoidal to "jellyfish" (Van Ganse et al., 2013; Aprin et al., 2015). The droplet size distribution and rising regime depend on the oil type (Clift et al., 1978); however, oil composition is in most case unknown due to unavailable in-situ samplings. In addition, the composition and properties of expelled oil from natural seeps can be altered by external factors including biodegradation (Head et al., 2003; Larter et al., 2003; Larter et al., 2006; Jones et al., 2008; Peters et al., 2007; Aeppli et al., 2014) and gas hydrate formation (Rehder et al., 2002; Leifer and MacDonald, 2003; McGinnis et al., 2006).

This paper aims to link sea-surface oil slicks to seep-related seafloor features by estimating the horizontal deflection of oil droplets, based on the integration of current measurements, satellite-based surface slick data, and high-resolution bathymetric maps. In addition, our objective is to quantify the temporal variability of the oil plume deflection offset through the water column. Indeed, affine deflection functions still need to be validated in open-sea conditions that are usually associated with a greater hydrodynamic complexity. Understanding the rise path of oil in a challenging area will definitely contribute to understand the probable deflection ranges of oil in other provinces.

2. Regional settings

The study area is located offshore Angola in the Lower Congo Basin (LCB) (Fig. 1), in water depths ranging from 1200 to 2700 m. The LCB deep-water province corresponds to one of the most important natural oil seep systems in the world, where 4380 m^3 of oil is expelled each year towards the sea surface (Jatiault et al., 2017). In addition, extensive oil and gas exploration activities in the LCB during the last decades have provided a large volume of geophysical data, both at the seafloor and in the water column. The LCB appears to be a key area for understanding the dynamic behavior of oil droplets rising through the water column.

The significant occurrence of oil seeps in the LCB is mainly associated to the presence of prolific source rocks intervals including to the pre-salt Early Cretaceous Bucomazi Fm (Burwood, 1999; Cole et al., 2000) and the post-salt Late Cretaceous Iabe Fm, (Cole et al., 2000; Schoellkopf and Patterson, 2000; Séranne and Anka, 2005). An efficient plumbing system is reported in deep province (Andresen and Huuse, 2011; Andresen, 2012, Gay et al., 2007) in association with strong compressive salt tectonics (Fig. 1; Marton et al., 2000; Brun and Fort, 2004; Fort et al., 2004; Séranne and Anka, 2005; Guiraud et al., 2010).

The LCB presents open-sea oceanic conditions characterized by a complex vertical succession of surface and deep currents (Peterson and Stramma, 1991; Schneider et al., 1996; Holmes et al., 1997; Stramma and England, 1999; Shannon, 2001; Hardman-Mountford et al., 2003; Hopkins et al., 2013; Phillipson and Toumi, 2017). The main currents in the LCB reported in the literature are shown in Fig. 1. The major surface current following along the coast is the Angolan Current (AC) transporting equatorial waters from 0 to roughly 300 m below the sea surface (Moroshkin et al., 1970; Hardman-Mountford et al., 2003). The AC is steady, narrow, and fast current flowing southwards with velocities ranging from 20 to 50 $cm\,s^{-1}$, and salinities around 36.4 (Moroshkin et al., 1970; Hardman-Mountford et al., 2003). The northernmost branch of the Benguela Coastal Current (BCC) is reported to bypass the border with the AC at the Angolan Benguela Frontal Zone (ABFZ), bringing cold and low salinity waters along the Angolan coast (Schneider et al., 1996; Hopkins et al., 2013). The influence depth of the BCC is limited to the surface and subsurface layers. The southward-flowing Southern Intermediate Counter Current (SICC), transporting Antarctic Intermediate Water (AAIW) (Stramma and England, 1999; Stramma and Schott, 1999; Shannon, 2001), controls intermediate water circulation (500 – 1000 m). The deep-water circulation along the Angolan coast corresponds to the slow southward flow of the North Atlantic Deep Water (NADW) (Lynn, 1971; Stramma and England, 1999; Arhan et al., 2003). This bottom boundary current could correspond to the eastern retroflection of the Deep Western Boundary Current (DWBC) (Garzoli et al., 2015).

3. Data and methods

3.1. Data

3.1.1. Mooring measurements

Currents were measured with RD® instruments Acoustic Doppler