Marine oil reservoirs are generally characterized on the sea surface by the presence of natural oil seeps (Sea Surface Outbreaks - hereafter SSO). The latter are easily evidenced with Synthetic Aperture Radar (SAR) images because of the dampening effect that oil has on the capillary and associated small gravity waves (Bragg waves). The sea surface outbreaks of oil seeps are offset from their source on the seabed (sea floor sources - SFS) by hundreds of meters or even kilometres. This displacement all along the sea water column is a function of the upward velocity of the oil droplet size, and the presence of lateral marine currents. This paper proposes a new Vertical Drift Model (VDM) method that combines both SAR images to get the source location and the hydrodynamic model (HYCOM) function of the oil droplet size to estimate the SFS. After oil seeps detection from SAR images, the VDM proceeds to a regression in time and space based on the upward velocity of the oil, based on Stokes law, and the hydrodynamic conditions (HYCOM) to estimate the location of the SFS on the seafloor. The upward velocity depends strongly on the unknown droplet size. We propose herein a new VDM method named "sources path" that allows to estimate the oil seeps sources on the seafloor without a priori knowledge of the oil droplet size by finding, for each oil seep, the sea floor sources corresponding to different diameters. We call "sources path" the line that joins the sea floor sources for an oil seep. The sea floor sources ought to be at the intersection of the maximum sources path. The methodology has been applied to the northern Gulf of Mexico where the locations of many prolific oil seep sites are well known. A first validation of the source path procedure is that the obtained SFSs correspond to the sea floor sources of oil droplets having the same diameter and seeped at different times. Another validation has been performed through the comparison of SFS locations and those of the occurring shallow salt. This comparison shows a good correlation and suggests that the oil seeps may be situated above the allochthonous toward autochthonous salt connections.

1. Introduction

The offshore exploration provided nearly 70% of the major oil and gas discoveries worldwide in the last decade (Sandrea and Sandrea, 2010). But, before any O&G drilling, it is required a real detail Exploration which implements both complex and expensive geological and geophysical techniques whatever the basin O&G content. Exploration need to be optimized in cost, time and focused in space by using SAR images in order to detect natural oil seeps (also called oil seepages) on the sea surface as they prove the presence of source rock and mature organic matter within the basin (Abrams, 2005). However, the detection of oil seeps on the sea surface remains insufficient: their precise sources locations on the seafloor appear of great interest for any marine E&P (Jauer and Budkewitsch, 2010).

Indeed, marine natural oil seeps are hydrocarbon extrusions occurring on the oil offshore areas (Kvenvolden and Rogers, 2005). They are visible on the sea surface because the oil density is lighter than sea water which allows oil to float on the sea surface. Oil extrusion is due to (1) the lack of cap/cover in the petroleum systems which lead to a direct oil migration to the surface, or (2) to its poor quality (altered/weathered and/or fractured by structures) allowing secondary migration through it. These expulsions are easily observable in the marine surface.

SAR images have proven to be a useful tool for oil slicks (from any
biogenic and/or mineral origin) mapping due to the dampening effect that oil has on the capillary and small gravity waves, so-called Bragg waves (Jackson and Apel, 2004; Brekke and Solberg, 2005; Mercier and Girard-Ardhuin, 2006; Shu et al., 2010; Xu et al., 2015). In fact, with higher surface tension than water, oil produces a smoother sea surface than an “oil-free sea surface” resulting in decreasing of the radar backscatter, and hence causing dark patches (Jackson and Apel, 2004; Mercier and Girard-Ardhuin, 2006; Shu et al., 2010; Xu et al., 2015). Consequently, oil seeps appear darker compared to the brighter radar backscatter produced by Bragg waves. In addition to oil seeps, many phenomena may appear as dark in SAR images (Najoui et al., submitted A and B). For instance, some natural features are biogenic oil from algae or phytoplankton blooms, upwelling, rain cells, wind shadows, internal waves, current shear zones, etc. Man-made oil pollution (oil spill) from ships, oil rigs or leaking pipelines, also produces dark signatures in SAR images. Non-oil seeps features are termed as oil seeps lookalikes (Espedal, 1999; Brekke and Solberg, 2005; Xu et al., 2014).

Unfortunately SAR images are able to detect marine oil seeps only on the water surface (Sea Surface Outbreak - SSO below). However, for Exploration purposes, it is compulsory to get the precise origin of the seeps on the seafloor (Sea Floor Source - SFS). In the literature, two approaches have been used to locate the seeps SFS: statistical analysis of surface marine oil seeps using SAR images (Dhont and Dubucq, 2016) and a 3D vertical drift model based on a hydrodynamic model (Mano et al., 2016). In this study, a combination of SAR images analysis and a vertical drift model has been adopted.

Note that the horizontal distance between the positions of the seafloor outbreak (SSO) and the seafloor source (SFS) of an oil seep depends on the upward velocity and the hydrodynamic system of the sea water column (Crooke et al., 2015). For instance, in the Gulf of Mexico, the distance between the positions of the SSO and the SFS of an oil seep can ranges between hundred and thousand meters (MacDonald et al., 2002) that contrast considerably with more than 50 kilometers obtained by Mano et al. (2016). Such important SSO/SFS deflection variation suggests high variations in the oil droplet size and the hydrodynamic conditions of the seawater column. To assess this variability, our study develops a vertical drift model (VDM) of natural oil seeps observed on SAR images. The VDM combines SAR images and the oceanic model HYCOM (HYbrid Coordinate Ocean Model) to trace the trajectory of an oil droplet of a given diameter (d) from the sea surface outbreak remotely identified from SAR images to the seafloor source. This VDM is based on a regression in time and space through the column water. To overcome the issue of the oil droplet diameter size, and that is the main novel of our article, the innovative method of “sources path” has been developed and applied to the northern part of the Gulf of Mexico (test area), well known for the locations of many prolific oil seep sites. To assess the effectiveness of the Vertical Drift Model and validate its outputs, a correlation with the available geological data has been established.

This paper is organised as follow. The section 2 focuses on the migration mechanisms of an oil seep from the sediments to the sea surface. In the section 3 a description of the tectonic, petroleum and oceanic settings of the study area (N. Gulf of Mexico) is briefly presented. Section 4 provides a detailed description of the used methodology that we settled in three main steps: (1) detection of oil seeps and their SSO from SAR images; (2) building the vertical drift model (VDM) using the hydrodynamic model HYCOM and the Stokes equations; and (3) application of the sources paths algorithm. Finally, results and validation are given in section 5 before the conclusions and perspectives.

2. Natural oil seeps migration from deep sediments to sea surface

Offshore natural oil seeps are streams of naturally occurring oils that migrate from the sediments below the seafloor and flow through the water column as oil drops, resulting in telltale slicks on the sea surface (Judd and Hovland, 2007). Oil seeps come from the decomposition of organic matter (plankton, plants, animals, etc.) accumulated in marine sedimentary basins. The organic matter evolves into oil with time, depending of the basin infilling, the temperature heat flow as well as pressure phenomena. Because of the lower density of oil compared to water, oil migrates to the sea floor surface through the sedimentary strata. During this migration, the oil may encounter an impermeable layer and thus be trapped below this “rooftop” (called cover-rock or seal) within a porous and permeable strata that becomes the reservoir rock. The couple reservoir-rock/cover-rock forms a so-called “oil trap” structure. The most common oil traps are: structural (anticlines, faults, salt dome) and stratigraphic traps (pichtout, lens and unconformity traps - see Fig. 1). The poor quality, or lack of a cover-rock, allows the oil to escape and reach the surface (Macgregor, 1993). Faults or fractures provide natural fluid pathways through which oil is released into the water column.

The hydrocarbons expelled from the sedimentary formations and arrived to the seafloor can either be stored on the seabed inducing positive topographies when the elements have a density higher than seawater or continue their migration in the water column until they reach the sea surface when their density is sufficiently low (Rollet et al., 2006). The migration of the expelled oil on the water column generally occurs in the form of bubbles (Körber et al., 2014). The understanding the mechanism of oil migration on the water column as well as the vertical drift requires a good knowledge of the currents, their impact on the oil droplets, and the oil droplets themselves. The residence time of the droplets in the water column is a function of the upward velocity, which is itself dependent on the type of oil, its density and the oil droplet size. The identification of recurrent surface oil seeps with spaceborne radar images enables the identification of oil seeping provinces and provides an additional means to validate hydrocarbon migration throughout the petroleum exploration workflow (Stalvies et al., 2017).

3. Study area

3.1. Tectonic and petroleum settings

The Gulf of Mexico is a small ocean basin of about 1.5 million square kilometers of arched shape connected eastward to the Atlantic Ocean by the Yucatan Channel and the Straits of Florida. The Gulf of Mexico is geographically surrounded on the north by the South United States of America coast (Texas, Louisiana and Florida) and on the south and the east by Mexico (Yucatan, Campeche, Tabasco, Veracruz, and Tamaulipas). The Gulf of Mexico is characterized by a passive margin that developed through an episode of rifting from the end of Triassic during the Mesozoic breakup of Pangea and specifically due to the separation of the North American and Yucatan plates (Salvador, 1987;
Sawyer et al., 1991; Buffler and Thomas, 1994a,b; Jacques and Clegg, 2002; Harry and Londono, 2004). The slow oceanic opening leads to the first salt-bearing deposits characteristic of a shallow depositional environment during the Jurassic (Callovian-Oxfordian ~ 160 Ma). These evaporites are deposited in the shallow basin while the ocean floor is not yet opened (Bird et al., 2005). During Kimeridgian time, the GOM was submitted to an extensional regime that deepens the basin that lead to the setting of oceanic crust and to the end of the evaporitic sedimentation (Buffler and Thomas, 1994a,b; Bird et al., 2005). The Oceanic opening which is characterized by a counterclockwise rotation of the Yucatan block divides the salt-bearing deposits into two different set: (1) Louann salts, located on the northernmost part of the Gulf of Mexico and (2) Campeche in the southern part (White, 1980; White and Burke, 1980; Winker and Buffler, 1988; Salvador, 1991; Angeles-Aquino et al., 1994; Buffler and Thomas, 1994a,b; Marton and Buffler, 1994; Pindell, 1994; Bird et al., 2005). The Berriasian marks the end of the oceanic rifting and the beginning of an intense salt tectonic activity (Pindell, 1985; Salvador, 1987, 1991; Winker and Buffler, 1988; Marton and Buffler, 1994; Bird et al., 2005). It is believed that the salt tectonic is responsible of the creation of the oil traps (Ingram et al., 2010). Thus, Gulf of Mexico is a province intensely explored by Oil companies and highly oil and gas producing area.

The Gulf of Mexico has been studied extensively over the past few decades. The evidence of natural hydrocarbon seepage in the continental slope as seen in radar remote sensing images due to oil slicks has been documented and reported earlier by Hood et al. (2002), MacDonald et al. (1993), and Suresh (2015). Thermally mature petroleum source rock strata occur in Jurassic, Cretaceous, and Early Cenozoic basal marls and shales, principally deposited during Eocene, Turonian, and Tithonian–Oxfordian depositional episodes (Hood et al., 2002). Generation phases have extended over several tens of millions of years, depending on source level, burial history, and ambient heat flow. The Gulf petroleum system is a large-scale vertical migration from Mesozoic source rocks into Cenozoic reservoirs (Galloway, 2008).

3.2. Oceanic settings

The sea currents in the Gulf of Mexico are dominated by mesoscale features that include the Loop Current (LC) and the Loop Current Rings (LCRs), also called eddies (Sturges and Leben, 2000; Zavala-Hidalgo et al., 2003; Smith et al., 2014). The Loop Current forms as the pre-Gulf Stream waters flow from the Caribbean Sea, through the Gulf of Mexico, and on into the Atlantic (Smith et al., 2014 - see Fig. 2). When the LC is in an extended northward state, it tends to form and ultimately shed an anticyclonic (clockwise circulation) eddy or LCR that drift to the west, driving the deep circulation just about everywhere in the Gulf (Sturges et al., 2005). LCRs may reach depths of up to ~1000 m and possess swirl speeds of 180–200 cm s⁻¹ (Oey et al., 2005; Smith et al., 2014). Cyclonic (counter-clockwise circulation) frontal eddies are also found along the edges of the LC and LCRs. They can have swirl velocities > 100 cm s⁻¹ (Vukovich and Maul, 1985) and can extend to 1000 m at depth (Oey et al., 2005).

4. Methodology

In order to identify and locate the oil seeps sources, we proceed herein by the three following steps. If the first step is based on the detection of oil seeps from SAR images (see section 4.1), the second one focus on the building of a vertical drift model (VDM) that considers two components: the upward velocity of the oil droplet strongly influenced by the diameter of the droplet and the marine currents (section 4.2). The last and third step consists in the application of the “source path algorithm” whose role is to locate the seafloor source on the sea floor taking into account the different diameters of the droplets, a priori unknown information (section 4.3).

4.1. Oil seeps detection using SAR images

Oil slicks are not visible on the ocean surfaces if the contrast between the slick and the surrounding water is not sufficiently high (e.g. at low wind speeds). Moreover, at high wind speeds, the oil slicks tend to break up into smaller parts thus hindering detectability from SAR sensors. Wind speed requirement for oil slicks detection has been reported to be 2.09–8.33 m/s (31) where the detectability increases with the increase of the wind speed. A variety of studies have been carried out about the range of wind speed that optimizes the oil slicks detection on SAR images. Wind speed requirement has been reported to be 3 to 7-10 m/s (Brekke and Solberg, 2005), 3.5–7 m/s (Garcia-Pineda et al., 2009).

In the literature, three approaches exist for oil slicks detection from SAR images: (1) a manual approach conducted by trained human operators who analyse individually each SAR images to detect oil slicks (Jatiaux et al., 2017), (2) the semi-automatic approach where a computer detects all the dark patches in the SAR image using different techniques of segmentation after which an experienced human operator classifies these objects as oil slicks or look-alikes (Liu et al., 1997; Solberg et al., 1999; Gasull et al., 2002; Kanaa et al., 2003; Angiuli et al., 2006; Chang et al., 2008; Garcia-Pineda et al., 2008; Del Frate et al., 2013), and finally (3) the automatic system that uses complicated image processing and programming techniques to perform both segmentation and classification (Solberg et al., 1999; Fiscella et al., 2000; Del Frate et al., 2000; Maged, 2001; Maged, 2014; 2015; Suresh, 2015; Mano et al., 2016).

Due to the real unknown accuracy of the semi-automatic and automatic approaches, we focus herein on a reliable manual detection approach even if it is needed to analyse several hundreds of images. In this study a dataset of 215 images (Fig. 3) from ENVISAT’s ASAR sensor acquired in Wide Swath Mode (WSM) has been used with a temporal coverage of 10 years (2002–2012). ENVISAT ASAR operates in C-Band (4.20–5.75 GHz). The WSM mode gives a 400 km by 400 km wide swath image. Its spatial resolution is approximately 150 m by 150 m with pixel spacing of 75 m by 75 m. ASAR WSM operates according to the ScanSAR principle, using five predetermined overlapping antenna beams which cover the wide swath. The images were provided by the European Spatial Agency (ESA), in digital numbers in a 16 bits format. All images have been georeferenced in the geographic coordinate reference system over the WGS84 ellipsoid, datum WGS84. An accurate land-sea mask has been applied. Thereafter, the images have been radiometrically corrected to ensure uniformity on offshore area by using an adaptation to a backscattering model (Riazanoff and Gross, 2013; Najoui et al., submitted B).

All SAR images have been manually interpreted. The manual detection and recognition of oil seeps are based on the “Synthetic Aperture Radar marine user’s manual” (NOAA, 2004). Each of the 215 SAR images has been interpreted independently from the others. Each oil slick has been categorised depending on the interpretation based on morphological and textural criteria (Fig. 4). Oil slicks are divided into two major categories: biogenic and mineral. Biogenic oil slicks are produced by plankton and fish substances normally released into the environment. The mineral oils are subdivided into those of natural seeps from the sea bottom or anthropogenic oil spills that originate from ships, refineries, oil terminals, industrial plants, oil platforms, and pipelines (Espedal and Johannessen, 2000).

“Oil seeps” are seen in SAR images as dark objects with a rather fine and often curved geometric shape. The shape of these seeps is the result of short-term local changes in wind and current conditions (Espedal and Wahl, 1999). They have the particularity to reproduce in time in the same place. The temporal repetitiveness of oil seeps is their most discriminating characteristic.

“Oil spills from platforms” are seen in SAR images as dark objects with an irregular geometric shape. Unlike oil seeps, oil spills from platforms may reach large extents. They have the particularity of being...
often repeated on several images at different dates. A second distinctive feature is their proximity to oil platforms. The latter are easily identifiable thanks to their bright signature on the radar images via an average analysis of several images.

“Oil spills from ships” are seen in SAR images as dark objects with a fine geometric shape. This shape is linear because the boat is moving. In some cases, the boat can be detected too if it is still close to the oil slick thanks to its bright signature on the radar images. Deballasting may be continuous or intermittent. In the latter case, the oil layer is generally in the form of several segments of oil slicks which keep their linearity. When the ship is immobile, the oil slick has an irregular geometric shape that can be confused with an oil spill from platform. Oil spills from platforms or ships induce significant pitfalls (Johannessen et al., 2000; Trivero and Biamino, 2010; Leifer et al., 2012).

“Biogenic oils” are most often laminar, sub-parallel and/or fitting the shapes of eddies or currents induced by the upwellings.

Thereafter, a multi-date analysis has been performed combining all SAR oil slicks analyses. We use all the interpretations at different dates.
in order to assess the manual interpretation. Indeed, repetitive slicks are more likely due to leaks from static objects, as a geological pockmark for oil seeps, or a platform or pipeline for oil spills. To perform and validate this manual classification, the manual detection output has been integrated within a GIS with several data (marine traffic, oil platforms, oil and gas fields, wind fields, bathymetry, etc.). Only high confidence oil slicks from natural oil seeps have been retained and thereafter studied. The oil seeps sea surface outbreaks (SSO herein) correspond to the probable impact area of the fresher oil droplets at the sea surface. The SSO is also called the Oil Slick Origin (OSO, of Garcia-Pineda et al., 2010; Körber et al., 2014; MacDonald et al., 2015). In this study, the term “OSO” has not been used as it is not precise enough to distinguish both Sea Surface Outbreak (SSO) and Sea Floor Source (SFS) which are quite different in location from the sea column point of view.

### 4.2. Vertical drift model

Once the SAR images have been analysed in order to detect manually the different oil seeps, the vertical drift model is built. As explained above, the oil seeps on the sea surface (SSO) are offset from their Sea Floor Sources by their ascending transit within the sea water column of several hundred meters or even kilometers depth. Because a continuous stream of oil in water column is scattered in independent droplets, one consider in that follows the motion of one droplet only. Note that the displacement of an oil droplet within the sea water column is a function of two components: a vertical component representing the upward velocity $V_t$ (also called terminal velocity), and an horizontal component representing the cumulated effect of the marine currents velocity $V_c$. Assuming a spherical oil droplet dynamic without consider the droplet size variations due to coalescence and dissolution process. $V_t$ can be calculated by the law of Stokes (eq. (1)).

$$V_t = \frac{12\mu}{d^2} \left( \frac{1}{27} \frac{\rho_{\text{water}} - \rho_{\text{oil}}}{\rho_{\text{water}}} \frac{g(d/2)^3}{\mu^2} + 1 - 1 \right)$$

Where: $V_t$ is the upward velocity in cm/s, $\rho_{\text{water}}$ is the water density in g/cm$^3$, $\rho_{\text{oil}}$ is the oil density in g/cm$^3$, $\mu$ is the cinematic viscosity of water in cm$^2$/s, $g$ is the gravitational acceleration (981 cm/s$^2$), $d$ is the diameter of the oil droplet in cm.

The temperature, salinity, and current data used come from the HYCOM-GOM (HYCOM for Gulf of Mexico, https://hycom.org/dataserver/gom-reanalysis) model. HYCOM is designed as a generalized hybrid (isopycnal/$\sigma$/z) coordinate ocean model. It is isopycnal in the open stratified ocean, but reverts to a terrain-following ($\sigma$) coordinate in shallow coastal regions, and to z-level coordinates near the surface in the mixed layer. HYCOM-GOM model has 1/25° equatorial resolution and latitudinal resolution of 1/25° $\cos(\text{lat})$ or $\sim 3.5$ km for each variable at mid-latitudes. The variables are temperature, salinity and currents. The reanalysis data used in this study are interpolated to form a vertical grid of 40 vertical z-level (at constant depth levels) with a temporal resolution of 3 h. The HYCOM-GOM model has been validated by several studies. For instance, Neary et al. (2012) highlights that the HYCOM-GOM model simulations produce valid representations of spatially and temporally varying power density. The study indicates also that HYCOM-GOM outputs matches closely with that measured by a submarine cable, the RMSD is only 10%, and bias difference is only 1%.

The keys parameters in the vertical model (currents, temperature, and salinity varies as a function of depth and time. Table 1 shows the variations of currents speed and direction given by HYCOM in the same location at three different dates for 6 depth levels. One may observe the variation of current speed and direction.

The mean current speed per depth in the Gulf of Mexico is given by Fig. 5. The mean has been calculated over 10 years (2002–2012) from 682 scattered locations in the Gulf of Mexico using HYCOM-GOM model. The data indicates that the mean current velocity is around 25 cm/s at the shallow water (0-50 m) and around 5 cm/s at deep water.

In the same way, the mean temperature and salinity have been

**Table 1**

<table>
<thead>
<tr>
<th>Depth (m)</th>
<th>2003/10/23</th>
<th>2009/09/14</th>
<th>2010/10/21</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Velocity (cm/s)</td>
<td>Direction (°)</td>
<td>Velocity (cm/s)</td>
</tr>
<tr>
<td>0</td>
<td>41.4</td>
<td>-77.74</td>
<td>7.7</td>
</tr>
<tr>
<td>200</td>
<td>9.6</td>
<td>-31.37</td>
<td>5.9</td>
</tr>
<tr>
<td>500</td>
<td>6.2</td>
<td>-33.94</td>
<td>5.1</td>
</tr>
<tr>
<td>1000</td>
<td>3.9</td>
<td>-25.27</td>
<td>9.5</td>
</tr>
<tr>
<td>2000</td>
<td>3.5</td>
<td>30.96</td>
<td>8.9</td>
</tr>
<tr>
<td>3000</td>
<td>3.4</td>
<td>12.38</td>
<td>3.4</td>
</tr>
</tbody>
</table>
calculated over 10 years (2002–2012) from 682 scattered locations in the Gulf of Mexico using HYCOM-GOM model. The outcome is given by Fig. 6. One may see that the water temperature decreases with the increase of the water depth whereas the salinity remains almost constant down to depths of 900 m.

Using the eq. (1), the upward velocity has been calculated from the HYCOM-GOM model for 682 oil seeps in the Gulf of Mexico for 4 different droplets diameter sizes ($D = 0.5$ mm, $D = 5$ mm, $D = 20$ mm, and $D = 100$ mm) as a function of the depth. The result is given by Fig. 7. One may see that the upward velocity decreases with the increase of the water depth. The upward velocity varies also according to the oil droplet size: the bigger the droplet, the more important the upward velocity. The time that takes an oil droplet to reach the sea surface depends on its diameter and the water column depth. As example, for depth ranging between 1000 m and 3000 m), the mean time is respectively about 20 h, 3 h and 31 min for oil droplet diameter respectively of 0.5 mm, 5 mm, and 100 mm.

The vertical drift model traces the trajectory taken by an oil droplet of a given diameter $d$ from its surface outbreak remotely defined to its seafloor source (SFS) by going backward in time and space over the whole water column (Fig. 8).

The application of the vertical drift model would have been sufficient to locate the seafloor source of a droplet if the diameter of the droplet was known. However, this step allows only locating the various probable locations of seafloor sources of a sea surface outbreak and this according to a variable: the diameter of a droplet. Hence, a third step is needed.
tical drift and must be taken into account in calculations aimed at locating the most common oil diameters SeaFloor Source for each matter within the source rock as well as its situation (such as due to its droplet at the SFS is function of the geochemistry of the initial organic required so-called the “sources paths” that correspond to the inverse location of the most common oil diameters SeaFloor Source for each SeaSurface Outbreak.

4.3. Sources paths algorithm

The diameter of the oil droplet is an important element in the vertical drift and must be taken into account in calculations aimed at locating the seafloor source (SFS). Effectively the diameter of the oil droplet at the SFS is function of the geochemistry of the initial organic matter within the source rock as well as its situation (such as due to its depth, the local heat flow, the pressure, and their residence time within both the source rock, the reservoir, as well as the different migrations (expulsion and secondary migration within the reservoir rock). The smaller it is the longer it stands within the reservoir. Indeed, as given by the equation (eq. (1)) and illustrated by Fig. 7, the upward velocity of a droplet varies substantially as a function of its diameter. Thus, the bigger the drop, the faster it rises to the surface. And the smaller it is, the slower it ascends (Fig. 9, left). The speed of a droplet to rise to the surface is capital since it determines how long the droplet will be under the influence of the marine currents in the water column. In summary, the bigger the drop, the faster it rise, and the less it drifts and vice versa.

As we do not know the diameter of the droplets -and this is the most interesting aspect of this study - we propose a method herein called “sources path” that inverse the SFS depending of the droplet size taking into account the SSO. The first step is to apply the vertical drift model for each oil seep with both different times and diameters. In other words, it consists in finding, for each oil seep, the seafloor sources corresponding to different diameters for a fixed SSO. The line that joins the seafloor sources for an oil seep is called the “sources path” (Fig. 9, left). Until now, the more or less exact location of the seafloor source (SFS) is not possible. In order for it to become so, at least a second path applied to different oil seep (different date) is required assuming the fact that they comes from the same SFS. Consequently the crossing of the two paths will give a point of intersection that we consider as the point of potential seafloor source (SFS - see Fig. 9, right). For a better accuracy of the location of the seafloor source, a multitude of multidate paths is necessary. Indeed, the greater the number of paths used in the analysis, the more likely the results will be accurate. However, the intersection of more than two paths multitudes in one point is unlikely. In most cases, one will have a set of points more or less close to each other. We will speak of a crossing area which delimits the seafloor source.

5. Results and validation

5.1. GOM oil seeps surface outbreaks (SSO) detection

The manual analysis of the 215 SAR images (acquired in between 2002 and 2012) led to the identification of 682 oil seeps in the Gulf of Mexico. The location of SSO has been drawn for each oil seep from the location of the fresher oil droplets (Fig. 10, left). Note that the oil seeps SSO form usually clusters structures patterns as shown by the normalized density map of the detected oil slicks (Fig. 10, right). The latter is computed as the kernel density with the QGIS toolbox (www.qgis.org) in order to better display areas of active seeps. The normalization of the density map has been done according to the SAR images occurrences shown in Fig. 3.

The detected oil seeps are concentrated in both (1) the northern part of the Gulf including the Texas-Louisiana Slope and Mississippi Canyon and (2) the south-west area that include the Campeche Knolls. This outcome is consistent with the previous studies (MacDonald et al., 1993, 1996, 2015; Mitchell et al., 1999; De Beukelaar, 2003; Suresh, 2015). According to the normalised density map of observed oil seeps, the northern Gulf of Mexico represents a relatively high density compared to the southern GOM (see Fig. 10). This is the reason why we choose herein as an example the northern GOM to illustrate this “sources path methodology”.

5.2. Estimated location of the GOM oil seeps seafloor sources (SFS)

The second and third steps of the methodology adopted within the framework of this paper (cf. 4.2 and 4.3) involve the application of the vertical drift model VDM) within the sea column taking into account the droplet size. In other words, for each oil seep SSO, the VDM has been applied to get the possible locations of the SFSs corresponding to different oil droplets sizes. The oil droplets size range between 0.5 mm and 100 mm with a stride of 0.05 mm. This interval has been fixed according to experiments founded in both the literature (Brewer Peter et al., 2002; Goncharov, 2009). The sources path of an oil seep SSO is the polyline that joins the seafloor sources locations obtained by applying the VDM to this oil seep SSO. Thus, the 1991 seafloor sources correspond to diameters ranging between 0.5 mm and 100 mm with a stride of 0.05 mm. Fig. 11 shows an example of two sources paths generated by the VDM from the SSOs of two oil seeps observed on Envisat ASAR WSM image acquired on 02 October 2010 at 16:00:50. The red arrows are the SSOs of the observed oil seeps while the blue points are the seafloor sources corresponding to the droplets diameters sizes (between 0.5 mm and 100 mm with a stride of 0.05 mm). The black polylines that joins the seafloor sources of an oil seep forms the sources path. For instance, the blue point with the value 0.5 correspond to the seafloor source related to the droplet diameter of 0.5 mm, the blue point with the value 100.0 correspond to the seafloor source related to the droplet diameter of 100 mm. One may see that the smaller the droplet is, the farthest the seafloor source from the SSO is.

An amount of 682 sources paths corresponding to the 682 oil seeps SSO have been computed. Therefore, the intersections between the 682 sources paths have been calculated. These intersections points correspond to the estimated oils seeps SFS location. For instance, each SFS point intersects two sources paths and therefore, contains two informations: 1/the diameter (d1) where he intersect the first sources path and 2/the diameter (d2) where it intersects the second sources path. The two oil seeps occurring on the sea surface at two different
dates and whose sources paths intersect at one point, are supposed to come from the same source on the seafloor so the intersection point of the sources paths which is the SFS. In an ideal case, the d1 and d2 corresponding to the SFS must be the same. To assess this, we compute the number of occurrences of the calculated oil seeps SFSs as a function of the diameter (d1 or d2) and the difference between d1 and d2 (|d1-d2|) as presented in Fig. 12. One may see in Fig. 12-a that the most of the occurrences (79%) of the calculated oil seeps SFSs correspond to diameters ranging between 0.5 mm and 2 mm with a low difference between d1 and d2 of the SFS. Fig. 12-b represents a zoom on Fig. 12-a on diameters between 0.5 mm and 2 mm and difference between d1 and d2 between 0.5 mm and 2 mm. One may see that the most calculated SFSs corresponds to diameters between 0.5 mm and 1.45 mm. The difference between d1 and d2 of the same SFS is zero. This outcome is a first validation of our methodology since the obtained SFSs correspond to the seafloor sources of oil droplets having the same diameter and seeped at different times.

An amount of 242 SFS have been obtained. Fig. 13 shows the sources paths (black lines) and their intersections (yellow dots) on the Texas-Louisiana continental Slope (left) and an example of the intersection of three sources paths corresponding to three SSO observed on the sea surface at three different dates (2003/10/23, 2009/09/14, and 2010/10/21). The horizontal deflection between the SSO and theirs SFS is given in Fig. 14. One may see that the average of the horizontal deflection between the SSO and their SFS is about 2500 m.

5.3. Geological validation

In this study, the geological validation focuses on the northern part of the Gulf of Mexico and especially in the Texas-Louisiana continental Slope. As explain above (3.1), the petroleum activity in the Gulf of Mexico is controlled by the salt tectonic (Salvador, 1991; Galloway, 2008). As shown by Fig. 15A, the oils seeps SFSs are all located on the outcropping shallow salt. We interpret this as the oil seeps are related to
the salt. Moreover, some seismic profiles have been published (Fort and Brun, 2012) among which given by Fig. 15C reveal that generally oil seeps come from the Allochthonous salt areas.

On Fig. 15B, we superimpose the hill-shade bathymetry, the SFS (red dots) and the seismic profile (see Fort and Brun, 2012). Therefore it appears clearly (Fig. 15C) that the four SFS correspond to the outcropping Cretaceous-Early Miocene rafts/salt boundary. We believe that the oil seeps may be situated above the allochtonous toward autochtonous salt connections but this needs to be carefully checked with further geological seismic sections as so few are published in the public domain.

6. Conclusion and perspectives

Indeed, the sea surface outbreak of a seepage derived from hundred meters to a few kilometres from its Sea Floor Source (SSF - see references above). We apply herein with a stochastic approach a vertical drift model (VDM) methodology that inverse the displacement within the sea water column of an oil diameter for an oil droplet for a given size in order to determine precisely its Sea Floor Source. We combine multiday oil seepages in their vicinity that are assumed to have the same SFS. By inverting their trip within the sea water column we are able to propose that their intersection of source path as their Sea Floor Source.

We illustrate this methodology to the northern Gulf of Mexico (GOM) where 682 oil seeps have been manually detected, between 2002 and 2012 using different SAR images. The application of the VDM methodology on a surface of 1.6 million km² (Gulf of Mexico), has allowed us, first, to significantly reduce the seepage zone to be studied, indeed, thanks to the analysis of the SAR images. The rest of the study (application of the vertical drift model and the development of source paths) has made it possible for the first time to locate in a more precise way both the oil seeps Sea Source Outbreaks (sea surface) as well as the Sea Floor Sources. The latter was located by the determination of the intersection of source paths inverting the drift within the vertical sea column.

The comparison of SFS locations and those of the outcropping
Fig. 15. The relationship between oil seeps SFS and the salt tectonic (modified from Fort and Brun, 2012). A: salt map with shallow salt and the oil seeps SFSs (red circles). B: zoom on the oil seeps SFSs with Google Earth bathymetry and the seismic profile C (white line). C: same the geolocated seismic profile (C) showing that the oil seeps may be situated above the allochtonous toward autochtonous salt connections. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)
shallow salt shows a good correlation. This outcome suggests that the oil seeps may be situated above the allochthonous toward autochthonous salt connections. In addition, 79% of the occurrences of the calculated oil seeps SFSs correspond to diameters ranging between 0.5 mm and 2 mm with a low difference between d1 and d2 of the SFS. This result is a validation of the sources path procedure.

The results of this study are a useful information and interesting complement for petroleum exploration in any marine areas.

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