Oil Seeps on the Seafloor of Perdido, Mexico*

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Abstract

After decades of estate monopoly, Mexico launched in the end of 2015 the first bid round of deep-water blocks, in a context of extremely low oil prices. In this scenario, it is crucial to use tools to help the prioritization of investments, increase success rates and reduce exploratory costs. This work presents an exercise for improving exploratory efficiency in Mexican GoM.

The strategy was to remotely identify areas on the seafloor where oil is seeping. Remote investigation presents reduced costs and can guide local investigation, reducing its cost also. The location of seep sources on the seafloor provides evidence of HC charge and a direct connection between oil seeps and geologic features in offshore basins, reducing risk. Hundreds of images of Synthetic Aperture Radar, onboard of satellites, were used to detect oil seep slicks on the sea surface in Cuenca Salina and Perdido, the two regions offered in the bid. In Cuenca Salina, many slicks were detected at the same position in different dates. In this case, the probable origin of these seeps on the seafloor is the vertical projection of the center of the cluster. However, in Perdido the seep slicks were spread on the sea surface, due to the joint action of more intense currents and winds, not generating clusters.

To solve this problem, two computational models were used to estimate the origin of the seeps on the seafloor. The hydrodynamic model rebuilds the 4D Ocean circulation in the date of detection of each seep; and the oil seep inverse model defines the trajectory of the oil, back in time, between the position where it was detected by satellite and the area in sea bottom, where the oil escaped to the ocean. In this work, we present results of the inverse modeling of the oil seeps in the region of the offered blocks in Perdido: slicks on the sea surface, their origin on the seafloor and a geologic interpretation of these results.

Introduction

After decades of estate monopoly, Mexico announced in the end of 2015 the first bid round of deep water blocks. Figure 1 presents the blocks that will be offered in the bid, concentrated in two main regions: Cuenca Salina and Perdido. Hundreds of images of Synthetic Aperture Radar (SAR), onboard of satellites, were used to detect oil seep slicks on the sea surface in these regions. Almost 300 seeps were detected considering

only the areas of investigation (the shaded areas involving the blocks in the figure), confirming previous findings in Mexican GoM (Pemex E&P, 2010; Padilha y Sanchez, 2014). This amount of seeps indicates the presence of a huge charge and active petroleum systems in deep waters in both regions and a great potential for new discoveries.

The seep dynamics in Cuenca Salina is very intense, whilst hydrodynamics is less intense, resulting in the generation of many seep clusters on the sea surface, i.e., the presence of many slicks in the same position in different dates. In this case, the probable origin of these seeps on the seafloor is the vertical projection of the center of the cluster. However, in Perdido, the seep slicks are less frequent and are spread on the sea surface, not generating clusters and, thus, making it hard to estimate their origin. The joint action of currents and winds can horizontally displace oil seeps more than 50 km far from their origin on the seafloor.

To solve this problem, two computational models were used to estimate the origin of the seeps on the seafloor. The hydrodynamic model rebuilds the 4D Ocean circulation in the date of detection of each seep; and the oil seep inverse model defines the trajectory of the oil, back in time, between the position where it was detected by satellite and the area in sea bottom, where the oil escaped to the ocean. Recent work demonstrated the ability of this technology to increase in 139% the success in finding HC shows in piston core campaigns (Mano et al., 2014). In this work, we present a case study of a seep area on the seafloor defined by inverse modeling within a block that will be offered in Perdido. This study shows the entire process to obtain the seep area polygon, from the detection of slicks on the sea surface until a geologic interpretation of the area.

Methodology

The remote study of oil seeps used to focus only on detections of seepage slicks on the sea surface, using satellite images. However, for exploration purposes, it is essential to connect the seep information with the geologic context and it is only possible if the origin of the seep on the seafloor (not on sea surface) is known. When the hydrodynamics is little intense, the slicks tend to show up almost in the same position in different dates, generating 'clusters' of seeps when the images are overlaid. In this situation, which is very rare in the offshore, we can infer the origin of the seeps by vertically projecting the center of the cluster. However, in most cases, the oil position on sea surface is far from its origin on the seafloor, due to the action of oceanic currents and winds. For these cases, we use the inverse modeling do define the origin of the seep on the seafloor (Mano et al., 2011). Figure 2 explains how the seeps are treated after being detected by satellites.

This work presents the results of the inverse modeling of six non-cluster seeps detected on the sea surface, whose backward trajectories, simulated by inverse modeling, converged to one seep area on the seafloor within a Round 1 block in Perdido. The methodology for identification of this seep area involves three remote technologies: remote sensing, hydrodynamic modeling and inverse modeling. After the geographic location of the seep area, it was ranked according to a score, called Reliability Factor (Rf), from 0 to 1, where the closer to 1, the higher is the chance of oil seeping.

Remote sensing is responsible for the detection of oil slicks on the sea surface using satellite images. The hydrodynamic modeling rebuilds the 4D oceanic circulation in the dates that the six seeps were detected. Inverse modeling imports the position of oil on the sea surface and the

results of hydrodynamic modeling and makes a regression in time and space to estimate the trajectory of the seeps from the position on the sea surface (where they were detected by the satellites) to the location where the seepage occurred on the sea floor (Figure 3).

After applying the remote technologies, there was an additional step to define and rank the seep area. The seep area identified by Inverse Modeling was analyzed in a regional geologic context, comparing the results with literature, available geological data and information about the main structural features. Figure 4 shows the four main steps of the methodology.

Remote Sensing: Oil Seepage detection on the sea surface

Usually, oil seeps are characterized by a thin layer that can be detected within some days on the ocean surface. The detection is possible due to the dampening of ocean surface capillary waves, caused by oil presence. This physical phenomenon can be captured in synthetic aperture radar (SAR) images. The detection of oil seeps on the sea surface was already widely validated (MacDonald et al., 1996; Scantland and Biegert, 1996; Biegert et al., 1997; Willians and Laurance, 2002; Miranda et al., 2004). Each image is taken in full resolution mode and a textural classification algorithm is performed to extract the features indicative of seepage slicks. The objective of the SAR image processing is to discriminate smooth texture areas (with low roughness) from areas of intermediate and rough textures (relatively higher roughness). Raster polygons defining smooth surface regions related to potential seepage slicks were then highlighted and subsequently isolated in vector format (Figure 5).

After detecting possible oil features, there is a process to classify them as: seepage, oil spill or false target (looks like oil, but it is not). All the dark patches detected in the satellites images are taken to a geographical database in order to be analyzed with the geological, bathymetric and environmental conditions available for that region and date. During the classification process, aspects such as meteorological and oceanographic features, geological province, the production context, the radar image characteristics and repeatability of oil features are observed for each oil feature. To better understand the influence of environment conditions in the SAR images, meteorological and oceanographic satellite data are retrieved to support the interpretation. Therefore, the process of detection and classification of oil slicks in SAR images includes an objective step, with textural algorithms, and a careful interpretation made by specialists. This classification method was calibrated over 12 years, when more than 13,000 oil features were validated by in-situ verification. The dark patches classified as oil seeps that do not generate cluster move forward, to the modeling step.

Hydrodynamic Modeling: Reconstruction of Ocean Circulation

The main objective of hydrodynamic modeling is to simulate the current field, using the physical principles related to conservation of momentum, energy and mass. These principles can be expressed in mathematical equations, building a system where the main unknowns to inverse modeling are the horizontal components of current velocity, in different vertical layers. From an initial state and boundary conditions, the resolution of this system of equations enables rebuilding the oceanic circulation of a given region. The result is a "cube" with current data. The grid used in the model must have spatial and temporal resolution configured to represent the main oceanographic features in the region (Mano et al., 2010).

Before running the inverse modeling, it is necessary to recreate the ocean circulation at each date of SAR image where a seep was detected. In the step of hydrodynamic modeling, each seep detected is associated to a 4D oceanic circulation and to a wind field, reproducing the same current conditions of the detection date. Therefore, if the seep was detected in an image of April 21, 2003, the hydrodynamic cube will reproduce the oceanic circulation of this date and of the previous dates, varying in time in an hourly frequency. This way, each seep has its own hydrodynamic cube and wind field, specific for the date when the detection happened. The displacement of the seep in the ocean will depend on the joint action of currents and wind. As currents and wind vary in time, seeps that came from the same origin can present very different trajectories, depending on the date the seepage occurred. In order to have the hydrodynamic cube the closest to reality, we assimilate satellite data into the model (wind, sea level and sea surface temperature), obtained for the same date. Algorithms based on statistic correlations extrapolate the sea surface information throughout the water column, making the whole cube close to the real ocean. Data assimilation in the hydrodynamic model aims to approximate the simulated circulation to the real circulation, respecting the physical principles established by the governing equations.

Inverse Modeling: Simulation of Oil Inverse Trajectory until Seafloor

In this step, we already have the geographic position on sea surface and date/time of a dark patch classified as an oil seep and its hydrodynamic cube. Now, the inverse modeling will go backward in time and space to estimate the trajectory of the oil between the position on the sea surface, where it was detected by satellite, and its origin at the ocean bottom (Figure 6). The 4D current and wind fields obtained by hydrodynamic modeling are imported by the inverse model. The inputs are bathymetry, current and wind, varying in time and three-dimensional space; and date, time and position of oil in the instant of detection by satellite. From the equation of transport, the model makes the regression in time, simulating the oil displacement from the position of detection until its origin on the seafloor.

Classification of Seep Areas: Mapping and Ranking

In a regular project, there might be hundreds of seeps. For each seep, tens of simulations of inverse modeling are performed, resulting in thousands of simulations. The definition of seep areas on the seafloor is based on the maximum convergence among the set of solutions. Algorithms were developed to automatically estimate those areas. After defining the seep area, it is classified according to a Reliability Factor (Rf), varying from 0 to 1 (lower to higher probability of oil escaping). The Rf is calculated using the following criteria:

- Classification of the seeps on sea surface
- Number of convergent seeps (number of convergent trajectories to the seep area)
- Number of different image dates of convergent seeps
- Distance between seep and its origin
- Geologic context of the seep area
- Seismic interpretation of the seep area (when available)

The integration of complementary information (inverse modeling and geological/geophysical data) builds a more precise knowledge of the overall dynamics of the petroleum systems and the assessment of exploratory potential of sedimentary areas. It is important to mention that the technologies used in this methodology can present errors (classification of seeps, space-time resolution of models, meteo-oceanographic data used as inputs etc.). However, recent studies (Mano et al., 2014), using geochemical analysis, showed that sediment samples collected inside seep areas had hydrocarbon evidence rates 139% greater than the ones collected in locations defined without using inverse modeling.

Results

Findings on the Sea Surface and On the Seafloor

In this section, we present the results of the case study, detailing the findings on the sea surface and the seep area on the seafloor, called IMX062, in Perdido region. Six seeps, detected on sea surface in five different images, converged on the seafloor to IMX062, after running the inverse modelling for each one. Table 1 presents the acquisition dates of these five SAR images, covering 14 years. The six seepage slicks are presented in Table 2 with respective identification code, date acquisition and geographic position. In a regional point of view, most of the seepage slick polygons are very small, which makes their representation almost impossible. In this case, each seepage slick is represented by its centroid location. The centroid is defined as the inside center of mass assigned to represent a particular polygon.

Figure 7 displays the seep area on the seafloor, the seepage slicks on the sea surface and their respective backward trajectories. It is located on the continental rise bathymetric province at Mexican Salina del Bravo province, within a block that will be offered in Round 1. The bathymetry values at this seep area ranges from 1,201 to 1,427 meters. Table 3 presents the length of the trajectory of each seepage slick, from the point where it was detected to the seep area IMX062. Each trajectory was obtained using the inverse modeling approach. Table 4 shows the geographic coordinates of the origin of the seeps on the seafloor.

The main characteristics of the Seep Area IMX062 calculated by inverse modeling are:

- Coordinates of NW corner: -96.03873 W and 25.12967 N;
- Coordinates of SE corner: -95.99789 W and 25.08476 N;
- Size of the area on the ocean floor: 20.48 km^2;
- Reliability Factor (Rf): 0.88.

Geological Integration and Interpretation

After defining the location of the seep area IMX062 on the seafloor, we integrated this information with available geological and geophysical data in order to increase the confidence about oil natural leaking in that region. According to CHN (2015), the Perdido Fold Belt Province is constituted by a fold system with NE-SW direction and reverse faults planes in the autochthonous Jurassic salt mass. The potential hydrocarbon traps are anticlinal structures nucleated by salt, long and tight, with water depths ranging from 2,000 to 3,500 m. It has confirmed the existence

of oil deposits reservoirs in sandstones placed in environments of lower Eocene turbidities fans and channels of turbidities sandstones in the Oligocene.

The seep area IMX062 is located in a region where many seepage slicks have been identified. The existence of active petroleum system with significant resources is confirmed in the region of shallow allochthonous salt bodies. This region is characterized by intense halokinesis where salt related faults penetrate overlying sediments and create potential migration pathways to the sea floor. The seep area therefore confirmed that halokinesis plays an important role in the process of hydrocarbon migration in the Perdido Fold Belt province. Following this geological trend to northwestern direction, in the American portion, Shell has the Perdido oil field production.

Digital image processing techniques applied to bathymetric data in raster format enhanced the sea-floor topography. In a local scale view, it is possible to observe an irregular relief with numerous valleys and hills as presented in Figure 8A. This ocean floor morphology occurs because of shallow allochthonous salt canopies (Figure 8B) where they are also associated to mini basin areas in the substrate rocks. These Mini-basin areas are located to the West and is represented by an almost parallel to the edge of the continental slope fringing area, affected by the presence of salt or clay diapirs associated to a eastward gravitational extensional system with a detachment level, creating and filling synsedimentary synclinal structures and sedimentary wedges against the salt or clay diapirs (CNH, 2015).

The seep area IMX062 is located in a bathymetric region next to an edge mound (in orange) characterized by a strong slope. This entire region is affected by shallow allochthonous salt canopies that contributed to create this irregular seafloor. According to CNH 2015, the seep area is in the border of the salt mass and the minibasin-diapir-fold province (Figure 8B), which probably caused migration pathways for oil moving from reservoir to the seafloor.

Discussion and Conclusion

A deep water well can cost over USD 100MM. To reduce the risk of dry wells, oil companies spend USD 10 billion per year collecting data. Even so, the success rates are around 25-35%. In times of low oil prices, industry needs to strongly pursue additional efficiency in exploration of offshore regions, where most of the new discoveries are located and where costs are significantly higher.

This work aims to contribute to the increasing of exploratory efficiency in offshore regions by adding a step of remote mapping of oil seeps sources to the exploration chain. Remote technologies, such as inverse modeling, can provide a more effective assessment of exploratory risk in offshore regions, helping to prioritize investments in deep waters and reducing risks and costs. To evidence this, we presented a case study in Perdido, Mexican GoM, where exploratory blocks in deep waters will be offered in the Bid Round 1.

According to petroleum system, the seep area presented corresponds to an important tool, which reflects the hydrocarbons saturation, and migration models established for the region. Vertical migration to the seafloor is highly affected by salt canopies through Cretaceous and Paleogene sediments. As a result, the geological features in the sub-surface and in the seafloor are in agreement with the interpretation derived from inverse modeling and attach to the bid block, where the seep area is located, a strong indication and confidence for hydrocarbon exploration.

Acknowledgments

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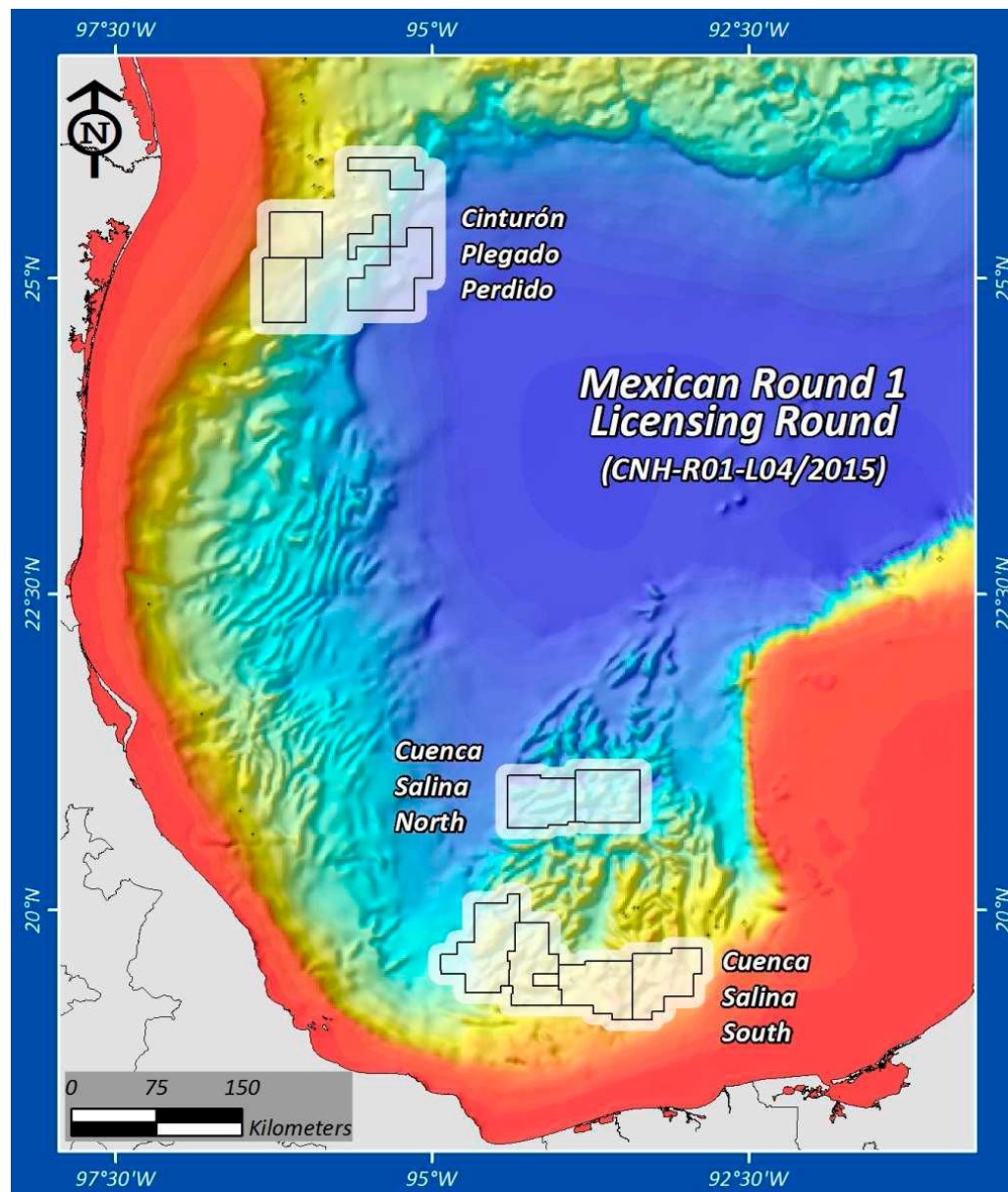
Figure 1. Blocks offered in the Mexican Round 1 Licensing Round for deep waters, divided into two regions: Cinturón Plegado Perdido and Cuenca Salina. Our investigations covered the shaded areas involving the blocks, which include the blocks and a buffer of 10km outside their limits. The present work focused in a case of study in Perdido.
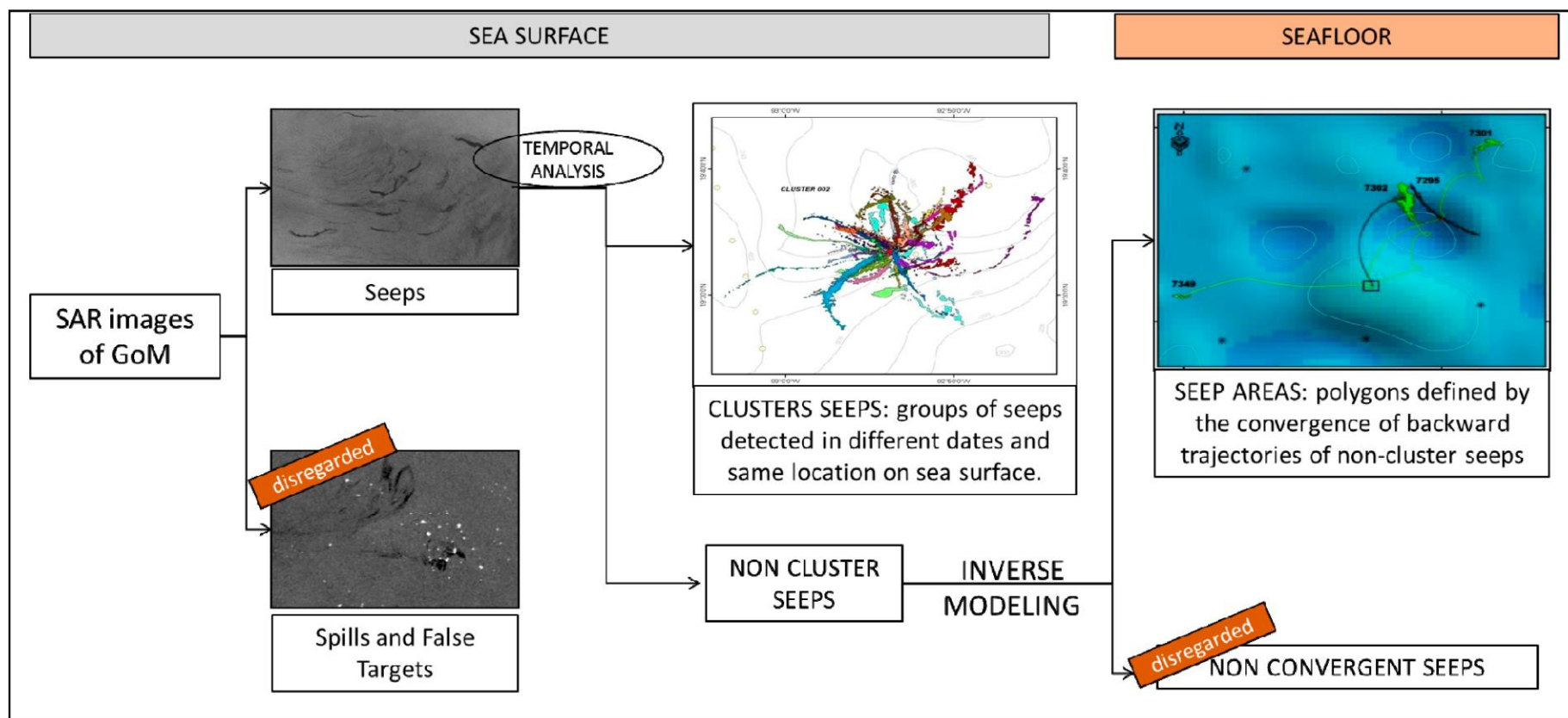
Figure 2. Process of oil feature analysis for exploration purposes: detection of oil feature; classification into seeps, spill or false target; temporal analysis for cluster mapping; and selection of non-cluster seeps to inverse modeling step.
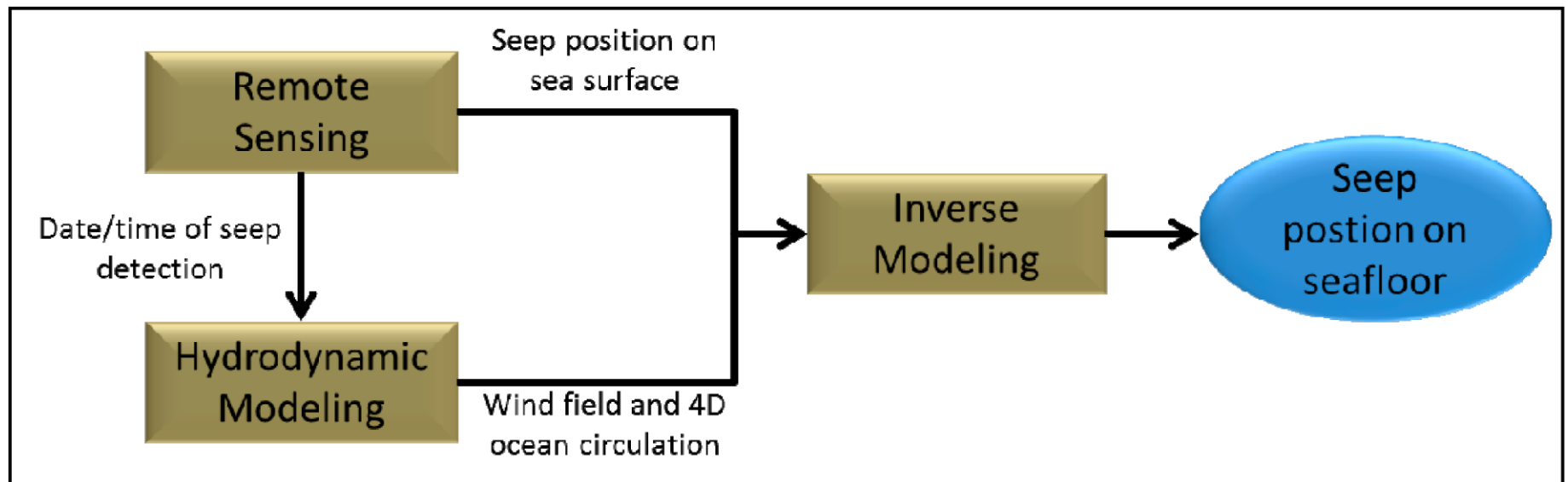
Figure 3. Flowchart of remote technologies, presenting inputs and outputs, since the detection using satellite to the mapping on the seafloor.
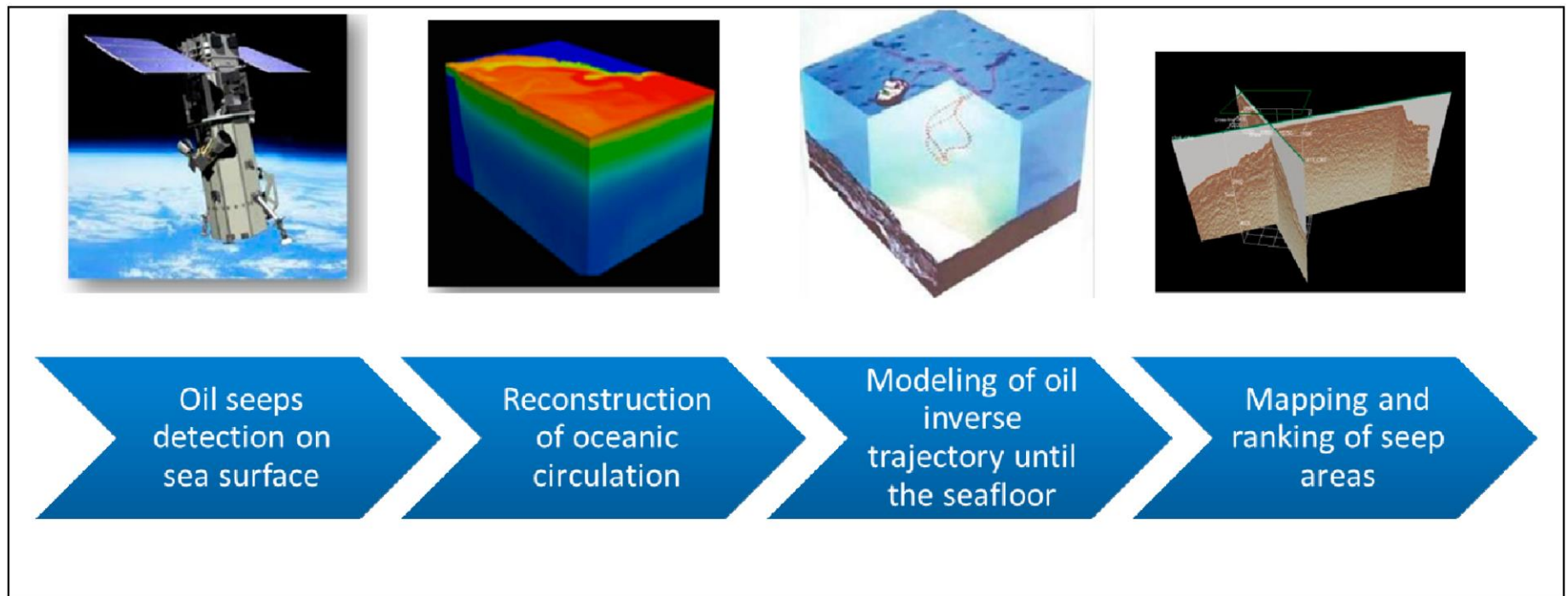
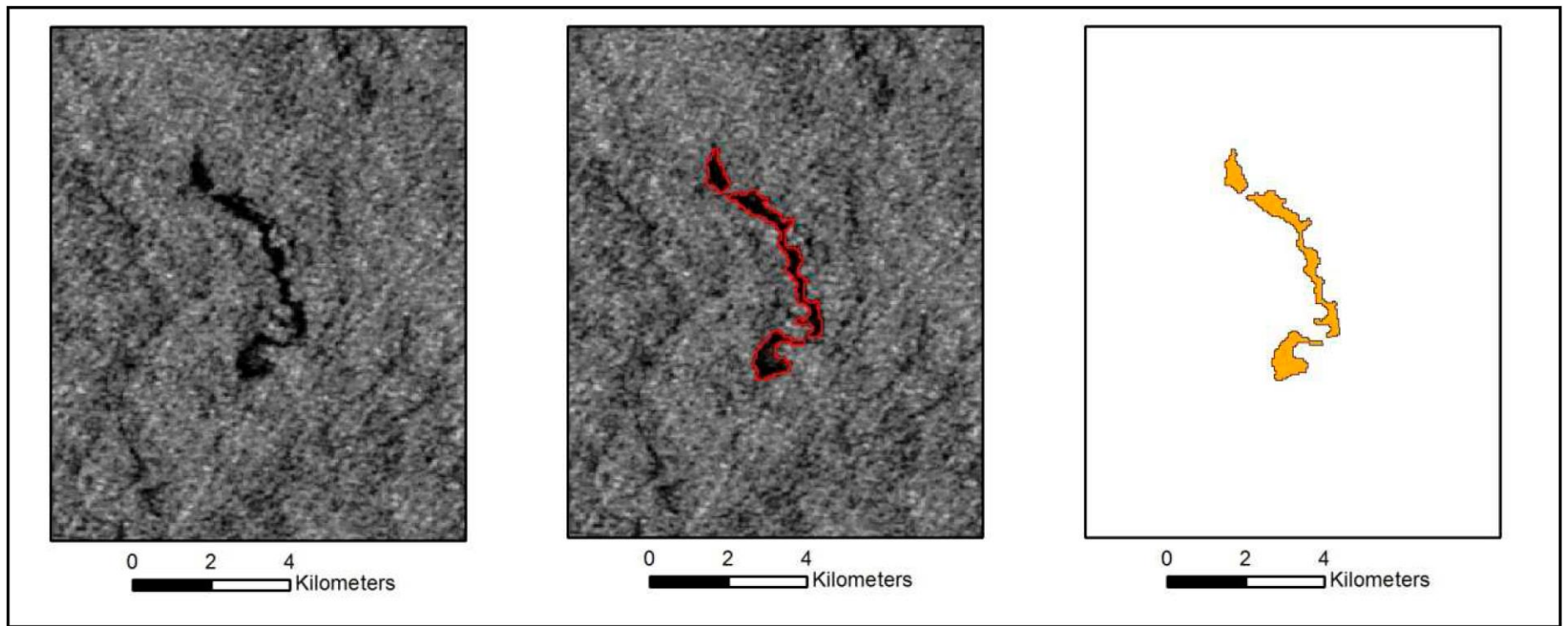Figure 4. Workflow of the methodology of the Oil Seep Inverse Modeling.

Figure 5. Example of a SAR subset with the result of an oil screening classification in a red vector and the polygon because of the thematic classification.
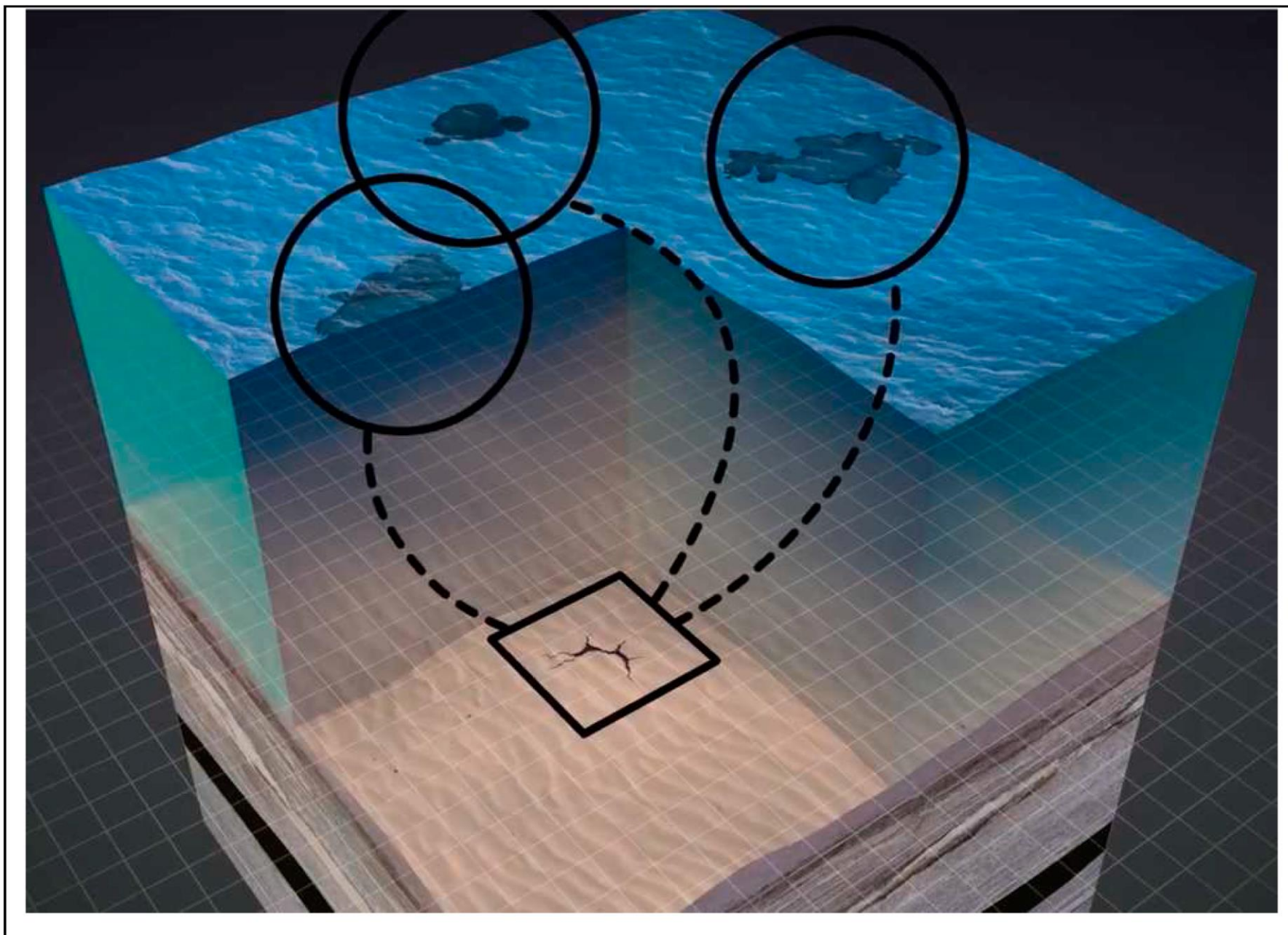
Figure 6. Inverse modeling concept showing the seeps on surface and their origin on the seafloor.
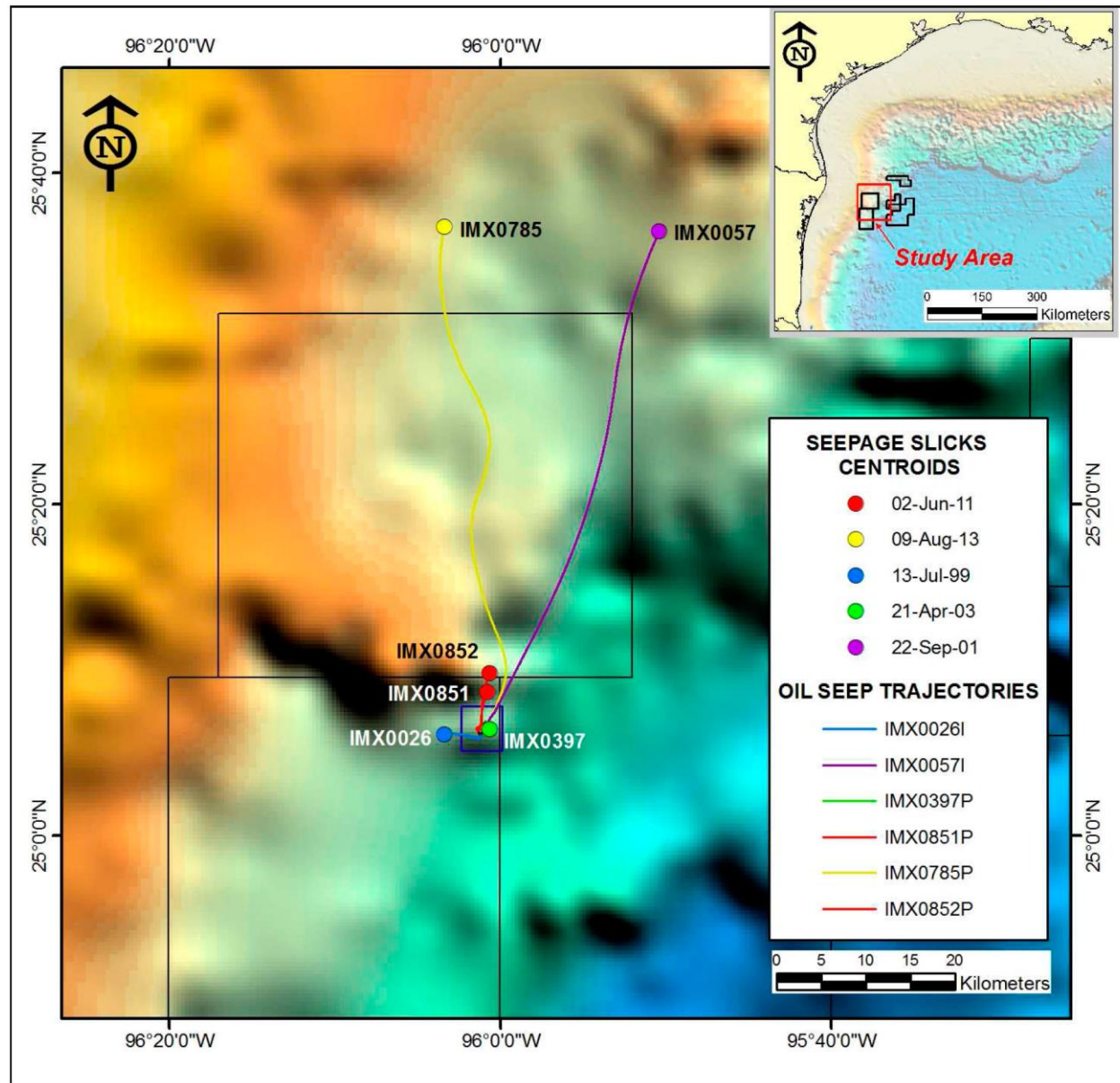
Figure 7. Detailed view of the Seep Area IMX062 (blue rectangle), the oil seeps identified on the sea surface (color dots meaning different data acquisition) and their trajectories (color lines) until the seep area. The blocks offered in the Bid Round 1 at Perdido Fold Belt are represented by black lines.
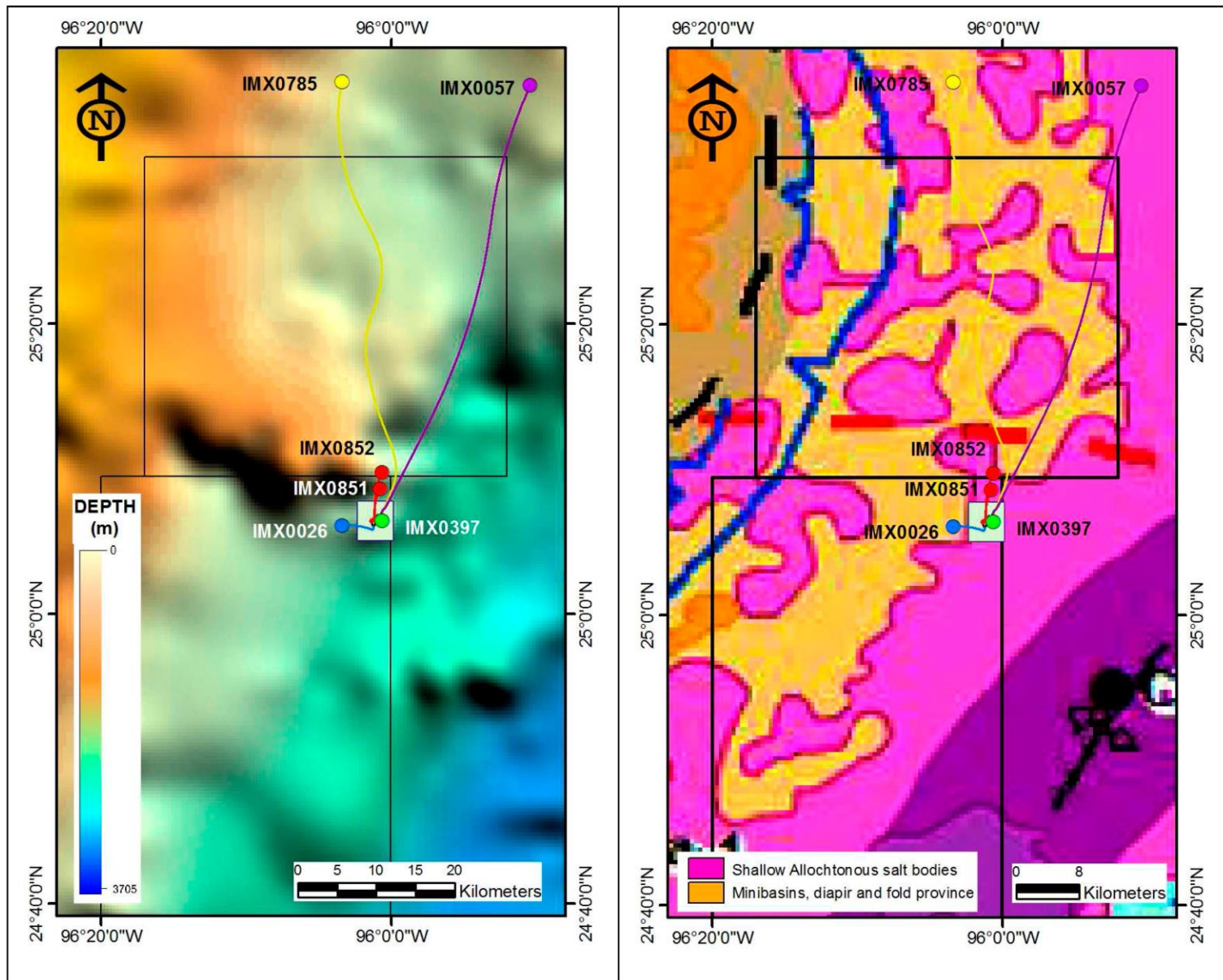
Figure 8. A - Seep area IMX062 and seepage slicks over the bathymetry raster image showing a very irregular sea floor topography (Blocks offered in the first Mexican bid round are in black); B - Seep area IMX062 and seepage slicks over the structural domains at Perdido Fold Belt province.

IMAGE	DATE ACQUISITION
1	13-JUL-1999
2	22-SEP-2001
3	21-APR-2003
4	02-JUN-2011
5	09-AUG-2013

Table 1. Synthetic Aperture Radar images used to map sea surface oil features.

ID	SAR DATE	LONGITUDE	LATITUDE
IMX0026	1999/Jul/13	-96.05560	25.10190
IMX0057	2001/Sep/22	-95.83970	25.60820
IMX0397	2003/Apr/21	-96.00986	25.10712
IMX0785	2013/Aug/09	-96.05577	25.61223
IMX0851	2011/Jun/02	-96.01214	25.14414
IMX0852	2011/Jun/02	-96.00985	25.16299

Table 2. Position on sea surface of the centroids of oil seeps that converged to the seep area IMX062.

SEEPAGE SLICK	LENGTH OF THE TRAJECTORY (km)
IMX0026	4.27
IMX0057	58.60
IMX0397	1.02
IMX0785	59.47
IMX0851	4.67
IMX0852	7.12

Table 3. Distances from the detection point of each seep to the seep area.

Seepage Slick	Longitude of the Origin	Latitude of the Origin
IMX0026	-96.02016	25.10013
IMX0057	-96.01327	25.10910
IMX0397	-96.01420	25.11430
IMX0785	-96.01662	25.10812
IMX0851	-96.02335	25.10635
IMX0852	-96.02250	25.10480

Table 4. Location of the source point of each seep that converged to IMX062.