Application of Stress Field Detection (SFD®) Technology for Identifying Areas of Hydrocarbon Potential in the Gulf of Mexico Region

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INTRODUCTION

PEMEX seeks to find innovative, environmentally-friendly technologies, which can complement their exploration programs and aid in the rapid identification of new prospects. In the Fall of 2012, PEMEX conducted an initial Stress Field Detection (SFD®) survey in onshore and offshore areas of the Gulf of Mexico region. The objective of this project was to obtain complementary geophysical data that supports seismic acquisition programs, to prioritize exploration opportunities, and optimize the use of resources.

The project was executed and NXT's recommendations were delivered at the end of 2012. This was followed by an extensive integration study conducted by PEMEX (PEMEX, 2012) that showed a significant correlation between the recommended SFD® anomalies and both the known oil fields and seismically identified structures of interest under study and evaluation. Additionally, SFD® anomalies were recommended in new areas where the petroleum system is well established and which are currently in the initial stages of exploration. In this paper, onshore and offshore case histories are presented, which demonstrate the capabilities of the SFD® technology.

EXPLORATION RISK

Once a petroleum system has been identified, geophysical exploration methods focus on assessing and mitigating geological exploration risks associated with trap configuration, reservoir quality and seal integrity. The inherent non-uniqueness of geophysical data and models demands that multiple independent datasets be used to develop integrated, geologically consistent earth models, which aid in mitigating technical risk.

No single geophysical method alone can satisfactorily address the non-uniqueness of the earth model. Geological risk mitigation is accomplished when several independent geophysical datasets such as seismic, gravity, full-tensor gravity (FTG), magnetic, and controlled-source electromagnetic (CSEM), are used in conjunction to reduce the number of possible models. The correlation of SFD® data with other geophysical, geological and engineering information is a fundamental step in assessing whether lead areas are then elevated to prospects, which can aid in risk reduction.

It is equally important to address the need to reduce the cost and time associated with hydrocarbon exploration. The SFD® system aids in rapid identification of prospect areas with potential trap, reservoir quality and seal integrity.

SFD® SYSTEM OVERVIEW

Methodology

The SFD® system utilizes quantum-scale sensors to detect gravity field perturbations induced by terrestrial stress energy variations, primarily in the horizontal plane. Significant subsurface discontinuities (anomalies) are inherently associated with and dependent on subsurface principal stresses (Bell, 1996; Zoback, 1998). As a consequence, the discontinuities will distort stress fields, resulting in a unique in-situ stress pattern. In addition to local effects, principal horizontal stresses define migration pathways, reservoir orientation and fluid expulsion (Baranova *et al*., 2011; Zeng *et al*., 2004).

The subsurface geological condition required for SFD® to detect gravity field perturbations due to stress variations in the horizontal direction is the occurrence of a structural and/or stratigraphic change (interface) with sufficient difference in elastic properties. An important source of elastic variations is the presence of trapped fluids (oil, gas, or water). Other sources include faulting / fracturing, over-pressure, major lithological changes and basin boundaries; generally, all major discontinuities will evoke a distinct SFD® response. For instance, if a dry rock body is in contact with a fluid saturated rock, the shear stress at the interface will be significantly reduced because fluids cannot support shear but the normal component of the stress remains continuous (Walley and Field, 2005). In general, the variation of shear component in reservoirs will result in the redistribution and orientation change of the stress fields. For the purposes of this paper, the term reservoir is used only in reference to porous rock containing trapped fluids.

Operation and Interpretation

The SFD® survey system is completely self-contained within the survey aircraft and utilizes 22 sensors (6 primary, 8 secondary and 8 Research and Development) flying at an altitude of roughly 3,000 m and a speed of approximately 500 km/h (Figure 1). A standard SFD® survey is normally flown in a grid pattern and is designed to detect anomalies with a linear extent of 2 km to 20 km. SFD® data are acquired at 2,000 samples/second and the output is displayed as voltage (V) vs. flight time (seconds). Anomalous areas which are identified during the SFD® interpretation process are assigned a relative ranking, indicative of the trap and reservoir potential.

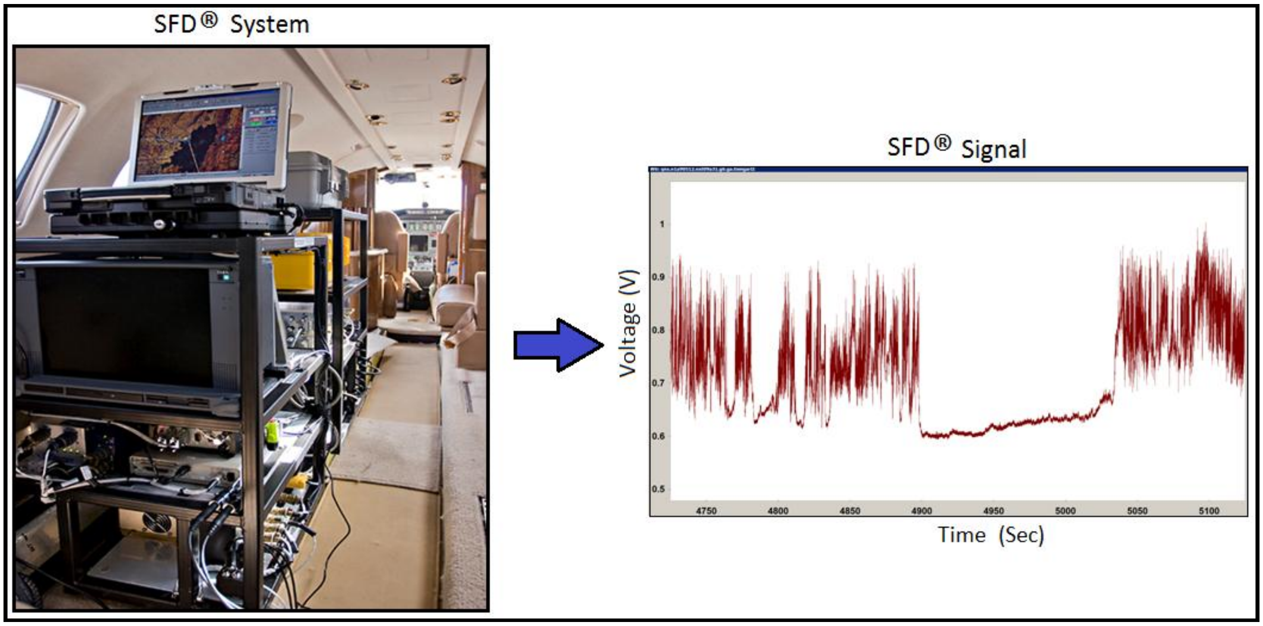

Figure 1: The SFD® system and a sample signal response over a 2.5 billion barrel field in Colombia.

Signal analysis (frequency, amplitude and character/pattern changes) and interpretation for each sensor are performed to identify prospective areas, without the aid of any *a priori* knowledge of the underlying geotechnical and engineering data along the SFD® flight path. The anomalies are also compared with NXT's database of SFD® signals that have been obtained over various geological features worldwide, which serve as templates for interpretation. SFD® anomalies are then ranked and then categorized according to prospectivity. For the purposes of this paper the sensor referred to as "String" is shown as an example of an SFD® signal.

Based on past experience, NXT has established that the area of investigation as identified by SFD® sensors is within 1.5 km on either side of the flight path. SFD® sensors adapt to the background stress field and only respond to the presence of an anomaly within the sedimentary column. At present, SFD® does not determine the depth of the anomaly or the type of trapped fluids.

SFD® SURVEY CONDUCTED BY PEMEX

The initial survey that NXT conducted for PEMEX in Fall 2012 focused on two objectives: 1) a "blind" test of the SFD® system over areas with significant proprietary geological and geophysical (G&G) information, and 2) identifying new prospective areas in the region. The survey area is geologically complex and covers the Salina del Istmo, Salina del Istmo Deep Gulf portion, Reforma Akal Pilar, Macuspana basins as well as the Sierra de Chiapas area and the Yucatan Platform. The sediments of these basins are terrigenous, carbonates, and in some areas there is presence of salt bodies.

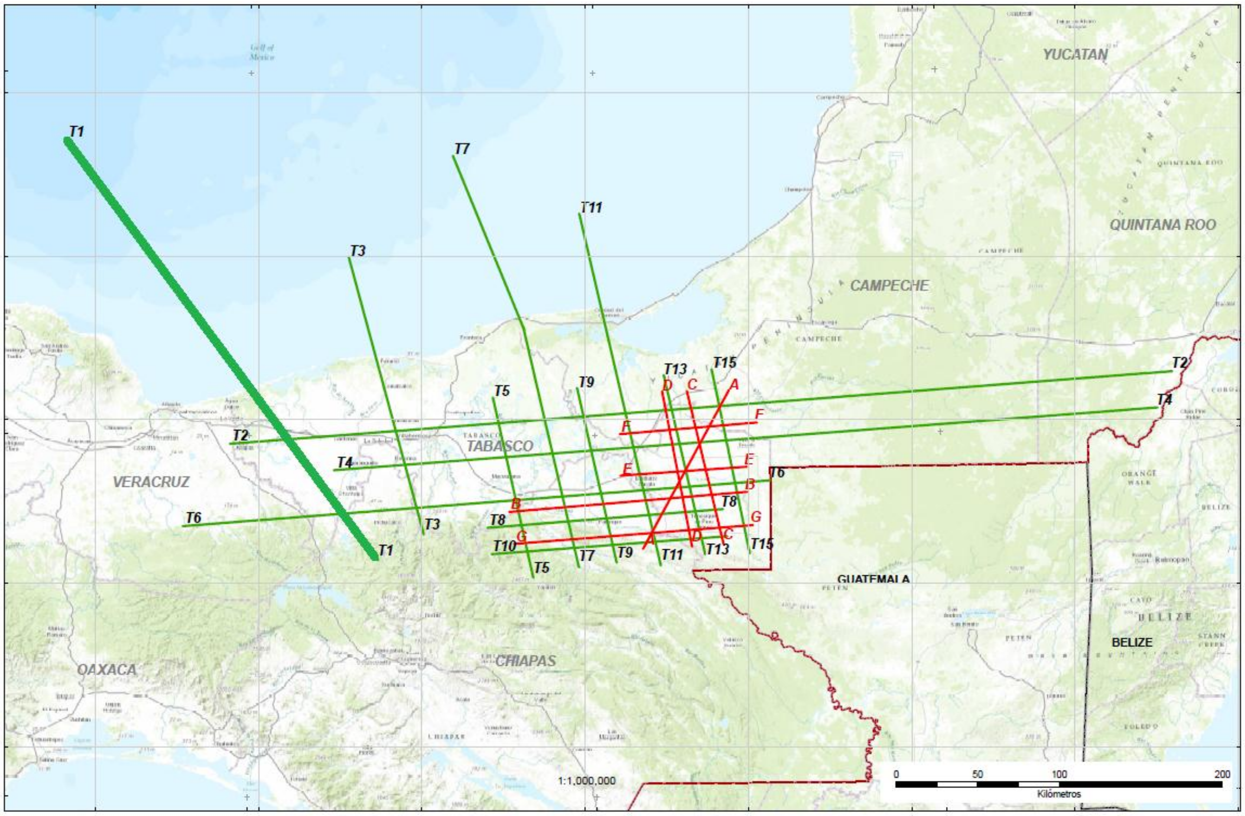

Figure 2: PEMEX 2012 SFD® Survey Program.

As shown in Figure 2, the program was conducted in two stages; the first program (green lines) of 3,188 line km was flown and PEMEX compared the initial results with its proprietary data. As a result, an additional 741 line km of SFD® was acquired (red lines), to increase data coverage within a particular area.

NXT identified a total of 72 anomalies within the boundaries of the surveyed area and ranked by prospectivity. Out of these 72 anomalies 16 were ranked as first order, 37 were ranked as second order and 19 were ranked as third order. Only the first and second order anomalies were recommended for further geological and geophysical investigation while the third order anomalies were recommended for additional SFD® flight coverage, perhaps from a different orientation or direction.

GEOLOGY

The lithostratigraphy of the region consists of the recent Pliocene, Miocene and Oligocene formations that are comprised primarily of terrigenous sediments. Cretaceous formations consist mainly of carbonate sediments which are in general naturally fractured. The Late Triassic and Early Jurassic formations basically consist of carbonates, continental clays and salt bodies whose age is considered to be Jurassic Callovian (Padilla y Sánchez, 2007; Lopez-Ramos, 1985, Sánchez-Montes de Oca, 1980). Presently, it is recognized that the main reservoir rocks are Miocene sandstones, Kimmeridgian and

Upper Cretaceous-Paleocene limestone, and that the hydrocarbon source rocks are mainly Tithonian Jurassic shales (Schlumberger, 1984; WEC Mexico 2009).

SFD® RESULTS AND CORRELATIONS

The integration results show significant correlation between SFD® anomalies and known hydrocarbon accumulations. The designed lines crossed a total of 64 known hydrocarbon accumulations of various sizes. PEMEX determined that SFD® successfully identified 47 of these known accumulations. Furthermore, these 64 accumulations represent an estimated total of 12,047.9 MMBoe of 3P reserves out of which the identified 47 accumulations represent a total of 11,918.7 MMBoe. The remaining unidentified 17 accumulations have a reserve total of 129.2 MMBoe that are primarily in isolated locations and have a linear extent of less than 2 km.

Furthermore, in areas of active exploration, it was shown that the SFD® anomalies exhibit significant correlation with seismically identified prospects as well as with prospects that were confirmed or located with other methods.

The results demonstrate that SFD® technology is capable of detecting geological traps with reservoir potential, irrespective of lithology. Moreover, the proximity to or position of salt bodies or water depth, does not inhibit the capabilities of SFD®.

The following case histories highlight the correlation of SFD® data in offshore and onshore scenarios with both known production and potential areas that are currently being investigated by PEMEX.

PMX-2.44, PMX-2.15, PMX-2.17, PMX-2.16 offshore and PMX-1.11 onshore SFD® anomalies along flight line T1 (340 km long) are used in this paper to illustrate their correlation with PEMEX seismic data (Figure 3).

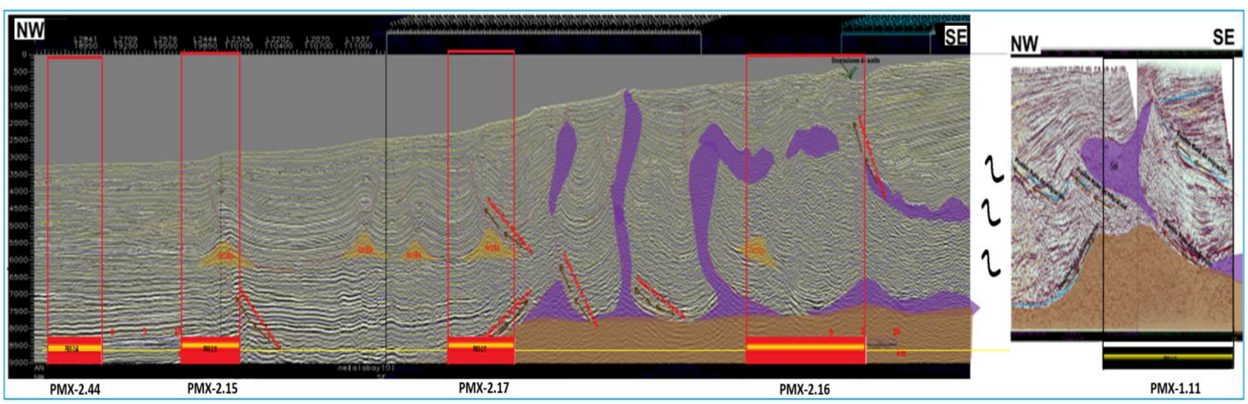

Figure 3: Seismic correlation with SFD® Anomalies

Case A: Offshore PMX-2.44, PMX-2.15 and PMX-2.17

The PMX-2.44 anomaly is located on a stratigraphic trap in the Deep Gulf of Mexico region where the water depth is between 2400 to 2600 meters. The target itself is located in the Upper Miocene approximately 3500 meters below the seabed. This prospect is currently in evaluation. The length of this anomaly is approximately 10 km (Figure 4).

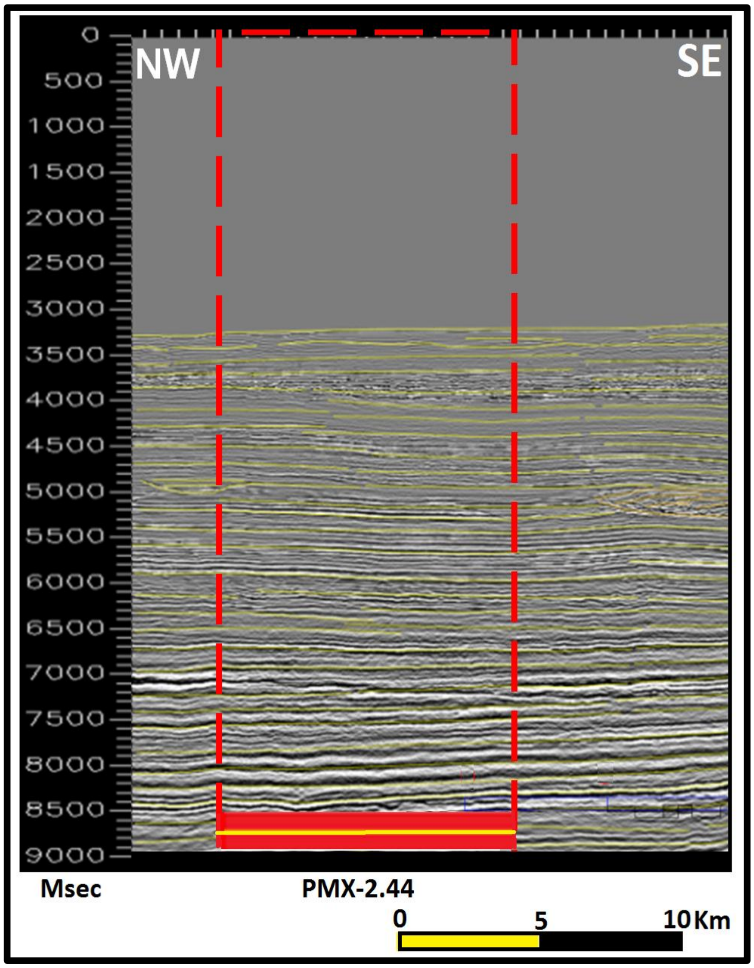

Figure 4: Seismic correlation with SFD® Anomaly PMX-2.44

The SFD® signal obtained over the PEMEX prospect PMX-2.44 is shown in Figure 5. Note that in general, when the baseline voltage is above 0.8 V anomalies will be recognizable around peaks and when the baseline voltage is below 0.8 V anomalies will be identifiable in the troughs. The upper bar represents the extent of the anomalous area while the lower bar represents the trap area. The center of the trap is at approximately 2760s where the strongest signal pattern and frequency changes can be observed.

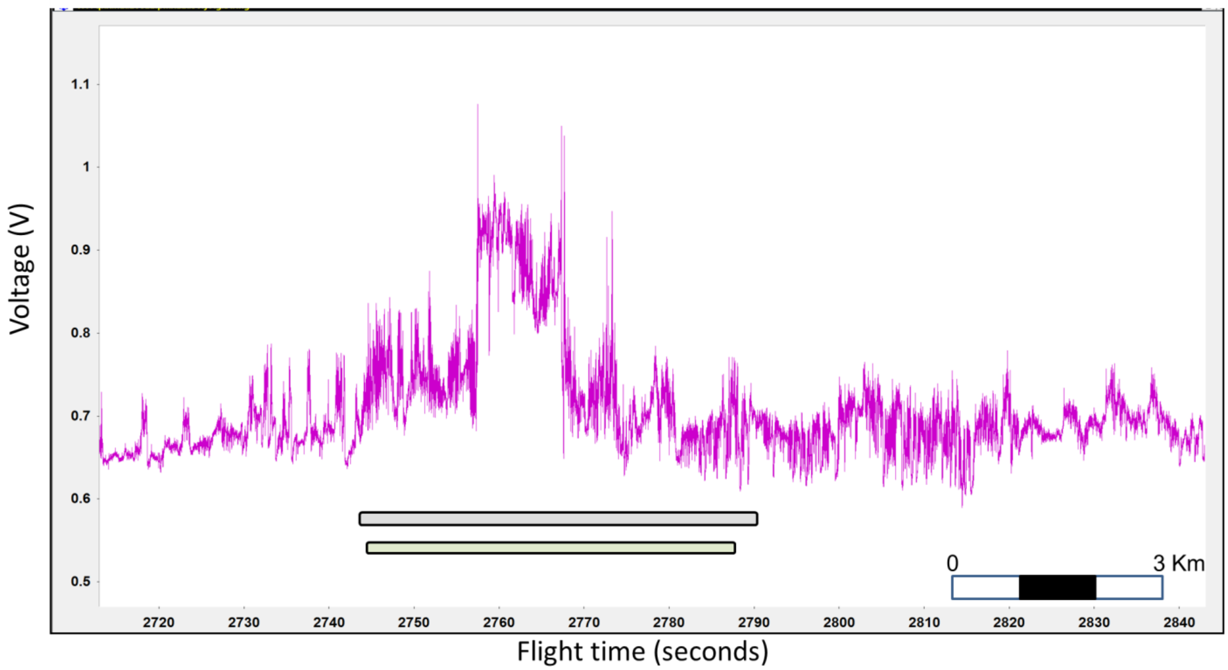

Figure 5: SFD® Signal over PMX-2.44

The second order PMX-2.15 anomaly is 9 km long, located in an anticline structure in the Deep Gulf of Mexico, where the water depth is between 2000 to 2500 meters. The main target is in the Upper Miocene approximately 2800 meters below the seabed, within sandstone and shale sequences (Figure 6). This prospect was a successfully drilled gas discovery.

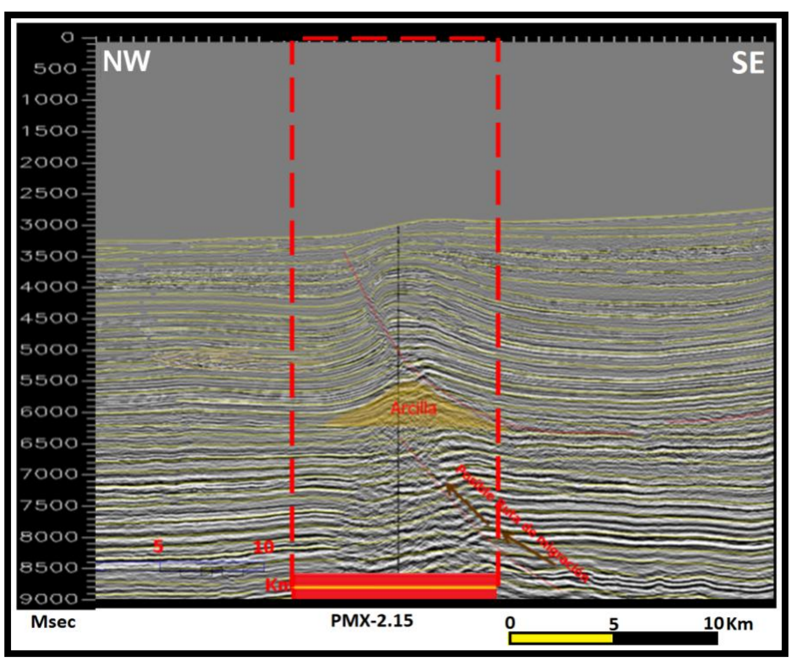

Figure 6: Seismic correlation with SFD® Anomaly PMX-2.15

The SFD® signal for PMX-2.15 is shown in Figure 7. The center of the trap is at approximately 2950s where the strongest signal pattern and frequency changes can be observed.

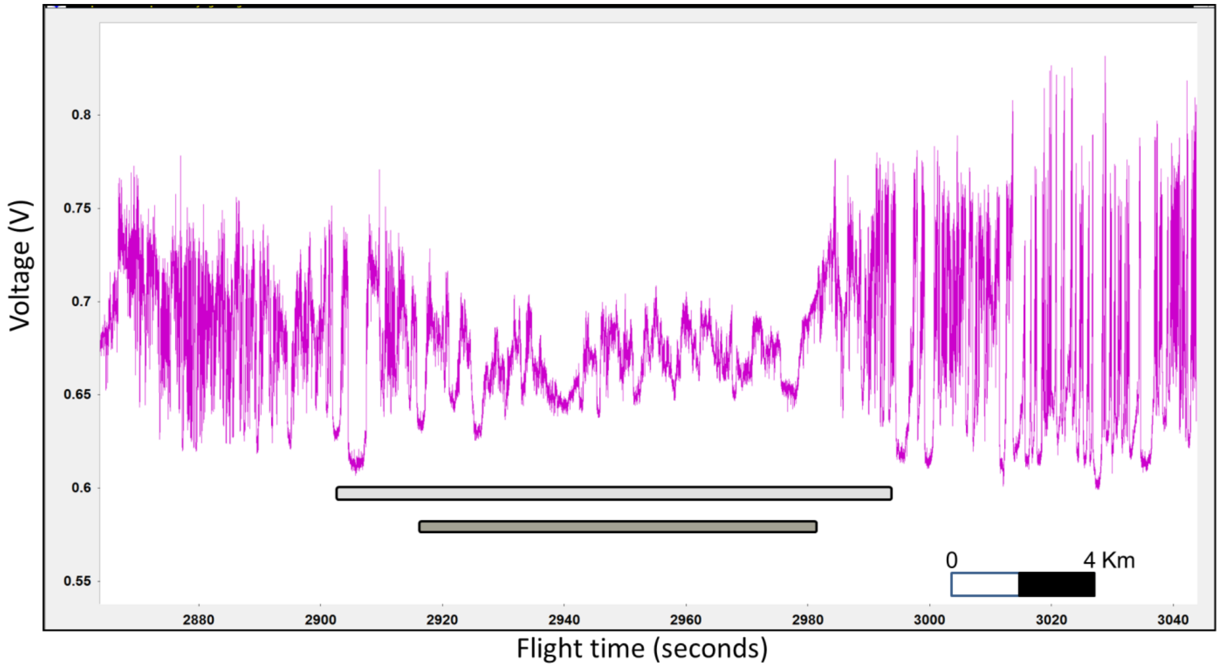

Figure 7: SFD® Signal over PMX-2.15

Studies in the PMX-2.44 and PMX-2.15 anomalies have been conducted with controlled source electromagnetic surveys (CSEM) that confirm the presence of resistive fluid in these structures (Figure 8).

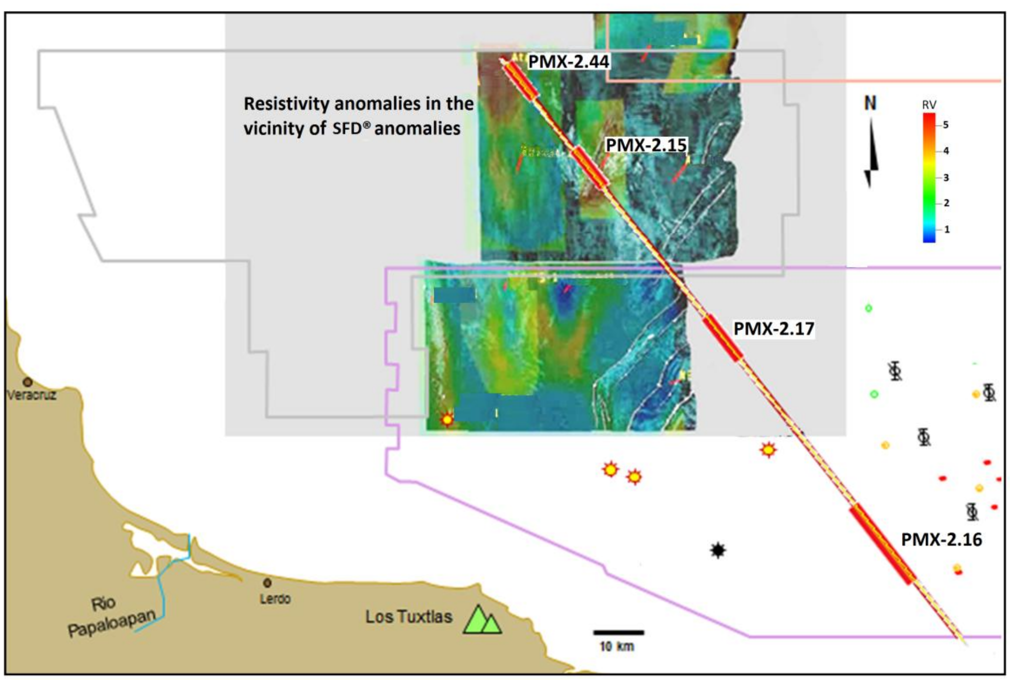

Figure 8: CSEM Resistivity anomaly correlation with the PMX-2.44 and PMX-2.15 SFD® anomalies

The second order PMX-2.17 anomaly is a 9.5 km long and is over an anticline structure in the Deep Gulf of Mexico, where the water depth is between 1300 and 1600 meters (Figure 9). The main target is in the Upper Miocene where the sediments are sandstone and shale sequences. This prospect currently is under evaluation and in a proven petroleum system with a high reservoir potential.

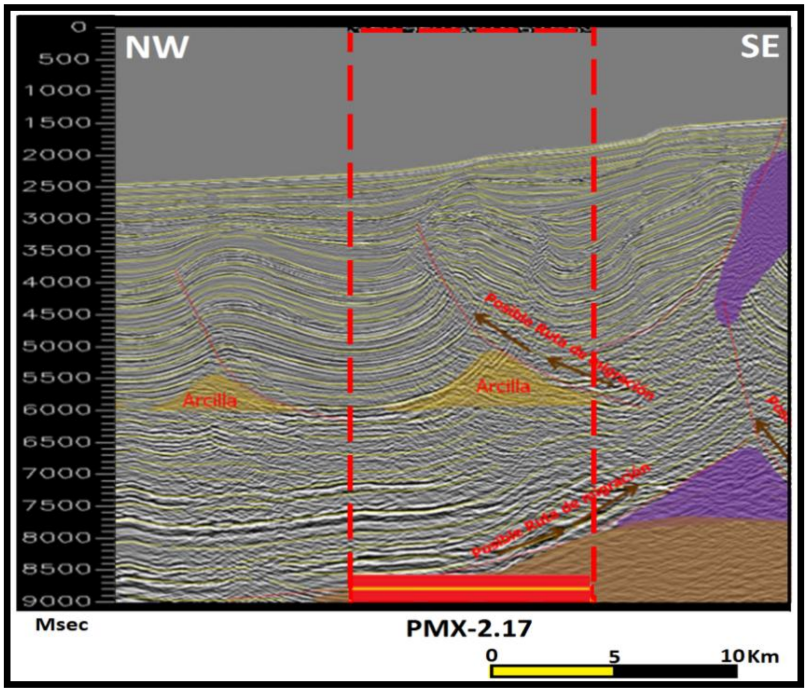

Figure 9: Seismic correlation with SFD® Anomaly PMX-2.17

The SFD® signal for this anomaly is depicted in Figure 10. The center of the trap is approximately at 3250 seconds where the strongest signal pattern and frequency changes can be observed.

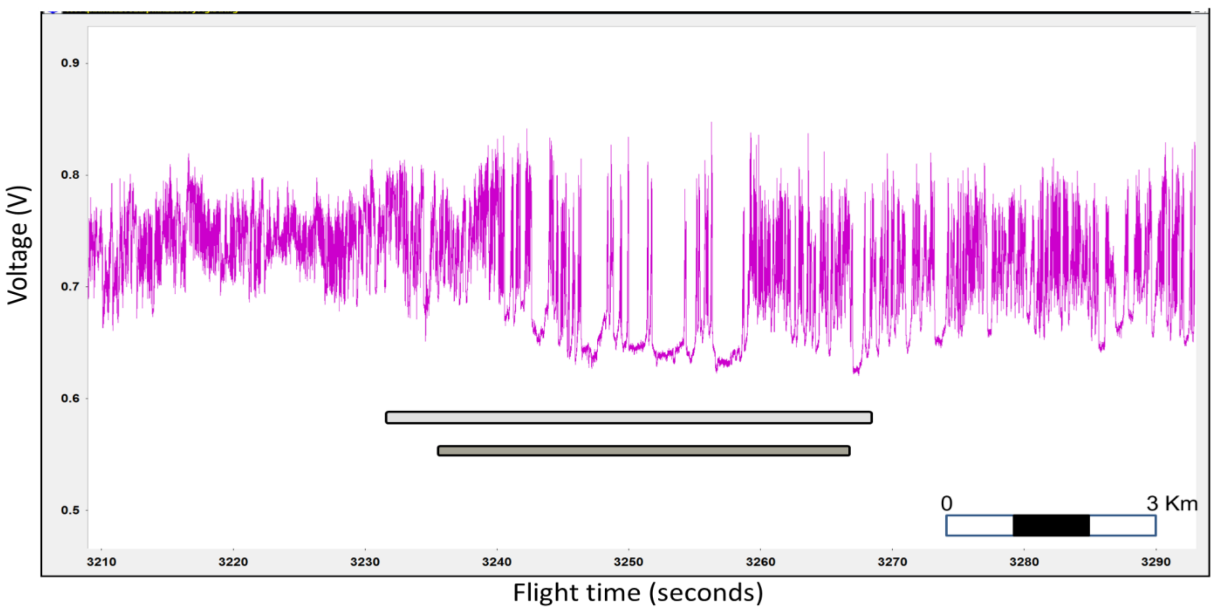

Figure 10: SFD® Signal over PMX-2.17

Finally, of particular interest are the two seismic structures, which were not recommended by SFD® (Figure 11). This area was considered during SFD® interpretation as having good trap indicators with diminished reservoir presence. Since the SFD® interpretation process is generally biased in favor of anomalies that show both good trap and reservoir development, such as the recommended PMX-2.17, this area was not recommended. It is further noted that the SFD® survey flight in this area was a single flight line, and thus may not have crossed the best portion of this anomaly. To increase confidence of identifying all relevant anomalies, NXT recommends performing SFD® surveys in the form of a grid, such as with 5 km x 5 km spacing.

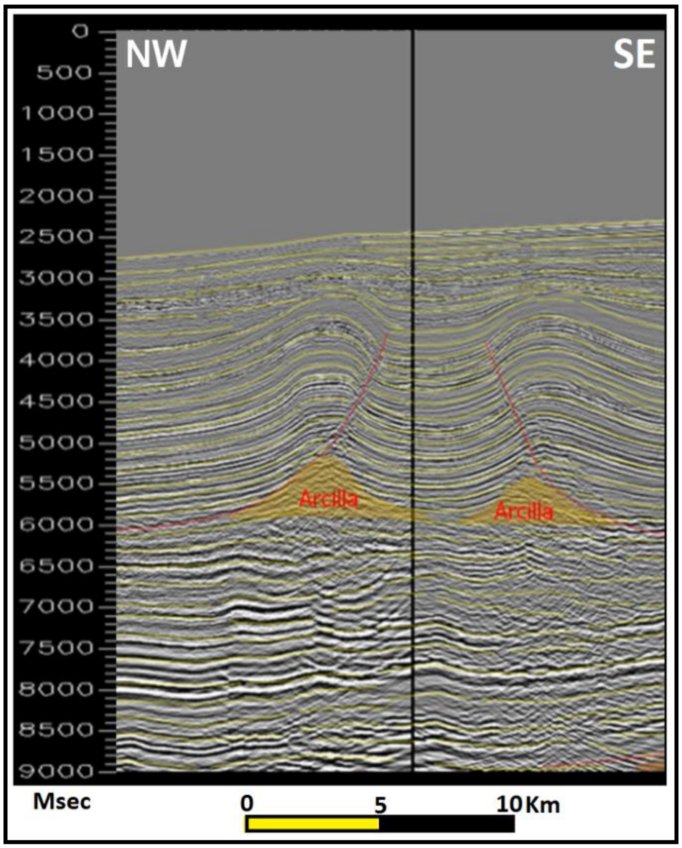

Figure 11: Seismic structures with weak SFD® signal response

Case B: Transition Zone PMX-2.16

PMX-2.16 second order anomaly is located on a combined structural-stratigraphic trap under a salt body in the Gulf of Mexico (Figure 12). The sediments correspond to Tertiary sand and shale sequences, where the water depth is between 300 to 550 meters. From a structural point of view, this trap is of interest since the salt body acts as a seal in the central portion and there is no apparent fault to allow fluid migration to the surface. However, multiple oil seeps have been detected via geochemical campaigns nearby. The extent of this anomaly is approximately 18 km. This area is currently under study. This case highlights the ability of SFD® to detect traps below or next to salt bodies.

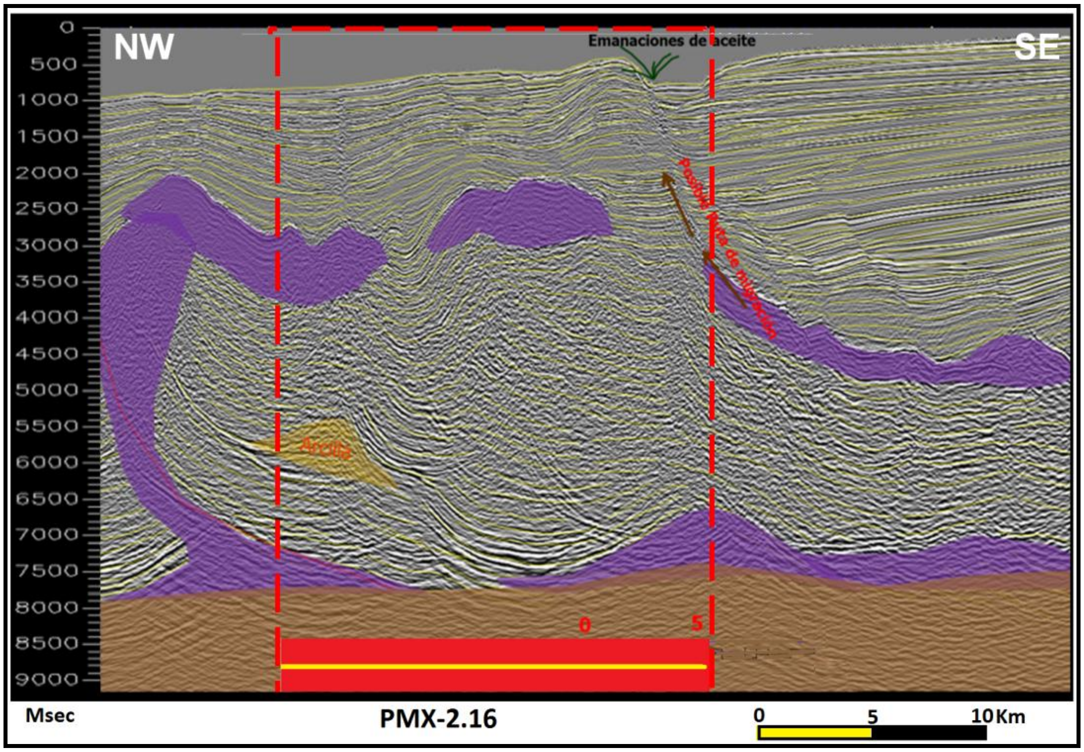

Figure 12: Seismic correlation with SFD® Anomaly PMX-2.16

The SFD® signal for PMX-2.16 is shown in Figure 13. This anomaly exhibits first order characteristics, however, it was recommended as a second order anomaly because it was only overflown once. The center of the trap is approximately at 3600s where the strongest signal pattern and frequency changes can be observed.

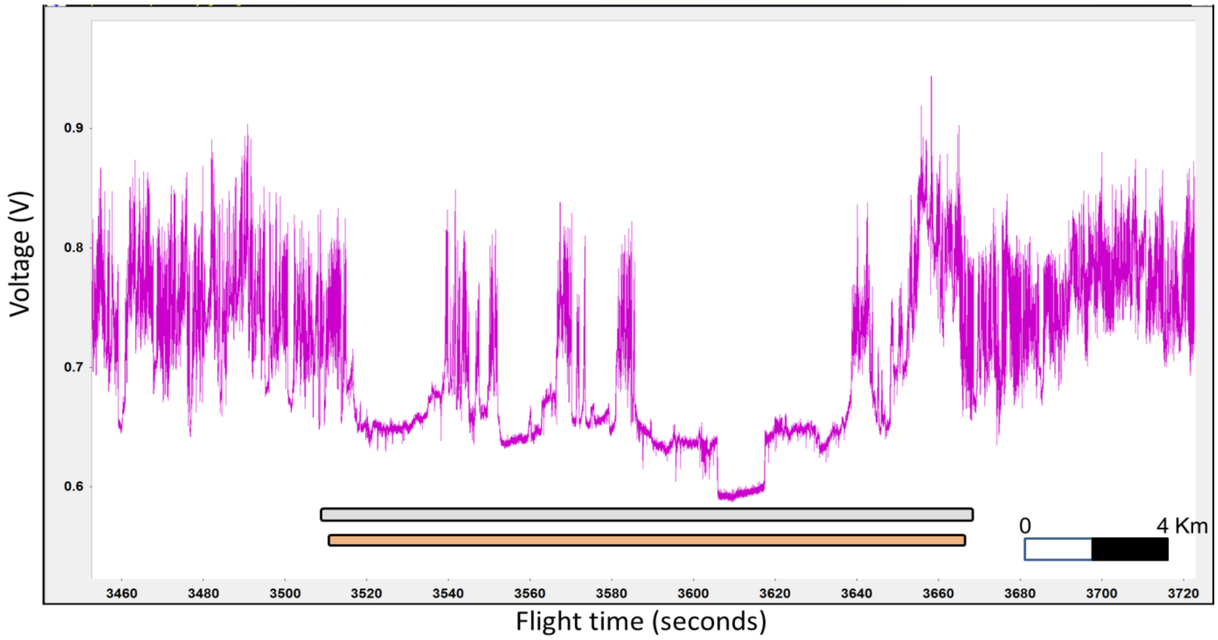

Figure 13: SFD® Signal over PMX-2.16

Case C: Onshore PMX-1.11

PMX-1.11 is a first order SFD® anomaly located over a structural trap associated with a salt body about 5 km long. In this area there are several important fields with oil and gas production in Tertiary formations in Tabasco State, with cumulative remaining 3P (proven, probable and possible) of 393 MMboe (Secretaría de Energía, 2012). This anomaly is approximately 22 km long (Figure 14).

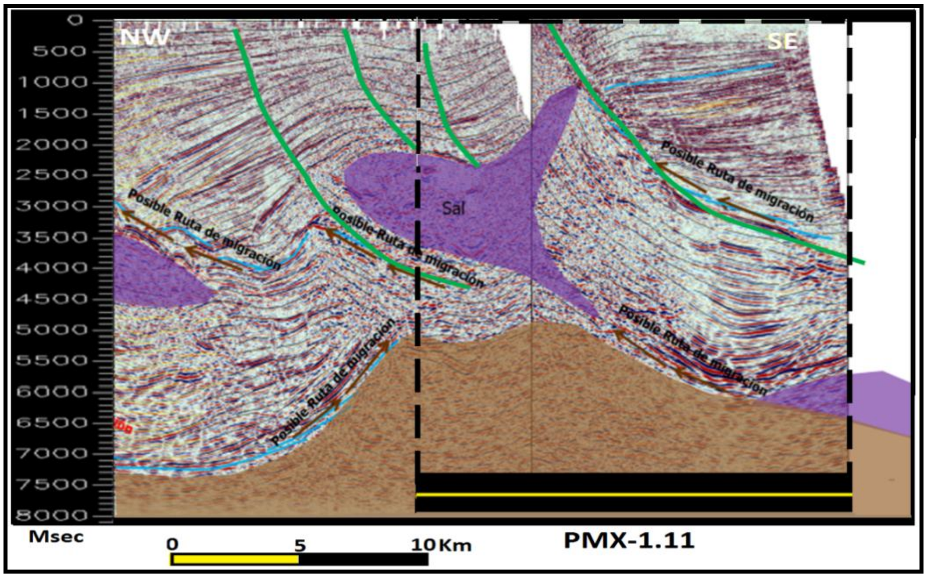

Figure 14: PMX-1.11 Seismic showing the structural trap and the associated salt body.

The SFD® signal for this anomaly is shown in Figure 15. The rapid evolution of signal amplitude suggests the presence of significant geologic changes. There are two highly anomalous areas centered at approximately 4190s and at 4290s. The signal relaxation events are indicators of excellent trap presence. This signal pattern has been observed in previous SFD® surveys over significant accumulations.

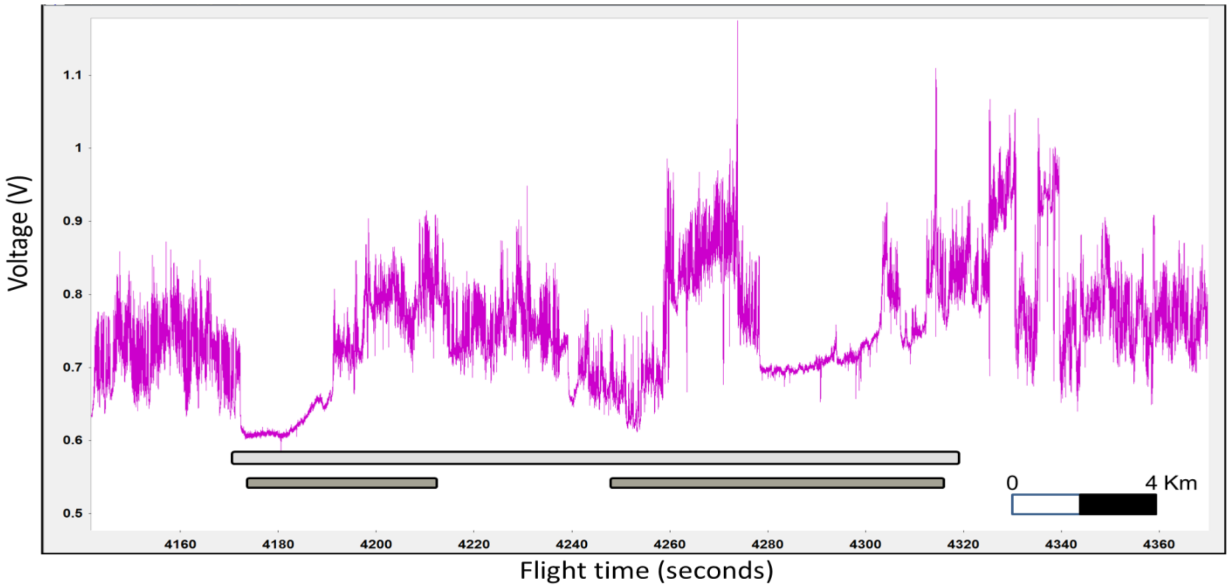

Figure 15: SFD® Signal over PMX-1.11

CONCLUSIONS

- Integration of PEMEX G&G data with of SFD® anomalies shows significant correlation with known hydrocarbon producing fields.
- SFD® anomalies have significant correlation with PEMEX seismically interpreted structures in active exploration areas.
- In regions with little or no existing G&G data, new areas of exploratory interest were identified by SFD®.
- SFD® is most effective at detecting anomalies with a linear extent greater than 2km.
- SFD® can detect geological traps which are prospective for storing fluids, regardless of the water depth or the presence of salt.
- SFD® is effective in both onshore and offshore environments.
- The SFD® system aids in rapid identification of prospect areas with potential trap, reservoir quality and seal integrity.
- SFD® helps focus and prioritize seismic programs.

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