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SFD® (Stress Field Detection) and its Integration with Seismic in Kharan Forearc Basin and its Implications for Hydrocarbon Exploration in a Frontier Area

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ABSTRACT

The SFD® technology, applied in numerous basins around the world, uses a unique quantum method to extract stress field anomalies and hence trapped reservoir information from the gravitational field. The gravity field acts as a carrier of stress induced energies that are the contributors to the gravitational field potential. Unlike traditional gravity measurement methods, the SFD® sensor can dynamically (integration of signal over time) and selectively (through resonance) interact with the gravity field and, as a result, is able to detect perturbations associated with trapped fluids (oil, gas and/or water) in the subsurface."

The Kharan Forearc Basin in Pakistan covers an approximately 30,000 km^2 area and is entirely obscured by superficial deposits of the Kharan desert. The regional geological analysis has been carried out by studying outcrops at Raskoh Range (Volcanic Arc) and Makran Accretionary Prism located just north and south of Kharan Forearc Basin respectively. The analysis shows that unexplored Kharan Forearc Basin could be a primary target for a potential Palaeogene petroleum system, a near perfect analogue of some of the world's producing forearc basins (Cook Inlet Basin, Alaska and Salin Basin, Myanmar). The trapping mechanism which is one of the key elements of a petroleum play, is difficult to envisage properly in the Kharan Forearc Basin due to presence of sand dunes at the surface, which enveloped the structural configuration of Kharan Forearc Basin.

For the purposes of locating an entrapment mechanism, a total of 1900 line km of SFD® data was acquired covering most of the Kharan Forearc Basin. The survey results have provided a series of high graded areas showing potential trapped reservoirs. A regional seismic survey has also been acquired recently which covered part of the anomalous areas identified by SFD®. Preliminary seismic interpretation and its integration with SFD® results has shown a reasonable correlation and an overlap of the SFD® identified anomalies and structural/stratigraphic leads indicated on seismic.

In addition to the SFD® survey in Kharan Forearc Basin, SFD® data was also acquired for templating purpose over some of the producing oil and gas fields in the Suleiman Ranges and Middle Indus Basin of Pakistan. The SFD® results over these fields provided a calibration point for SFD® data as well as demonstrating the technology's validity. These examples have further demonstrated that technology is applicable and conveniently applied for various structural/stratigraphic settings and field sizes. This study presents a case where integration of SFD® survey and 2D seismic has helped in mitigating the risk associated with trap failure as well as allowing a ranking of the identified structural/stratigraphic leads on seismic data in the frontier Kharan basin. The drilling of these leads will eventually provide a further test of the SFD® technology in such exploration settings.

SFD® TECHNOLOGY

The SFD® technology responds to horizontal stress changes caused by geological anomalies such as structures, fault systems, lithological changes and perhaps most importantly to reservoir accumulations. SFD® employs particle scale sensor elements for the detection of anomalies, which enable selective sensitivity to directional changes in the stress regime due to the variations of the subsurface poro-elastic properties.

The SFD® sensor system detects perturbations of the gravitational field that contains information related to stress changes. Regionally, tectonics determines the magnitude and direction of S_{Hmax} and S_{hmin} and it also defines the regional orientation of the horizontal gravity field maxima, which becomes significant considering the more uniform horizontal distribution of mass. In contrast local subsurface discontinuities will alter the regional direction of horizontal stresses (Figure 1). The resulting 'stress-states' cause perturbations in the gravitational field that are detectible by moving SFD® sensors. The SFD® sensor does not respond to slowly varying gravitational sources in any direction. However, it does respond to deviation from the background orientation of S_{Hmax} irrespective of the direction of SFD® survey flight. The effects of sub-surface discontinuities on the stress field cause an increase in S_{hmin} and a decrease in S_{Hmax}. Whilst the total energy entering and leaving the system remains constant, the (stress) energy distribution and orientation within the system can change significantly.

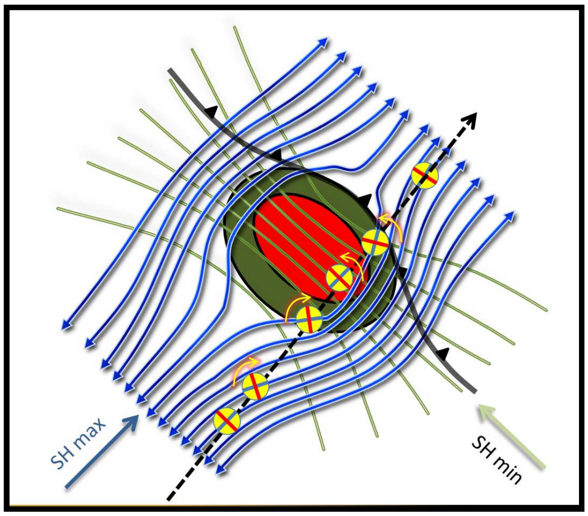

Figure 1: Horizontal stress orientation changes around a trap

The Kharan Forearc Basin is located in District Kharan, Baluchistan , Pakistan (Figure 2). The Kharan exploration blocks lie in the Kharan Trough which is a 150 km wide by 300 km long forearc basin bounded by the RasKoh Volcanic Range to the north and the Makran Accretionary prism to the south (Aziz et al., 2005, Khan et al., 2011). It extends to the Hamun-I-Mashkel Depression across the Iranian border to the west. The basin covers approximately 30,000 km^2 and is almost entirely covered by superficial deposits of the Kharan desert (Aziz et al., 2005, Khan et al., 2011).

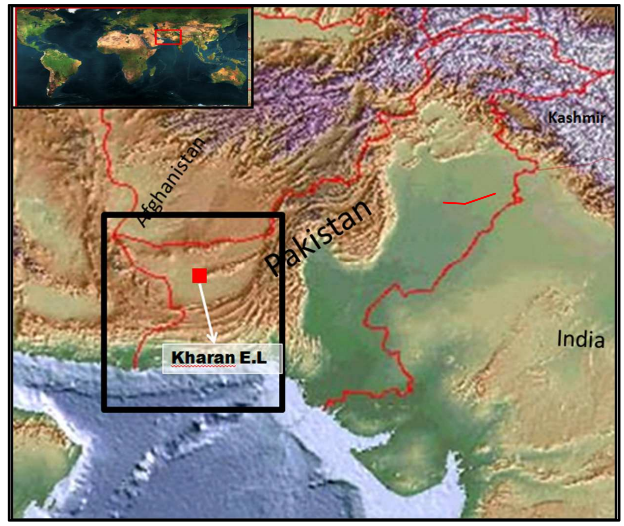

Figure 2: Map showing Location of Kharan Forearc Basin

TECTONIC SETTING

The Baluchistan Province is an Upper Cretaceous structurally defined basin related to under-thrusting of the Arabian Plate beneath the Eurasian margin (Farhaudi and Karig, 1977, Jacob and Quittmeyer, 1979, Arthurton et al., 1982). It is bounded by the major Chaman-Ornachnal Fault Zone to the east and Makran Accretionary Prism in the south.

The Kharan Forearc Basin is a part of the arc– trench system of Arabian and Afghan tectonic plates Jacob and (Quittmeyer, 1979). There are two main prospective zones: Kharan-Mashkhel Trough/Forearc Basin and the Makran Accretionary Prism (Khan et al., 2011, Aziz et al., 2005) (Figure-3)

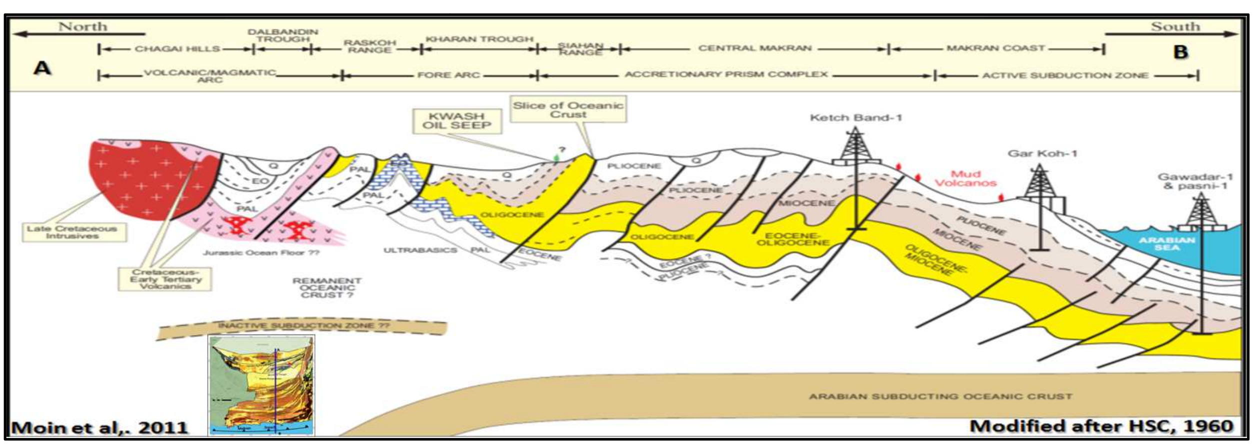

Figure 3: Tectonic setting of Baluchistan Basin (Khan et al., 2011)

STRATIGRAPHY & PETROLEUM SYSTEM

The Baluchistan Foldbelt Basin is characterized by Late Cretaceous and Tertiary successions composed of limestone, mudstone, sandstone, and volcanic (Siddiqui, 2004, Khan et al., 2011). Fault bounded slices of metamorphosed Jurassic ophiolites, radiolarian cherts and accretionary mélange are overlain by thick successions of Cretaceous basinal muds, pillow lavas and volcaniclastics recording the evolution of volcanic island arc (HSC, 1960, Siddiqui, 2001, Aziz et al., 2005, Khan et al., 2011). The volcanic successions are overlain by Late Cretaceous limestone and thick succession of Paleogene turbiditic shale, sandstone and conglomerate of the Rakhshani Formation. This was following a period of uplift and relative tectonic stability in the Eocene recorded by platform carbonates and basinal muds. These sediments are overlain by deep marine muds and distal prodeltaic turbidites of the Oligocene, which shallow upwards in the east into delta front sands and muds of the Oligocene Nauroze Formation (Khan et al., 2011). Terrestrial to shallow marine clastic and carbonate sediments of the Amalaf Formation were deposited, interrupted by episodic explosive volcanic activity. The Miocene and Pliocene are dominated by continental conglomeratic facies of the Dalbandin Formation (HSC, 1960, Khan et al., 2011). The Mid-Pleistocene to Recent time was dominated by uplift across the Baluchistan , which led the deposition of Kamerod Formation (Figure-4).

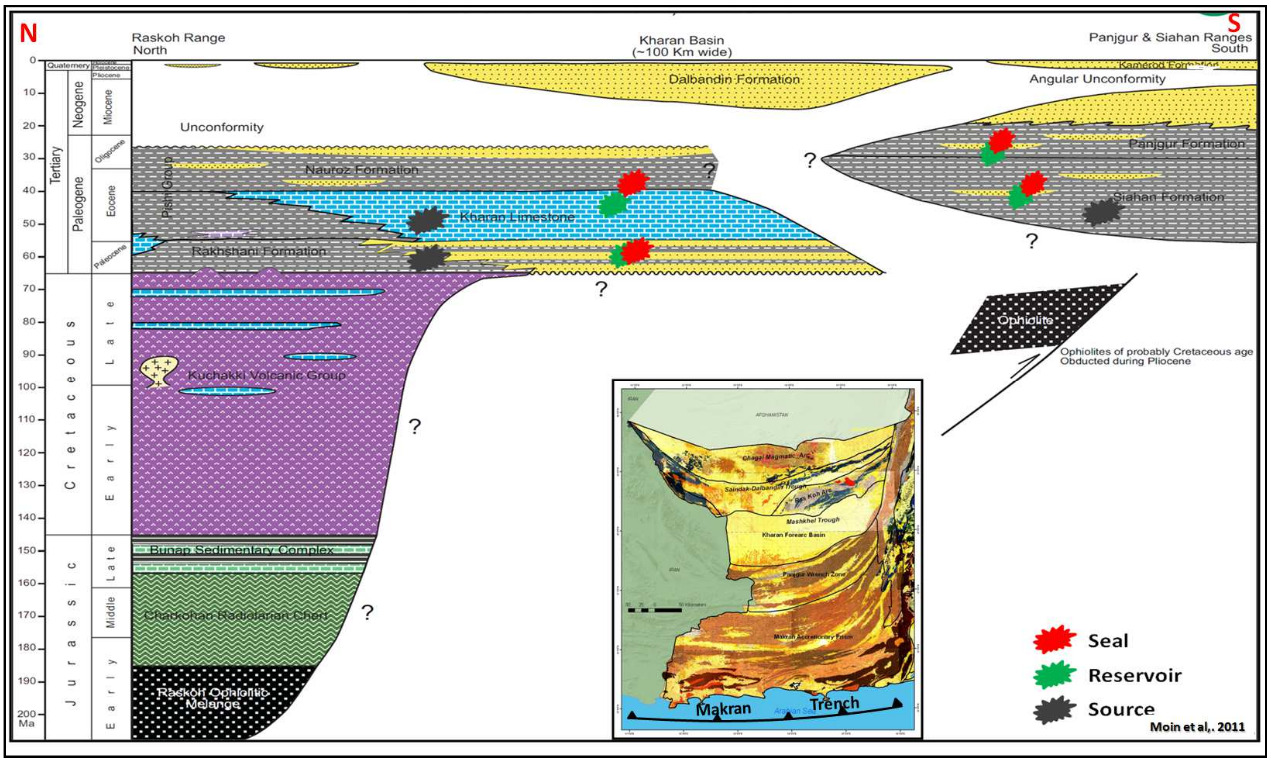

Figure 4: Stratigraphy of the Kharan Forearc Basin (Khan et al., 2011)

There is no oil and gas discovery in the basin so far, however, the potential can be determined through analysis.

The potential source rocks of the area are Rakhshani Formation of Paleocene age and Early to Middle Eocene Kharan Limestone. Rakhshani Formation of Paleocene age contains source horizons in shale layers. Its source potential in terms of Total Organic Carbon content is moderate to good. Kharan Limestone has a fetid odor and the basal part of the formation, which is composed of wackstone, deposited in an environment favorable for the accumulation and preservation of organic matter. These source rocks are presently predicted to be mid to late-mature for oil generation and mature for gas generation (Khan et al., 2011, Aziz et al., 2005).

Paleocene sandstone of Rakhshani Formation, Eocene limestone of Kharan Formation and sandstone of Nauroze/Amalaf Formation of Oligocene age are the potential reservoirs in the basin. The Rakhshani Formation sandstones have favorable reservoir quality in the outcrops. Kharan Limestone is massively bedded, vuggy, and cavernous and has favorable reservoir characteristics. The Oligocene sequence is composed of shelf-marginal marine sandstones and deep-water turbidites. In outcrops these sands have good reservoirs characteristics (Khan et al., 2011).

Intra-formational shale of Rakhshani, Kharan/Saindak and Nauroze formations have the potential to act as seal. Based on the tectonic setting of the Baluchistan Foldbelt Basin the trap types can vary from highly complex to simple. In the area adjacent to the Chamman Fault System, which is a transform plate boundary, highly complex structures are expected. Further west of the Chamman Fault, in the Mashkeland Dalbandin troughs, less complex thrusted anticlines, pop-ups and fault propagation folds are expected (Khan et al., 2011).sandstones have favorable reservoir quality in the outcrops. Kharan Limestone is massively bedded, vuggy, and cavernous and has favorable reservoir characteristics. The Oligocene sequence is composed of shelf-marginal marine sandstones and deep-water turbidites. In outcrops these sands have good reservoirs characteristics (Khan et al., 2011).

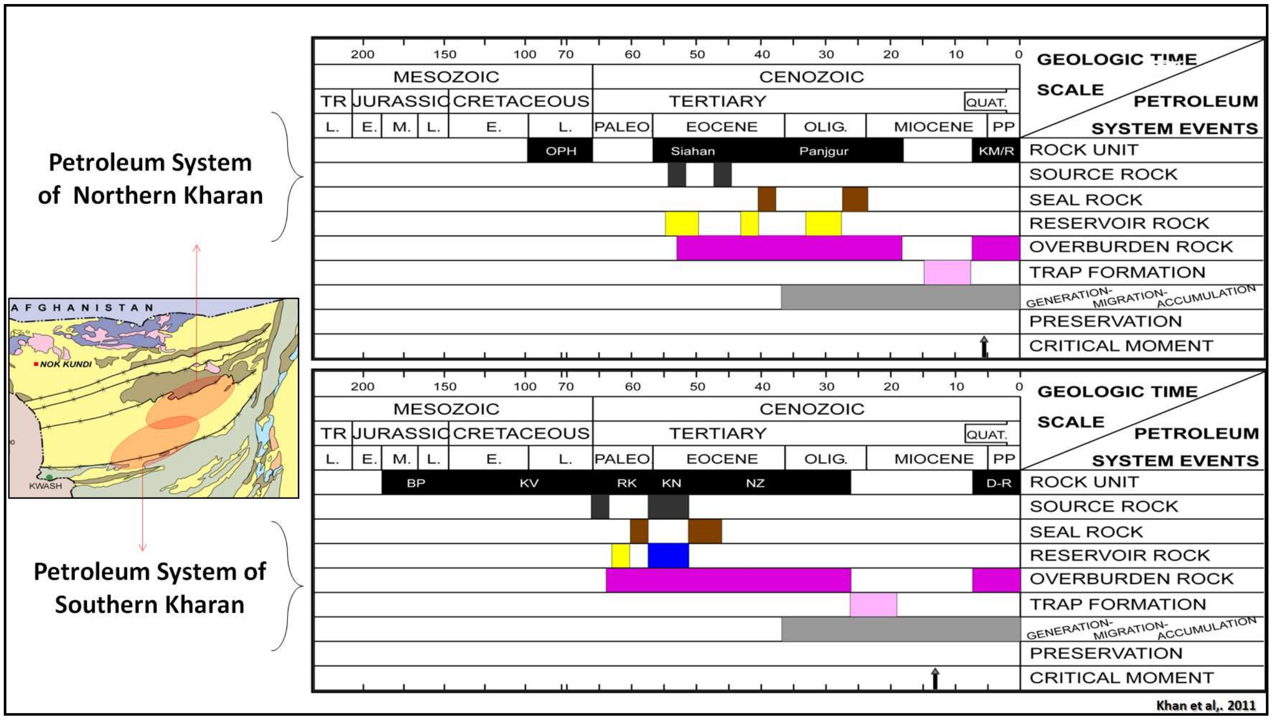

Figure 5: Petroleum System of the Kharan Forearc Basin (Khan et al., 2011)

SFD® SURVEY AND RESULTS

Due to the remoteness, hard terrain and security issues associated with the Kharan area a Stress Field Data survey (SFD®) was planned for delineation of areas prospective areas for focused exploration activities. The SFD® survey was conducted simultaneously with the 2D seismic survey. The SFD® flights commenced on December 11th 2012 and were completed on January 4th 2013. Twenty nine SFD® flight lines were conducted in the Kharan blocks (Figure 6). Four SFD® flight lines were re-flown in order to ensure maximum data quality. No significant weather problems were encountered during the Kharan SFD® survey and all flight parameters (altitude, speed, trajectory, turbulence, turn radii and GPS coverage) were within NXT established and accepted values.

All flight lines were interpreted and identified and ranked a total of twenty one lead which were further subdivided in order of prospectivity into five primary, twelve secondary and four tertiary leads. The SFD® ranking method is a qualitative and relative grading system; therefore the assigned SFD® ranks are unique and only pertain to the identified lead areas. The trap potential of the primary and secondary lead areas is clearly identified and well represented by the SFD® sensor responses. The dominant response of the SFD® sensors is by way of an amplitude, frequency or character change to the presence of trapped fluid (e.g. – oil, gas, water etc.) in the

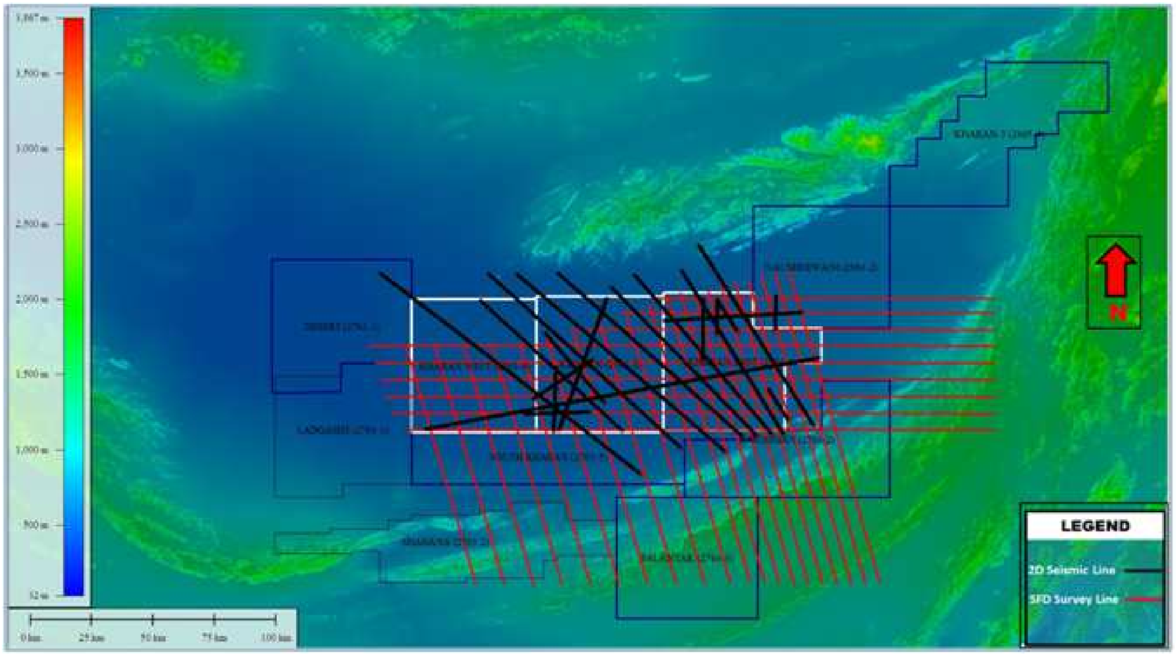

Figure 6: SFD® Flight Lines in the Kharan Exploration Blocks

subsurface. SFD® signal responses do not necessarily differentiate between the types of trap – structural, stratigraphic, some combination thereof or otherwise.

The primary and secondary SFD® anomalies exhibit similar trap characteristics but are differentiated by the strength and quality of the reservoir attributes (frequency and pattern changes) in the SFD® signal response while the tertiary lead areas are characterized by more moderate trap responses and compartmentalized / minor reservoir indicators. As a result these tertiary areas may be representative of geological events such as faulting, fracturing or other lithological changes.

One of the primary SFD® lead areas was selected for the initial integration with available geological and geophysical data i.e., seismic section and structure maps. The SFD® anomaly has strong reservoir indicators as demonstrated by the frequency responses on primary SFD® sensors. Trap development is shown by the amplitude changes and a pronounced "closure" to the signal. Overall the sensors show all the required major signal attributes - frequency, amplitude and character changes. Furthermore this lead exhibits a high level of confidence because the aforementioned signal characteristics are observed on the multiple line crossings of different orientations.

The lead areas have very good correlation with the seismic results (Figures 7 & 8). The correlation of SFD® lead area with seismic allows some insight into the possible trapping areas. The lead area exhibits all the aspects of a trapping system and also contain indicators of an older rift sequence below the basal unconformity on seismic. The down lap and truncation of the possible Paleocene strata above the basal unconformity makes the case for a very good trapping configuration. In addition a prominent possible Paleozoic basin exists which could lead to the potential of an additional older source rock.

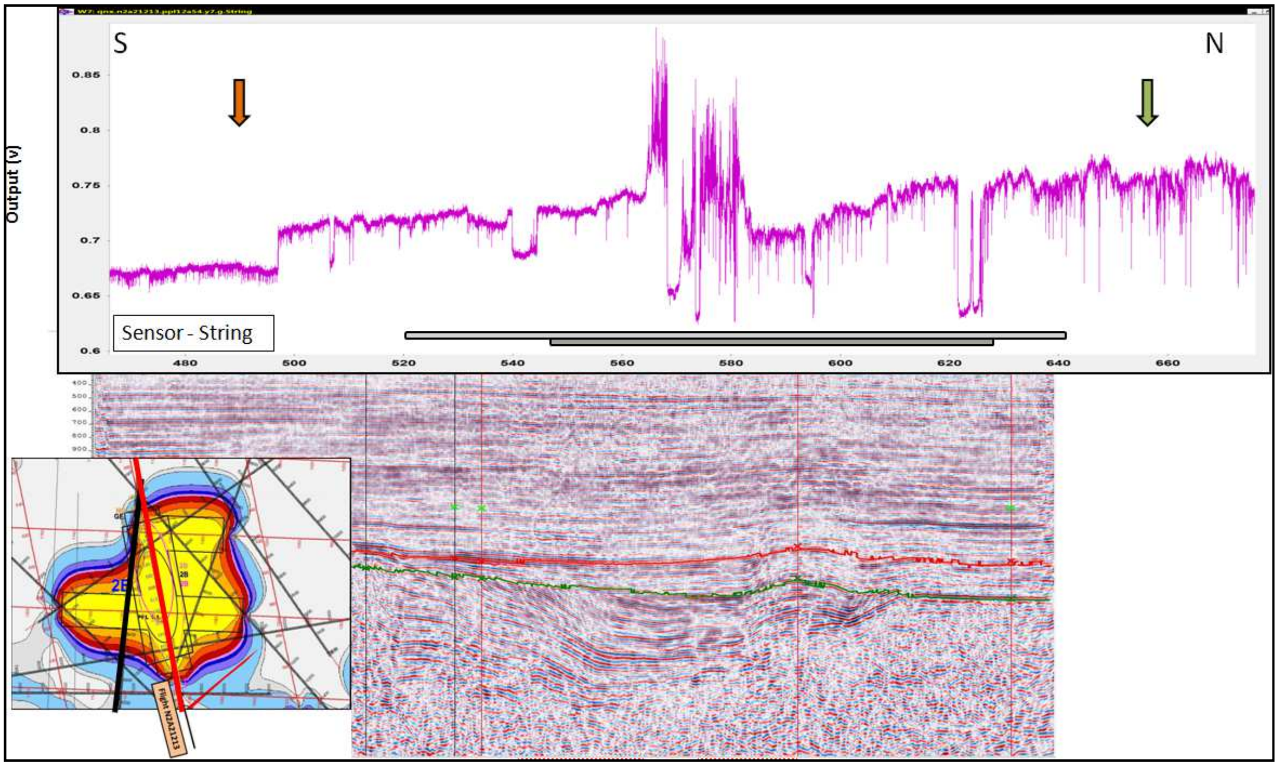

Fig.7: SFD® and Seismic data correlation and Interpretation

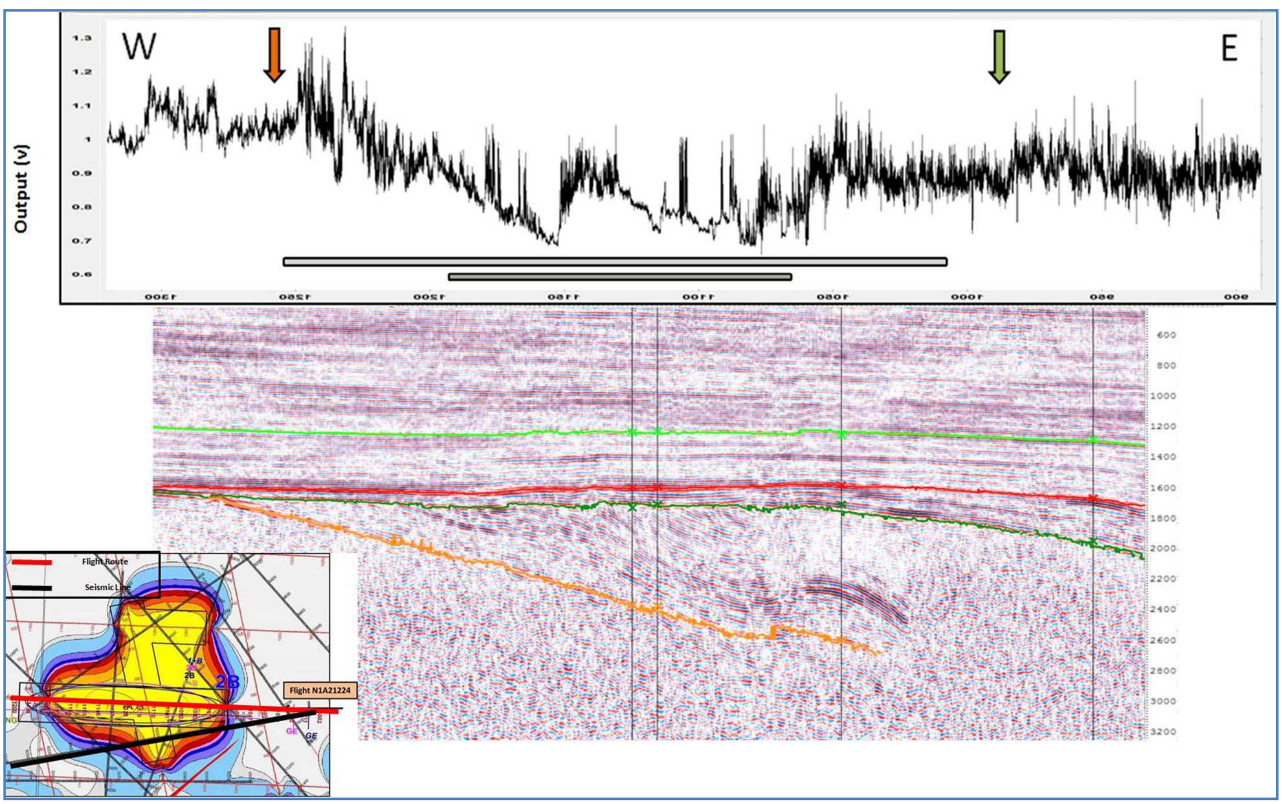

Fig.8: SFD® and Seismic data correlation and interpretation

CONCLUSIONS

NXT has identified and ranked a total of twenty one SFD lead areas; five primary, twelve secondary and four tertiary in the Kharan Forearc Basin which required seismic to map the traps. The SFD ranking method is a qualitative and relative grading system - therefore SFD ranks assigned are unique and only pertain to the lead areas identified. The integration results show significant correlation between SFD® anomalies and prospective area evaluated using seismic and geological data sets. The results demonstrate that SFD® technology is capable of detecting geological structural elements in Kharan Forearc Basin area that could act as fluid traps.

SFD® does recognize the major traps and also provides indications of faults. The SFD® data is very useful in high-grading the areas when used in conjunction with regional geology and geophysics to minimize the risk associated with the trapping of reservoir. Although SFD® is a very powerful reconnaissance tool for wide area exploration; it does not stop there in any way. Once the other datasets like seismic, wells etc. are integrated with the SFD® results, it becomes a verifying tool and may be used to high-grade the prospective trap areas. The use of SFD® as an independent tool can help reduce the exploration risk.

This paper is intended to define the role of SFD® in an exploration scenario over frontier areas and its scale of investigation and limitations.

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Moin R. Khan received his B.Sc. (Hons) & M.Sc. degrees in Geology from the University of Karachi and MS in Geosciences from the University of Tulsa in 1985. Soon after his return, he joined Pakistan Petroleum Limited where he is presently working as Deputy Managing Director looking after Exploration, International Assets, Production and Petroleum Engineering & Development Functions. During his stay outside PPL during 1994-2004, he has worked in various companies i.e. UTP (converted into ARCO, then BP and now UEP), Lasmo and Eni at different technical and management positions. During his tenure with UTP he was posted in Houston for a brief period; and during his association with Lasmo/Eni he was seconded to their London office from August 2000 to October 2002, where he worked as Team Leader on various international exploration projects extending from North Sea to East Africa, Middle and Far East.

Moin has presented several technical papers in various national and international conferences. He remained Chairman PAPG from April 2010 to 2013. He is a keen public speaker on a variety of E&P topics.

George Liszicasz is the inventor of the Corporation's SFD® technology and has been Chairman and Chief Executive Officer since the Corporation's inception in 1996. He was born in Hungary where he received his degree in Electronics in 1975, and later attended the University of British Columbia, majoring in physics. Mr. Liszicasz is an inventor of a number of novel technologies, including electronic control systems, medical lasers and geophysical instruments.

Mr. Liszicasz' primary responsibilities as the President and CEO are to oversee all operations and to further develop the SFD® technology.

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