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Key words

Low Frequency Passive Seismic (LFPS), Broadband (BB) seismometers, V/H Ratio, Power Spectral Density (PSD),

Abstract

Low Frequency Passive Seismic (LFPS) method uses the energy of extremely low amplitude & low frequency micro-tremors generated from natural seismicity of earth. Majority of these survey are reported in onshore areas. The LFPS data are recorded on earth's surface using very high sensitive 3C Broadband sensors.

It is observed that spectral attributes of these events indicate anomalous response over hydrocarbon pools in 2-4 Hz range. The study focusses on calibration at known well location and then to analyse nearby unknown targets.

LFPS is a cost effective Prospect ranking passive imaging tool. It has high potential in risk mitigation of development & exploratory drilling and value addition for Petroleum Exploration & Production in India.

Introduction

Seismic methods can be broadly divided in three groups depending upon the type of energy source - **Conventional, Triggered** or **Induced** and **Passive** Seismic. Conventional Seismic uses External sources like Explosives, Vibrators, Airguns etc., Triggered or Induced Seismic uses energy from induced activities like fractures during Hydro fracturing whereas Passive Seismic does not use any external source rather uses energy of micro-tremors generated from natural seismicity of earth. Passive Seismic events are usually extremely low amplitude & low frequency in 1-10 Hz range. These are recorded on earth's surface using very high sensitive 3C Broadband sensors.

Majority of published literature pertains to LFPS in onshore areas and only few cases in offshore.

It is observed that over hydrocarbon pools, these micro-tremors indicate anomalous response in some of their spectral attributes like relative increase in V/H ratio attribute in 2-4 Hz range.

The present paper briefly describes the salient issues related to study of LFPS data, the Opportunities & Potential Challenges and its application for Petroleum Exploration and Production

Low Frequency Passive Seismic (LFPS) method

Contrary to the Conventional or Triggered / Induced Seismic, Passive Seismic does not use any external energy source rather micro-tremors generated from natural seismicity of earth are recorded on the surface by very high sensitive (Sensitivity > 1000 V/m/s) 3C Broadband (BB) seismometers which are widely used for earthquake measurements. The data is recorded for few hours in quiet environment. Frequency band of LFPS data is confined in 1-10 Hz. Like Seismogram,

LFPS field data is known as Spectrogram (Time displayed on x axis and Amplitude on y axis).

Fig 1 depicts the general comparison ie source receiver layout and the corresponding frequency spectrum of the seismic response from Conventional or Triggered/Induced and Passive Seismic methods. (source: compiled after input from different websites)

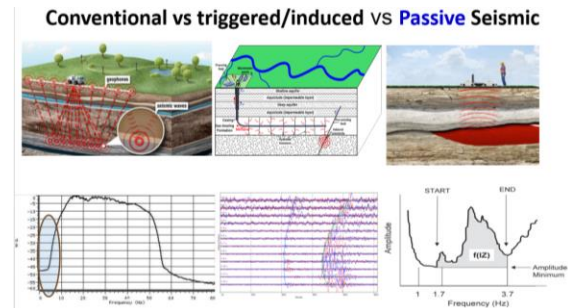


Fig1. Conventional vs triggered/induced vs Passive Seismic

LFPS is a cost effective passive imaging tool which is less dependent on weather, season, environment and does not require compute intensive processing.

Case studies include onland areas in Abu Dhabi, Austria, Brazil, Germany, India, Indonesia, Iran, Java, Mexico, Saudi Arabia, Turkey, Uganda etc. the detailed analysis of these case studies further indicate that the size of the project areas are very small (typically few tens of SqKM and majority of them are situated close to sea shore. The area usually covers producing wells, dry wells and the exploratory or development wells over prospective areas.

The layout of sensors is usually along planned profile(s) or in Grid Pattern with 200x200 to 500x500m spacing. It is observed from their analysis that over hydrocarbon pools, these micro-tremors indicate anomalous response in their spectral attributes like relative increase in V/H ratio attribute in 2-4 Hz range.

Schematics of Passive technology showing anomaly over Hydrocarbon pool (Source: Steiner 2009) is shown in fig 2

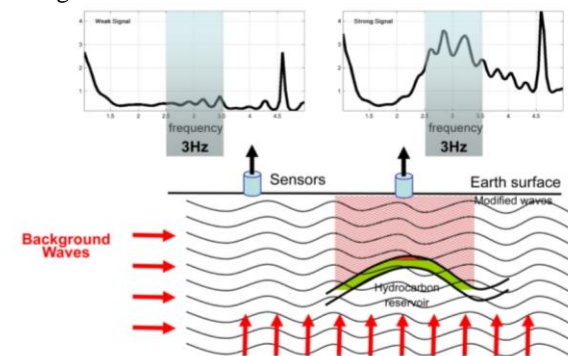
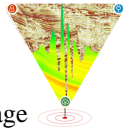


Fig.2 Anomaly over Hydrocarbon pool (Steiner 2009)



Passive seismic data was recorded by 3C broadband seismometers at about 700 stations for around 200 km over a Tight gas field in Mexico (<https://www.hindawi.com/journals/js/2016/4378540>). Power Spectral Density (PSD) from the passive seismic wavefield over gas and dry well shows anomalous response in frequency range of 0.5 to 7.4 Hz is shown in fig 3a & 3b

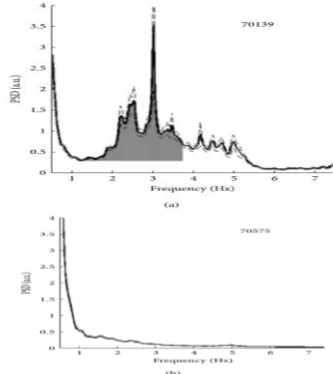


Fig3 Power Spectral Density(PSD) for gas (a)& dry well (b)

Contrary to conventional seismic wave propagation like Reflection, Refraction, Diffraction etc., it is believed that Resonance is the main cause for LFPS events.

Some of the widely accepted phenomenon are:

- Resonant amplification occurring at the pore scale within the reservoir, whereby seismic energy is trapped in a multiphase fluid system and then emitted with detectable energy levels.
- Resonant scattering due to complex impedance contrasts between hydrocarbon bearing rocks and the surrounding media alter the ambient seismic wavefield to become detectable at low frequency.
- Poro-elastic effects within an oil reservoir may cause low-freq. ambient wavefield modifications observed at oil fields, Lambert et al (2013)

Spectral modifications of naturally occurring background waves in 0.1-20 Hz range over hydrocarbon bearing porous structures have been reported by Hydrocarbon Micro-tremor Analysis (HyMAS) (Holzner et al 2005).

Based on research studies and exploration operations M/s CJSC Gradient (www.gradient-geo.com) have described various aspects of LFS method - Physical theory, data acquisition, data processing and Data interpretation using their developed software.

As per their theoretical understanding, the nature of anomaly associated with resonance of seismic waves between the surface and the oil and gas deposit. Identification and analysis of Primaries and their Modes in the LFPS data helps to estimate the depth and the shape of the anomalies to relate with fluid type & layer(s).

Despite empirical evidences, cause of anomalous LFPS response in 2-4 Hz is yet to be fully understood and precise physical mechanisms to be identified. However, the quantitative estimates relating to depth & thickness

of hydrocarbon layers fluid type, etc. and the weightage of various attributes & their pattern of anomalies are yet to be firmly established.

LFPS - Data acquisition

LFPS data is recorded using very high sensitive (Sensitivity > 1000 V/m/s) 3C Broadband (BB) seismometers which are widely used for earthquake measurements. Before deliberating on data acquisition, it is very important to discuss the about the technical features of BB seismometers deployed for this purpose.

LFS Sensors/ Seismometer

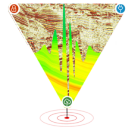
A seismometer is a kind of inertial sensor which can detect the smallest ground motions in specified frequency band. LFPS Sensors are basically Broadband seismometers which can detect motions which are as small as the background motion at a hypothetical quiet site. The use of displacement transducers and force feedback results in an instrument with better linearity, lower self-noise and higher sensitivity at long periods. They are installed in a carefully designed vault to minimize the spurious signals and other environmental factors.

Broad features of Broadband Sensors for LFPS are:

- Technology-Force Balance or Force feedback velocity sensor or Molecular-electronic seismometers
- Comprise of 3 transducers or 3 Orthogonal seismometer (3C)
- Sensitivity very high > 1000 V/m/s
- Useful frequency range 0.1 Hz to 10 Hz
- Levelled & planted below surface usually in Vertical, N-S, E-W direction
- Signal output type - Velocity and Acceleration which are merged through a transfer function to get broadband response
- Data recording format: MiniSEED
- Characterized in Period (sec) in stead of natural freq. (Hz), ie, 5 /10 /50 /120 Sec => which is eq. to 0.2/ 0.1/ 0.02/ 0.005 Hz
- 5/10 sec BB sensors should be adequate for LFPS surveys
- Linear Amplitude & Phase Response in desired signal zone say 1-10Hz

In view of above,

- Amplitude & Phase Response of Broadband Sensors used for LFPS data should have near flat pattern in desired signal zone say 1-10Hz.
- Field study indicates that less than 1Hz (>10 second) BB sensors usually indicate non-linearity in desired LFPS frequency range and hence may not be necessarily suitable for LFPS study.
- Transfer function to merge velocity & acceleration signals of the BB sensors differ for each make & Model. This should be invariably obtained from OEM even if the merged data is recorded as output because Hor.(Hx,Hy) and Vert comp (Z) response should be usually different.



Grid layout of sensors

The sensors are well protected for wind noise, wet soil etc. and hence buried in 1-2 ft pit below surface. Depending on S/N study, the data is recorded for 4 - 24 hrs. in quiet environment often in early morning. The data should be free from surface / industrial noise.

Layout of sensors is usually along planned profile(s) or in Grid Pattern with 200x200 to 500x500m spacing over an area covering various producing, dry or proposed wells.

Some important Operational points are as below:

- Calibration & faithful recording of data for all 3 components
- Grid layout, Best operating window & Recording duration (length)
- Local variations -weathered/wet soil, groundwater table etc.
- Repeatability of observations should be ensured
- Anthropogenic noise in 0.1-2 Hz (more near coastal areas) helps as reference signal for all sensors. However, it should be filtered out while processing /analysis of the data.
- Data harvesting and release of sensor's memory for next recording

LFPS – Data Processing

The main steps of data Processing are:

- Initial review of all the Spectrograms
- Separation of 3 components & Data conditioning,
- Analysis of background trends,
- Stripping, Narrow & Broad band noise filtering,
- Generation of spectrograms and Histograms,
- Relative V and H spectra,
- Derivation of various spectral attributes

It is pertinent to mention that Artificial Intelligence plays a major role in processing of LFPS data.

LFPS – Data Analysis

Before starting the analysis of LFPS data, a thorough understanding about the subsurface data, production history & behaviour of wells in proposed area should be aggregated. Analysis should start from establishing anomalous response and suitable attributes at known wells before moving away/around in remaining area. Specific objective(s) for analysis of LFPS data need to be clearly set. The results of Feasibility and Pilot study, if available, should be invariably looked into.

Consistency & evidence of identified anomalies as well as the Calibration & Correlation with well data are very critical elements for this study. LFPS data processing & analysis are interactive & reiterative activities and hence should not be done in mutually exclusive setup. Suitable attributes are chosen for data analysis like:

- Ratio of Vertical and Horizontal amplitudes (V/H),
- Integral of Spectral Ratio of Vertical & Horizontal comp. (IVH),
- Power Spectral Density (PSD),
- Power Spectral Density-integral of vertical component (PSD-IZ),

- Peak Frequency Distribution (PFD),
- Frequency Shift of Maximum Spectral Peak,
- Polarisation (Dip, azimuth, recti-linearity and largest eigenvalue).

Many experts develop a mix of attributes suitable for specific area. Recommendations are made by combined study of overlapping correlating anomalies.

An example of integrating multiple attributes from LFPS Survey in Kalimantan, Indonesia is shown in fig 4: (source: Billy Sugiartono Prabowo et al 2017 IOP Conf. Ser.: Earth Environ. Sci. 62 012020)

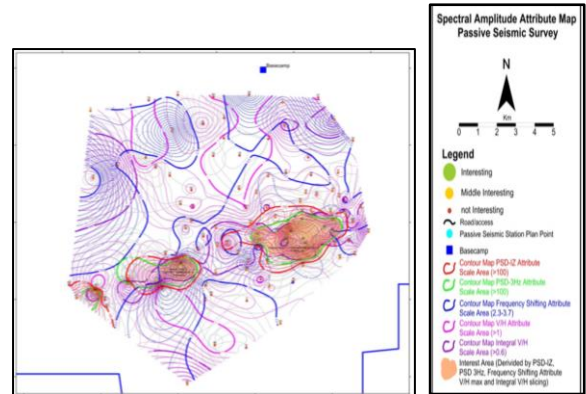


Fig 4: overlay of multiple LFPS attributes- Kalimantan, Indonesia

Low Frequency Passive Seismic in India

Oil and Natural Gas Corporation Ltd. (ONGC) took initiative in implementing Low Frequency Seismic (LFS). Its Ankleshwar asset carried out 1st LFS survey during Oct-Dec 2016 in Gandhar field through M/s Stork International GmbH.

After its positive results, implementation in other areas were taken up by ONGC's departmentally. Efforts were made by Geophysical Services of ONGC to induct and develop in-house capability on API of LFPS data.

LFPS Pilot study was done in association with Institute of Seismological Research (ISR), Gandhinagar. During June-July 2018, LFPS data was acquired in 4 areas (3 in Jotana & 1 in Mansa fields in Cambay basin, Gujarat India) by deploying Lennartz make 10 sec/5 sec LF Sensors and digitizers.

- Profile-1 in Jotana: 3 km (100m sensor Int.) through 5 wells (3 Oil & 2 Dry)
- Profile-2 in Jotana : 3 km (100m S Int.) thru 11 wells(4 Oil, 2 Abandoned, 2 To be abandoned,1 Effluent Disposal & 2 Water Injection)
- Profile-3 in Mansa : 5 km (200m sensor Int.) thru 3 wells(3 Oil, Gas/Abandoned & 1 Dry)
- Areal data over 200 x 200 m grid around the oil well in Jotana area

A sample of vertical (Z) component data at 3 stations, Spectrogram of 60 minutes and Stripping of noise bursts in a record from Jotana Pilot area are shown in Fig 5a,b,c (Source: ONGC report)

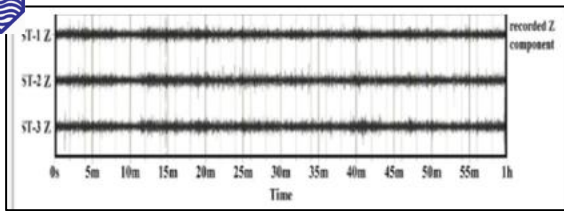
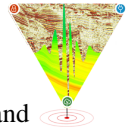


Fig 5a Z component data at 3 stations

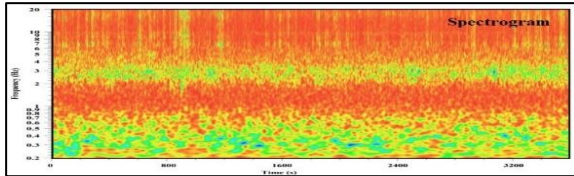


Fig 5b Sample spectrogram of 60 min record

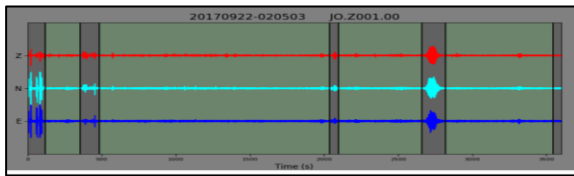


Fig 5c Stripping of noise bursts in record

V/H ratio attribute observed during pilot study near Oil & Dry well in Jotana Pilot area are shown in Fig. 6

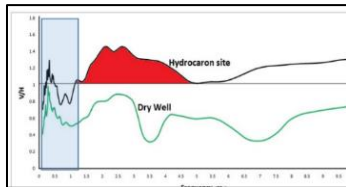


Fig.6 V/H ratio near Oil & Dry well in Cambay basin

Subsequently a dedicated field crew had been carrying out LFPS surveys in many oil fields in India like Gandhar, Jotana, Mansa, Ashokenagar, Padra, Umra, Dabka etc.

Anomalous response as relative increase of varying degree in V/H ratio in 2-4 Hz have been observed.

Model Activity plan for execution of LFPS Project

Thorough understanding about the subsurface and production history & behaviour of wells in proposed area. All available geoscientific data and E&P challenges should be aggregated prior to start of project. The best strategy should be to fan out from known to unknown locations. LFPS projects should be executed in stages with specific objectives.

Stage I: Feasibility study

The main objective should be to establish efficacy of LFPS technique in the area

- to look at signal response of the target area
- to identify the nature of anomaly correspond different producing reservoirs

Stage II: Pilot study

The main objective should be to identify and analyse the lateral variation of anomaly(ies) in LFPS data over

a small target area covering cluster of producing and adjoining proposed or dry wells.

- to establish the pattern of anomaly(ies) for different oil/gas pools as well as dry wells and generate templates for each project area
- Sensor layout should include few profiles of adequate length by placing sensors at 250-300 m interval. Spacing may vary depending on well location, plantation condition etc.
- These profiles should connect to the wells of target reservoirs.
- Each profile should also connect different wells preferably at same pay levels viz, Oil, Gas, Oil/Gas, Dry, Water injection, abandoned wells, etc.
- To optimize the Record length, the initial data should be recorded for 4 -12 hrs. Based on the analysis of data in terms of quality, S/N ratio, standout of anomalies etc. record length should be optimized & reduced.
- Generation of Initial processing workflow

Stage III: LFPS Project-Data Acquisition and Analysis

In this stage, Operational planning, Project-wise objective oriented Data Acquisition, Processing and Analysis of LFPS data is done and final conclusions & recommendations are made. Some of the main steps in this stage are:

• Pre-survey study

The objective of survey is based on the thorough study of available geoscientific data, Well completion reports, deviation data, 2D/3D subsurface models & isopach maps, missed targets due to complications / testing, oil/gas shows, thin & low resistivity reservoir, production profiles of producing/abandoned wells, proposed exploratory and development wells etc.

These inputs help decide the size of proposed area and layout of the survey.

Besides above, the tectonic activities in and around area, earth quakes prone distance of nearby seashore and tidal activities, industrial noise etc. during the course of LFPS study are very important

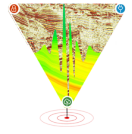
• Layout and production

Sensors are laid over the area covering cluster of wells either in grid pattern with 250-300 m spacing or along few profiles in different direction over a reservoir. The station spacing should be fine-tuned as per requirement after review of the few data sets.

The record length may be optimized and reduced to 4-6 hrs based on assessment and results of Stage I analysis.

• Data Processing, Analysis and Time Scheduling

The acquisition time schedule shall depend upon available sensors, S/N condition leading to optimal record length, station spacing, surface & fair weather condition etc. whereas LFPS response, optimal



anomaly templates in terms of spectral attributes etc. shall affect the time required for data Processing & Analysis. The time is usually reduced further by doing P&A concurrently with acquisition.

Data acquisition should be very carefully planned in view of handling/safety of buried equipment, rains/waterlogging, local noise conditions and fair weather window. There can be flexibility in station interval.

For illustration, a typical stage wise model activity chart for a LFPS Project over a typical 20 SqKm area and 2 profiles passing through the specific pools of the target field with deployment of 5 sensors while pilot study and 10 sensors during normal project execution is shown in fig .7

Tentative plan with Resources & parameters	Activity after mobilization/ Time duration in weeks	Weeks																								
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	
Stage I Feasibility study total 3-5 stations @ 10-12Hrs recording Sensor 01 No.	Data acquisition																									
	Analysis(P&A)																									
Stage II Pilot study 5 profiles, total 100 stations @ 10-12Hrs recording, Sensors 05 nos.	Data acquisition																									
	Analysis(P&A)																									
	Report submission/Presentation																									
Stage III Project A area 20Sq, total 350 stations Layout Grid 250mx250m as well as 2 profiles for specific pools @ 4-6 Hrs recording, Sensors 10 nos.	Pre-survey study																									
	Data acquisition																									
	Analysis(P&A)																									
	Report preparation/ submission/Presentation																									
	Submission of Deliverable																									

Note: Time schedule may vary depending upon available sensors, S/N condition, record length, station spacing, surface & fair weather condition while acquisition whereas LFPS response, optimal anomaly templates in terms of spectral attributes etc. while data Processing & Analysis

Fig 7: Typical stage wise activity chart for LFPS Project

Based on my practical experience, feasibility study is the most critical and guiding activity for deciding the entire LFPS program.

After successful induction of this technology, Annual work planning & Regular Production throughout the year is done for effective utilization of resources and value addition to E&P initiatives by the company.

Post drilling review, updation after new geoscientific data and the evolving newer best fitting attributes for different areas are the continual jobs to be undertaken.

Potential Challenges for LFPS Data Acquisition & Analysis

- Estimation of micro-tremor response (pattern of Fundamental & Modes) due to type and depth of reservoir(Oil and/or gas),Thickness of Single / Multiple reservoir(s), Pressure depletion, movement of OWC/GOC, Bypassed oil zones, Low resistivity/non-conventional reservoirs
- Optimization of operational parameters viz,
 - Nature of noise(s)-> Best operating window & Record length,
 - Area of influence for point receiver-> Grid layout & Contouring,
 - Seasonal & Diurnal & Local variations - weathered/wet soil, groundwater table etc.
- Non-availability of commercial software
- Full understanding of principle/causatives, processing workflows & optimized analysis parameters for best values,

- Repeatability of observations,
- Preparation of a library of LFPS template at field scale for oil/gas pools at different depth, single/multi-level, Thin/Thick reservoirs.

Opportunities for LFPS in Petroleum Exploration and Production

There are vast opportunities for LFPS mainly related to:

- Reserve accretion,
- Enhanced recovery & field growth by De-risking of proposed exploratory/ development / Infill wells,
- Identification of Bypassed oil areas and Relook at missed opportunities like untested zones, Non-conventional reservoirs etc.
- Hydrocarbon assessment in seismically difficult/ less-friendly areas
- Prospect ranking tool
- Logistically Challenging & inaccessible areas -
 - Logistics - Townships, hilly terrain in MP, NE,HP, deserts, ravines, rivulets
 - Near surface - Kutch, Saurashtra & Trap covered areas
 - Areas Prohibited for conventional seismic etc.

Recommendations

Anomalous response in the LFPS spectral attributes like relative increase in V/H ratio attribute in 2-4 Hz range has been well established by ONGC over hydrocarbon pools in many Indian oil fields.

Now, it is high time to capitalize by other E&P companies operating in Indian sedimentary basins. Directorate General of Hydrocarbons (DGH) may look into the feasibility of suitably deploying this technique in prospective blocks.

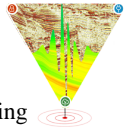
It is a cost effective passive imaging tool, it is less dependent on weather, season, operational logistic constraints and also does not require high end compute intensive processing.

In my opinion, the priority areas for LFPS study in India include Coal Bed Methane (CBM) blocks, Ultra shallow pools & Gas pockets of uncertain size, High pressure Gas pools, Fractured & small pools, isolated sand pools, hilly terrain in Himalayan region, MP and Northeast India, seismically difficult areas in Kutch, Saurashtra, Deccan plateau etc.

Study of low-frequency Krauklis waves may help in imaging & characterization of fracture networks specially in CBM areas.

Further, to accelerate the pace of application LFPS in E&P, following need immediate attention:

- Enhanced R&D efforts to harness the potential of LFPS technique for E&P.
- Collaboration with suitable Research Institutes & close interaction with experienced professionals



- Preparation of a library of LFPS template at field scale for oil/gas pools situated at different depth, single/multi-level, Thin/Thick reservoirs etc.
- Pilot studies in offshore, by concurrent deployment of few Broadband sensor nodes with regular OBN nodes over a small area covering oil/gas, dry & proposed wells.
- Develop LFPS as a Prospect ranking tool

Conclusion

Anomalous LFPS response of spectral attributes in 2-4 Hz range over hydrocarbon pools has been well established in many Indian onshore oilfields especially by ONGC. Now, the study should expand across other challenging areas and Pilot projects in offshore areas.

Despite empirical evidences, cause of anomalous LFPS response in 2-4 Hz and precise physical mechanisms is yet to be fully understood. Concerted professional efforts are required to relate quantitative estimates with depth, thickness, fluid content etc. of hydrocarbon layers and also to establish the weightage pattern of various anomalous attributes.

A library of LFPS templates should be made at field scale for oil/gas pools situated at different depth, single/multi-level, Thin/Thick reservoirs etc.

The study should step out from known to unknown targets with initial focus on development locations to quickly establish the LFPS response and then use as an effective prospect ranking & de-risking tool for exploratory locations.

Now, it is high time to capitalize on LFPS by other E&P companies operating in Indian sedimentary basins. Directorate General of Hydrocarbons (DGH) may further facilitate in suitably deploying this technique in various existing and new prospective blocks.

In my view, LFPS technique has huge potential in risk mitigation and opportunities in value addition for Petroleum Exploration and Production in India.

Acknowledgement

The author sincerely acknowledges to all the distinguished contributors whose work from reports/published literature/websites are referred and few included in this study as illustrations.

The author is indebted to ONGC for giving opportunity to associate with induction of LFPS while in service.

The author is thankful to Society of Petroleum Geophysicists, India for acceptance of this paper and opportunity for presentation.

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