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Micro Seismic Evidences in Active Seismic Data: Resonant Near Infrasonic Micro-Seismic Emission as Direct Hydrocarbon Indiator (DHI) (A case study from Upper Assam Basin, India)

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Summary

Signals from an impulsive source like dynamite, when gets trapped within a medium of high acoustic impedance contrast (like low velocity fluid filled reservoirs with in host rocks), continues to resonate at certain frequencies in infrasonic range and generates circumferential waves. These circumferential waves travel along the exterior of the reservoir radiating durable infrasonic seismic emission to surrounding medium which further travels in the form of shear body waves that can be recorded through MEMS based digital sensors.

Spectral highs (peaks) in infrasonic frequency range are observed due to slow amplitude decay of circumferential waves. On 2D seismic shot gathers, these spectral peaks appear as quasi-hyperbolic events with high amplitude at later part of the seismic record (after all primary waves i.e., PP, PS & SS waves are gone). Mapping of these hyperbolic signatures with respect to their geometry & amplitude may quantitatively define the location, in terms of surface coordinate & depth, of the causative body and can be used as Direct Hydrocarbon Indicator (DHI). These late arriving near infra resonance signatures could be hidden or invisible in raw seismic shot gathers but the same could be made visible as prominent quasi-hyperbolic signatures through application of AGC & Band pass filtering at near infrasonic resonant frequency at low end of the spectrum. The curvature analysis of these hyperbolic signatures reveals that the apex of these hyperbolas could correspond to the lateral location of the subsurface resonant source while its characteristics (best-fit matching & high amplitude strength) could have a direct relationship with the depth of the resonant source.

In this paper, an attempt has been made to correlate & identify hydrocarbon reservoir (which is expected to be a resonant source) from the analysis of resonant frequency over known reservoirs in Oil India Limited (OIL)'s oil and gas fields in Upper Assam, India and it has been extended to identify unknown hydrocarbon reservoirs in the subsurface. Resonant near infrasonic seismic emission has been observed in seismic shot gathers over a few unknown hydrocarbon reservoirs where locations have been released based on existing 3D seismic reflection data to drill the wells. Further observations of bright spot and AVO response in NMO corrected CMP gathers of available 2D seismic data over the same unknown hydrocarbon reservoirs strongly supports the observed resonant near infrasonic micro-seismic emission in 2D seismic shot gathers. Utilization of resonant infrasonic micro seismic emission in shot gathers could add value to prevailing conventional seismic practices in hydrocarbon exploration and also could mitigate exploration risks.

Keywords: *Micro-seismic, Creeping Circumferential waves, Resonant infrasonic seismic emission, Buried Source.*

Introduction

Micro-seismic events are caused when human activities such as mining or oil and gas production or normal active seismic operations, change the stress distribution of a rock mass. When the rock attempts to redistribute the stress within the rock mass, it will suddenly slip or shear along pre-existing zones of weakness such as along faults or fracture networks. This small failure results in the release of energy in the form of seismic waves and is known as a micro-seismic event.

The well established concept of "Spectral high in low frequency range (2-6 Hz)" has been one of the basis

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of looking for hydrocarbon where the seismic data, recorded through MEMS (Micro Electrical Mechanical Systems) based accelerometers (frequency bandwidth of 0-800 Hz), are available. This concept has been derived from the study that the signals from an impulsive source, when gets trapped within a medium of low acoustic impedance with respect to surrounding medium (like that of hydrocarbon reservoirs), it continues to resonate at certain frequencies in infrasonic range (2-6 Hz) generating creeping circumferential waves. These circumferential waves are studied to be as of 4-types viz. i. Frantz wave (propagating around the reservoir with velocity nearly close to the velocity of the surrounding medium, radiates energy to outer medium & decays rapidly), ii. Whispering Gallery Waves (propagating inside the low acoustic medium, gets multiplied from the curved interface of the object and decays rapidly), iii. Raleigh Waves (propagating with initial small amplitude signals which dominates the seismic records over a long period of observation) & iv. Stonely Waves, generated in the fluid medium and propagating as waves with slowly decaying amplitudes. The spectral peaks of these signals appear at infrasonic frequency range because of the slow amplitude decay of the creeping circumferential waves, where the reservoir geometry allows a constant rotation period around it. These circumferential waves, acts as secondary source in generating resonant emission in the form of scattered shear body waves as shown in Figure-1

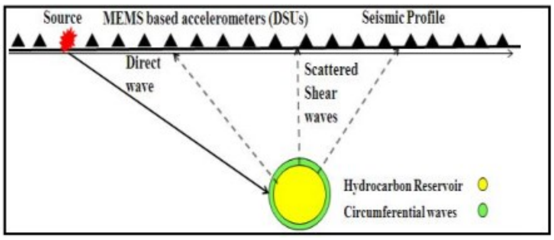

Figure-1: The resonant emission from circumferential waves at reservoir level, acting as secondary source and transmitting shear body waves.

The Resonant Infra Seismic Emission can be seen in seismic raw shot gather over hydrocarbon reservoirs which remains as buried signal in conventional seismic analysis that mainly deals with strong primary scatter waves (PP, PS & SS) in frequency range 1-120 Hz plus noises. However, these buried signals can be analyzed after digging out the signals through processing of raw shot gathers that involves mainly Spectral Analysis, application of long AGC window covering the entire record length and Band Pass filter. Following this process, these buried signals appear as hyperbolic events in seismic shot gathers. Subsequent imaging of these low frequency, low velocity shear waves at late arrival times, after all primary waves (PP, PS & SS) are gone. The resonant seismic emission move with a constant phase velocity and generate high amplitude anomaly, at the depth corresponding to the depth of the resonant source, on the stacked image of all the traces sorted to a common mid source (the resonant source) gather. Since the type of geological system, structure, stratigraphic and lithology will have no effect on low frequency anomalies, infra resonance could play a key role in complex geological systems where seismic reflection finds its limitations.

This paper extends the above concept of imaging the late arrival shear body waves, generated from the secondary source at reservoir level, over known hydrocarbon reservoir in OIL's area of operation in Upper Assam as discussed in following paragraphs.

Case study

The study area is located in Oil India Limited's (OIL) operational areas around Kathalguri, Jutlibari, Nahorkatia, Dulijan and Matimekhana in upper Assam in North-East of India as shown in Figure-2.

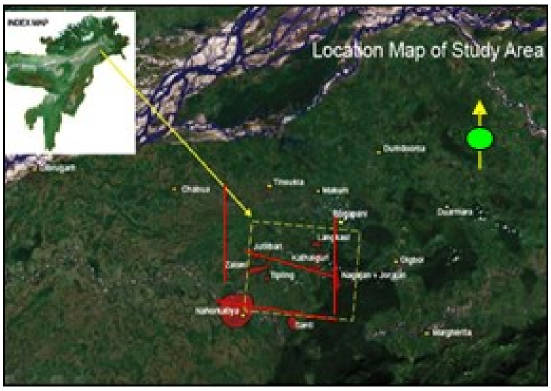

Figure-2. Study area with Seismic profiles (Red in color) passing through a known and unknown hydrocarbon fields.

Infra resonance or resonant infra micro seismic emission has been observed in most of the shot gathers in a number of 2D-3C seismic profiles passing over the known reservoirs in Kathalguri area.

One of these seismic profiles A-A' has been selected for the present study to correlate & identify hydrocarbon reservoir (which is expected to be a resonant source). Seismic profile A-A' was passing through Kathalguri and Jutlibari hydrocarbon producing fields. In Kathalguri area, hydrocarbon is being produced from Late Miocene (Tipam) and Upper Eocene-Oligocene (Barail) formations at depth ranges of about 2265-2278m and 3121.5-3133m respectively. Available well data showing the hydrocarbon pay zones is shown in Figure-3. Later on, the study has been further extended to other seismic profiles which were passing through both known and unknown hydrocarbon reservoirs.

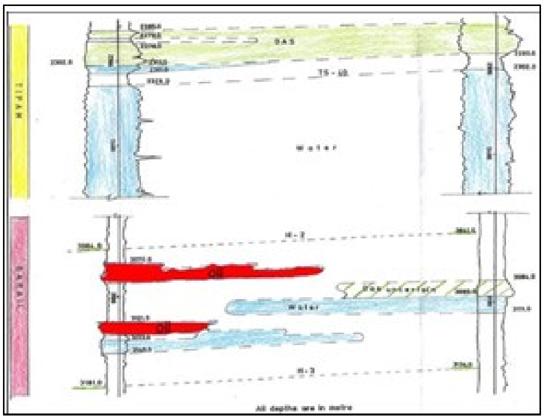

Figure-3. Well logs over the gas producing depth range 2265m-2278m (Tipam formation) and oil & gas producing depth range 3121.5-3128m (Barail formation).

Seismic Data

2D-3C Seismic data has been acquired in the area during the year 2009 with the recording parameters as given in Table below:

S.No.	Recording or Geometrical Parameter	Variant
1	Seismic Source	Explosive
2	Receiver	DSU-3
3	Shot or receiver Interval	20 m
4	Active Receivers per shot	360 to 490
5	Shooting Geometry	global shooting
6	Total Shots acquired	364 shots
7	Fold	90 to 154
8	Recording Length	12 sec

In general, the S/N for the data recorded in the area are fair to good for distinguishing resonant infra seismic emission from the secondary source (lower acoustic impedance zone) in the subsurface. From screening and scanning of 364 Shot records on E-W seismic profile A-A', some of the shot gathers have been identified for the study of possible infra sonic resonance from possible lower acoustic impedance zone corresponding to hydrocarbon reservoir. For the present study, the Shot gathers 250 & 259, with clear presence of resonant infra seismic emission, located over the producing Kathalguri structure have been selected in an attempt to validate the anomaly from the known hydrocarbon reservoir. Other seismic profiles also, have been showed resonant infra micro seismic emission from known and unknown hydrocarbon reservoirs. The encouraging results suggested that this technique is quite useful in oil and gas exploration and it is discussed as a case study in the below paragraphs.

Resonant near infra micro seismic evidences and its imaging on Kathalguri Structure

The data scanning for resonant infrasonic seismic evidence & analysis has been carried out as mentioned in following steps:

Step-1: The raw shot of gathers, in their original form do not depict the presence of infra sonic signals as shown in Figure-4. Therefore, single window AGC (3000 ms window) has been applied to the raw shot gathers and 2-gathers of 250 & 259, with prominent evidence of resonant near infra micro seismic emission have been selected for further analysis.

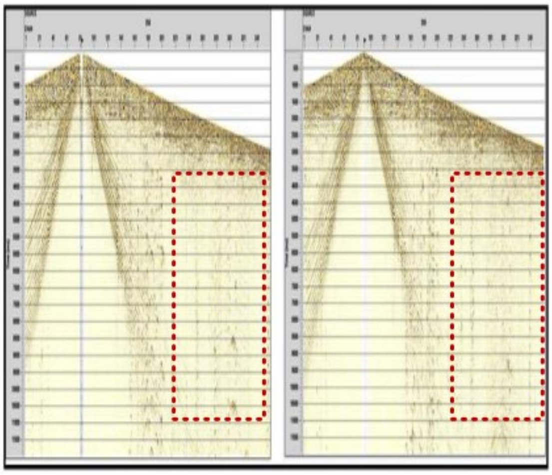

Figure- 4. Field recorded raw shot gathers of 250 & 259 of 1-360 channels of seismic profile over Kathalguri structure in the study area (no apparent visibility of infrasonic signals in red colour boxes).

Step-2: Spectral Amplitude Analysis has been carried out on one of the traces from the raw shot gathers, close to the known reservoir from the gas well. Spectral Amplitude Analysis, before and after AGC 3000ms window are given in Figure-5. Durable oscillations in late arrivals are observed with highest spectral peak at 2.8 Hz frequency, near infrasonic range.

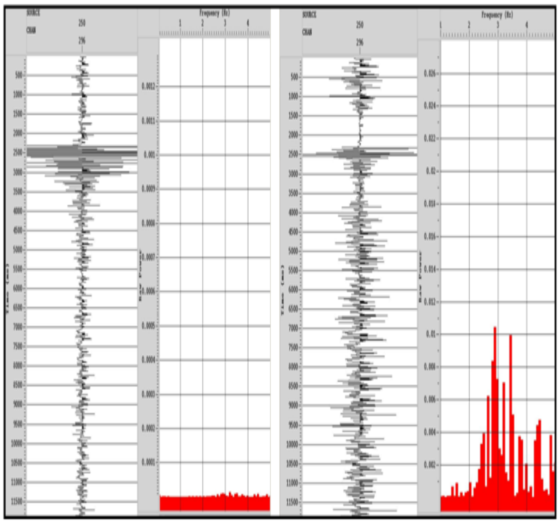

Figure-5. Spectral amplitude analysis in near infrasonic frequency range (2.8 Hz) on trace No. 296 of Shot gather 250 (before AGC (left) and after AGC (right).

Step-3: Further, the noise components have been filtered out with application of Band Pass Filter (2-4 Hz) and the signals corresponding to infra resonance frequencies range have been enhanced. The signature of the infrasonic signals appears with characteristic quasi-hyperbolic travel time patterns over hydrocarbon reservoirs as shown in Figure-6.

Thus with the above seismic data conditioning, the hyperbolic events in shot gathers, which otherwise were buried in raw shot gathers, could be enhanced. The Resonant images, appearing as high amplitude quasi-hyperbolic events at a significantly later times, were analyzed to ascertain the lateral position of the causative body (here the reservoir) and the depth of the reservoir.

It may be noted here that, the spectral peaks of infra sonic signals appear because of the slow amplitude decay of the creeping circumferential waves, where the reservoir geometry allows a constant rotation time around it. Thus,

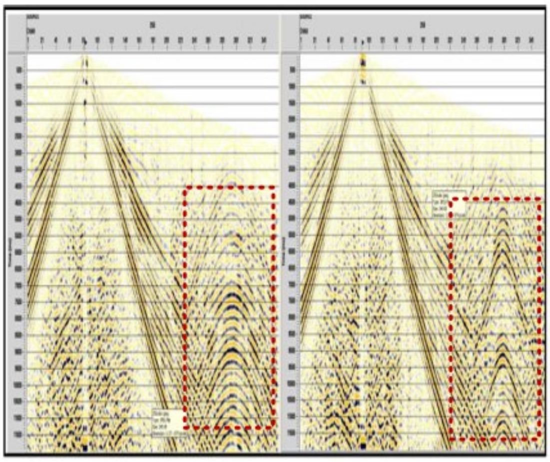

Figure-6. Shot gathers 250 & 259 of 1-360 channels of seismic profile; after AGC and band-pass filtering around 2.8Hz shows infra sonic signature in form of quasi-hyperbolic events (highlighted in red colour boxes).

the circumferential waves are likely to generate the wave fields more than once which are transmitted to the surrounding medium and travel as shear body waves. Accordingly, one single hydrocarbon pool at a particular depth can emit seismic energy in infrasonic range for more than once which appear as multi-sets of hyperbolic events at different times / depth in the later part of record.

Similarly, multiple resonant sources which may correspond to multi-pools at different spatial positions in the subsurface could exhibit multiple resonant seismic emission in form of multi-sets of hyperbolic events in seismic shot gathers but with different spatial & temporal positions and with different curvature properties like phase velocity and alignment of the apex of the hyperbolas. Hence, one particular phase slope for different hyperbolic events with same lateral position of the apex could be the evidence of one resonant source i.e one hydrocarbon pool. Deeper the resonant source is, broader is the hyperbolic anomaly and the reverse is for shallower resonant source.

Resonant near infra micro seismic emission evidences, as recorded in strike and dips direction, could confirm the exact position of the apex of hyperbolic events pertaining to one or more hydrocarbon pools at different depths with same lateral position but with different phase velocity; thus separating them from each other.

Step-4: The travel time-Offset (T-X) plot analysis to determine the lateral position of hydrocarbon reservoir and the correct phase slope has been carried out at 3-trace location on 2-sets of hyperbolas observed on shot gathers 259 and is given in Figure-7.

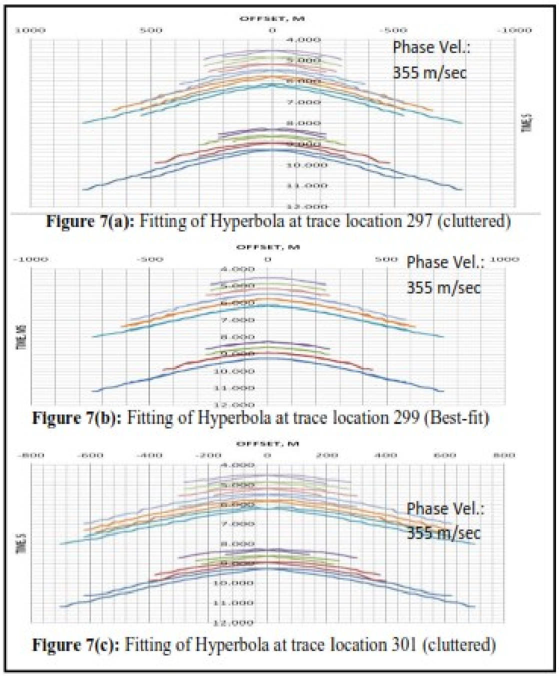

Figure 7(a): Fitting of Hyperbola at trace location 297 (cluttered)

Figure 7(b): Fitting of Hyperbola at trace location 299 (Best-fit)

Figure 7(c): Fitting of Hyperbola at trace location 301 (cluttered)

Figure -7. Travel time vs Offset (T-X) plot for the resonant hyperbolic anomaly spreading over channel 270 to channel 336 for shot gathers 259.

The T-X plots for the hyperbolic events at trace 297, 299 and 301 are given in Fig. 7(a), Fig. 7(b) and Fig. 7(c) respectively. It is seen that the hyperbolic events are best fitted at the trace location 299 (Fig. 7(b)) which could correspond to the buried source location.

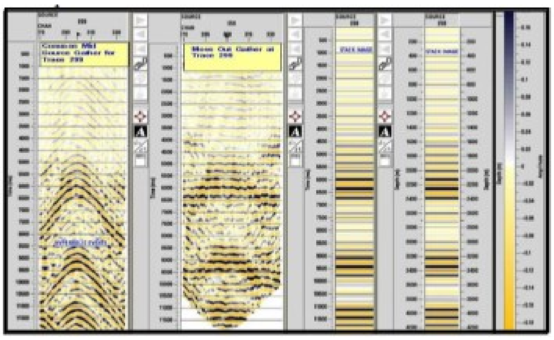

Figure-8. Common mid source gather at trace 299, Move out gather with Phase slope 355 m/sec, Stacked image of all the traces in time and depth (left to right) showing high Amplitude events against the hyperbola.

Step-5: Therefore, geometry for further processing to determine the depth of the resonant source has been prepared with the trace 299 at the center (zero offset trace). The Move out correction with Phase Slope of 355 m/sec was applied to flatten the hyperbolic events to zero dip events. As seen in Figure-8, the highest stack amplitude occurs at around the depth of 2260 m which corresponds to gas sand reservoir within Tipam. The highest stack amplitude occurs at around the depth of 2260 m which corresponds to gas sand reservoir within Tipam formation in Kathalguri structure. For easy visualization, the amplitudes have been digitized and plotted against depth, at trace 299 (Figure-9). The highest stacked amplitude of the hyperbola occurs at depth 2260m, which could be the common mid source location, at trace location 299.

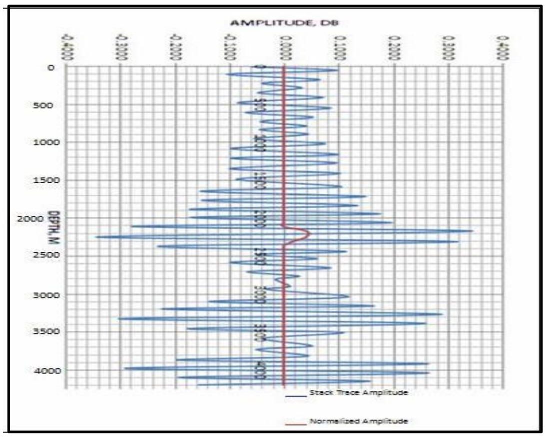

Figure-9: Depth vs. Stacked Amplitude for the hyperbolas shows the maximum stack value of the amplitude at trace 299 at a depth of 2260 m.

Similar study has been carried out for shot gather 250. Apex of hyperbolic anomaly is at 296 trace (corresponding mid source location) for shot gather 250. The phase velocity at this location has been 400 m/s. It is clearly noticed that hyperbolic events at mid source location 296 shows highest amplitude corresponding to reservoir at depth 3080m within Barail formation (Figure-10) in Kathalguri structure.

It may be noted that the apex of the hyperbola for Barail formation has shifted by 3-trace locations when compared to that of Tipam reservoir and is of a different Phase slope of 400 m/sec as against that of 355 m/sec for Tipam reservoir. In case of multiple reservoirs at same location, it is expected that the Phase slope could be the criterion in distinguishing the reservoirs.

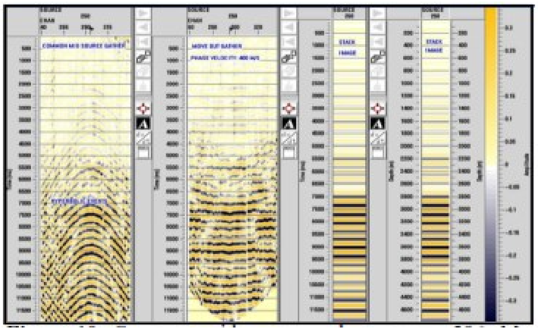

Figure-10. Common mid source gather at trace 296, Move out gather with Phase slope 400 m/sec, Stacked image of all the traces in time and depth (left to right) showing high Amplitude events against the hyperbola.

Resonant near infrasonic micro seismic evidences on other producing fields

Hyperbolic events are observed in Shot gather on hydrocarbon producing fields of Jutlibari and Nahorkatia as shown in Figure-11 & 12.

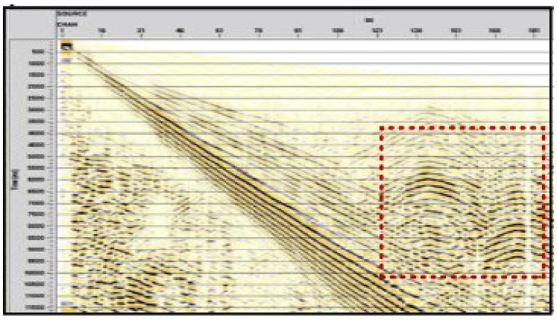

Figure-11. Shot gather over Jutlibari structure; after AGC and band-pass filtering around 3 Hz shows resonant infrasonic micro seismic emission as hyperbolic events (highlighted in red colour box).

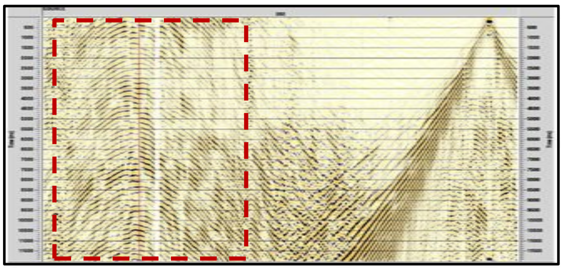

Figure-12. Shot gather over Nahorkatia main structure; after AGC and band-pass filtering around 3Hz shows resonant infrasonic micro seismic emission as hyperbolic events (highlighted in red color box).

Resonant near infra micro seismic emission evidence in Dulijan area for possible hydrocarbon

Hyperbolic events are observed in Shot gather in Dulijan area related to possible hydrocarbon is shown in Figure-13. Well has been drilled based on available 3D seismic data and well operations are going on for hydrocarbon discovery.

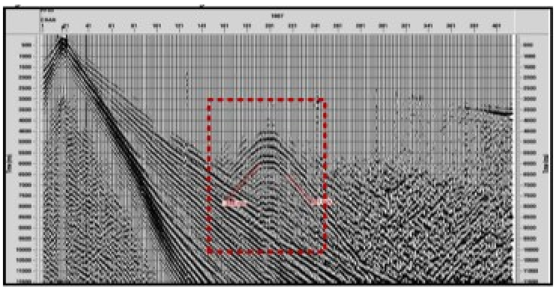

Figure 13. Shot gather over Duliajan structure; after AGC and band-pass filtering around 3 Hz shows resonant near infrasonic micro seismic emission as hyperbolic events(highlighted in red color box).

It is observed that phase slope is 330 m/s and maximum amplitude contribution of hyperbola is at nearby 6 sec in shot gather in time domain (see Figure-13). Therefore, resonant source (possible hydrocarbon) depth is at 1980 m (6 sec X 330 m/s = 1980 m)

Seismic reflection stack section against the apex of resonant hyperbolic anomaly shows bright amplitude event that may be gas accumulation (see Figure-14)

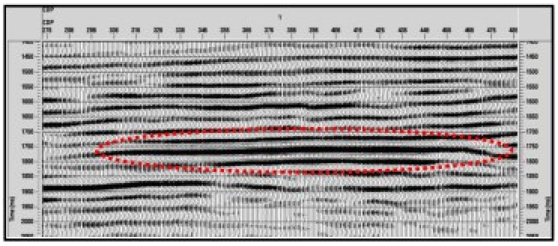

Figure-14. Seismic stack section: shows slight arched reflections (highlighted in red color) presumably from top of gas sand.

AVO response within the bright amplitude event is showed in Figure-15 suggests possible gas sand there

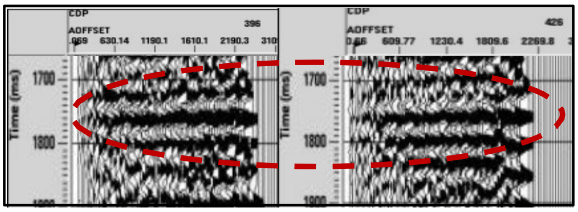

Figure-15. NMO corrected CMP gather – Trough amplitude increases with increasing offset (highlighted in red color) shows the class-III AVO response for gas accumulation.

Resonant near infra micro seismic emission evidence in Matimekhana area for possible hydrocarbon

Hyperbolic events are observed in Shot gather at Matimekhana area related to possible hydrocarbon is shown in Figure 16. Location has been released based on 3D Seismic data.

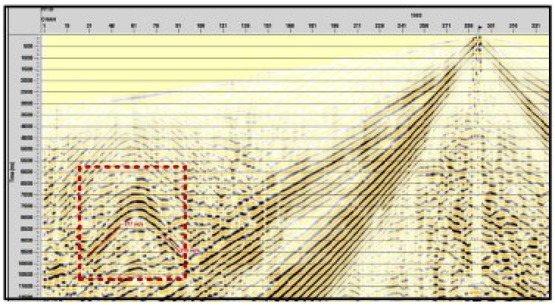

Figure-16. Shot gather: after AGC (2500 ms) and band-pass filtering around 2.7 Hz shows resonant near infrasonic micro seismic emission as hyperbolic events (highlighted in red color box).

It is observed that phase slope is 315 m/s and maximum amplitude contribution of hyperbola is at nearby 8 sec in shot gather in time domain (see Figure-16). Therefore, resonant source (possible hydrocarbon) depth is at 2520 m (8 sec X 315 m/s = 2520 m)

Seismic reflection stack section against the apex of resonant hyperbolic anomaly shows bright amplitude event that may be gas accumulation (see Figure- 15). This event comes at a time that would be predicted for a reflection from possible gas saturated sand, and its lateral boundaries correspond to that of limits of gas accumulations.

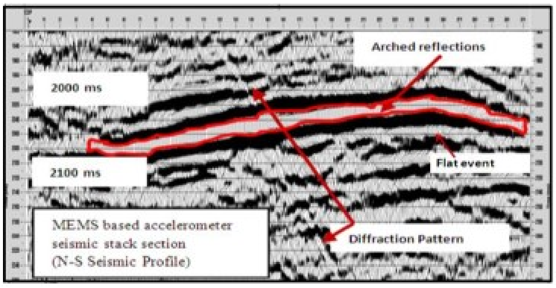

Figure-15. Seismic stack section: shows arched reflections (red in color) above flat event, presumably from top of gas sand. Diffraction pattern is noticed at the edge of flat event towards down dip limit of reservoir.

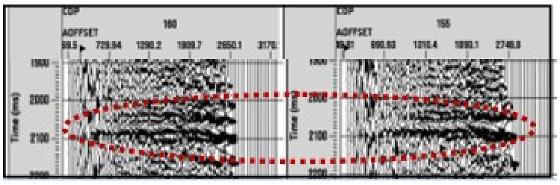

Figure-16. NMO corrected CMP gather – Trough amplitude increases with increasing offset (highlighted in red color) shows the class-III AVO response for gas accumulation.

Conclusion

Hydrocarbon reservoirs of high acoustic impedance contrast with respect to the embedding medium can trap seismic energy and act as a secondary buried resonant source and radiates energy in infrasonic frequency range to the surrounding medium. This energy generates waveforms which travel in form of shear body waves and can be recorded by MEMS based accelerometers. In a conventional seismic shot gather, they appear as durable late arrivals with respected to primary body waves, and are characterized as sequence of quasi-hyperbolic events. The curvature analysis of these hyperbolic events reveals that the apex of the best-fit hyperbola corresponds to the lateral location of the buried source. The maximum stack amplitude of the traces corresponding to the best fit hyperbola approximates to the depth of the buried source.

The above concept of using late arrival infrasonic signals from a buried resonant source, which could be a hydrocarbon reservoir of high acoustic impedance contrast, has been applied to two of the known reservoirs in one of the operational areas of OIL in Upper Assam and the results of the study have been outlined in this paper. The encouraging results of the study further extended to other known and unknown reservoirs. The results of the entire study strongly suggested that resonant infrasonic micro seismic emission may add enormous value towards fast, dependable & cost effective exploration and development of oil & gas prospects.

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