CONTINUOUS WAVELET TRANSFORMS FOR DELINEATION OF THIN SAND RESERVOIRS OF MIANO AREA, SOUTHERN INDUS BASIN, PAKISTAN

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ABSTRACT

This research endeavor to provide a workflow that may open the ways to explore the clastic reservoirs by the application of continuous wavelet transform technique of spectral decomposition and conventional seismic attributes such as average energy, reflection strength to a 3D seismic data set of Miano gas field, Lower Indus Basin of Pakistan. Miano Gas field is one of the distinct hydrocarbon producing zone located in Lower Indus Basin, Pakistan. Lower Goru is the principal hydrocarbon reservoir of Fluvial-deltaic depositional environments. Extensive geophysical studies have been done in this area to explore these clastic reservoirs. Predicting the thin reservoir sands within these laterally heterogeneous environments is a challenge for the Geoscientists. To overcome this issue, we have applied spectral decomposition; a vigorous seismic interpretation tool for delineating the channel geometries and the potential thin beds of hydrocarbon bearing sands. This technique can detect thin gas sand reservoirs which conventional seismic attributes cannot do due to their bandwidth limitations. Average energy could only give clue for these depositional features due to bandwidth limitation. However, continuous wavelet transform technique of spectral decomposition has remarkably delineated the channel geometries and the thin gas sand beds associated with these depositional features. Therefore, continuous wavelet transform in conjunction with some conventional seismic attributes can be used for future delineation and characterization of Fluvial-Deltaic reservoirs by giving optimal well locations of Miano area, Lower Indus Basin, Pakistan.

Keywords: *CWT-Spectral Decomposition, Seismic attributes, Fluvial-deltaic sands.*

1. INTRODUCTION

Fluvial-deltaic clastic reservoirs are becoming the focus of interest in the exploration of hydrocarbons. As these reservoirs are the combinations of various stratigraphic traps in the form of stacked channel sands. Lower Goru is one of the distinct clastic reservoirs of Miano Gas field Lower Indus Basin of Pakistan that has been producing the hydrocarbon for the last few decades. Many extensive geophysical studies have been carried on this area with the object to explore these clastic reservoirs. The complex fluvial dominated deltaic depositional environments acts as a barrier to successfully detect and delineate the reservoirs in perspectives of lithology and the hydrocarbon prospecting which is always remained a challenge for the Geoscientist. These sand systems consist of an organization of thick gas sand prone geometries such as point bars together with the levees and overbanks deposits.

The practical implications for characterizing these clastic reservoirs is that the crevasse, levees and point bars are the excellent geometries for hosting the hydrocarbon producing sands which can be delineated through various advance seismic interpretation tools. The aim of the research is to provide a workflow by the application of continuous wavelet transform technique of spectral decomposition (CWT-SD) to detect and delineate the thin sand reservoirs to a 3D post stack seismic data set of the area.

The prime objectives of this research work is to execute spectral decomposition as a key seismic interpretation tool for possible lithology and hydrocarbon producing zones detection through thin reservoir delineation. We have also incorporated average energy and (Instantaneous amplitudes) reflection strength attribute as a lithology indicator, but, we our focus remained on CWT-SD tool for possible thin reservoirs delineation.

Earlier in the same area we have applied seismic attributes and spectral decomposition for relatively thin. There is variety of spectral decomposition techniques with different applications. Each technique has its own advantages and disadvantages [1]. However, in theory, CWT-SD technique have proved it's excellent ability for

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providing the image with high resolution as it is out of bound for pre-selecting the time window length and does not have predetermined time – frequency resolution [2]. The suggested design of study can be helpful for delineating the remaining hydrocarbon potential sand reservoirs in the area.

2. GEOLOGICAL SETTING OF AREA

The dominantly north-south–trending Indus Basin is bounded by the Indian shield to the East, the Kohat Potwar Plateau to the North, and the fold and fault belts of the Sulaiman and Kirthar ranges to the West (Fig. 1) [3]

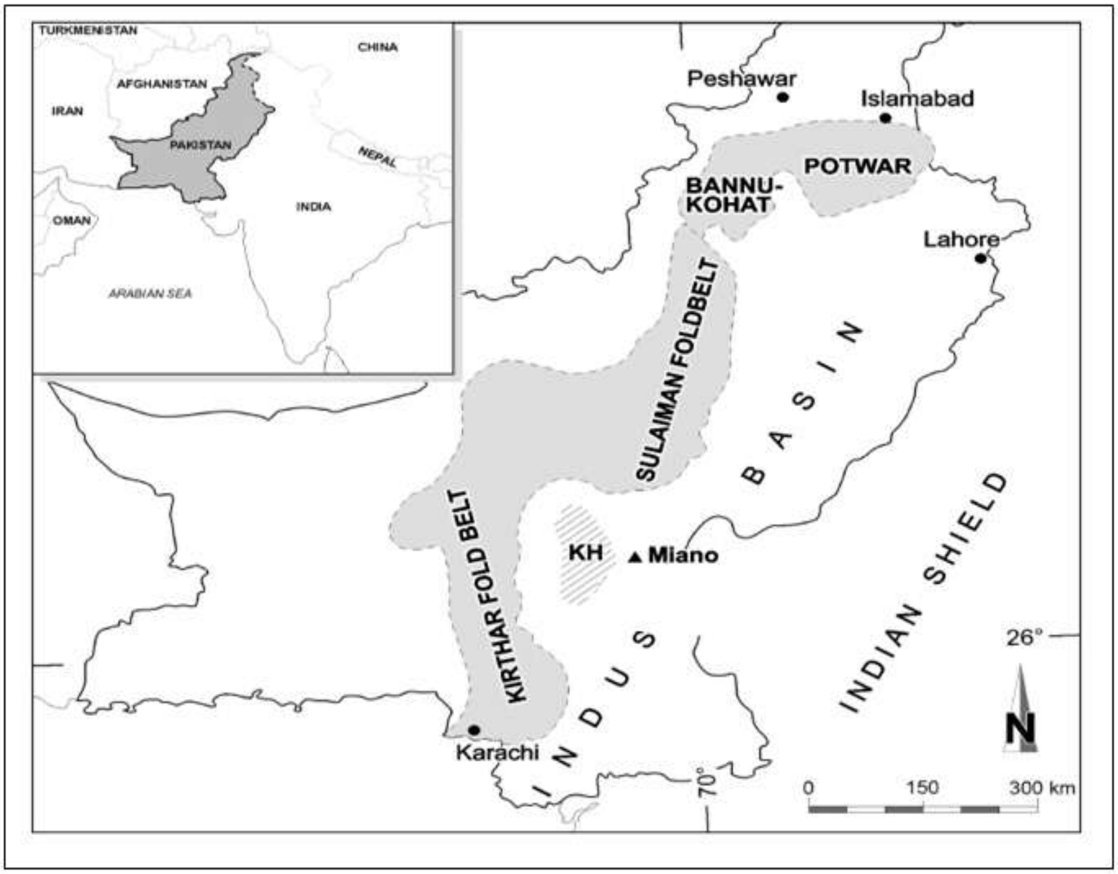

Figure-1. Map of Pakistan Showing Miano Gas Field.

The major structures and sedimentlogy of the Lower Indus Basin are rifting of the Indian Plate from Gondwanaland (Jurassic or Early Cretaceous) which probably created NE-SW to N-S rift systems, isostatic uplift or ridge-push at the margins of the newly developed ocean probably caused uplift and eastwards tilting at the start of the Cretaceous. Separation of the Madagascan and Indian plates in the Middle to Late Cretaceous may have caused some sinisterly strike-slip faulting in the region and hotspot activity and thermal doming at the Cretaceous-Tertiary boundary [4-5]. This in turn caused uplift, erosion, extrusion of the Deccan flood basalts and probably the NNW-striking normal faults.

2.1 Depositional Environments and Reservoir Characteristics

The dominant lithology is medium to coarse-grained sandstones of shallow-marine setting which constitute the major hydrocarbon producing reservoirs in Miano gas field. There is a variety of reservoirs characterized by deposits of a proximal wave-dominated delta system of fluvial-deltaic and barrier-bar complex with a variety of sub environments. Organic-rich shales within the Sembar Formation are the main hydrocarbon source rock for the lower and middle Indus basins [6].

Lower part of Lower Goru Formation is already producing gas, which is further divided into four sand sequences as shown in (Fig.2 A, B, and C and D) [7]. Predominantly gas-saturated Pay sands, These sands show anomalously high porosities and permeabilities at high temperatures and depths of are lying in the depths intervals between (1900m to 3800m) with average absolute porosities, are 16%, reaching more than 35%, are mostly encountered within mainly thin fluvial-deltaic sand systems.

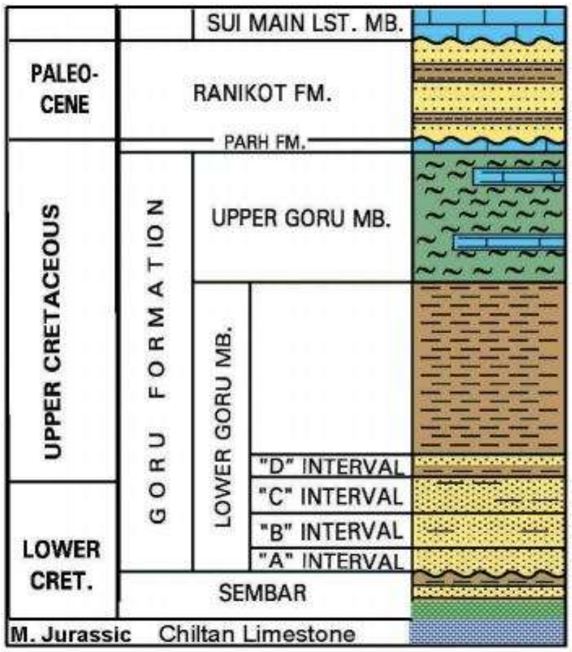

Figure-2. The Stratigraphic Column showing the subdivisions of Lower Goru Formation into Sand intervals A, B, C and D [7].

3. DATASET AND METHODOLOGY

The area is one of the leading hydrocarbon gas producing fields of Southern Pakistan. The used volume covers an area of 450 Km^2 of Miano gas fields which was acquired in vintage1999. This volume is divided into 340 Inlines and 450 cross lines which were used for this research work. The data was sampled at 2ms. Vibroseis eneregy source was used for the data acquisition. Data of six wells has been utilized for this research work.

Synthetic seismograms were generated for wells to link logs (in depth domain) to time domain seismic data and to observe the seismic character of sands within the area. Well to seismic ties were performed by establishing correlation between the seismic and synthetic seismograms by adjusting T-D functions through stretch and squeeze method (Fig.3). The zone of interest lies between 1.55 s to 1.68s (3000m to 3350 m) window of the reservoir zone.

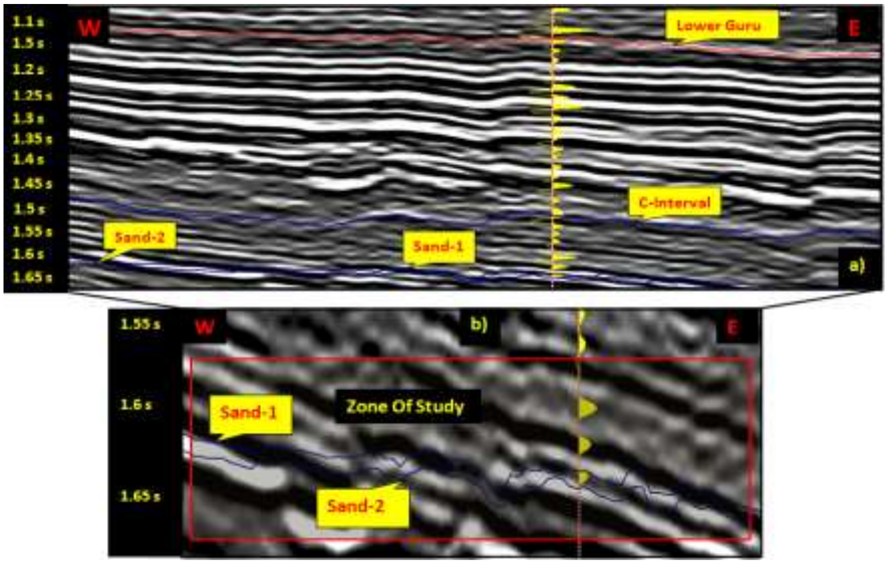

Figure-3. a. The Conventional Seismic Section and Zoomed Section at Reservoir level of interest

b. Yellow Wiggles is the Traces of Synthetic Seismogram.

Two horizons namely Lower Goru and informally nomenclature C-Interval habe been marked. It is important to mention here that two surfaces have projected and named as Sand-1 and Sand-2 by taking the reference of Lower Goru horizon for the purpose of visualizing the depositional features at the reservoir level.

Spectral decomposition is a tool for enhanced imaging and mapping chronological bed thickness using 3D seismic data [8] and it aids in seismic interpretation by analyzing the variation of amplitude spectra. There is a Variety of spectral decompositions methods. Each method has its own advantages and disadvantages and different applications require different methods [1]. The aim of all these methods is to decompose a seismic signal into its constituents in order to achieve better geological information. For instance, the discrete Fourier transform is a traditional frequency decomposition method. The transform determines the relative strength of each frequency component of the entire signal but does not provide information on how the frequency content changes with time. Therefore, the discrete Fourier transform method is not suitable for analysis of non-stationary signals since it is unable to localize frequency variations over time.

Therefore, in this study, we have applied CWT- SD on full stack high resolution 3D seismic data to check the frequency response of fluvial-deltaic sands and calculated iso-frequency volumes using the output spectra of spectral decomposition of CWT for analysis of reservoir sands of various thicknesses. However, theoretically, CWT technique have better ability to provide the image with high resolution as it does not restricted to the pre-selection of the time window length and does not have fixed time – frequency resolution [2].

Mathematically, the continuous wavelet transform is calculated as by summing over all time of f (t) convolved and shifted versions f the analyzing wavelet function ψ:

$$C\ (\text{scale, translation}) = \int_{-\infty}^{+\infty} f(t)\psi\ (\text{scale}, \text{translation}, t)dt$$

$$C\ (\sigma, \tau) = \int_{-\infty}^{+\infty} \frac{1}{\sqrt{\sigma}}\psi\ \left(t - \frac{\tau}{\sigma}\right) f(t)dt$$

Where the term $\frac{1}{\sqrt{\sigma}}\psi\ \left(t - \frac{\tau}{\sigma}\right)$ is a an envelope of the scaled and the shifted wavelets and σ, τ are scale and shift parameters, respectively [2]

For establishing the relationship between frequency and the layer thicknesses, we have made a cross plot of frequencies and the sand bodies thicknesses. From this cross plot, we have analyzed the spectral decomposition response of bright amplitude responses of various sand bodies. We selected sand bodies of various thicknesses such as 12m, 14m, 18m, 19m, 26m, and 30m from the surrounding wells. These sand thicknesses were plotted against the various CWT-frequencies.

In addition to spectral decomposition we have also calculated the average attribute and reflection strength attribute. Average energy is defined as the square of RMS amplitude. There are two main applications of average energy; depicting the depositional environments, sharp interfaces of lithogical contrast. Thus, it is important to incorporate for inferring the depositional environments.

Reflection strength has wide application for reservoir characterizations. It is defined as the Envelope amplitude or reflection strength is defined as the root square of square seismic trace plus square quadrature trace. Highest value of envelope amplitude infer as major changes in the lithology such as unconformities or presence of gas [9].

Mathematically, it is defined as

$$E\ (t) = \sqrt{[f^2\ (t) + g^2\ (t)]}.$$

t varies approximately between 0 and the maximum amplitude of the trace. The envelope relates directly to the acoustic impedance contrasts. And therefore, can be used as hydrocarbon indicator.This attribute was incorporated for inferring the channel fill lithology. First, we have generated the horizon slice at the shallow reservoir level, and proceeded at the deeper reservoir level to have a clue for the deeper reservoir level. For this purpose, we have generated some time slice of amplitude at two shallow levels (Fig. 4).

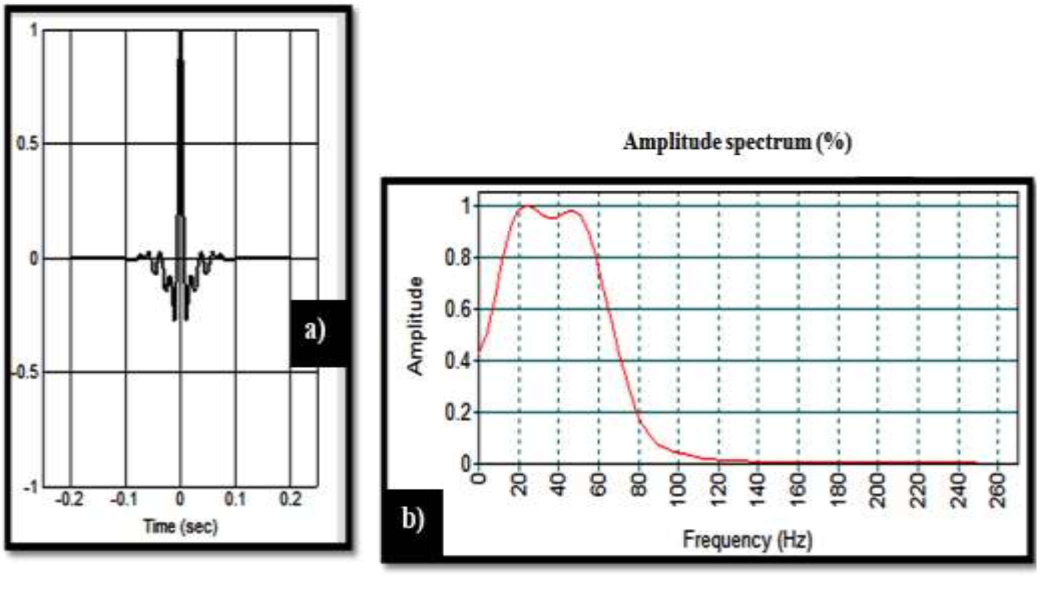

Figure-4: Computed Amplitude Spectrum at the reservoir level. a. Extracted Wavelet b. Frequency Spectra.

4. RESULTS AND DISCUSSIONS

4.1 Synthetic Seismogram

The seismic data is of normal polarity with an increase in acoustic impedance being represented by a peak. The Synthetic seismogram of one well is used for the reflector marking (Fig. 3).

4.2 Spectral decomposition Model of sand bed thicknesses

According to the cross plots of sand bodies and frequency (Fig.5), as the frequencies increases we are getting the thin sand beds. From the frequency – thickness relationship, it may be infer that which frequency will be suitable for exploring the specific sand body of various thicknesses. As an example, one can infer that to explore the thin bed of less than 10 m thick sands, it would be better to analyze the 80 Hz frequency slice for lateral distribution of this sand bed. Similarly, to explore the sand bed of 30 m thickness, it's better to analyze the 15 Hz frequency band of CWT-SD. It is also clear that, the amplitude spectrum of these sand bodies drops drastically between 30 Hz and 50 Hz. However, we may infer that bright amplitude at frequencies between 30Hz and 40 Hz may show the thick sand between 15m and 25m According to the spectrally decomposed output cubes at the representative wells, robust results for sand layer thicknesses are observed, and are depicting the significantly excellent response of spectral decomposition from different sand bodies' thicknesses. At the same sand bed thicknesses in a well, low frequencies are showing the thick sand beds (Fig. 6a, and b), while the higher frequency components of amplitudes brighten, above the 1550 ms (Fig. 6c, and d), thin beds are encountering in the high frequency volumes, while the thick beds of sands are encountering in the low frequency components [10]

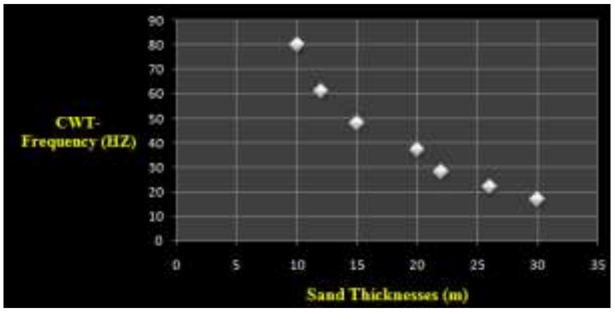

Figure-5: Cross Plot between Sand Thicknesses and Frequency Maximum Amplitude Response

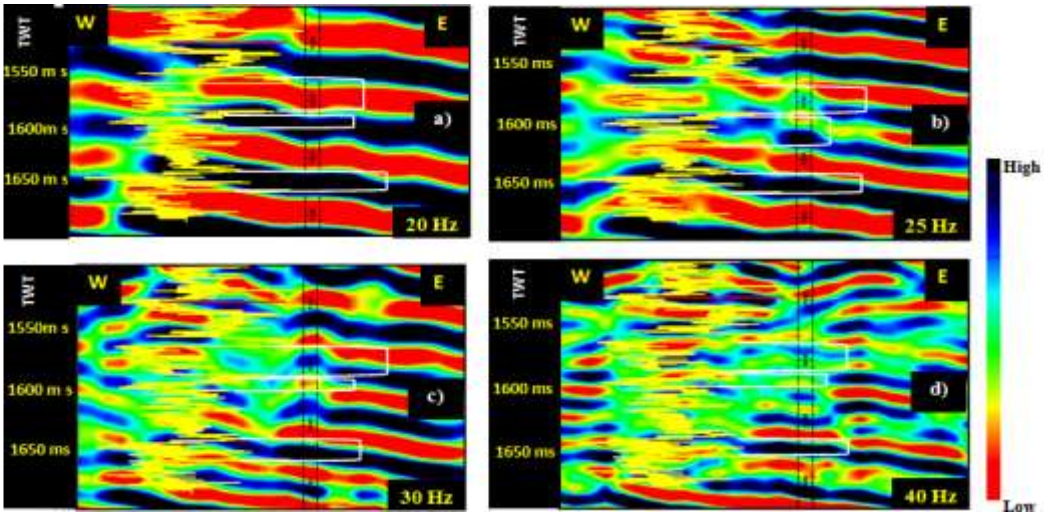

Figure-6: Spectrally decomposed CWT isofrequency volumes along the representative well section a.20 Hz, b.25 Hz, c.30 Hz, and d.40Hz.Thick sand beds demonstrate bright amplitudes at low frequencies (a and b), while the thin sand beds demonstrate bright amplitudes at higher frequency (c and d). Yellow curve is the gamma ray curve (increases towards right) while the white flags are the gas pay zones encountered in the reservoir zone of interest.

5. SEISMIC GEOMORPHOLOGY AND HORIZON ATTRIBUTES ANALYSIS

Multiple horizon slices such as Lower Goru, C-Interval, Sand 1 and Sand 2, were thus selected in the zone of interest to understand the lateral and vertical variations in sand distribution patterns occurring in the channels geometries by observing different seismic attributes. Our main emphasis remained on CWT –SD 22 Hz horizon slices.

This is the shallowest slice of seismic amplitude attributes (Fig.7). As, the seismic amplitude provides detailed stratigraphic and reservoir characteristics [11]. This horizon slice clearly demonstrates the point bars indicated by red arrow at the SW margins. Length of this meander belt is about 7 km with sinuosity index of 1.9.

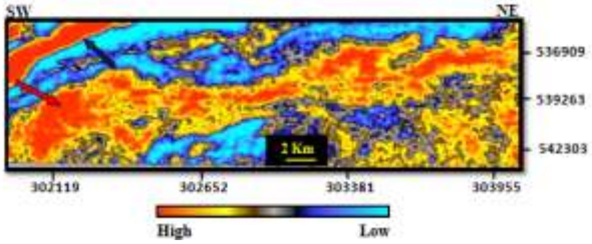

Fig 7: Amplitude Time Slice at 1212 m.sec.

5.1 Analyses of CWT-SD Sand Horizon Slice

This is the horizon below C-Interval. We may see that the 22 Hz iso frequency volumes and average energy (Fig 8a, b) indicate low sinuosity features as compare to the seismic amplitude slice (Fig.8). Due to limitations; average energy is not presenting the best image for crevasse splay like feature indicated by red arrow a the southwestern flanks (Fig 8a.) However, CWT-SD 22 Hz, have excellently imaged these hydrocarbon bearing features. Southern most margins there are some high amplitude (Fig. 8a). These high energy zones are showing the massive sand lithologies, which are also confirmed from the nearby producing wells. Hence, these zones can be interpreted as high energy environments (Fig. 8a). On the other hand, CWT-SD 22 Hz (Fig. 8b), the broad amplitudes are now becoming narrow on the northeastern margins indicated by blue arrow. Northwest –southeast trending regional faults are also shown by the blue lines on both the slices (Figs. 8a, b).These faults most probably be created by the channel. On the south western regions on both the slice (Fig. 8a, b), the crevasse like features indicated by the red arrow on (Fig. 8a), and by large blue arrow (Fig. 8b) where there is massive sand presence is obvious. Paleo-flow of water was northwestern to south eastern directions.

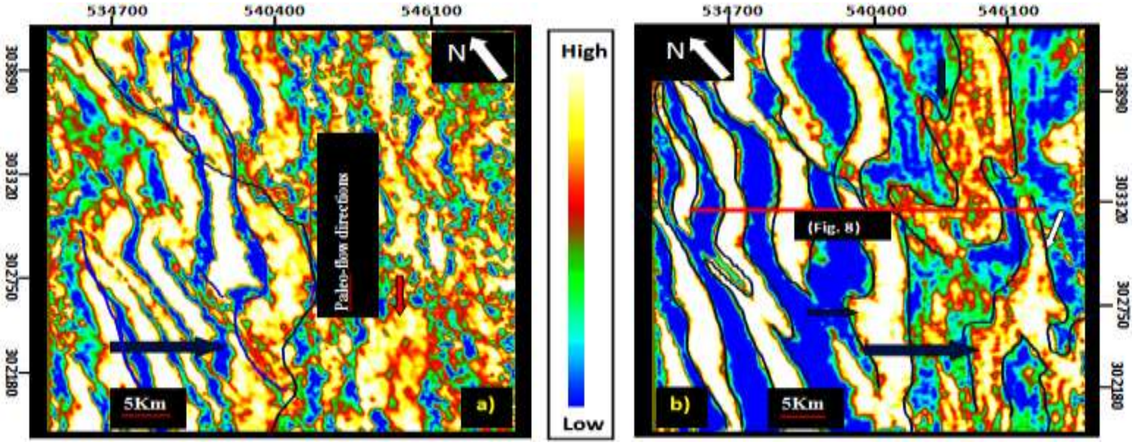

Figure-8. Horizon Slices at Time 1644 msec. a. Average Energy b. Spectral Decomposition 22 Hz.

Now, as the deeper reservoir level encounters (Fig. 9), the bright amplitudes broad point bars are encountering. There are the amplitude attenuations at the reservoir level of interest. This amplitude attenuation may be attributed to the gas presence in point bars geometries. According to literature, the depositional environment of reservoir strait is fluvial-deltaic. (Fig. 9), the central part is showing the meander feature surrounded by the wells, and extending from southern to northern margins. The length of this meander belt is 3.5 km. On the north-eastern flank, that there is a massive sand body present. This sand body is 1.5 km wide. So, north-eastern most margins are showing positive signs for the presence of hydrocarbon prone sand in the form of bright amplitudes of point bars. So, the eastern flanks of the survey may be more promising than the western flanks for hydrocarbon perspectives. There is a good well control and these bright low amplitudes of CWT-SD are also confirmed from the nearby surrounding wells (Fig.10).Gas pay zones are encountered at various levels. Although the broad sand geometries are surrounded by the wells-05, well-06, and well-07. But, the well-05 (Fig. 10) is depicting more positive signs for the hydrocarbon presence.Well-05 may be more productive in the future as, gas pay zones are encountering at both the shallow and the deeper reservoir level. These pay zones are lying in the reservoir level, which also validates our results regarding the hydrocarbon presence.

A comparison between the CWT-SD 30 Hz and 40 Hz slice is shown (Fig.10).It is obvious that, again the eastern flanks of the survey are showing a little narrow meander belt (40 Hz) right as compared to the (30 Hz) left slice. From the cross plots for frequency and the layer thicknesses (Fig.5), these observations are now validated form these two slices of (30 Hz) left and (40 Hz) right CWT-SD slices. As the higher frequency component come across more thin beds are attain and vice versa. Similarly, these possible hydrocarbon prone geometries are also confirmed from the nearby wells. (Fig.11)

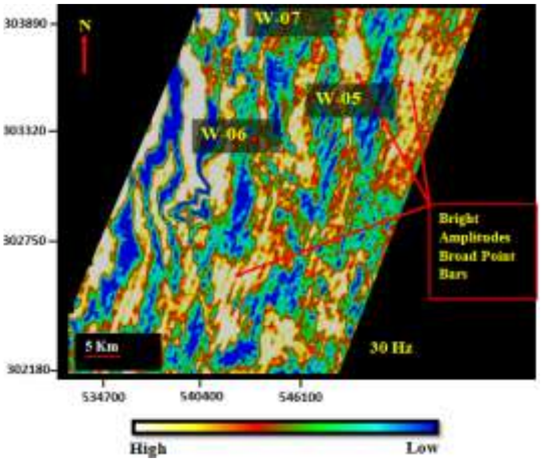

Figure-9: 30 Hz Amplitude Slice at 1655 ms of the Reservoir Level.

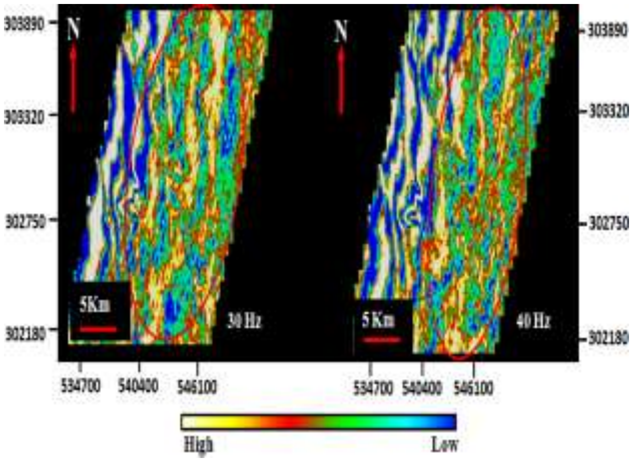

Figure-10: 30 Hz and 40 Hz Amplitude Slices at Deeper Reservoir Level of 1677ms.

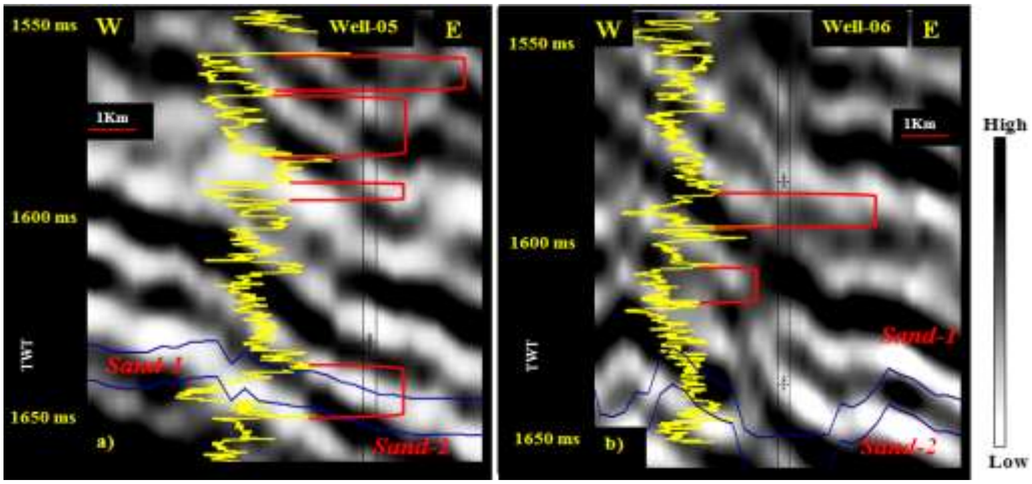

Figure-11: Amplitude seismic sections along the representative wells.a.well-05, b.Well-06.Red blocks are representing the gas pay zones.Well-05 is showing the gas pay zones at both the shallow and deeper reservoir level, but, Well-06 represents gas pay zones at the middle reservoir level.

5.2 Lithological Analysis

Up to this stage phase of the research, the lateral sand distribution was analyzed. For accessing this accuracy, we have utilized the vertical seismic sections of instantaneous amplitude (reflection strength) and the seismic amplitudes (Fig. 12a, b). The fluvial-deltaic heterogeneous environments have created the difficulty for exactly matching the channel filled lithology so, to identify the exact lithology of the reservoir formation, reflection strength was the best choice for this purpose. And it is incorporated for identifying the hydrocarbon prone sand infill lithologies.

Lithology identification within the channel fills can be inferred from the instantaneous amplitude (reflection strength) which has various applications, but this attribute is incorporated as a hydrocarbon indicator by inferring lithologies of the channels fills (Fig. 12b). High values are revealed by yellow colour depicting the high energy, porous sand filled channels (Fig. 12b), while the black colour is providing a match for convex downward amplitude channels (Fig. 12a). As, the massive point bars and the crevasse like stratigraphic depositional features are of hydrocarbon interest, hence this attribute can be used for detection of the sand filled channel lithologies that are showing different acoustic impedance contrasts [12].

Coarse sand filled channels are the reflections of high energy environments and the intermixed mud filled lithologies are the reflections of low energy environments. These depositional features may be seen on the displayed vertical seismic inline 2960 section (Fig. 12), where there is strong reflection amplitude (Fig. 12a) and the high amplitude high energy environment is confirmed from the vertical section of average energy attribute (Fig. 11a).(Fig.13) depicting the of the sand filled channels. The channel fill lithology is diligently confirmed from the vertical section along a representative well.

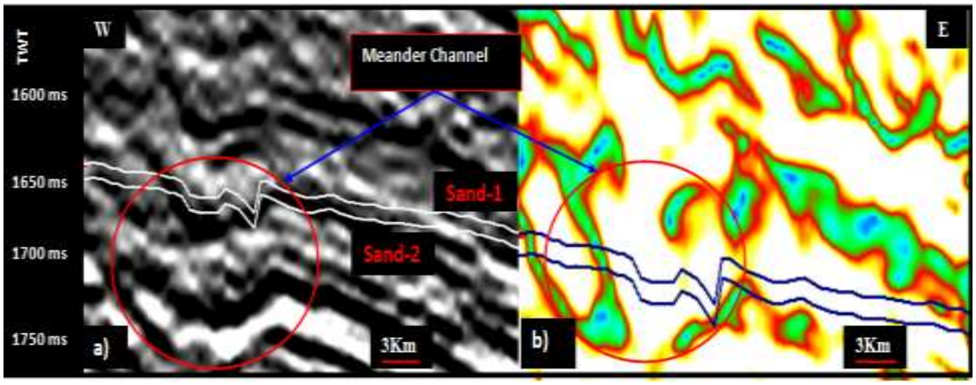

Figure-12. a. Seismic Inline 2960 Passing the Meandering Channel. b. Reflection Strength Attribute Applied to the Same Section.

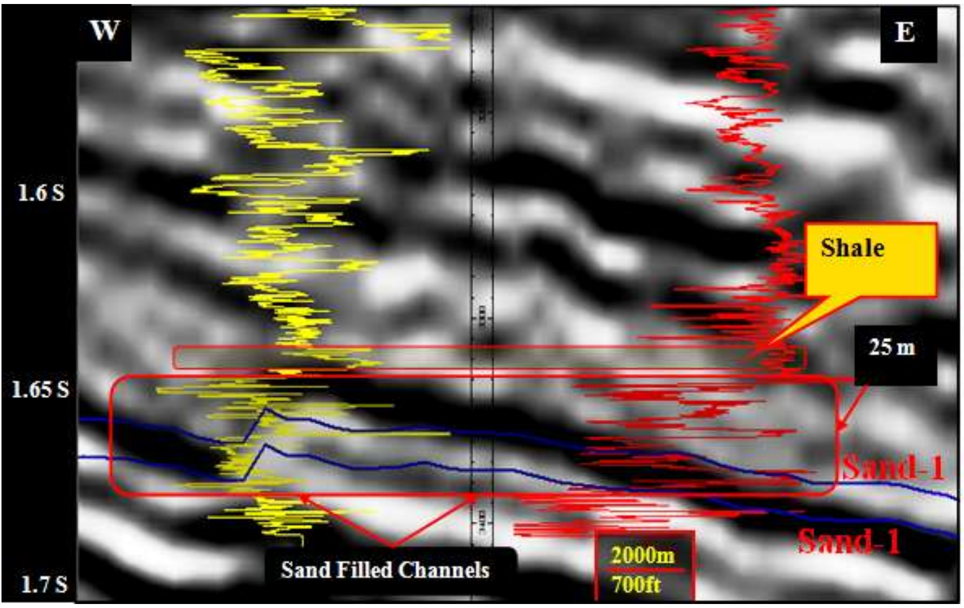

Figure-13: Amplitude section along the representative well. Lower black bar represents the gas sands pay zones, while the upper small block showing the shale interval at the reservoir level. Red curve is the density log, while yellow curve is representing the gamma ray log (both increasing towards right).

In summary, the bright amplitudes broad point bars, and crevasse like depositional features may be more favorable for hydrocarbon exploration on eastern flanks as compared to the high amplitudes narrow channel like features on the northwestern flanks of the horizon slices (Figs. 7, 8, 9,10).

6. CONCLUSIONS

Investigations have been carried on the Miano Gas Field in perspectives of lithology and possible hydrocarbon prone thin sand reservoir recognizing by the approaches of continuous wavelet transform technique of spectral decomposition and conventional seismic attributes such as average energy, reflection strength to a 3D post stack seismic data. Since, massive sand facies such as point bars, crevasse like depositional features are of great importance in context of hydrocarbon exploration. At the Lower Goru level, average energy could only give clue for these depositional features due to bandwidth limitation.

However, CWT-SD has proved and the continuous wavelet transform technique of spectral decomposition has remarkably delineated the channel geometries and the thin gas sand beds associated with these depositional features. Therefore, CWT-SD along with some conventional attributes can be used to identify the remaining hydrocarbon prone features by planning of wells of Miano Gas Field, Lower Indus Basin of Pakistan.

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