Curvature attributes for identification of faults and fractures: A case study Padra field, Cambay Basin

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Abstract

Faults and fractures play key role in generating effective porosity for hydrocarbon traps in volcanic reservoir. Mapping the location, intensity, density and orientation of these faults and fractures can aid in the positioning of wells. Often it is difficult to map subtle faults and other trace to trace discontinuities hidden in 3D seismic data. They may appear as minor changes in the seismic waveform that are not easily discernable using conventional interpretation of seismic cross-sections. To map these changes we have investigated and computed several seismic attributes sensitive to the presence of small faults and fractures in the target reservoir in the Deccan Trap in Padra field. Volumetric curvature attributes including most positive, most negative curvatures and coherency horizon slices have been used to map possible faults/ fractures within Deccan Trap. Images of the borehole wall from FMI data and detailed fracture measurements derived from curvature attributes horizon slice from post stack seismic data have been used to visualize the fractured /faulted zones in the area.

In this work, we have used curvature attributes horizon slice to visualize and delineate fractures and lineaments in the Padra area. A 3D Pre-STM seismic volume was used to predict density and orientation of fracturing and faulting within the volcanic rock and validated with FMI log data.

Keywords: Volcanic rock, Seismic attributes, Curvature, Coherence.

Introduction

The Cambay Basin in Gujarat was formed during Early Cretaceous as a result of rifting along Dharwarian orogenic trends. This rift phase of Indian plate witnessed volcanic events in the western India during K/T times. The subsequent synrift phase of the basin comprises of Olpad Formation, Older Cambay Shale Paleocene/Early Eocene age and Ankleshwar and Post Ankleshwar sediments of Mid Eocene to Oligo-Miocene age followed by Post rift sediments in the basin. Padra field is located in the eastern margin of South Cambay Basin (Fig.1). Padra Field has attained special significance for its commercial hydrocarbon production from non-conventional fractured reservoirs namely Deccan Basalt, besides younger pays. More than 98 wells have been drilled in the field and it has been established that the porosity, permeability and hydrodynamic behavior within Deccan Trap are attributed to natural fractures present in it (Sushil et al., 2011). Barefoot completion procedures have been adopted for testing the basalt section drilled within Deccan Trap (100-150m). Wells in the area are average to poor producers. Highly skewed frequency diagram of initial production (IP) rate and cumulative production (CP), a characteristic feature of a fractured reservoir worldwide, is also observed in Padra Field. Fractures can provide both storage and pathways for oil production and connection to adjacent aquifers. Fracture prediction in subsurface is critical for exploration/exploitation of hydrocarbons. Surface seismic data may help in the prediction of minor faults/fractures orientation and intensity resulting in identification prospective areas. In this study we have integrated seismic attributes, in particular the most positive curvature and coherency attributes to delineate areas consisting of significant faults / fractures, which are beyond seismic resolution within Deccan Trap in the Padra Field, which are then correlated with borehole image logs (FMI) from drilled wells.

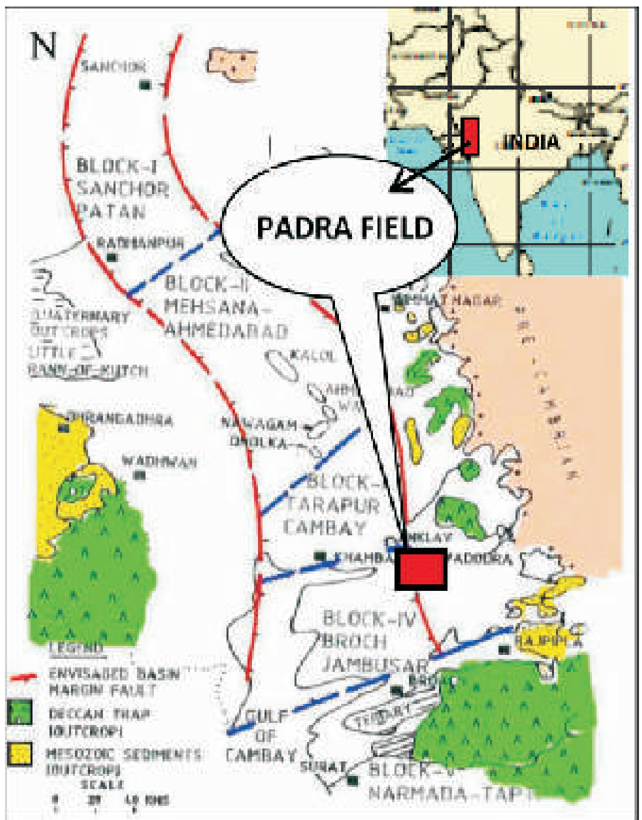

Fig. 1: Location map of the Padra Field in the Jambusar-Broach Block.

Seismic Characterization of Fractures

Identifying and predicting subtle faults and fractures which are near or below seismic resolution limit is one of the major objectives of present study. Geometric attributes such as coherence and curvature derived from Post Stack seismic data, are useful in understanding the structural deformation of the rock. Rijks and Jaufred (1991) showed that dip magnitude and dip azimuth can illuminate subtle faults having displacement significantly less than the size of a seismic wavelet. Coherence attributes (Bahorich and Farmer, 1995) measures lateral changes in seismic wavelet. Since the fault disrupts inter-trace coherence, calculation of coherence points will result in lineaments of poor coherence along the faults.

Lisle (1994) and Hennings et al. (2000) have calibrated the fractures measured from outcrops with curvature attributes. The curvature attributes have been found to be useful in delineating faults and fracture orientation and their distribution (Roberts, 2001, Hakami et al. 2004).

Curvature is a two dimensional property of a curve and describes bending of curve at particular point on a curve i.e., how much the curve deviates from straight line at this point. Fig-2 shows a simple curve (2D surface) in XY co-ordinate, this curved line can be thought of being made of arcs of circles having different radii along the points on the curved surface (Sigismondi and Soldo, 2003). The curvature at any point on this curve is defined as reciprocal of the radius of that particular arc of the circle at that point. It can also be defined as the derivative of the curve's tangent angle with respect to position on the curve at that point. If θ(s) denotes the angle that the curve makes with some fixed reference axis as a function of the path length along the curve, then 2D curvature k_{2D} is defined as (Sigismondi and Soldo, 2003).

$$k_2D = 1/R = d\theta/ds = d\theta/dx * dx/ds \quad (1)$$

In XY co-ordinate system θ can be expressed as

$$\tan(\theta) = dy/dx,$$

$$d\theta/dx = d[\tan^{-1}(dy/dx)]/dx = \{d^2y/dx^2\}/[1+(dy/dx)^2] \quad (2)$$

A plane curve is represented by Y=f(X), where X and Y are Cartesian co-ordinates and very small arc length on the curve ds can given by geometric principle $(ds)^2 = (dx)^2 + (dy)^2$ which can be rearranged as

$$dx/ds = [1+(dy/dx)^2]^{-1/2} \quad (3)$$

Substituting equation (1) with equations (2) and (3) leads to

$$k_2D = d\theta/ds = d\theta/dx \ * dx/ds = \{d^2y/dx^2\}/[1+(dy/dx)^{3/2}] = 1/R \ (4)$$

Thus 2D curvature is defined as the change in the radius of curvature, and hence the angle of the normal with vertical, $\theta = \tan^{-1}(y/x)$. Sigismondi and Soldo (2003) show that peak value of curvature will occur at the crest of fold images is $k_2d = d^2y/dx^2$, zero dip situation. We can get a sense of both magnitude and sign of curvature of a curve by replacing these radii with normal vectors as proposed by Roberts (2001) Fig-2. Planner surfaces have zero curvature, anticlines positive curvature and synclines negative curvature and vector are parallel diverging and converging respectively. In 3D space, curvature evaluation depends upon direction (Lisle, 1994; Roberts 2001) and scale.

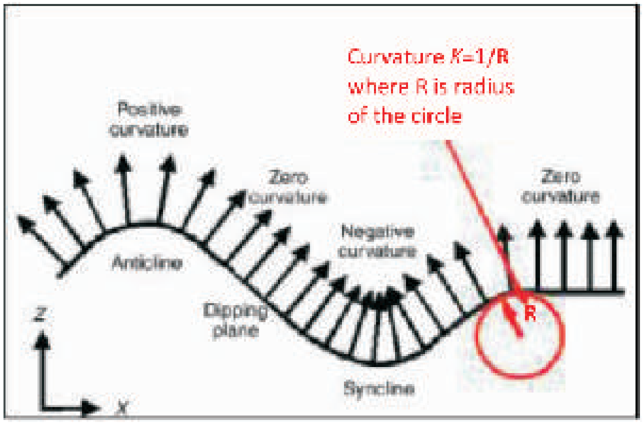

Fig. 2: Showing definition of 2D curvature k. Black Arrow indicates vectors normal to the surface. Synclinal features have converging vectors as negative curvature, anticline feature have diverging vectors as positive curvature and planner features have parallel vectors as zero curvature. (After Roberts 2001)

Al-Dossary and Marfurt (2006) extended the concept of volumetric estimates of curvature having significant advances over horizon based curvature as the former does not influenced by horizon interpretation. Curvature attributes measure the structural shape of the seismic data (Chopra and Marfurt, 2010). Most positive curvature attribute map indicate the hinge zone of anticlinal or dome feature. Negative values of most positive curvature indicate bowl features. Most negative curvature attributes map highlight synclinal or bowl shaped features.

However, positive values of most negative curvature indicate a dome feature. Nelson (2001) described how zones of greatest curvature are related to the zone of greatest strain in the rock. The relation between curvature and strain allows us to use curvature measures from 3D seismic to infer presence of fractures. Although curvature measures relative bending, structural deformation and possible fractures at the time of deformation, therefore true value of this measurement may be needed to be derived from stress field from borehole breakout, image logs and other measurements.

Present work

3D Prestack Time Migrated seismic volume of Padra Field is used for present study for identification of Faults and fractures within Deccan Trap. Inbuilt application of Landmarks software has been used for filtering / image enhancement of seismic data and volumetric attributes computation. As curvature attribute involves computation of second derivative, it is necessary to remove coherent noise. For image enhancement Coherency filtering process with horizontal window of 25 traces and time window of 100 msec was applied to the seismic volume to remove coherent noise, preserve fault edges, and improve better signal to noise ratio. Seismic line 620 Fig-3 is showing improvement in clarity of faults, reduction in background noise, focused image after coherent noise removal respectively. Most positive and Negative curvature attribute volumes are generated using 50ms window.

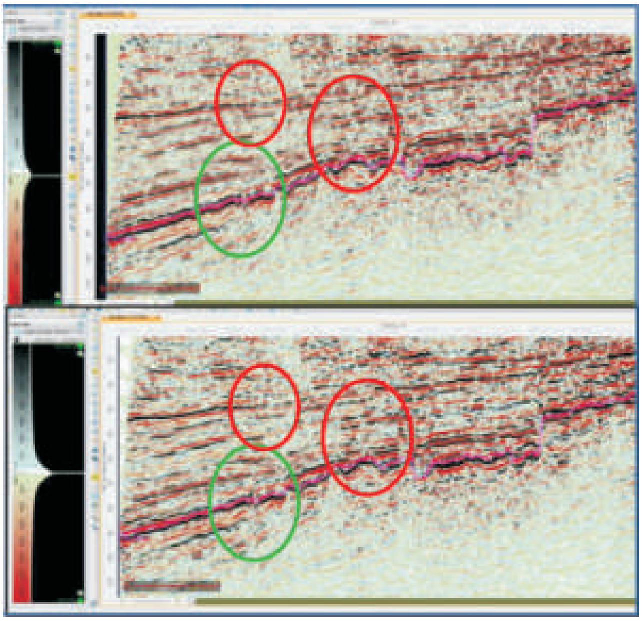

Fig. 3: In-line 620 from the PSTM volume of Padra area (top) and after application of coherency filter (bottom), shows improvement in seismic image by application of coherency filter. Random noise is reduced shown by red color circle, fault are better defined indicated by green color circle and trap top (pink color).

Faults/fractures are better defined on curvature attributes slice as compare to time slices Fig-4. Minor discontinuities are brought out clearly interpreted as fault / fracture network on curvature attributes. Coherency attribute generated on preconditioned seismic data and horizon slice near Trap top is extracted from coherency volume. Fig-5 compares the horizon slices extracted from Coherency, Most Positive and Most Negative curvature attributes volumes. It is observed that curvature attributes slice are depicting more detailed faults / fractures lineation on most negative curvature attribues. Coherency attribute slice is able to detect major faults while curvature attribute horizon slice shows lineations of minor faults which are difficult to map by traditional method. Detailed information about fractures in subsurface is interpreted from FMI log data recorded in bore holes. FMI data of one the well PA is shown in the Fig-6 and number of fracture zones identified indicated. Wells PA penetrated more than 100m Trap section and borehole image log (FMI) were recorded in this well. Trap top is encountered at 741m & 598m (KB relative) depth. FMI logs interpreted in these wells suggest that well PA is having high density of vertical faults / fractures. Density and orientation of these fractures computed are plotted on Rose diagram Fig-7. Rose diagram indicates that major fracture orientation is N-S and NNW-SSE direction Sushil Kumar et al 2011.

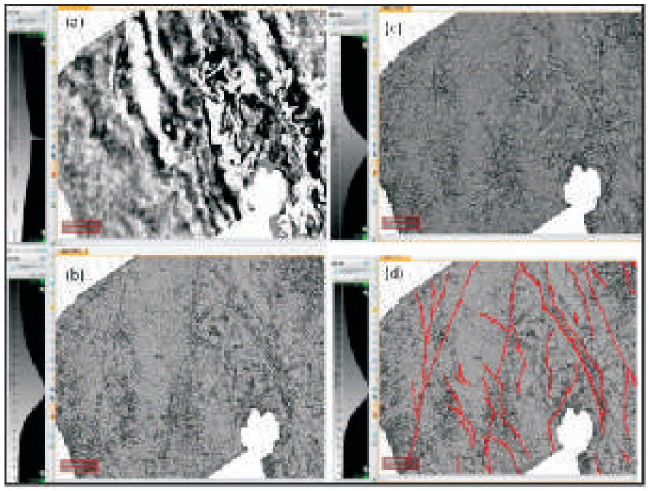

Fig. 4: Time slice at 630 ms from PSTM data after noise removal (a), Most positive curvature (b) and most negative curvature attribute volume(c). Interpreted fault polygons (red color) are overlaid on most positive curvature attribute slice (d). High value of curvature attributes on respective time slices represent faults / fractures in the area. Fault geometry on curvature attribute slices removes the uncertainties / difficulties in envisaging fault lineation on the basis of vertical cross-sections, time slices and coherency slices.

Fig. 8(a) and 8(b) show core photographs of Deccan Trap in depth interval from 700.5-708 m & 714.5-722 m, from one of the exploratory wells located in southern part of the field outside the 3D area, in which entire section of 100m drilled in the Deccan Trap is cored to carry out detailed study about fractures. The photograph show presence of sub-vertical, sub horizontal faults and fracture in the trap.

In order to quantify the faults orientation seen on Curvature images, faults segment are drawn on most positive curvature image and computed the azimuth of individual fault segment and generated the rose diagram for the time window in the zone of interest. Horizon slice for 30 ms window from trap top of most positive curvature attribute is shown in Fig. 9 (A) Un-interpreted (B) Interpreted, fault lineation's are drawn in red color and lineation's are annotated with number. Azimuth of fault lineaments computed and divided in class of angle range and the fault frequency (number of fault lineaments) in that class is mentioned in Table-1. Rose diagram of these fault segments prepared using mid angle of the class and fault frequency representing length of rose petal Fig-10. Rose diagram is prepared by considering various orientations in all directions into a single rose diagram with angles ranging from 0 to 180^0 for each fault lineament. Rose diagram clearly display two major axes of fault orientation as N-S and NNW-SSE conforms to fracture orientation observed on FMI log of well PA. Another fault WSW-ENE also present on both rose diagram. Most positive

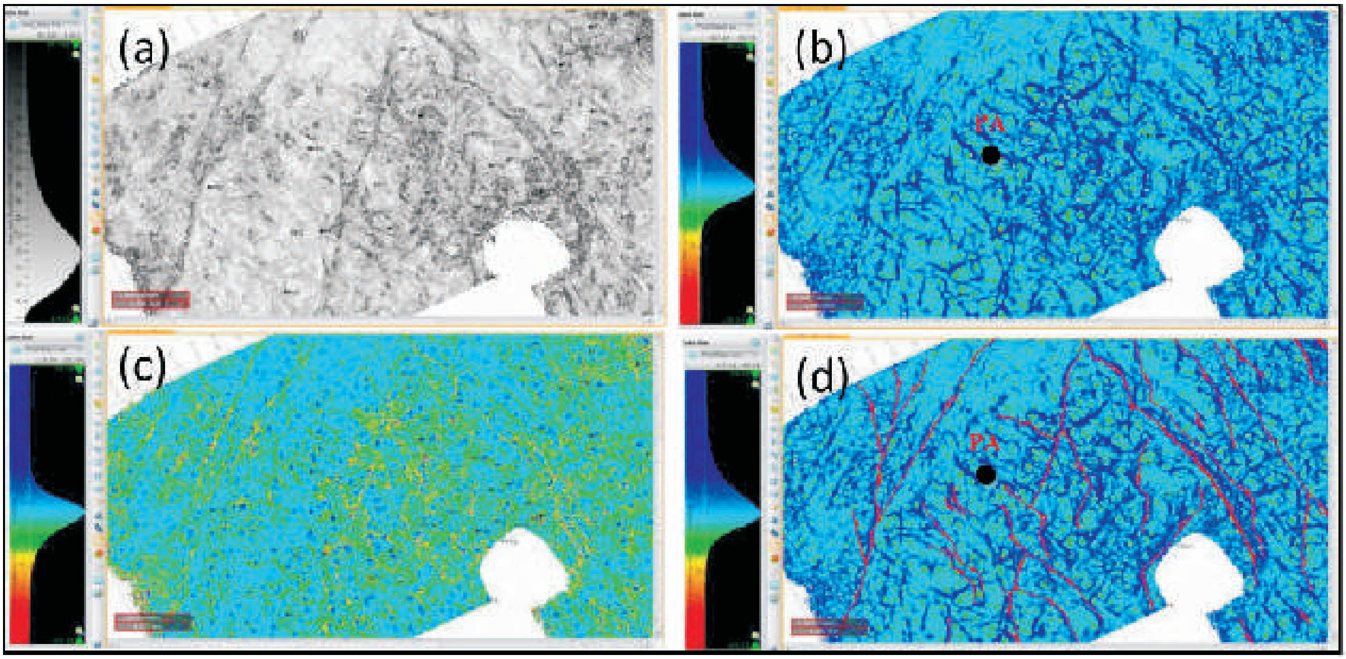

Fig.5: Horizon slice near Trap top (a) Coherency attribute maximum dissimilarity indicated by dark grey color (b) most positive curvature attribute. (c) most negative curvature attribute (d) most positive curvature attribute overlaid with interpreted fault (red color). Drilled wells are shown by black color. Major fault are seen on coherency attribute whereas minor faults and cross-faults are not illuminated by coherency attribute. Faults and Fractures geometry is better defined on curvature attributes. Faults / fractures are more focused on most positive curvature attribute. Curvature attribute predict areas of higher fracture intensity.

Table 1: Computed Azimuth of Fault lineaments interpreted on most positive curvature horizon slice Fig-9(B).

Azimuth Angle Degree			Number of Faults
From	To	Mid Angle	polygon
0	5	2.5	2
5	10	7.5	2
10	15	12.5	4
15	20	17.5	2
20	25	22.5	1
40	45	42.5	1
60	65	62.5	2
135	140	137.5	3
165	170	167.3	2

curvature attribute provide detailed and defining subtle lineaments related to regional or local stresses. Thus faults and natural fractures are genetically related, are developed under same stress conditions. Densely spaced fractures associated with faults and flexures (Fracture Swarm) are sweet spot from hydrocarbon point of view as high permeability is expected around fault planes and fault zones.

Integration of Geometric attributes such as coherence and curvatures derived from seismic data, are useful in delineating fault/fracture lineation which are beyond seismic resolution, thus help in exploration of hydrocarbon in Trap.

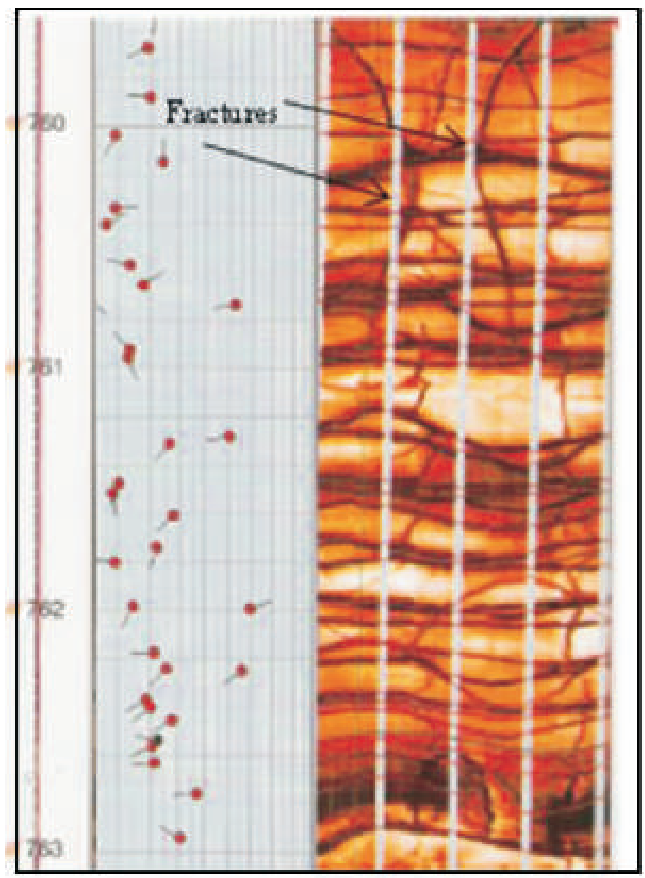

Fig. 6: Borehole image (FMI) of well PA, in depth range 760-763 m showing fractures within Deccan basalt. Fractures are sub-vertical to sub horizontal. (Saikia et.al., 2011).

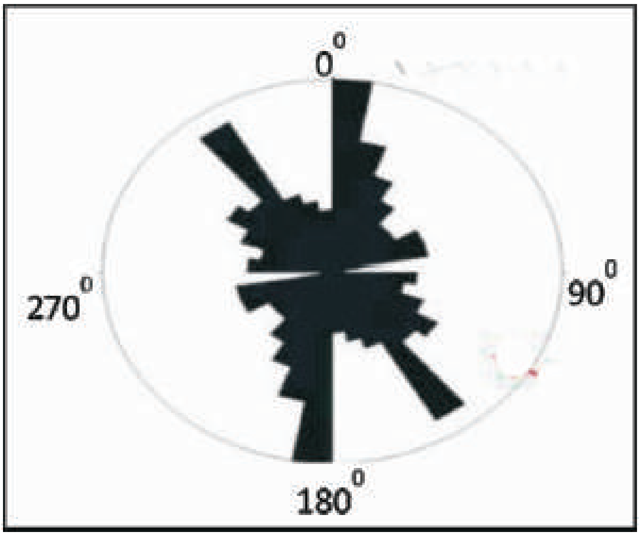

Fig.7: Rose diagram shows fractures azimuth with in Trap based on FMI log of the well PA for the interval 750-830m (Sushil kumar et al, 2011). Fractures are oriented in N-S and NNW-SSE.

Fig.8: Core photograph of Deccan basalt. Core from depth 700.5 - 708m, recovery 81.7%, hard dense basalt with sub horizontal and sub vertical fractures filled with secondary minerals and dead oil (a). Core from depth 714.5-722, recovery 100% altered basalt showing numerous fractures filled with dead oil and Bitumen (b).

Conclusions:

1 Padra field is producing oil and gas from unconventional fractured Deccan Trap. Fractures play important role in hydrocarbon production in unconventional reservoir. Thus mapping of the faults and fractures, their orientation and intensity will be important for drilling a well.

2 Curvature attributes provide important information with respect to commonly used seismic attributes in identifying subtle faults and fractures associated with folds and flexures which are beyond seismic resolution.

3 Curvature attribute predict high density of fractures, their orientation is needed to be calibrated with borehole image logs.

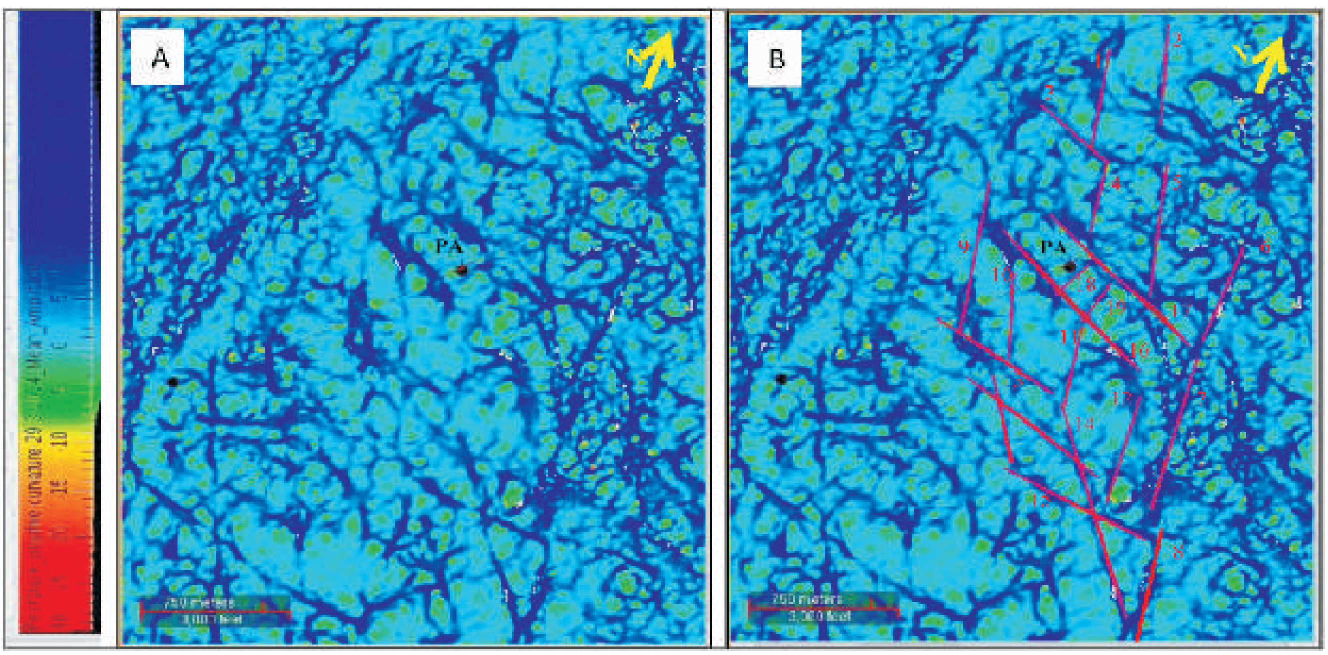

Fig.9: Zoomed part of Horizon slice near the study well PA from Most positive curvature attribute 30ms window from Trap top. (A) Un-interpreted (B) Interpreted, lineaments of fault on positive curvature attribute are marked with red color in the vicinity of well PA. Fault lineaments are annotated from 1-19. Color bar shows positive curvature value by blue color and negative curvature by green yellow to red color.

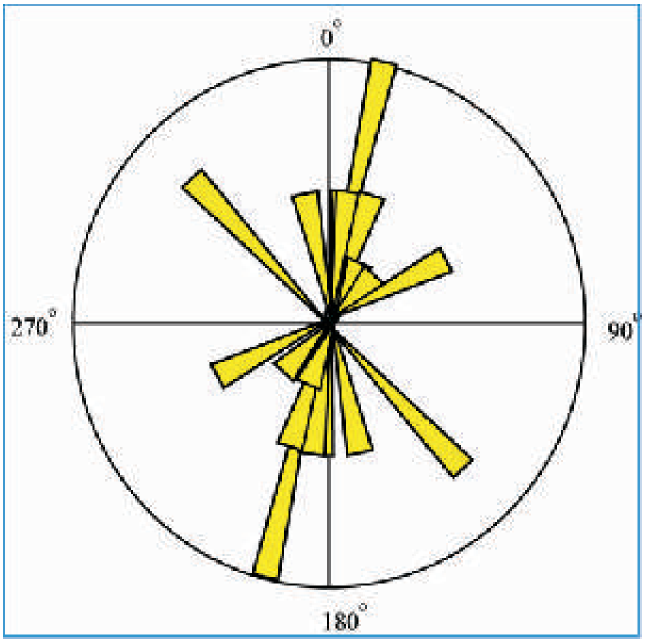

Fig.10: Rose diagram of fault lineaments based on most positive curvature attribute horizon slice (0-30ms window), shows two major fault orientations as N-S and NNW-SSE conform to the fracture orientation from Rose diagram of FMI log of well PA.

4 To extract meaningful information from seismic attributes proper pre-conditioning of seismic data is necessary.

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