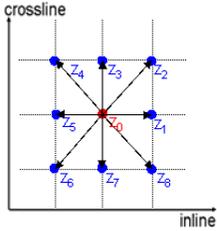


# IMPROVING STRUCTURAL SEISMIC INTERPRETATION USING 3D CURVATURE ATTRIBUTES

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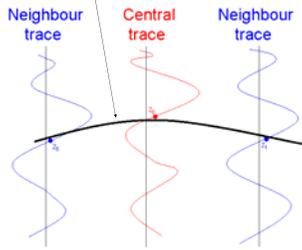
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## MATHEMATICAL FORMULATION



$$\text{Quadratic surface } z(x,y) = \sum_{0 \leq i+j \leq 2} a_i x^i y^j$$

The coefficients are solutions of the following least-squares problem:  $\min_{a_i} \sum_k (z(x_k, y_k) - z_k)^2$



- The proposed estimation of curvatures is performed in three stages:
- First, for each volume sample, a small surface is propagated around the sample within the defined horizontal range of analysis. The surface z-positions are found by finding the maximum cross-correlation value over a vertical analysis window between the central trace and each surrounding trace within the defined range for analysis. The cross-correlations are back interpolated, using a parabolic fit to determine the precise vertical shift of the maximal cross-correlation.
  - Then a least squares quadratic surface  $z(x,y)$  of the form is fitted to the data within the analysis range.
  - Finally, the set of curvature attributes are computed from the coefficients of quadratic surface using classic differential geometry (Roberts).

Principal curvatures:  $\kappa_{\min, \max} = H \mp \sqrt{H^2 - K}$

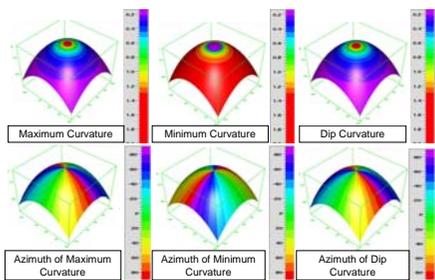
with 
$$H = \frac{a_{20}(1+a_{01}^2) - a_{10}a_{01}a_{11} + a_{02}(1+a_{10}^2)}{(1+a_{10}^2+a_{01}^2)^{3/2}}$$

$$K = \frac{4a_{20}a_{02} - a_{11}^2}{(1+a_{10}^2+a_{01}^2)^2}$$

Dip curvature:  $\kappa_{dp} = \frac{2(a_{20}a_{10}^2 + a_{10}a_{01}a_{11} + a_{02}a_{01}^2)}{(1+a_{10}^2+a_{01}^2)^{3/2}(a_{10}^2+a_{01}^2)}$

- The curvature attributes most frequently used are the normal curvatures, they are defined by orthogonal planes to the surface (Roberts).
- The greatest normal curvature is called **maximum curvature**  $\kappa_{\max}$ .
  - The curvature taken in the direction which is horizontally orthogonal to the direction of maximum curvature is called **minimal curvature**  $\kappa_{\min}$ . The maximum and minimal curvatures constitute the principal curvatures.
  - The **dip curvature**  $\kappa_{dp}$  is the curvature extracted along the dip direction and measures the rate of dip variation within the direction of the maximum dip.

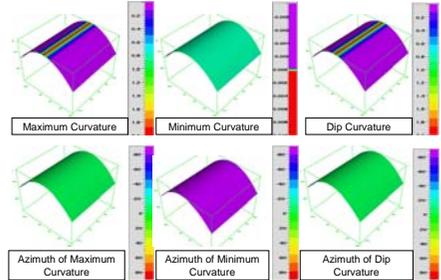
## APPLICATION ON SYNTHETIC DATA SET



**Current shape:** elliptic paraboloid shape.

**Geological analogy:** karsts dissolution, diapir, basin...

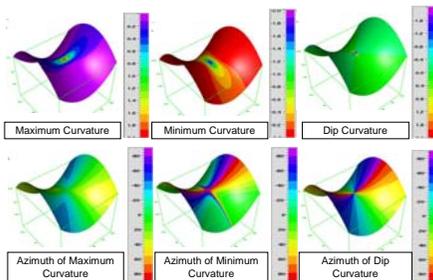
**Comments:** Evolution of maximum, minimum, and dip curvature is radial. Azimuth of the dip curvature is equal to the azimuth of the maximum curvature.



**Current shape:** cylinder shape

**Geological analogy:** diapir, synclinal, anticlinal...

**Comments:** Minimum curvature is equal to zero. Azimuth of the dip curvature is equal to the azimuth of the maximum curvature. Lineaments of the maximum curvature and dip curvature are parallel and show the apex of the antiform or the axis of the synform.



**Current shape:** Hyperbolic paraboloid shape

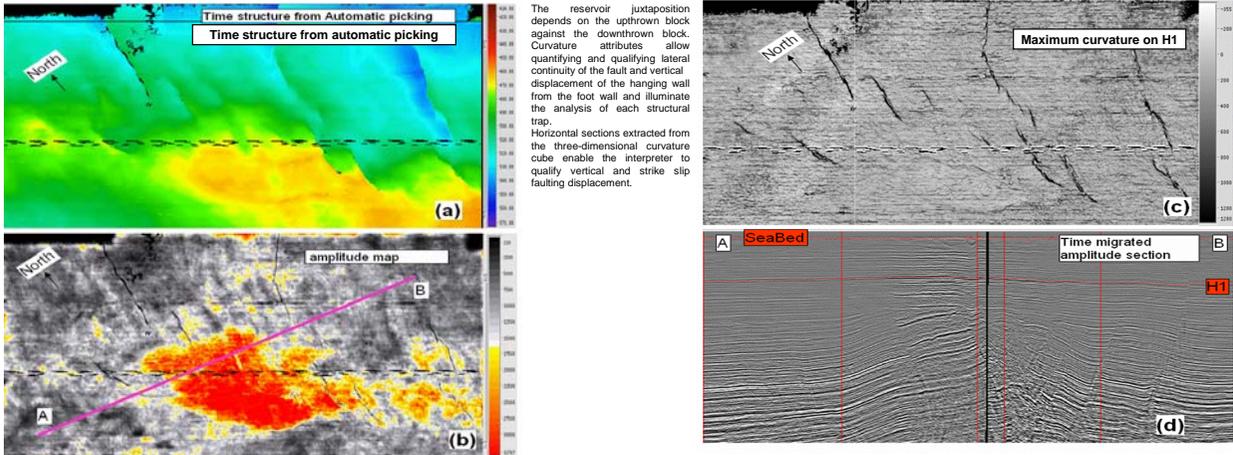
**Geological analogy:** diapir, spill point...

**Comments:** Lineaments from maximum curvature and lineaments for minimum curvature are orthogonal. The intersection of the both lineaments corresponds to a possible spill point.

# CASE STUDY: STRUCTURAL CLOSURE

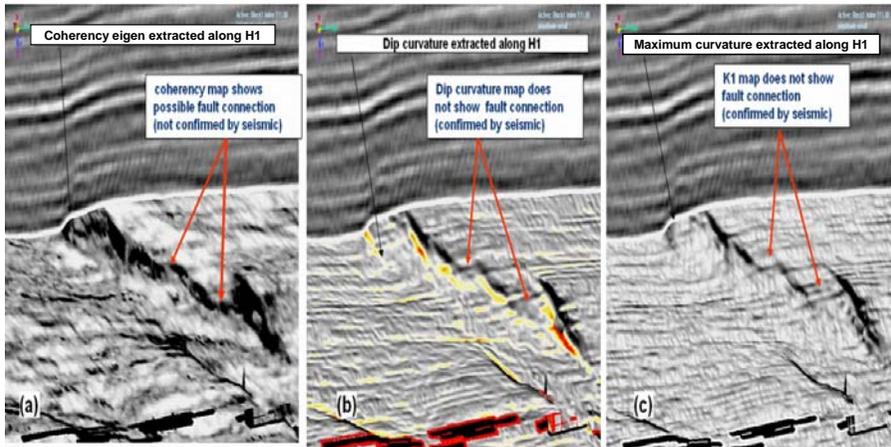
## General overview of the data set from Offshore Indonesia.

(a) Time structure of the shallow event; (b) Amplitude map extracted along H1; (c) Maximum curvature extracted along H1; (d) Time migrated amplitude section.



## Dip curvature and max curvature: image improvement.

(a) Structural slice on coherency; (b) Structural slice on dip curvature; (c) Structural slice on maximum curvature.



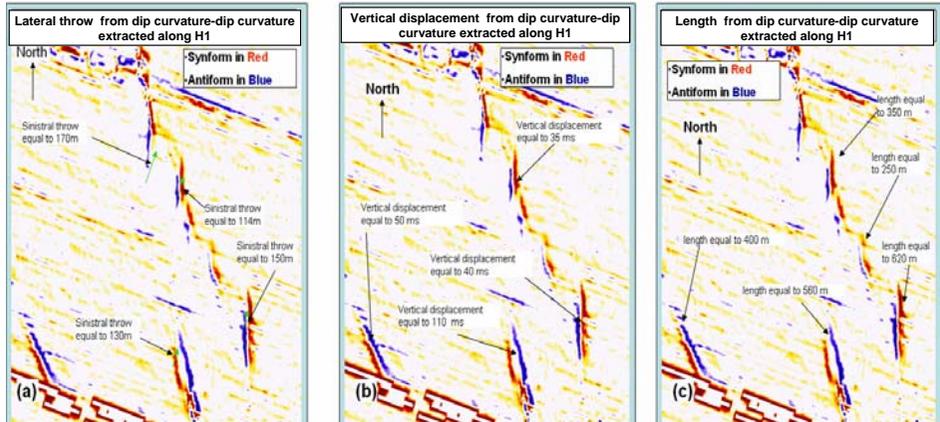
Minimum curvature and maximum curvature attributes are highly sensitive to brittle deformation especially in the fault nose areas. High values of major curvature correlate directly with high values of brittle deformation. High values of minimum curvature and maximum curvature will be spatially arranged in such a way that they will define geological lineaments corresponding to faults. (Figure c) Lateral continuity, length, orientation, spacing between faults are defined from the analysis of lineaments on horizontal sections (slices) extracted from the minimum and maximum curvature 3D attribute cubes. The result of this analysis will help to appraise the possible connectivity between both blocks.

## Dip curvature quantitative analysis, length, lateral throw and vertical displacement measurement.

(a) Lateral throw from dip curvature; (b) Vertical displacement from dip curvature; (c) Length from dip curvature.

Lineament analysis shows en-echelon patterns with an average length of the fault equal to 400 meters (Figure c). Dip curvature is an attribute which often highlights the areas where the layer is broken. Positive values of this attribute correspond to "bottom-up" shapes such as fault noses; negative values correspond to synform shapes such as erosional scours. High values of this attribute indicate the deformation is brittle, relatively low values indicate ductile deformation or no deformation at all. Limits between ductile and brittle deformation may be highlighted on maps by colour coding. Lateral misalignment of these limits between the foot wall and the hanging wall will reflect strike slip movement. Qualification and quantification of the strike-slip displacement is then possible. In the current case study, sinistral movement was evidenced with a horizontal average throw equal to 150 meters (Figure a). Separation between strong negative and strong positive values of the dip curvature attribute (red and blue colours on Figure) measures the vertical displacement. In the present case study, the vertical displacement was varying from 35 to 110 milliseconds (Figure b).

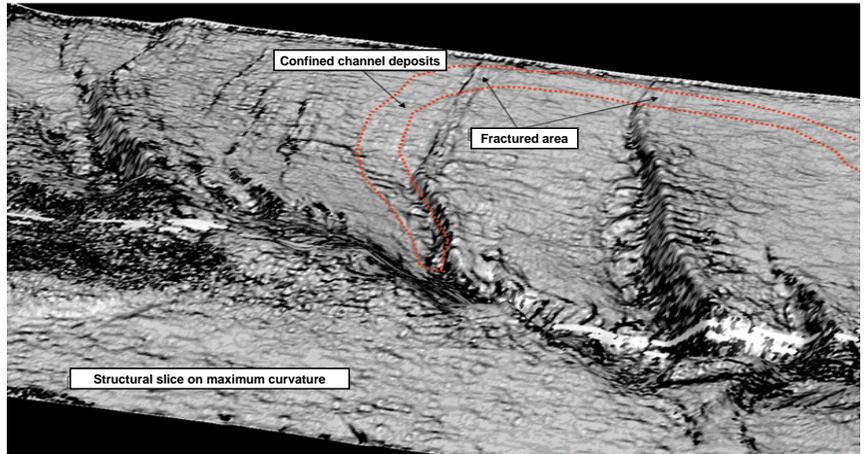
Using the above-mentioned attributes, it has been inferred that hydrocarbon trapping in the study area is controlled by a series of normal north to south trending en-echelon faults. The major curvature and dip curvature attributes suggest that the regime of constraint is a transensional stress with northeast-southwest sinistral shear.



# CASE STUDY: RESERVOIR CHARACTERIZATION. FRACTURE ANALYSIS.

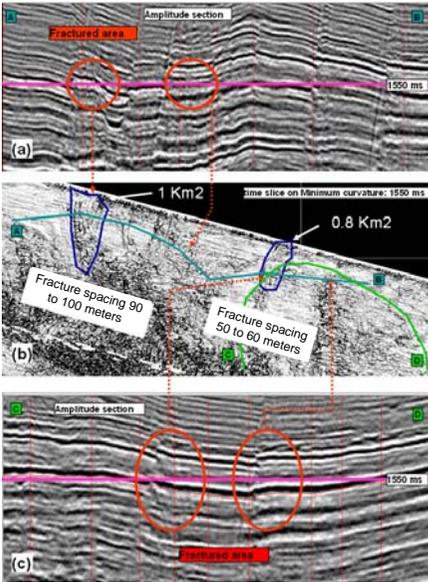
Fracture area illuminated by the minimum principal curvature; Structural slice on minimum curvature.

Naturally fractured reservoirs are an important component of global hydrocarbon reserves. It is important for the prediction of future reservoir performance to detect zones of fracturing and, at least qualitatively, estimate their basic parameters, for example, the density and orientation of the fractures. Fractures are usually difficult to resolve from seismic amplitude data due to the seismic frequency content which limits seismic resolution. In our example data set, despite the fact that the fractures are poorly illuminated, the curvature attribute detected the fractured areas. Fracture signatures derived from curvature attributes are indicated by a relatively medium to high value of the minimum curvature. Most of the lineaments defined by the spatial arrangement of the minimum curvature attribute correspond to fractures. In the present case study, zones of fracturing are mainly detected close to the major brittle fault events.

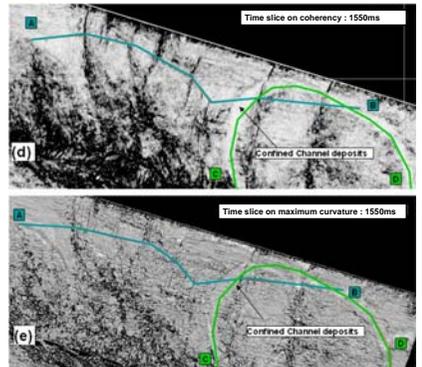


## Basic parameters fracture estimation: density and orientation

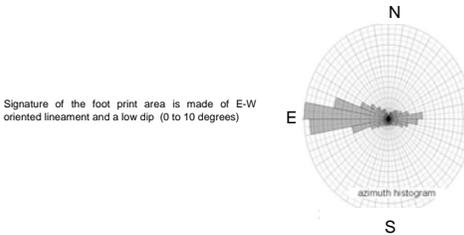
(a) Time migrated amplitude section; (b) Time slice on minimum curvature; (c) Time migrated amplitude section; (d) Time slice on coherency; (e) Time slice on maximum curvature



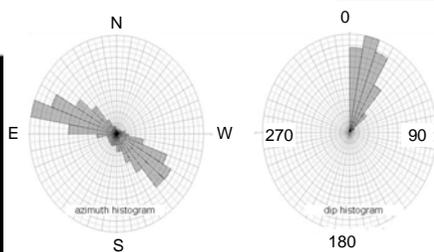
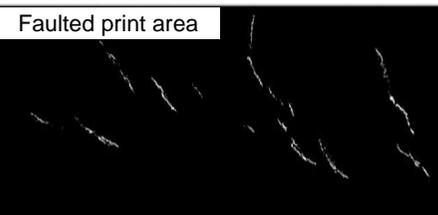
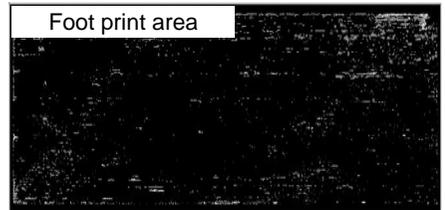
The area of the zone affected by fracturing is approximately equal to 0.8 km<sup>2</sup> for the channel and 1km<sup>2</sup> for the western part from the main fault (Figure b). Fractures are parallel to the main fault, and the estimated density of fracturing is 50 to 60 meters in the area of the channel and 90 to 100 meters in the western part of the survey (Figure b).



## Azimuth and dip histogram for high maximum curvature



Signature of the foot print area is made of E-W oriented lineament and a low dip (0 to 10 degrees)



Signature of the faulted print area is made of NE-SW oriented lineament and a medium dip (from 10 to 50 degrees)

**References**  
 Bahorich, Farmer, 3D seismic coherency for faults and stratigraphic features, The Leading Edge 14,1995,1053-1058.  
 Donias M., Baylou P., Keskes N., Curvature of oriented patterns: 2-D and 3-D Estimation from Differential Geometry: ICI'98, 246-250.  
 Al-Dossary, Marfurt K., 3D volumetric multispectral estimates of reflector curvature and rotation, Geophysics 71,2006,P41.  
 Chopra S., Marfurt K., Curvature attribute applications to 3D surface seismic data, The Leading Edge, April 2007, 404-414.  
 Roberts A., 2001, Curvature attributes and their application to 3D interpreted horizons: first break,19,2, 85-100.  
 West B. P., May S. R., Gillard D., Eastwood J. E.,Gross M. D., Frantes T. J. Method for analyzing reflection curvature in seismic data volumes : US Patent No 6,745,394.  
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