3-D Seismic Fault-Plane Images from Offshore Myanmar, Gulf of Thailand, and Lake Maracaibo: Insight into Regional Stresses and Hydrocarbon Migration Pathways*

John D. Pigott[1] and Non Prapasanobon[2]

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[1]Conoco-Phillips School of Geology & Geophysics, University of Oklahoma, Norman, OK (jpigott@ou.edu)
[2]PTTP Company Limited, Bangkok, Thailand

Abstract

Fault zones play critical roles in petroleum systems, potentially providing conduits and barriers for hydrocarbon migration pathways from source pods and, if associated with fractures, forming significant reservoirs. Insight into the regional stresses responsible for their formation and into the consequent fluid-gas pathways developed may be obtained through 3D seismic images of the fault-plane entity.

Through meticulous systematic line-by-line interpretation of the terminations of horizon reflectors against a consistent vertical displacement zone in the volume, a three dimensional fault-plane entity can be constructed. The subsequent 3D visualization product reveals geomorphologic features, such as grooves, ridges, and steps similar to those commonly observed in fault zones macroscopically in outcrop and microscopically in slickensides. Such interpretations were performed on 3D seismic volumes from three different regions of the world: normal faults from offshore Myanmar, transtensional faults from the Gulf of Thailand, and transpressional faults from the Maracaibo Basin, Venezuela.

The Offshore Myanmar normal faults reveal grooves and ridges that yield normal dip slip in an N-S direction. A transtensional fault example from the Gulf of Thailand reveals normal dip-slip motion in a NE-SW direction on the vertical seismic data and reveals oblique normal dip-slip motion in an E-W direction developed by dextral strike-slip motion in a NW-SE direction. The transpressional fault example from Maracaibo Basin, Venezuela, is manifested as reverse dip-slip motion in a NW-SE direction and reveals an oblique reverse dip slip in a NWW-SEE direction formed by dextral strike-slip motion in a NE-SW direction.

Seismic attribute maps reveal seismic anomaly patterns on the fault planes parallel to the ridge and groove trends. As the ridges, grooves, and steps are parallel to the direction of fault-slip motion, they provide the direction of fault-gouge and fault-breccia production and, if permeable, the likely pathways of gas-fluid migration along the fault planes with preference given to the fault-plane ridges.

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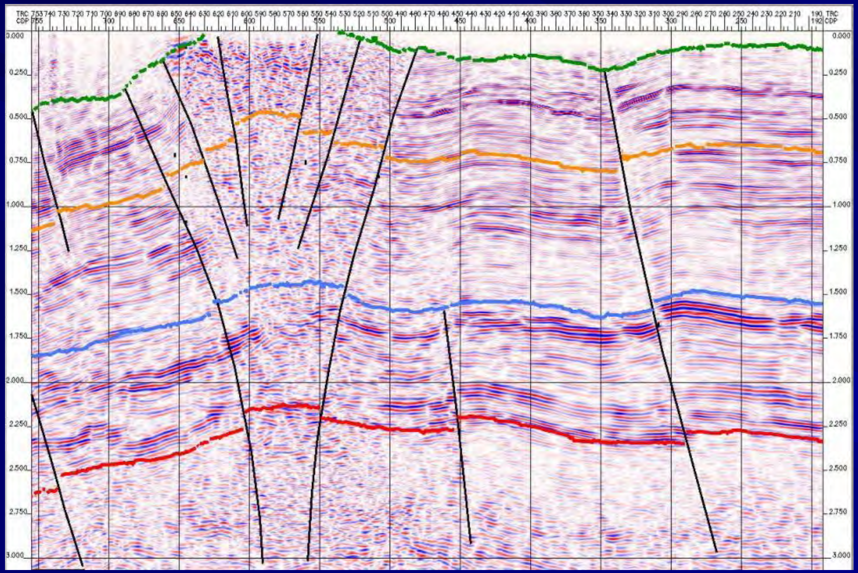
By

John D. Pigott[1] and Non Prapasanobon[2]

[1]University of Oklahoma, Norman, OK USA; [2]PTTEP Company Limited, Bangkok Thailand

“In reality, what do faults really look like?”

Like this? The *a priori* assumption.



Inferred from reflector discontinuities

Or like this? The *a posteriori* reality.

Fault plane in outcrop in Southern Turkey.

As seen in outcrop

PROBLEM DEFINITION:

- There is much potential information to be extracted from faults beyond the simple spatial positioning of their fault traces on 2D and 3D seismic. Is it possible for one to seismically describe the geomorphology of the fault plane itself, and in so doing, provide important insight into its effectiveness as a petroleum system conduit, barrier, or reservoir?

OBJECTIVES

- Construct a method for effective fault plane interpretation on 3D seismic data.
- Visualize and describe the 3D geomorphology of fault planes of different structural styles.
- Attempt to relate the fault plane geomorphology to the seismic anomalies and to the petroleum system.
- And, thus lay the groundwork for future geomorphologic studies of seismic fault planes.

STRATEGY

- Fault Plane Identification and Terminology
- Logic
- Normal Fault Examples: Offshore Myanmar
- Transtensional Fault Example: The Gulf of Thailand
- Transpressional Fault Example: Maracaibo Basin
- Petroleum System Implications
- Conclusions and Recommendations

Study Areas


(Dhaka)
Myanmar (Burma)
(Hanoi)
Laos
(Vientiane)
(Rangoon)
Thailand
Paracel Isla
Vietnam
(Bangkok)
Cambodia
(Phnom Penh)
(Ho Chi Minh City)
Offshore
Myanmar
Gulf of
Thailand
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Malaysia


Montse
Maracaibo
Basin
Curacao
Isla de Margarita
osta Rica
(Panamá City)
Panama
Venezuela
Colombia
Image NASA
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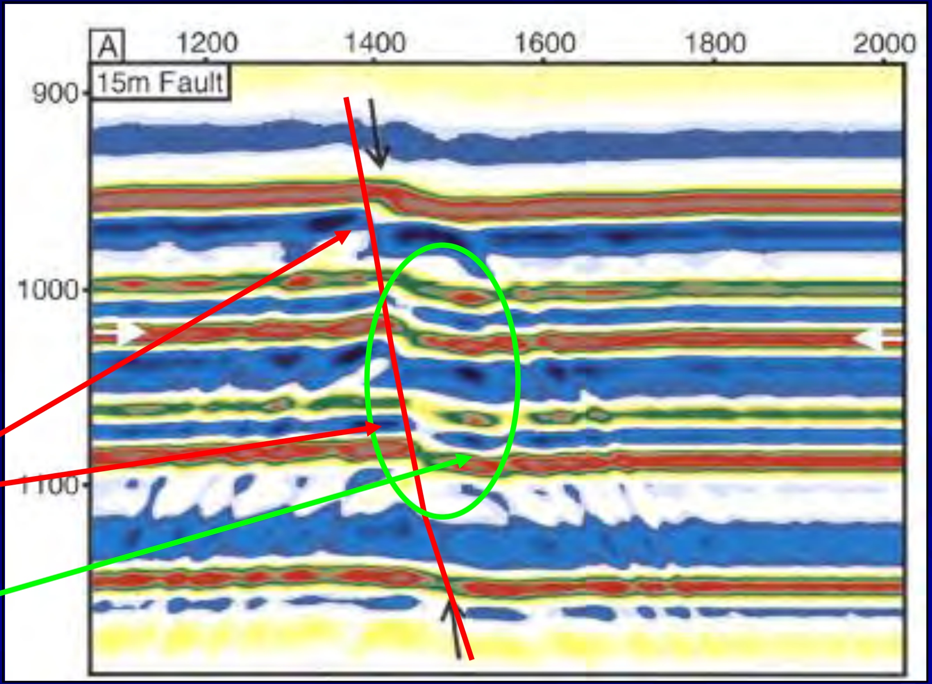
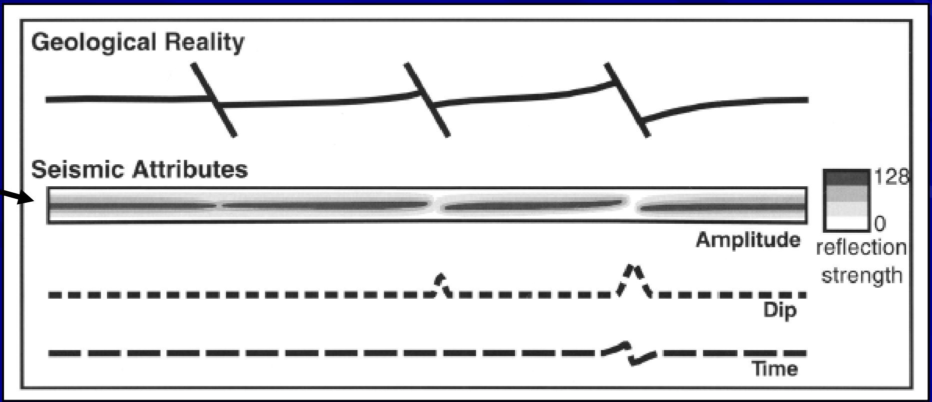
© 2008 LeadDog Consulting
851 km
ointer 5°17'00.80" N 66°27'04.85" W
Streaming 100%

FAULT PLANE IDENTIFICATION AND TERMINOLOGY

Contemporary Fault Identification Methods

- C. Townsend et al. (1998):
  - The discontinuity on seismic reflectors.
  - Change in apparent dip of adjacent seismic reflectors.
  - Amplitude dimming along the cut seismic reflectors.

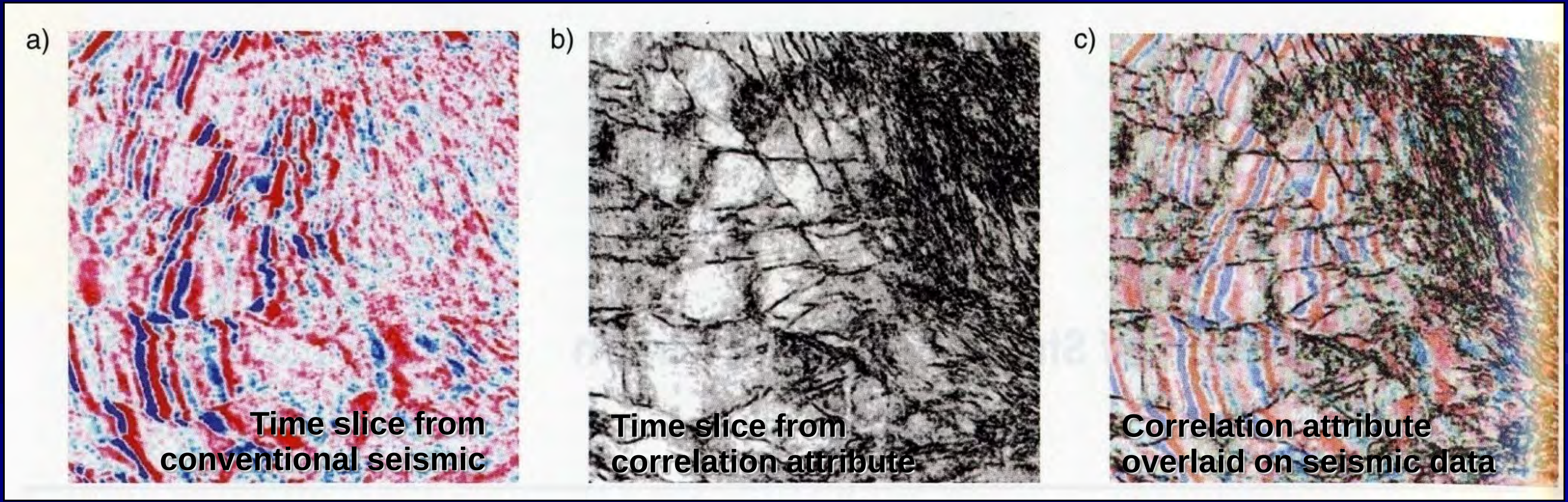




*Both modified after C. Townsend et al. (1998)

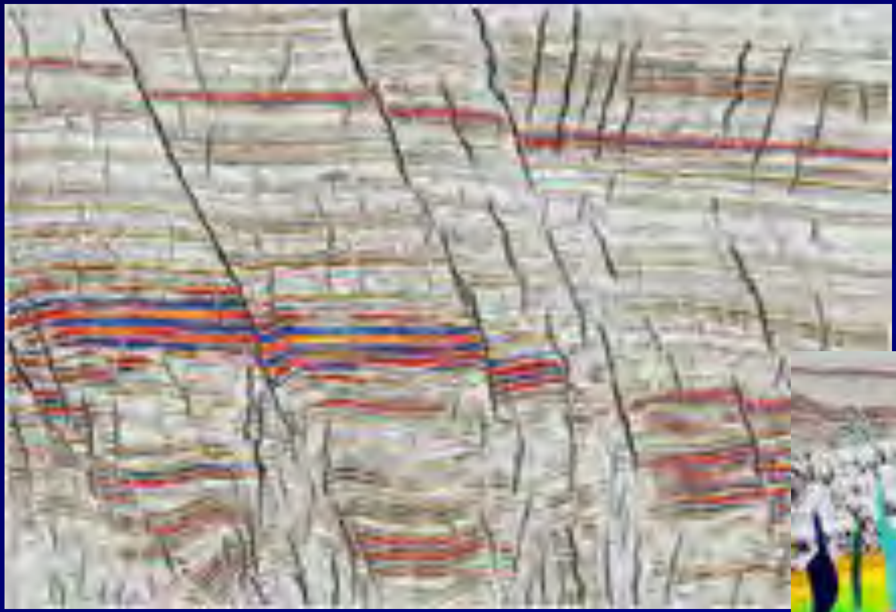
Contemporary Fault Identification Methods: Image Analysis

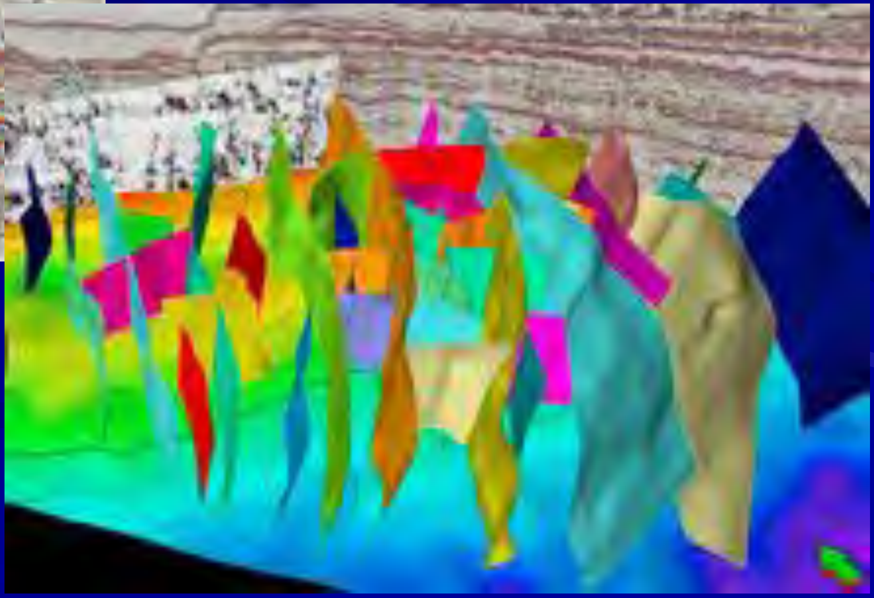
- Correlation-coherency mapping on seismic time slices.
  - Cross-correlation of adjacent traces in a time window (Charisma Geoframe , 2011).
  - Identify seismic expression of the faults on time slices of correlation attribute (Chopra S. and Marfurt L., 2007).



*Modified after Chopra and Marfurt, (2007)

Contemporary Fault Identification Methods: Automation, e.g., "Ant tracking*"





*Petrel ®

Fault Planes

– The irregularities in the fracture surface of faults form ridge-in-groove lineation or fault mullions (Twiss and Moores, 1992)

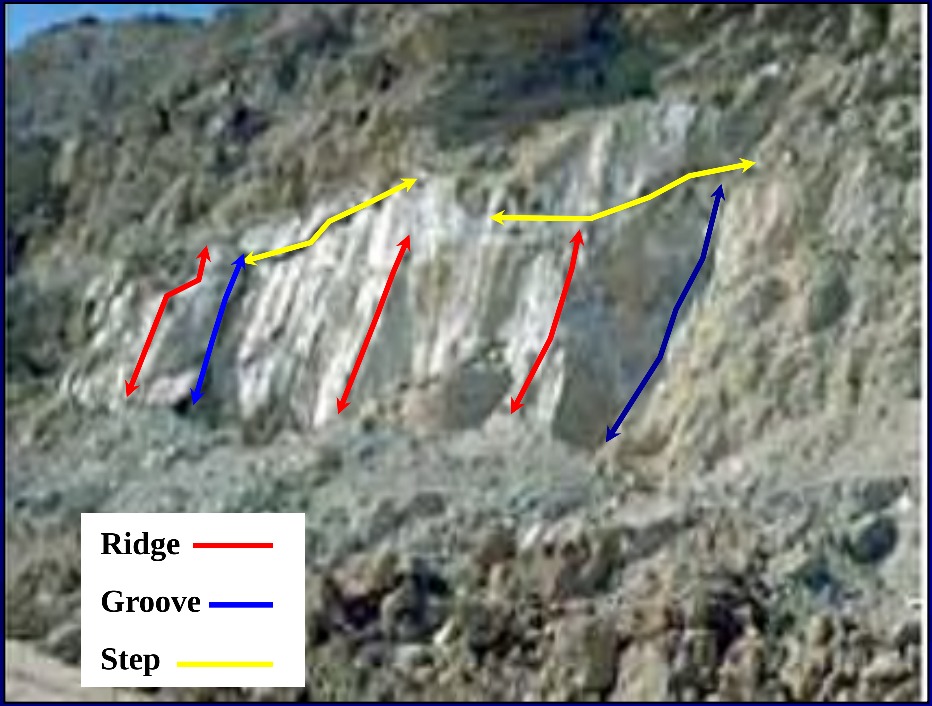


*Figure modified after http://www.science.ubc.ca/~eosweb/slidesets/keck

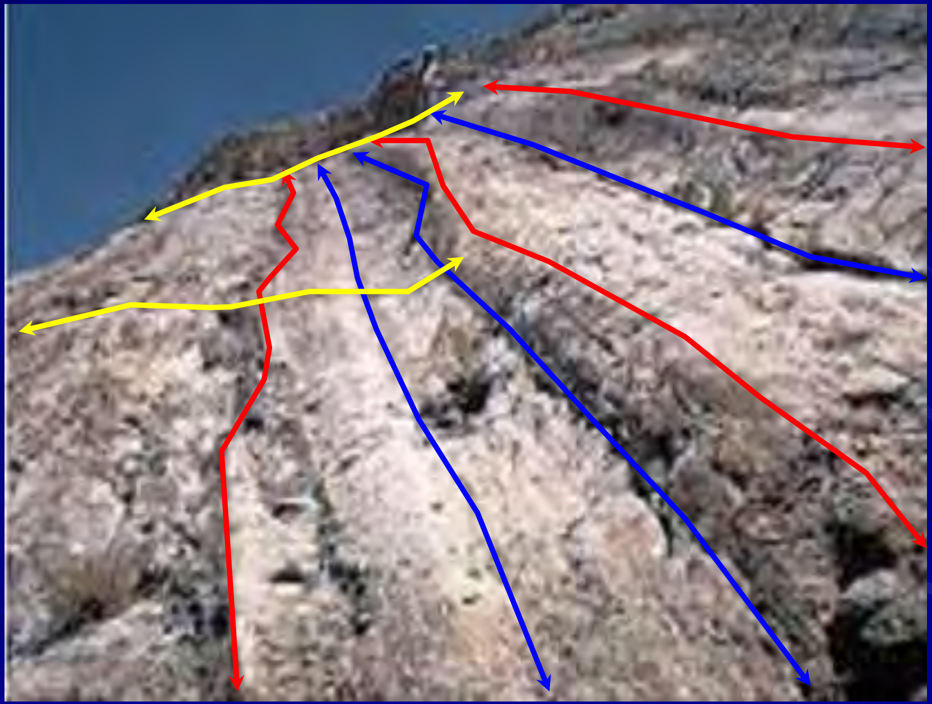


*Figure modified after http://ic.wcsc.edu~earth150/Photos/index.htm

Fault Planes

- Fault Surface Morphology
  - A fault surface contains linear features parallel to the direction of fault slip: ridges, grooves, and slickenfibers or mineral streaks (Twiss and Moores, 1992). Ridges and grooves are produced from scratching and gouging and form hard protrusions or asperities (ibid).

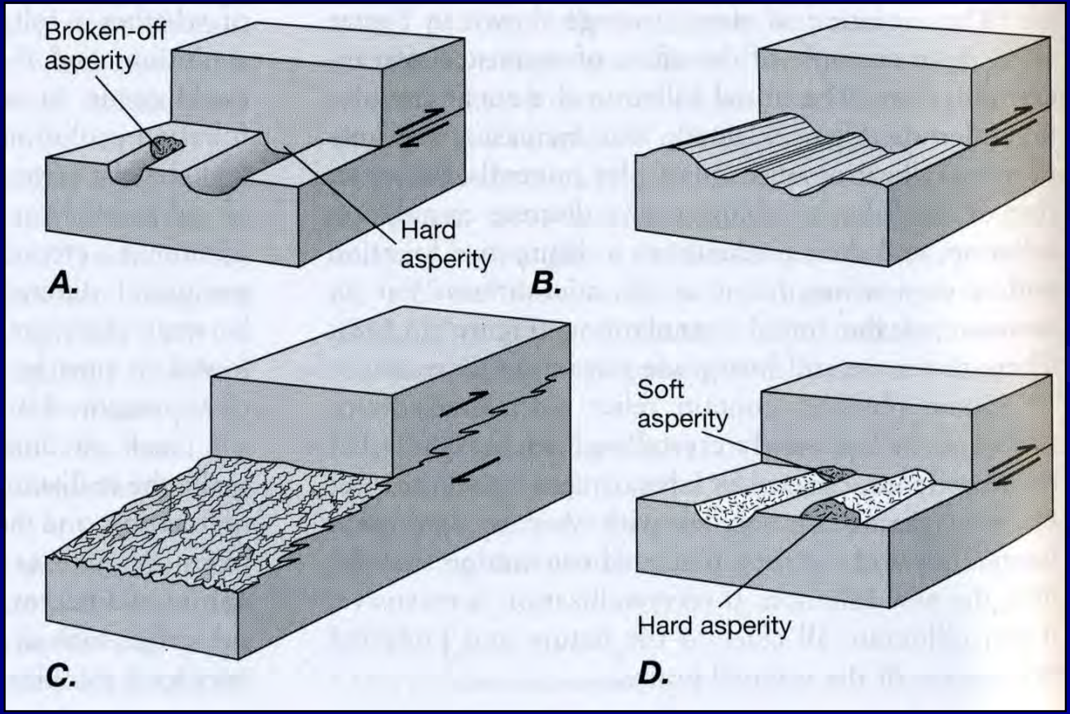
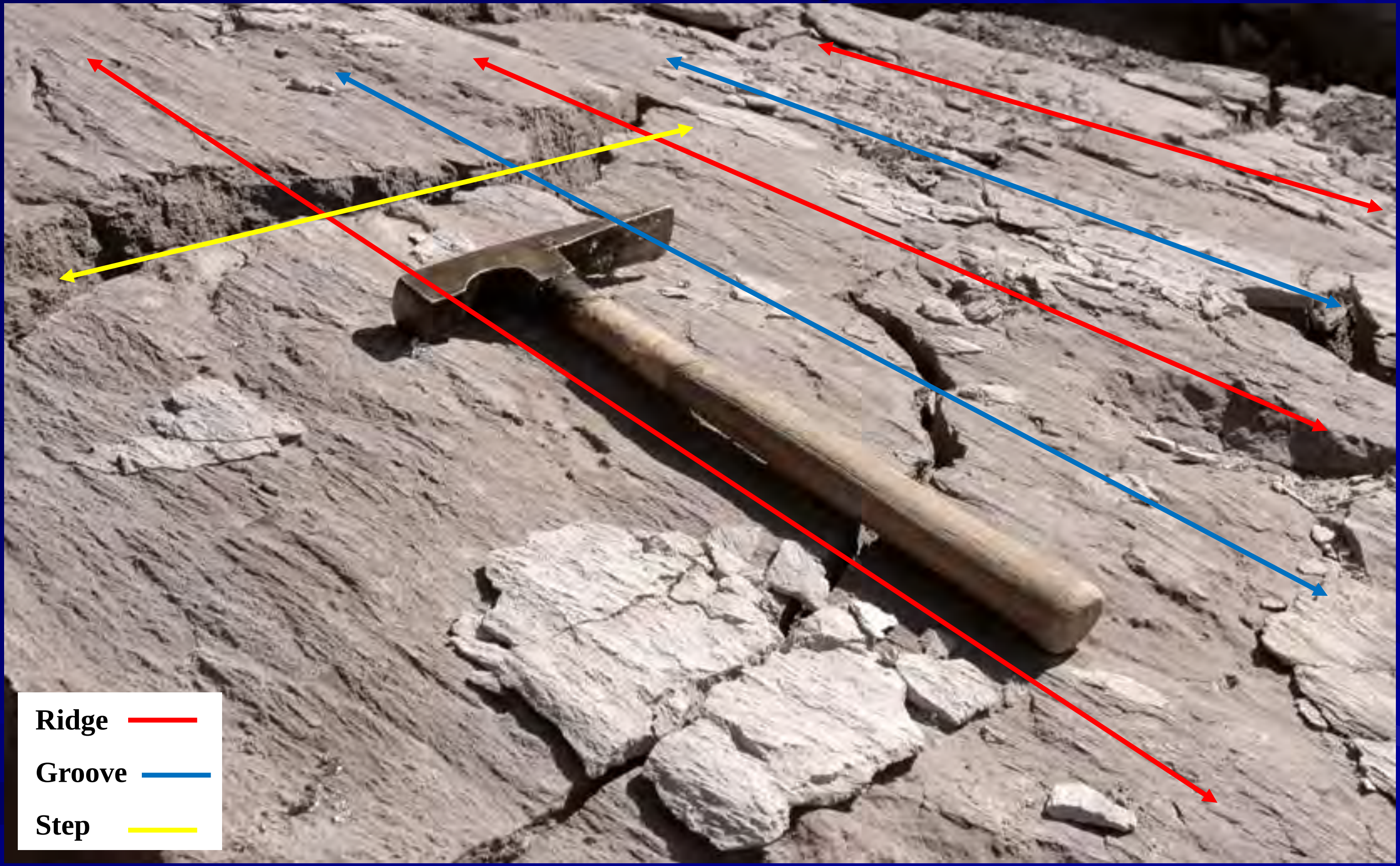


*Figure from Twiss and Moores (1992)

And these geomorphic features appear to be scale independent…



The slickensides and lineation patterns on fault surfaces are kinetic indicators of the direction of fault slip (Doblas, 1998).

- First Display of Fault Plane on Seismic Data
  - Marchal et al. (2003) first attempted to display a fault plane by integrating 3D fault-plane intersections or time horizons from onshore Niger Delta. The display reveals a general surface map of the vertical and horizontal undulations on the fault-plane surface portrayed as a footwall. Marchal el al. suggest undulations are an artifact.

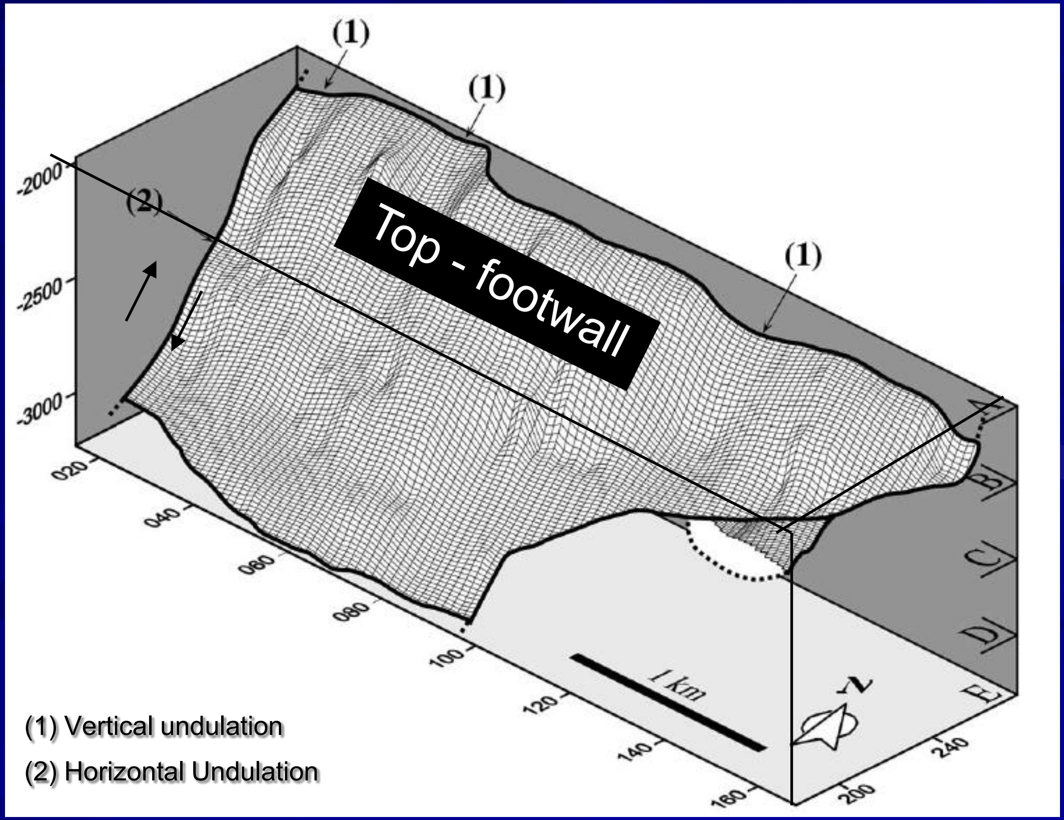


*Figure from Marchal, et al. (2003)

- Effects of Fault Gouge and Fault Breccia upon Permeability
  - Fault gouge is fine clay-size infill material and fault breccia is a zone of crushed rock, both produced by frictional contact along the fault surface (Pipkin, et al., 2005).
  - Generally, fault gouge yields low permeability and seal while fault breccia provides high permeability and fracture connectivity along the fault plane (Takashi et al., 2003).

- Fluid Migration along Fault Planes--Direct Evidence
  - An example from the Hawkesbury sandstone and the Wianamatta shale in Sydney, the quartz overgrowths and dissolution cavities indicate the low temperature hydrothermal fluids migrating through and reacting with the fault gouge (Offler et al., 2006).

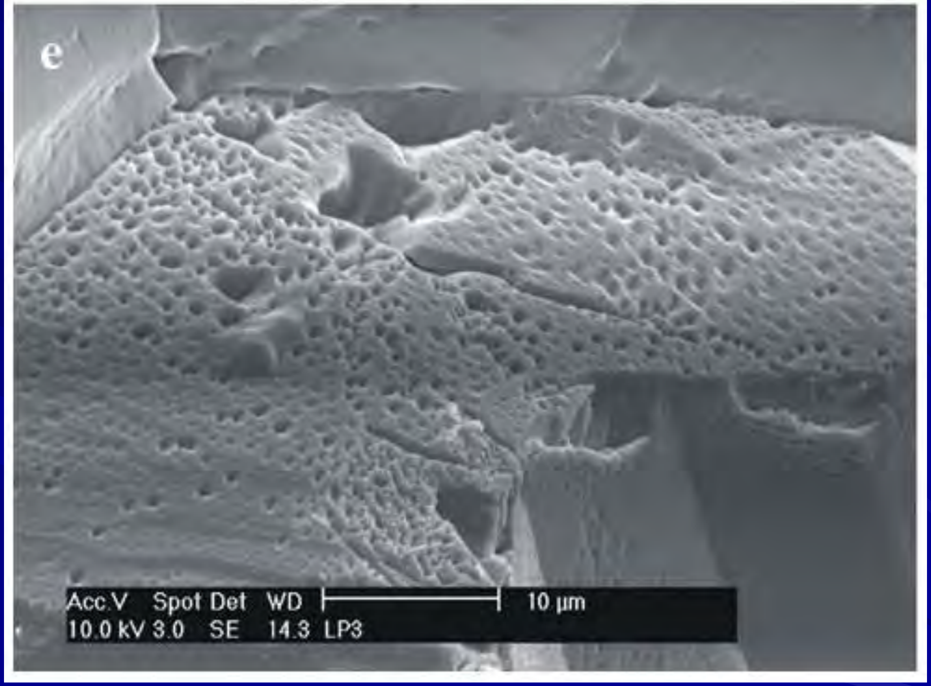


*Figure from Offler et al. (2006)

- Fluid Migration along the Fault Planes: Direct Evidence
  - An example from Bristol Mine, Nevada shows an ore-bearing breccia pipe on irregular surface of fault indicating the migration of hydrothermal fluid (Woodcock et al., 2006).

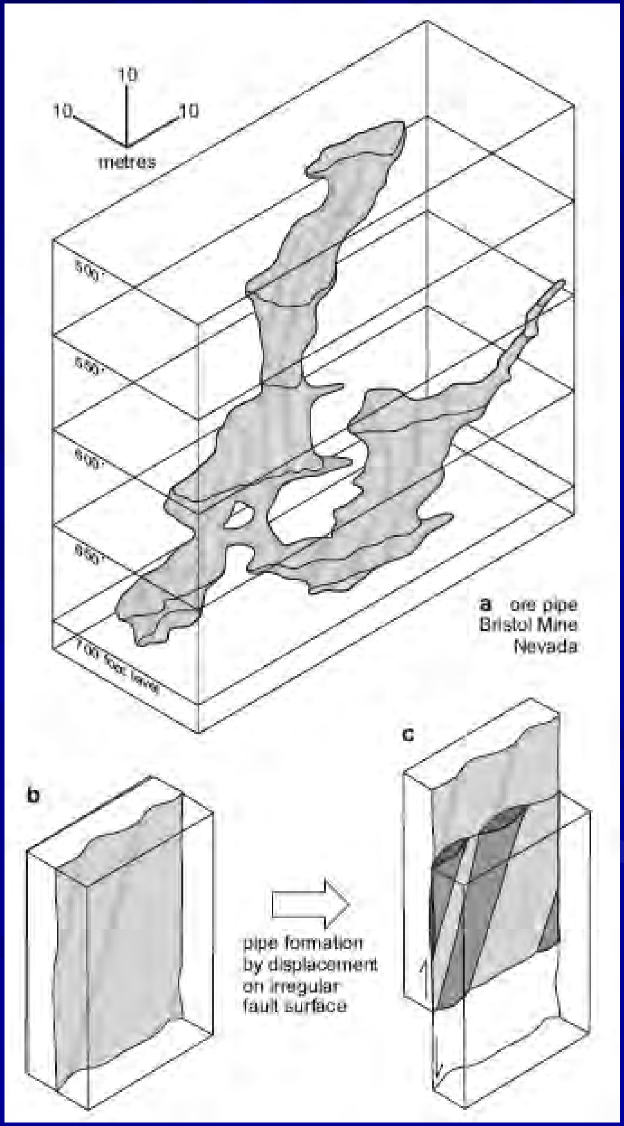


*Figure from Woodcock et al. (2006)

- Fluid Migration along the Fault Planes: Indirect Evidence of Potential
  - An example of porosity changes across fault planes from Pirgaki fault, Greece, reveals porosity to be higher in the fault core zone than in the footwall and hanging wall (Geruad et al., 2006).

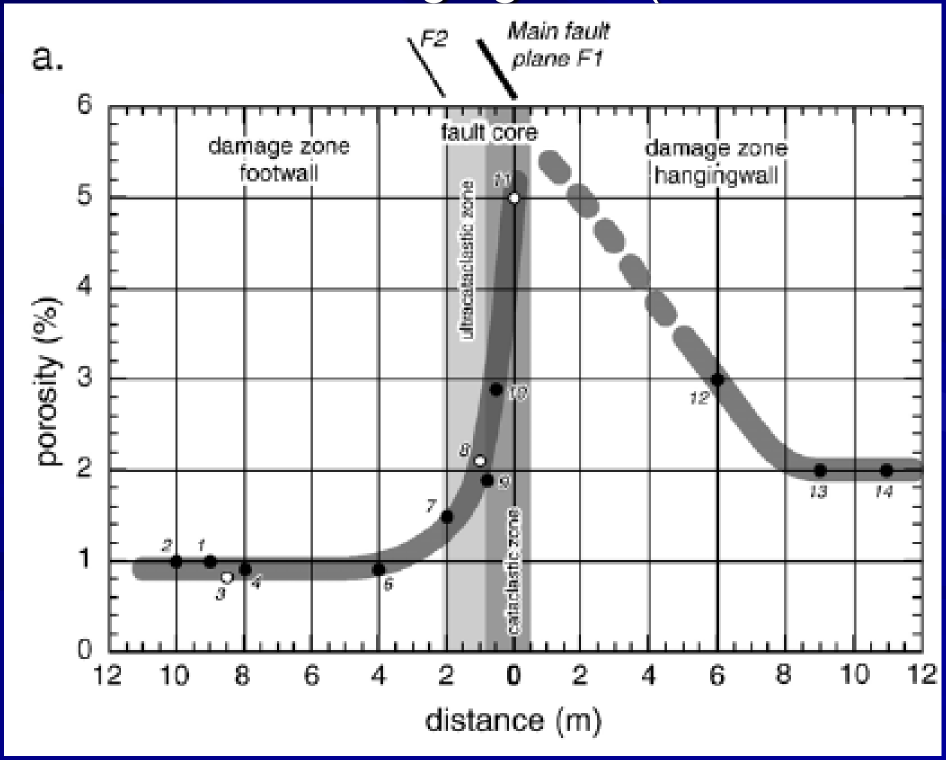


*Figure from Geraud et al. (2006)

- Fluid Migration along Fault Plane: Indirect Evidence
  - Bright spots adjacent to faults within the Plio-Pliestocene sediments of the Barents Sea suggest gas migration from deeper source rocks into the reservoirs above (Andreassen et al., 2007)

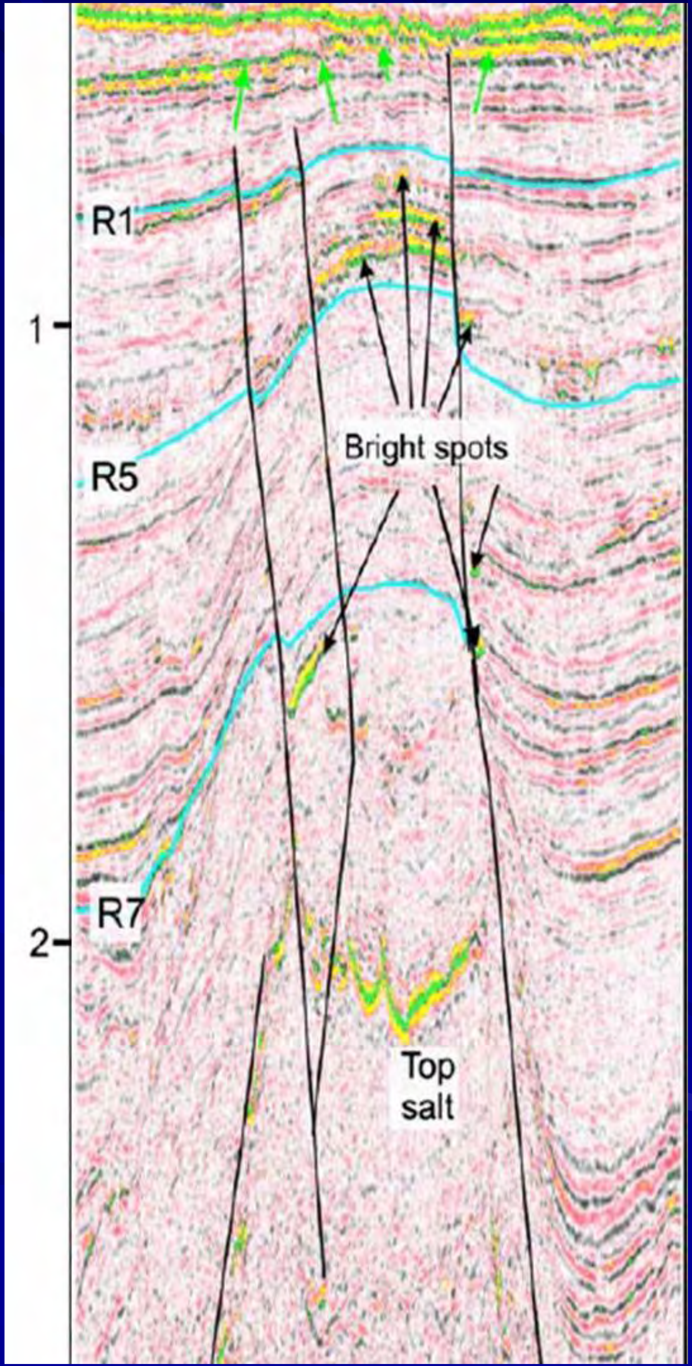
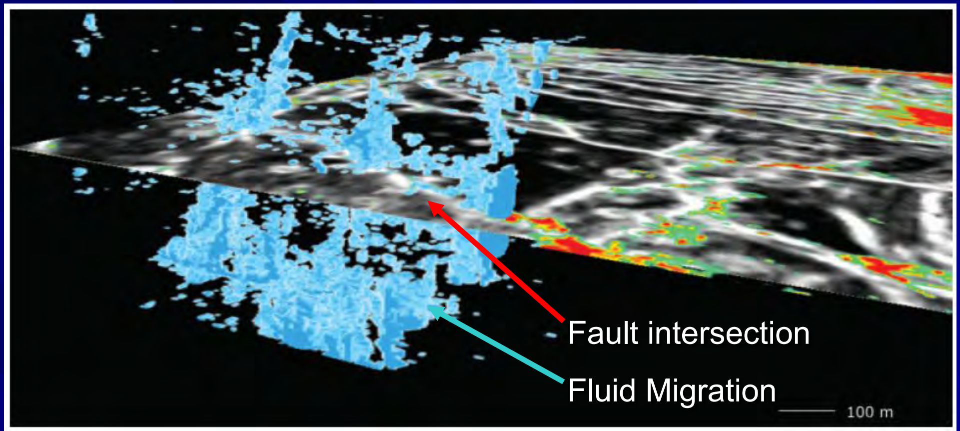
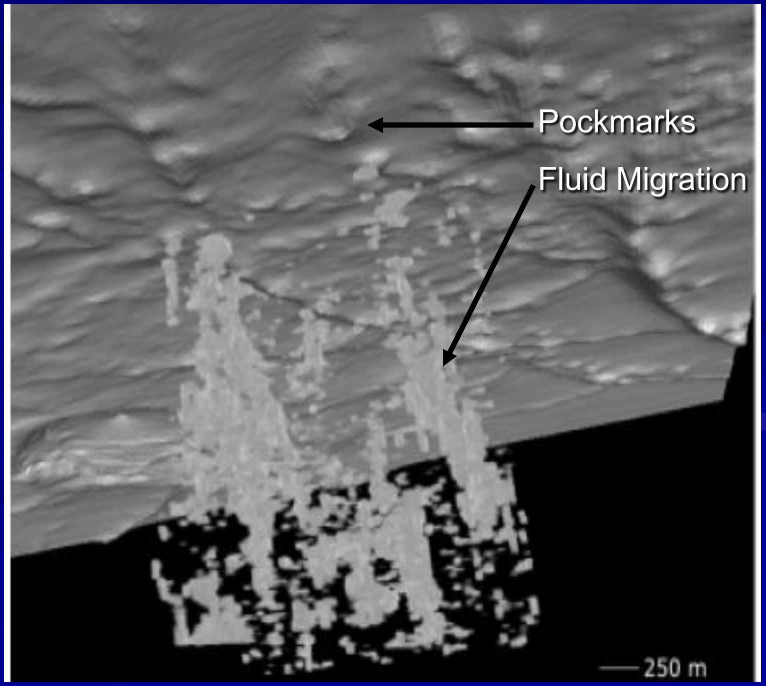


*Figure modified after Andreassen et al. (2007)

- Fluid Migration along Fault Planes: Direct Evidence
  - The trained neural network on seismic data from offshore West Africa shows fluid migration along the fault zone as linear columnar flow patterns which are lined up with the pockmarks on the seabed (Ligtenberg, 2005).





*Both figures modified after Ligtenberg (2005)

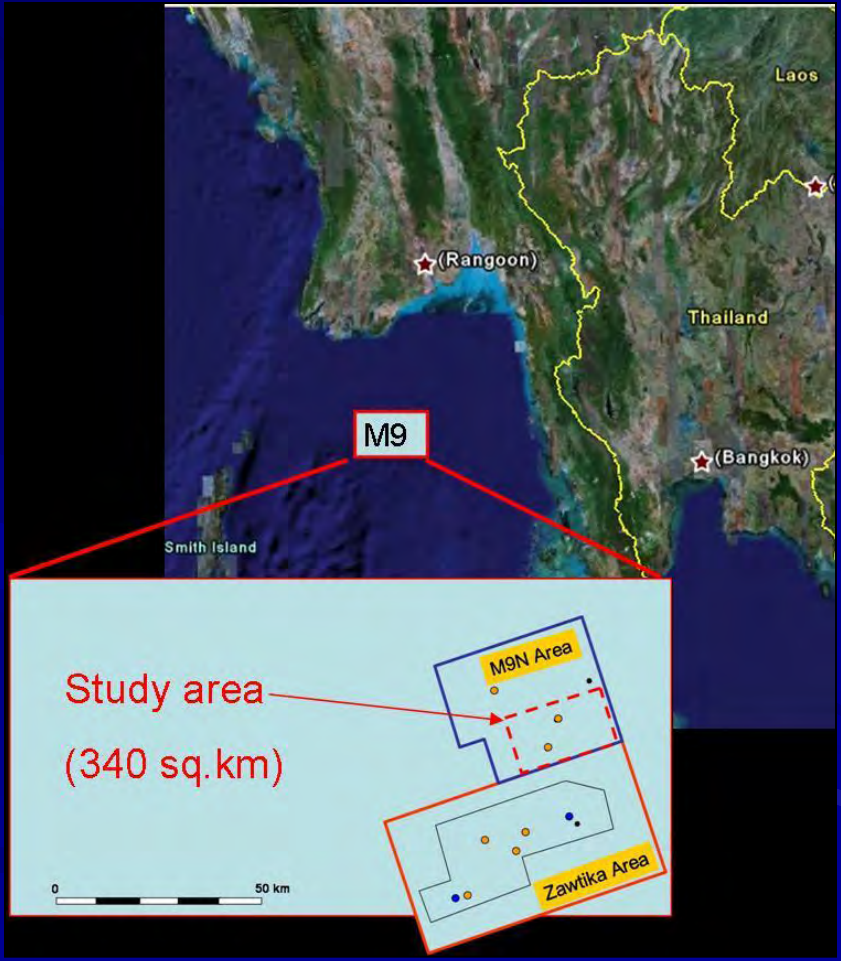
Logic

- Premise 1
  - If one may seismically visualize the fault-plane geometry and its geomorphic features: ridges, grooves, and asperities
- Premise 2
  - If these elements indicate the direction of fault-slip motion and maximum permeabilities
- Argument
  - Then, these planes may indicate potential hydrocarbon migration pathways from source rock pod to the reservoir via the fault planes.

OBSERVATIONS

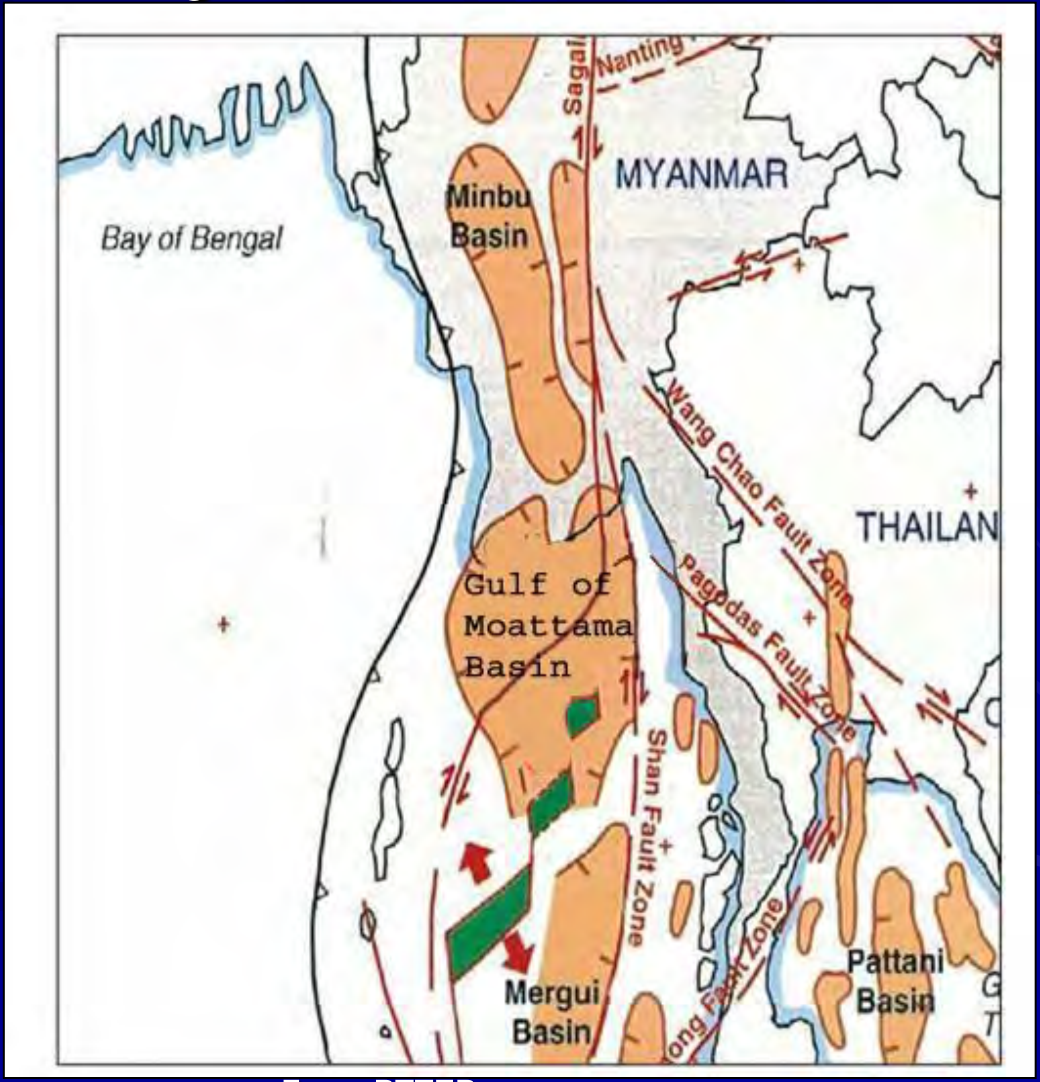
Normal Fault Examples: Offshore Myanmar

- Offshore Myanmar
  - The study area is located in Block M9N, the Gulf of Moattama, south of the Ayeyarwaddy Delta and north of the Andaman Sea.



Normal Fault Examples: Offshore Myanmar

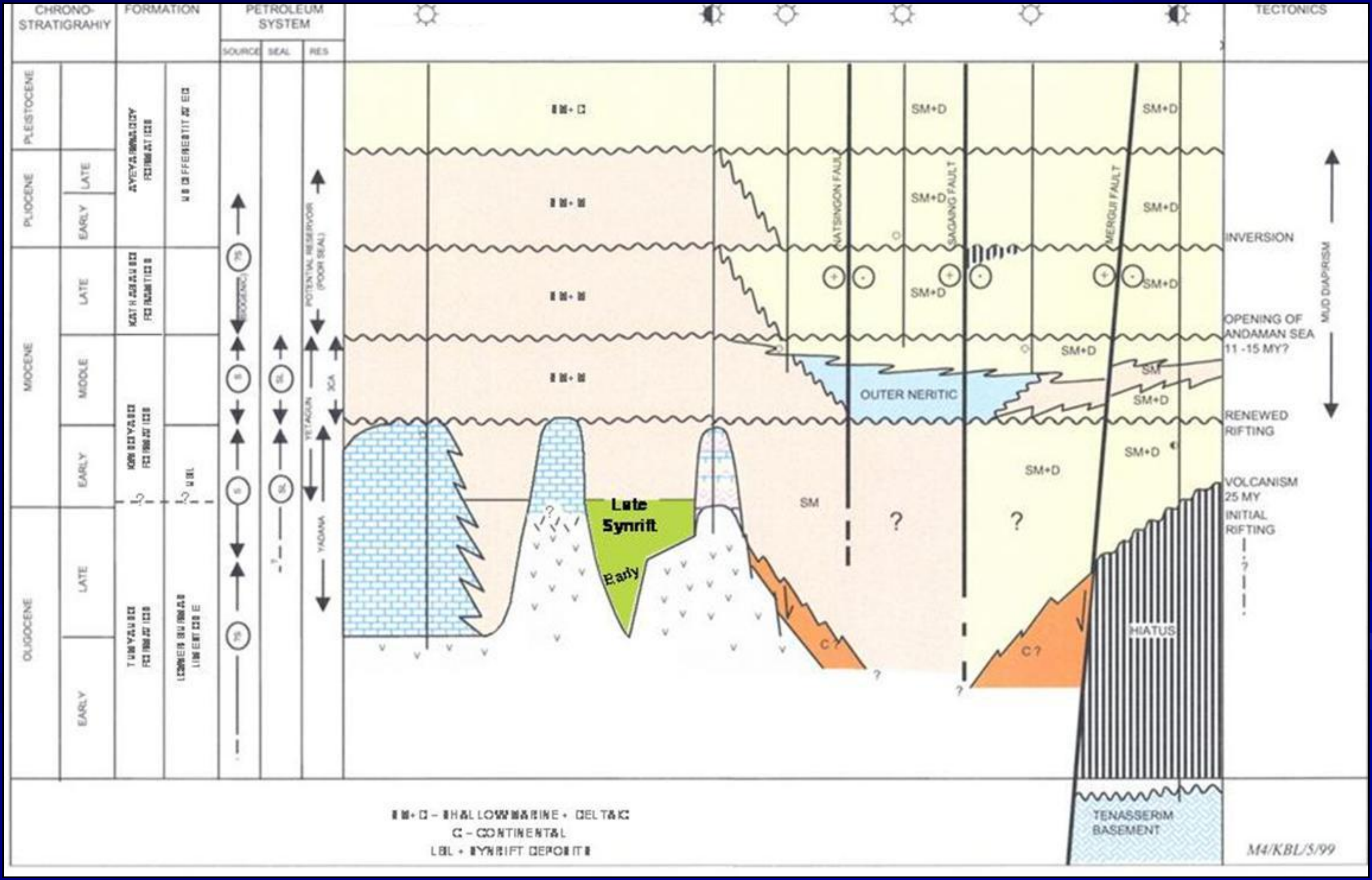
- Tectonic Setting
  - Related to the subduction of the Indian Plate under the Eurasian Plate
  - Tectonic events
    - Cretaceous: rifting and formation of grabens
    - Paleocene- Eocene: uplifting of Indo-Burman Ranges
    - Oligocene: regional hiatus
    - Middle Miocene: Beginning of dextral strike-slip faults
    - Holocene: extensional tectonics with deltaic progradation



From PTTEP

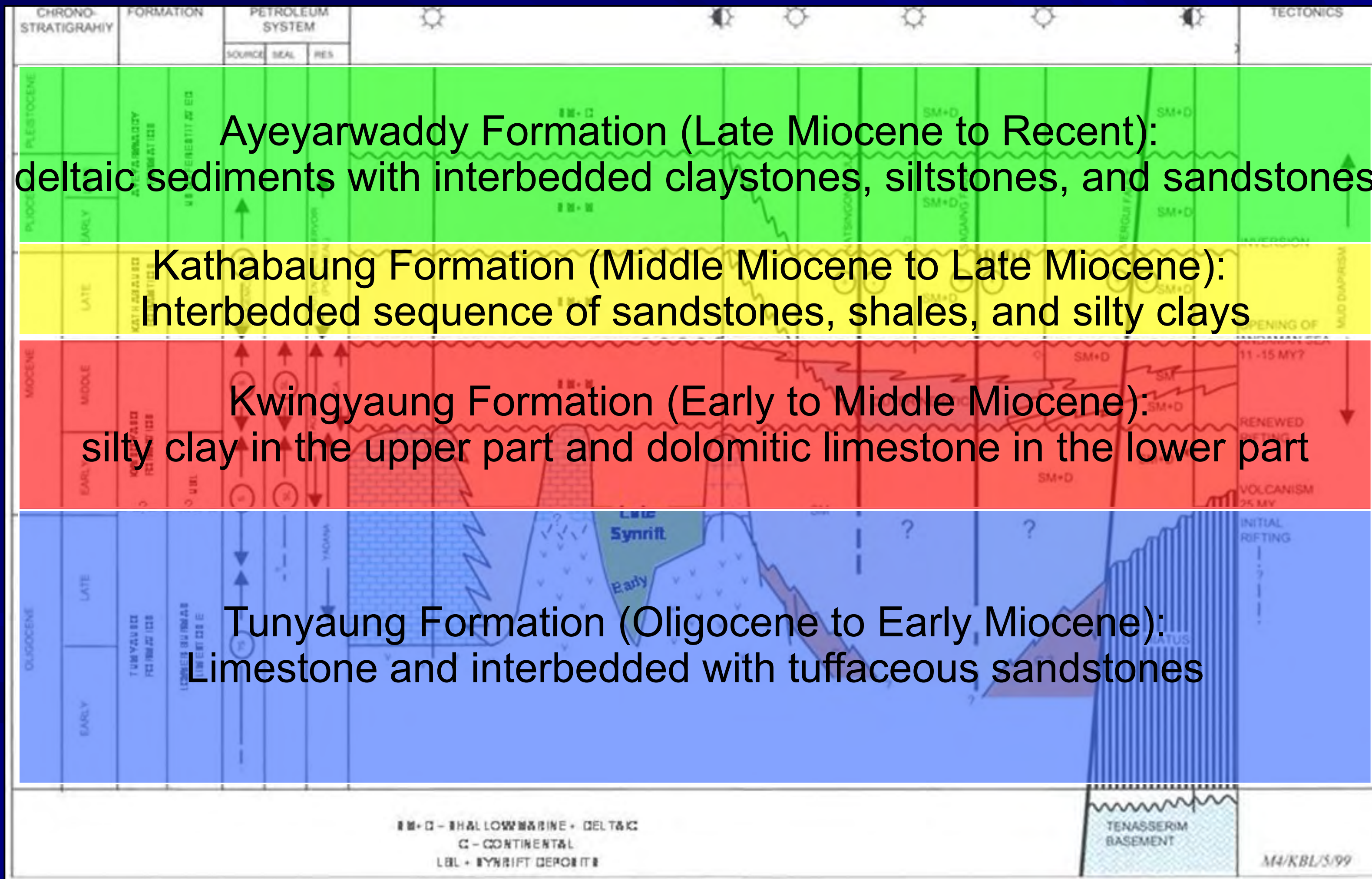
Normal Fault Examples: Offshore Myanmar

- Regional Stratigraphy (from PTTEP)



Normal Fault Examples: Offshore Myanmar

- Regional Stratigraphy (from PTTEP)

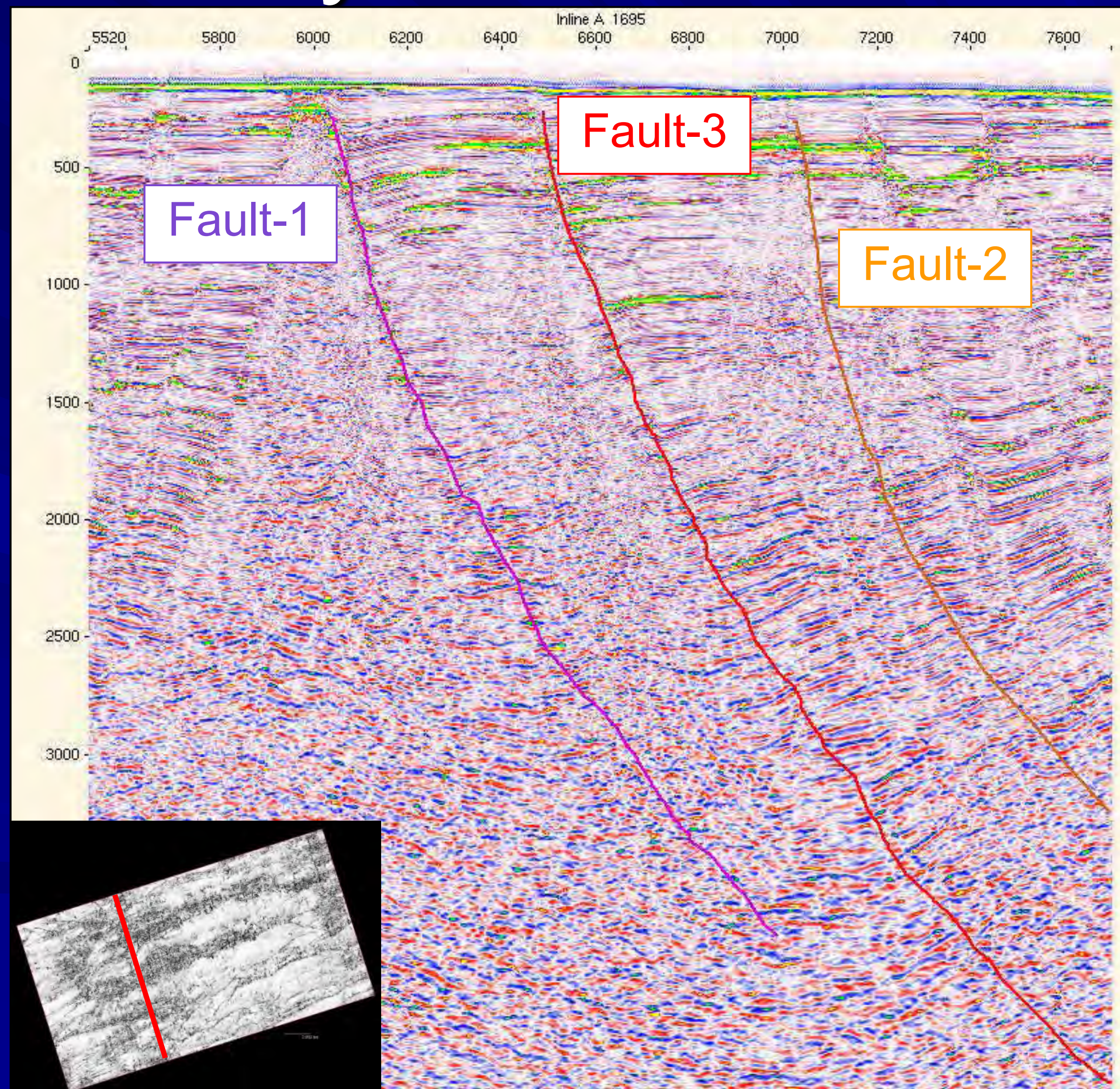


Normal Fault Examples: Offshore Myanmar

- Petroleum System
  - Source rocks: Oligocene, Middle-Lower Miocene Type III source rocks provide gas; also includes thermal gas sources.
  - Migration: Miocene source rocks still generate today, Oligocene source rocks generated in Pliocene, and Eocene source rocks generated in Miocene migrating via basin flank and deep seated normal faults
  - Reservoirs: Miocene sandstones, Pliocene sandstones, and Miocene-Oligocene carbonates
  - Trap and Seals: fault closures, thick-shale-interval seals, and fault-throw seals

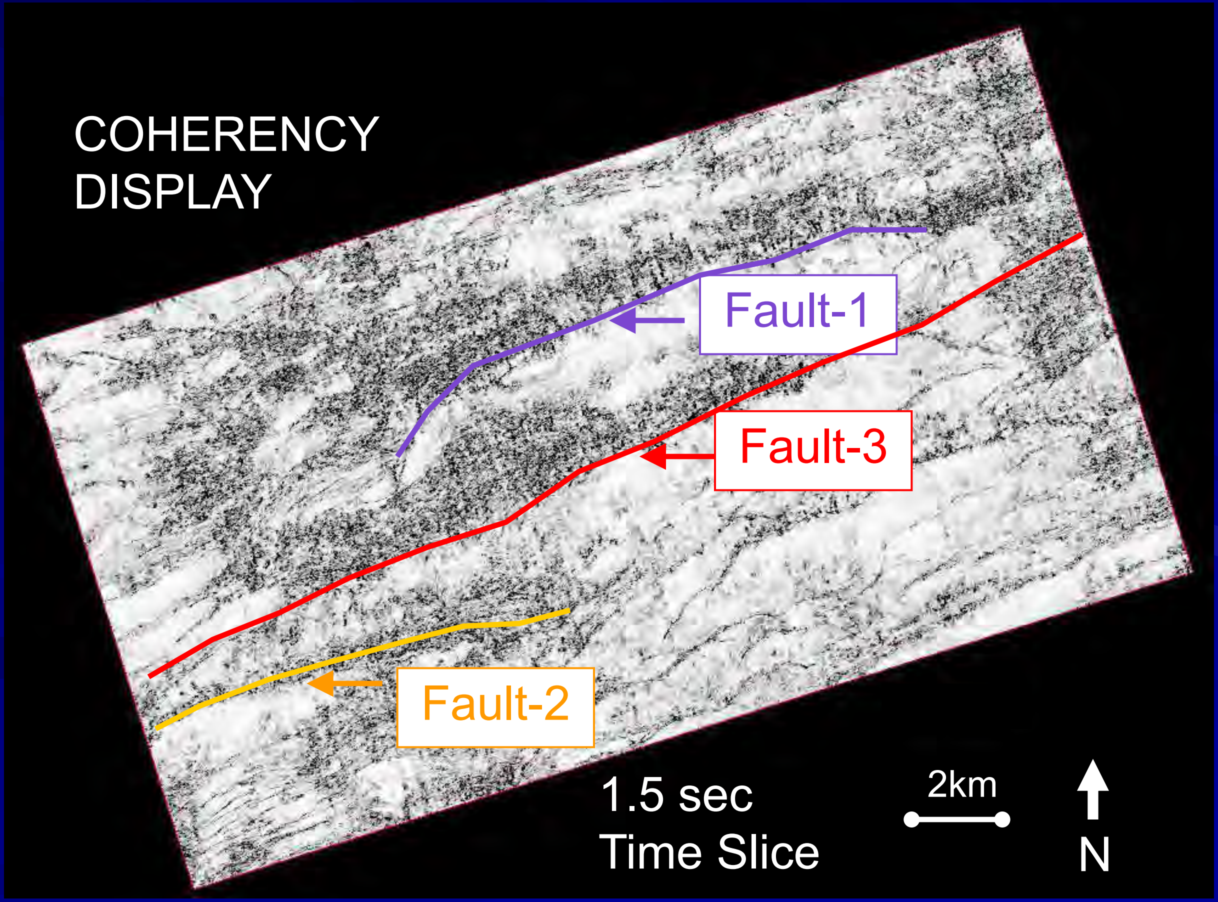
Normal Fault Examples: Offshore Myanmar

- Fault Interpretation on the 3D seismic data
  - Choosing the fault locations from their deep penetration into thermal source intervals, cutting to shallow depth reservoirs, and with wide lateral propagation.
  - Interpreting the faults as horizons to extract the time structure maps with close distance Inline and Crossline spacing (~125 meters)



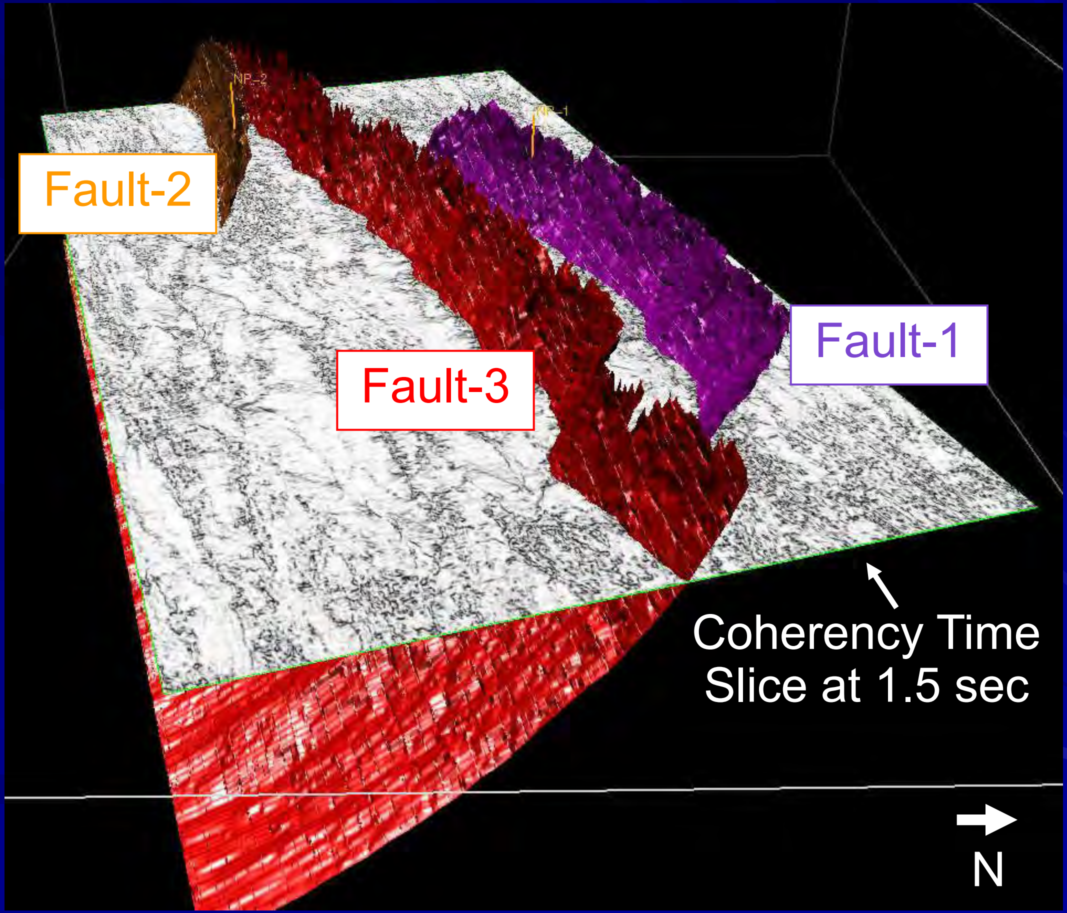
Normal Fault Examples: Offshore Myanmar

- Fault Interpretation on the 3D seismic data
  - Northeast-Southwest trend of the normal fault systems with general dip to the Southeast

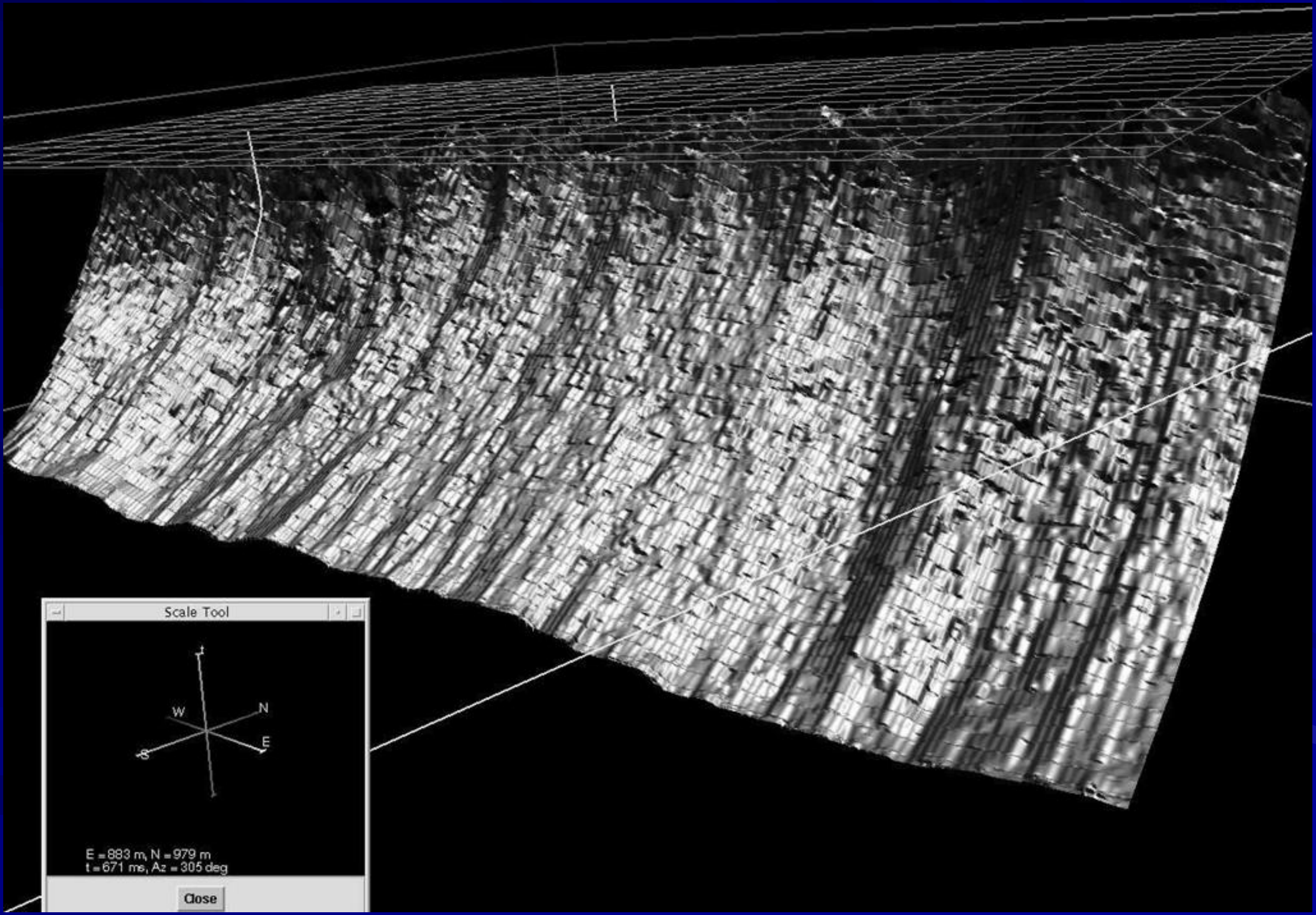


Normal Fault Examples: Offshore Myanmar

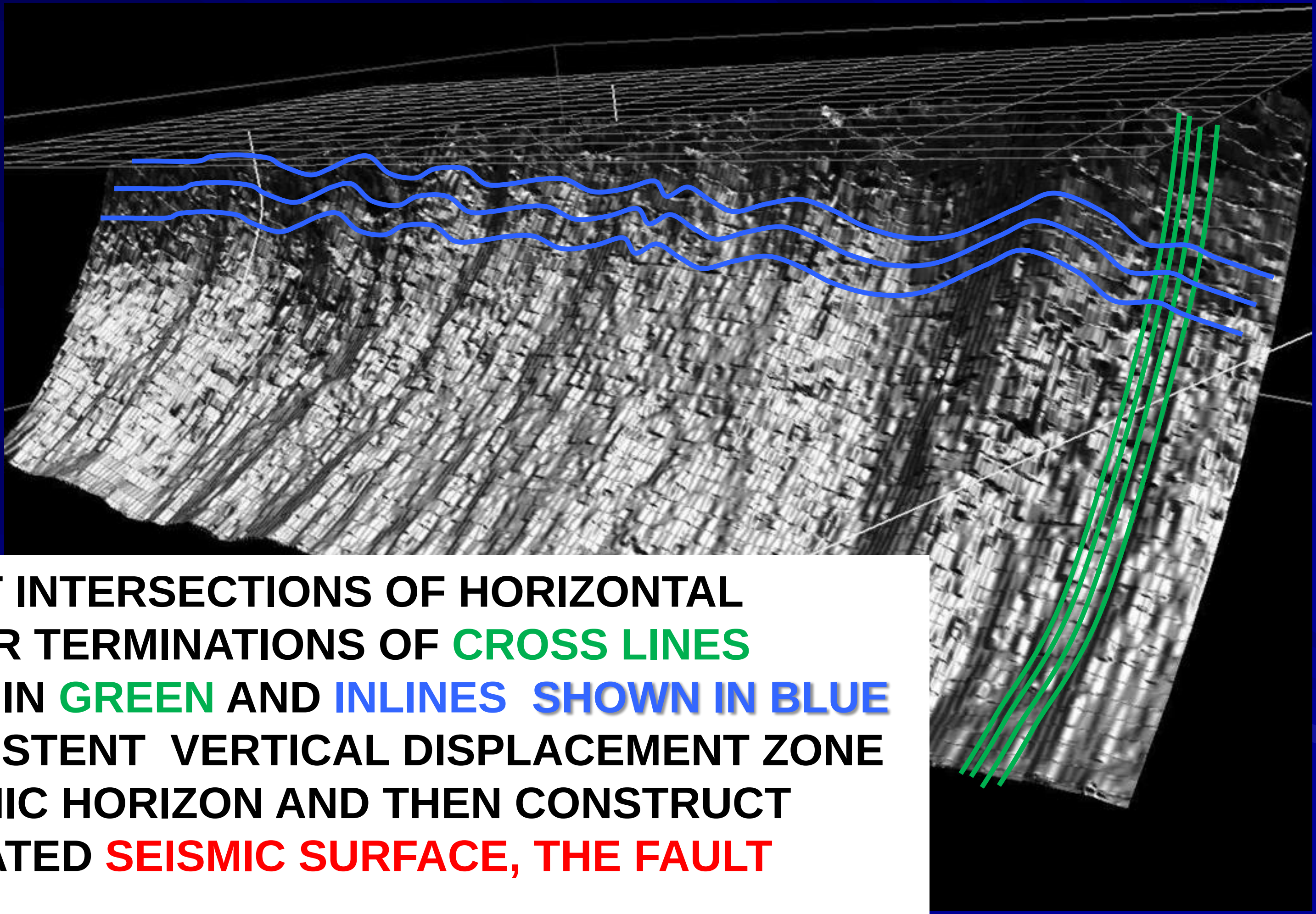
- 3D visualizations of the three interpreted fault planes



3D Fault Plane Interpretive Procedure

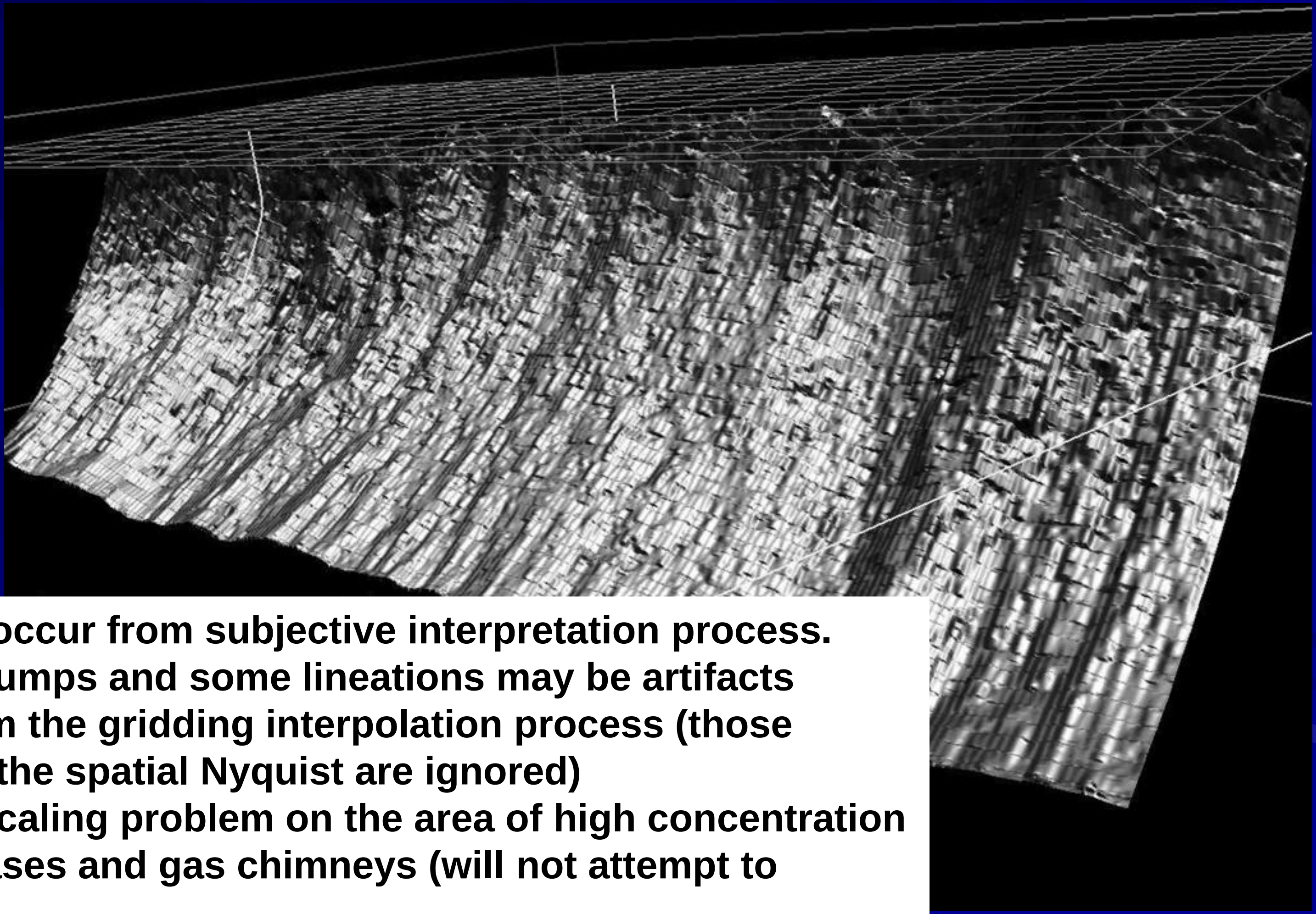


Fault Plane Interpretive Procedure



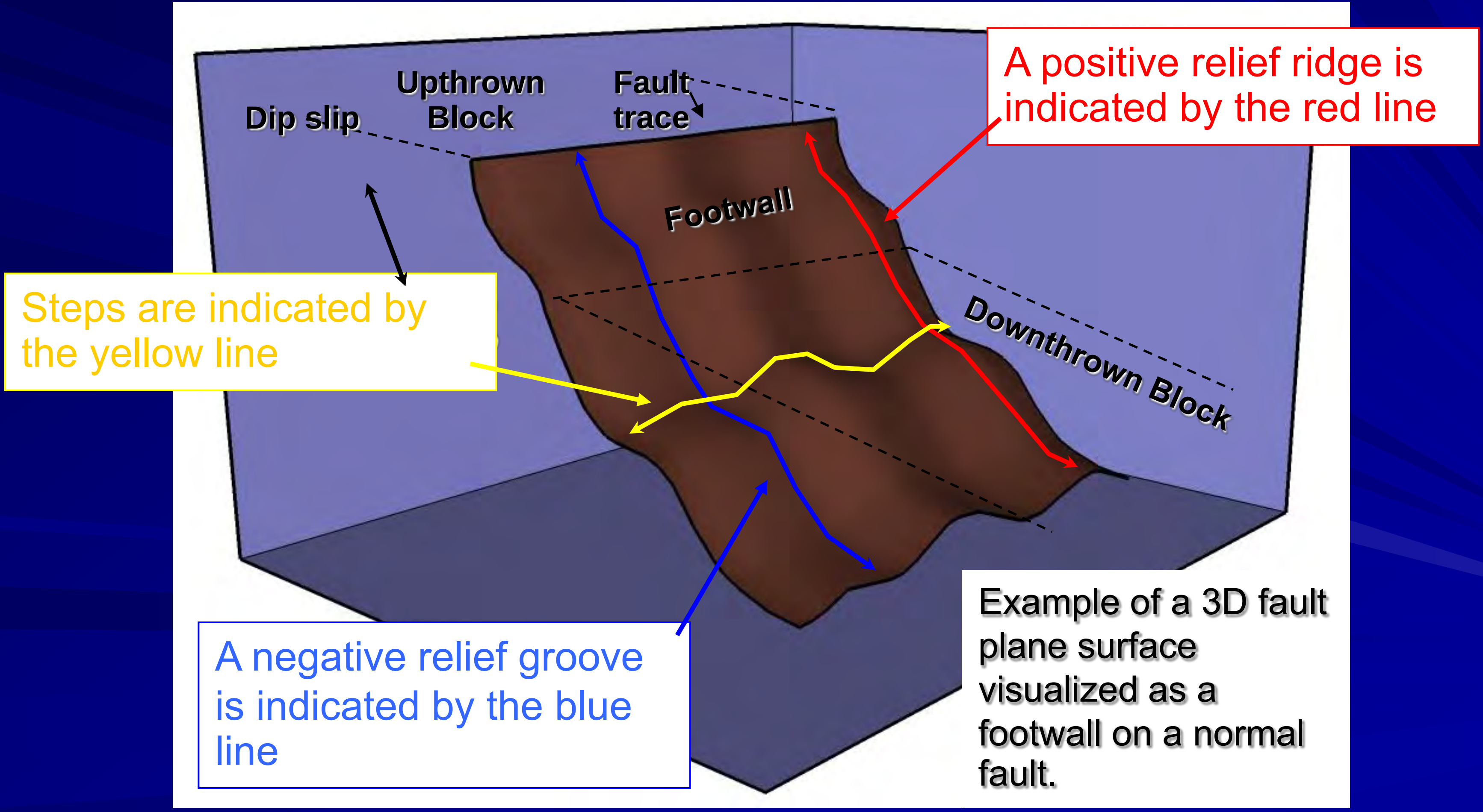
INTERPRET INTERSECTIONS OF HORIZONTAL REFLECTOR TERMINATIONS OF CROSS LINES INDICATED IN GREEN AND INLINES SHOWN IN BLUE AT A CONSISTENT VERTICAL DISPLACEMENT ZONE AS A SEISMIC HORIZON AND THEN CONSTRUCT INTERPOLATED SEISMIC SURFACE, THE FAULT PLANE.

Fault Plane Interpretive Limitations



- Errors may occur from subjective interpretation process.
- Holes and bumps and some lineations may be artifacts resulting from the gridding interpolation process (those smaller than the spatial Nyquist are ignored)
- Amplitude scaling problem on the area of high concentration of shallow gases and gas chimneys (will not attempt to quantify).

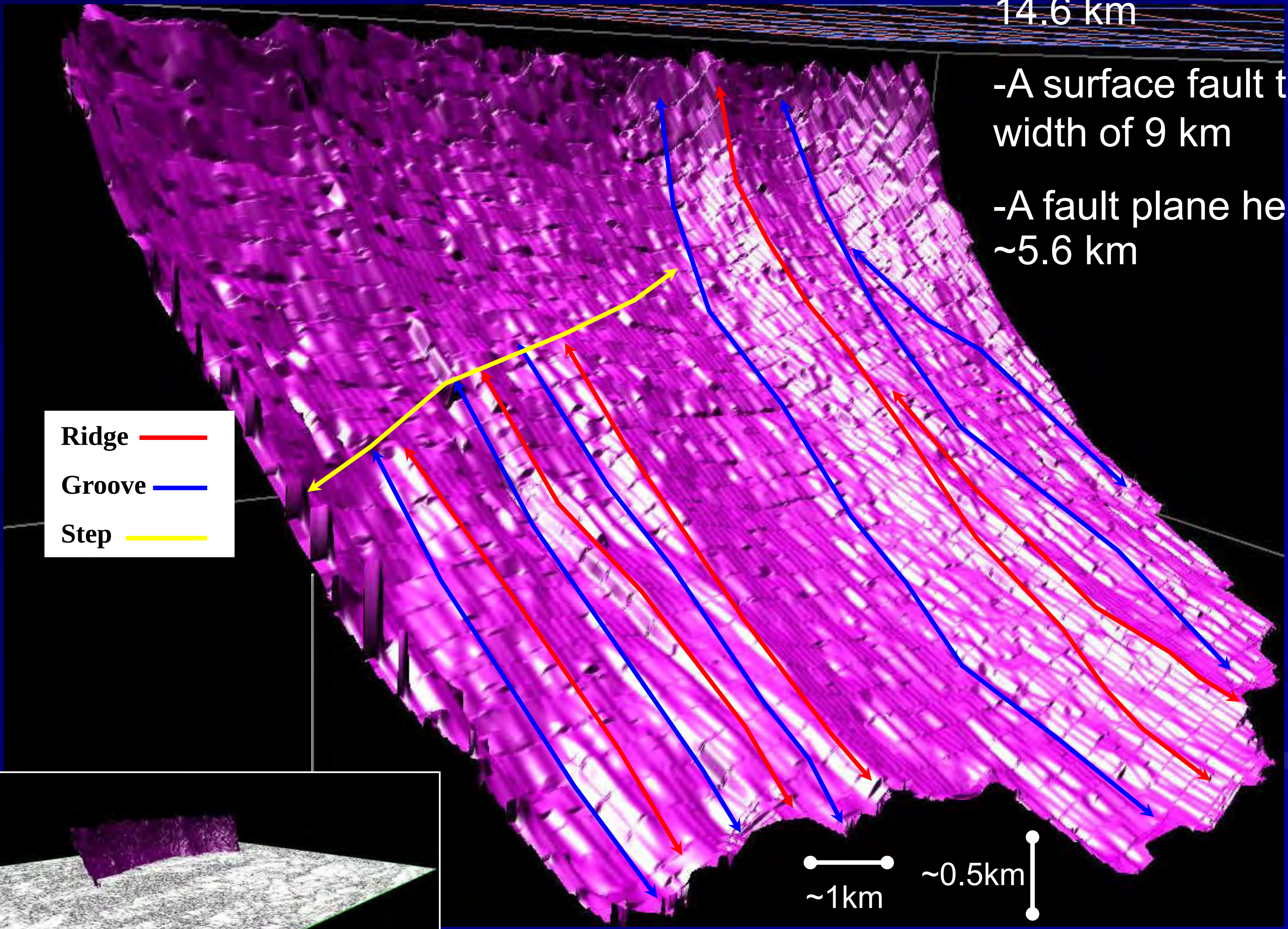
- Principal Geomorphic Elements Observed on Seismic Fault Plane Image: Ridges, Grooves, and Steps on 3D Image of Normal Fault Plane Footwall

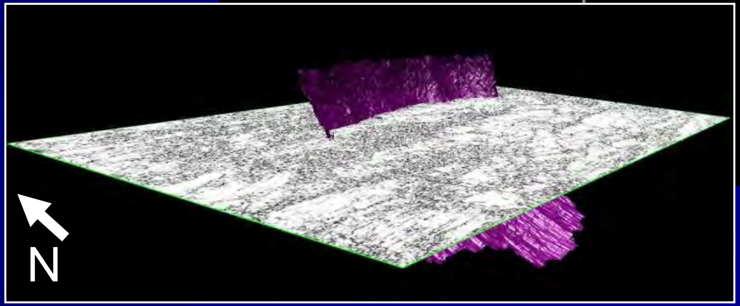


Example of a 3D fault plane surface visualized as a footwall on a normal fault.

The 3D fault plane surface of Fault-1

- A fault trace length of 14.6 km
- A surface fault trace width of 9 km
- A fault plane height of ~5.6 km



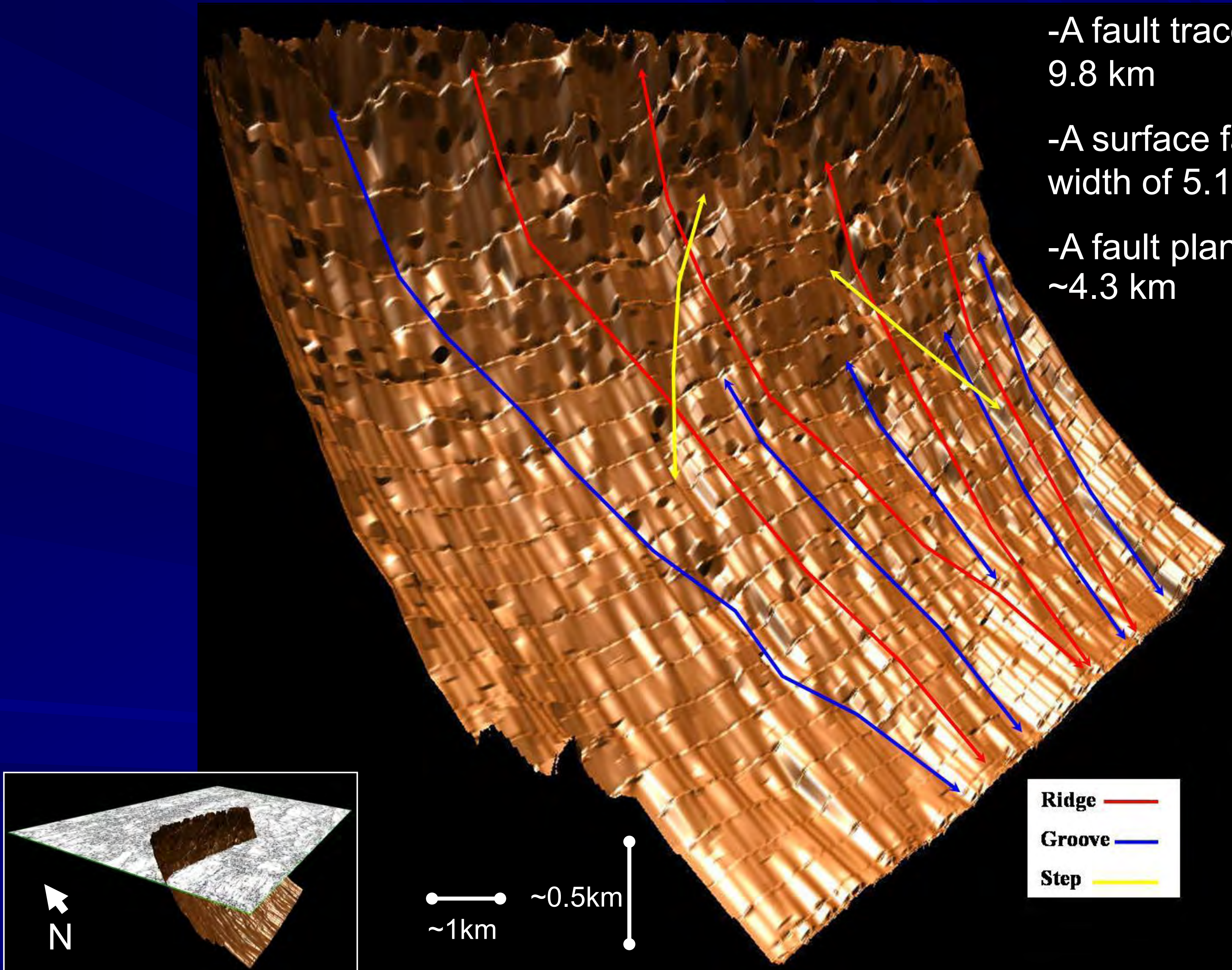


The 3D fault plane surface of Fault-2

-A fault trace length of 9.8 km

-A surface fault trace width of 5.15 km

-A fault plane height of ~4.3 km

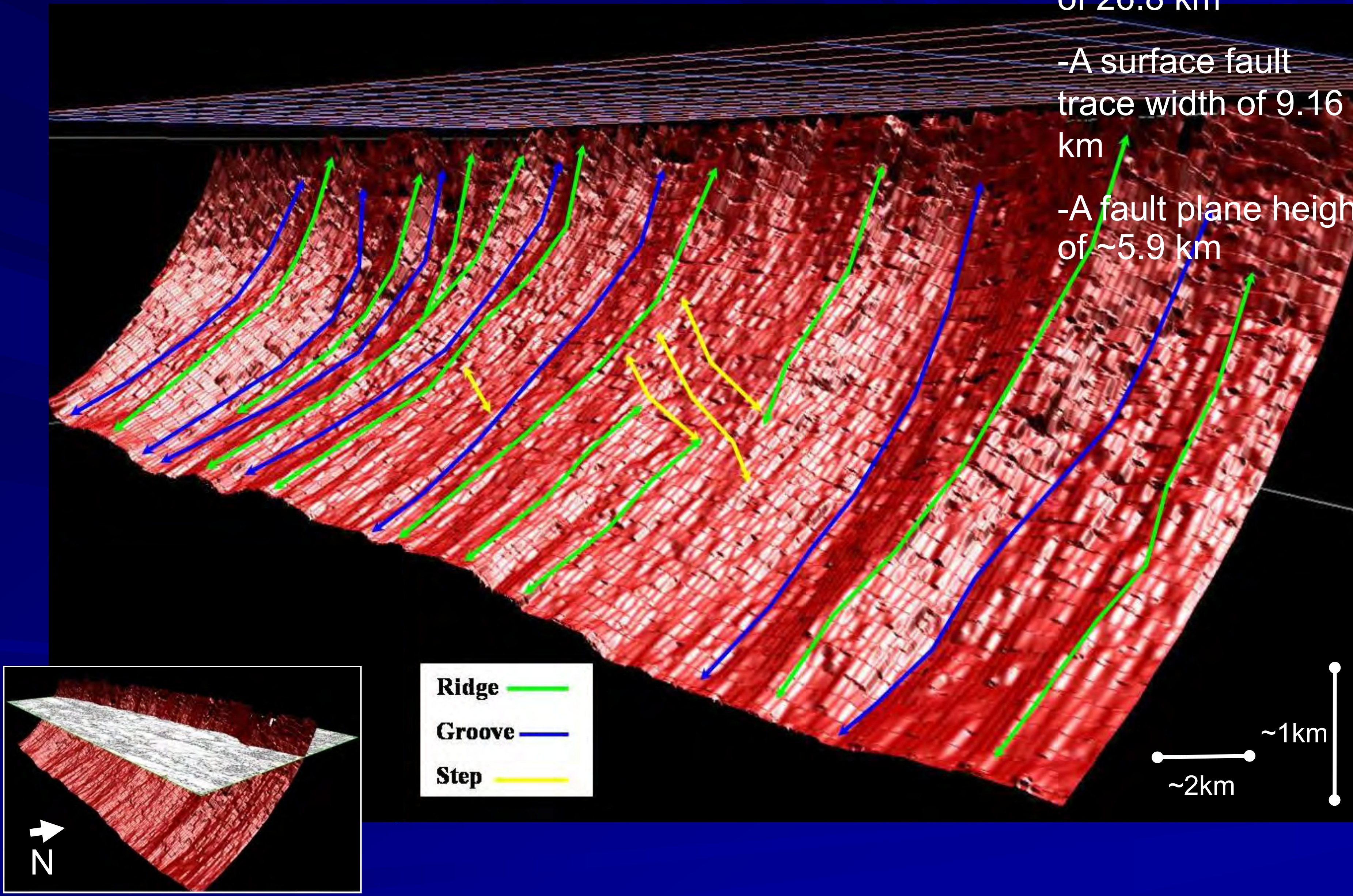


The 3D fault plane surface of Fault-3

-A fault trace length of 26.8 km

-A surface fault trace width of 9.16 km

-A fault plane height of ~5.9 km



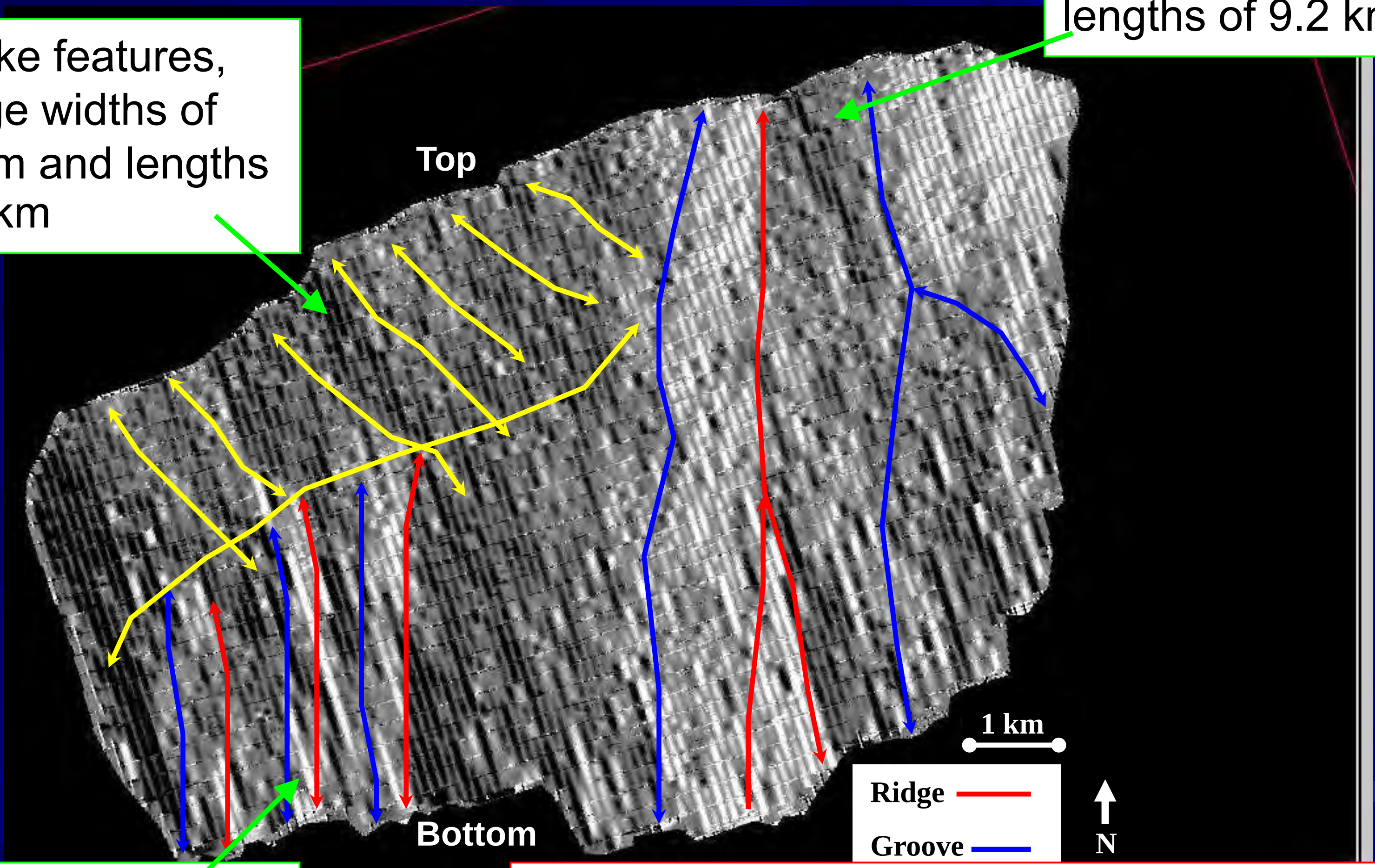
Normal Fault Example: Offshore Myanmar

- Seismic attribute map analysis on the fault planes
  - Azimuth display: provides the detailed orientation and dimensions of ridge, groove, and step features on the fault planes.
  - Reflection Strength display: shows the inferred seismic anomaly pattern on the fault planes.

Azimuth Display of Fault-1

Big ridges and grooves, average widths of 2.25 km and lengths of 9.2 km

Step-like features, average widths of 0.16 km and lengths of 3.3 km

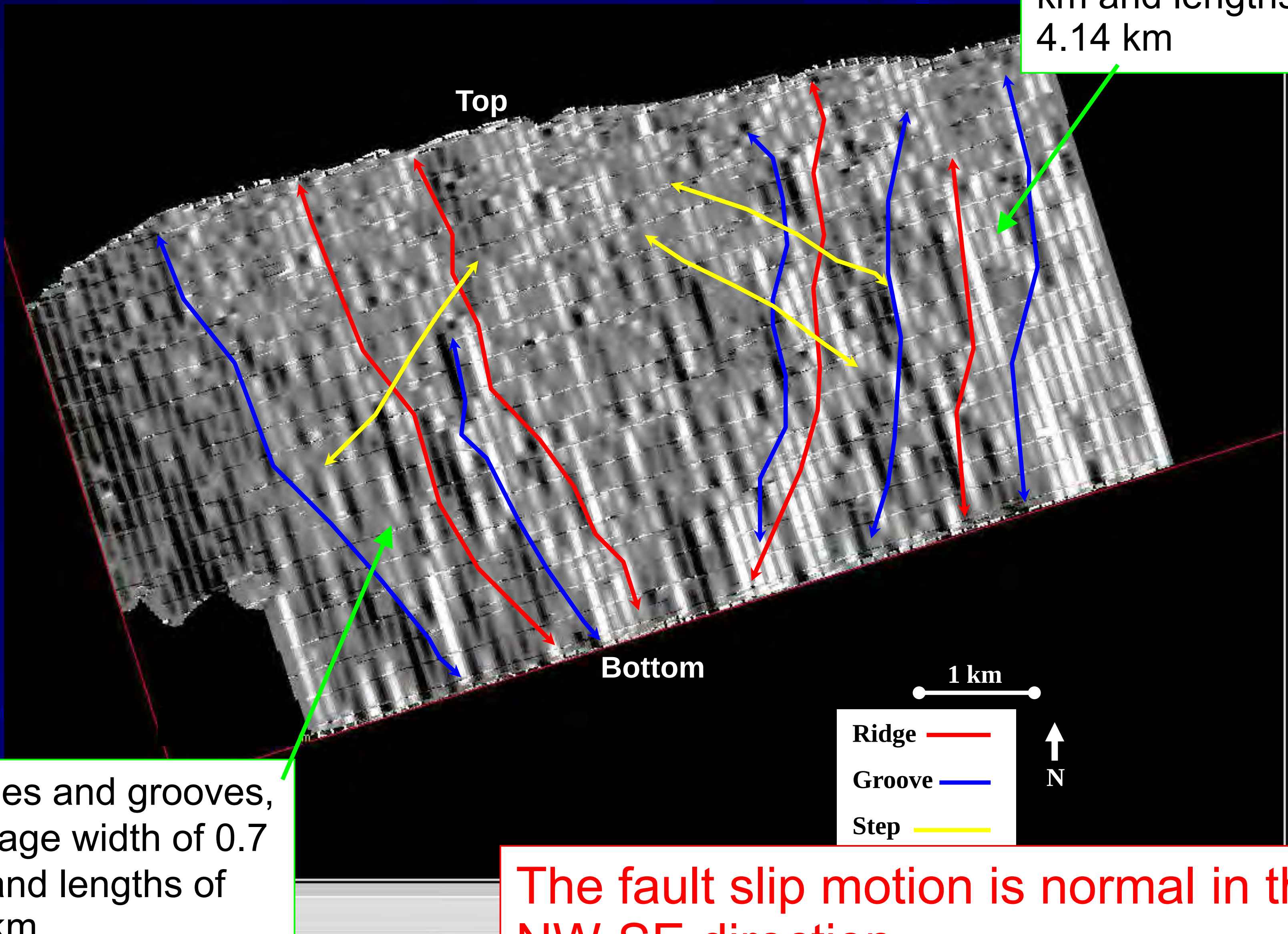


Small ridges and grooves, average widths of 0.75 km and lengths of 4.8 km

The fault slip motion is normal on the N-S direction but exhibiting oblique slip

Azimuth Display of Fault-2

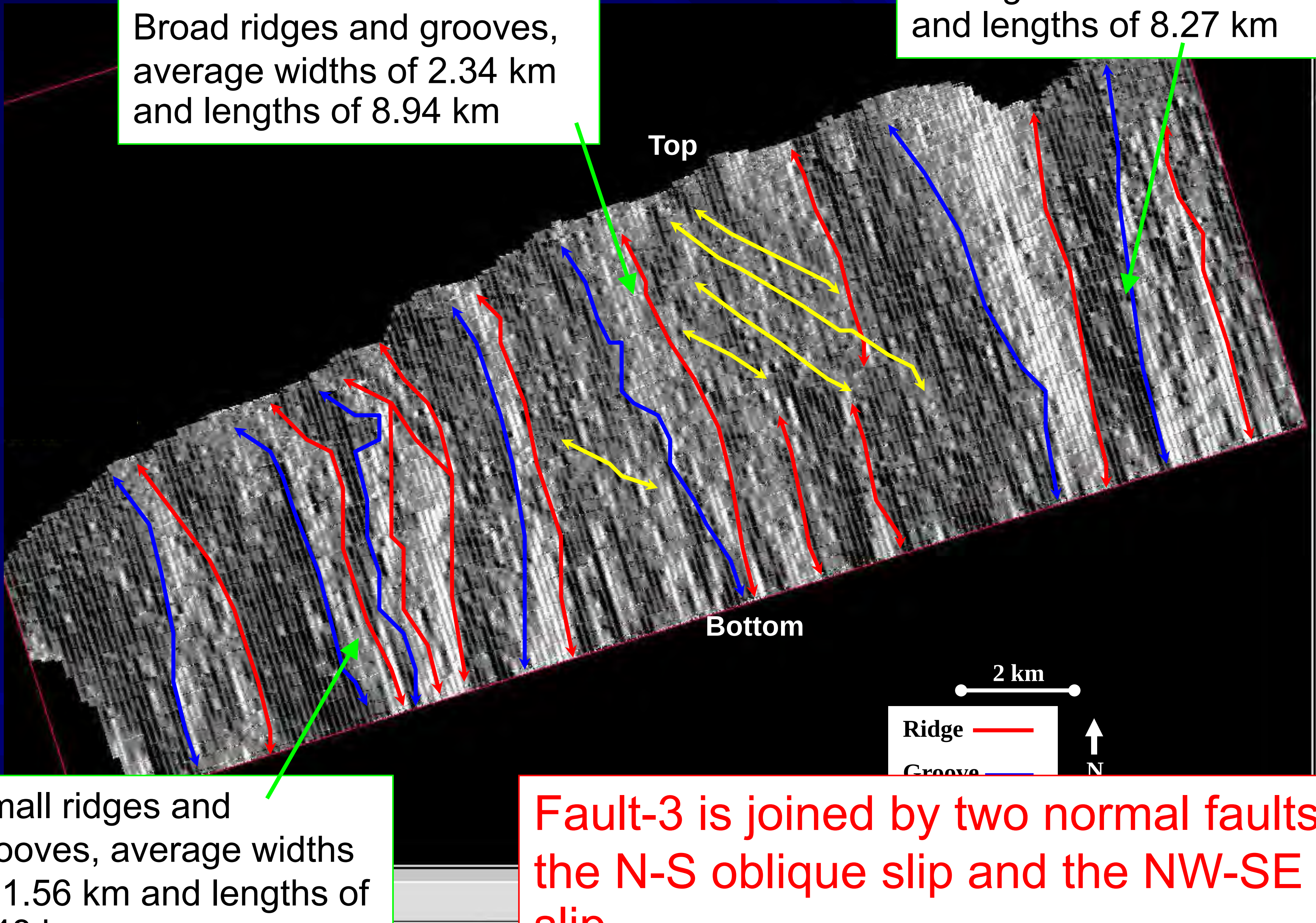
Ridges and grooves, average widths of 1 km and lengths of 4.14 km



Ridges and grooves, average width of 0.7 km and lengths of 4.9 km

The fault slip motion is normal in the NW-SE direction

Azimuth Display of Fault-3



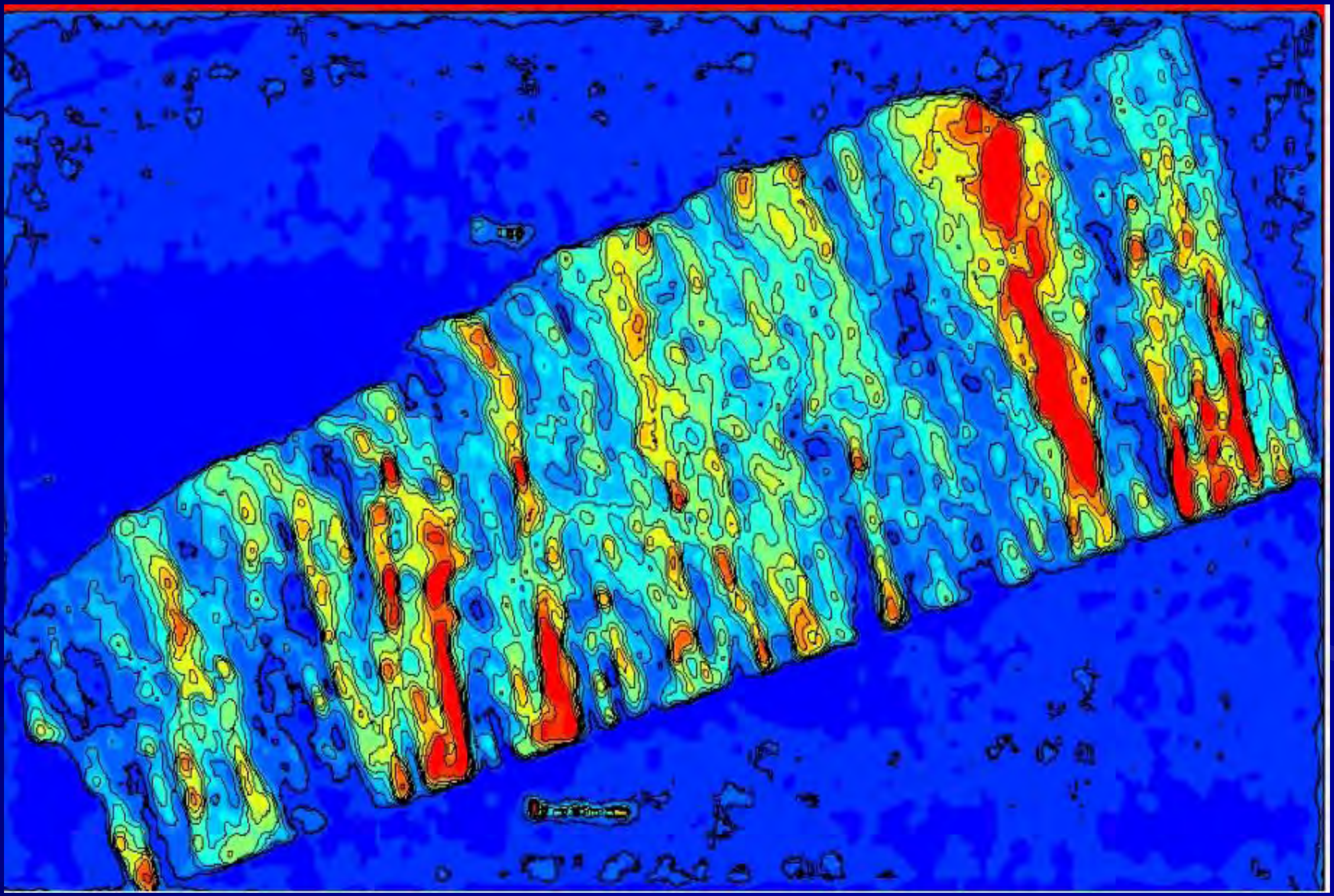
Broad ridges and grooves, average widths of 2.34 km and lengths of 8.94 km

Big ridges and grooves, average widths of 2.79 km and lengths of 8.27 km

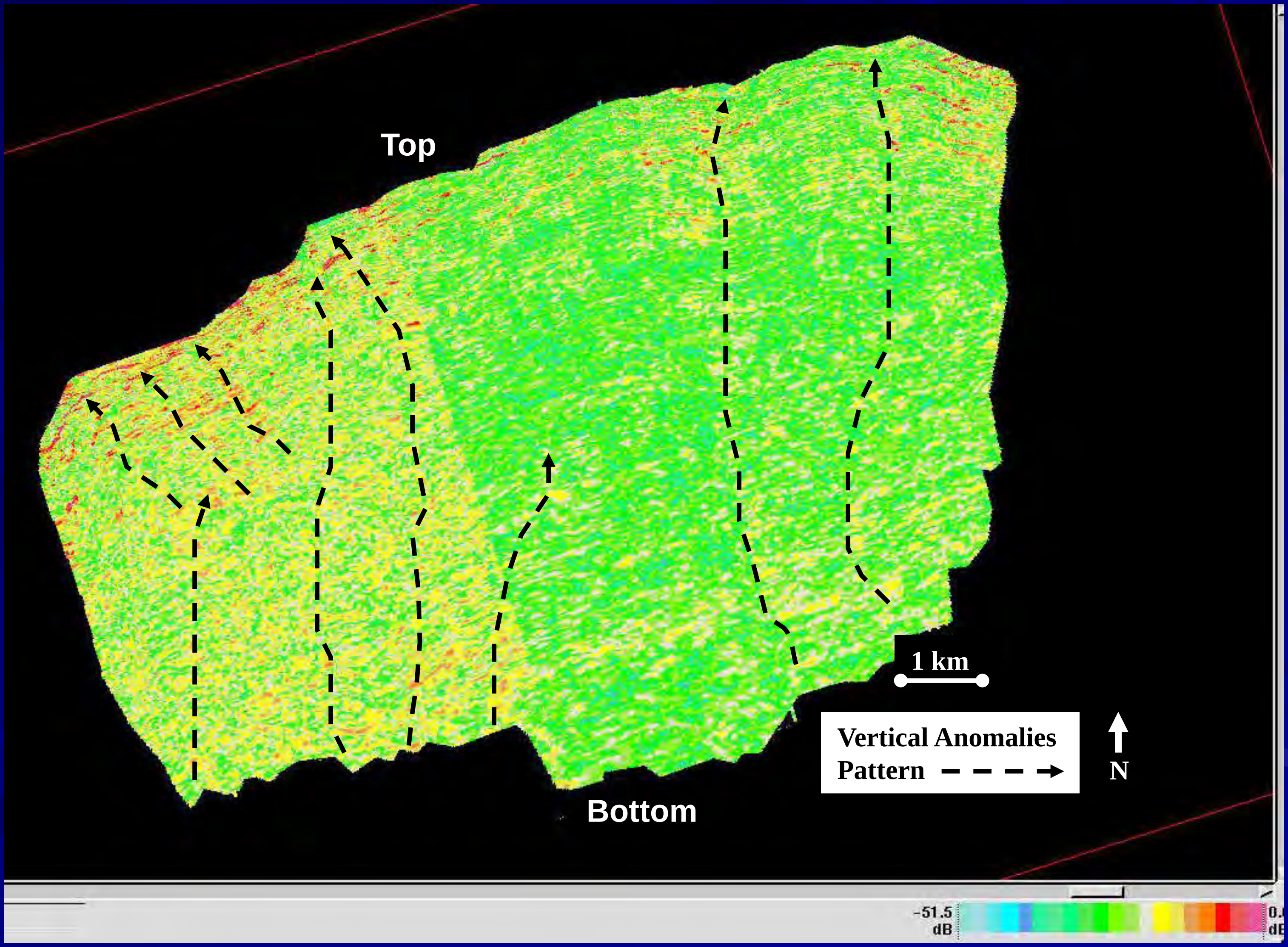
Small ridges and grooves, average widths of 1.56 km and lengths of 7.48 km

Fault-3 is joined by two normal faults in the N-S oblique slip and the NW-SE slip

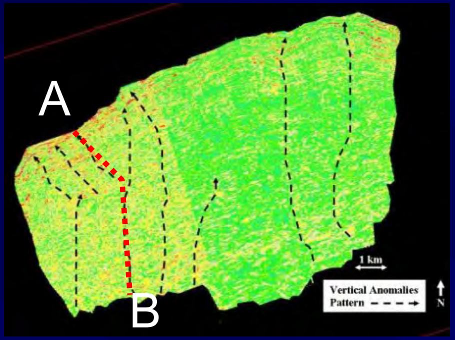
- Contour of the Geomorphic Fault Plane Surface of Fault-3: Ridges in red, Grooves in blue.



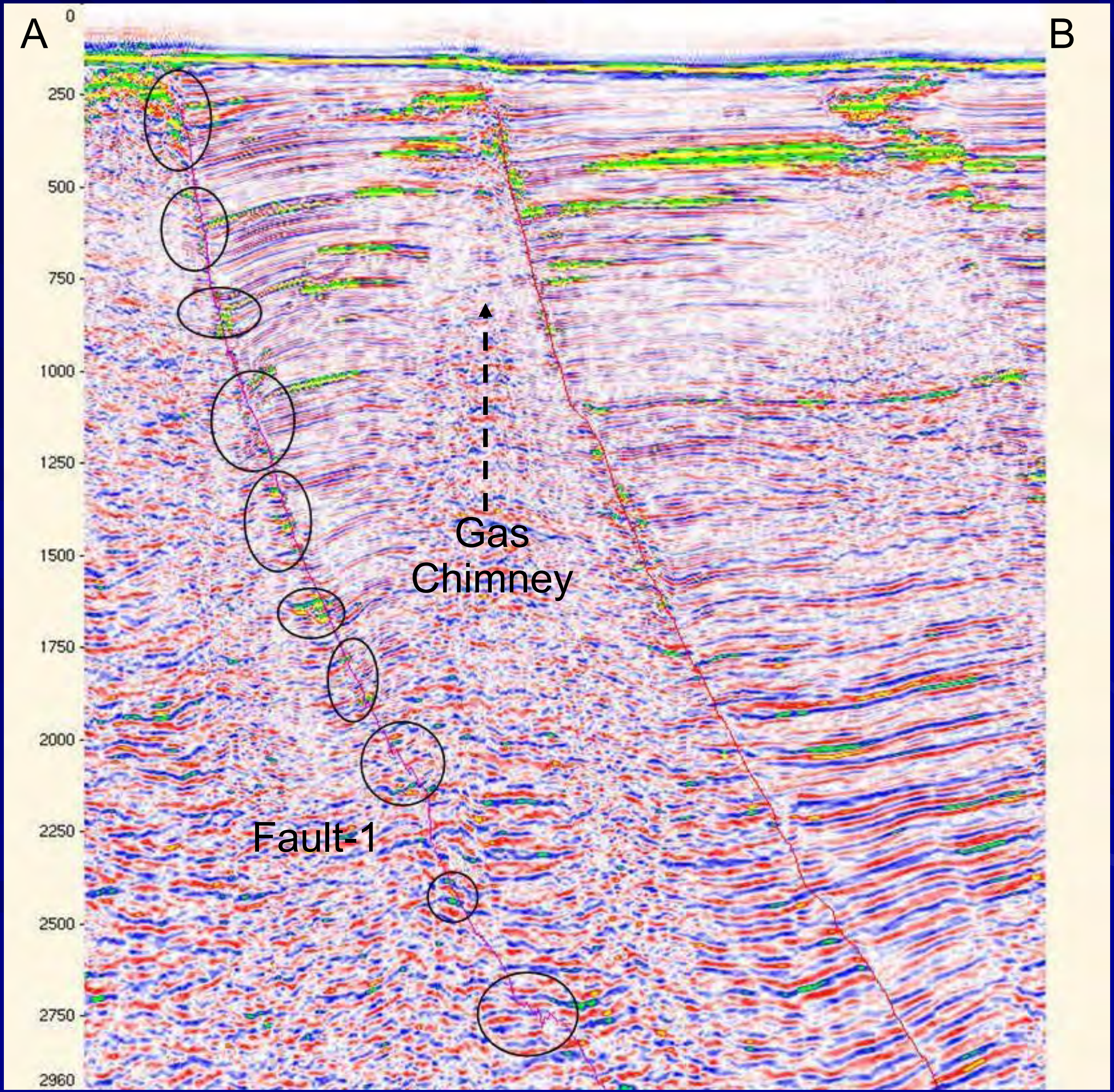
Reflection Strength Display of Fault-1



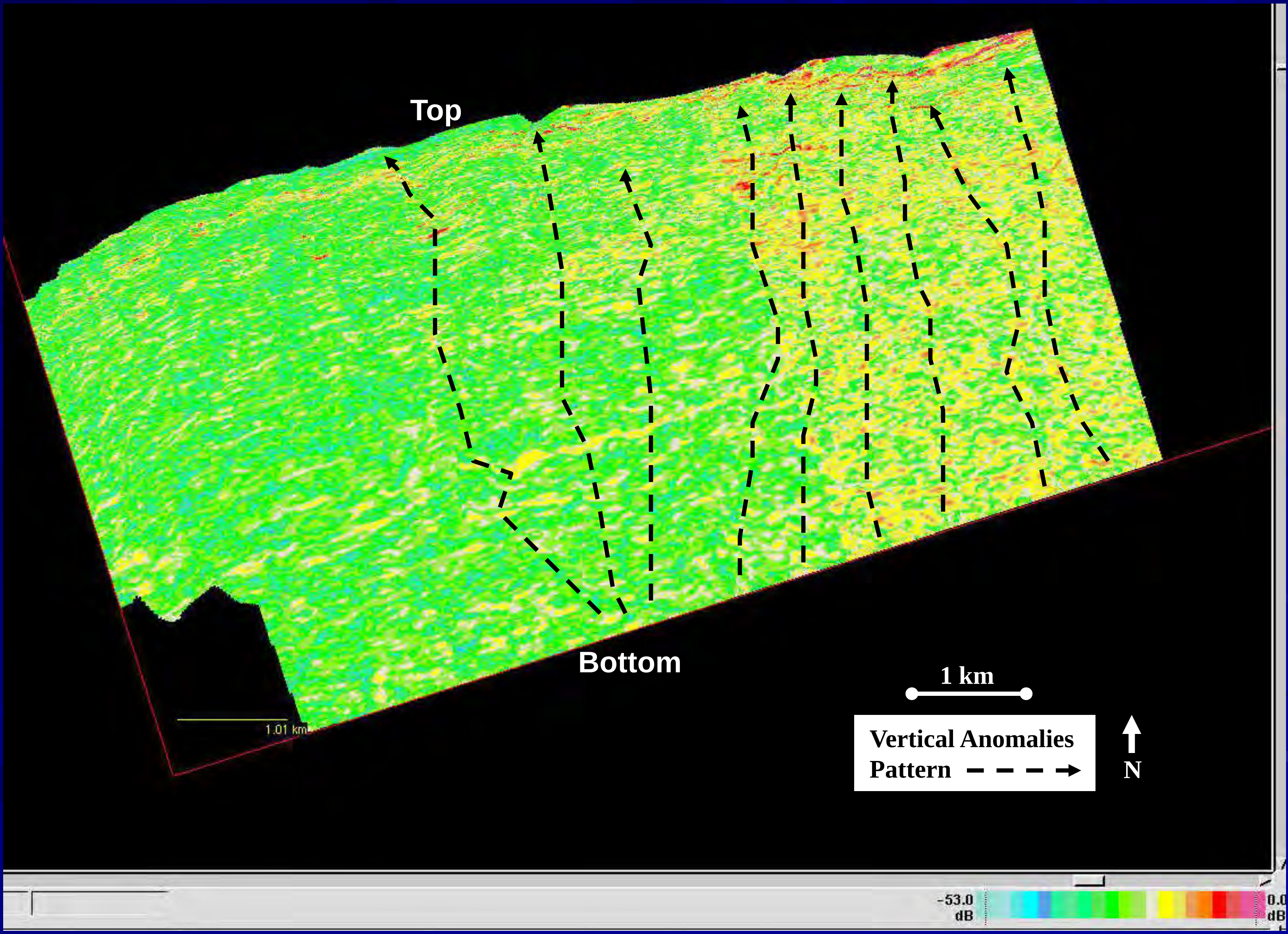
Random Seismic Line Crossing Fault-1



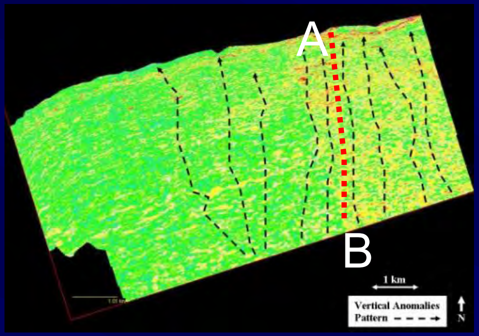
Seismic anomalies along Fault-1 are indicated by the black circles



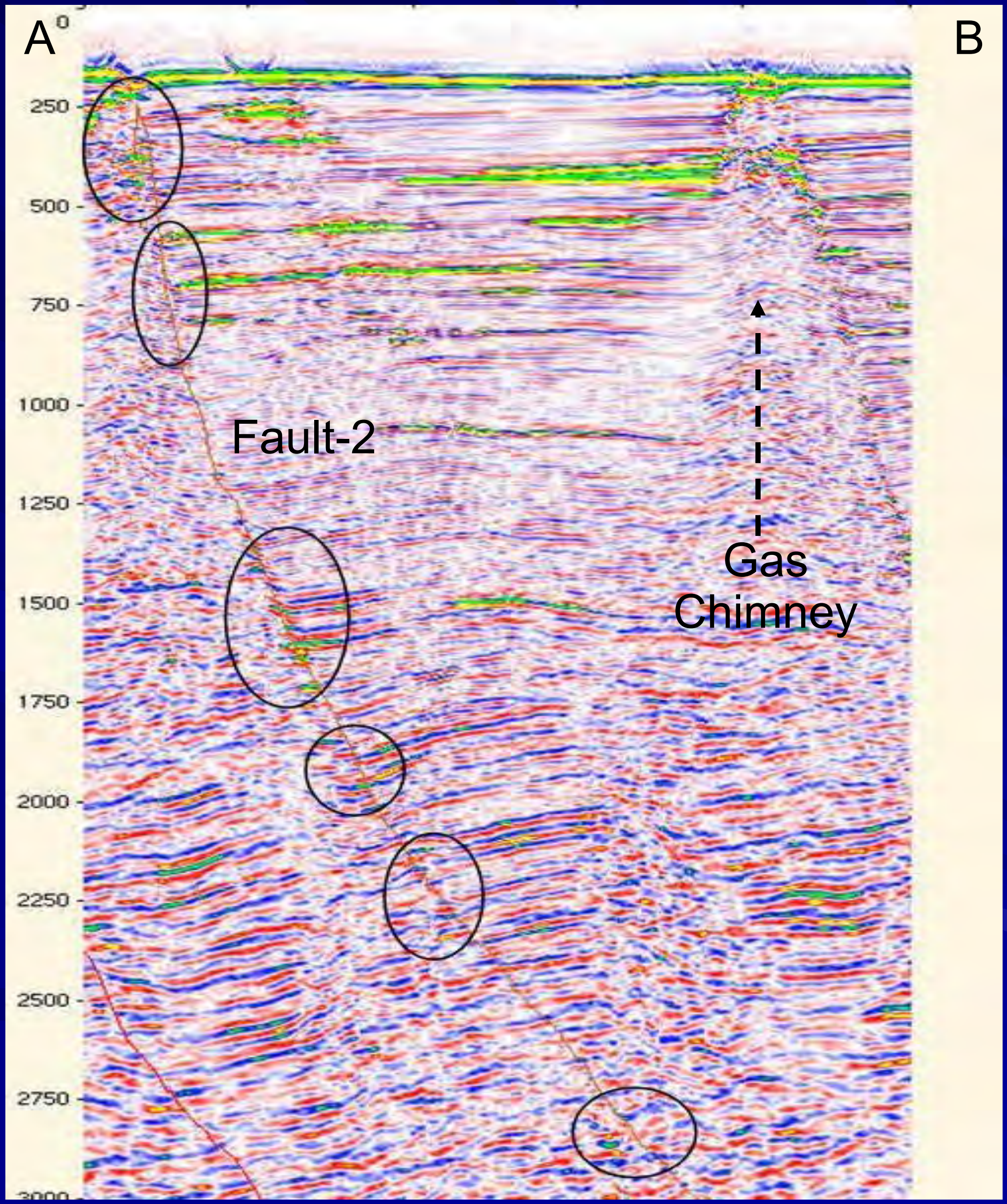
Reflection Strength Display of Fault-2



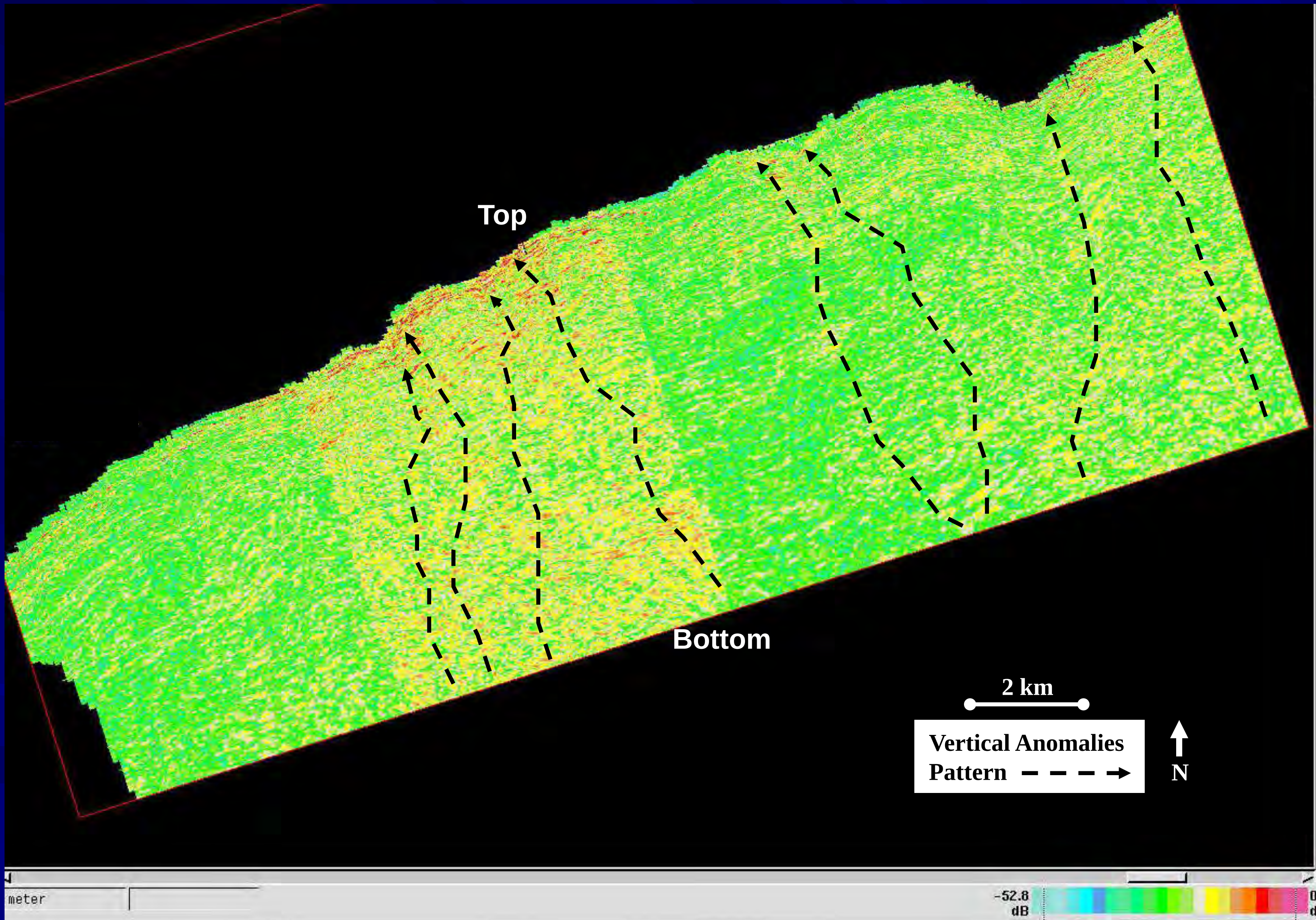
Random Seismic Line Crossing Fault-2



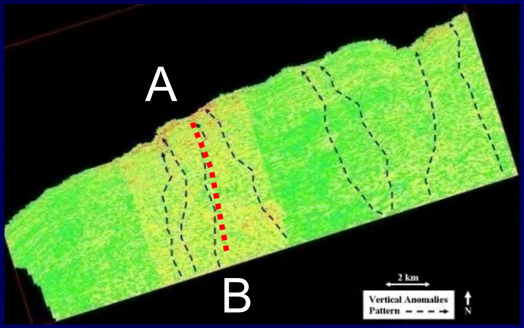
Seismic anomalies along Fault-2 indicated by the black circles



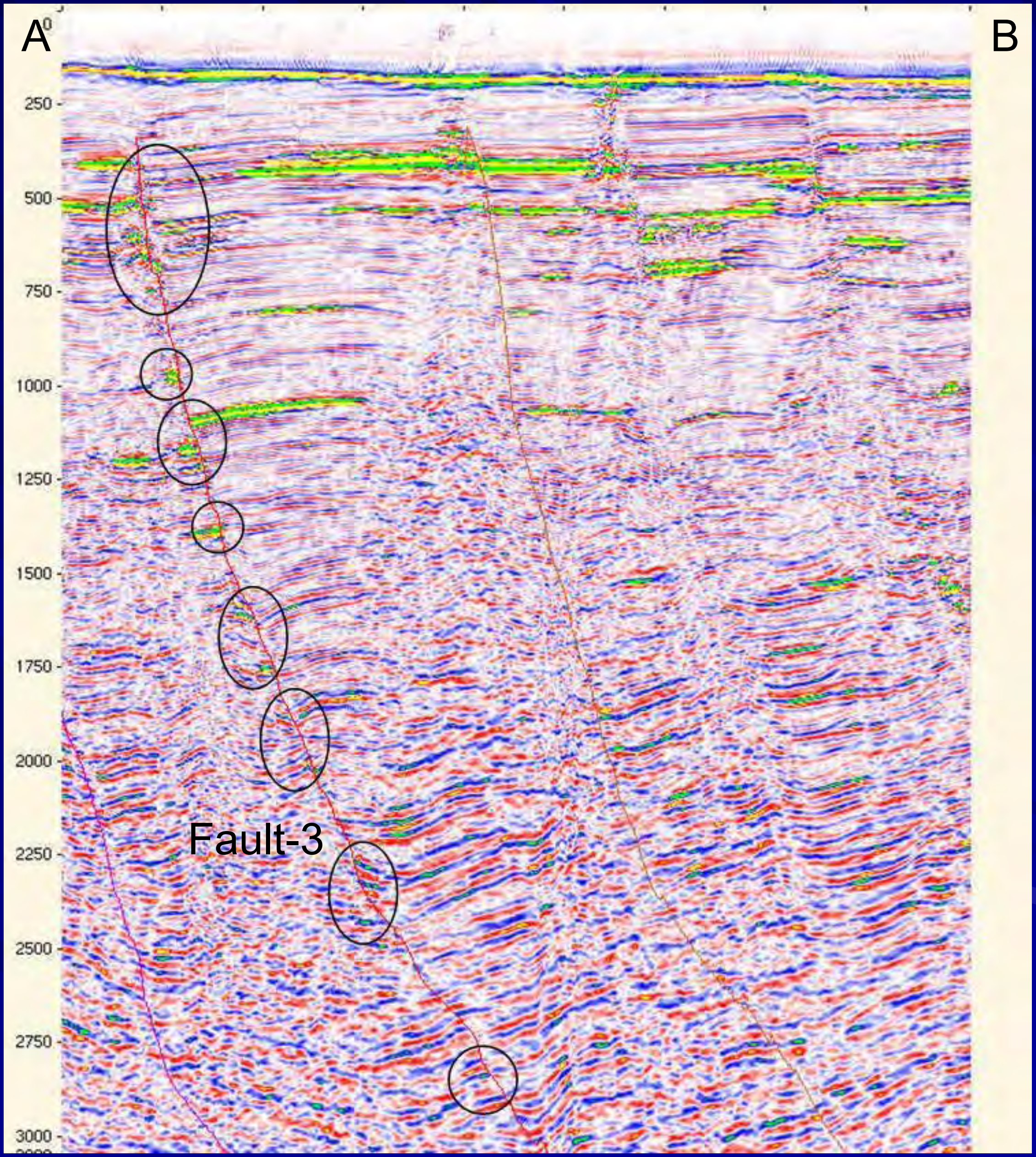
Reflection Strength Display of Fault-3



Random Seismic Line Crossing Fault-3



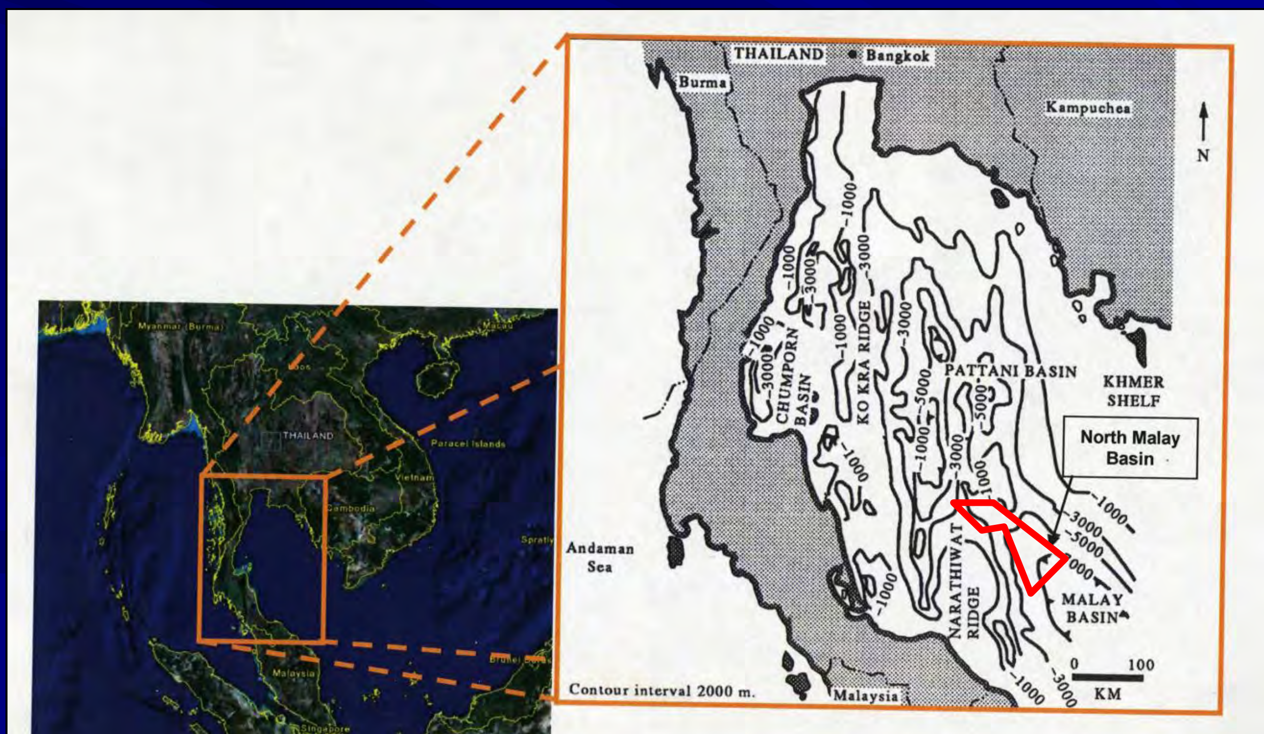
Seismic anomalies along Fault-3 indicated by the black circles



TRANSTENSIONAL FAULT EXAMPLE: GULF OF THAILAND

Transtensional Fault Example: Gulf of Thailand

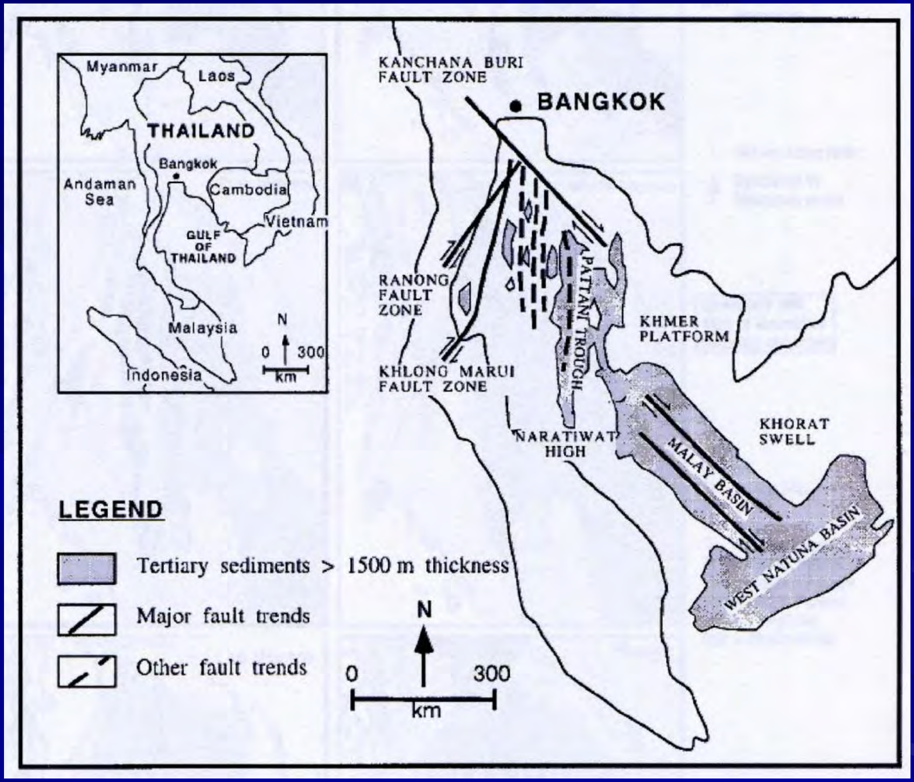
- Gulf of Thailand
  - The study is located on the northwestern flank of the Malay Basin in the Gulf of Thailand, 600 km south of Bangkok.
  - 3D seismic volume occupies area of approximately 5500 square kilometers.



*From Uttarathiyang (2008)

Transtensional Fault Example: Gulf of Thailand

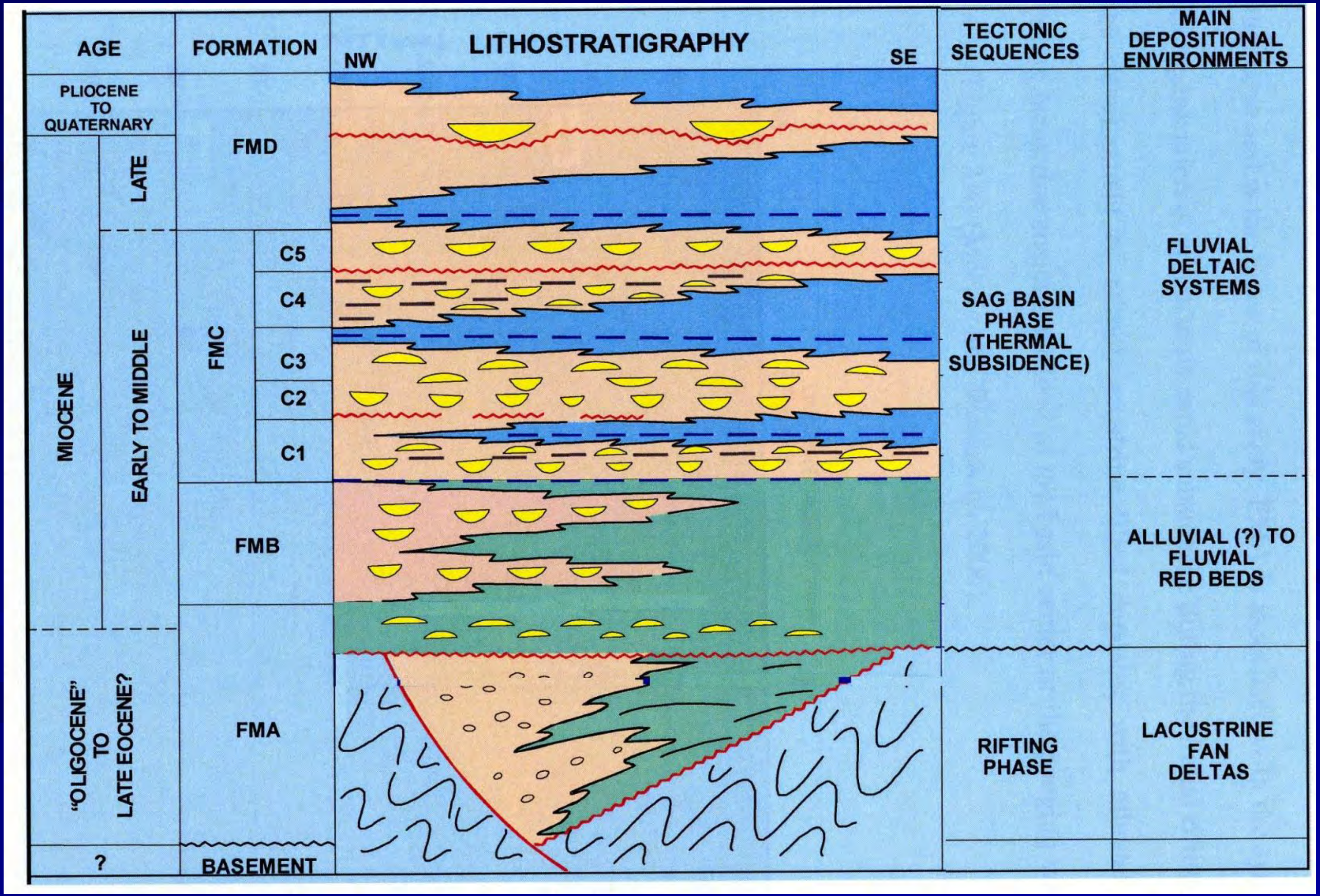
- Tectonic Setting
  - Early Oligocene: major strike-slip NW-SE right lateral transtension (Indian and Asian Plate) and beginning of rifting (Polachan and Sattayarak 1989; Polachan et al., 1991; Pigott and Satayarak, 1993).
  - Early-Middle Miocene: N-S transtension associated with NW-SE right-lateral strike-slip tectonics.
  - Late Miocene: NNW-SSE normal fault system developed obliquely to the earlier trends. (Uttarathiyang, 2008)



*From Kongwung and Ronghe (2000)

Transtensional Fault Example: Gulf of Thailand

- Regional Stratigraphy



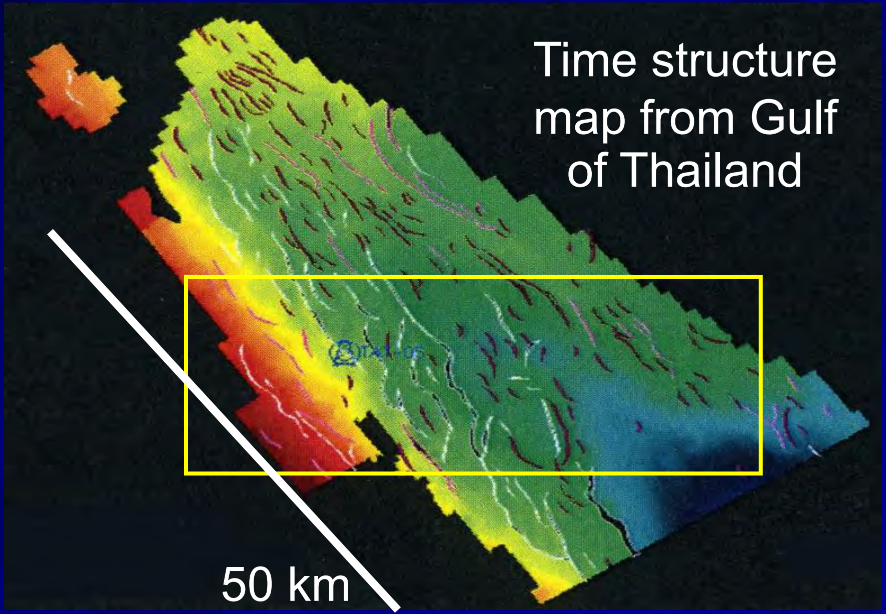
*From Uttarathiyang (2008)

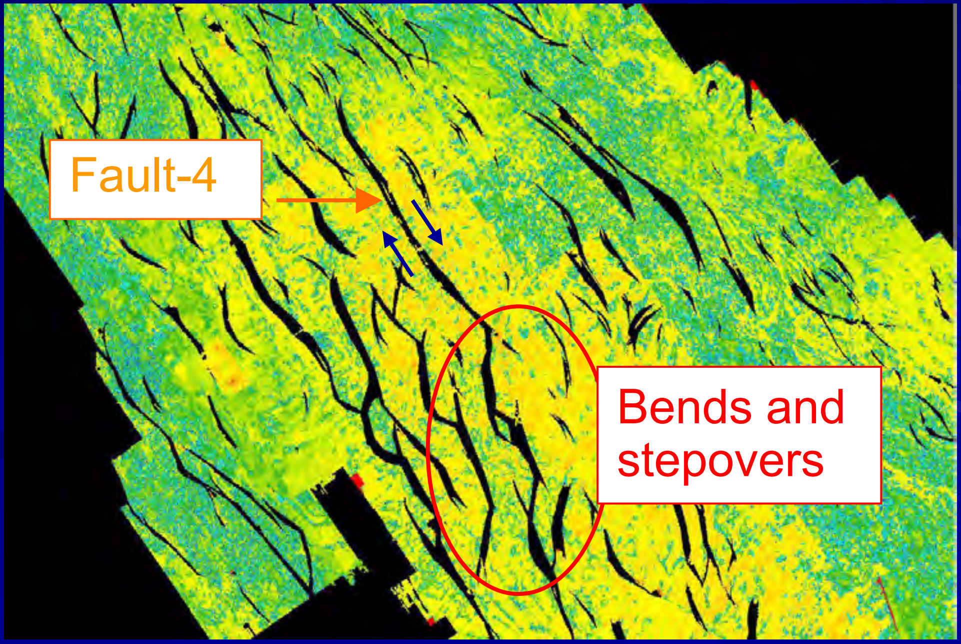
Transtensional Fault Example: Gulf of Thailand

- Petroleum Systems
  - Paleogene Formation A petroleum system of lacustrine-marine Type II oil, gas, and condensate.
  - Neogene Formation C petroleum system of coaly Type III source rocks providing gas and condensate.

Transtensional Fault Example: Gulf of Thailand

- Fault Interpretation on the 3D seismic data
  - Northwest-Southeast trend of the normal fault systems and dipping toward the center of the basin.
  - The time structure map shows bends and stepovers on the selected fault location indicating right lateral strike-slip motion

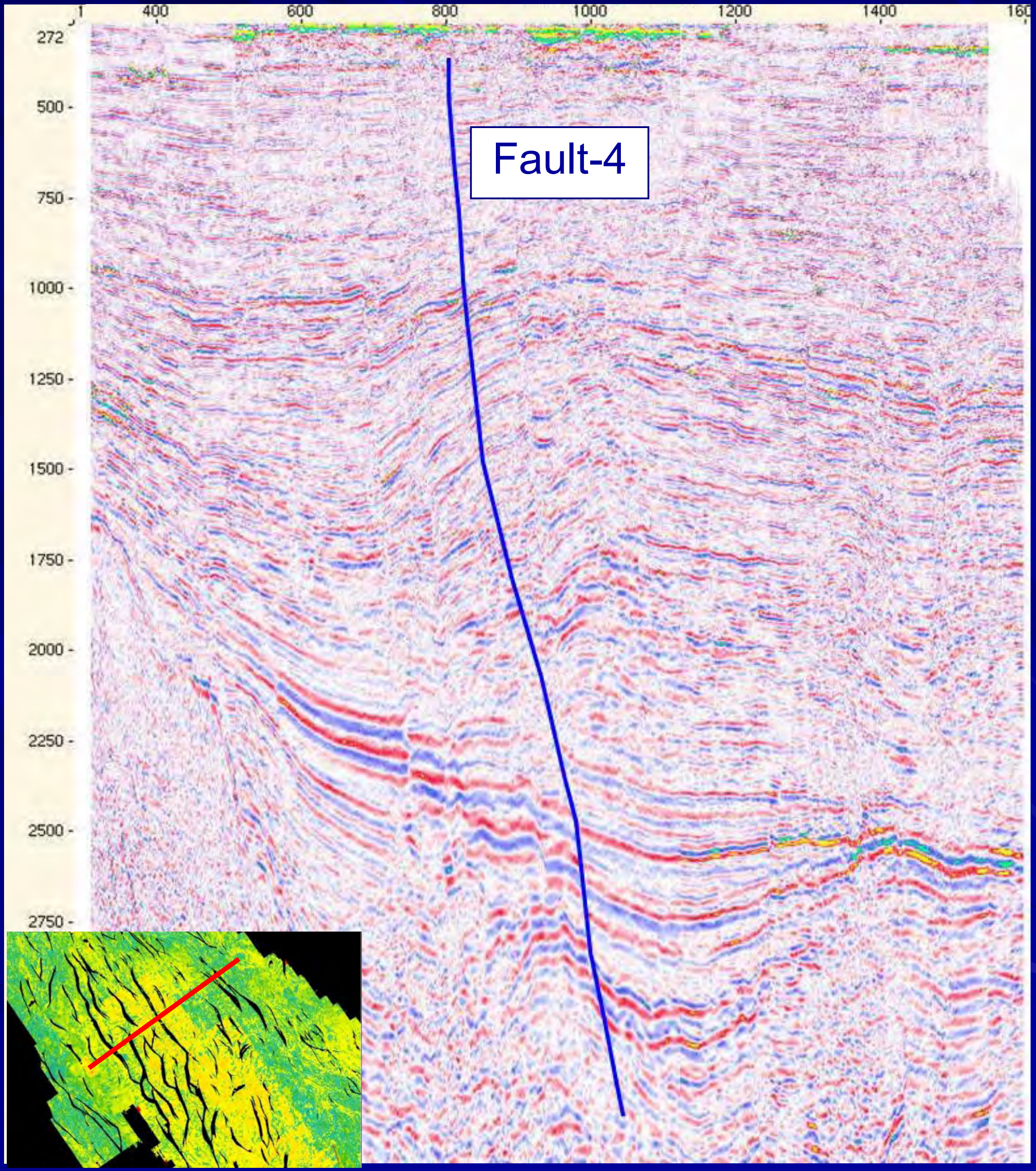




*Both figures from Uttarathiyang (2008)

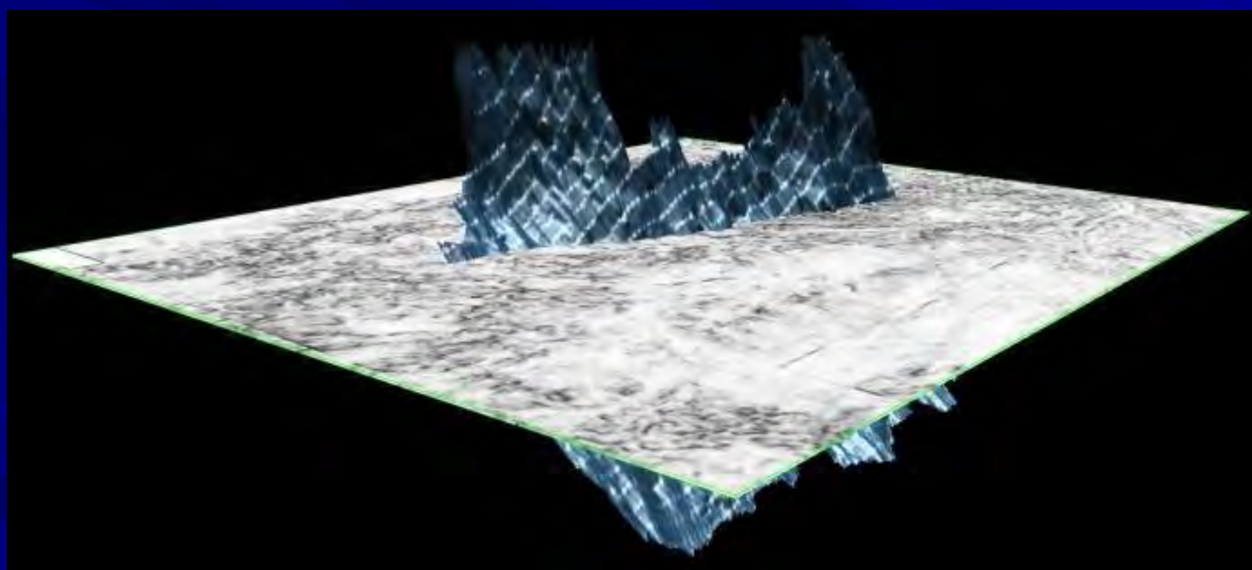
Transtensional Fault Example: Gulf of Thailand

- Fault Interpretation on the 3D seismic data
  - Fault-4 shows the gently dip slip motion. The seismic reflectors cannot easily be correlated across the fault indicating substantial horizontal strike-slip displacement.
  - Interpreting the faults as horizons to extract the time structure maps with close distance inline and crossline spacing (~125 meters)



Transtensional Fault Example: Gulf of Thailand

- 3D visualization of the Fault-4 plane cutting a coherency surface (1.75 sec) display of the fault trace.



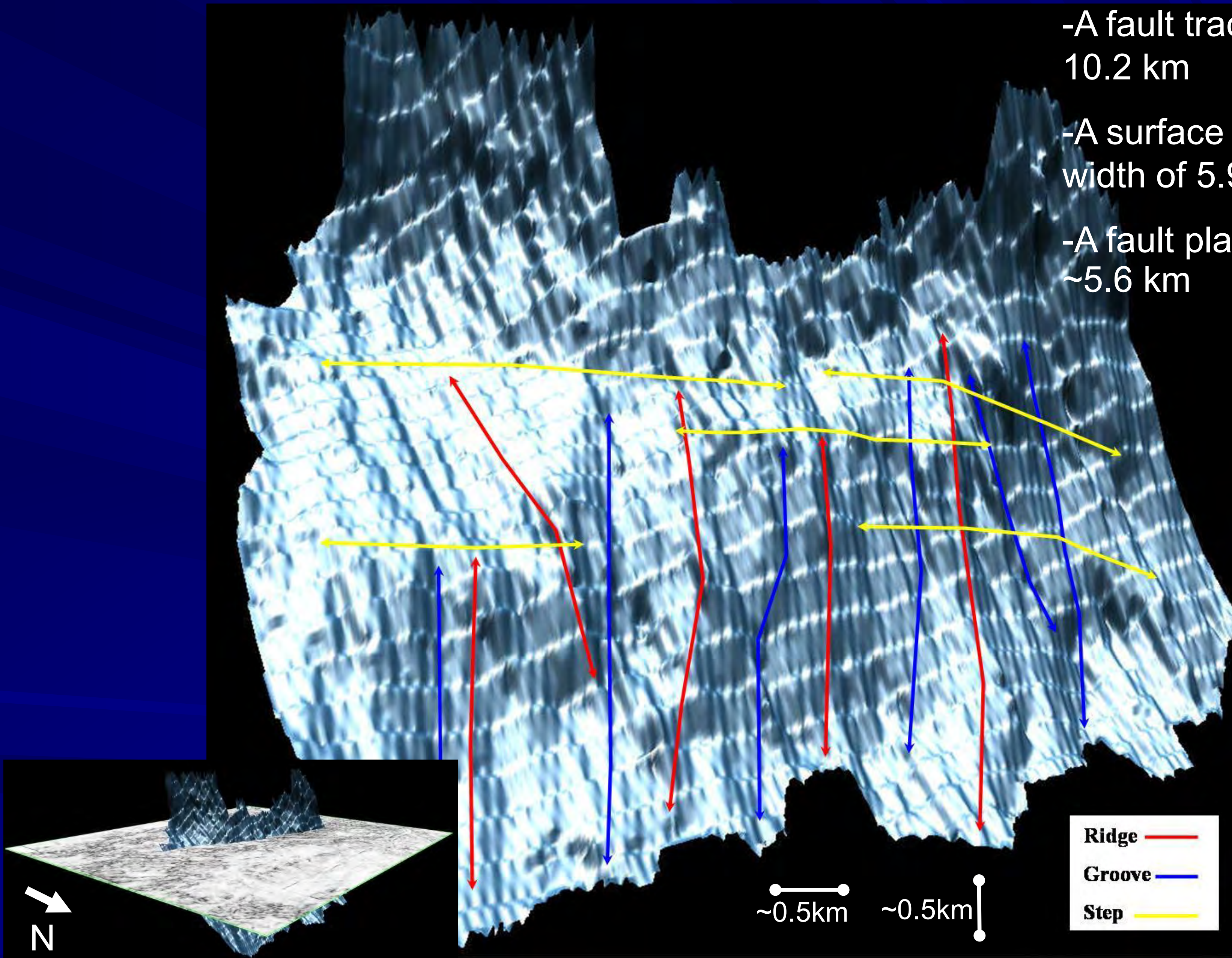
N

3D Fault Plane Surface of Fault-4

-A fault trace length of 10.2 km

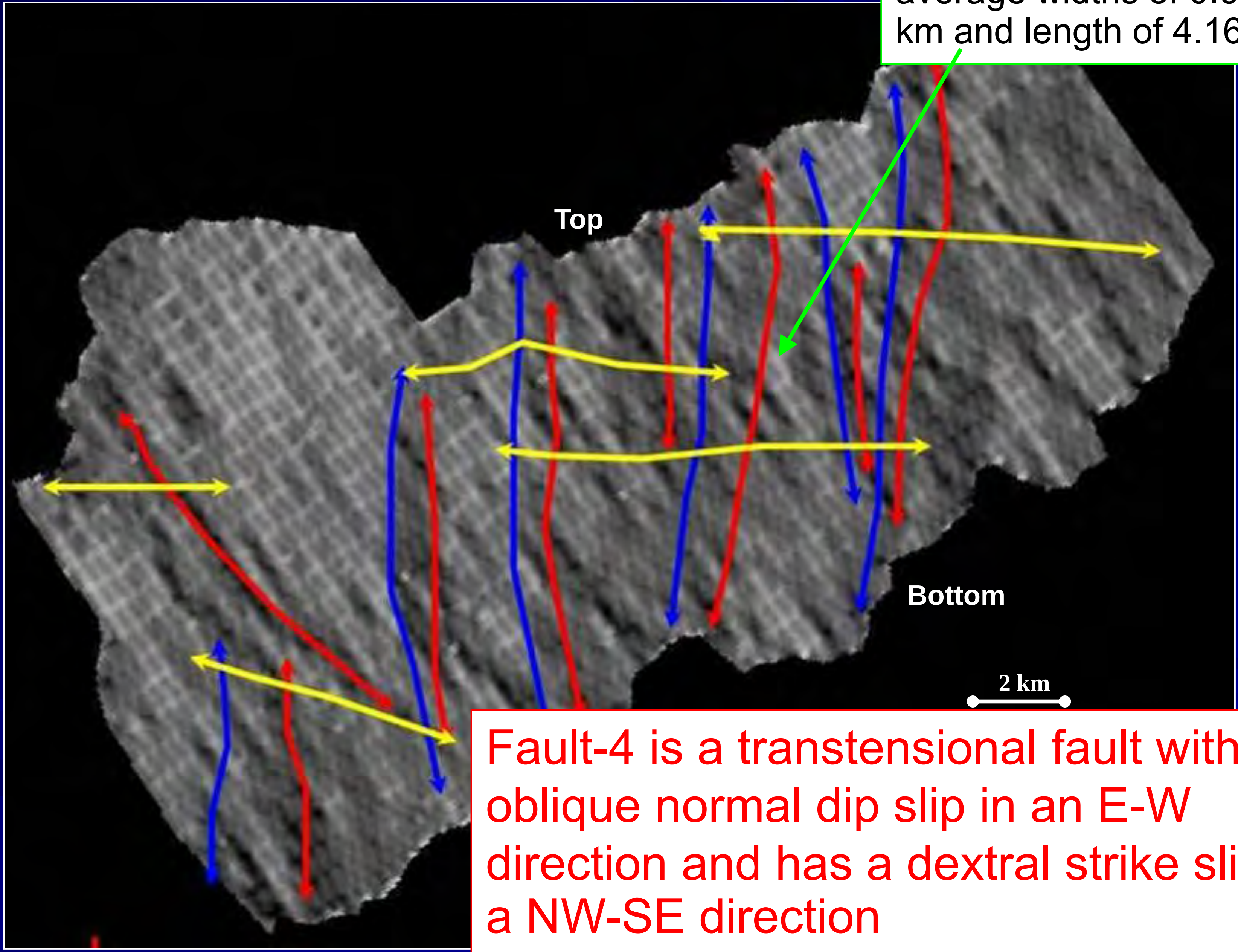
-A surface fault trace width of 5.96 km

-A fault plane height of ~5.6 km



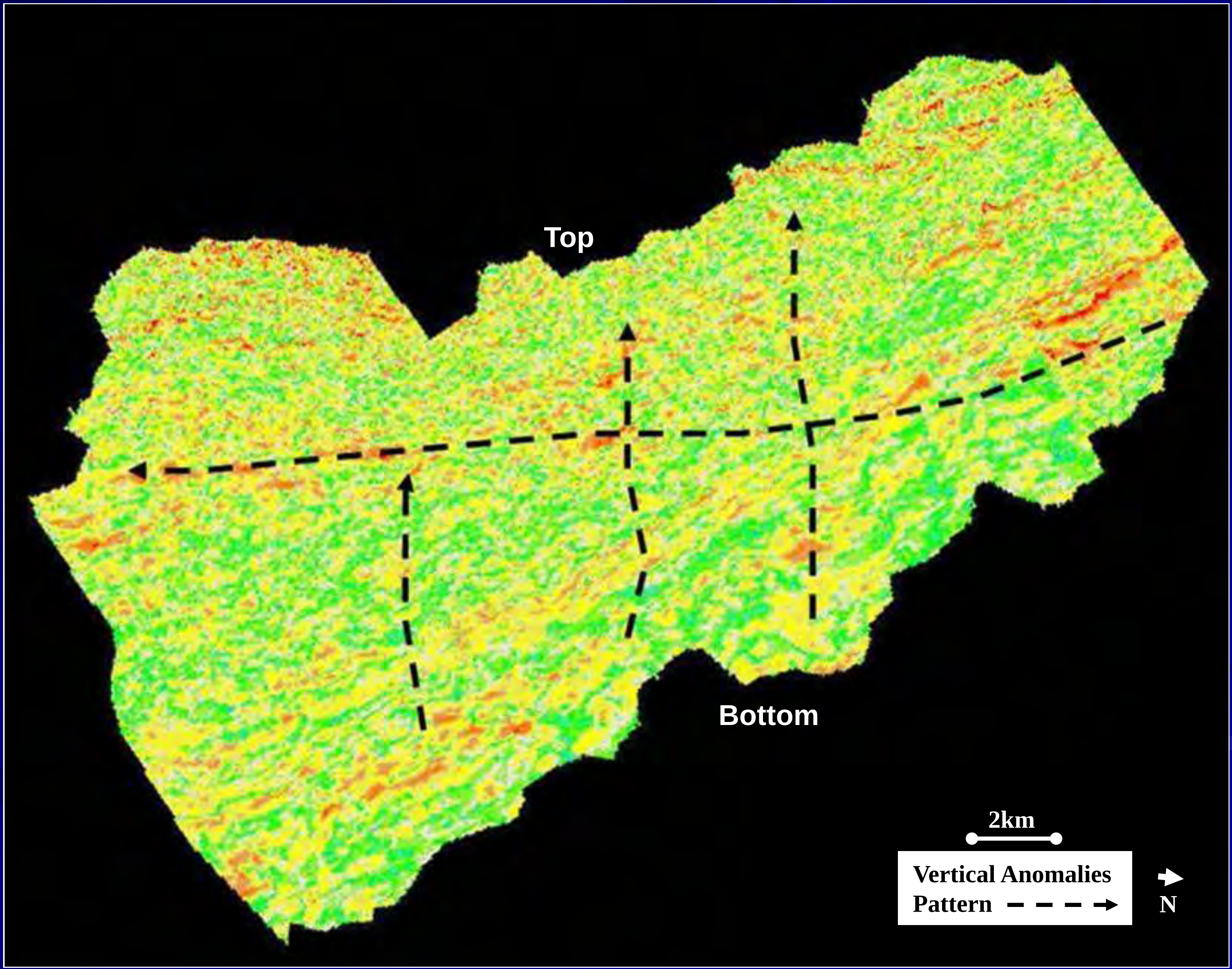
Azimuth Display of Fault-4

Ridges and grooves, average widths of 0.64 km and length of 4.16 km

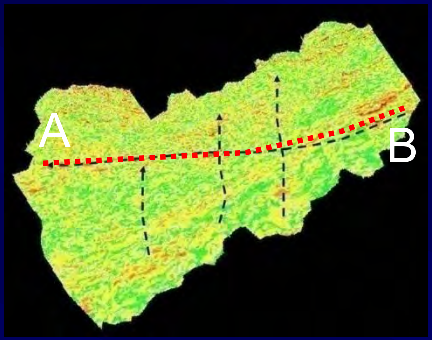


Fault-4 is a transtensional fault with an oblique normal dip slip in an E-W direction and has a dextral strike slip in a NW-SE direction

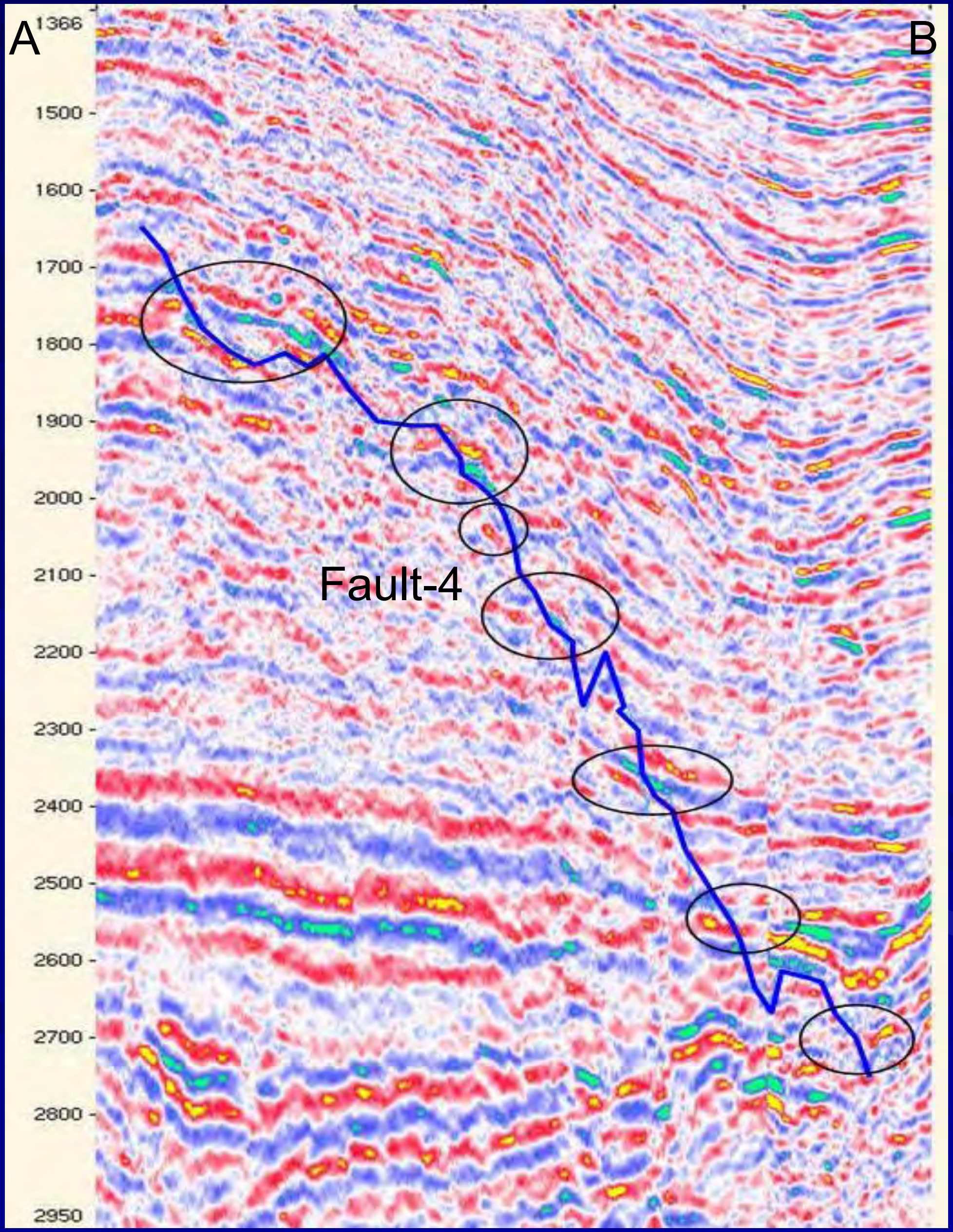
Reflection Strength Display of Fault-4



Random Seismic Line Crossing Fault-4



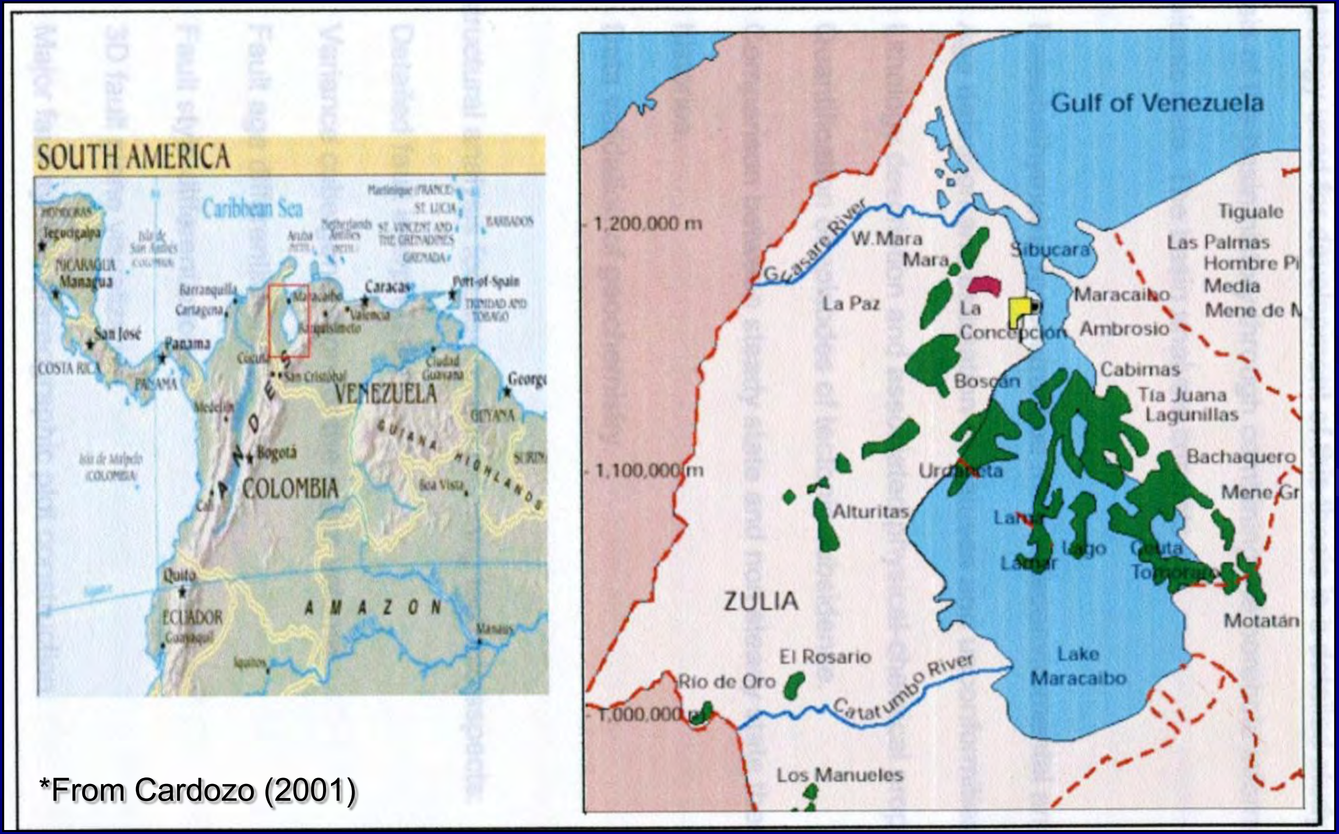
Seismic anomalies along Fault-4 are indicated by the black circles



TRANSPRESSIONAL FAULT EXAMPLES: MARACAIBO BASIN

Transpressional Fault Example: Maracaibo Basin

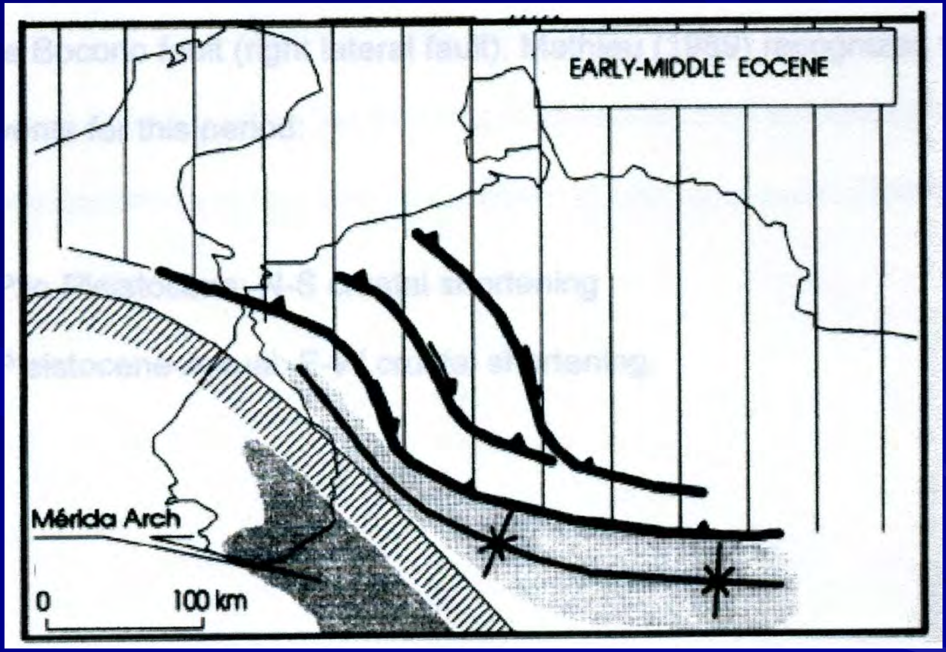
- Maracaibo Basin, Venezuela
  - The study area is located in La Conception Field in the northwestern part of the Maracaibo Basin.
  - 3D seismic data occupies 248 square km of area coverage.



*From Cardozo (2001)

Transpressional Fault Example: Maracaibo Basin

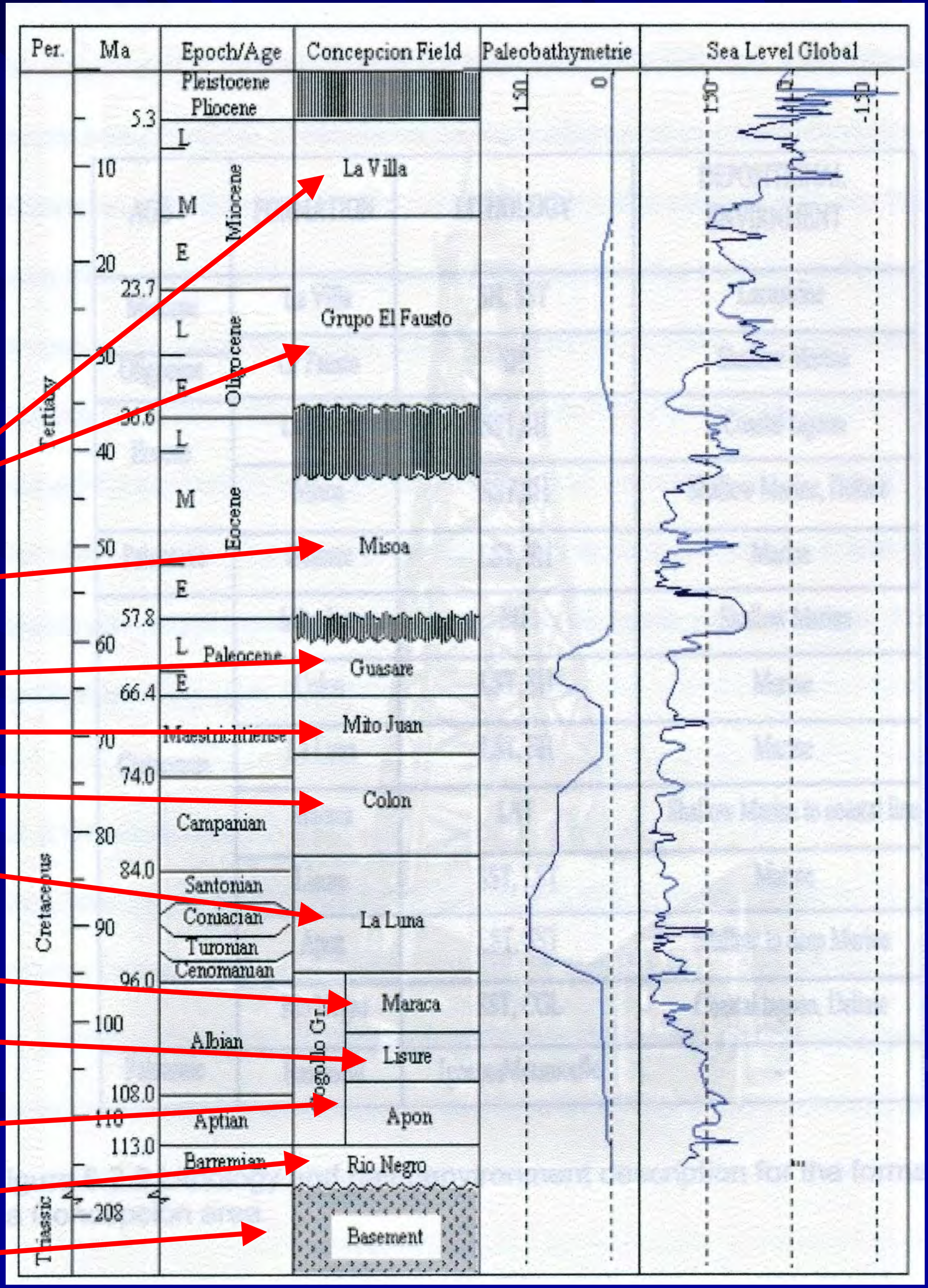
- Tectonic Setting
  - Jurassic: extensional tectonics in a N-S dipping direction (Cardozo, 2001).
  - Cretaceous: Inversion and the beginning of the collision between the Caribbean Plate and the Bahamas Platform (Ostos, 1990).
  - Paleocene: the development of foredeep of Maracaibo Basin (Lugo and Mann, 1995).
  - Eocene: Transpressive tectonic activity (Cardozo, 2001).
  - Pleistocene – Bocono fault, right-lateral strike-slip fault (Cardozo, 2001).



*From Lugo and Mann (1995)

Transpressional Fault Example: Maracaibo Basin

- Regional Stratigraphy
  - Red clays and green sandstones
  - Red-brown clays and shales
  - Conglomerate sandstones, limestone
  - Limestone layers, sandstones
  - Gray to black sandstones, shale
  - Gray to black shale
  - Limestones and calcareous shales
  - Sandstones, coal, limestones
  - Sandstones and sandy limestones
  - Conglomerates, dolomites
  - Coarse sandstones, shales
  - Phyllites, Jurassic red rocks



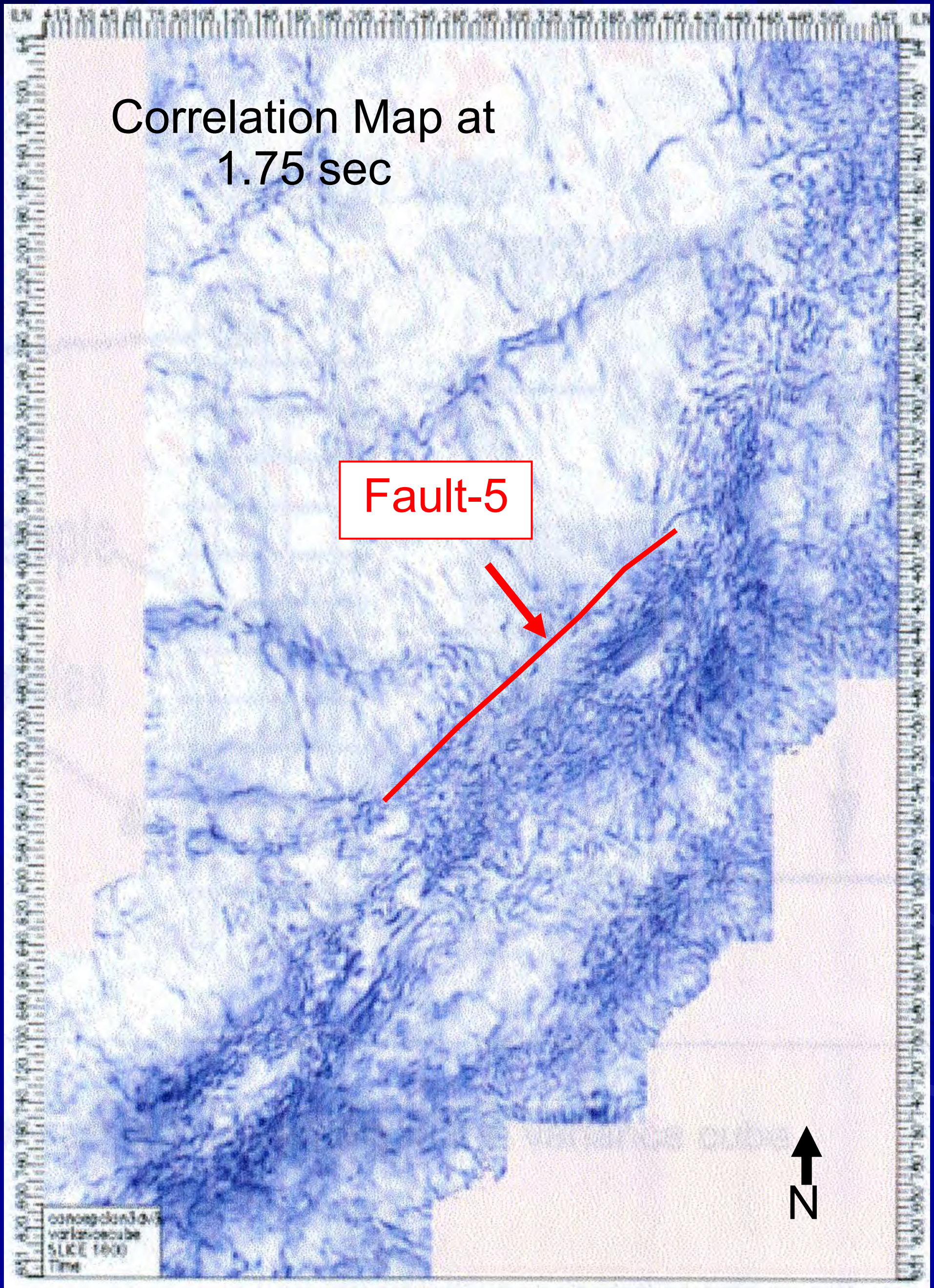
*From Tipword et al. (1996); Haq et al. 1988)

Transpressional Fault Example: Maracaibo Basin

- Petroleum System
  - Oil was generated in the Late Eocene (Cardozo, 2001)
  - Faults and fractures formed during the Cretaceous to Paleocene and reactivated during the Eocene yield the migration pathways and structural traps (ibid).
  - The oil migration is related to the Post-Cretaceous faults and the older (ibid).

Transpressional Fault Example: Maracaibo Basin

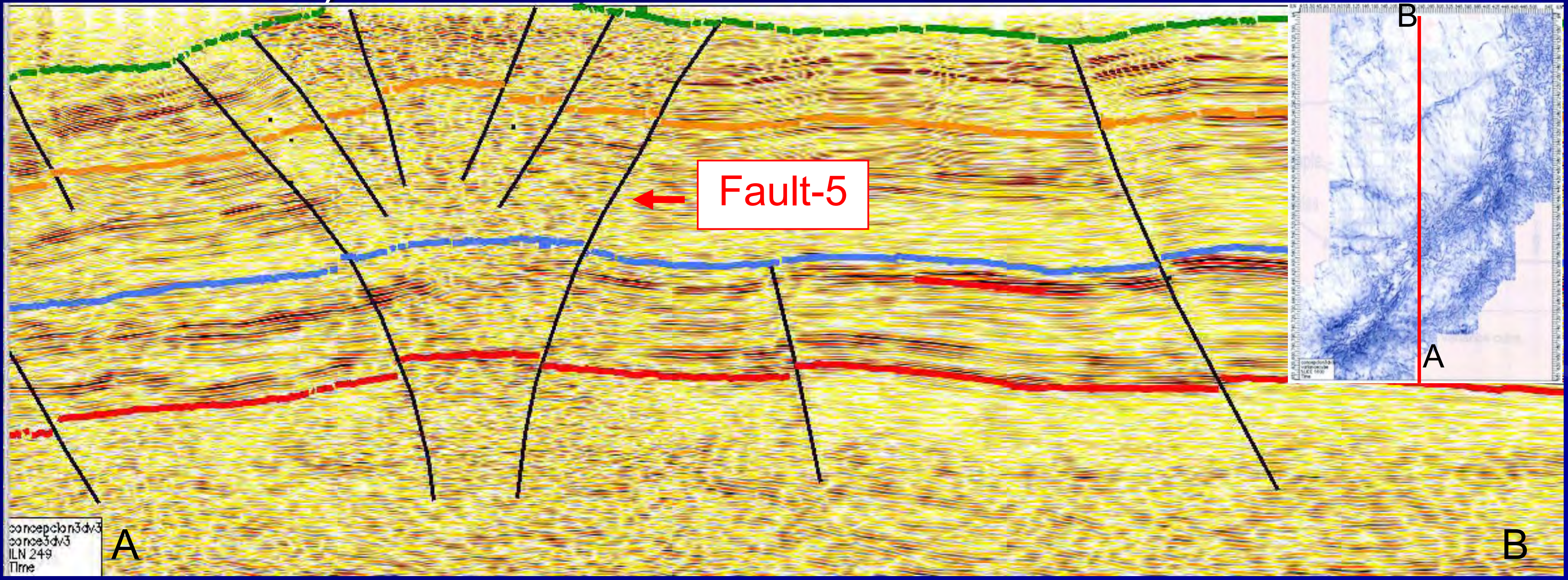
- Fault Interpretation on the 3D seismic data
  - Northeast-Southwest trend of the transpressional fault systems and dipping toward the center of the flower structure.



*From Cardozo (2001)

Transpressional Fault Example: Maracaibo Basin

- Fault Interpretation on the 3D seismic data
  - Fault-5 shows the reverse dip slip motion toward the flower structure.
  - Interpreting the faults as horizon to extract the time structure maps with close distance inline and crossline spacing (~125 meters)



*From Cardozo (2001)

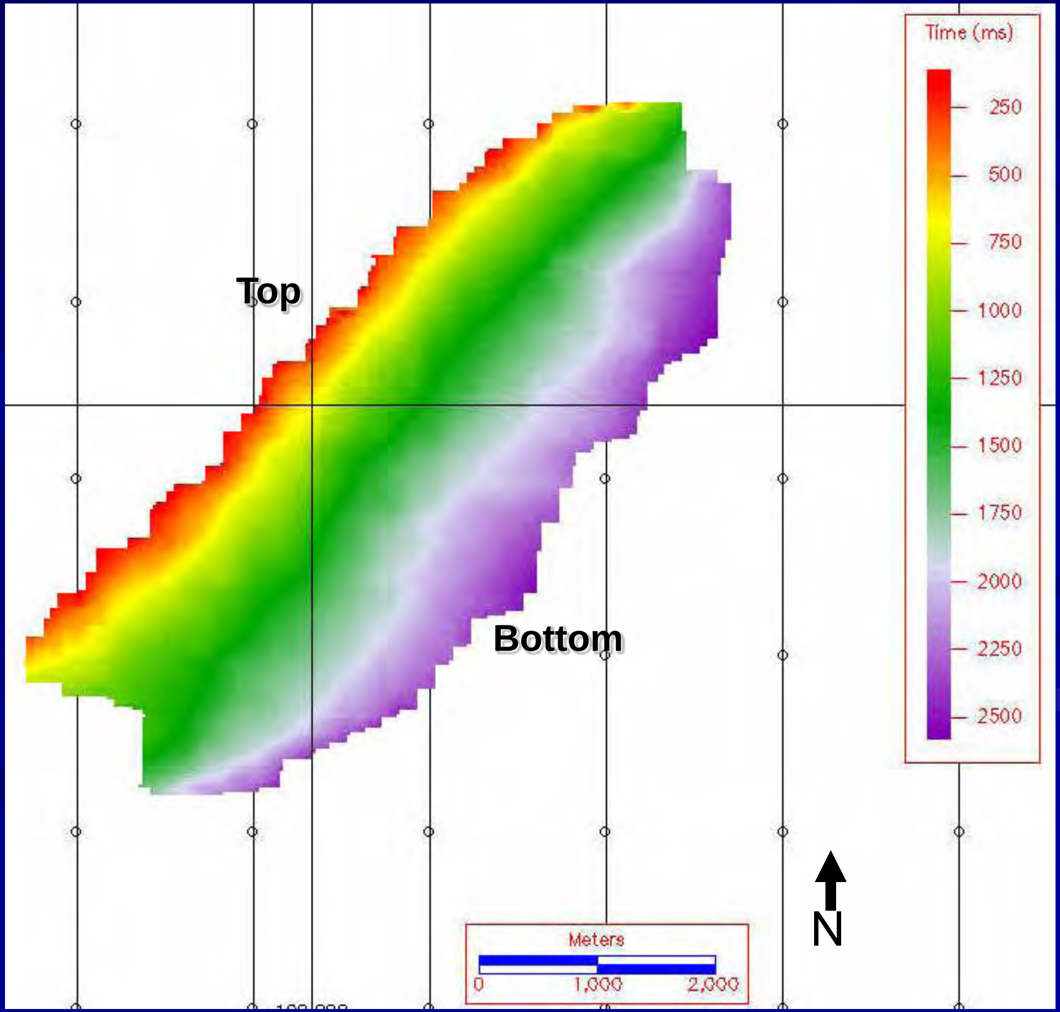
Transpressional Fault Example: Maracaibo Basin

- The time structure map of Fault-5

-A fault trace length of 7.25 km

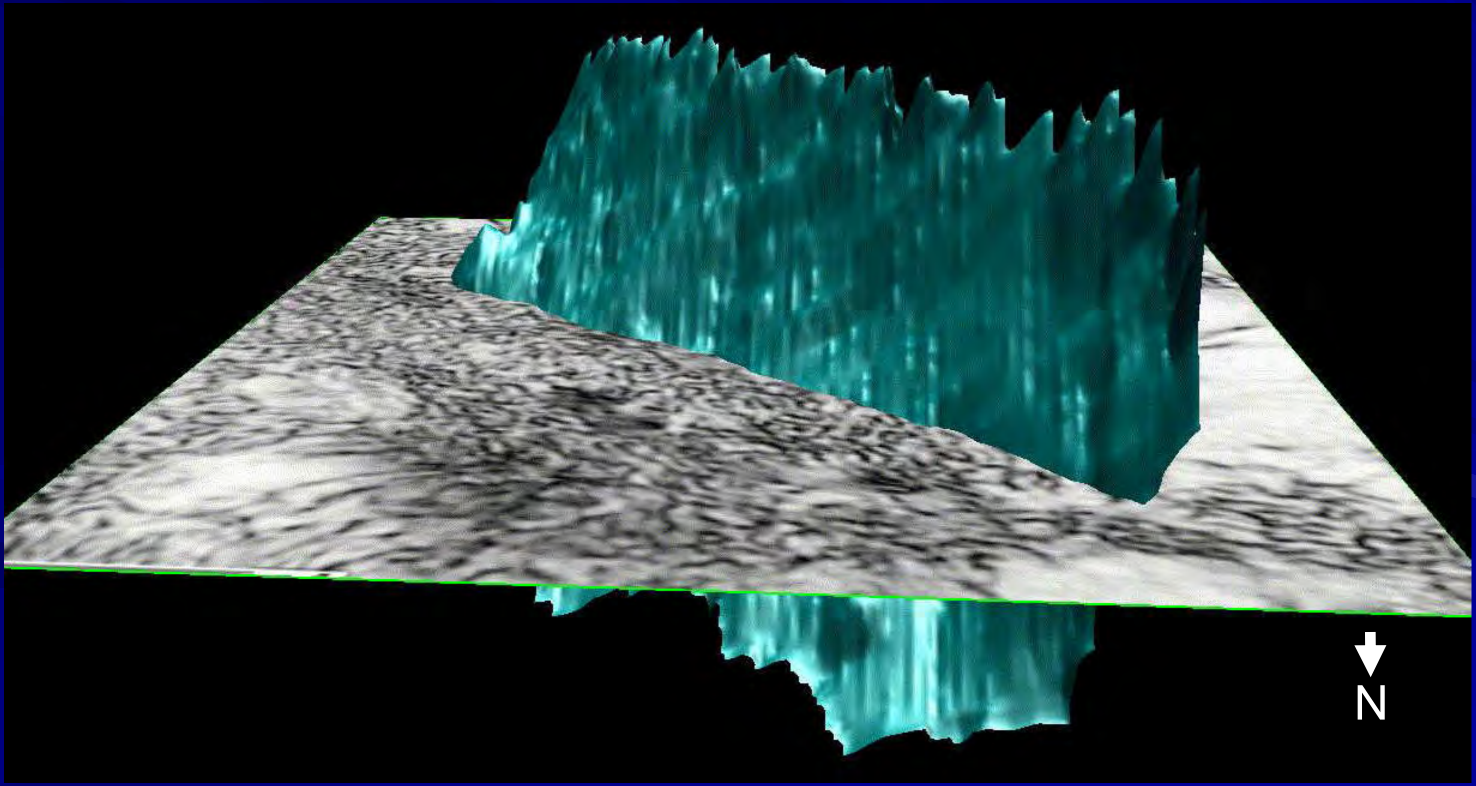
-A surface fault trace width of 2.83 km

-A fault plane height of ~7.25 km

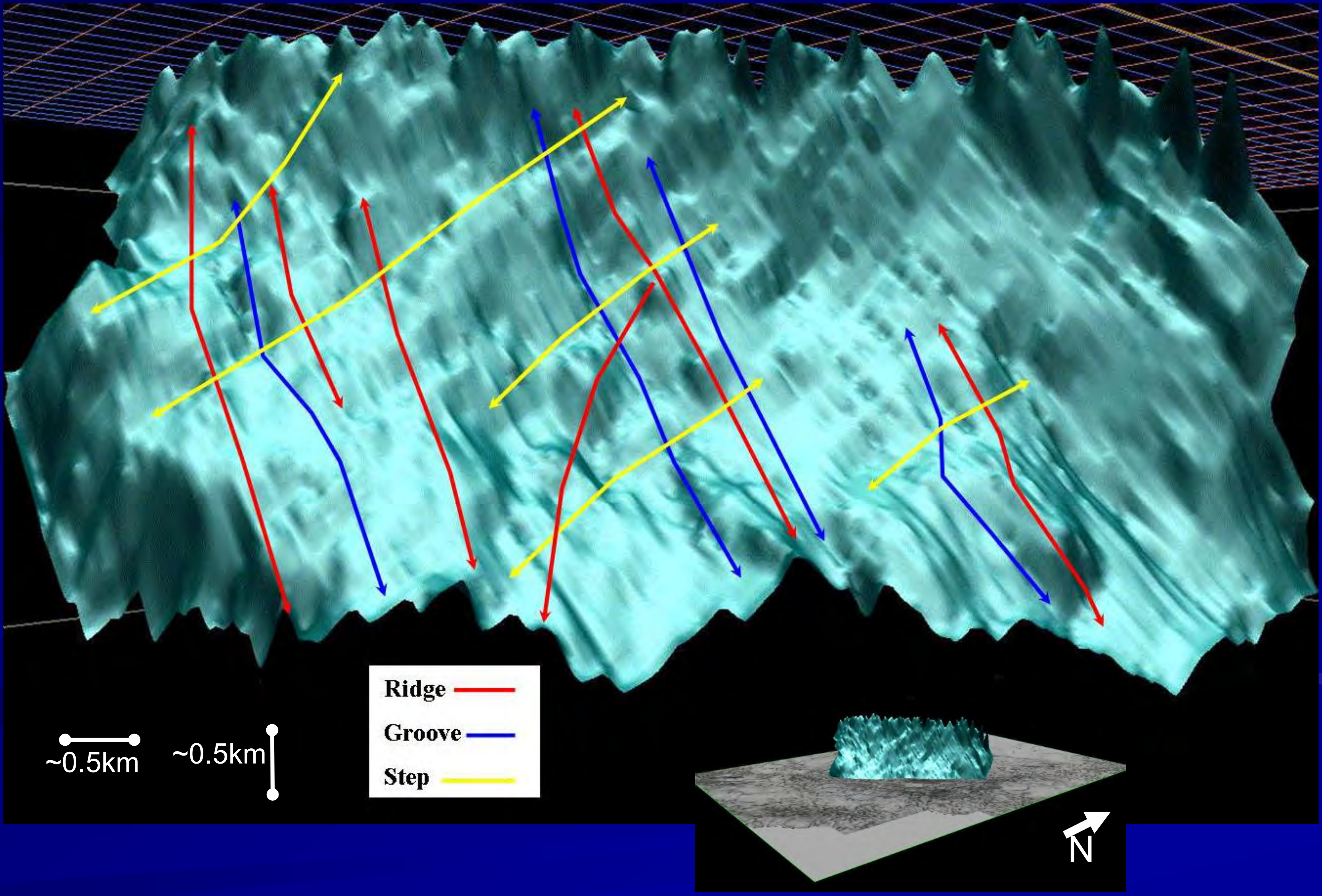


Transpressional Fault Example: Maracaibo Basin

- 3D visualization of the fault plane cutting a coherency surface (1.75 sec) display of the fault trace.



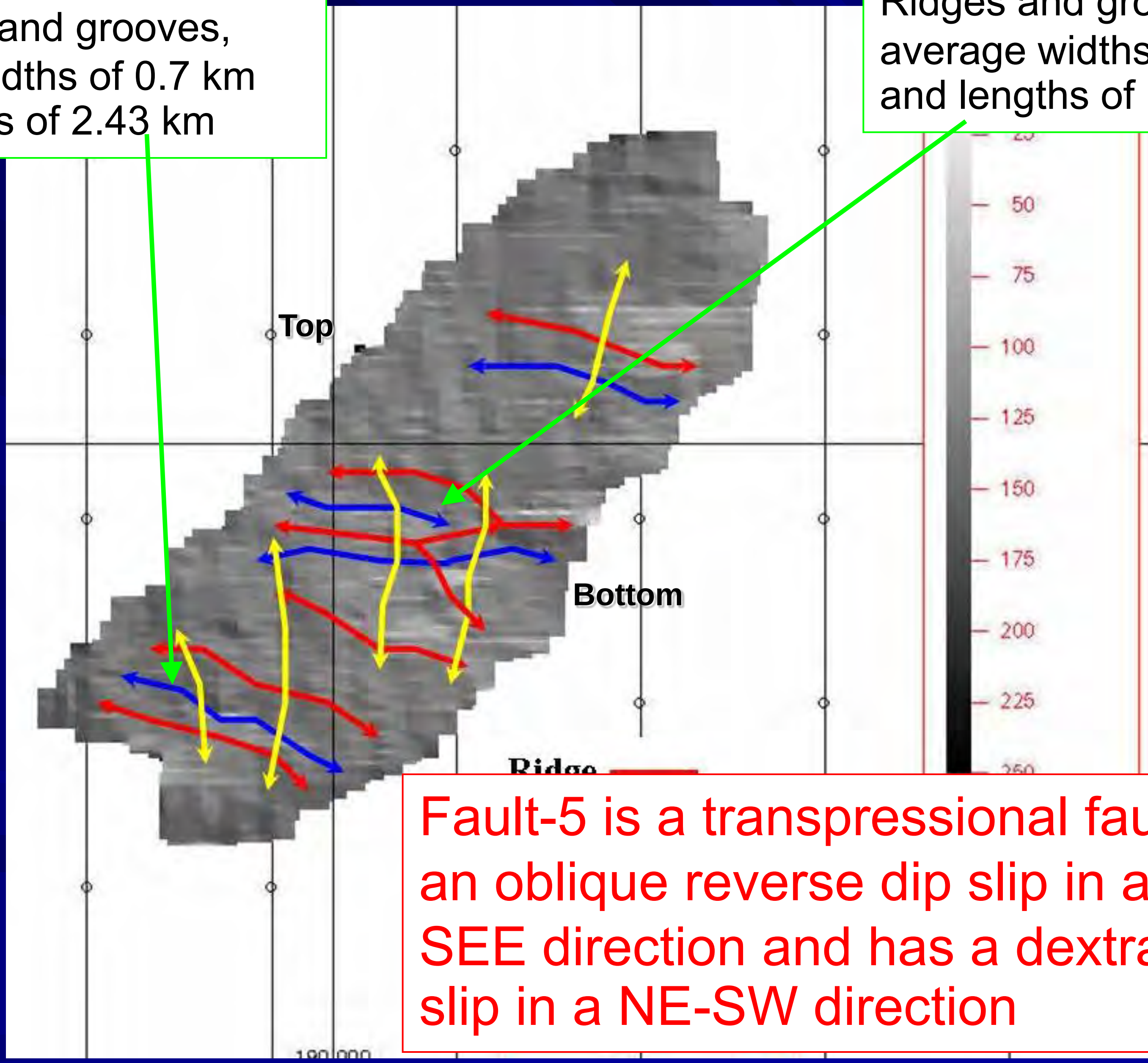
3D Fault Plane Surface of Fault-5



Azimuth Display of Fault-5

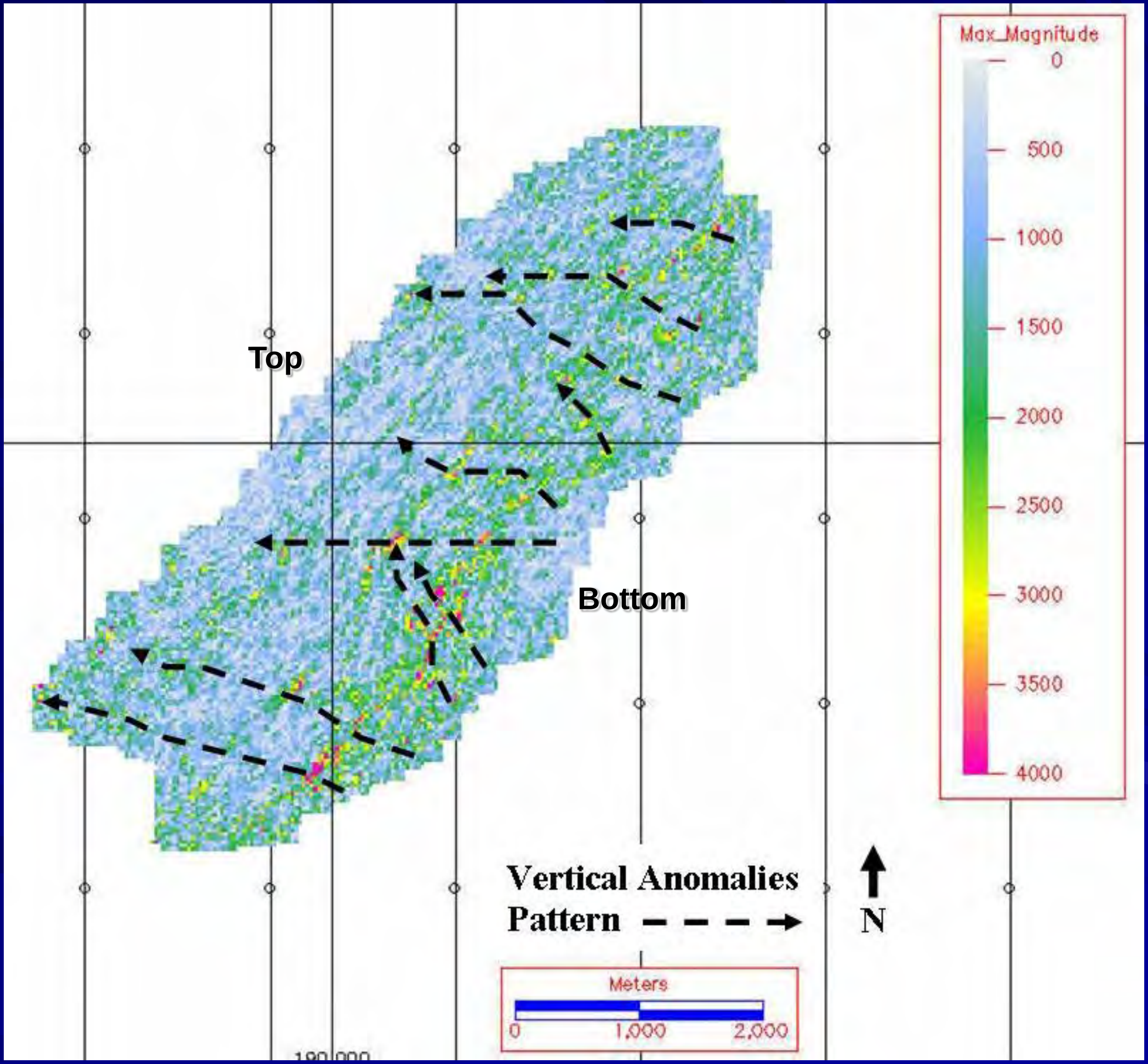
Big ridges and grooves, average widths of 0.7 km and lengths of 2.43 km

Ridges and grooves, average widths of 0.45 km and lengths of 1.48 km

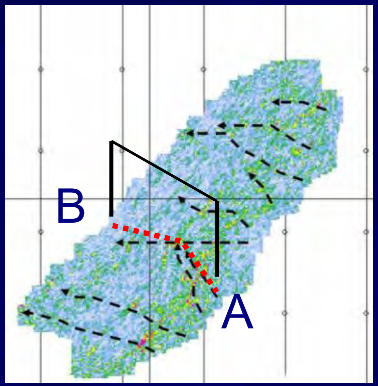


Fault-5 is a transpressional fault with an oblique reverse dip slip in an NWW-SEE direction and has a dextral strike slip in a NE-SW direction

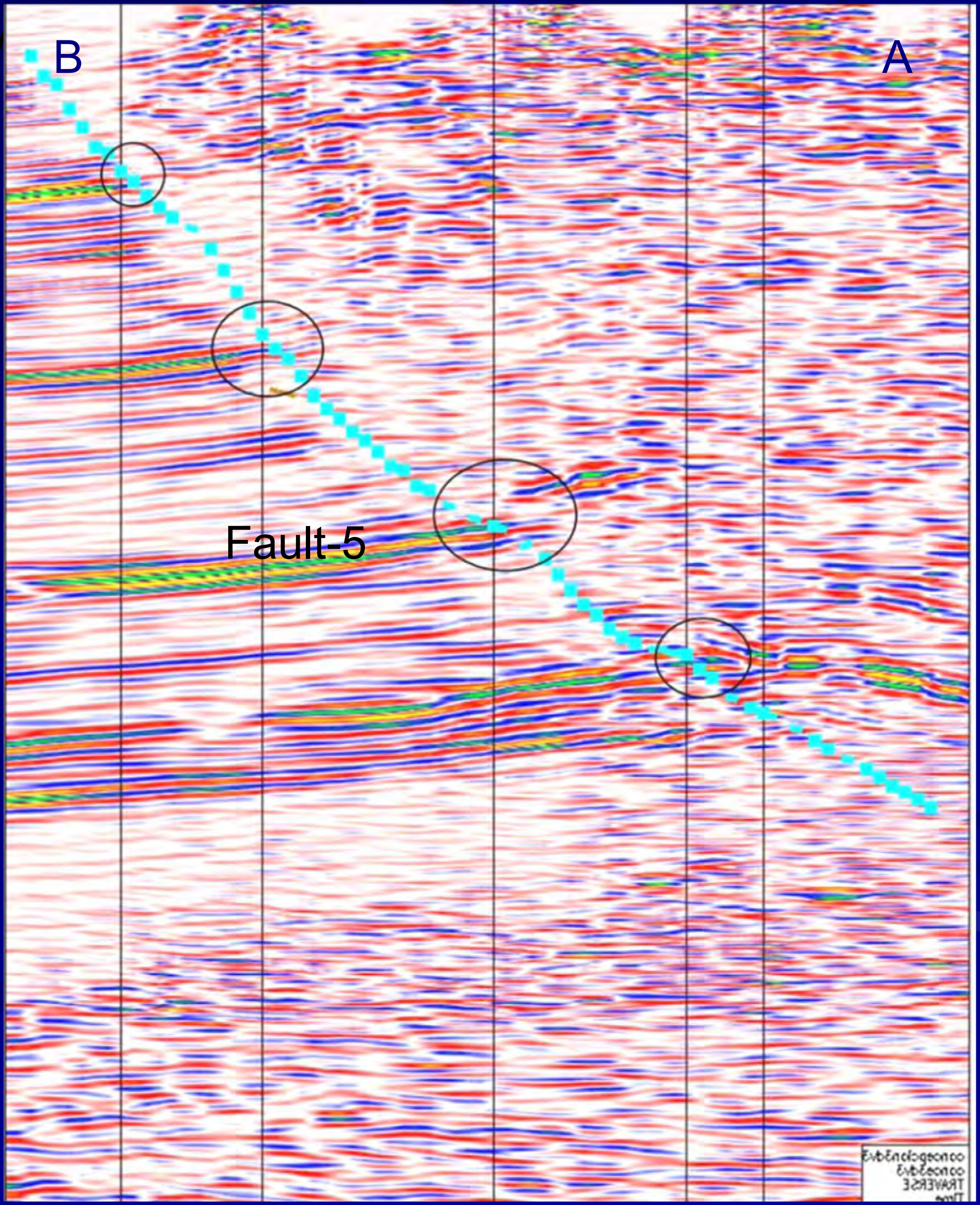
Reflection Strength Display of Fault-5



Random Seismic Line Crossing Fault-4



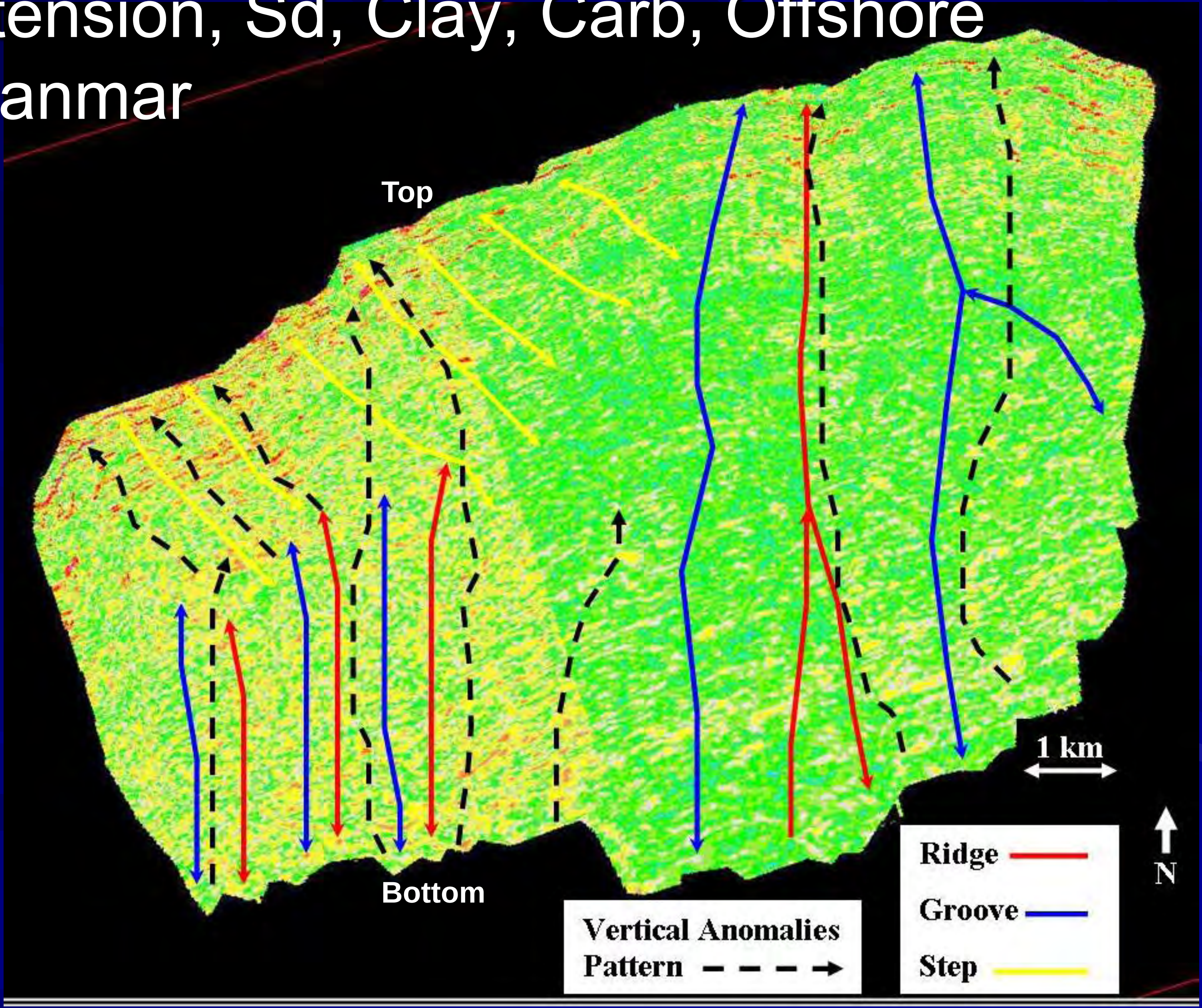
Seismic anomalies along Fault-5 are indicated by the black circles



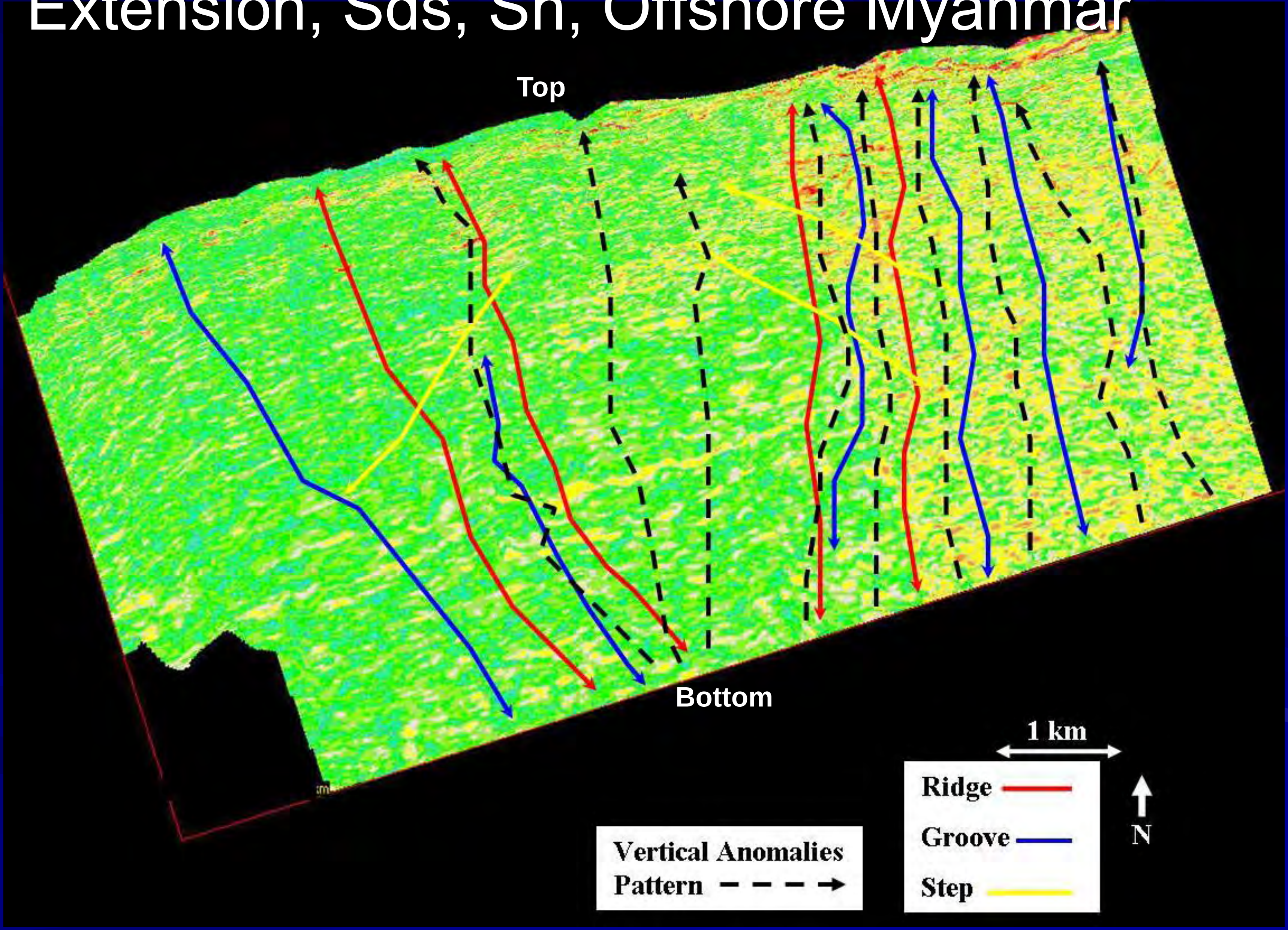
PETROLEUM SYSTEM IMPLICATIONS

- Composite Analysis Map
  - The schematic sketches of geomorphologic features on the azimuth displays are overlaid together with the inferred seismic anomaly patterns on the reflection strength displays.
  - This method reveals the relationships between the seismic fault geomorphology and possible fluid migration pathways.

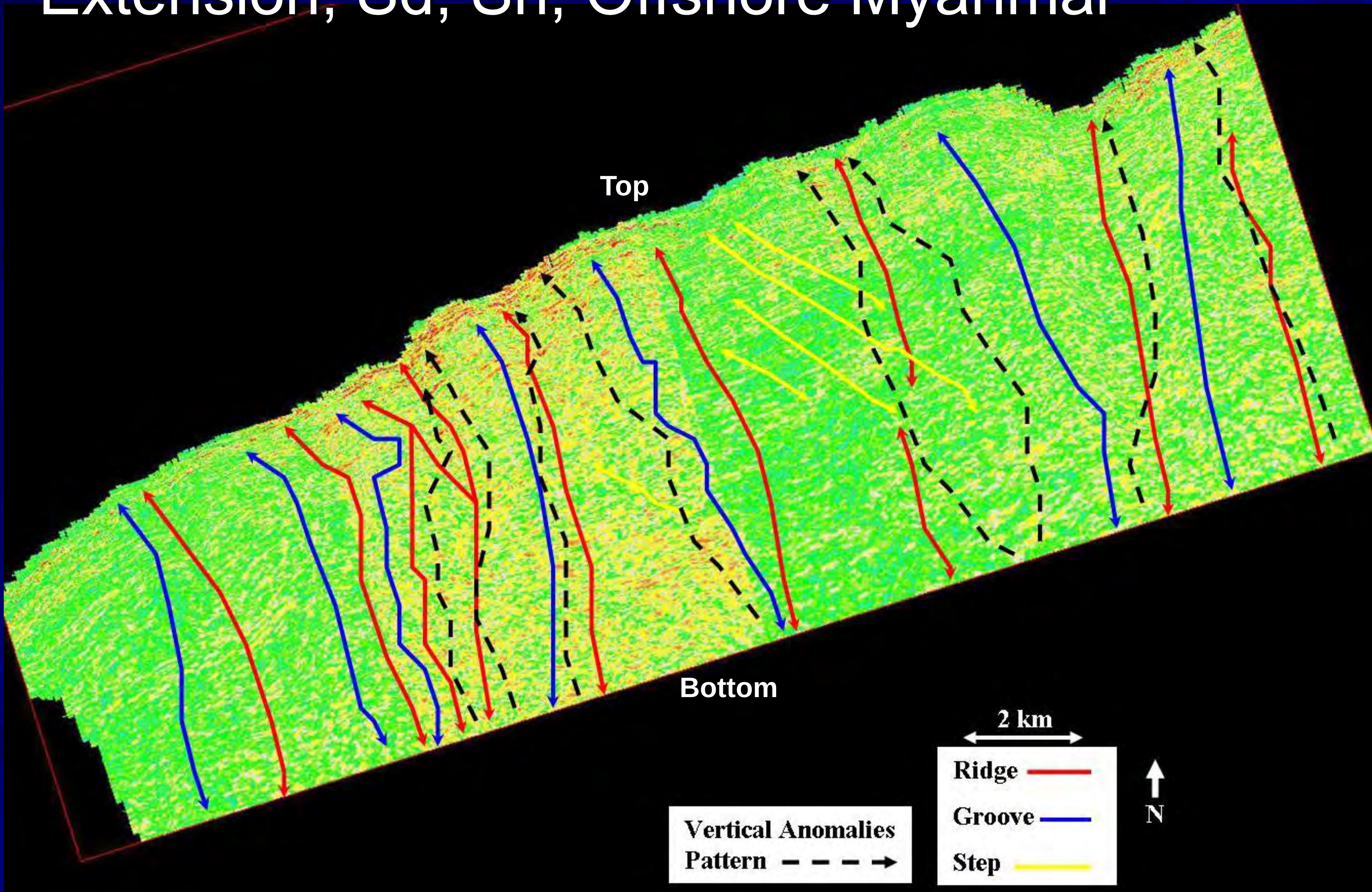
Composite Analysis Map of Fault-1, Extension, Sd, Clay, Carb, Offshore Myanmar



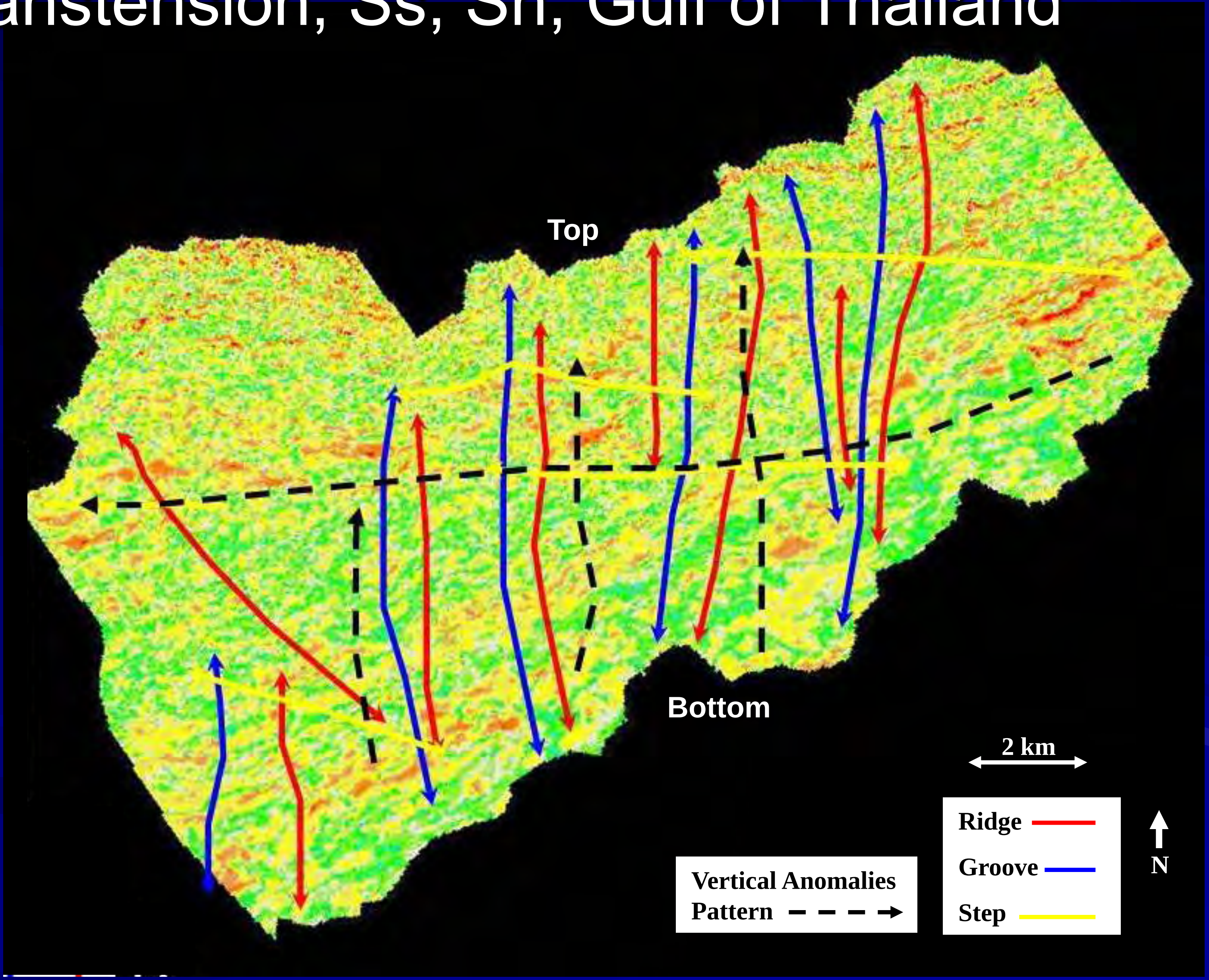
Composite Analysis Map of Fault-2, Extension, Sds, Sh, Offshore Myanmar



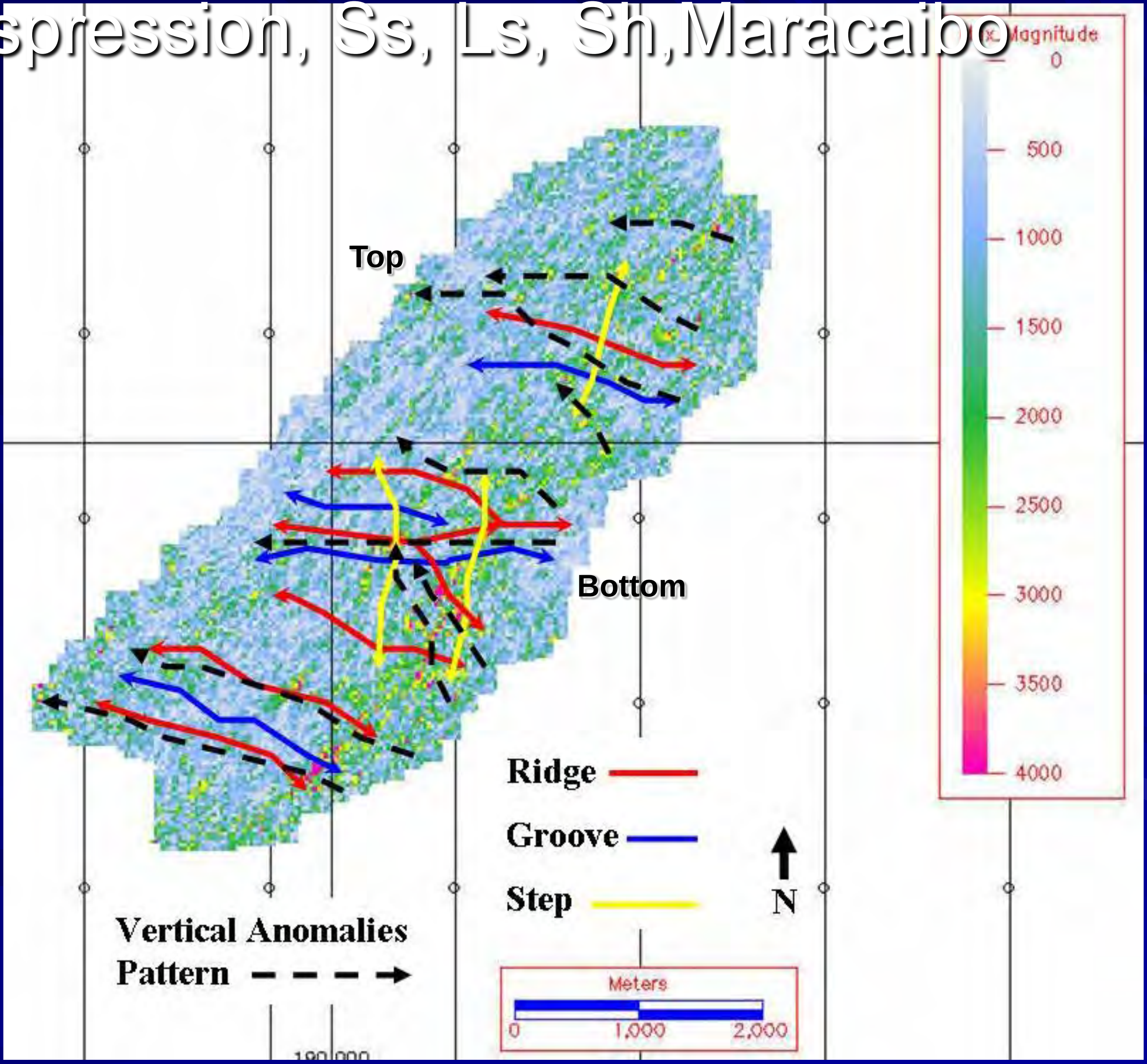
Composite Analysis Map of Fault-3, Extension, Sd, Sh, Offshore Myanmar



Composite Analysis Map of Fault-4, Transtension, Ss, Sh, Gulf of Thailand



Composite Analysis Map of Fault-5, Transpression, Ss, Ls, Sh,Maracaibo



- Implication Synthesis
  - The locations of the seismic anomalies along the fault planes are implied as accumulations of gaseous hydrocarbons.
  - The trend of geomorphologic features on the fault planes line up well with the inferred seismic anomaly patterns, most commonly with fault plane ridges.
  - We can imply that the direction of the hydrocarbon migration pathway may be influenced if not controlled by the direction of ridges and grooves and steps on the fault plane surface.

CONCLUSIONS

- Ridges, grooves, and steps on fault planes can be imaged on 3D seismic in a variety of tectonic settings and rock types.

- The geomorphic fault elements appear remarkably similar to those observed at different scales of brittle deformation (to outcrop to slickensides).

- Inferred directions of slip motion from the fault-plane geomorphic elements are consistent with regional geological interpretations of stress.

- Seismic anomalies along the fault plane suggest gas-fluid migration pathways and if present may lessen risk of reservoir charge.

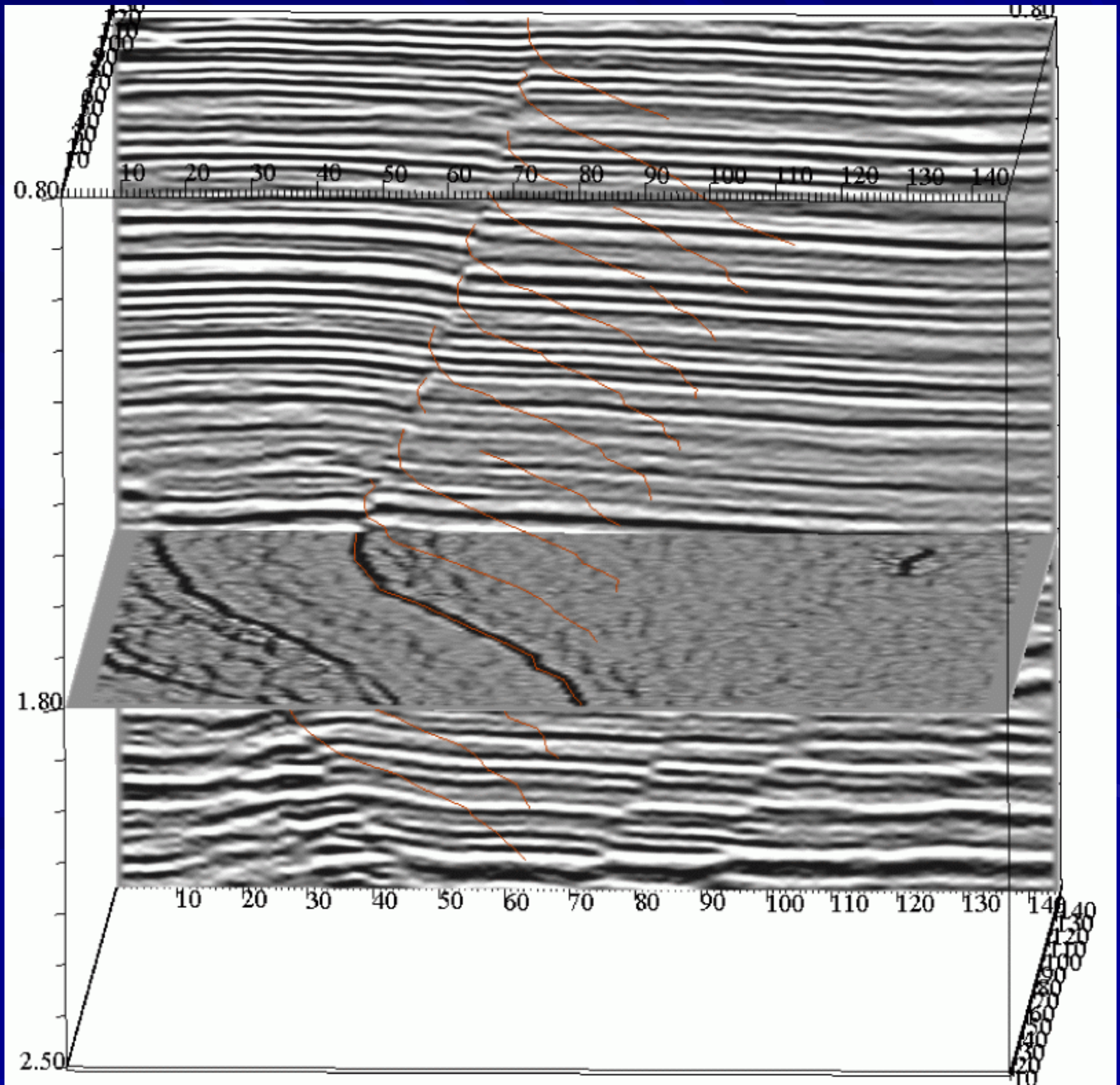
Questions to be answered

How are observed geomorphic fault-plane elements, e.g., the spacing and magnitude of the ridges, grooves, and steps

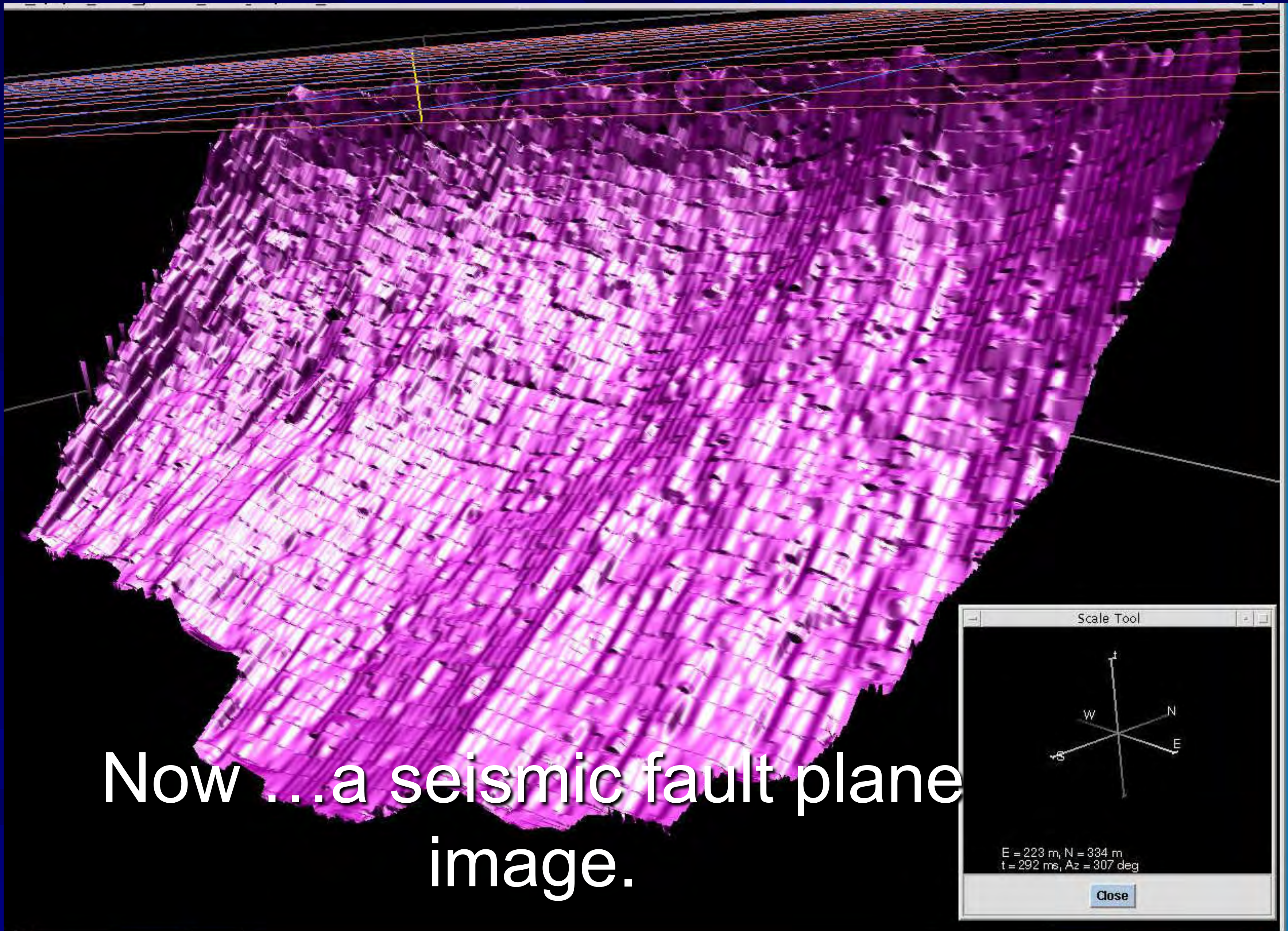
- Related to lithology?
- Related to permeability?
- Related to displacement?
- Related to fault mechanical stratigraphy and stress history?
- Related to reservoir charge risk?

Let us summarize…

- Previously, a seismically interpreted fault:

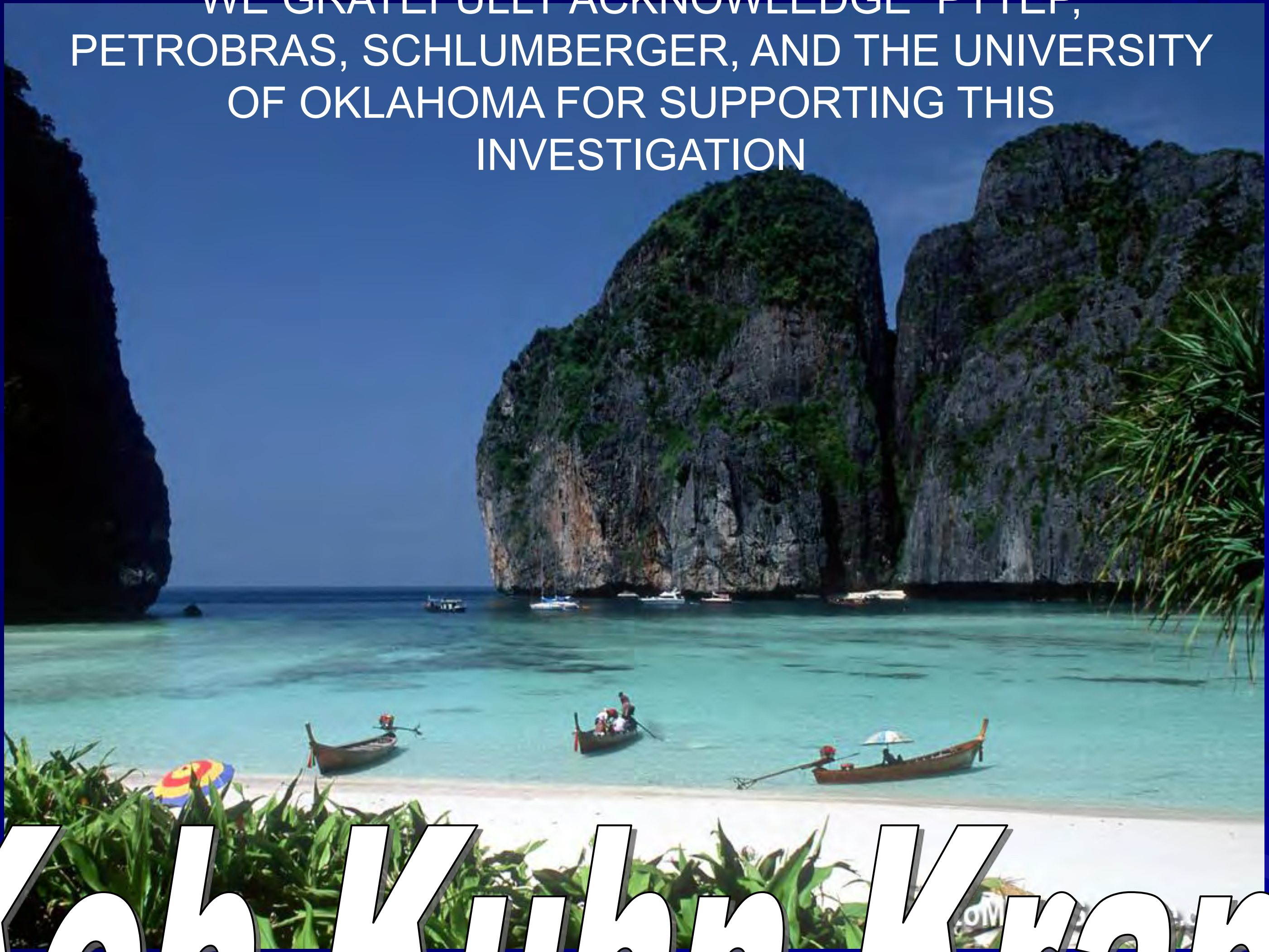


- A geologically observed fault plane in outcrop:



Now …a seismic fault plane image.

WE GRATEFULLY ACKNOWLEDGE PTTEP, PETROBRAS, SCHLUMBERGER, AND THE UNIVERSITY OF OKLAHOMA FOR SUPPORTING THIS INVESTIGATION



Kob Kuhn Krap!