A Re-Look at Borehole Images: What Are We Missing?*

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Abstract

Borehole Image (BHI) logs have been in the geoscientist's tool kit for over 30 years. But despite being seen as a mostly mature technology, they are generally underutilized by geologists both for basic geological interpretations and reservoir characterization. This is surprising because BHI logs provide nearly the "ground truth" resolution of cores, and in certain aspects provide superior data. The most common applications focus on fracture characterization, stress field analysis, and structural interpretation. Much more information, however, can be gathered from a BHI data set. We review examples that highlight novel applications in structural analysis, sedimentologic and stratigraphic studies, and reservoir evaluation. A structural analysis of Ventura Avenue Field illustrates how BHI logs delineate a specific deformational style leading to a new interpretation of fault geometry. Image logs also reveal the heterogeneous character of a major fault and associated damage zone along a four-mile transect. This heterogeneity impacts the interpretation of fault seal and reservoir pressure compartments. BHI logs are most underutilized in sedimentologic and stratigraphic studies. The best interpretations are developed in conjunction with core calibration, but even in the absence of cores BHI logs enable the interpretation of sedimentary structures, diagenetic features, significant stratigraphic surfaces, and the stacking patterns of associated facies. These observations are critical for developing stratigraphic frameworks and depositional models. We illustrate with examples from both fine-grained sediments and coarser-grained clastic systems. Our final examples highlight reservoir characterization and productivity studies integrating core, image logs, and well test data. These integrated data sets can reveal the distribution of fluid saturation in the reservoir, mechanical stratigraphy related to fracturing, and fluid entry into the wells. BHI logs are not necessarily standalones in these applications but are a critical element in the interpretation. BHI logs are commonly acquired for many wells, but the available data are often underutilized. Re-examining the role of image logs in both academic and industry evaluations has significant potential for more robust understanding of subsurface geology and improved integrated interpretations.

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A re-look at borehole images: What are we missing?

Jon Schwalbach

Tom Hauge — *Hauge Geoscience*

John Harris — *Numeric Solutions LLC*

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Thesis:

- Borehole images provide significant subsurface data that the geologist is uniquely qualified to interpret, but generally the data are underutilized.
- Example applications cover a broad range of structural, stratigraphic and well productivity studies (something for everyone’s area of expertise!)
- Potential for many other innovative applications, both in academic and industry studies - just awaiting a geoscience perspective and posing the right questions.

Roadmap

- *Borehole Image Log Overview*

- *Fault Characterization* - structural study of Ventura Field, fault styles and heterogeneity

- *Sedimentology and Stratigraphy* – sed structures, stratigraphic stacking and facies variation

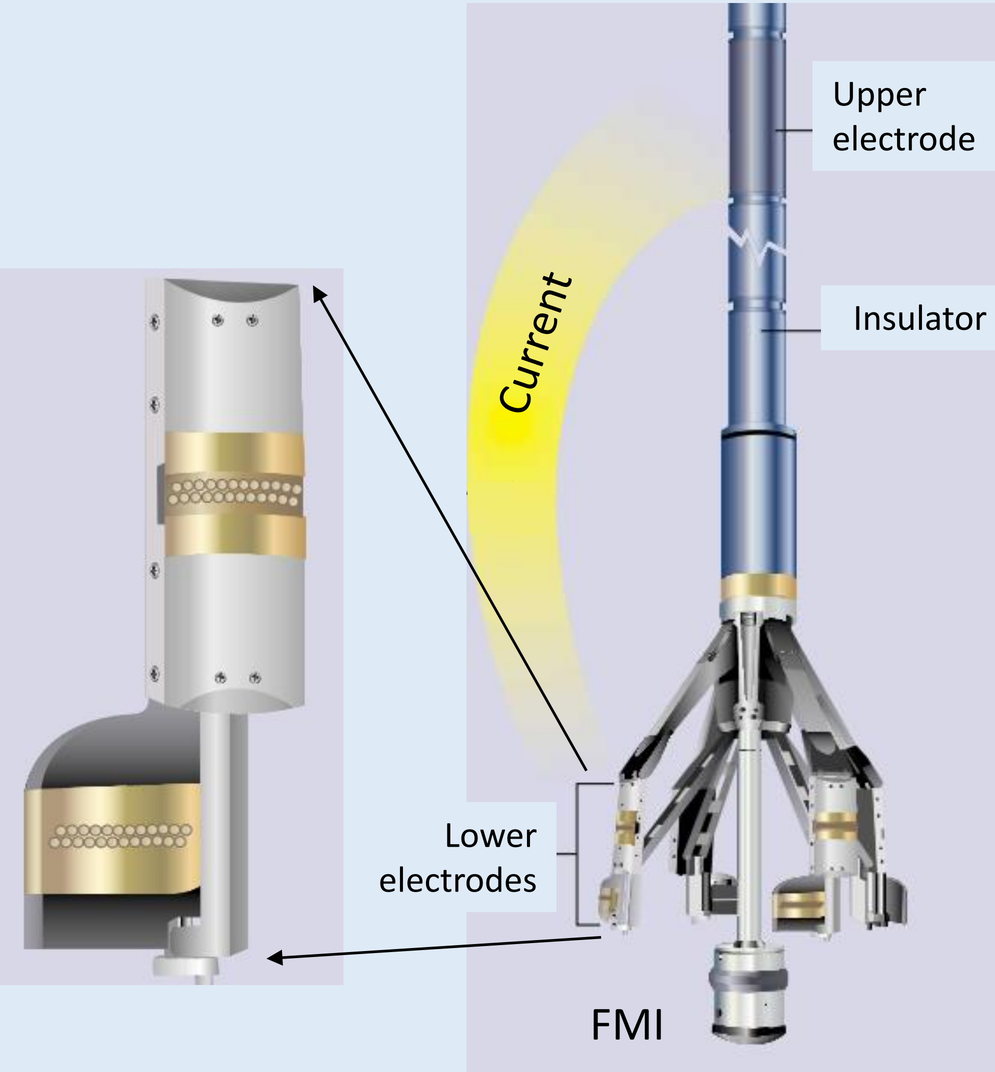
- *Well Productivity* – fluid entry into the well, permeability distribution, completion strategy

✓ We focus on electrical imagers, which tend to be the most common have some of the highest resolutions
✓ Acoustic and density measurements can be used to construct borehole images.
✓ Logging While Drilling (LWD) imagers have evolved rapidly.

Electrical Borehole Image Logging Tools

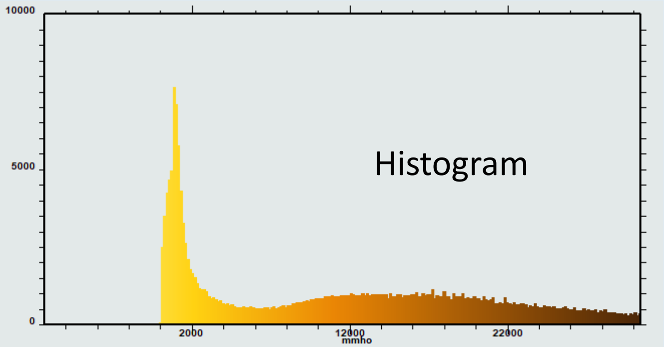
- Require pad contact with the borehole
- Closely spaced electrodes (buttons) provide 0.1 - 0.2” resolution

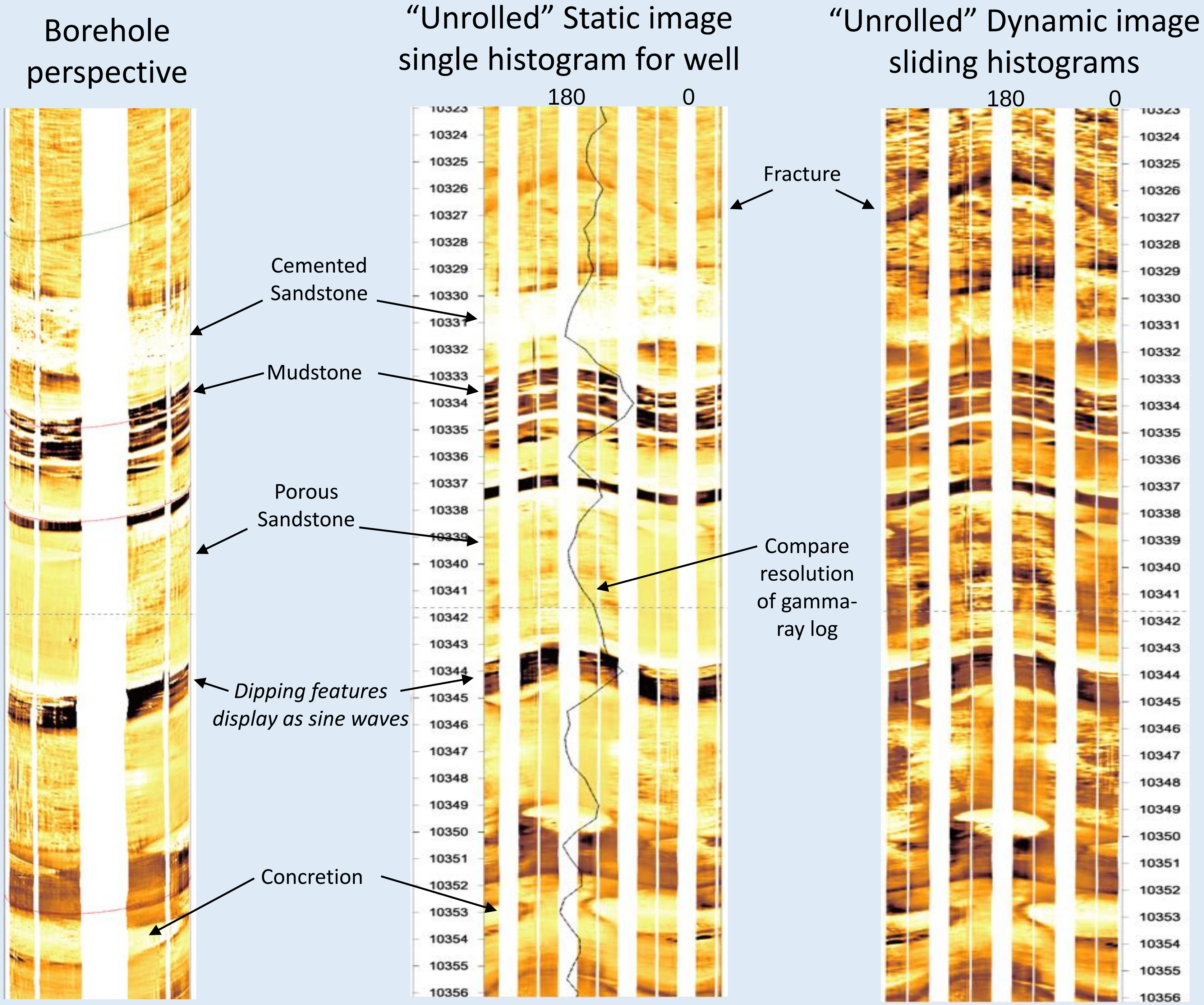
(images from Schlumberger (FMI), Weatherford (CMI) and Halliburton (XRMI) web pages)



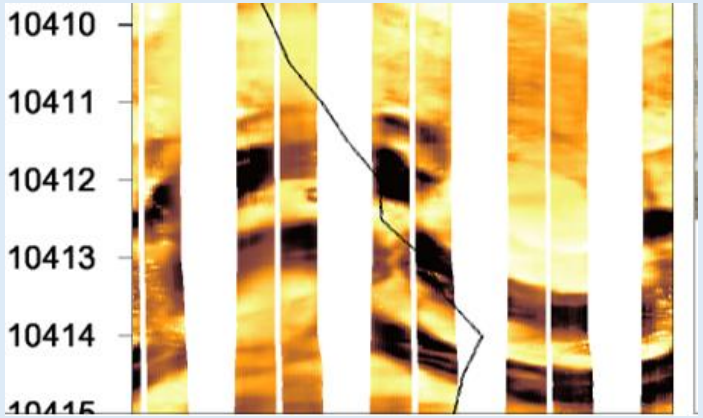
Electrical Borehole Image Log Data

- Array of high density conductivity data "mapped" to the borehole wall
- Software processes and displays using a variety of scaling and color options
- These examples illustrate a common color scheme and some standard processing displays
- Darker colors map higher conductivity (generally mudstone, ash beds)
- Lighter colors map higher resistivity (generally sandstone and lower porosity cemented zones)

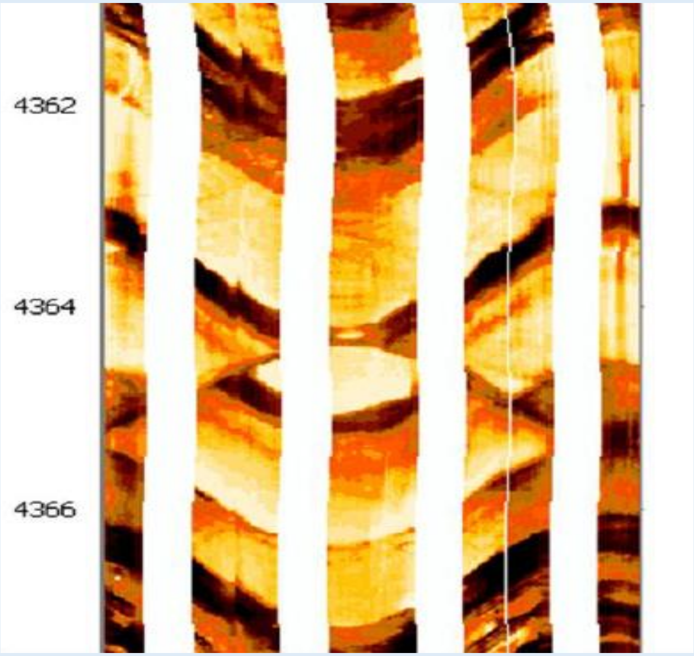




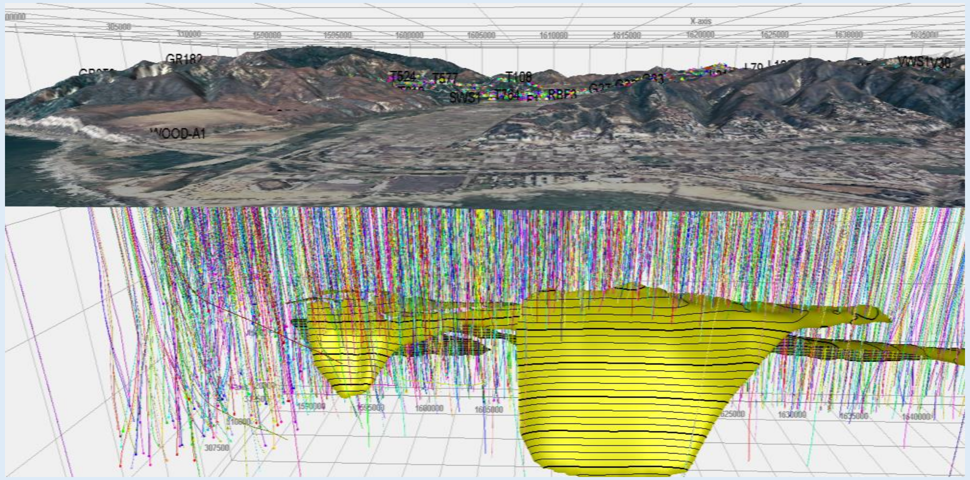
Fault Characterization

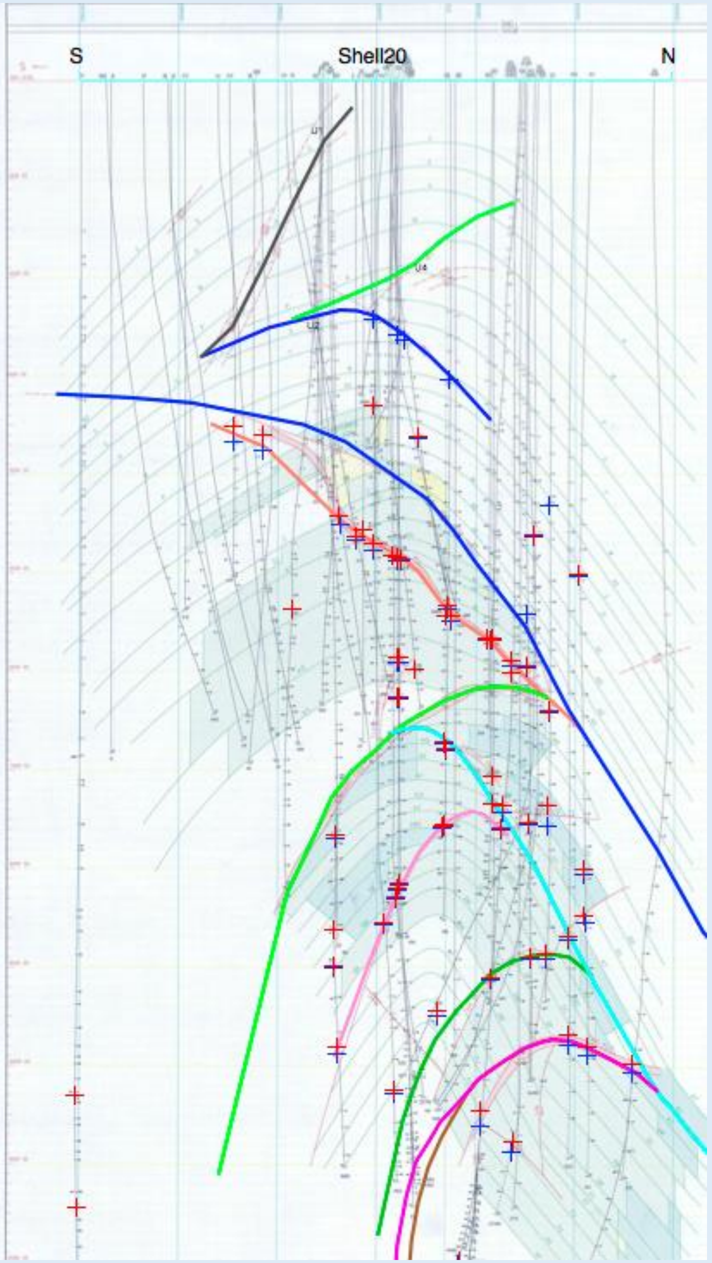


small faults

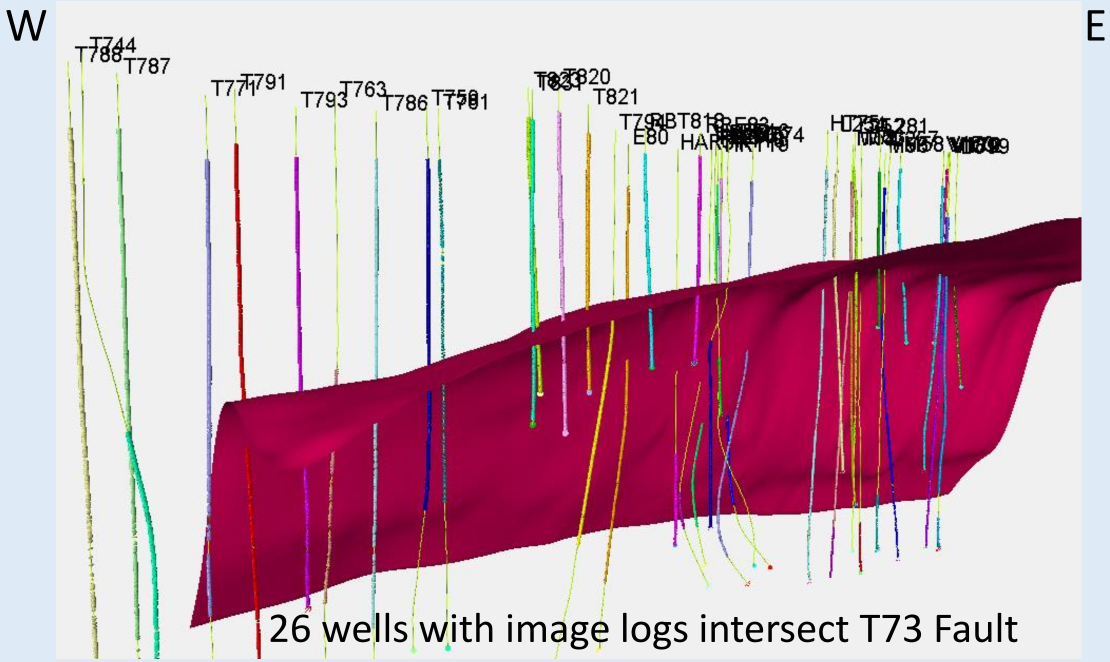


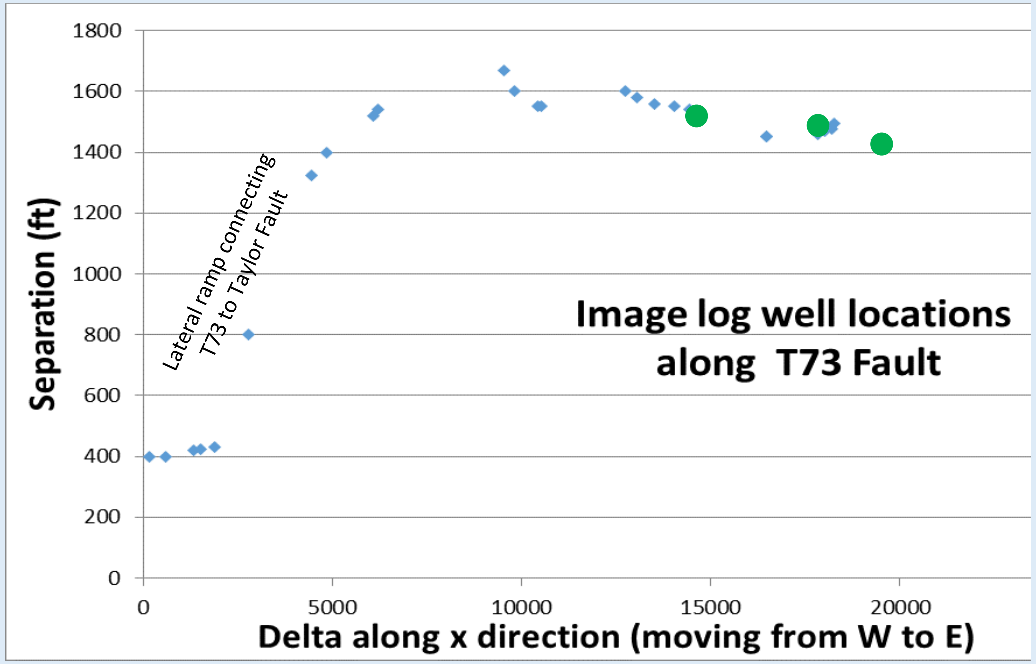
Ventura Field Fault Analysis: Large Thrust Faults



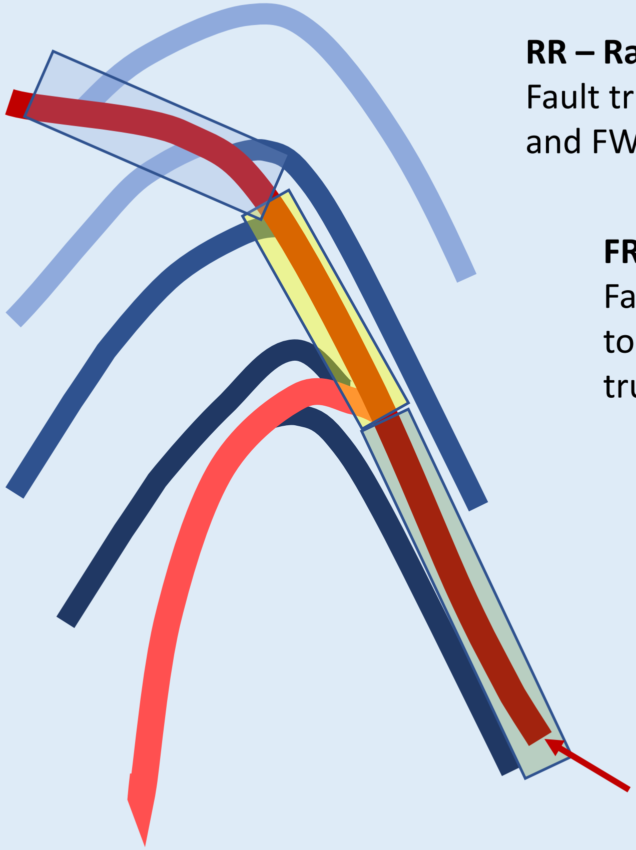


Ventura Field Fault Analysis





3 Structural Domains



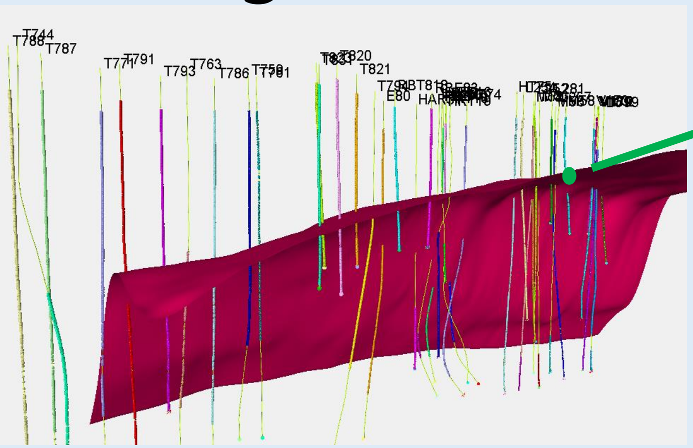
RR – Ramp on Ramp, Fault truncates HW and FW beds

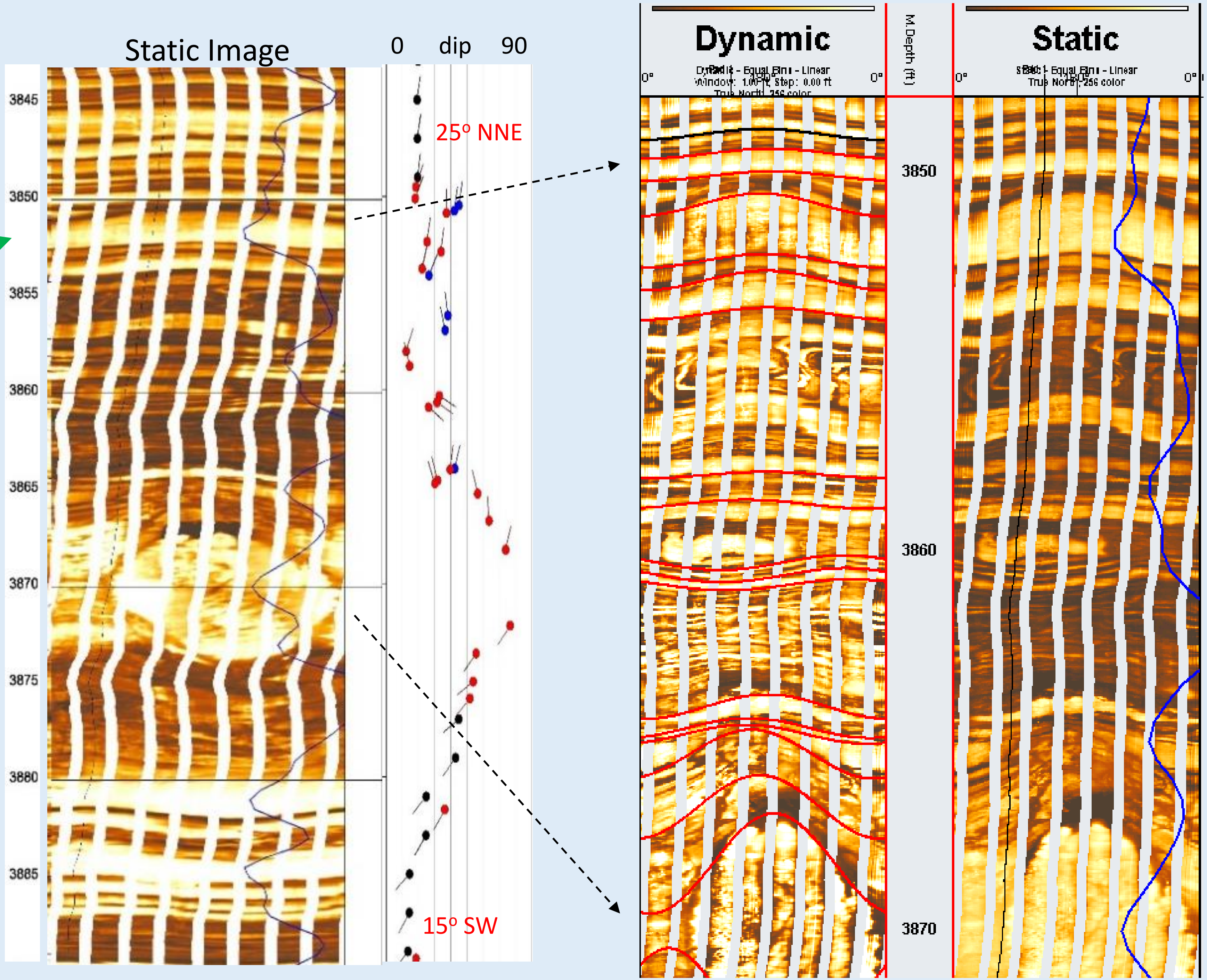
FR – Flat on Ramp, Fault sub-parallel to HW beds, truncates FW beds

FF – Flat on Flat, Fault sub-parallel to HW and FW beds

Ventura fault study examples modified from Schwalbach et al., 2014 (Search and Discovery article #20255)

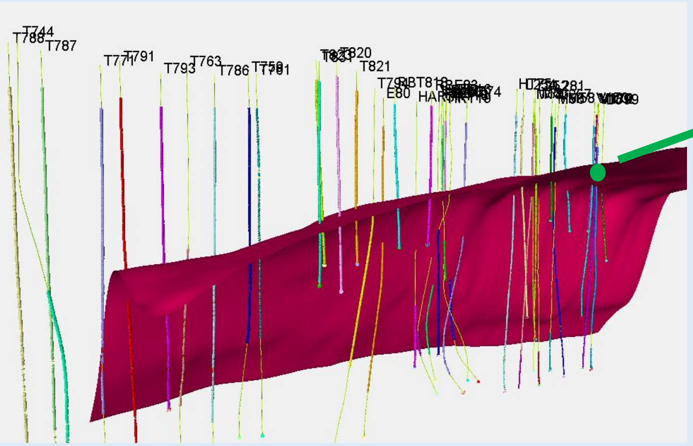
Image log through T73 Fault



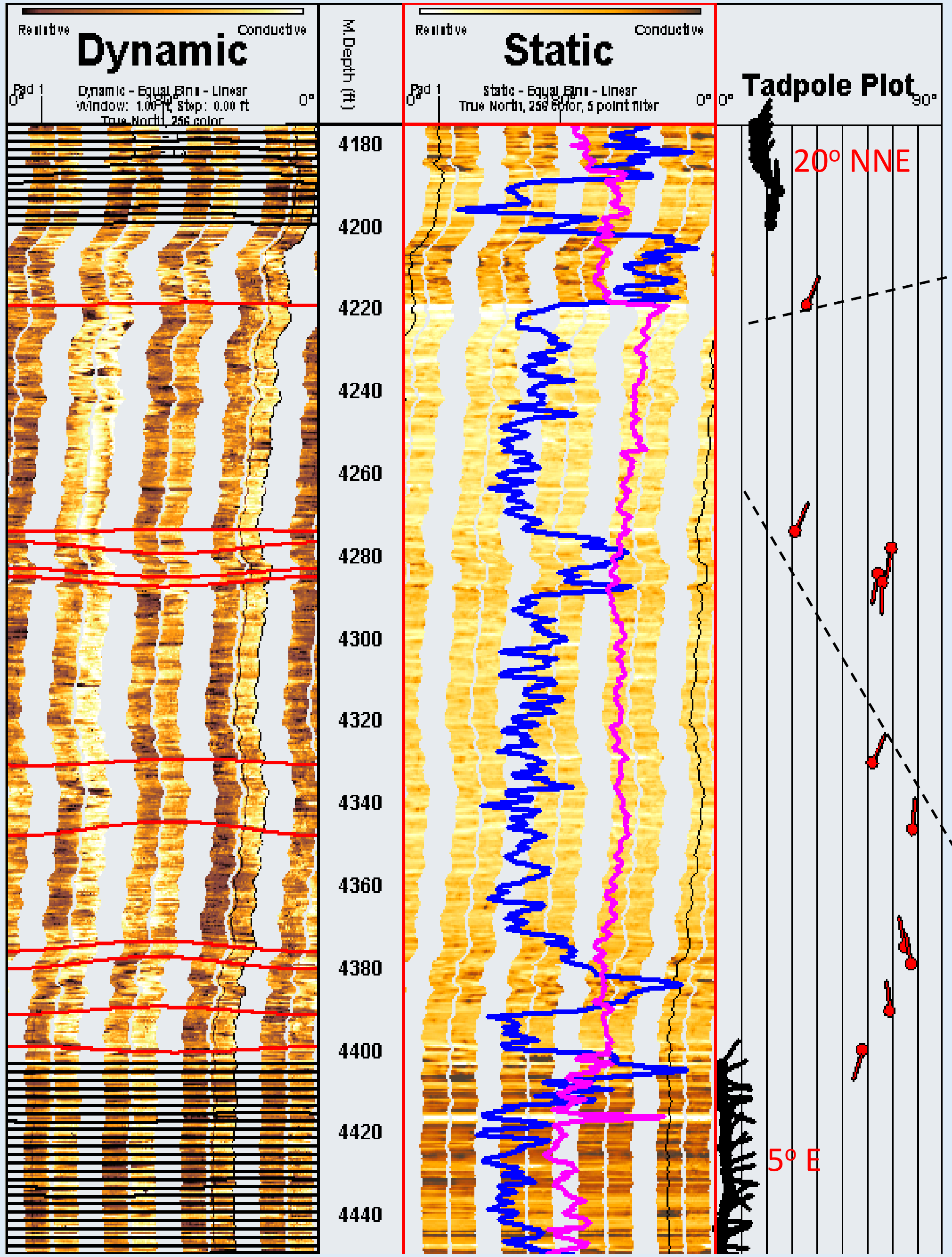


- Ramp-Ramp position
- Relatively narrow damage zone (20-25 feet)
- Deformed mudstones
- Narrow fault core

Image log through T73 Fault



- Ramp-Ramp position
- Much wider damage zone (200 feet)
- Deformed mudstone brackets thicker, cemented fault core



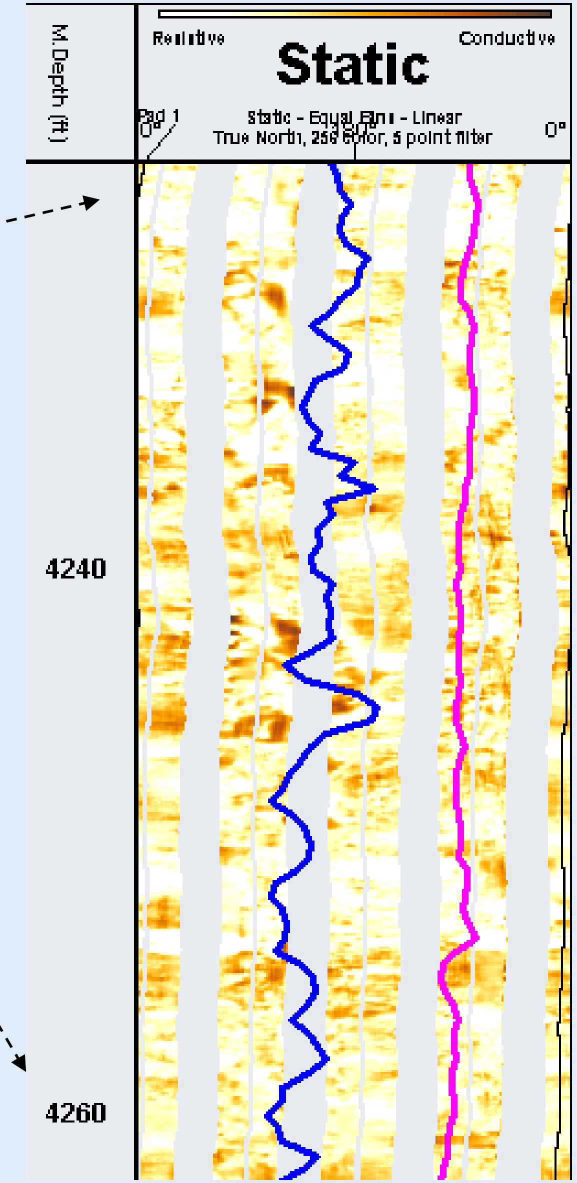
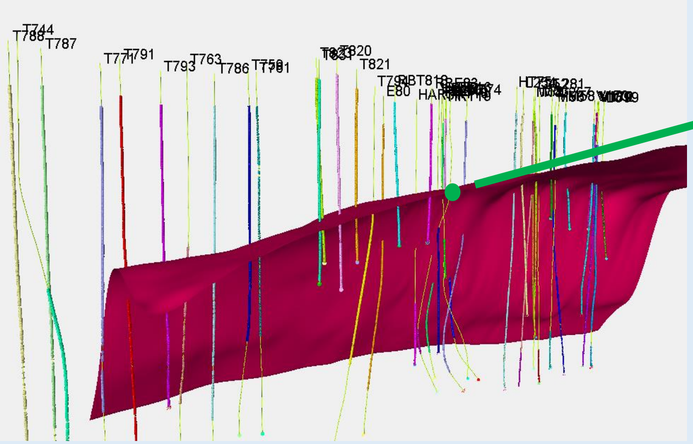
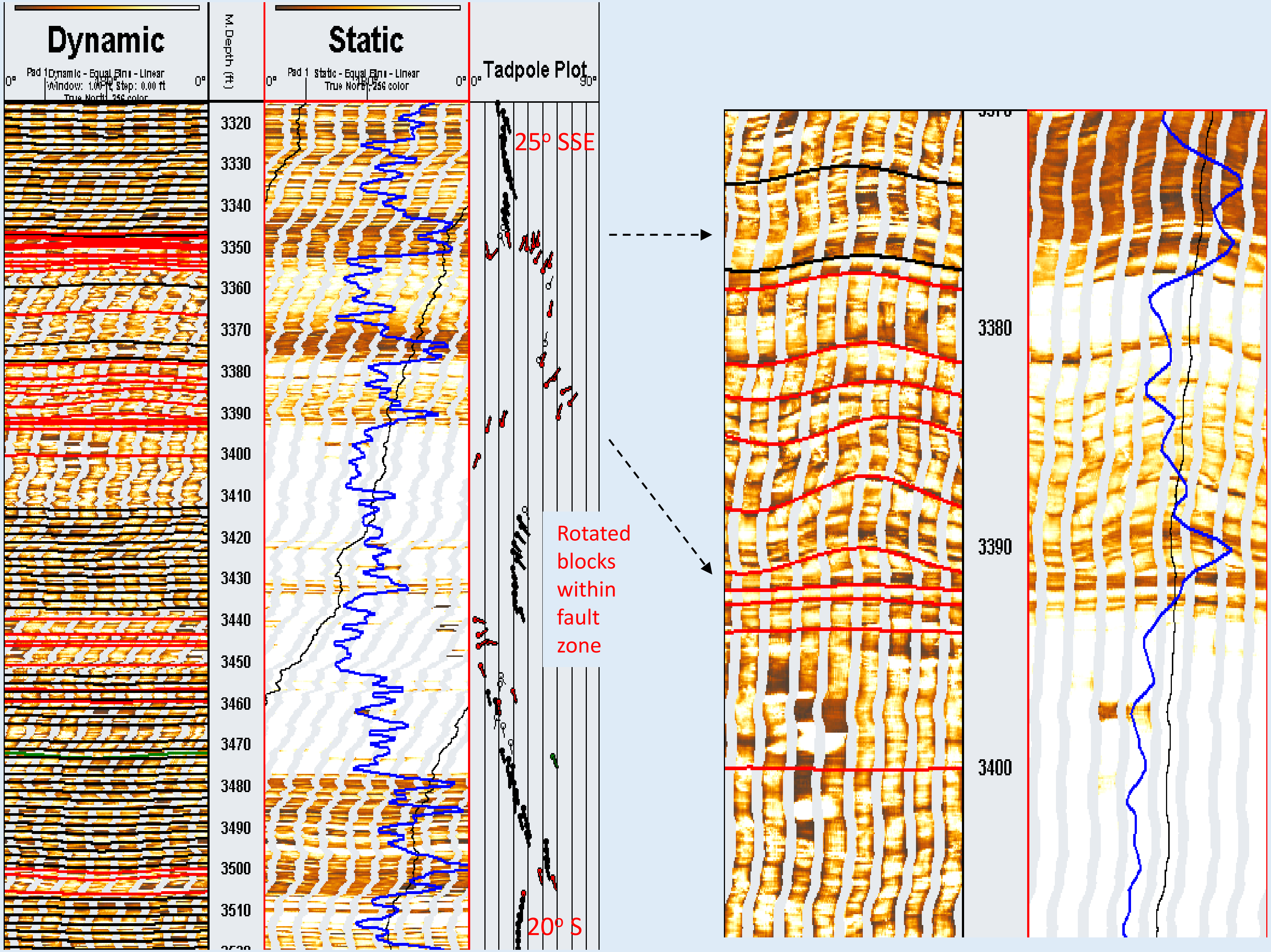


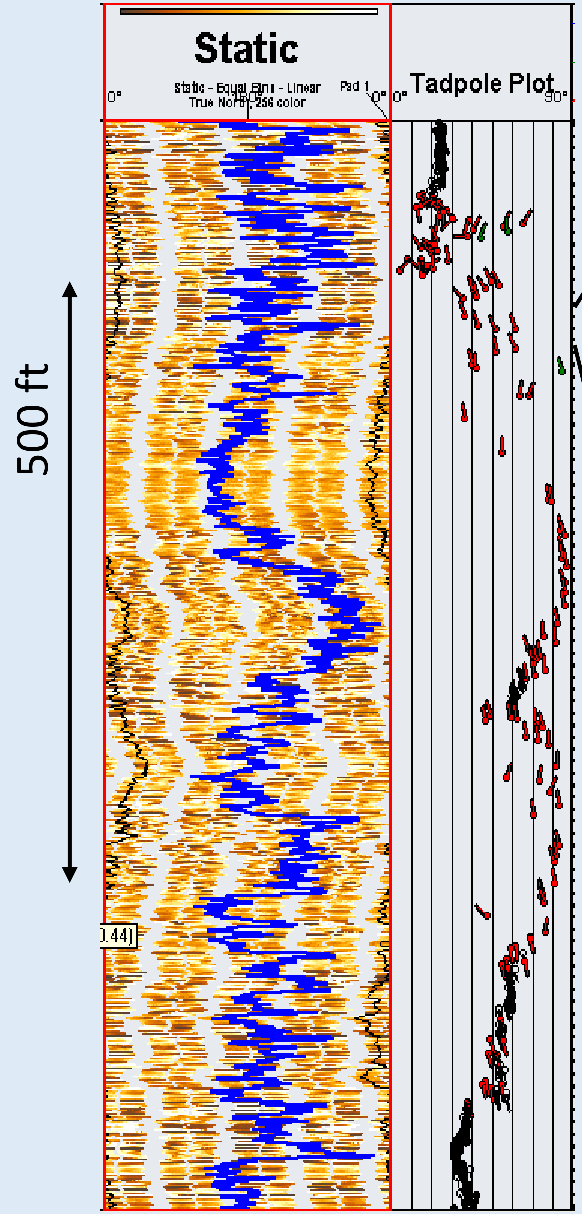
Image log through T73 Fault

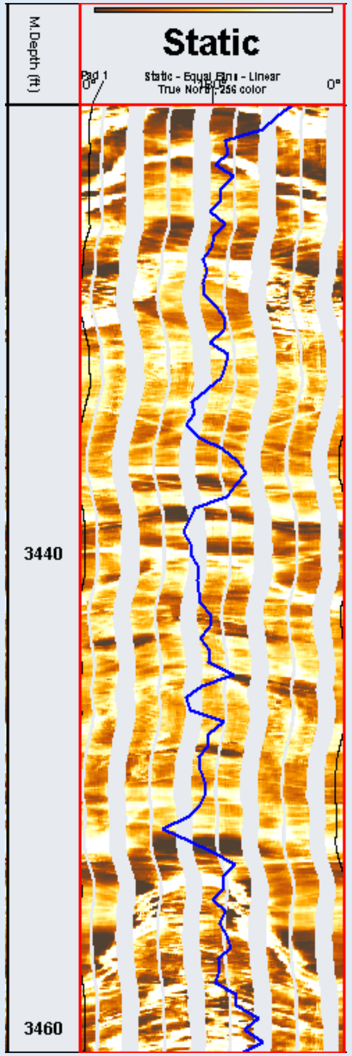




- Ramp-Ramp position
- Broad fault zone (160 feet) with rotated blocks and cemented sands
- Mudstone units bound thicker fault core (detachment layers)

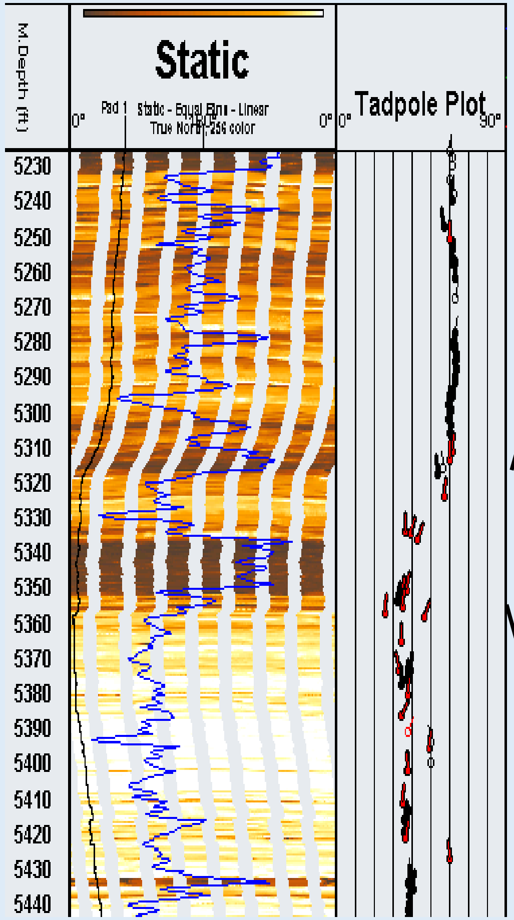
Lateral Ramp where faults overlap

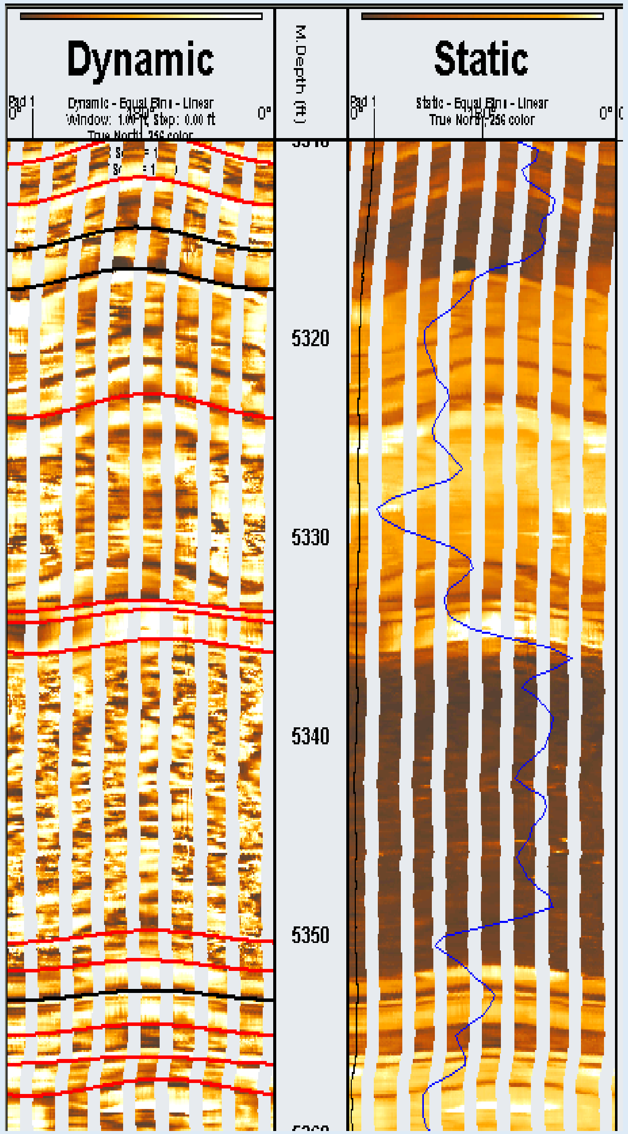




Broad zone of deformation, internal shear zones and deformation bands

Flat-on-Ramp: Narrow zone of deformation





Dip change occurs across 15-ft-thick mudstone with little deformation above or below

Ventura Field Image Log Analysis of Faults

- Highlights the **heterogeneity** of deformation encountered along a fault
- Deformation likely a function of position along the fault, fault movement, and mechanical properties of rocks involved
- Structural domains feature specific characteristics
  - Flat-on-Flat: bed-parallel features and detachments
  - Flat-on-Ramp: mudstone layer boundaries, rotated blocks
  - Ramp-on-Ramp: mudstone layer boundaries, cemented sands, deformation bands, cataclasis, rotated blocks

General Applications

✓Fault seal analysis (juxtaposition or shale gouge model appropriate?)

✓Reservoir quality around fault zones (diagenesis, fracturing, cataclasis, deformation bands - barriers or enhancements to fluid flow)

✓*Improved mapping from better understanding of fault geometry*

✓*Deformation style, mechanics around fault for hazards prediction*

Stratigraphic Stacking and Diagenetic Discriminator

Monterey Formation
Elk Hills

Needed core calibration to verify

Reservoir characterization
✓ Net pay
✓ Silica diagenesis
✓ Mechanical stratigraphy

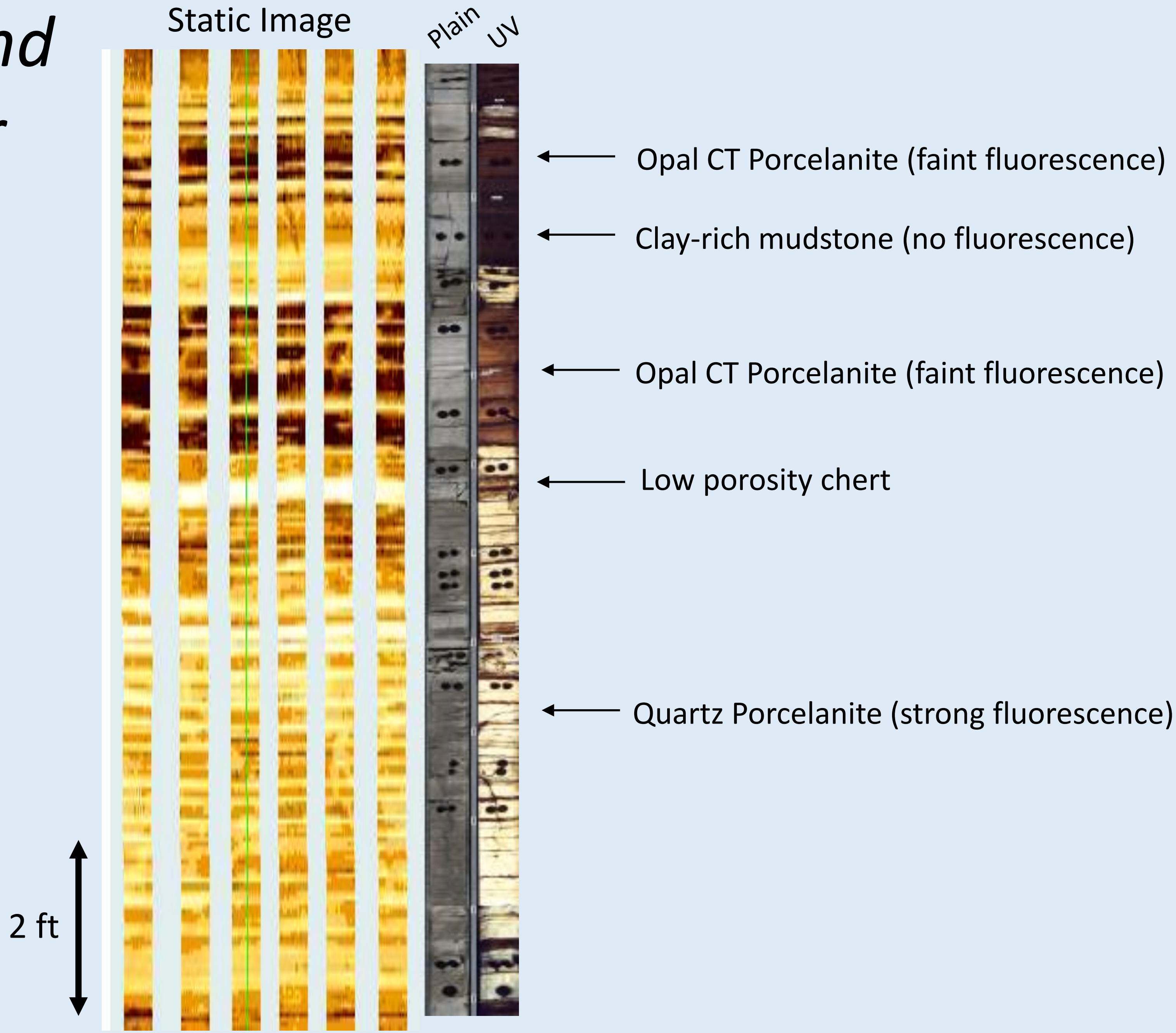
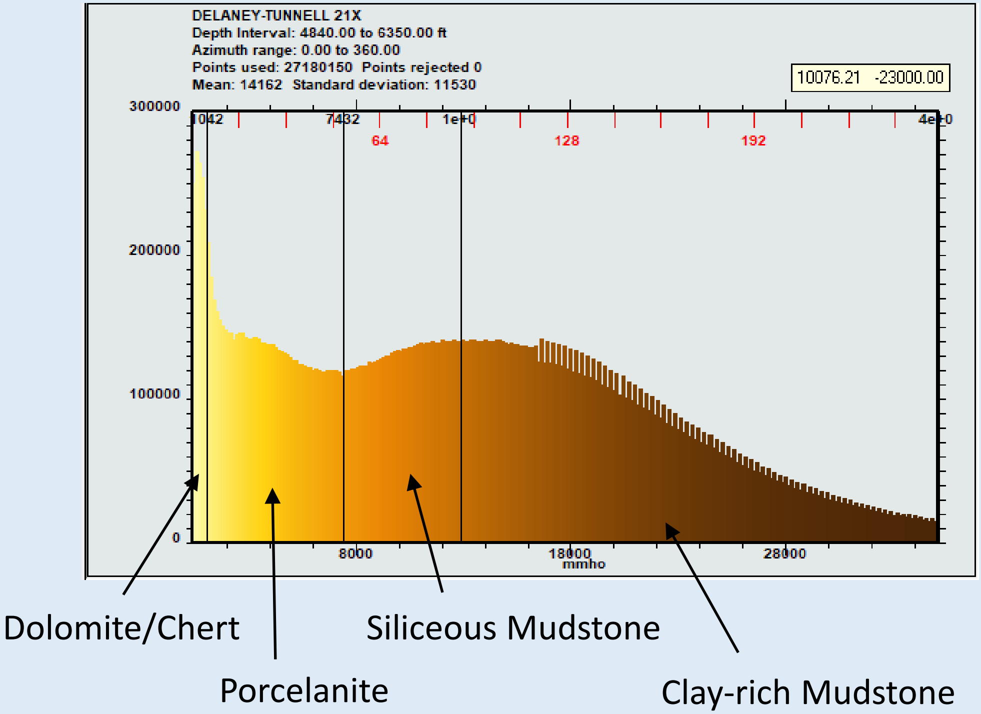
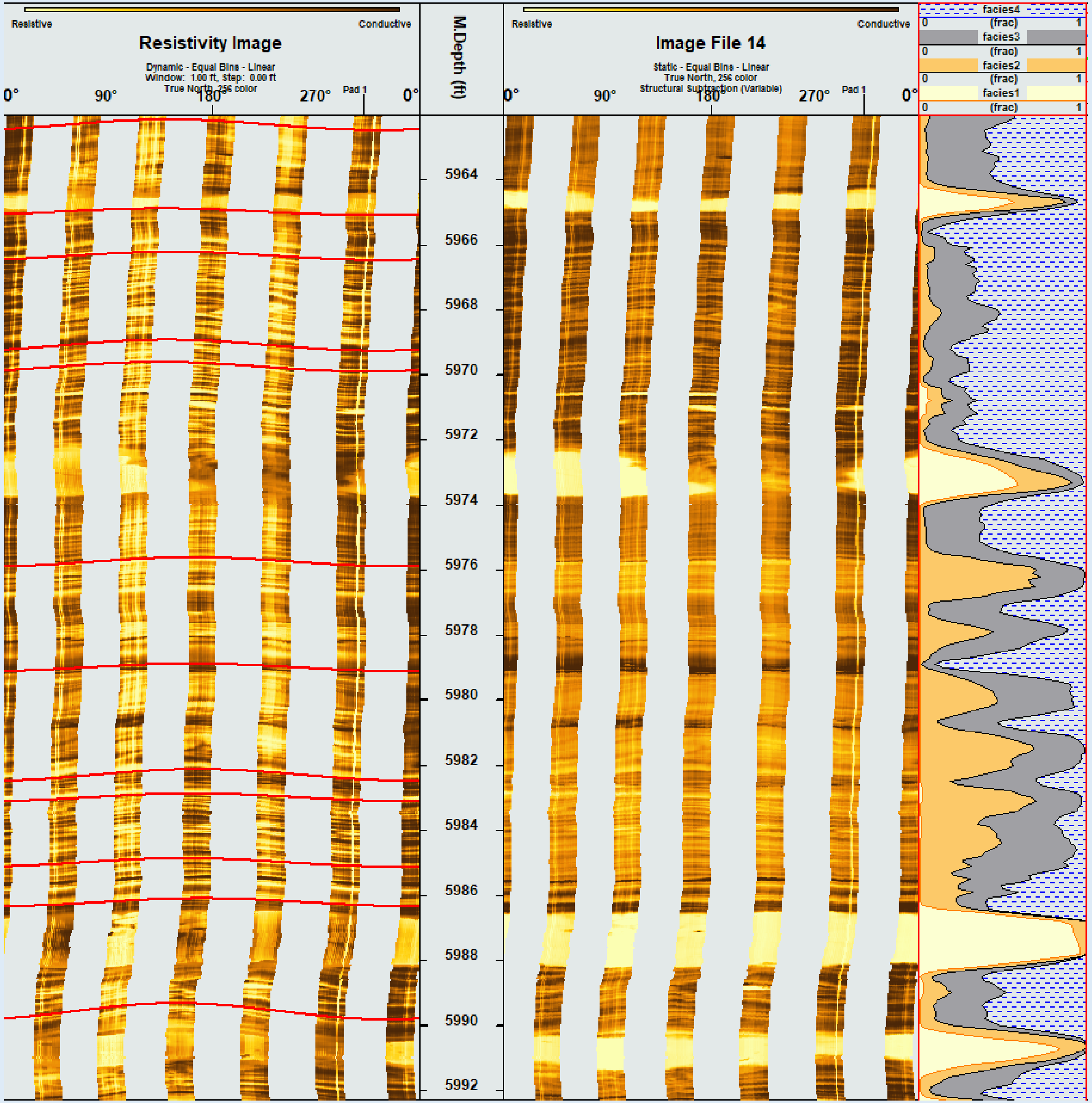


Image Thresholding as a Lithologic Discriminator

- Discriminate based on **Static** image conductivity
- Flatten image to mitigate "smearing" dipping beds
- Best when calibrated with core but still useful with general lithofacies knowledge





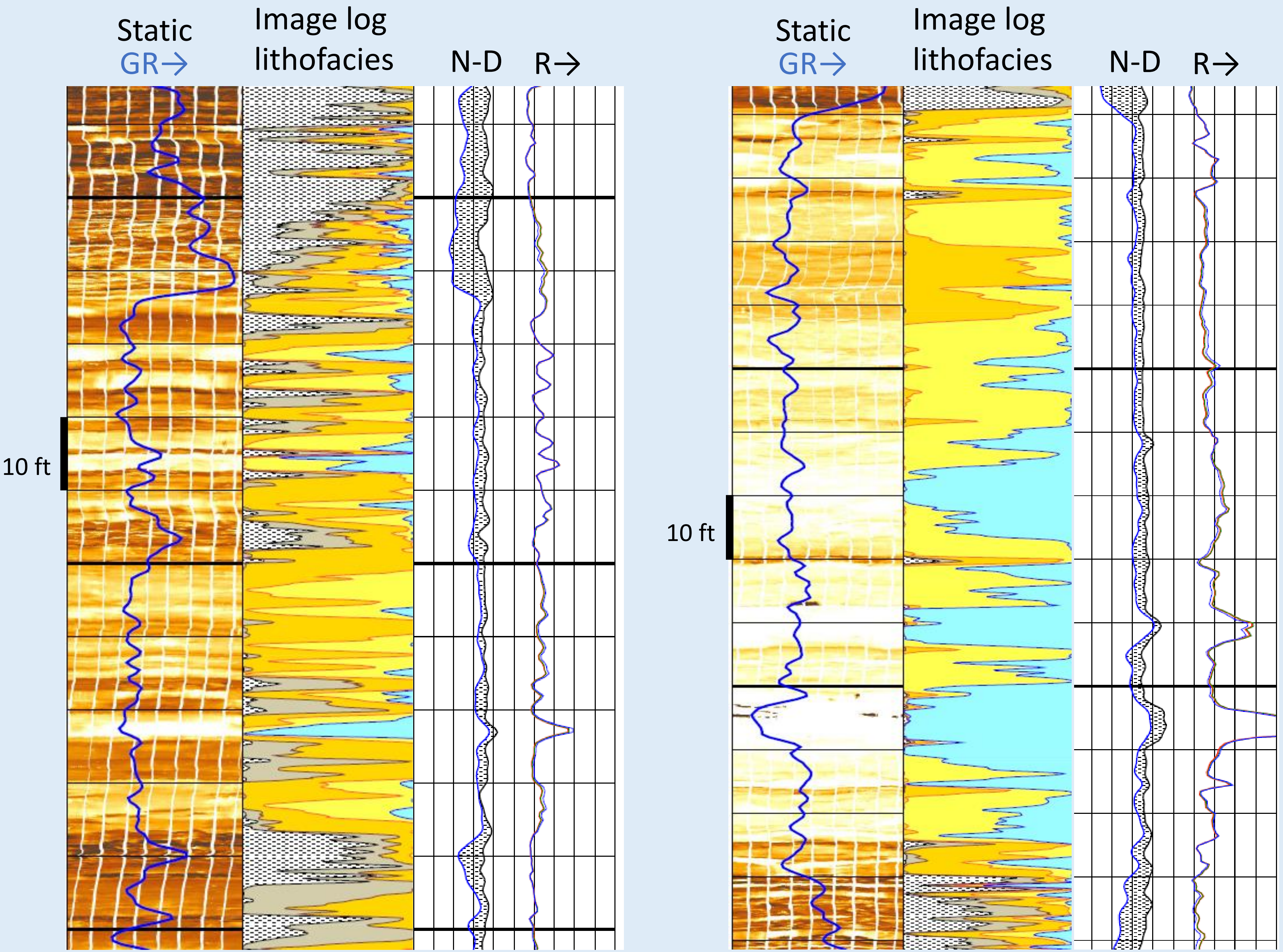
Monterey Formation, Santa Maria onshore

Deep Water Clastics

Lithofacies predicted by image log conductivity

Predicted lithofacies

- Mudstone
- Silty Mudstone
- Fine – Med. Sandstone
- Coarse Sandstone
- Cemented Sandstone

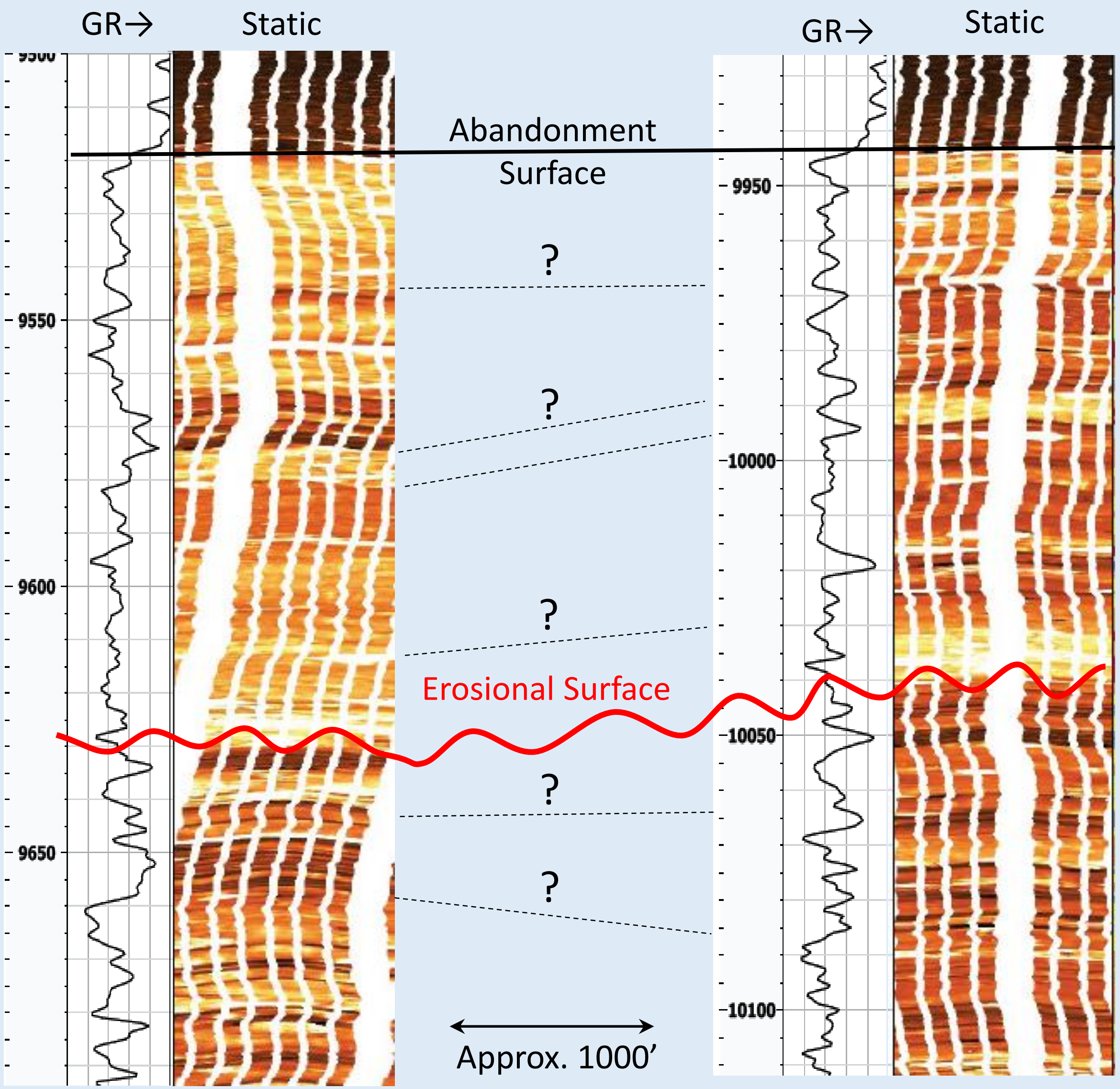


Fining up stratigraphic section

Cemented Sandstone, degraded reservoir

Deep Water Clastics: Correlation with Images

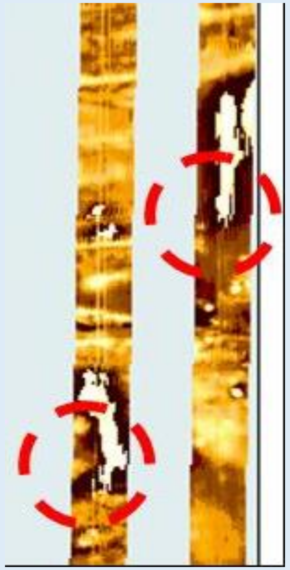
- Reveal details of stratal stacking
- Help bracket uncertainty in well-to-well connectivity
- Highlight stratal heterogeneity and bed (dis)continuity
- Map extent of depositional environments and lithofacies variability



Well Bore Productivity

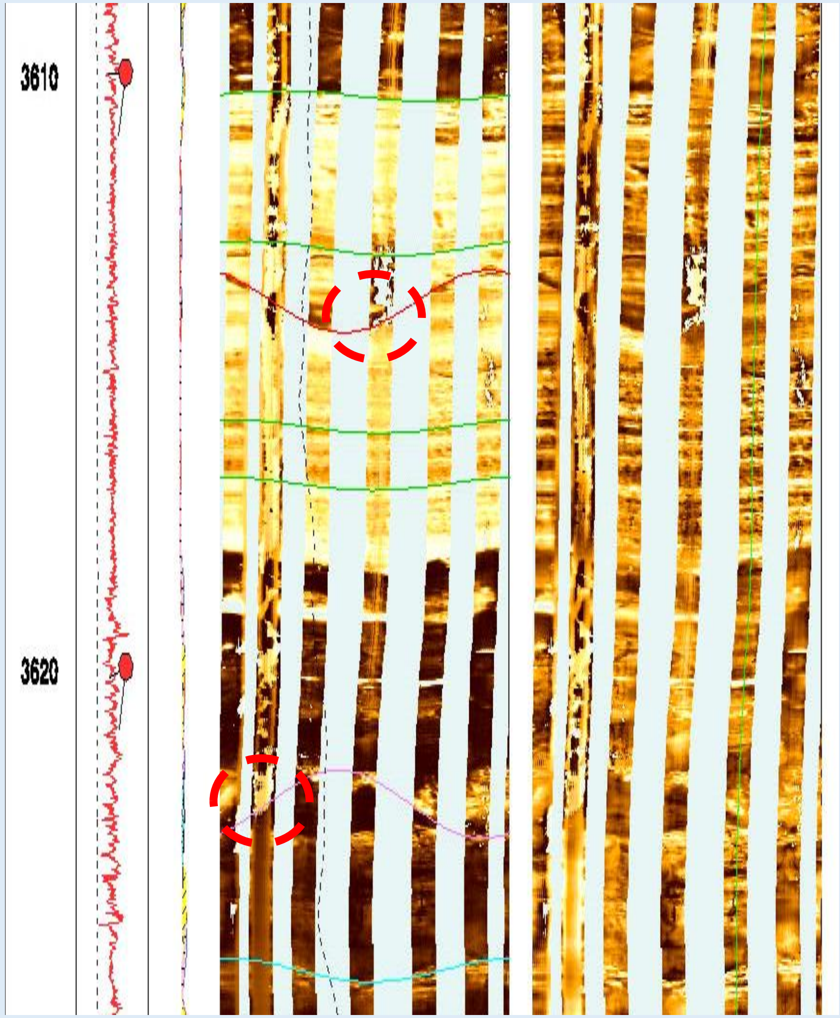
Image logs can detect fluid entry into well bore

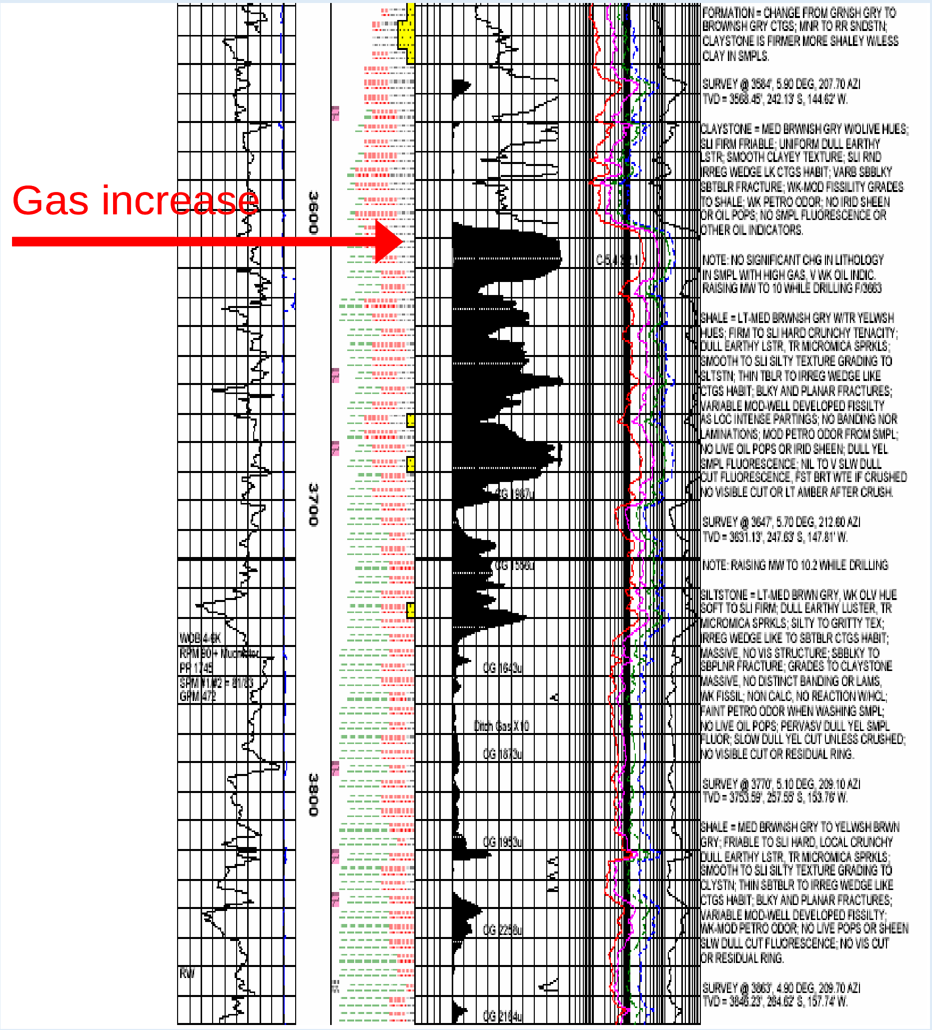
As the image log pad is dragged up the borehole, gas is entrained in the mud, causing extremely high resistivity (off-scale).



Zoomed in example

Static Dynamic

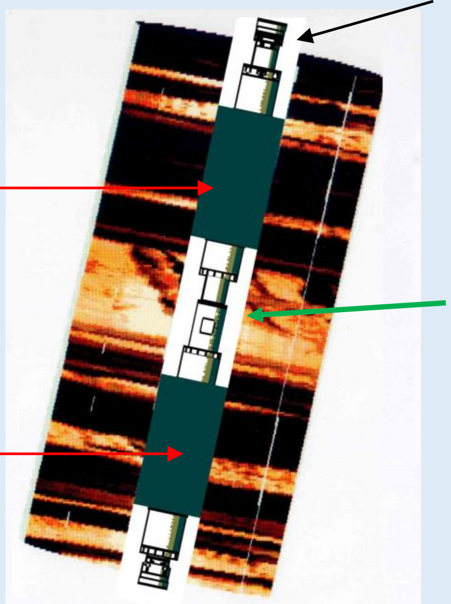




Mudlog (Shaded black where gas is on backup scale)
Etchegoin Formation, San Joaquin Valley

Interval Tests in Conjunction with Packer Modules

Offshore Monterey Formation

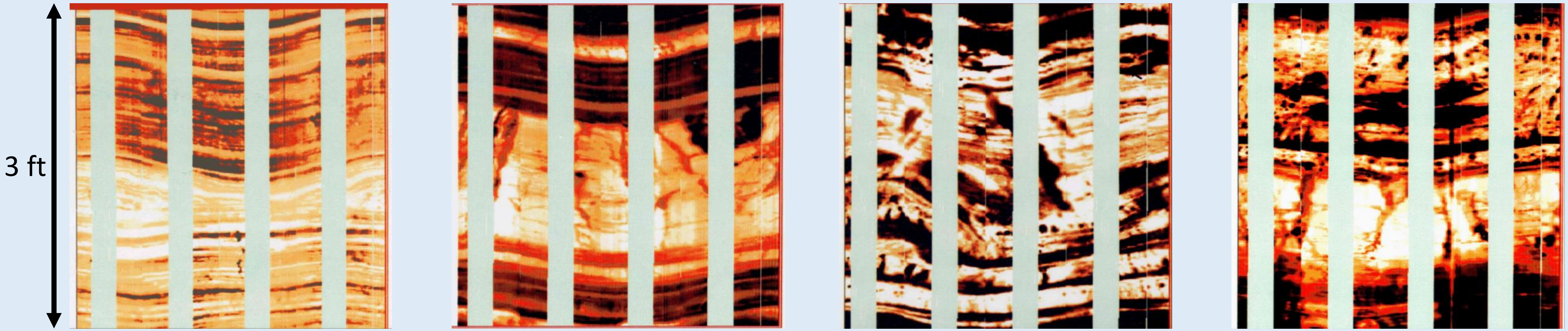


Porcelanite and mudstone

Dolomite and mudstone

Chert and porcelanite

Chert and dolomite



Effective Perm to Gas = .0024 md

Effective Perm to Oil = 499 md

Effective Perm to Oil = 744 md

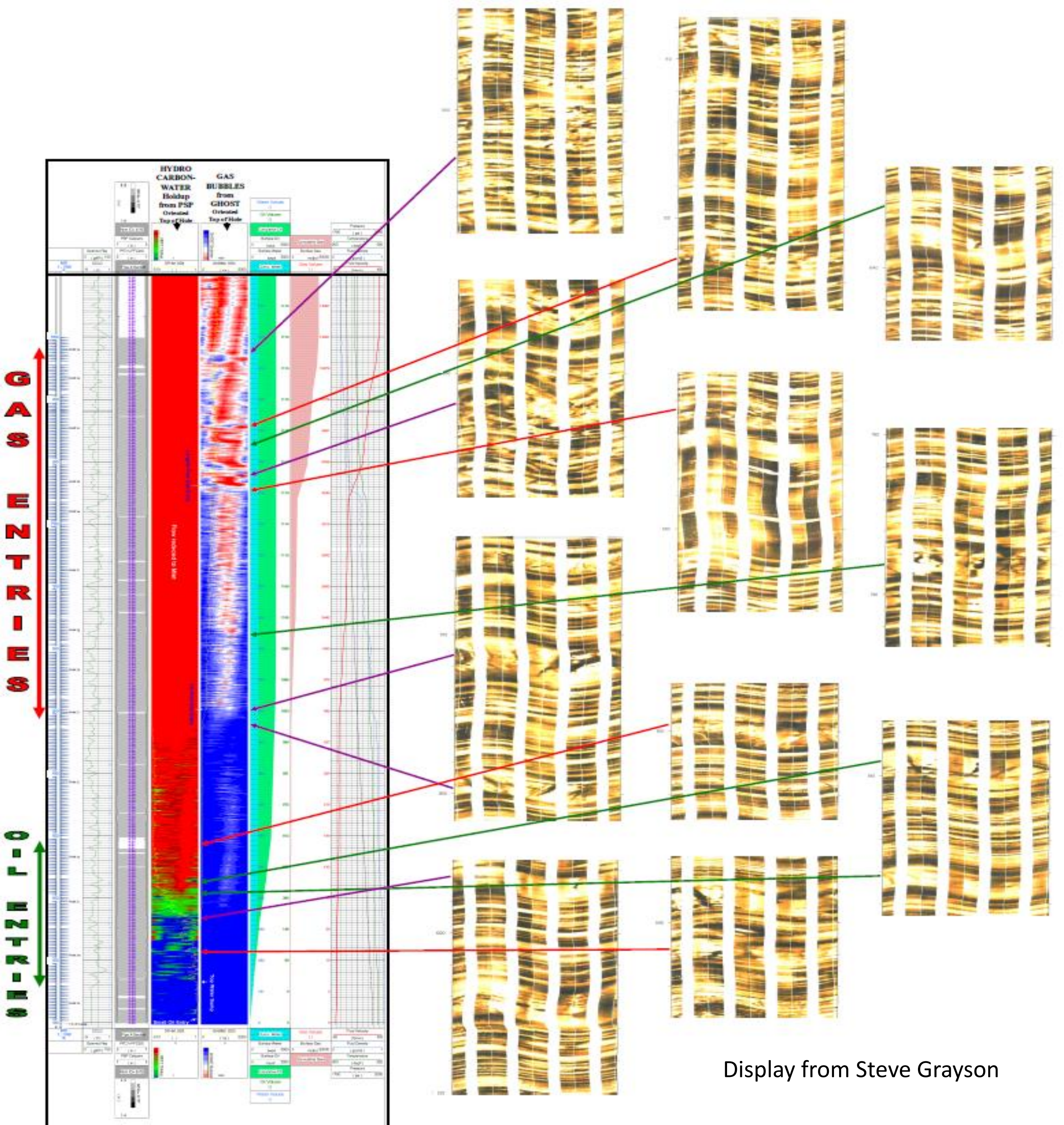
Effective Perm to Oil = 1017 md

Modified from Grayson et al., 2000 SPE# 62532

BHI and production logs document point-source entry to wellbore from fractures

Offshore Monterey Formation example

- Nearly all the oil and gas entering the well coincides with fractured intervals.
- Implications for optimizing well completion strategy and reservoir management (don’t need to perforate or stimulate non-fractured intervals).



Display from Steve Grayson

Summary

- Borehole images provide unique insights to subsurface geology in multiple disciplines (*not just a source of dip and fracture data*).

- Geologists are best equipped to integrate and expand the utility of these data because of their overall subsurface expertise.

- Borehole image interpretation shouldn’t be strictly the realm of petrophysicists and image log specialists.

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Amer Aimen

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Bill Benmore

Michael Glascock

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