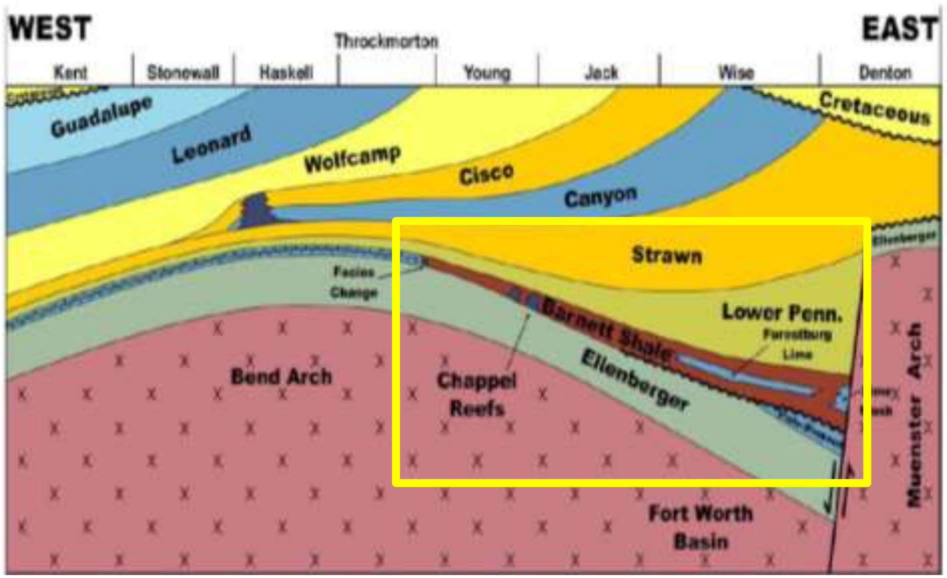
Investigating the Barnett Shale

An Integrated Workflow from Petrophysics to Visualisation and Seismic Decomposition

Paradigm®

Vision for Energy

The Barnett Shale

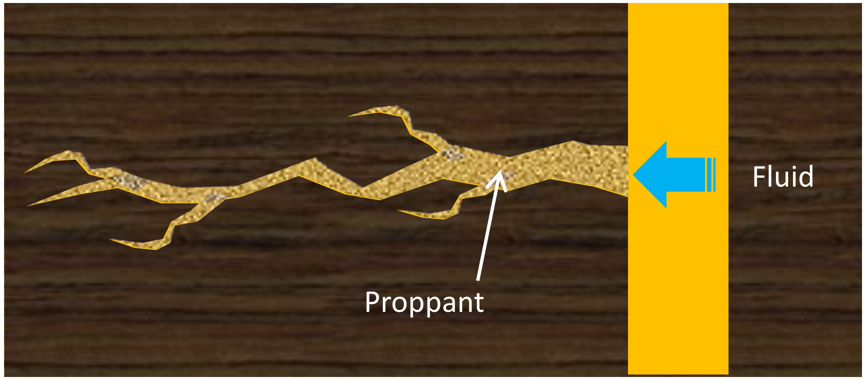


After Roth, Fracture Interpretation in The Barnett Shale, Using Macro and Micro seismic Data

- 1981: Barnett Shale discovery
- 8,000+ wells to date
- Challenges:
  - Low Permeability > Identify Zones for Hydraulic Fracture Stimulation
  - Careful well placement and fracturing relative to collapse structures

Paradigm®

Hydraulic Fracture Stimulation



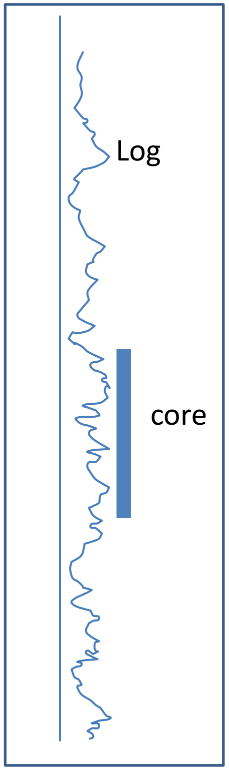
Brittleness	Fluid Type
70%	Slick Water
60%	Slick Water
50%	Hybrid
40%	Linear
30%	Foam

Proppant Type
Sand
Resin coated sand
Ceramic
Bauxite (intermediate-high strength)

- Increase shale permeability by injecting fluids + proppant to promote fracturing
- Analysis of shale characteristics
  - Brittleness ~ fluid type
  - Closure stress ~ proppant type
- But availability of core data tends to be limited

Petrophysical Screening

- By calibrating log data to core data we extend reservoir knowledge away from well bore
- Brittleness / Ductility ~ petrophysical modelling
- Cum. TOC > 30 / Kerogen content ~ petrophysical modelling
- Shale thickness and lateral extent ~ seismic interpretation



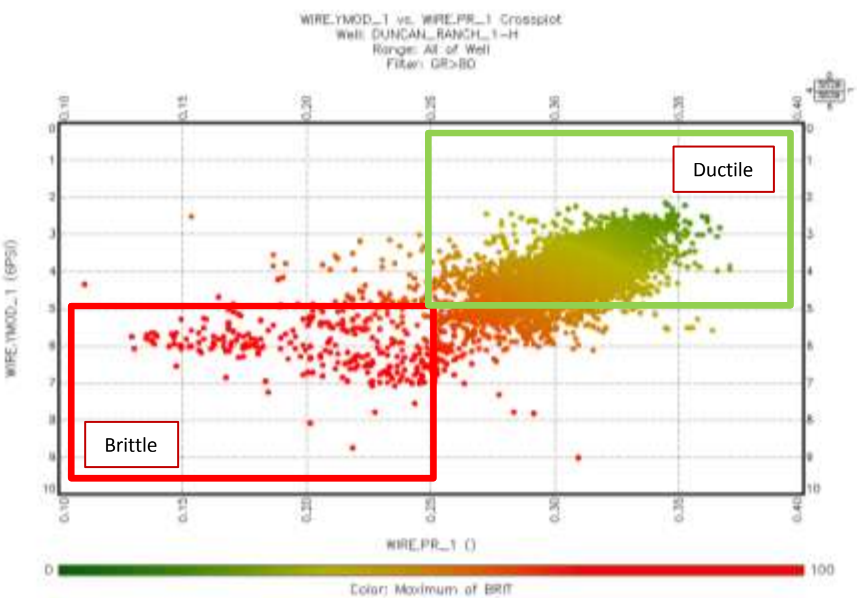
Paradigm®

Workflow Requirements

Our interpretation workflow will include methods to:

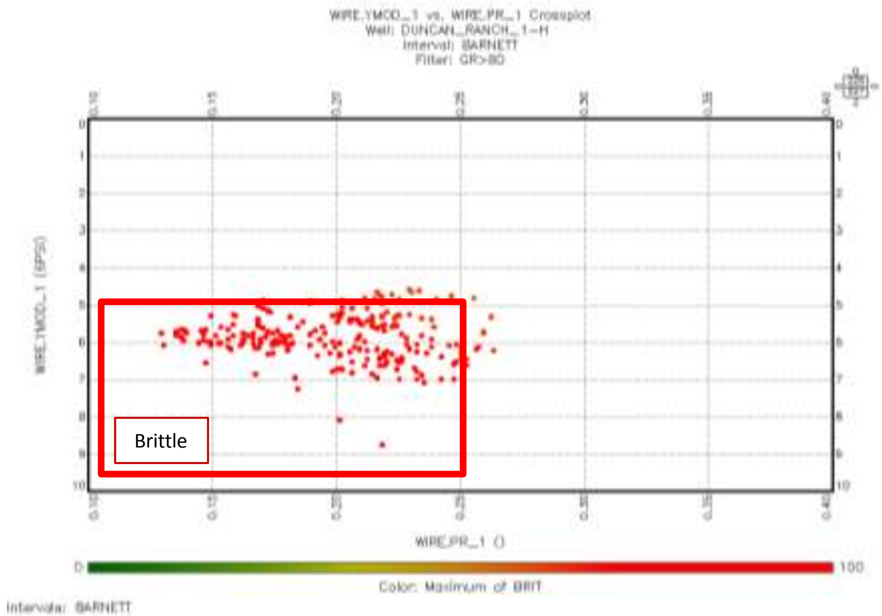
- **Identify optimum fracing zones using petrophysical modelling**
  - Brittleness
- **Identify organic-rich shale zones from petrophysical modelling**
  - Kerogen content
- **Identify extent of prospective zone**
  - Seismic interpretation / classification / visualisation
- **Extract Fracture Orientation by Full Azimuth Seismic Decomposition**
  - Seismic Anisotropy – Stress Direction
- **Monitor fracture development for environmental impact**
  - Micro-seismic

Brittleness



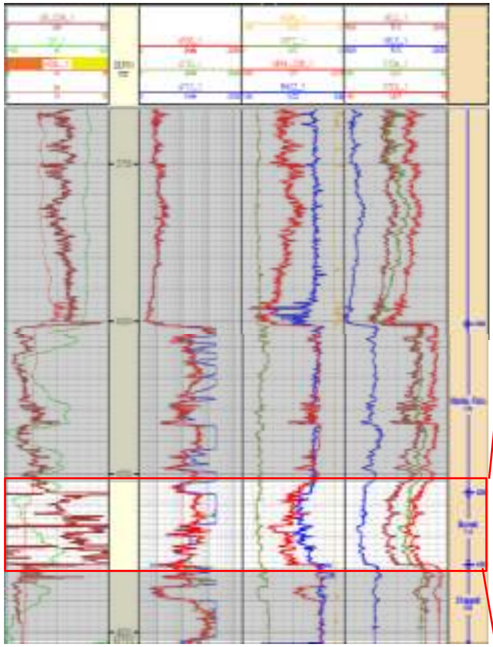
- All zones
- Brittleness from Poisson's Ratio and Young's Modulus
  - Low PR / High YM = brittle
  - High PR / Low YM = ductile
- Brittle
  - Fractures
  - Reservoir
- Ductile
  - Fractures heal
  - Seal

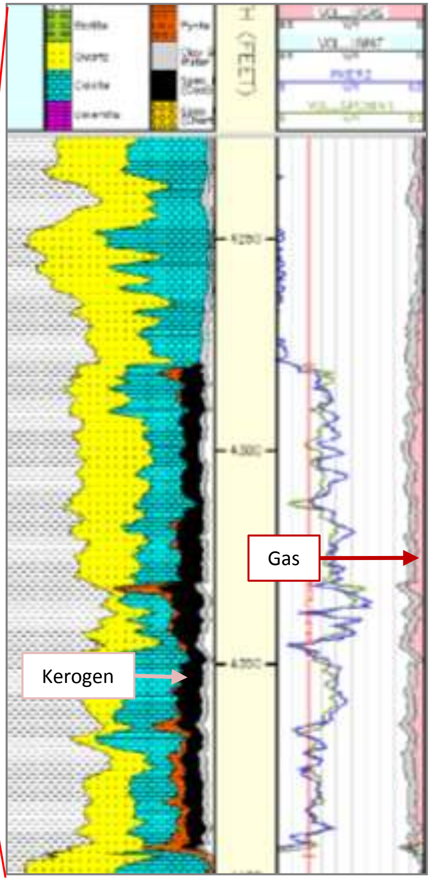
Brittleness



- Barnett Shale only
- Optimum brittleness

Kerogen Content

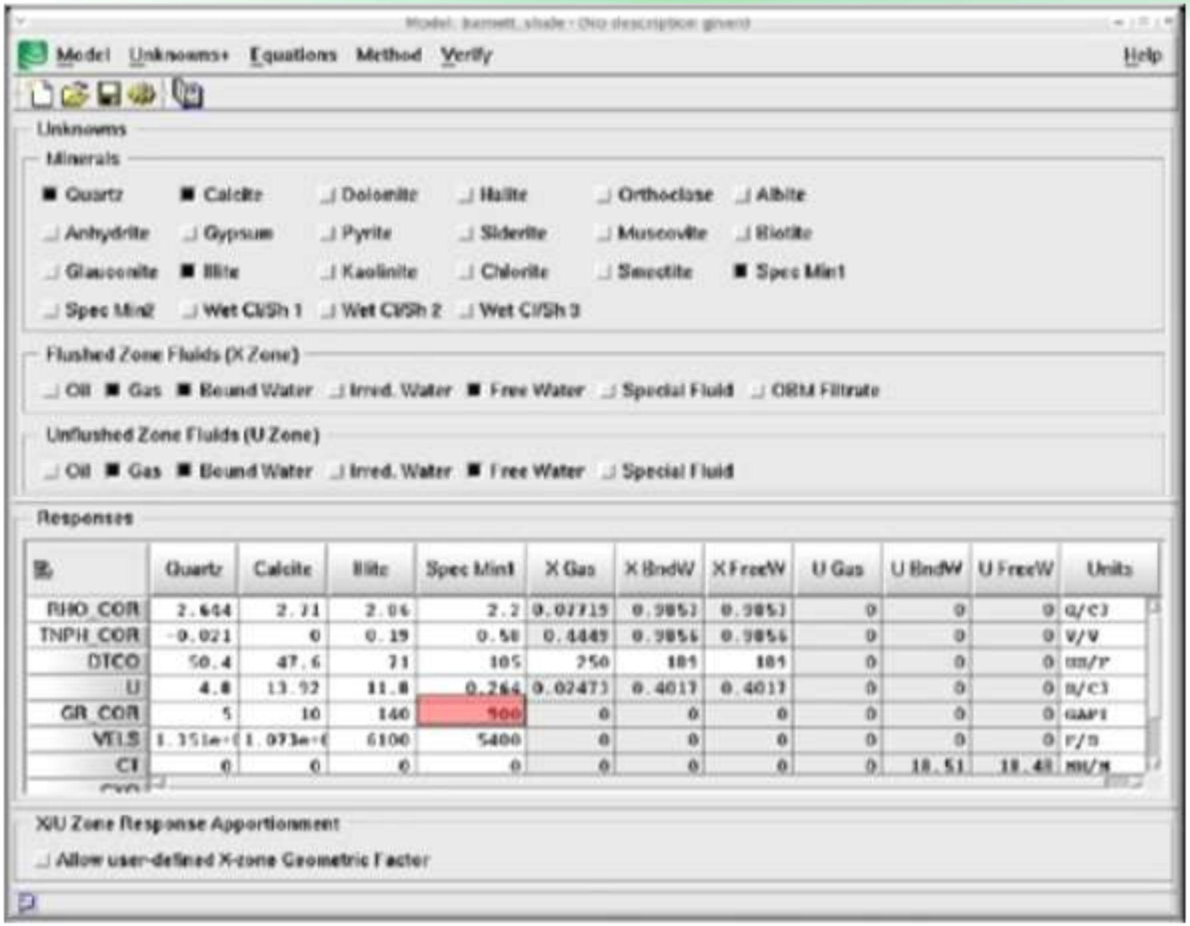




- High GR response indicates uranium associated with organic content
- Multi-mineral Petrophysical modelling provides a route to model Kerogen content from GR*

*Spears et al, Petrophysics, Feb 2009, modified using Passey et al, AAPG Bulletin, Dec 1990.

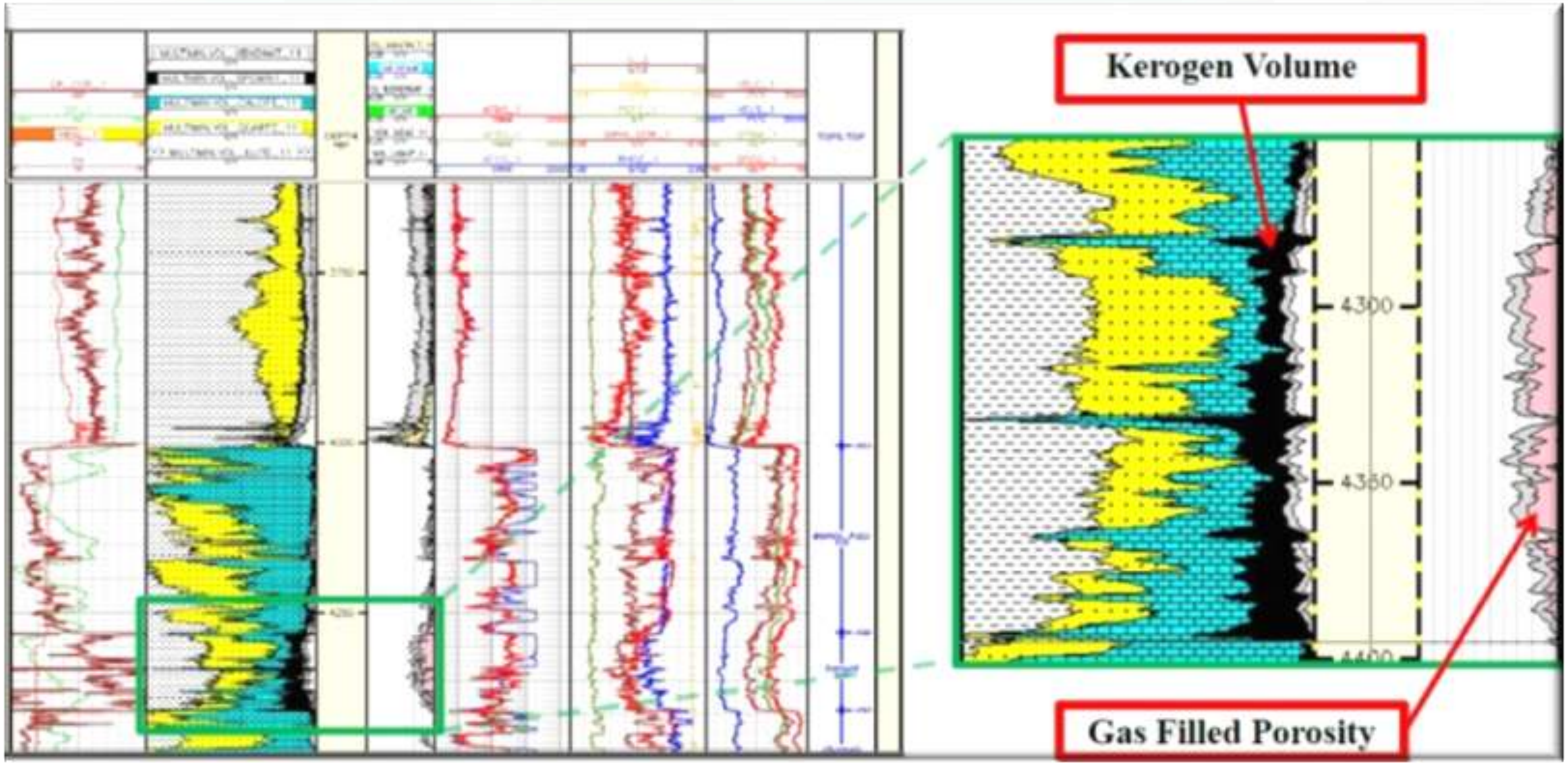
Kerogen Determination – Add Special Mineral to Multimin



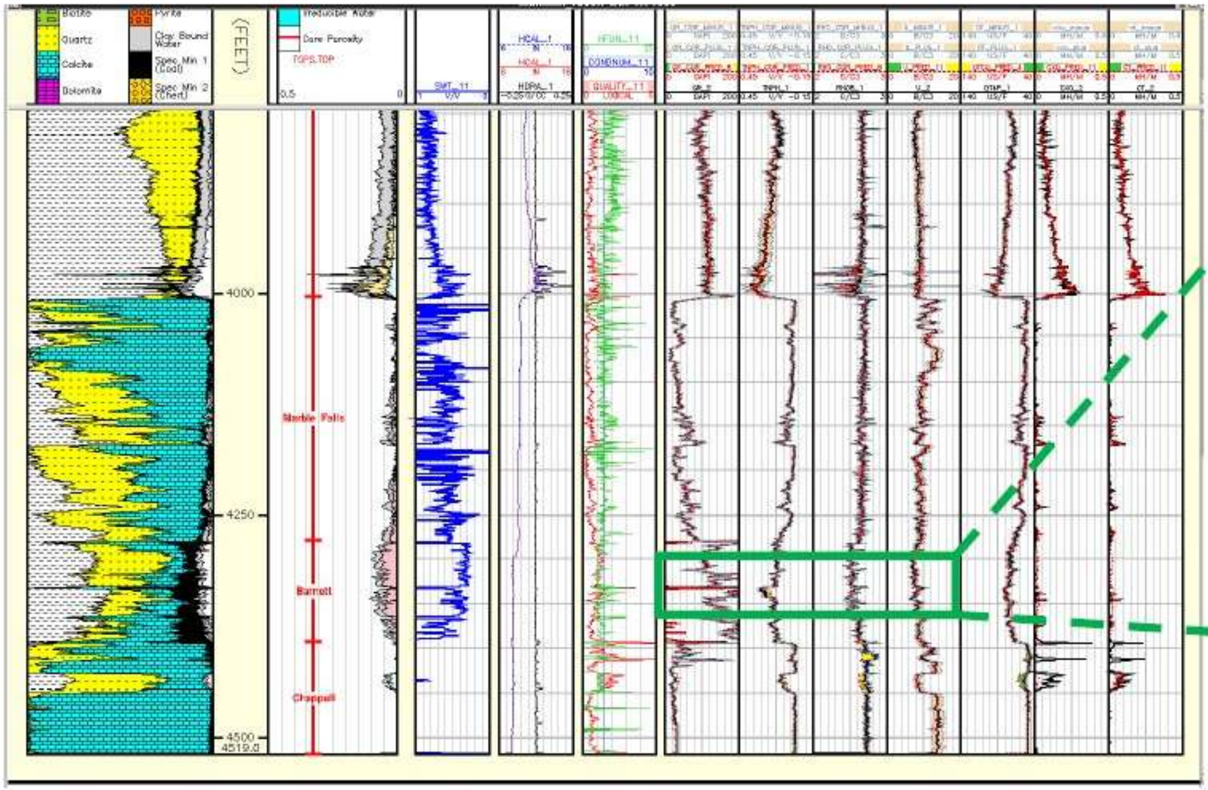
Principle of Optimising Petrophysics

Special Mineral equates to coal, with elevated GR

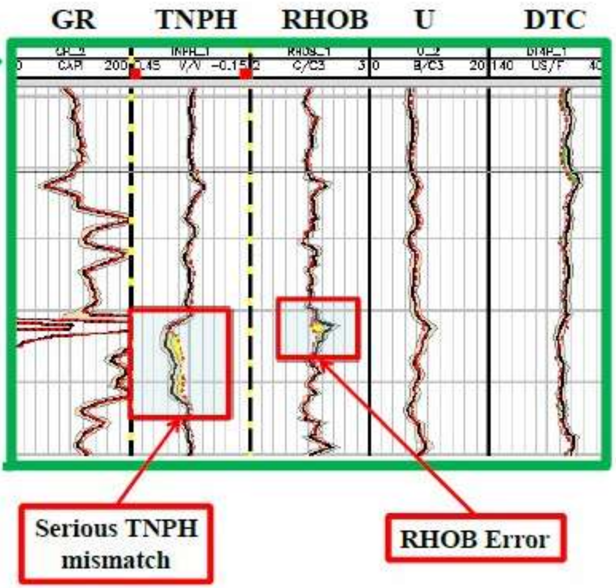
Multimin results : Kerogen and Gas Content



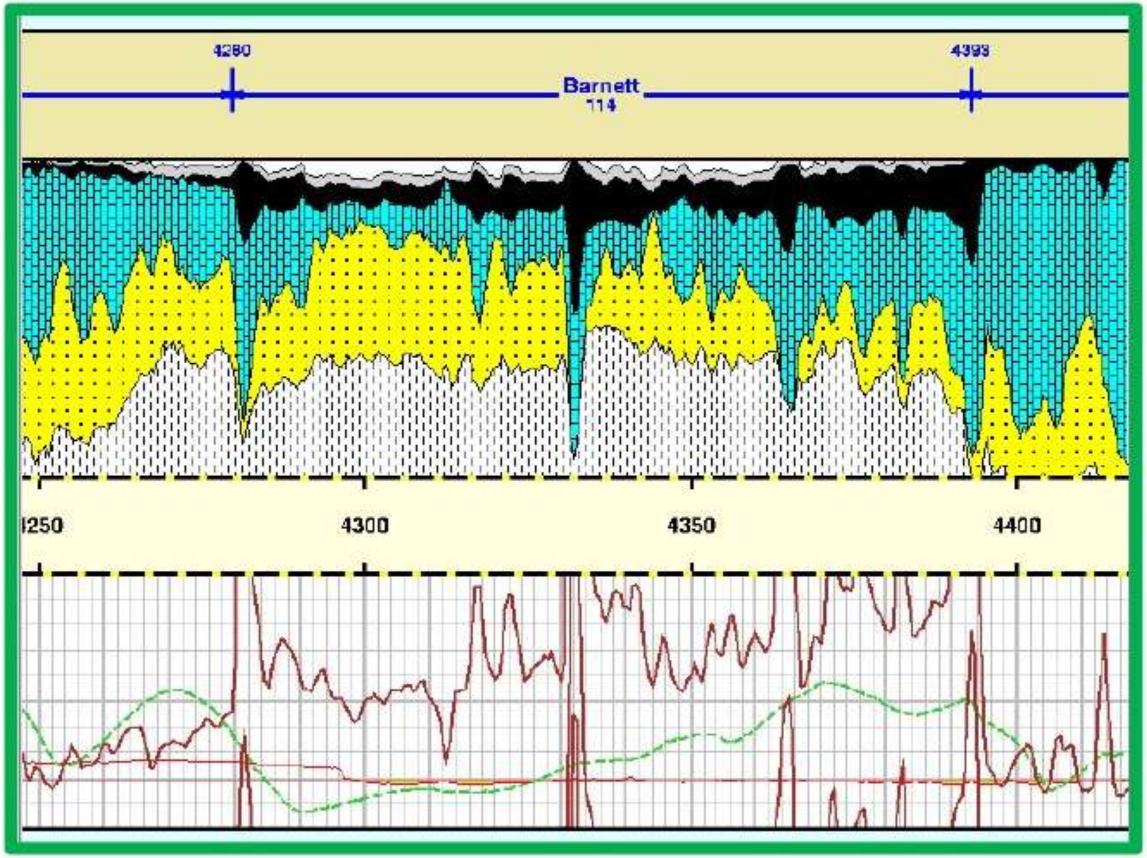
Multimin Quality Control Curves



While overall quality is good, there are some obvious areas of concern.



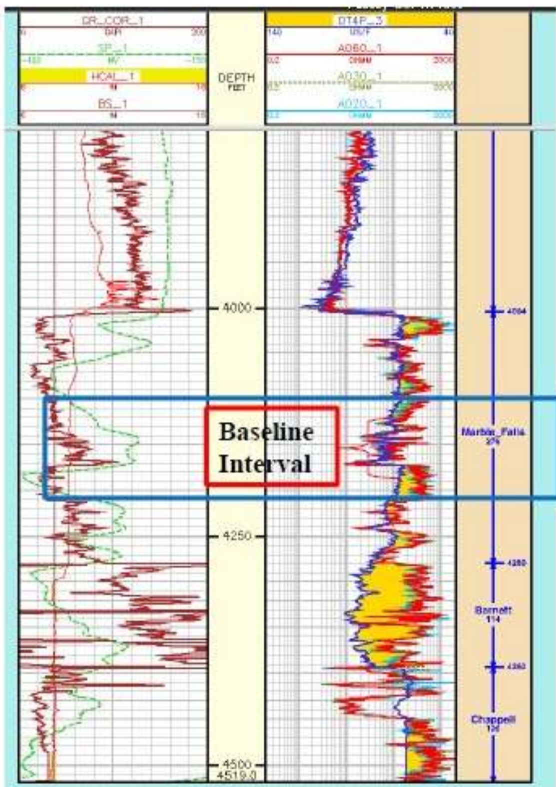
Kerogen Content from GR is highly variable



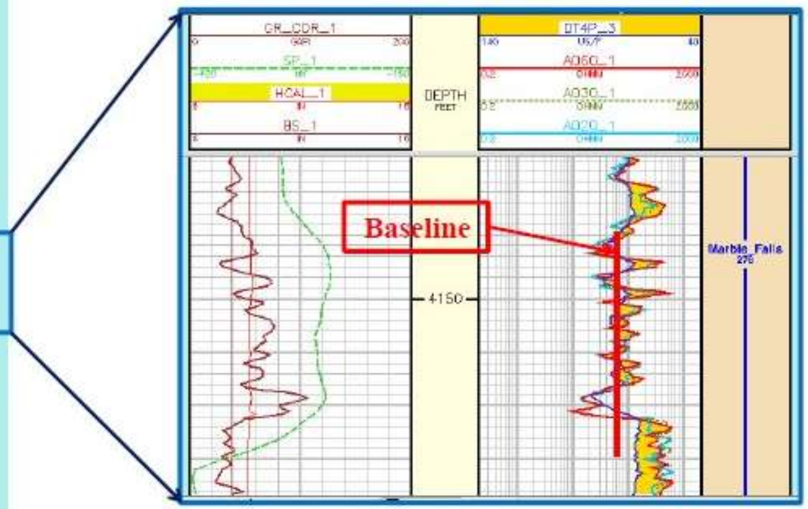
The variations in the amount of Kerogen predicted by the Multimin Model is not surprising since the GR dominates the percentage of Kerogen computed.

The increase in Carbonate volume with increasing Kerogen volume is a result of the Multimin method of minimizing error.

Application of Passey Method..



R_baseline = 78 ohmm
DT_baseline = 60 usec/ft



Picking the baseline interval is a non-trivial task. It is not obvious how this could be automated and is a source of potential error in this methodology.

The DT_baseline is the DT reading over the baseline interval

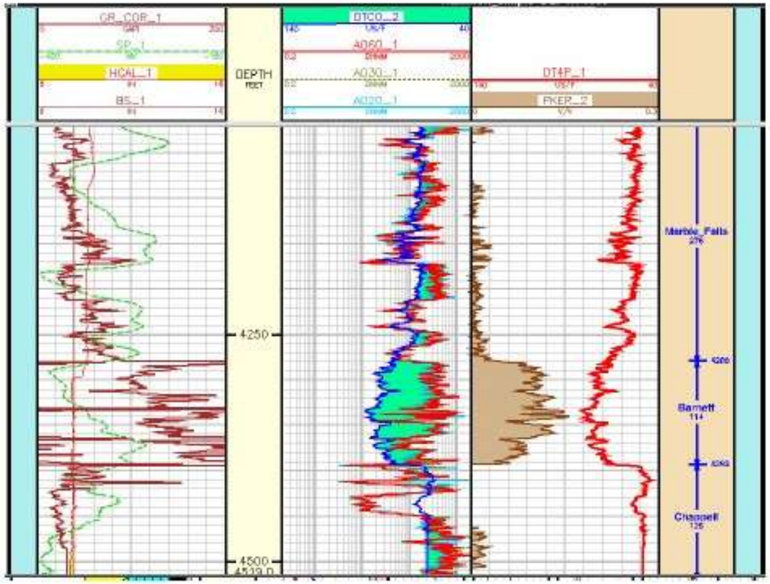
Paradigm®

So – compute Kerogen volume using Loglan

	Location	Mode	Comment	Unit	Name	Value
1	Parameter	In_Out	Detal Time baselin	US/F	DT_BASELINE	60
2	Parameter	In_Out	resistivity baseline	OHMM	RBAS	78
3	Parameter	In_Out	Maturity of kerogen		LOM	11.2
4	Log	Input	Deep Induction Standard Processed Resistivity	OHMM	RILD	AT60
5	Log	Input	Delta Time	US/F	DT	DT4P
6	Log	Output	Kerogen content	V/V	PKER	PKER

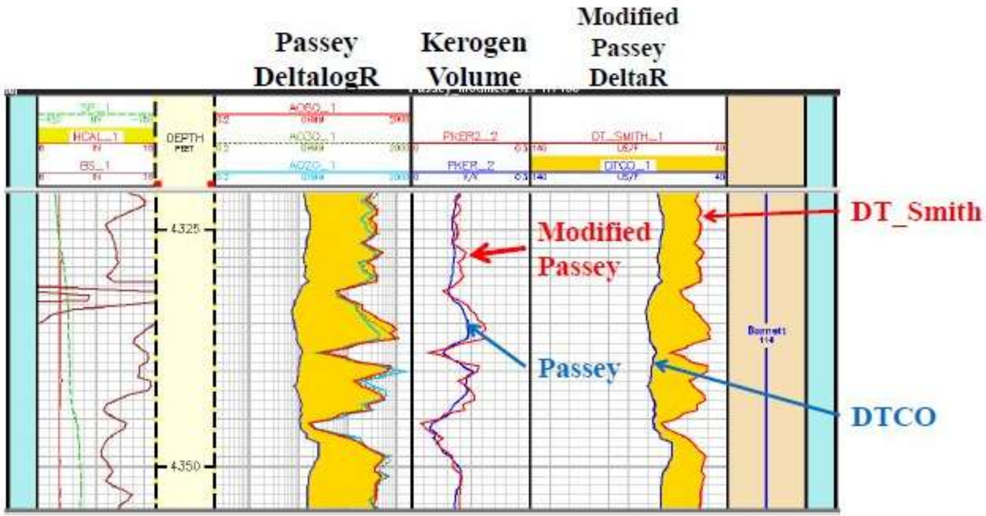
```
dowhile GET_FRAME ()

        dlogr = log(RILD/RBAS) + (.2*(DT - DT_BASELINE))
        PKER = (dlogr * 10**(2.297 - (0.1688 * LOM)))/100


    call PUT_FRAME ()

enddo

end
```

The LOM parameter used in the Loglan is the Level of Maturity as described by Passey



Paradigm®

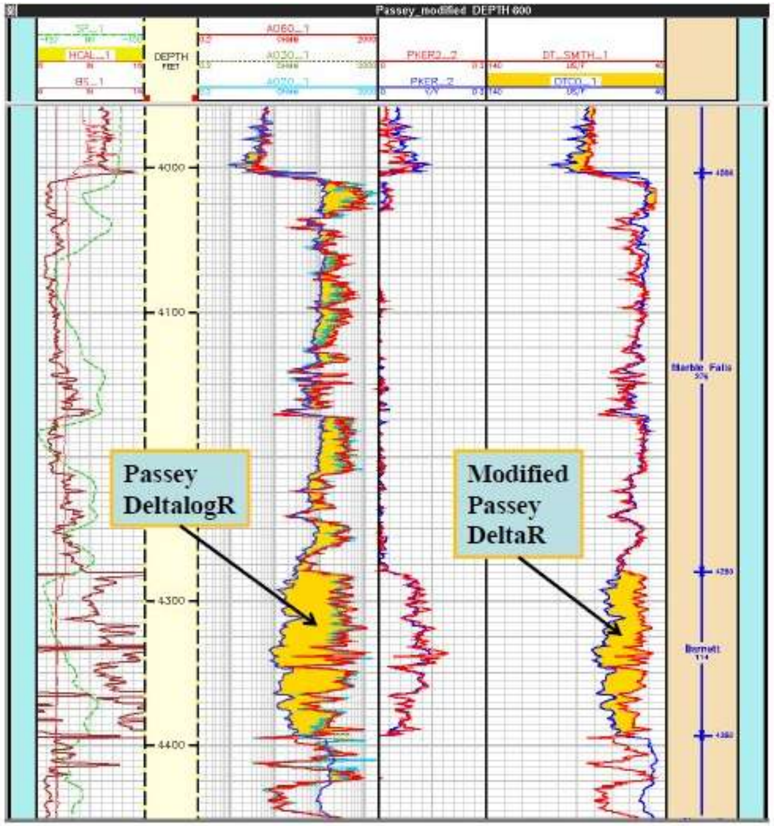
Modified Passey Approach



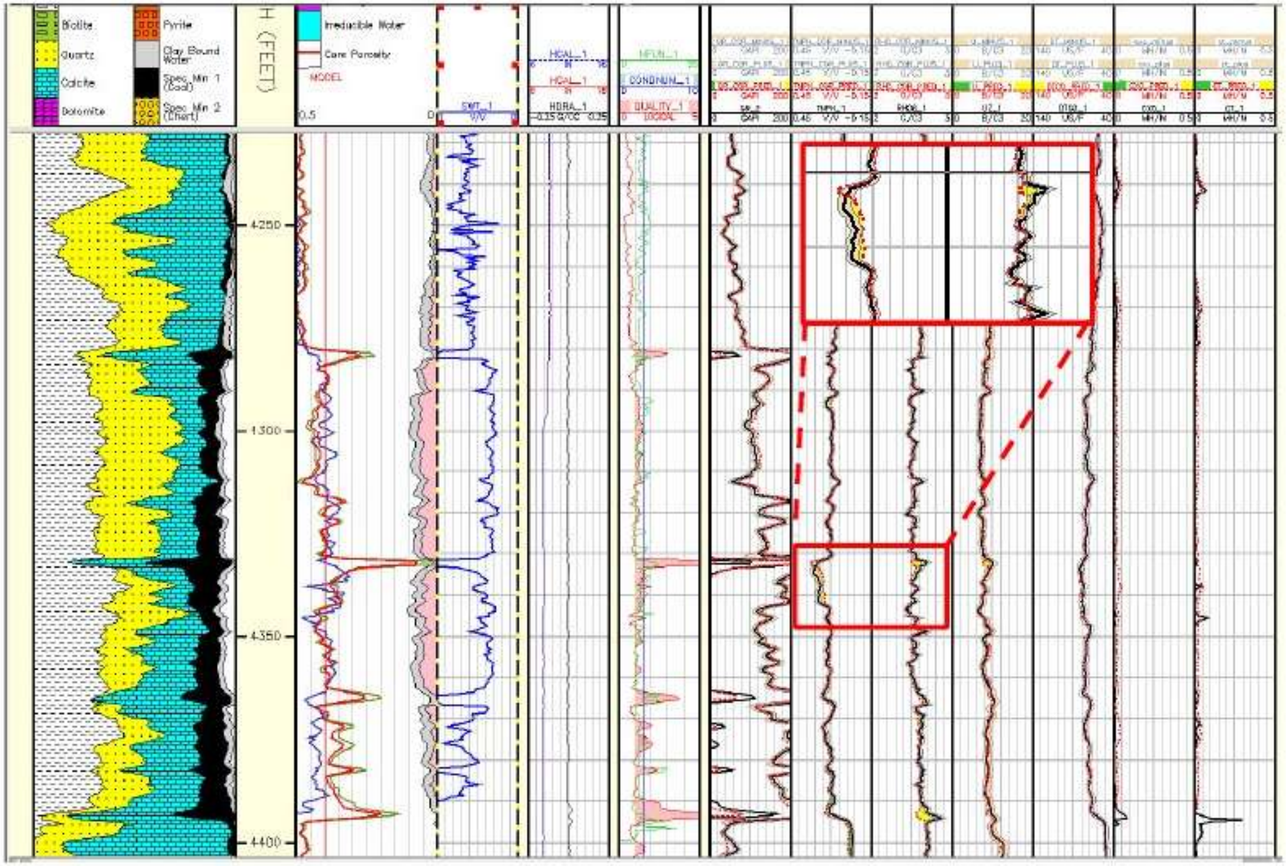
The modified Passey approach is to model a sonic curve using a resistivity transform (Smith in this example) and then compute the Kerogen volume using the following algorithm:

```
KER = (PCOEFF * (DT - DT_COMP))/100
```

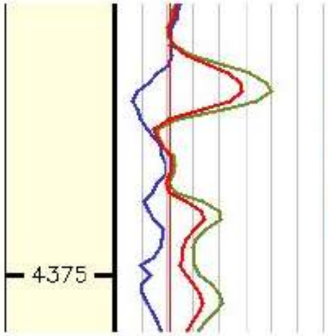
The PCOEFF constant is no doubt related to Kerogen maturity and given sufficient data, this relationship could be quantified



Use Modified Passey Kerogen Volume as input to Multimin



The model is significantly improved with the addition of Kerogen as an input curve, but it still has issues.

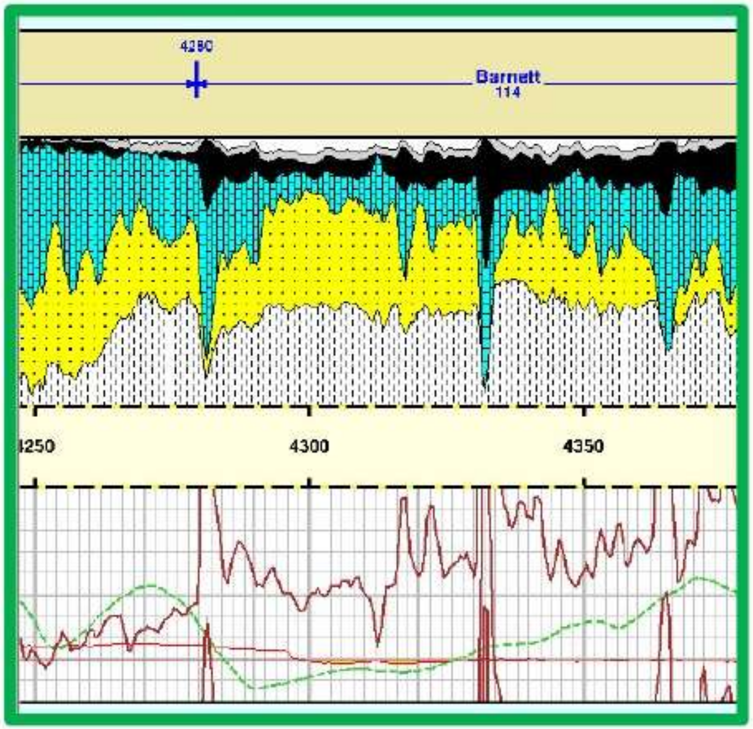


The Kerogen content has been reduced in the highest GR areas

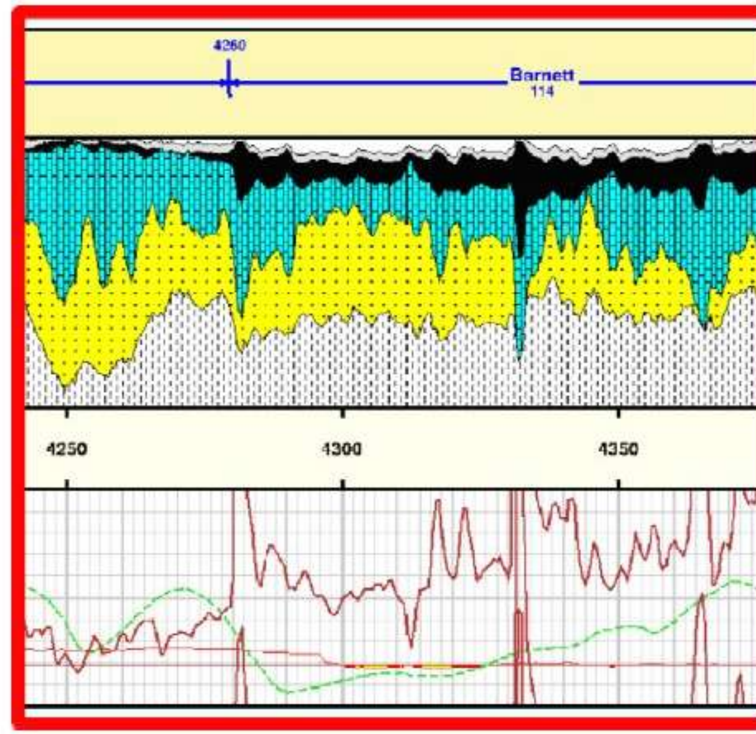
The red curve is the newly calculated Kerogen, while the blue is the modified Passey and the green curve is the original multimin using GR.

Paradigm®

Comparison of Multimin Results



Multimin Model with Radioactive Coal



Multimin Model with Radioactive Coal
and Kerogen from modified Passey

Add a second Special Mineral (Pyrite) to the Multimin Model

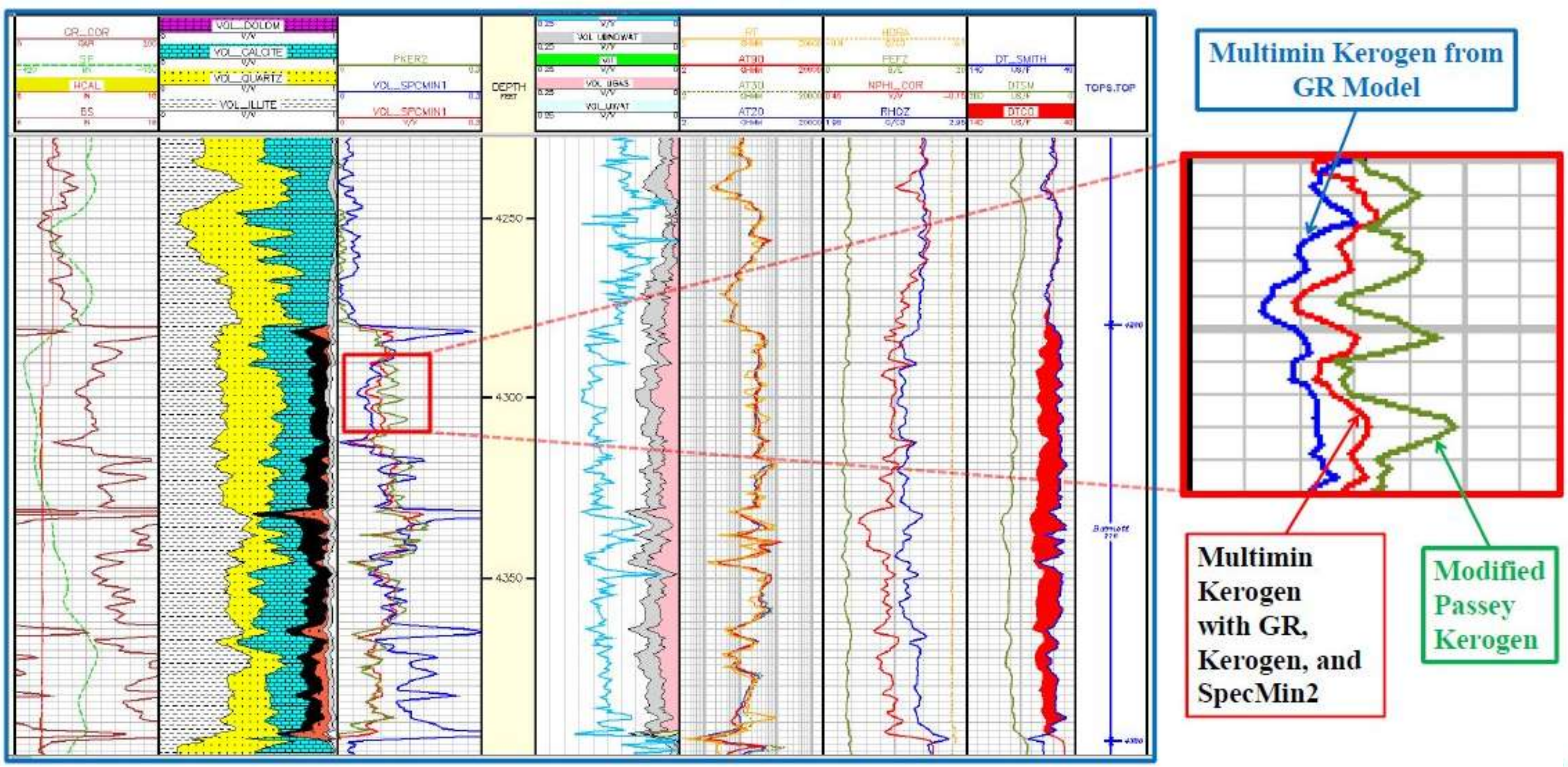
Special Mineral 2 has properties very similar to that of pyrite. The parameters have been modified to provide a better fit to the log data.

	Quartz	Calcite	Illite	Spec Min1	Spec Min2	X Gas	X BndW	X FreeW	U Gas	U BndW	U FreeW	Units
RHO_COR	2.644	2.71	2.88	1.2	4.4	0.07719	0.9853	0.9853	0	0	0	G/C3
TNPH_COR	-0.025	0	0.23	0.61	-0.02	0.4449	0.9856	0.9856	0	0	0	V/V
DTCO	50.4	47.6	72	105	47	250	189	189	0	0	0	US/F
U	4.8	13.92	9.6	0.28	30	0.02473	0.4017	0.4017	0	0	0	B/C3
GR_COR	5	10	140	700	1400	0	0	0	0	0	0	GAPI
VELS	1.351e+(	1.073e+(	6100	5400	1.5e+04	0	0	0	0	0	0	F/S
CT	0	0	0	0	0	0	0	0	0	18.51	18.48	MH/M
CXO	0	0	0	0	0	0	18.51	0.8255	0	0	0	MH/M
PKER2	0	0	0	1	0	0	0	0	0	0	0	V/V

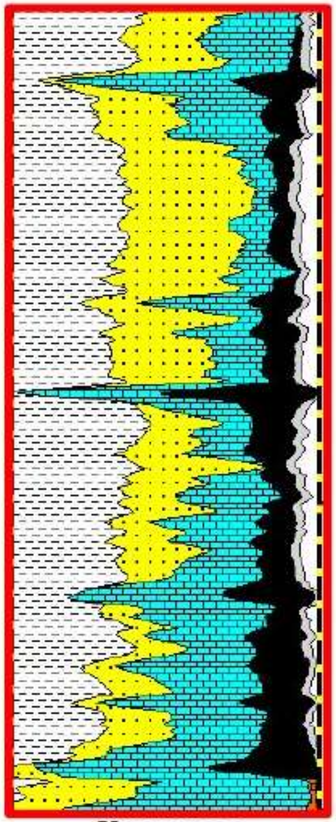
The parameters for Special Mineral 1 have been modified

The values for Special Mineral 1 more closely resembled coal rather than Kerogen in earlier models. This issue has now been addressed.

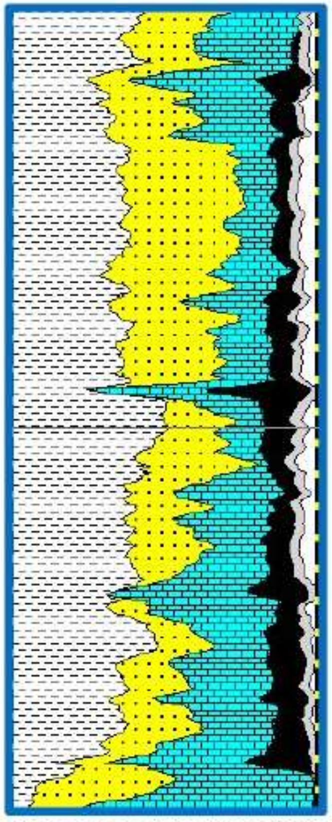
Multimin Model with Kerogen and Special Mineral 2



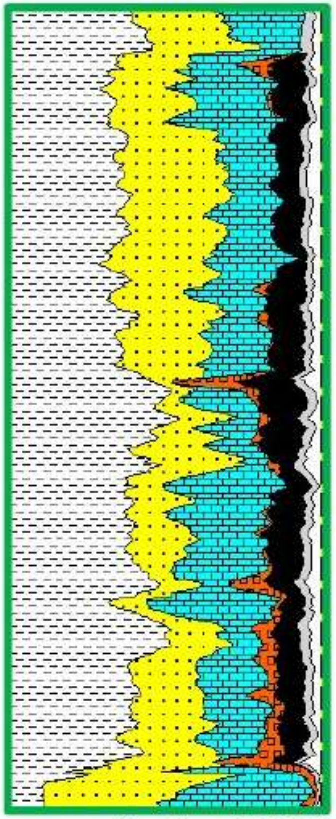
Comparison of Results



Kerogen as a
Function of GR

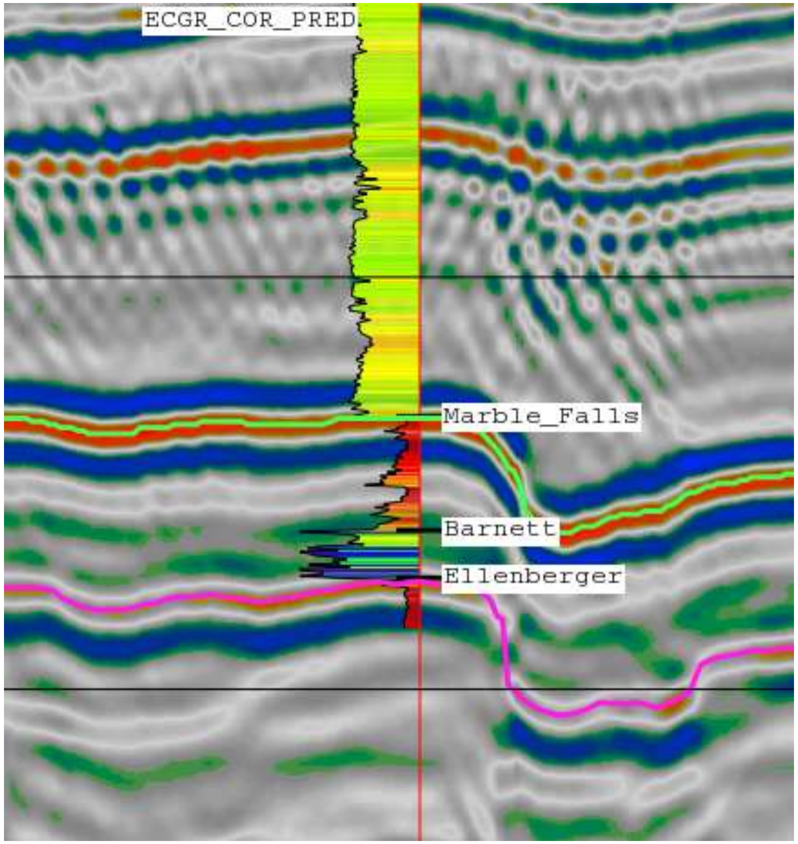


Kerogen as a function of GR
and Modified Passey Kerogen



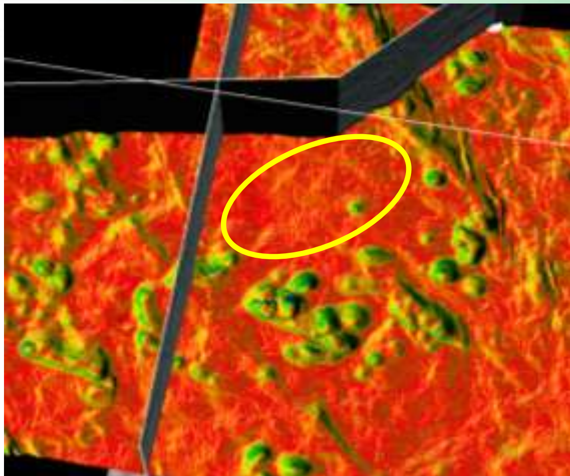
Kerogen as a function of GR, Modified
Passey Kerogen, and SpecMin2

Seismic Interpretation

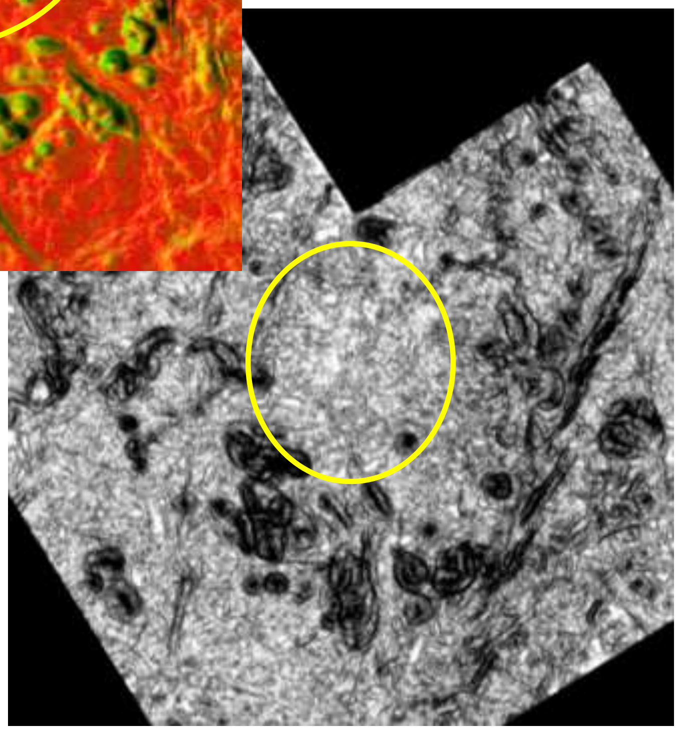


- Correlate sweet zone from GR to seismic
- Interpret main seismic events bounding Barnett Shale with 3D Propagator

Seismic Interpretation



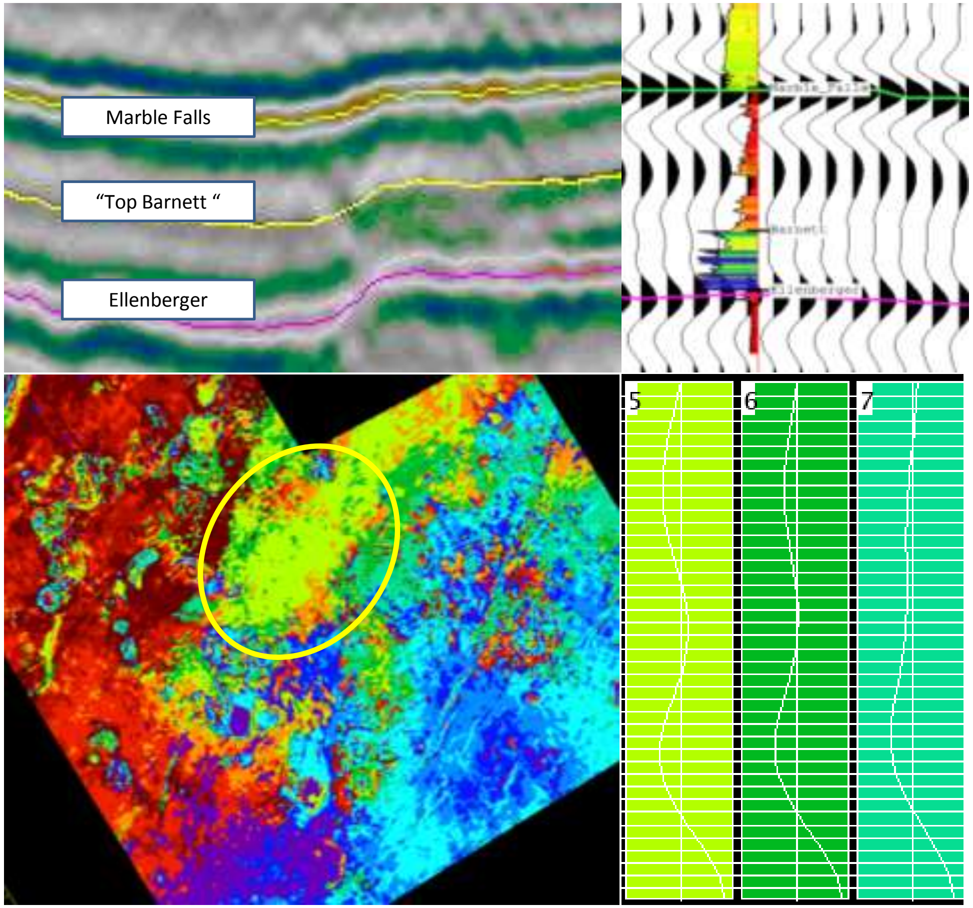
Dip



Eigen

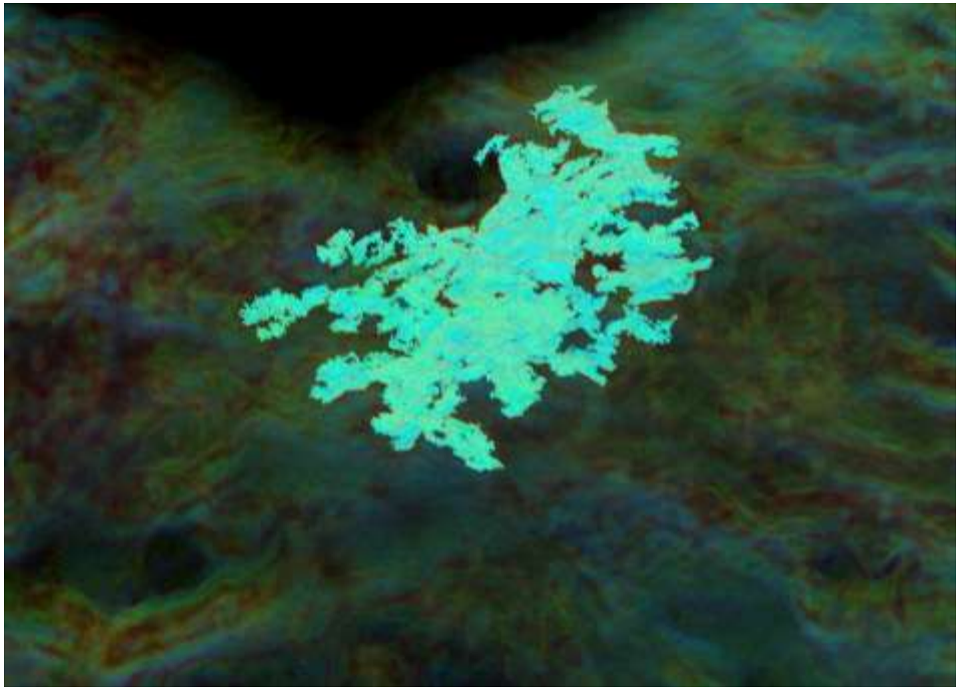
- Fault orientation
- Collapse structures originating in Ellenberger
- Circled area = AOI
- But does shale with the right qualities exist here?

Seismic Interpretation



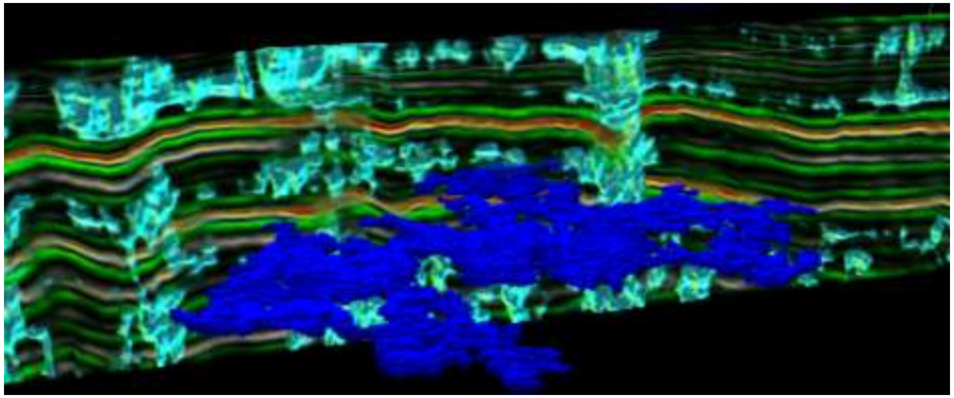
- Isoproportional layering
- Seismic facies classification over interval corresponding to Bartlett Shale
- Identify trace shape similar to Barnett Shale at well location

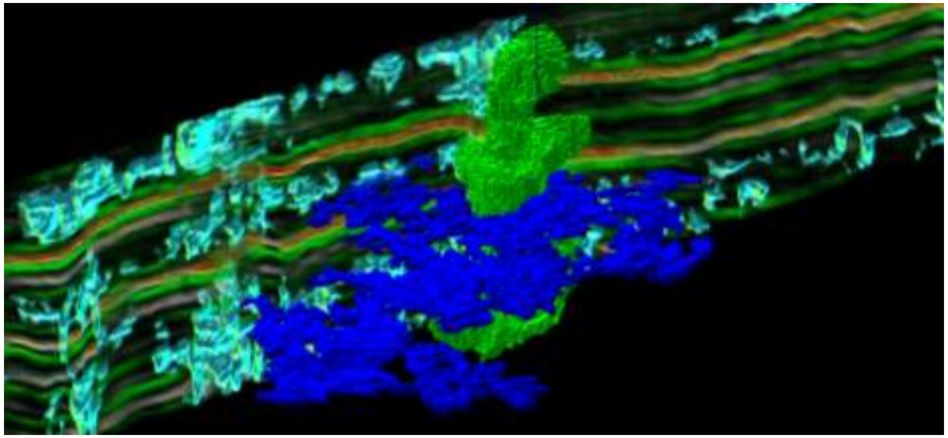
Seismic Interpretation



- Seismic facies classification to produce facies cube
- Isolation of sweet spot using sub-volume detection

Seismic Interpretation



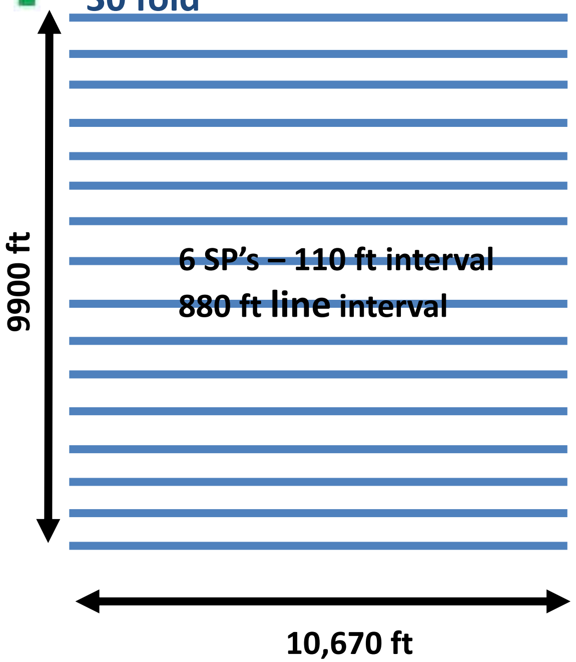


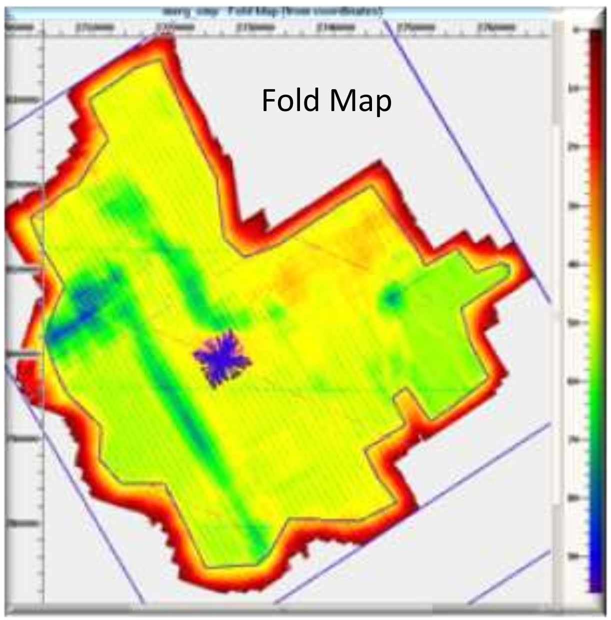
- Attribute mixing
  - Amplitude – stratigraphy
  - Eigen – structural

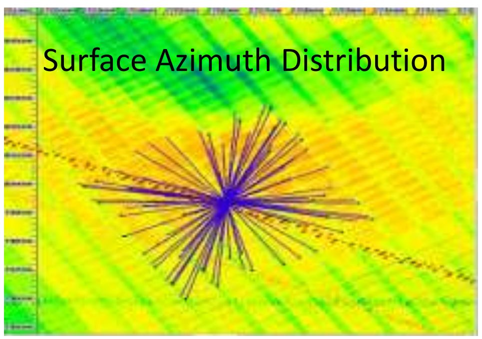
- AFE Eigen enhances collapse structures

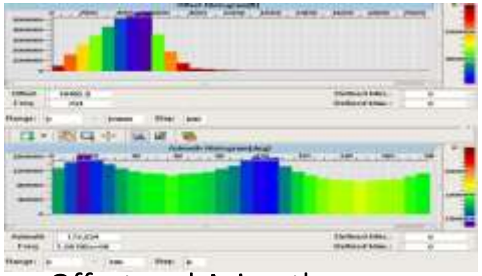
Survey Review

- Output Area ~ 75 Square miles
- 16 receiver lines, 98 channels each,
- 21,750 SPs (290 / sq mi)
- 29,100 Receiver Stations (388 /sq mi)
- 30 fold





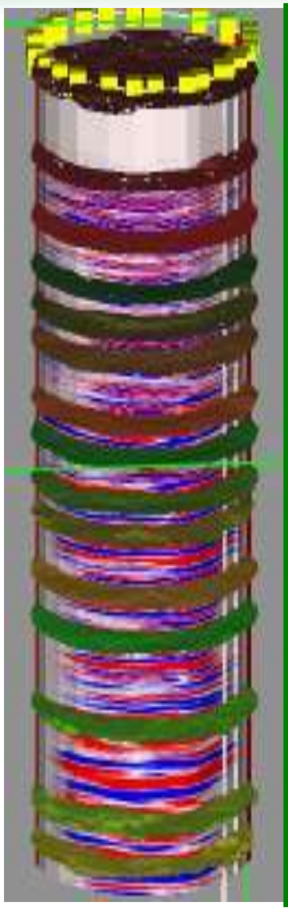


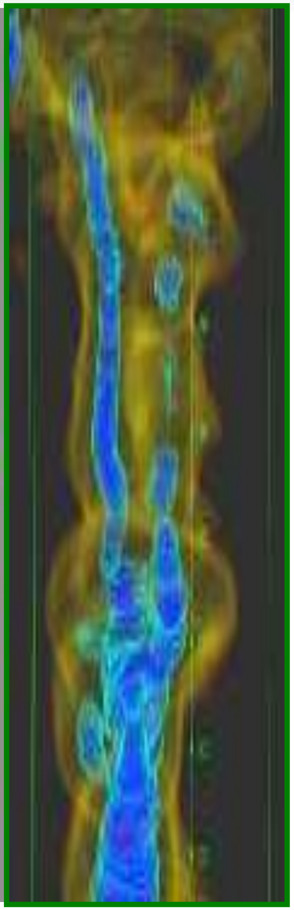


Offset and Azimuth Histogram

Seismic Decomposition

- Seismic imaging solutions differ in their ability to decompose the recorded wavefield into useful organized domains (Pre-stack Data)
- Subsurface domains are preferred to surface acquisition domains for decomposing seismic data
- Azimuth is a very useful domain for decomposition
- Can we recover in-situ and continuous azimuthal data from recorded seismic data?





Recovering azimuthal data with sectoring

- Sector Decisions
  - Driven by convenience
- Sector Resolution
  - Generally compromised
- Sector Effort
  - Quite onerous
- Sector Integrity
  - Not preserved

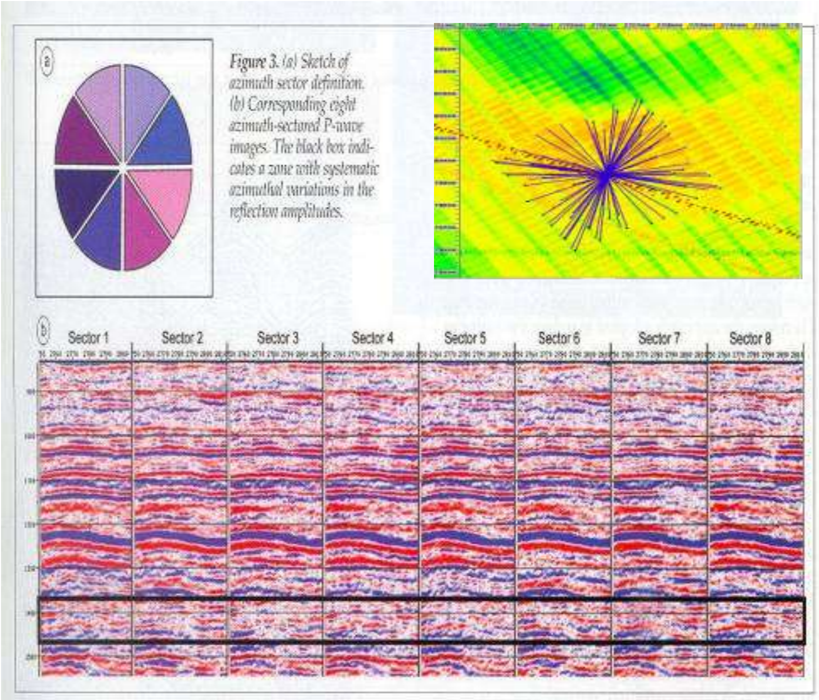
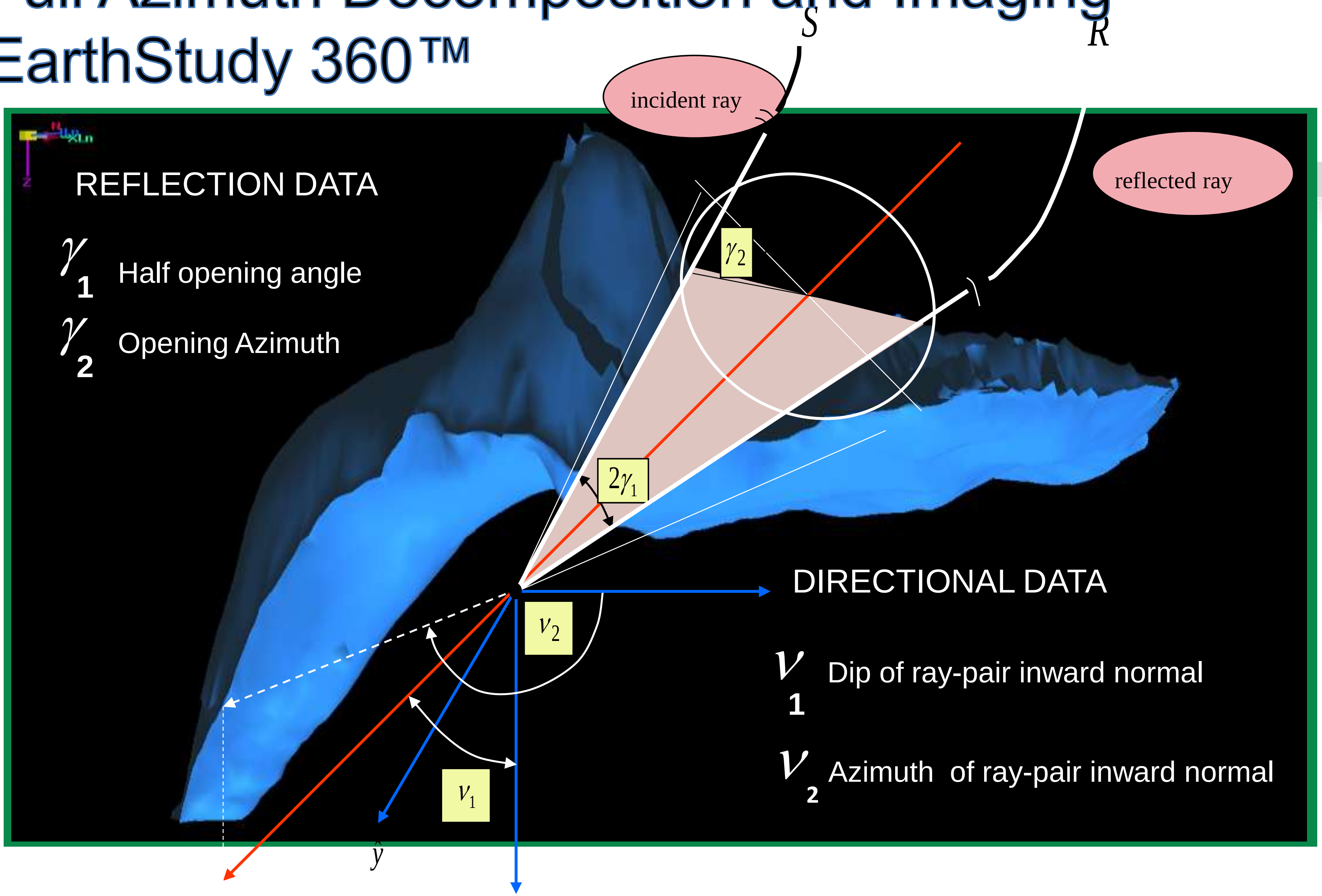


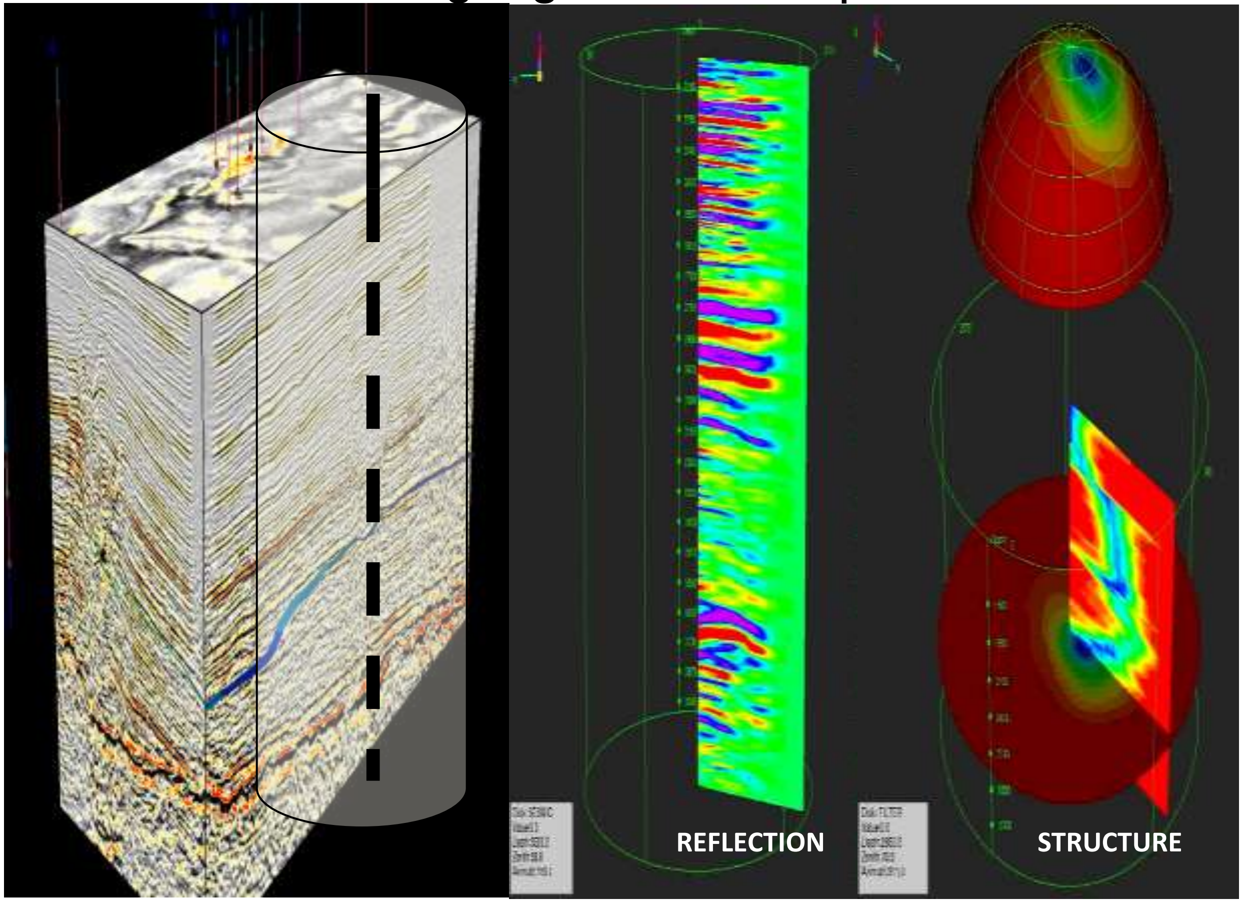
Figure 3. (a) Sketch of azimuth sector definition. (b) Corresponding eight azimuth-sectored P-wave images. The black box indicates a zone with systematic azimuthal variations in the reflection amplitudes.

Full Azimuth Decomposition and Imaging EarthStudy 360™



Decomposition in the local angle domain

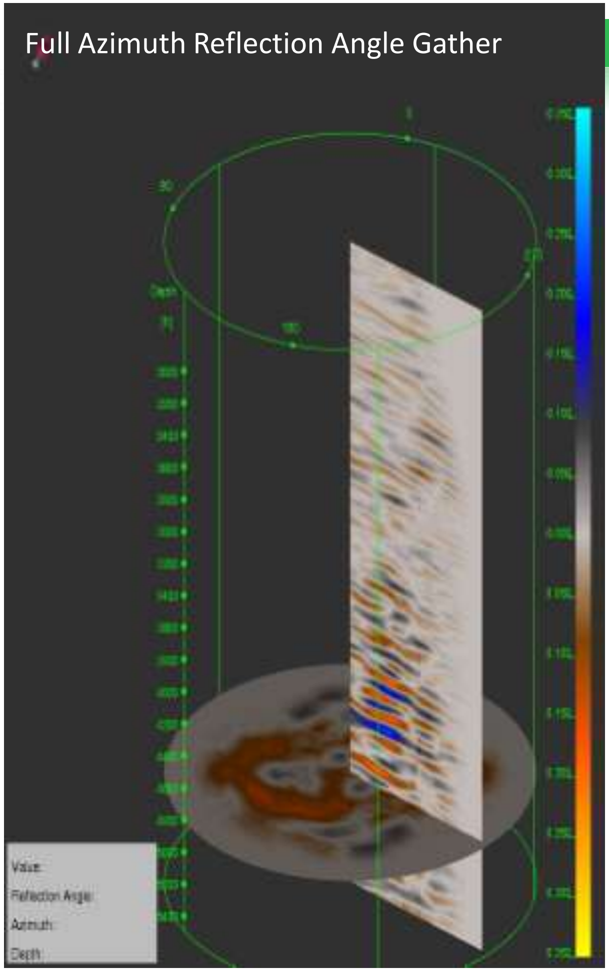
- Full azimuth angle gathers in depth

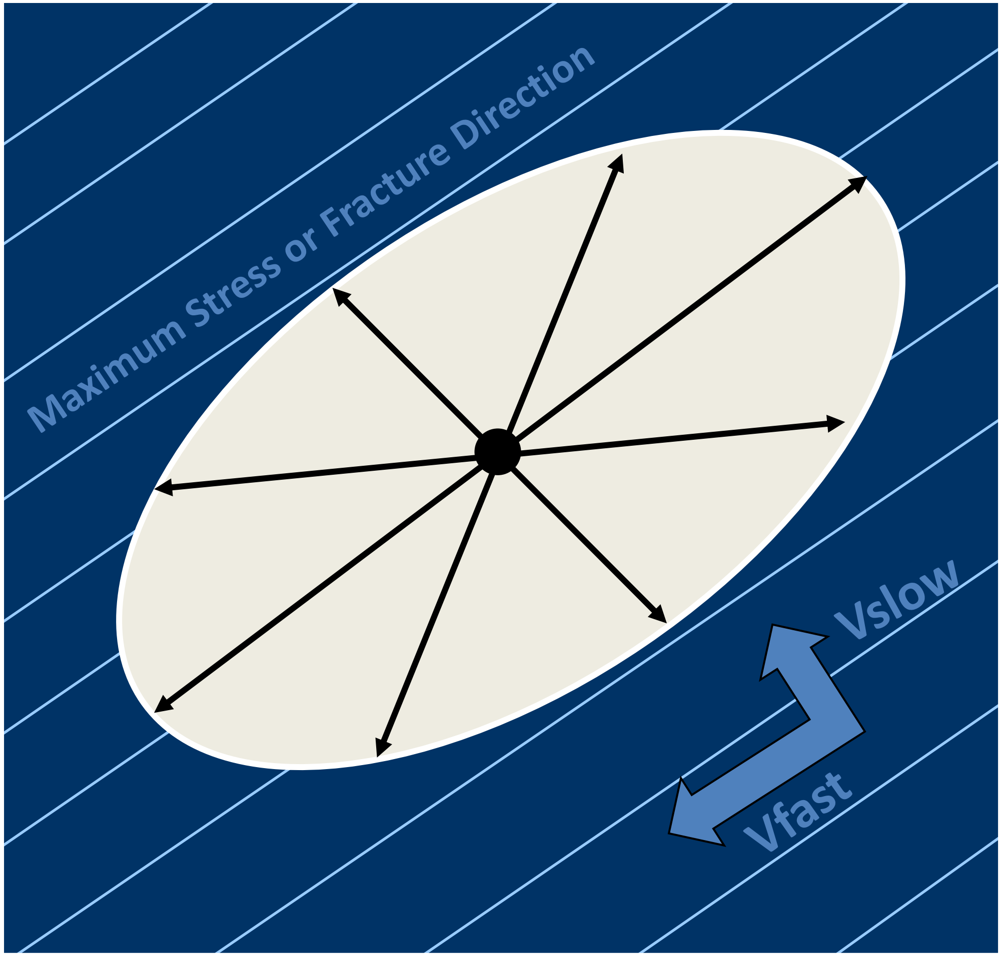


- **EarthStudy 360 Full Azimuth Decomposition**
  - Reflection and structural
  - Specular and scattered
  - Primary and multiple

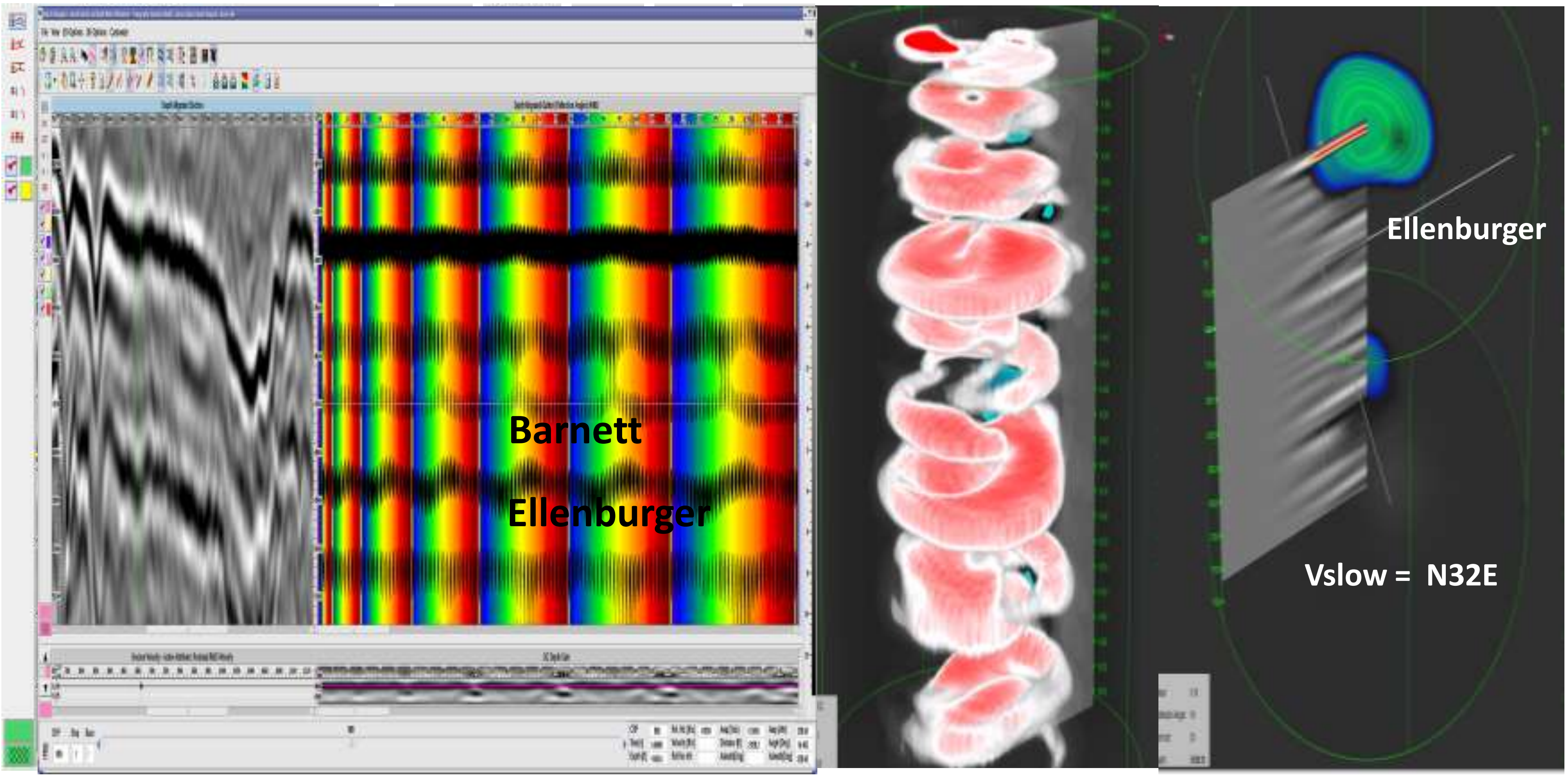
Stress orientation and intensity determination

An anisotropic (HTI) Problem…i.e. a directional problem



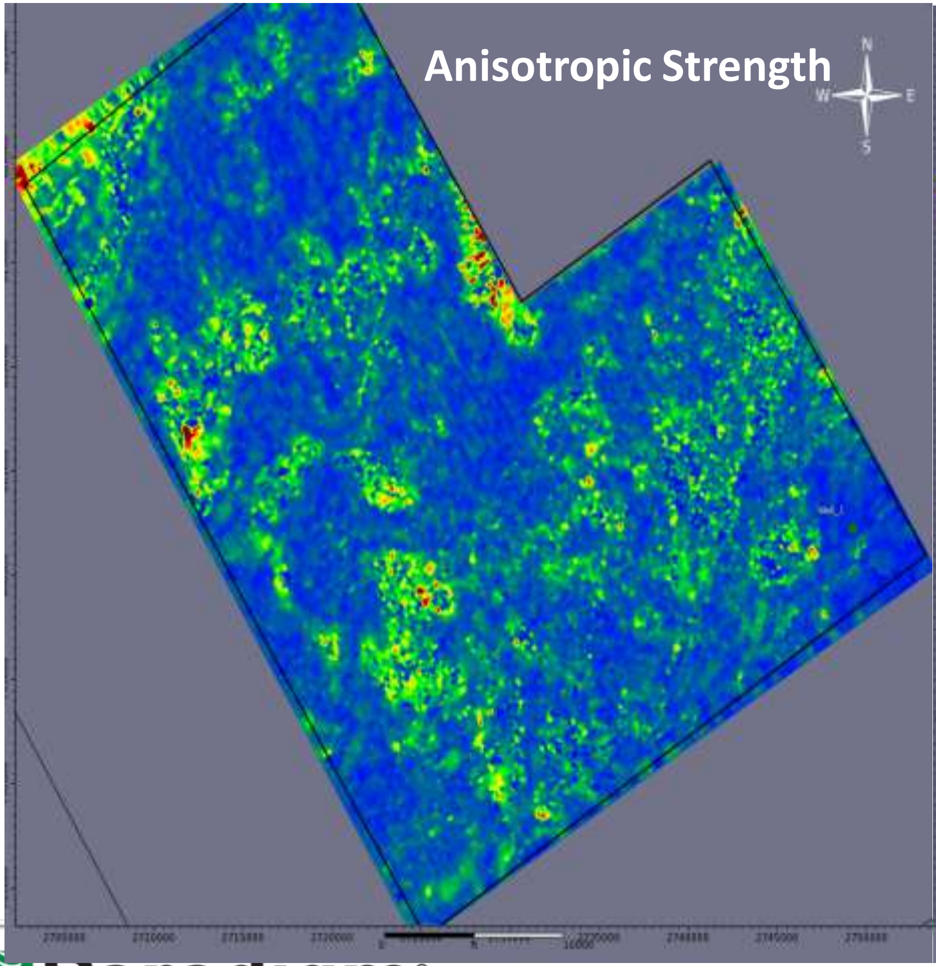


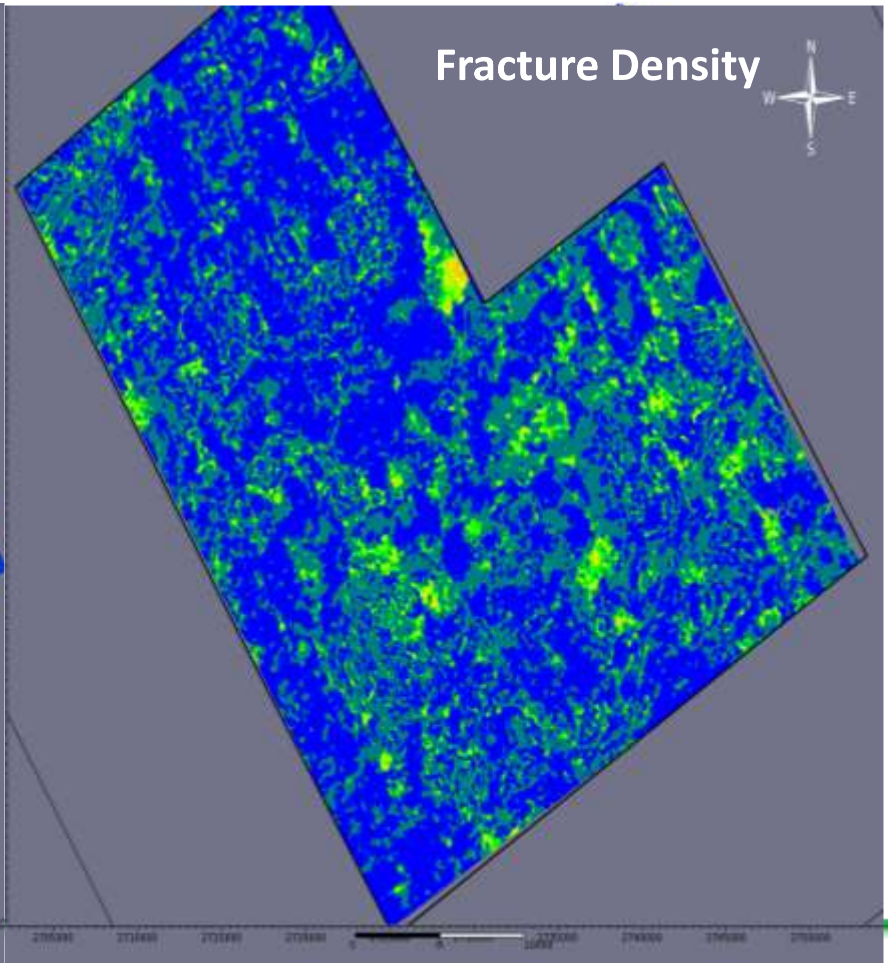
Decomposition in the local angle domain



Full Azimuth Inversion

- Residual Moveout Inversion AVA(Z) Inversion



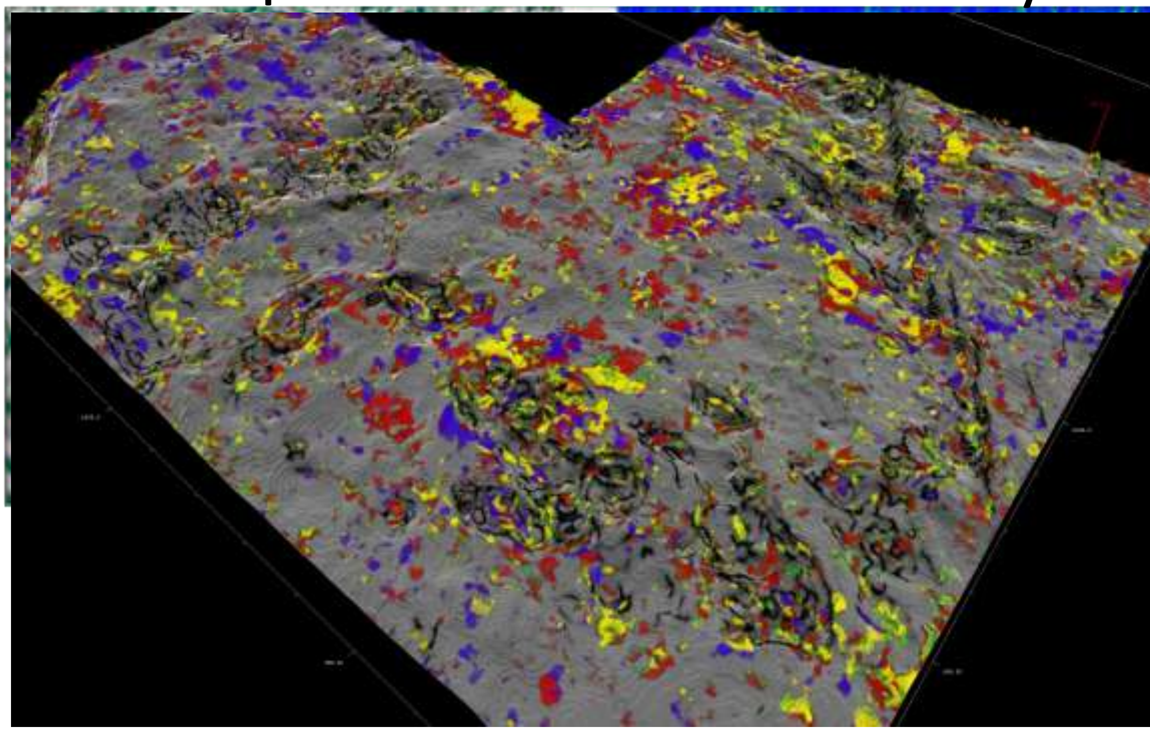


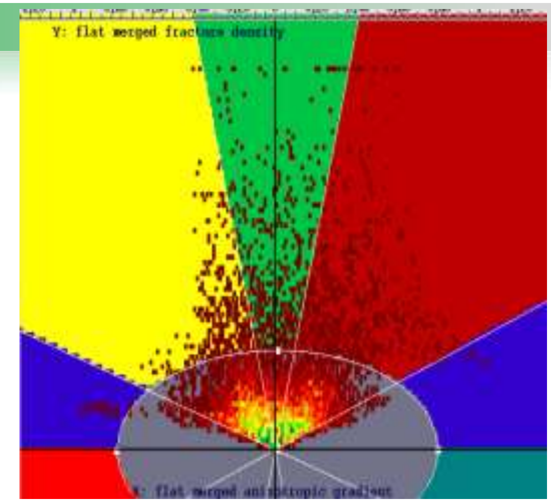
Paradigm®

Example 1

Cross plotting of Anisotropic Gradient and Fracture Density

Anisotropic Gradient **Fracture Density**



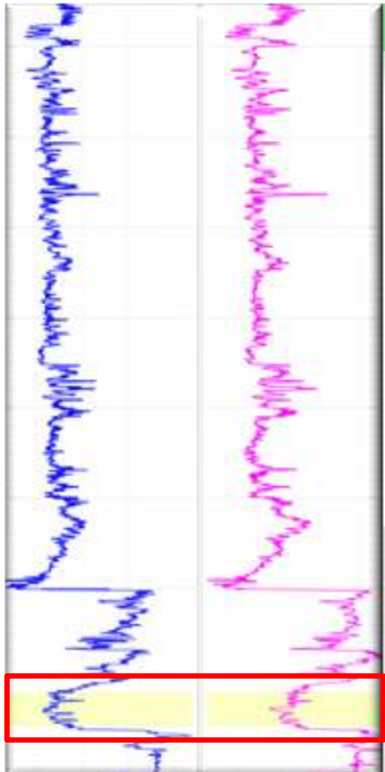


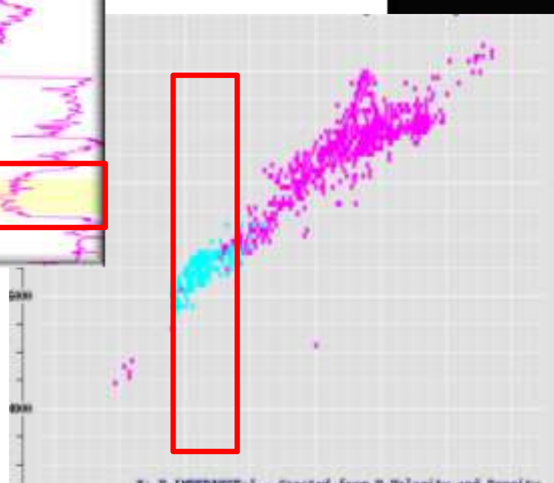
Fracture Density

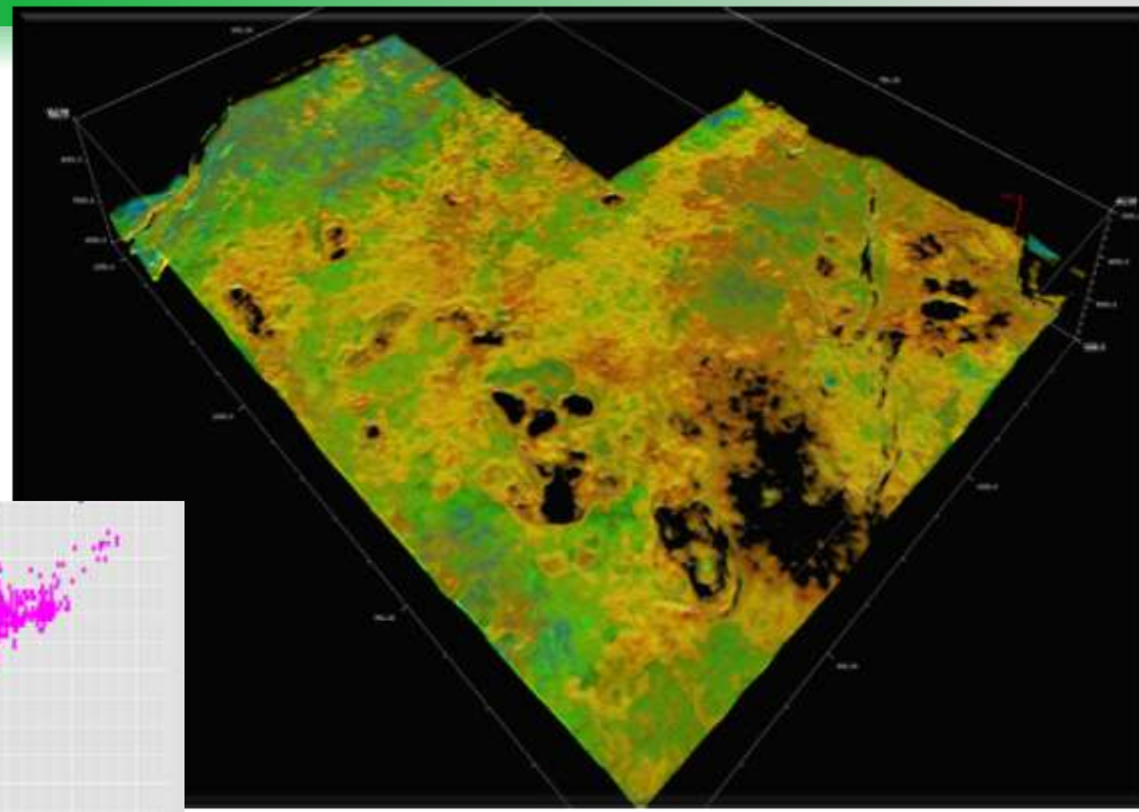
Anisotropic Gradient

Example 2

Impedance and thickness of Barnett shale



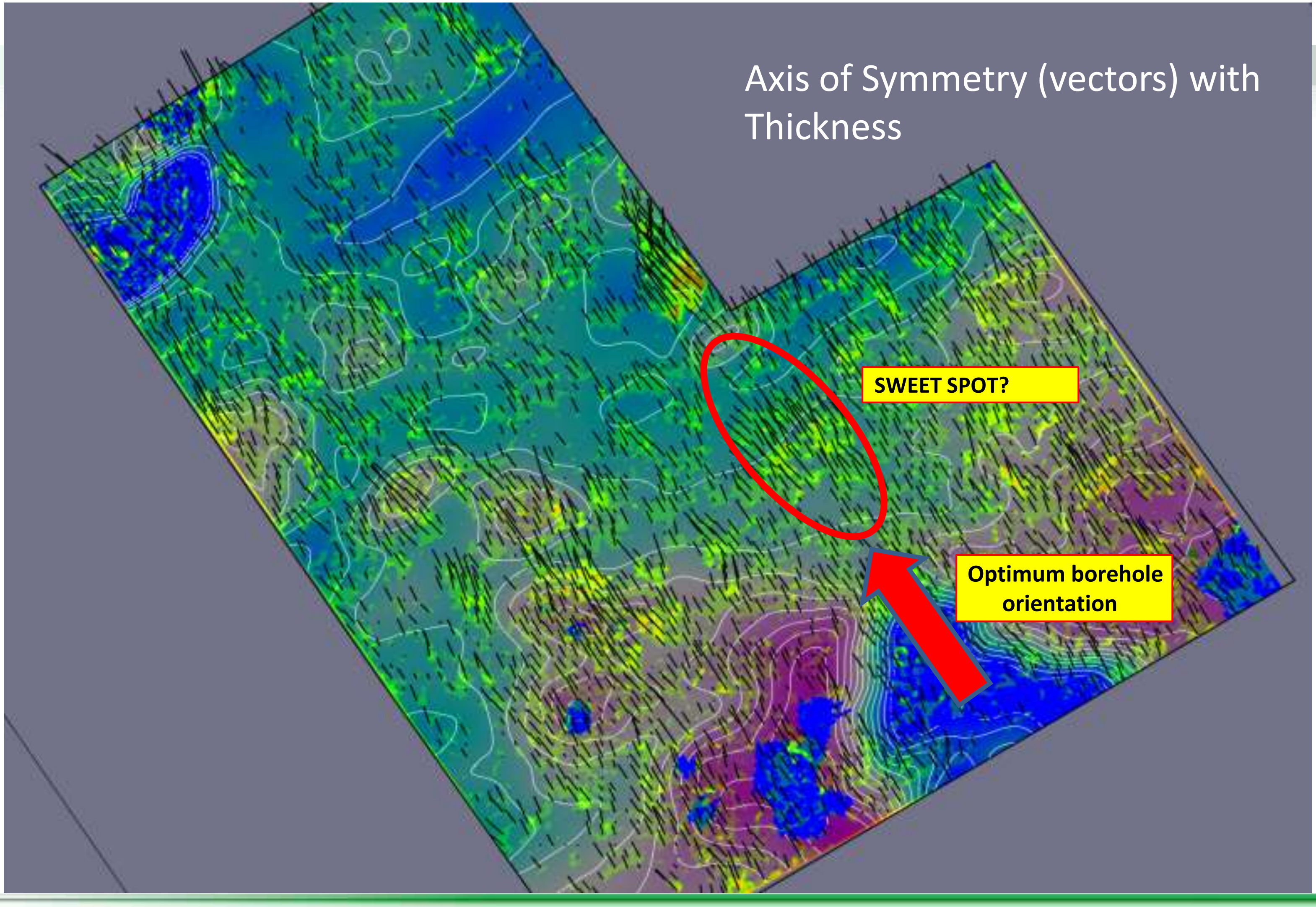




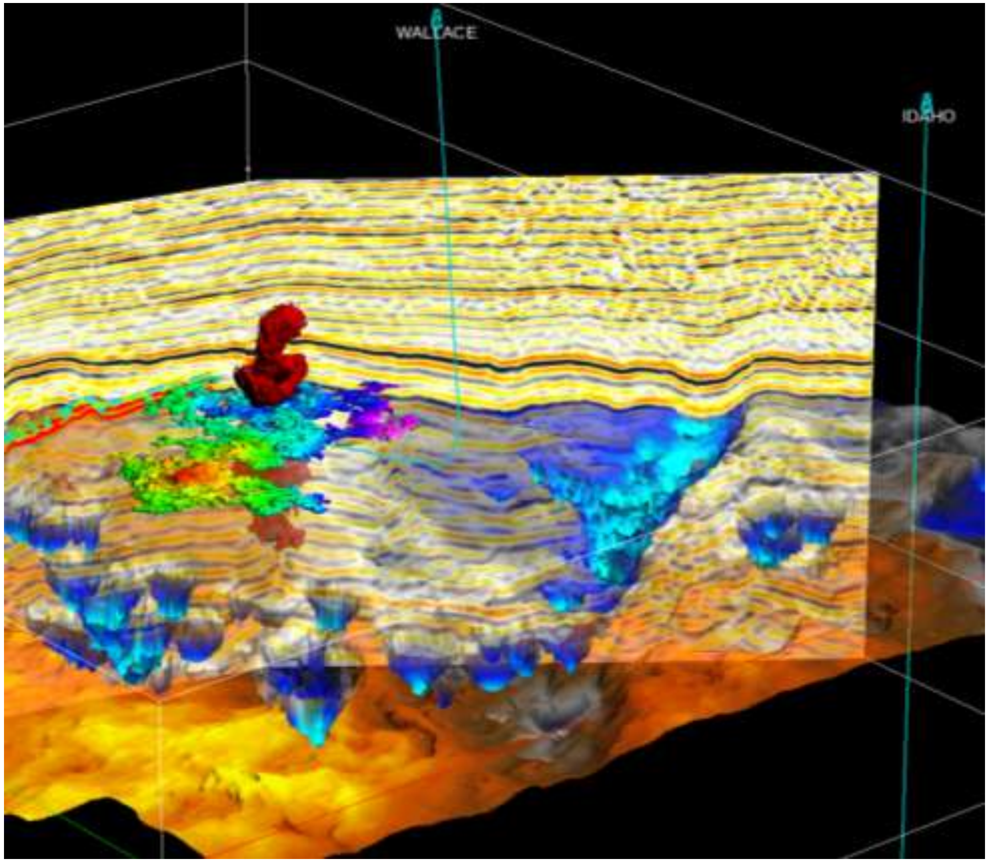
Black is zero thickness,
Green is maximum thickness

Example 3

Co-visualization of Axis of Symmetry and thickness



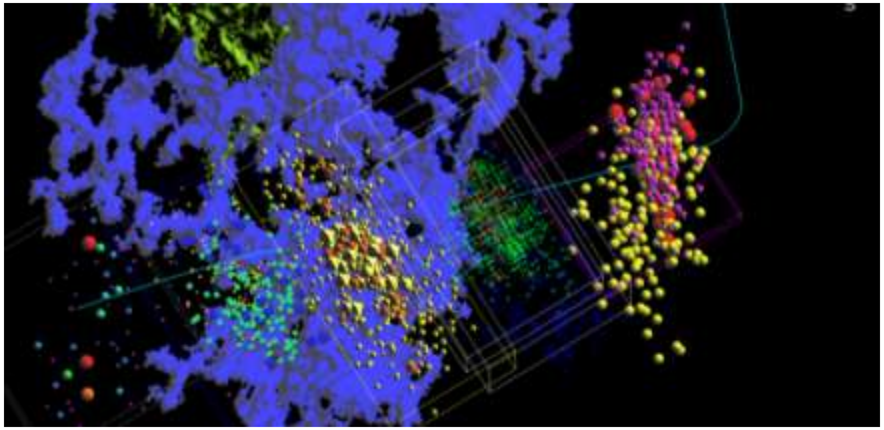
Seismic Interpretation

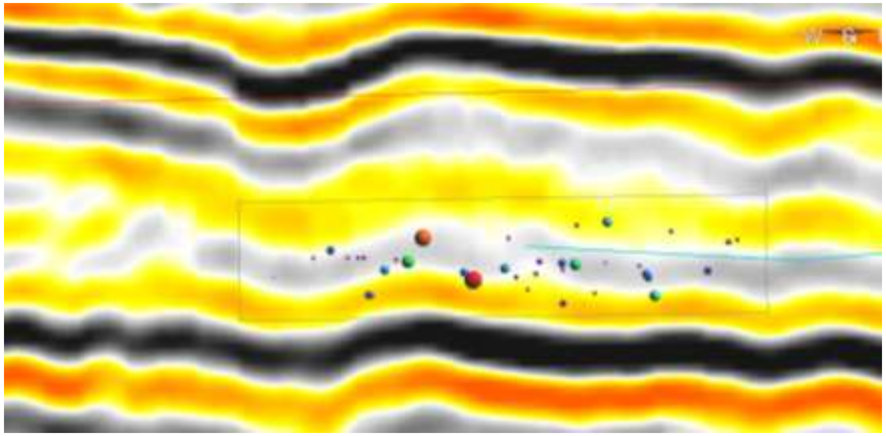


Workflow so far....

- Brittle / high TOC shales identified from log data
- Correlated to seismic and shale zone interpreted
- Seismic facies at well location identified in other areas
- ‘Sweet spot’ isolated and karst interpreted
- Optimum Borehole Orientation defined
- Zone identified for hydraulic fracture stimulation

Fracture Monitoring





- Well Planning:
  - Avoid karsts
  - Avoid water bearing Ellenberger
- Fracture development:
  - Avoid penetrating karsts
  - Degrades gas recovery
- U.S. Env. Protection Agency, Safe Drinking Water Act 1974
- Injection fluids / waste water
  - Far below drinking water supplies
  - 1 mile of impermeable rock

Summary

- Integrated environment from petrophysics to geological modelling
  - **Paradigm Geolog™** petrophysics
  - **SeisEarth™** seismic interpretation
  - **Stratimagic™** seismic facies analysis
  - **VoxelGeo™** visualisation
  - **EarthStudy360™** Full Azimuth Seismic Decomposition
  - **SKUA™** well planning and structural modelling

- Efficient, unrestricted workflows maximising data sharing

- Total freedom to explore your data

Thankyou!

Like to know more?.....Visit us later

Paradigm®

Vision for Energy