Geomechanical Controls on the Gas Production in the North Parachute Area, Colorado*

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Abstract

Tight gas plays often need a natural fracture network to provide sufficient system permeability for commercial production rates. Although hydrocarbon production is correlated to higher reservoir porosities and lower water saturation, production is enhanced where the stress state and fracture orientations interact to enhance fracture aperture, and increase the permeability of the natural fracture network. This study shows that geomechanical and structural factors are key controls on gas production in the North Parachute area of the Piceance Basin.

Structural analysis provided the basic framework for this geomechanical study. A systematic workflow was developed to analyze regional and local scale reservoir features in the context of the multiple regional tectonic events and cycles of syn-tectonic sedimentation. This analysis indicates that the thrust fault at depth within the study area was reactivated in compression during the Laramide Orogeny, whereas NW- and NE-striking normal faults at reservoir depth are neo-formed and younger.

To analyze the effect of stress heterogeneity on fractures and reservoir scale faults, geomechanical analysis was conducted at the wellbore- and field-scale. Boundary element modeling (BEM) was used to predict the pattern of sub-seismic fractures associated with faulting. Finite element modeling (FEM) was used to investigate the effect of the topography, faults, and mechanical stratigraphy on local stress variation. Local stress variation was calibrated by stress gradient at the well-scale. A multivariate analysis and prediction approach to permeability modeling is undertaken to integrate geomechanical influences with other effects on permeability. The results indicate that gas production in the North Parachute area is ~82% correlated to geomechanical effects. This correlation can be explained by permeability enhancement due to natural fractures that interact favorably with the present-day stress environment. This

study indicates that the first-order geomechanical and lithological modeling can be used to assess the system-scale effect on fracture permeability and therefore can be used to identify sweet spots in tight sand reservoirs.

Reference

De Voto, R.H., B.L. Bartleson, C.J. Schenk, and N.B. Waechter, 1986, Late Paleozoic stratigraphy and syn-depositional tectonism, northwestern Colorado, *in* D.S. Stone, (ed.) New interpretations of northwest Colorado geology: Rocky Mountain Association of Geologists Guidebook, p. 37-49.

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Notes by Presenter: Good morning everyone. I will talk about "title".I want to acknowledge my co-authors for their contributions in this project. This project is an integrated work among Regional and Local scale structure geology and wellbore and reservoir geomechanics. I will go through the integration workflow and related conclusions.

Outline

- **Regional structural geology and 3D-framework**
- Outcrop and Wellbore observations
- Correlation to Gas production (MV analysis)
- Reservoir scale stress modeling
- Conclusions
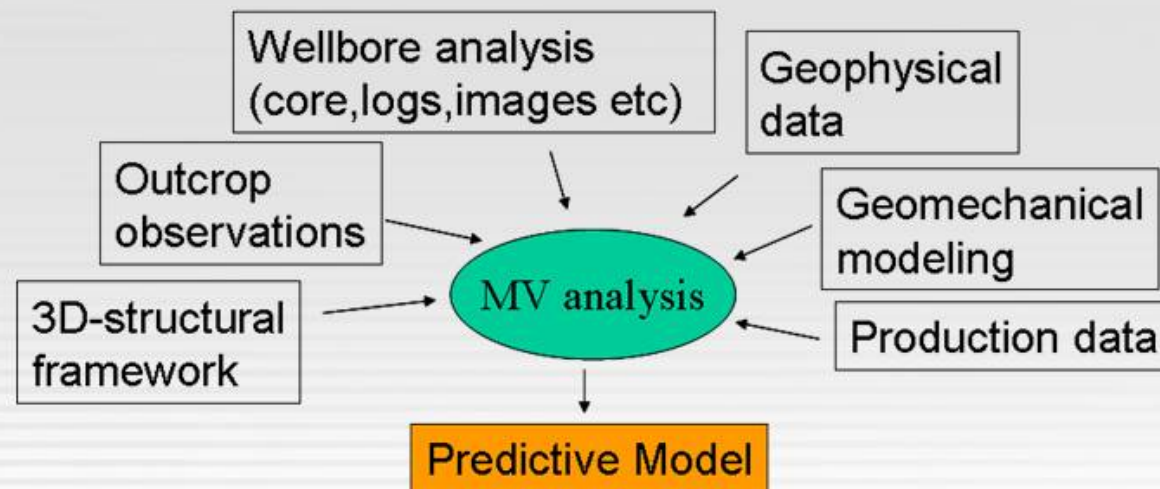
Notes by Presenter: This is outline of my talk. I will start with regional structural geology and development of 3D-framework. Then I will discuss the outcrop and wellbore observations. Third part will be integration of data using multi-variate analysis. As shown below various kind of observations and studies including geomechanical modeling has been integrated using the multi-variate analysis. I will focus on geomechanical modeling, which came out as one of the most important factor correlated to Piceance gas production.

# Piceance Basin in context: the Laramide Orogeny
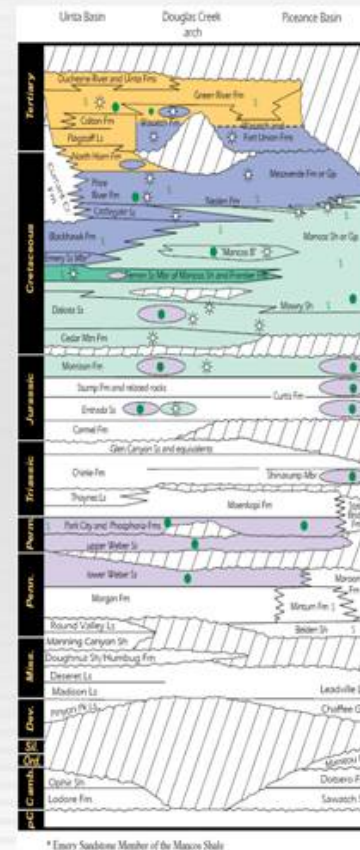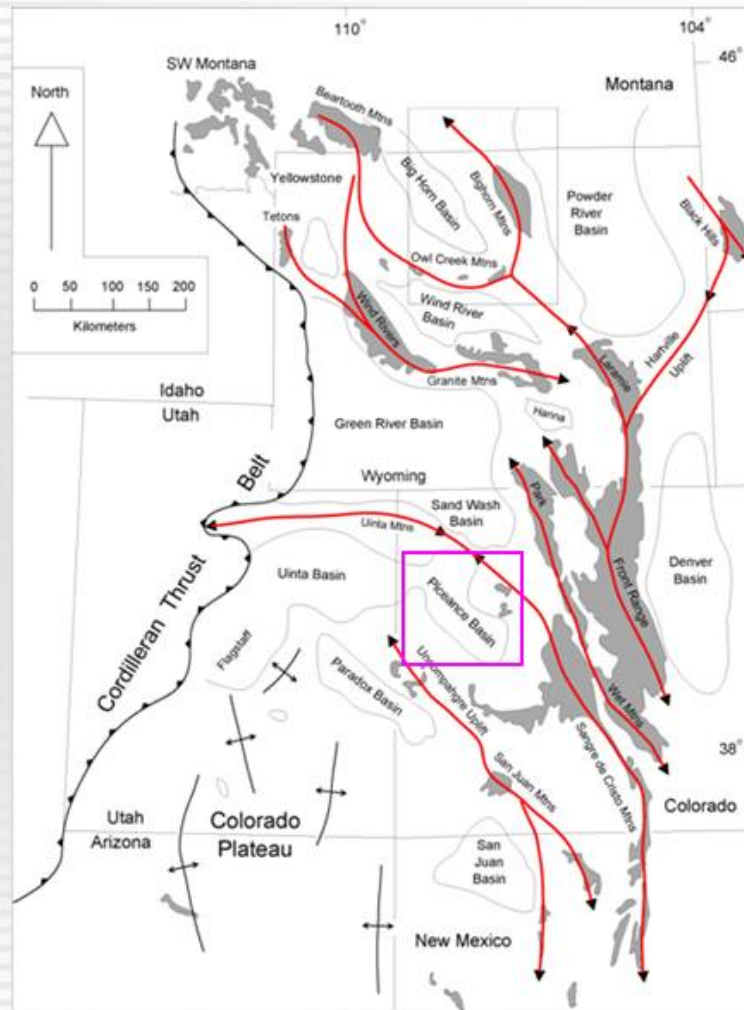
Notes by Presenter: Piceance basin is located in the north of Colorado. It is considered to have a syntectonic origin with the Laramide Orogeny (~70-55 Ma). We will see the regional structural framework in the next Slide..

On the right you see a generalized stratigraphic column. William Fork is the main reservoir, which is a tight sandstone. Cameo Coal just below this formation is considered as the source rock for this reservoir.
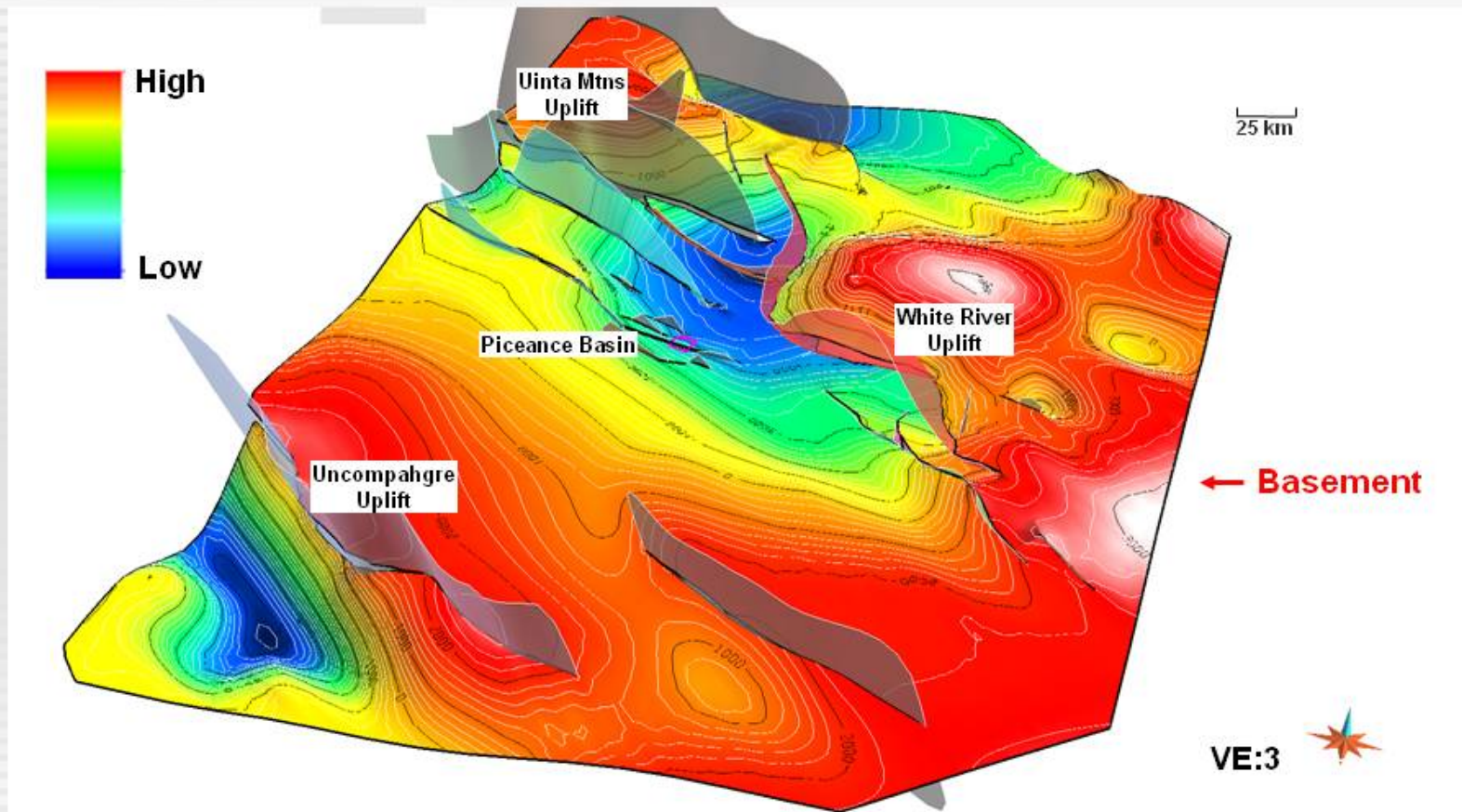
Notes by Presenter: This is the basement horizon at regional scale. Piceance basin is located on the west side of White River uplift. As you can see, in the study area basement is intersected by few reverse faults. The majority of basement-cored faults reactivate Proterozoic & Paleozoic structural trends and Proterozoic rifting in the Uinta Mountains (De Voto et al. 1986)

Local Structural Setting
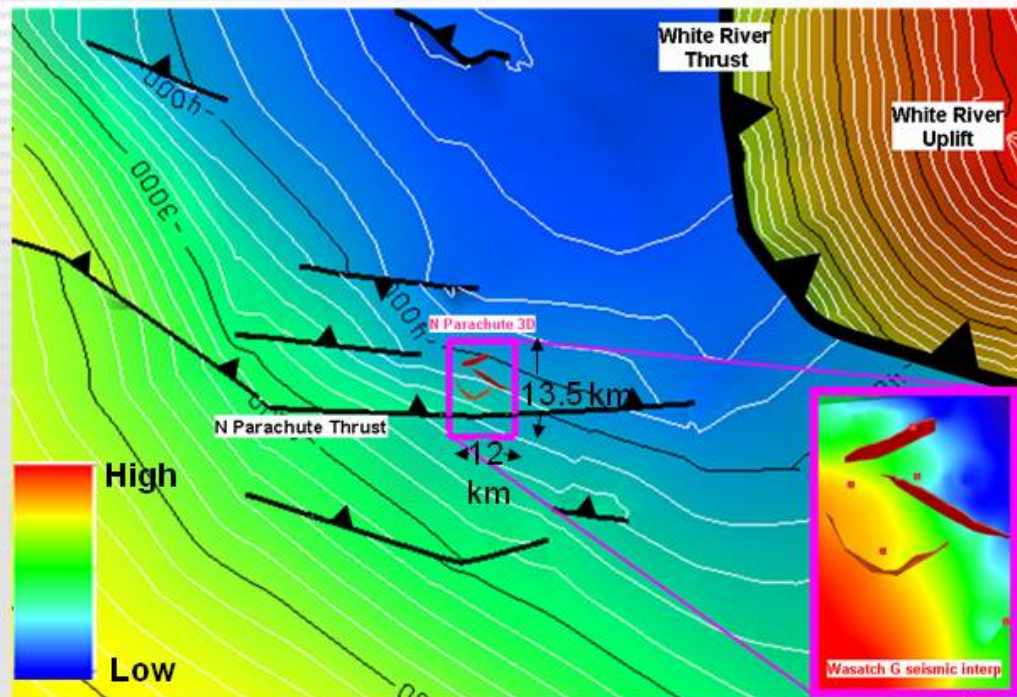
general homoclinal dip to the north

shallow normal faults with ~25-50 m throw

situated above a reactivated basement thrust
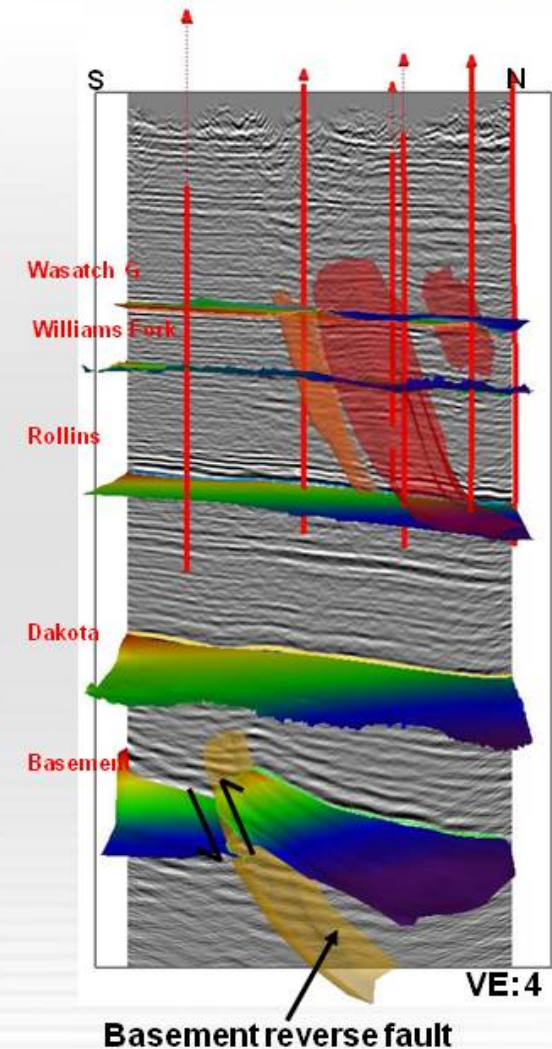
Notes by Presenter: This is a closeup look at reservoir depth. There is a general homoclinal dip to the north. We see shallow normal fault with ~25-50 m throw. As shown in the cross-section map these shallow faults are situated above a reactivated basement fault and intersect william fork and wastach formations. Several wellbores cross mapped faults within the Wasatch and Williams Fork Fm.s, so we wanted to know any link between the well production with the 3D-structural framework. This 3D-framework was used as a base structure for the geomechanical modelings.
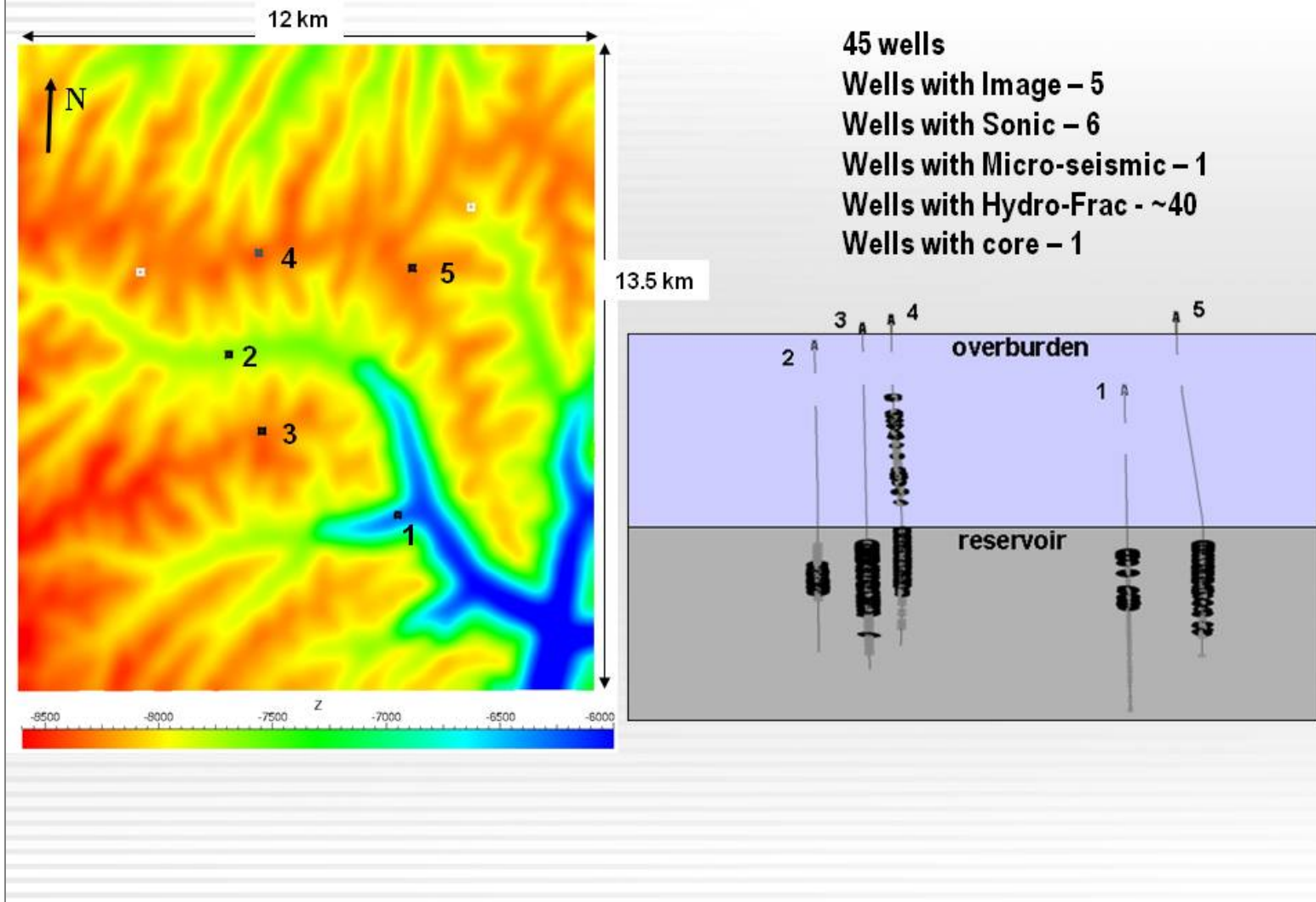
Outline

- Regional structural geology and 3D-framework
- Outcrop and Wellbore observations
- Correlation to Gas production (MV analysis)
- Reservoir scale stress modeling
- Conclusions

Notes by Presenter: Next step was to correlate outcrop and wellbore observations in a context of 3D-framework and reservoir production.

Notes by Presenter: Topography of the North parachute area, which is included in the geomechanical study. We had ~45 wells in this area with 40 hydraulic fracture data. Five of the wells have image and sonic data for fracture and stress characterization. As indicated on the map and cross section, these wells are located at topographically different locations. The elevation difference between well 1(a valley well) and 5 (a mesa well) is ~2500 ft.

We also did few outcrop studies of William Fork sandstone

Natural fracture in the William Fork formation
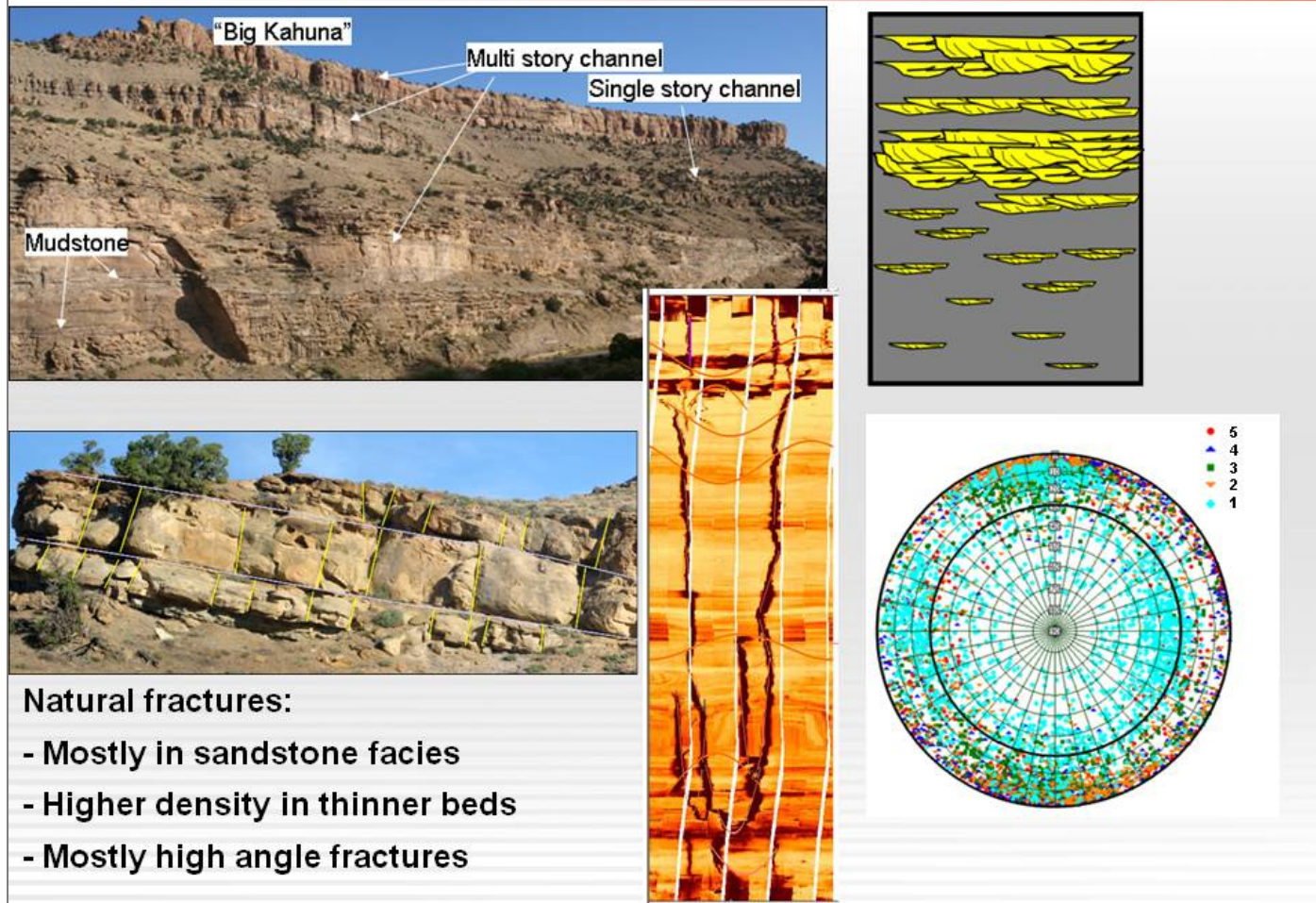
Notes by Presenter: As indicated on the top figures, William fork sandstone is made of single and multi-storage channel deposits, which gives different thickness to sand units. Bottom Figure indicates fractures intensity related to bed thickness. Fractures are generally observed in sandstone units. More fractures are observed on thinner beds. Fractures generally have high angle.

Image log also support the field observations, which indicate bed-bounded sub-vertical fractures. Stereonet plotting the orientations of all fractures interpreted within the Williams Fork unit from the five wells. Interior heavy black circle plots the 60° dip line and indicates that many fractures with dips near 60°, in addition to many high-angle fractures, have been interpreted in image data from the North Parachute field.

In the next Slide we will see the summary from each well in their stress model.
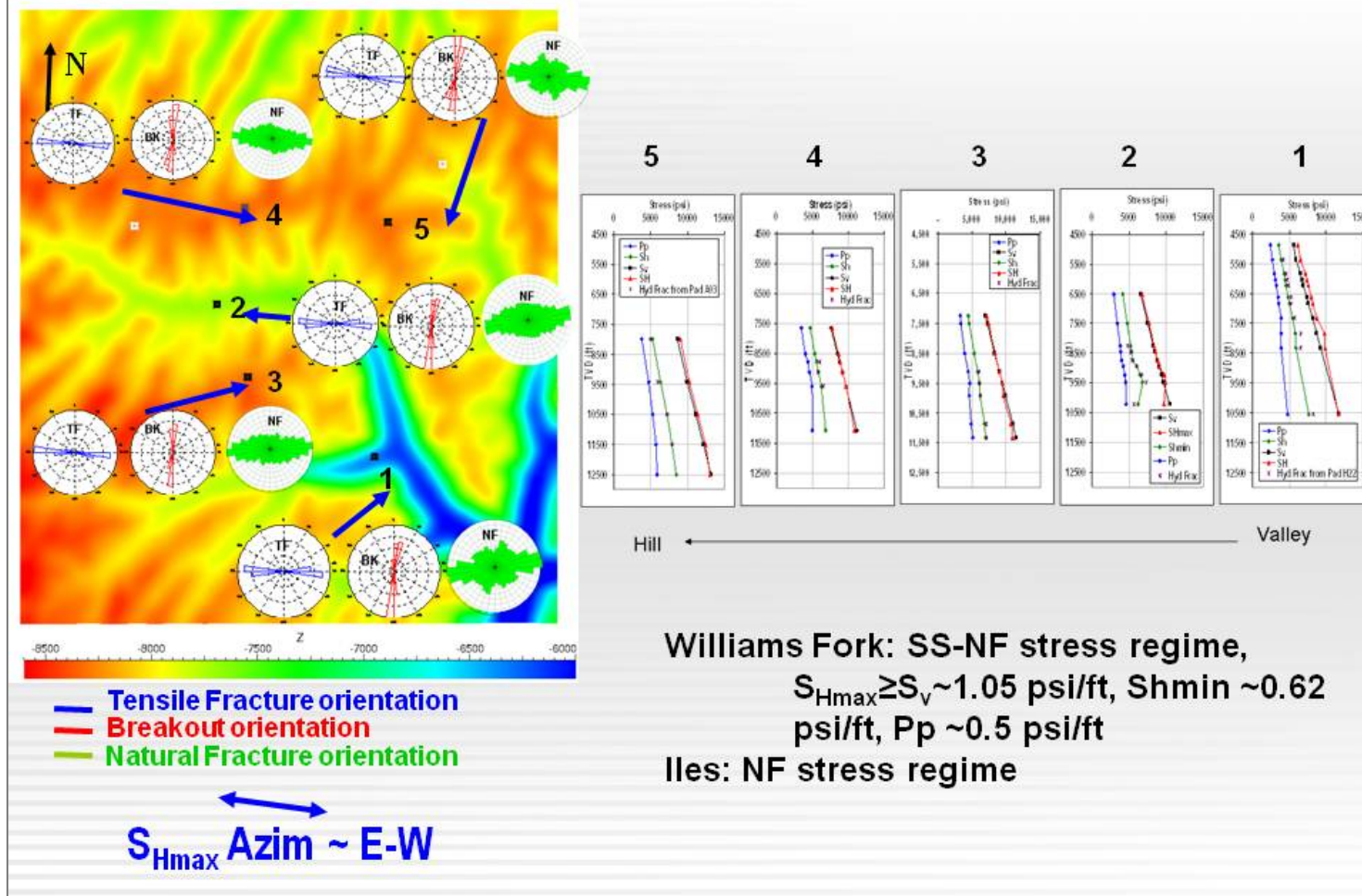
Notes by Presenter: On the left you see rose diagram plots for drilling induced tensile fracture, breakouts, and natural fracture from these wells. Breakout and tensile fractures indicate a consistent SHmax orientation ~E-W. In general, natural fractures are also aligned with this direction.

On the right you see stress estimation from these five wells at reservoir depth. We used frictional equilibrium concept to estimate the stresses. At william fork depth, stress seems to look like SS-NF and below is NF regime.

Next we try to check the behavior of natural fractures in the given stress regime
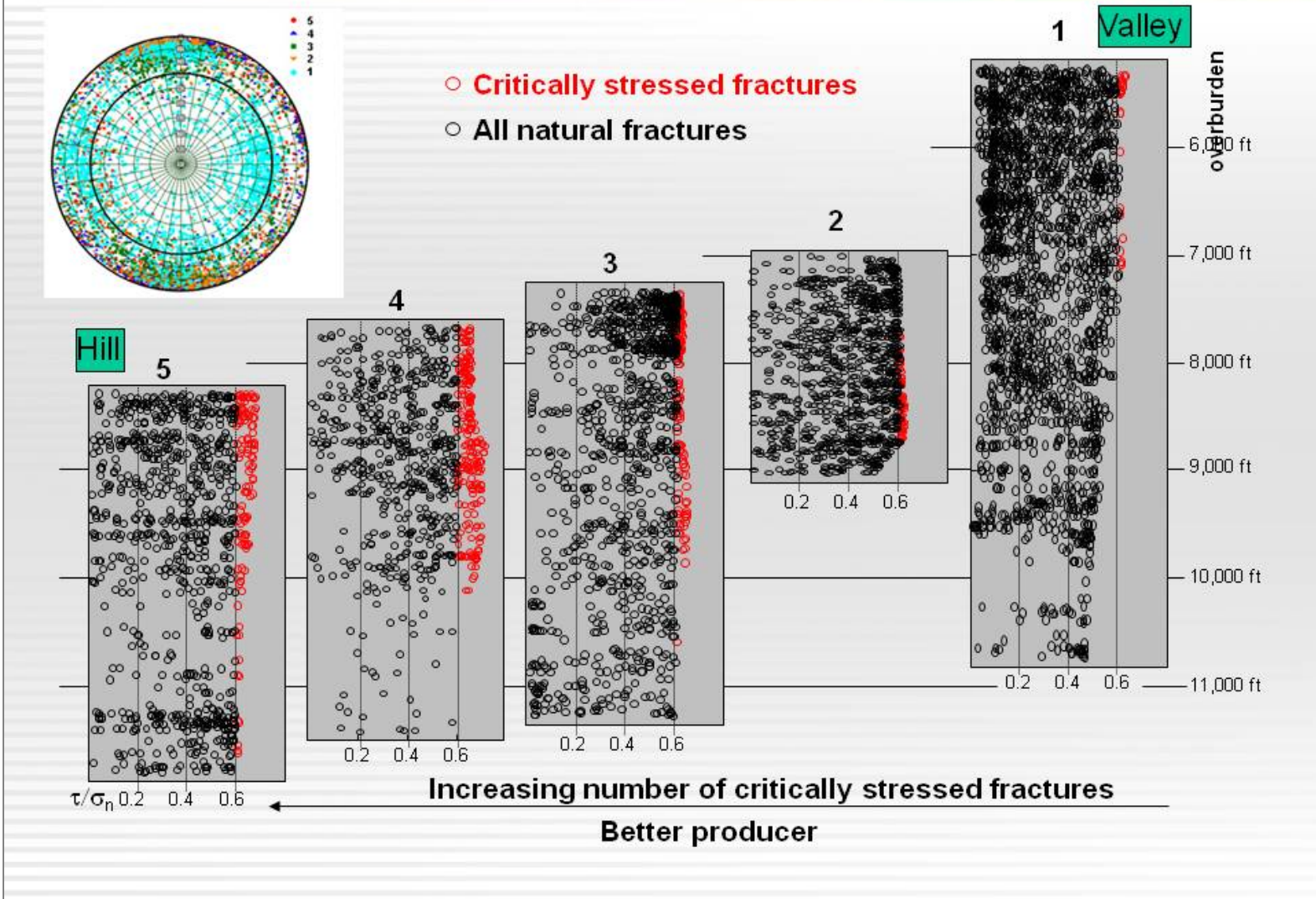
Notes by Presenter: Here you see the critical stress analysis on all the natural fractures from these well. Critical stress analysis tells the tendency of shearing of natural fractures in the given stress field. Red dots indicate the critical stressed fractures, which has a increasing trend towards the wells in hilly areas. Surprisingly they tend to be a better producer too.

Next we try to integrate the well production with other kind of studies

139 Attributes vs. gas production

Geometric (16)	Geomechanical (33)	Stratigraphy (18)	Petrophysical (50)	Geophysical (22)
1. Formation depth 2. Formation thickness 3. Distance from fault	Stress distribution using FEM: 1. Displacement 2. Differential stress 3. Stresses 4. Strains Fracture intensity attributes using BEM: 1. Mean stress 2. Maximum tensile strength 3. Differential stress 4. Maximum Coulomb shear stress Others: 1. Pore pressure	Frequency of sand units in different formations	1. Net thickness 2. Net-to-Gross 3. Porosity 4. Water saturation 5. Movable water 6. Shale volume 7. Gas thickness 8. Porosity thickness 9. Shale thickness 10. Moveable water thickness	1. AVO 2. Coherency 3. Velocity Anisotropy 4. Curvature volume

139 attributes from five categories are correlated with the gas production using Multi-variate analysis

Geomechanical attributes are one of the most correlated factors with gas production

Notes by Presenter: Here you see categories of 139 attributes we correlated with the gas production. 16 geometric attributes e.g formation depth, thickness and distance from the fault. 33 geomechanical attributes include finite element and boundary element modeling results, that we will discuss in more details, 18 stratigraphic attributes including frequency of sand units/thickness/fracture etc, 50 petrophysical attributes including net to gross, , net thickness, porosity, water saturation etc., 22 geophysical attributes include AVO, coherency, velocity anisotropy, curvature volume etc.

We used multi variate analysis to correlate and integrate these attributes to the gas production

MV Analysis Key to Deciphering Complexity
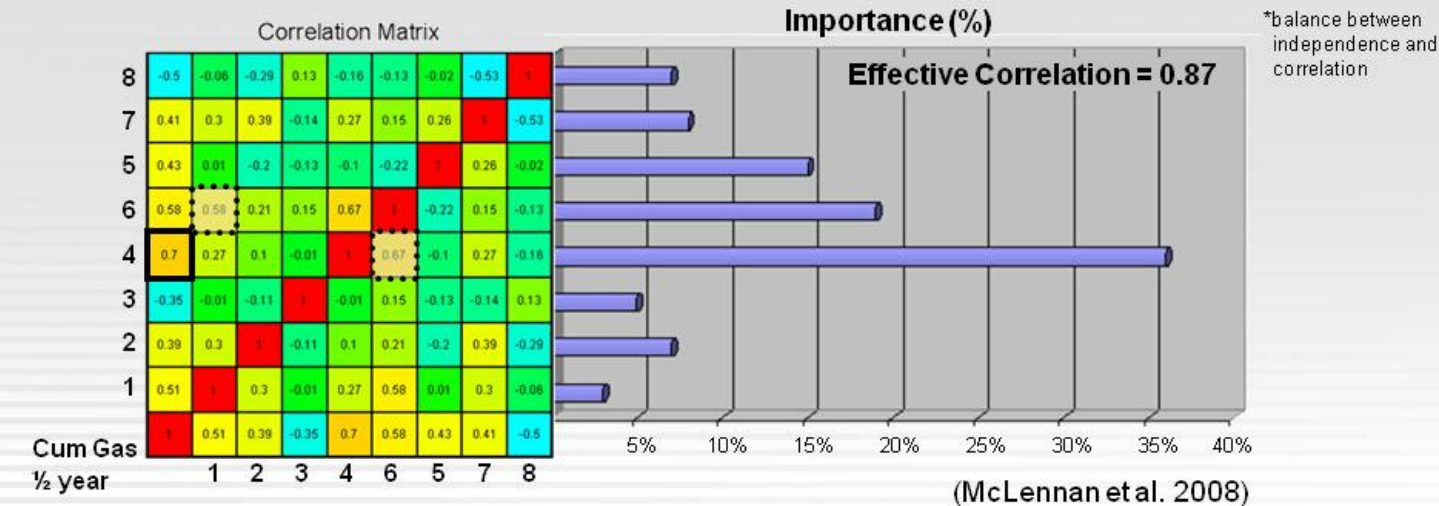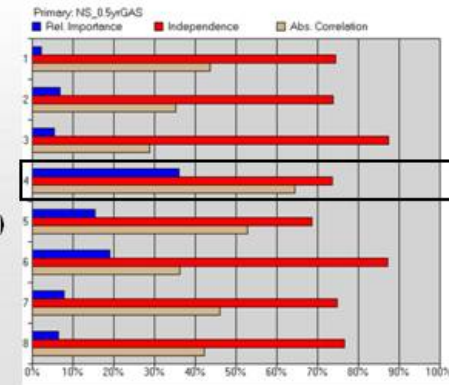
Notes by Presenter: Out of 139, here are the top 8 came out from multi-variate analysis with their relative importance, on which geomechanical attributes show more than 70% of importance. Multi-variate analysis is based on Bayesian concept. It gives the higher importance if absolute correlation between the primary and secondary variable is high and secondary variable is independent from other secondary variables. The correlation matrix indicates the absolute correlation between primary and secondary and between secondaries.

Cum gas production of first 182 days is the primary variable in this case. In the next section I will talk about geomechanical attributes

Outline

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Reservoir scale geomechanical modeling

Boundary Element Modeling (BEM): fracture intensity associated with the faults (3 reservoir faults)

Finite Element Modeling (FEM): stress perturbation due to topography, faults, mechanical stratigraphy, and pore-pressure.
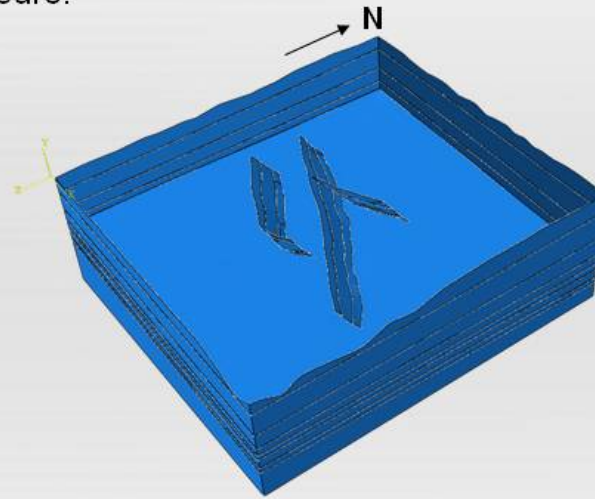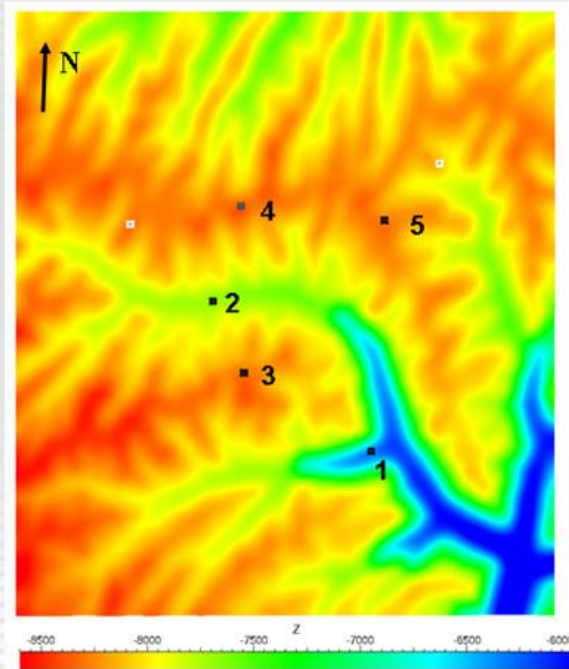
7 mechanical layers from Surface to Rollins
3 reservoir faults

Notes by Presenter: As mentioned before, there are two types of geomechanical attributes we have used.

First, boundary element modeling, which gives the fracture intensity associated with the faults at reservoir depth. These fracture intensity may provide enhanced permeability for the economic production.
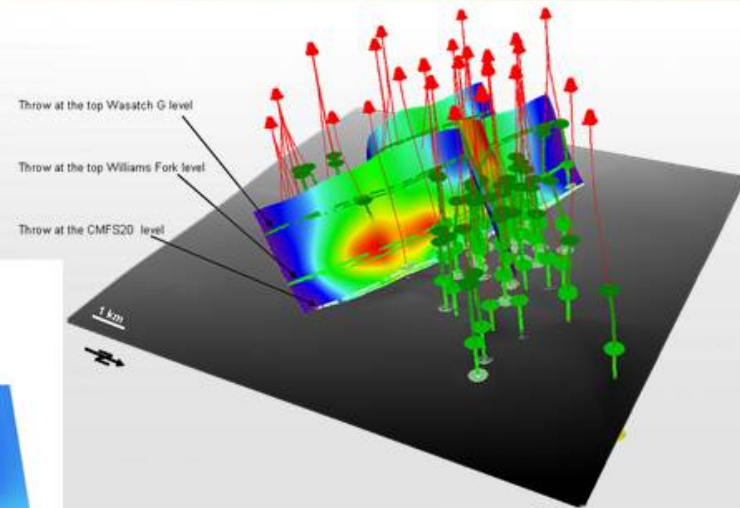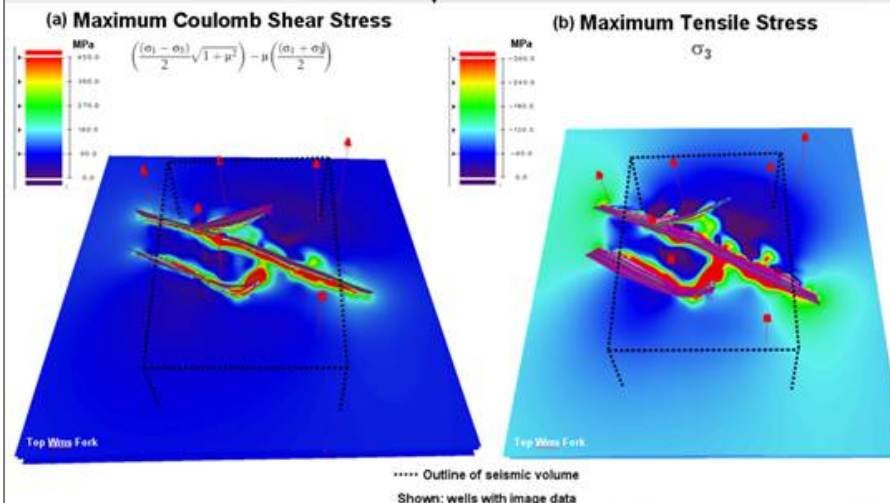
Second, is Finite Element modeling, which gives the stress distribution in the area due to topography, fault, mechanical stratigraphy, and pore pressure. This gives the effect of stress on macro and micro scale fractures.

We used the complex topography as the top surface and 7 horizons below and 3 reservoir faults for the modeling.

Fracture intensity with faults using BEM

Warmer colors in shear and tensile attributes indicate higher possibility of fault related fractures

Throw at the top Wasatch G level

Throw at the top Williams Fork level

Throw at the CMFS20 level

1 km

(a) Maximum Coulomb Shear Stress

MPa

$$\left(\frac{(\sigma_1 - \sigma_3)}{2}\sqrt{1 + \mu^2}\right) - \mu\left(\frac{(\sigma_1 + \sigma_3)}{2}\right)$$

Top Wms Fork

(b) Maximum Tensile Stress

MPa

σ_3

Top Wms Fork

····· Outline of seismic volume
Shown: wells with image data

stress perturbations predict that distributed fracturing is expected to surround the seismically interpreted faults, with the most enhanced fracturing located in areas of fault interaction

Notes by Presenter: BEM is done with pre-exiting fault to estimate the stress concentration around the faults due to the existing throw on the faults.

BEM output:(a) A shear stress attribute that can be used to predict shear fractures or small scale (subseismic) faults. (b) A tensile stress attribute that can be used to predict jointing. Color bars have been scaled so that reds represent areas most likely to contain faulting related fracturing.

Reservoir scale stress modeling using FEM
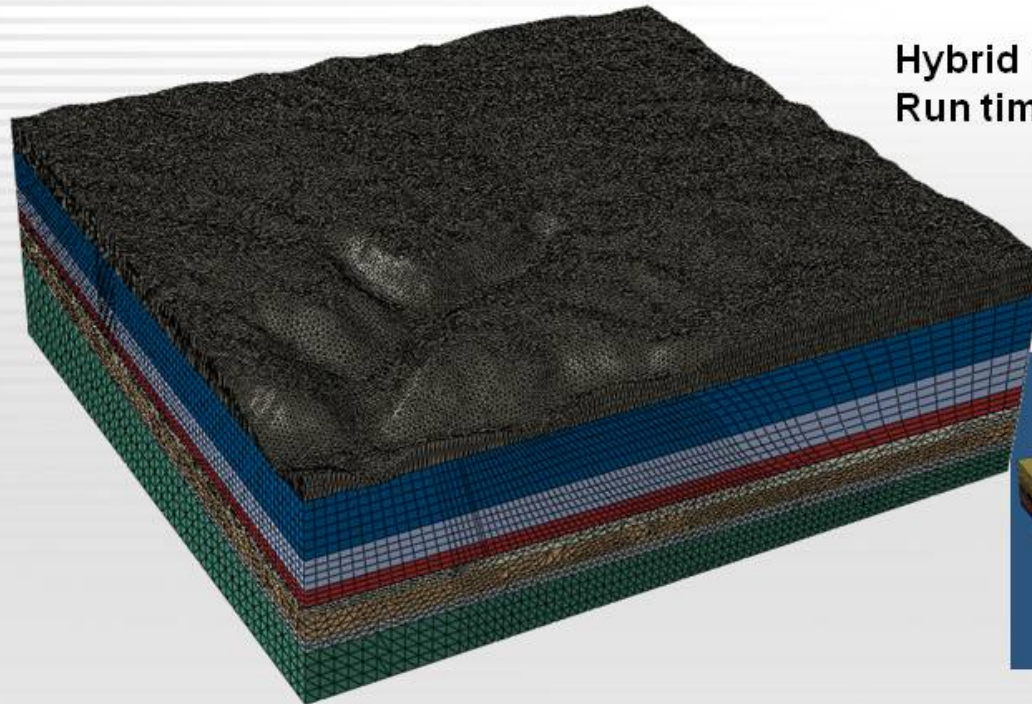
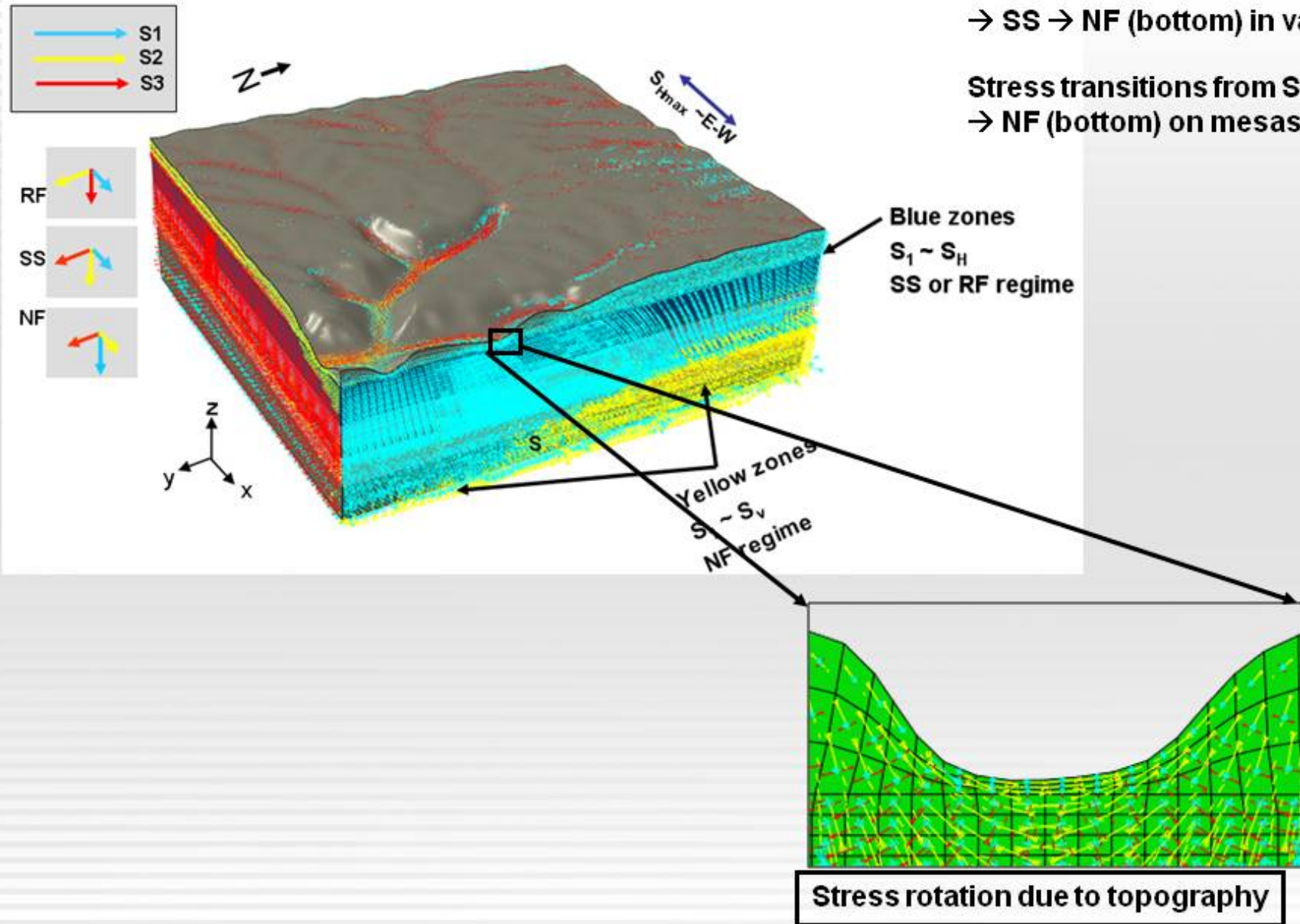**Hybrid mesh ~1 million elements**
Run time ~ 8hrs

Faults inside the model
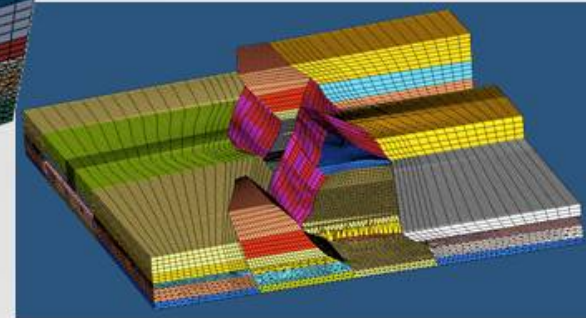
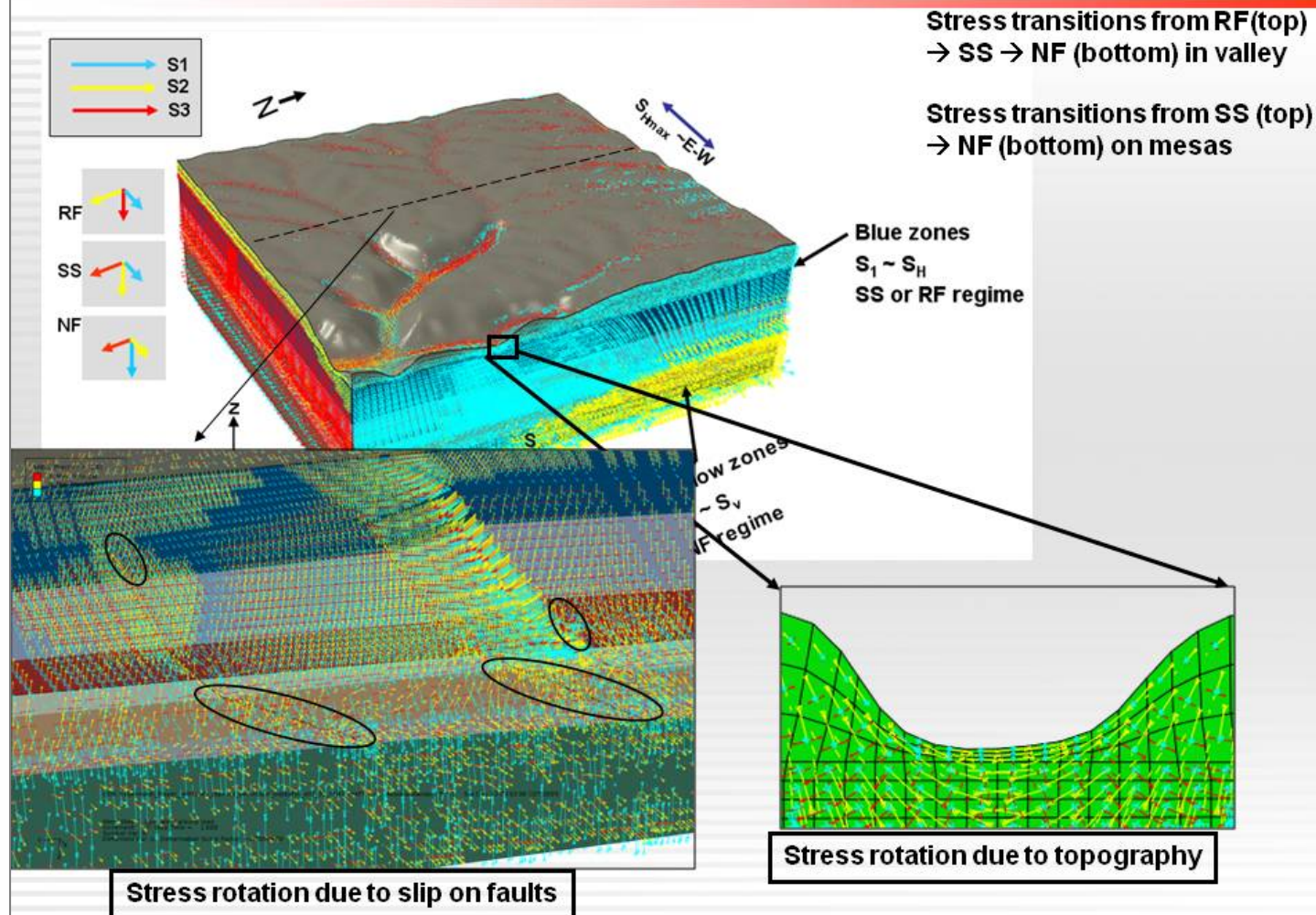|	Avg density	Young's modulus	Poisson's ratio	Pore Pressure
	kg/m3	Pa		Pa/m
surface-Top Wasatch	2460	1.562E+13	0.29	6500
Top Wasatch-Wasatch G	2537	1.479E+13	0.31	10200
Wasatch G – Top Williams Fork	2562	1.977E+13	0.30	10200
Top Williams Fork – Top Mid WF	2534	2.701E+13	0.26	11250
Top Mid WF – Top Lower WF	2529	3.146E+13	0.21	11450
Top Lower WF– Cameo	2559	3.219E+13	0.21	12250
Cameo – Rollins	2547	2.988E+13	0.24	11650
Rollins –Dakota	2592	3.686E+13	0.20	10125

Notes by Presenter: Advanced Field-Scale Static Geomechanical Modeling.3D discretized mesh generated directly from seismically interpreted horizons and faults and a digital elevation model of the topographic surface that has been broken into eight stratigraphic units. It is a hybrid mesh with ~1 million elements to preserve the details of topography, thin beds, and features close to the faults. Mechanical properties used in the model is shown in the table.

Stress orientation volume

Stress rotation due to topography

Stress orientation volume

Stress transitions from RF (top) → SS → NF (bottom) in valley

Stress transitions from SS (top) → NF (bottom) on mesas

Blue zones $S_1 \sim S_H$ SS or RF regime

Stress rotation due to slip on faults

Stress rotation due to topography

Notes by Presenter:
- 3D FEM model showing orientation of the three principal stresses. Blue arrow indicates max principal stress, yellow middle and red least principal stress. These are the combination for RF, SS, and NF situations. We can see top blue zones are SS or RF, then we can see the top most part is RF. In valley we have RF→SS NF transition while in mesa we have SS NF transition.
- stress rotation due to the change in elevation.
- Cross sectional view through the three faults in the field, showing a rotation in principal stresses and an increase in principal stress magnitudes (represented by arrow size) near the faults.
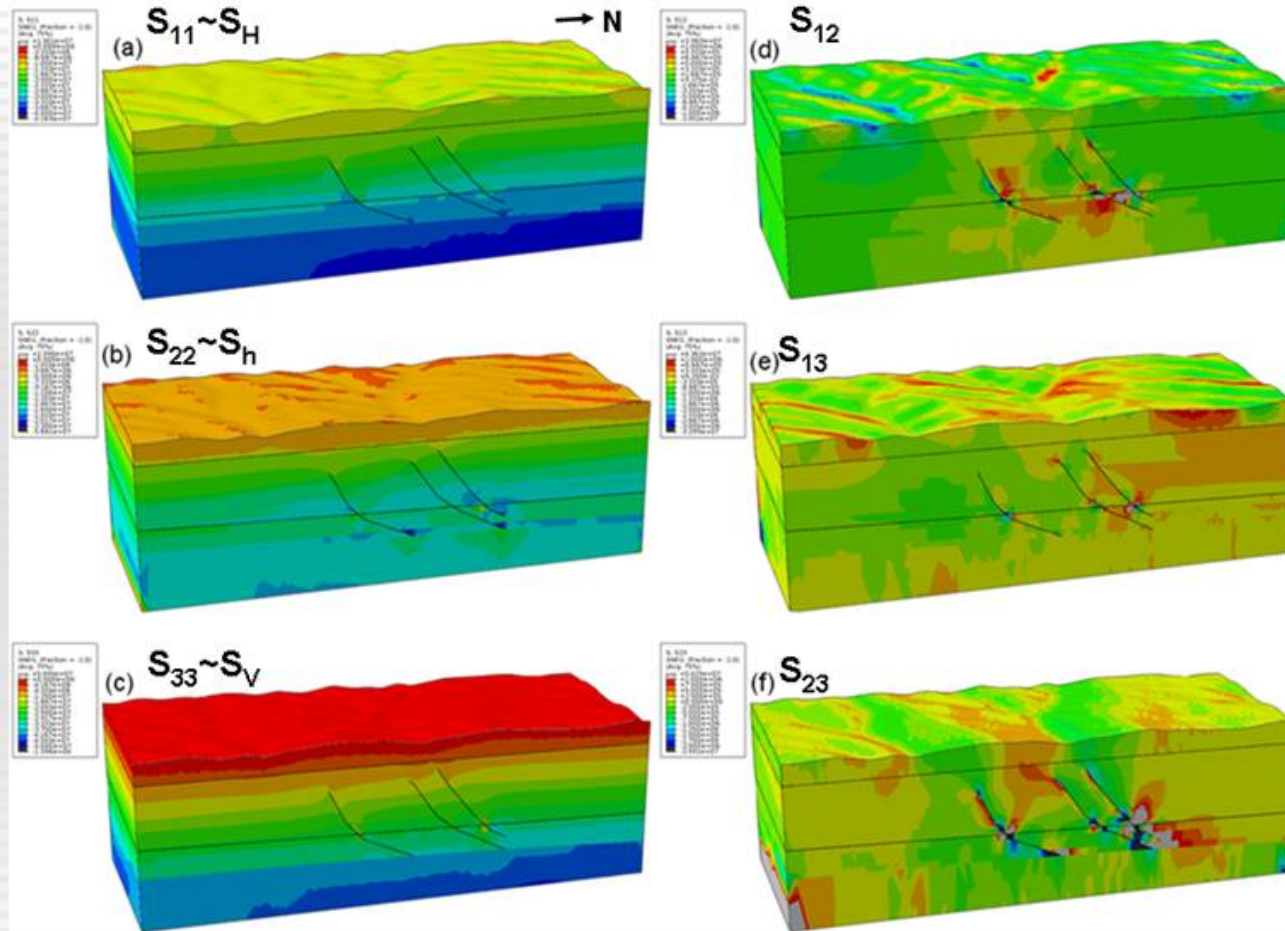
Notes by Presenter: FEM model displaying various stress components. Hot colors on the color bar represent the most tensile stresses while cool colors represent the most compressive stresses. (a) Stress acting in the X or E-W direction. (b) Stress acting in the Y or N-S direction. (c) Stress acting in the Z or vertical direction. (d) Shear stress acting on an X plane in the Y direction. (e) Shear stress acting on an X plane in the Z direction. (f) Shear stress acting on a Y plane in the Z direction.

Prediction of gas production using MVA
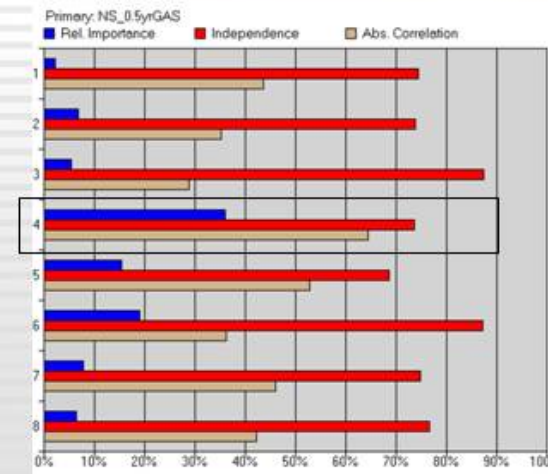
(4) 36% Horizontal Stress Difference (S_{11}-S_{22})

(6) 19% Horizontal to Vertical Stress Difference (S_{11}-S_{33})

(5) 15% Total displacement

(7) 8% ϕ_{av} at completed zones

(2) 7% geomechanical tensile stress

(8) 7% S_w at completed zones

(3) 5% geomechanical differential stress MWF

(1) 3% overburden thickness
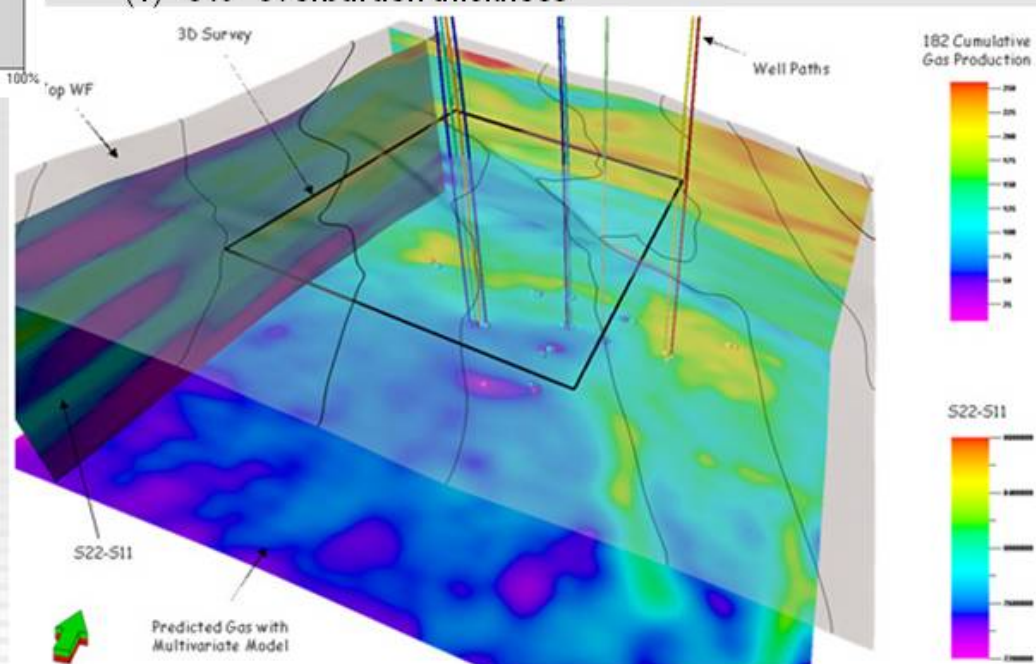
Predicted gas production using the final multivariate model

Notes by Presenter: Prediction at locations increasingly further away from well control is increasingly reliant on the likelihood, which is a combination of the most important attribute information as parameterized in the matrix of correlations. Notice these maps are influenced according to the relative influence of the most important attributes driving the spatial heterogeneity in the production variable.

Conclusions

North Parachute area has a complex structural history and has significant topography, creating variability in present-day loading conditions

Multivariate analysis suggests that geomechanical attributes strongly correlate to gas production

Wellbore geomechanical modeling shows that natural fractures are critical productivity elements to enhance the permeability

Finite Element Modeling suggests stress perturbation due to faults, mechanical stratigraphy, topography, and pore pressure.

Model productivity appears to be controlled by the permeability enhancement of tight sands due to fracture-stress interaction