Eolian Architecture of Sandstone Reservoirs in the Covenant Field, Sevier County, Utah*

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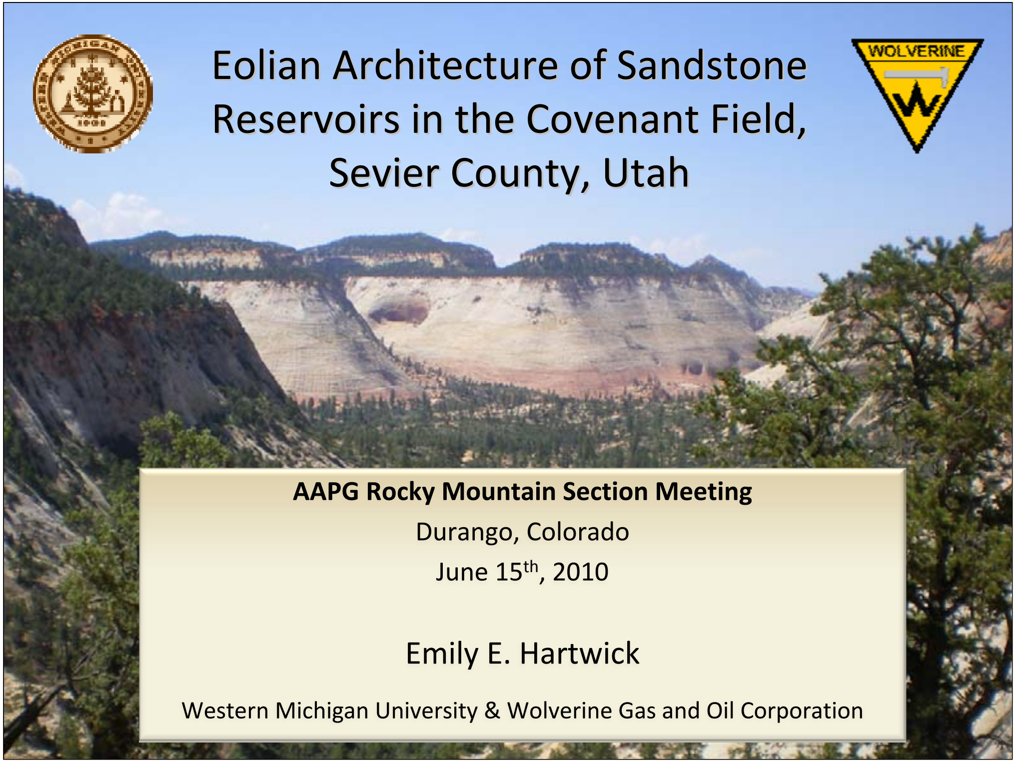
Abstract

The Lower Jurassic Navajo Sandstone and the sandstone of the Middle Jurassic White Throne Member of the Temple Cap Formation compose the primary reservoirs at Covenant Field in the central Utah thrust belt. Analysis of the stratigraphic and structural features identified from resistivity-image logs along with core and standard electric logs permitted the definition of dune architecture and permeability anisotropy caused by crossbedding within the eolian reservoir units.

Sandstone bodies in these units are dominated by barchanoid dune types and commonly lack inter-dune deposits. Paleo-wind-transport directions were calculated for the White Throne and Navajo sandstones. These directions are southwest and south-southeast, respectively, giving the two sandstones unique paleo-wind-transport directions. Therefore, maximum permeability directions within each reservoir are different and must be considered for optimum well placement. Triaxial permeability measurements indicate a horizontal to vertical permeability anisotropy ratio of 2.4 in the White Throne and 2.7 in the Navajo. The average width of individual dunes was estimated by examining the preserved dune-set thicknesses in each sandstone. Average calculated dune widths for the White Throne and Navajo are 1650 ft and 2200 ft, respectively. Drainage ellipses were constructed using the paleo-wind-transport directions, permeability-anisotropy ratios, and estimated dune sizes. The validity of the drainage ellipses is supported by well interference identified from production data.

Rocks previously known as the "Upper Navajo" at Covenant Field have recently been assigned to the White Throne Member of the Temple Cap Formation, based on regional outcrop studies, subsurface correlations, palynology, and radiometric dating. This assignment is supported by comparing the calculated paleo-wind-transport directions for the White Throne and Navajo sandstones at Covenant Field to measured Jurassic outcrop sections. The distinct lithologic and diagenetic attributes of each horizon also suggest they were deposited in different environments.

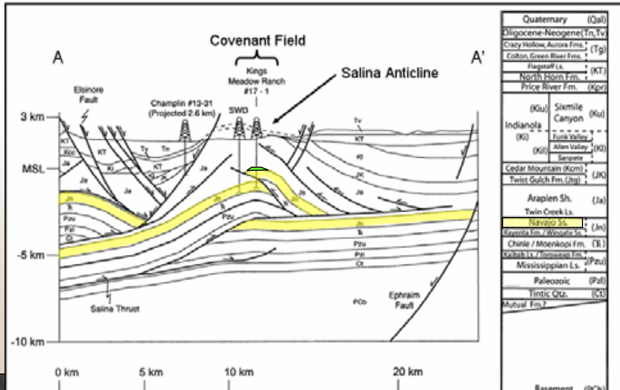


Presenter's Notes:

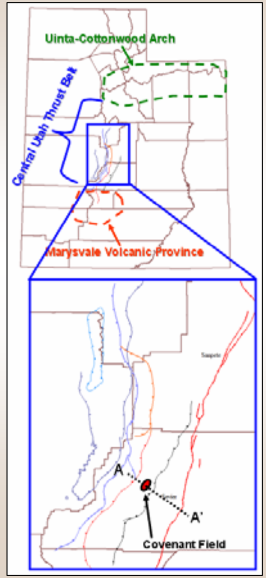
I shall describe the results of the bedding architecture study and make some observations on the role that normal faults play in Covenant Field.

Covenant Field Background

- Discovered by Wolverine Gas & Oil Corporation in Dec. 2003
  - Discovery well: Kings Meadow Ranches 17-1
    - Porous sandstone at 5,846’ MD
    - ~500’ pay section
    - 40 ° API sweet crude oil
- Covenant Field is a structural trap located on a back-thrust within the Central Utah Thrust Belt



(Schelling and Vrona, 2007)



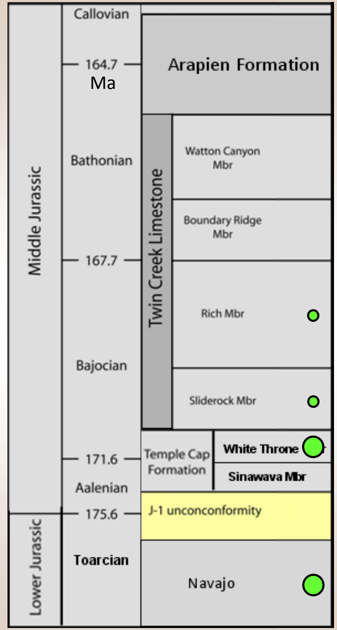
Presenter’s Notes:

Covenant field lies in the Central Utah Thrust Belt in Sevier County, Utah. As the inset map of Utah shows, the thrust belt is bounded on the north by the Uinta-Cottonwood Arch and on the south by the Marysvale Volcanic Complex. It also represents the boundary between the Colorado Plateau to the east and the Basin and Range Extensional Province to the west.

The field was discovered by Wolverine Gas & Oil in December, 2003, with the Kings Meadow Ranches 17-1 well. The field is a structural trap within a back-thrusted sheet of the Salina Anticline (cross-section A-A’). The oil column is represented by the very thin green polygon within the back-thrusted sheet.

Covenant Stratigraphy

- Arapien Formation at Surface
  - Mix of carbonates, clastics and evaporites
- Twin Creek Limestone
  - Important indicator of structural dip
  - Secondary reservoir where fractures are developed
- Temple Cap Formation
  - White Throne Mbr is reservoir quality sandstone
    - Avg. 8 % Core Porosity & 40 mD Core Permeability
  - Sinawava Mbr is tight siltstone
    - Important indicator of structural dip
- Navajo
  - Reservoir Quality Sandstone
    - Avg. 13 % Core Porosity & 100 mD Core Permeability



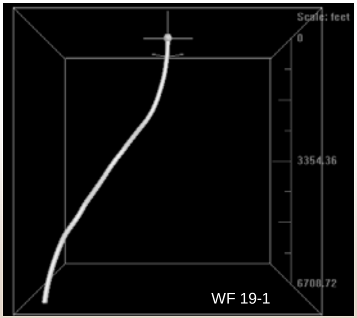
Modified from Sprinkel et al, 2009

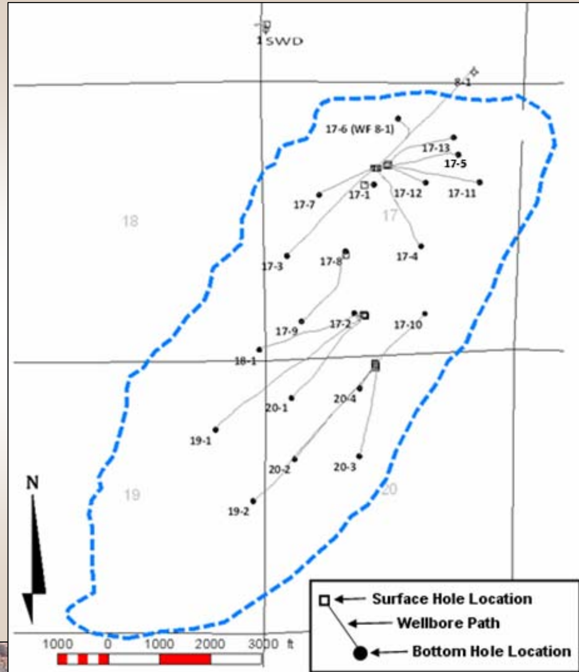
Presenter's Notes:

The stratigraphic section at Covenant field consists of the Arapien Formation at the surface, followed by the Twin Creek Limestone, an important indicator of structural dip, which is a secondary reservoir where fractures are developed; it overlies the Temple Cap Formation, which consists of the White Throne Member, a reservoir-quality sandstone, and the Sinawava Member, a tight non-reservoir siltstone; the Temple Cap overlies the Navajo Sandstone, which is also of reservoir quality. The two reservoir sandstones, White Throne and Navajo, are the focus of the rest of the presentation.

Covenant Field Wells

- 20 Producing wells
- 1 Dry hole
- 1 Salt water disposal well
- Wells are directionally drilled from several surface pads





Presenter's Notes:

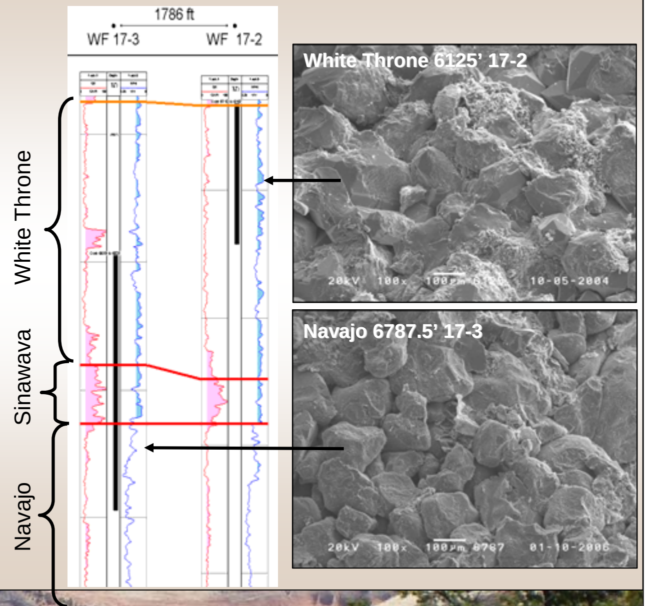
This map of Covenant Field shows the existing wells and an outline of the productive limits of the field.

Currently there are 20 producing wells, 1 dry hole, and one salt water disposal well to the north. Wells within the field are directionally drilled from a few surface locations; the profile of the 19-1 wellbore is shown in the lower left. Currently, wells are completed in either the Navajo or the White Throne interval, although almost all wells have pay intervals in both sandstones.

From these wells, there is a large dataset of open-hole logs, including resistivity image logs, conventional and sidewall cores, and production data.

Primary Sandstone Reservoirs: White Throne and Navajo

- Lithologically similar
  - Fine- to medium-grained, poorly to very well sorted, quartzarenites, subarkosic arenites and sublithic arenites
    - White Throne more "quartz-pure" than Navajo
- Different depositional environments and diagenetic pathways (Oolithica Geoscience LTD, unpublished data):
  - Navajo: primarily eolian
    - Clay rims on quartz grains preserved primary porosity
  - White Throne: eolian and mixed marine
    - No clay rims on quartz grains led to more pervasive quartz cementation



Presenter's Notes:

The White Throne and Navajo Sandstones are lithologically similar; the compositional difference is that the White Throne has slightly less detrital feldspar and lithic fragments.

The two reservoirs are thought to have been deposited in different depositional environments, which ultimately led to different diagenetic histories. The Navajo is primarily eolian, whereas the White Throne is a mixed eolian-marine deposit.

The logs shown here (from the 17-3 and 17-2 wells) are the gamma ray in pink and density porosity in blue. The porosity curve is filled in blue where it is less than 10%. The White Throne is generally less porous than the Navajo. On the right are SEM photographs of the White Throne and Navajo, showing the differences in quartz cementation (much more pervasive quartz cement in the White Throne, including occurrences of well developed crystal forms, as in the upper right of the photograph).

Research Goals

- To understand how the eolian sedimentary fabric impacts fluid flow within the White Throne and Navajo sandstone reservoirs

Dip Spectral Analysis

– What was the paleowind transport direction of the reservoir sandstones at Covenant?

– What dune forms were preserved?

Drainage Ellipse Mapping

– Does dune architecture influence fluid movement?

– Can we see evidence of dune architecture influence in the production history?

Presenter's Notes:

The broad goal of this research was to achieve a better understanding of how the eolian sedimentary fabric impacts fluid flow within the White Throne and Navajo sandstone reservoirs. The specific questions addressed in order to reach this understanding are:

What was the paleowind transport direction of the reservoir sandstones?

What dune forms were preserved?

Does dune architecture influence fluid movement?

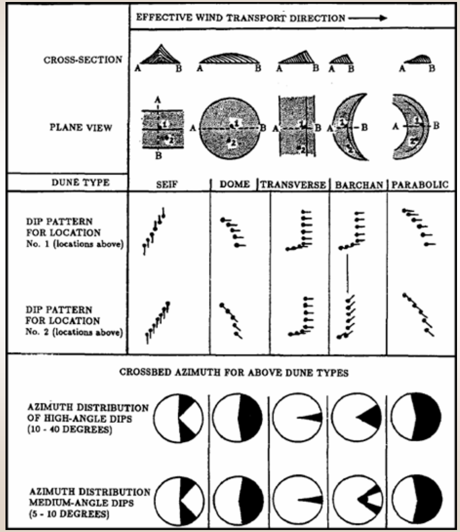
Can we see evidence of dune architecture influence in the production history?

The first two questions have been addressed by the dip spectral analysis technique and the last two questions were answered with drainage ellipse mapping.

Dip Spectral Analysis Method

- Divide the sandstone reservoirs into layers
- Tabulate low, medium, and high angle dips
- Determine dune type and wind transport direction

Navajo At Zion National Park, August 2009



From Nurmi, 1985

Presenter's Notes:

Dip spectral analysis is a technique that is used to identify the bedding planes for calculating paleowind transport direction (paleocurrents).

First, I divided the reservoir sandstones into roughly parallel horizontal layers, similar to the stacking patterns of the Navajo observed at Zion National Park, shown here. Next, using the bedding dips that were interpreted from the resistivity image logs, I tabulated low-, medium- and high-angle dips and their azimuths. From this spectrum of dip azimuths, it was possible to determine the dune type and the paleowind transport direction.

This table from Nurmi (1985) shows the basic premise of dip spectral analysis –that each dune form has unique internal architecture or dip patterns and also unique azimuthal distributions of dip spectra.

White Throne and Navajo Sandstone "Stacking Surfaces"

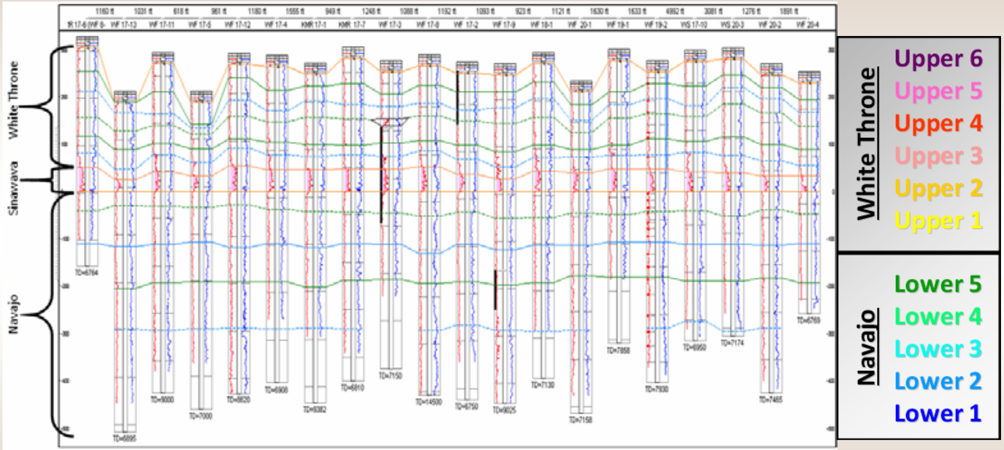
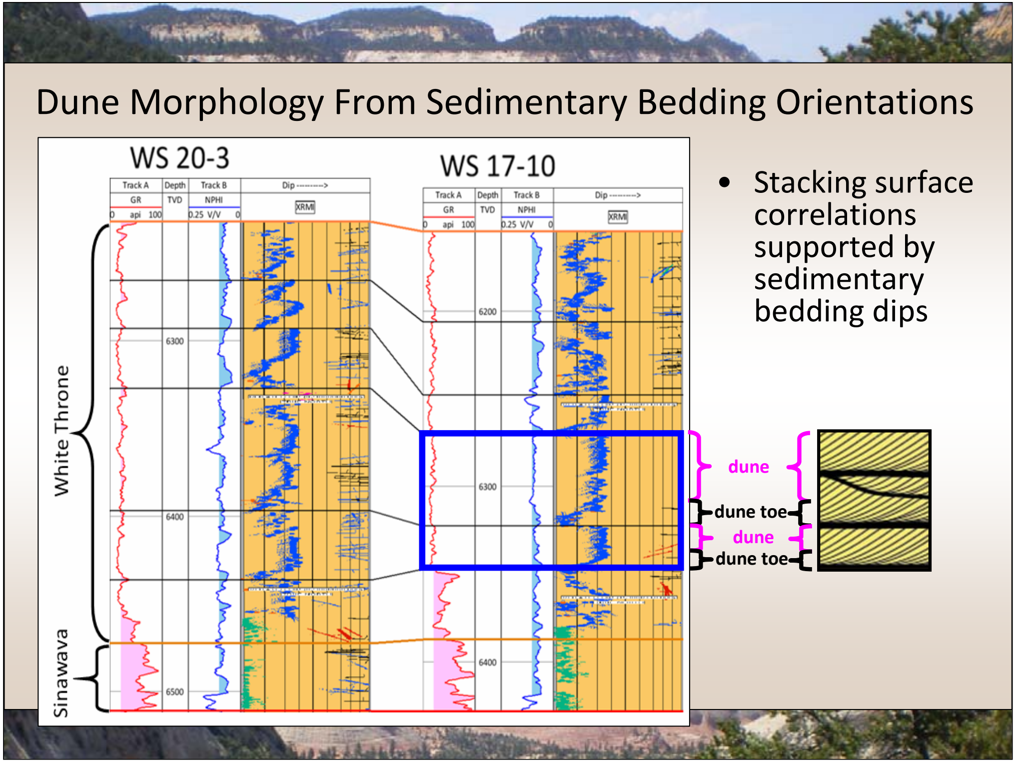


Figure 11: Cross section depicting stacking surfaces within the White Throne and Navajo sandstone reservoirs at Covenant Field. Cross-section is flattened on the base of the Sinawava member. Gamma ray is shown as a red curve with pink area fill at depths where curve reads greater than 20 units; Neutron porosity is shown in blue with blue area fill at depths with less than 10% porosity. Wells ordered generally from north to south, see Figure 4 for well locations. Black bars indicate conventionally cored intervals. Vertical scale shown by 100 foot depth increments along right and left margins (scale shown in feet above or below the base of the Sinawava member, horizontal distance between wells indicated along top of cross section.

Presenter's Notes:

This slide just shows my correlation of layers for the White Throne and Navajo across the field. I divided the White Throne into 6 layers and the Navajo into 5 layers. Dip spectral analysis was performed on each layer within each well.



Presenter's Notes:

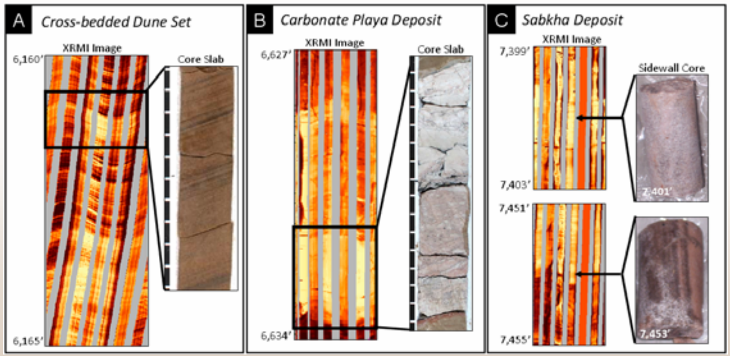
This slide shows an example of the dune morphology by using the sedimentary bedding dips interpreted from the image logs (shown as blue tadpoles in the gold colored track).

The correlation of stacking surfaces or layers in the White Throne and Navajo is supported by the dip patterns, as they allowed us to identify the steeper dipping portions of the dune and the lower dipping portions of the dune toe. Logically the layer boundaries were placed at dune toes, rather than in the middle of a dune set.

White Throne Dune Morphology

- Dominated by small barchanoid dune types

	Layer	Averge Dune Set Height (ft)	Average Dune Set Width (ft)	Average Dune Set Length (ft)
White Throne	Upper 6	14.47	1,447	2,894
	Upper 5	18.19	1,819	3,639
	Upper 4	13.65	1,365	2,729
	Upper 3	24.06	2,406	4,812
	Upper 2	17.68	1,768	3,536
	Upper 1	10.77	1,077	2,154
	AVERAGE	**16.47**	**1,647**	**3,294**



Core photos by OMNI Labratories, Inc; Sidewall Core Photos by David Hansen

Presenter's Notes:

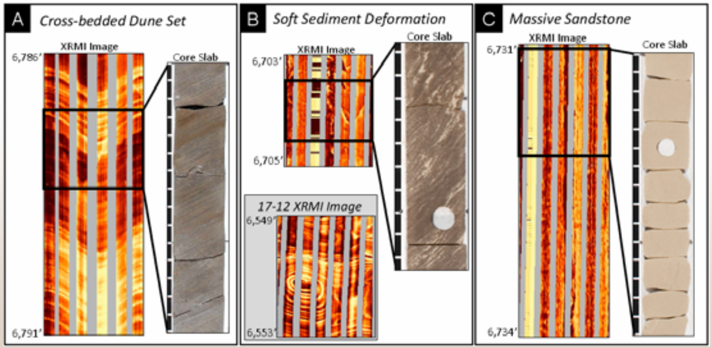
The White Throne was dominated by small barchan-like dune types that average about 16.5 feet high – from that number we can estimate the dimensions of the preserved dune in the subsurface.

Shown here are a series of resistivity images and the corresponding core samples over the same interval for comparison--to show the general facies we were able to identify. In addition to the cross-bedded dune sets which represent the majority of the section, we observed rare carbonate deposits that we interpret to represent marine or playa deposition, and also possible sabkha environment. These different facies support the interpretation of the White Throne being a mixed eolian-marine deposit.

Navajo Dune Morphology

- Dominated by slightly larger barchanoid dune types

	Layer	Averge Dune Set Height (ft)	Average Dune Set Width (ft)	Average Dune Set Length (ft)
Navajo	Lower 5	19.61	1,961	3,922
	Lower 4	22.18	2,218	4,435
	Lower 3	21.77	2,177	4,354
	Lower 2	21.92	2,192	4,383
	Lower 1	24.29	2,429	4,857
	AVERAGE	**21.95**	**2,195**	**4,390**

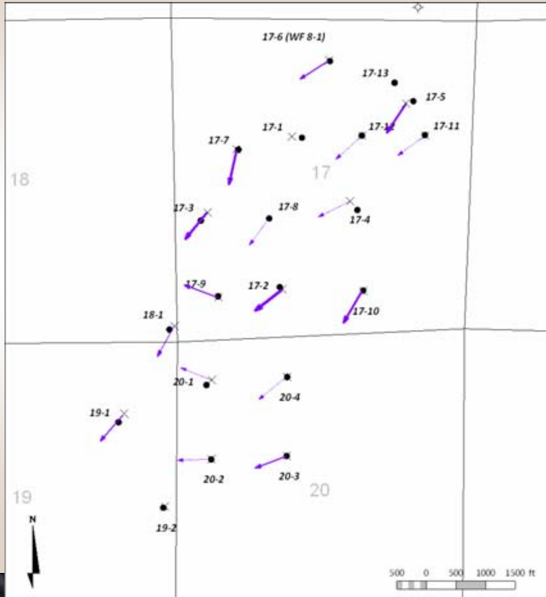


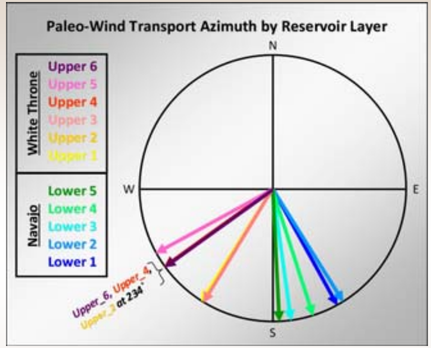
Core photos by OMNI Labratories, Inc

Presenter's Notes:

The Navajo was also dominated by barchan-like dune forms, although they average slightly higher, at almost 22 feet. Within the Navajo are typical cross-bedded dune sets, along with soft-sediment deformation, and also massive structureless sandstone.

Paleowind Transport Directions





Data Coverage Quality (dips/ft)	Line Style	Example
0 - 1.5	0 pt. dash	------------▸
1.5 - 3.0	1 pt. line	⟶
3.0 - 4.5	3 pt. line	⟶
> 4.5	5 pt. line	➞

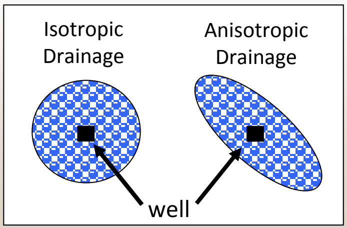
Presenter's Notes:

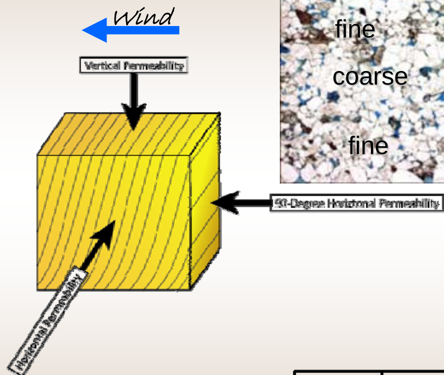
After tabulating the dip spectral analyses for each layer in each well, I mapped the paleowind transport directions across the field. On the field map, the arrow indicates the paleowind transport direction calculated for each of the wells and also the data coverage quality, with bolder arrows representing statistically more significant data points. The average vector of each layer is shown on the stereonet in the upper right.

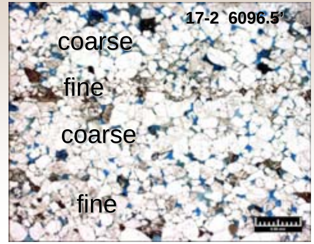
From Navajo to White Throne time, the wind direction swung from south-southeast to southwest. We shall now view a series of field maps that show the wind direction for each layer, starting from bottom of the sand deposit in Navajo: layer 1 to layers 2, 3, 4, 5 and then to White Throne layer 1 to layers 2, 3, 4, 5, 6.

Permeability Anisotropy

- Eolian cross-bedding consists of alternating layers of finer and coarser grains
- Grain textures are more continuous perpendicular to the wind transport direction
  - Permeability anisotropy







			K_H		K_V		K_{90}		
Formation	Dominant Facies	Wells Sampled	Average	n	Average	n	Average	n	K_H/K_V
White Throne	Eolian Dune	17-2, 17-9	36.95	144	15.18	60	19.12	49	2.43
Navajo	Eolian Dune	17-9	100.18	76	37.36	72	94.39	75	2.68
Navajo	Massive Sand	17-9	24.85	85	24.33	28	22.67	28	1.02

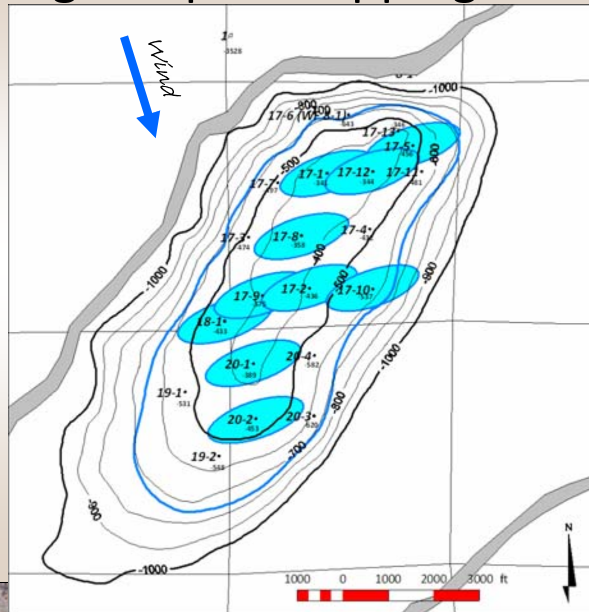
Presenter's Notes:

Why is paleowind transport direction important? The cross-bedding in the reservoir sandstones, the product of the wind-controlled deposition, consists of alternating layers of finer and coarser grains. In barchan dunes, that texture is more continuous perpendicular to the wind transport direction. This directionally dependent textural continuity causes a permeability anisotropy within the rock. This may lead to anisotropic drainage – where a well produces fluids from ellipse-shaped planes around the wellbore, as opposed to more circular planes, if the permeability were isotropic.

We can quantify permeability anisotropy by making triaxial core measurements, illustrated on the hypothetical cube of cross-bedded sandstone. We take a horizontal core, a vertical core, and a 90-degree offset to the original horizontal core and measure the permeability across each. This was performed on White Throne and Navajo samples from Covenant field; the results show a horizontal to vertical permeability ratio of 2.43 for the White Throne and 2.68 for the Navajo within the dune facies. This ratio helps us to estimate the shape of the ellipses (or ellipsoid) from which a given borehole is draining.

Navajo Drainage Ellipse Mapping

- Assumptions
  - Dune width = 2,200
  - KH/KV ratio = 2.7
  - Maximum permeability direction = ENE-WSW
- Ellipses placed at bottom hole locations of wells completed in the Navajo



Presenter's Notes:

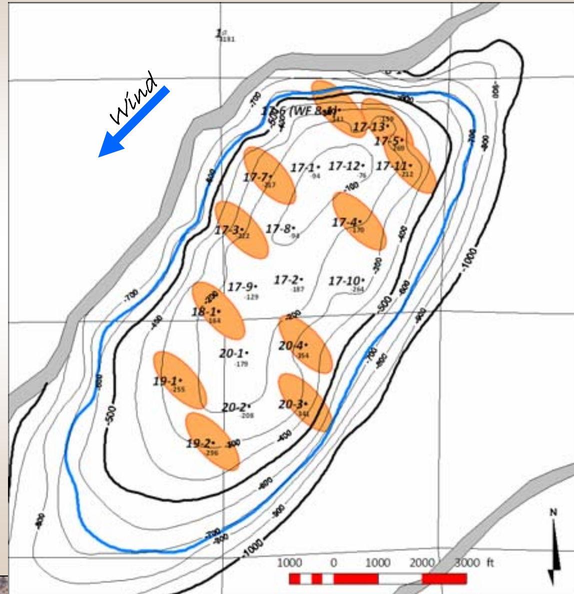
Using the average dune widths estimated from the preserved dune set height, the horizontal to vertical permeability ratio from core measurements, and the maximum permeability direction from the dip spectral analysis, I was able to create drainage ellipse maps for the Navajo and White Throne reservoirs.

Shown here is the map for the Navajo. The ellipses are placed at wells that are completed and produce from the Navajo interval. The long axis of the ellipse is aligned perpendicular to wind transport direction, the length of the long axis of the ellipse is determined by the calculated average dune width, and the ratio of long to short axis of the ellipse is determined by the permeability ratio.

By creating these maps, one can hypothesize which wells may be interfering with each other, or competing for the same fluid within the reservoir. There are several instances of overlap for wells completed in the Navajo. For the most effective placement of primary production wells, the drainage ellipses should not overlap.

White Throne Drainage Ellipse Mapping

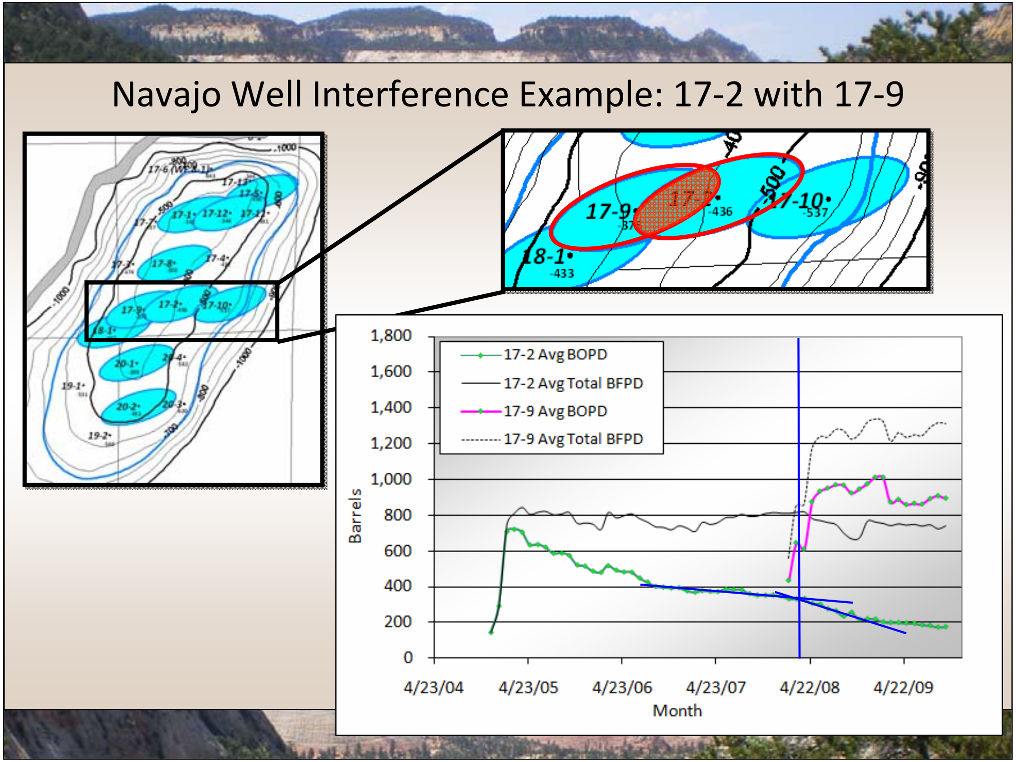
- Assumptions
  - Dune width = 1,650’
  - KH/KV ratio = 2.4
  - Maximum permeability direction = SE-NW
- Ellipses placed at bottom hole locations of wells completed in the White Throne



Presenter’s Notes:

Shown here is the drainage ellipse map for the White Throne; note that a couple of wells also have overlapping ellipses in the northeastern portion of the field.

The production profiles of the wells with and without drainage ellipse overlap generally show that interference exists between wells that have overlapping drainage ellipses. This is marked by a change in produced fluid ratios in the existing well when the second overlapping well begins to produce.



Presenter's Notes:

Illustrated here is an example from two wells. the 17-2 and 17-9. completed in the Navajo reservoir. Their ellipses overlap by approximately ¼ of the suggested drainage area of each well. The production histories show that the 17-2 well was negatively impacted when the 17-9 well began producing above 800 barrels of total fluid a day, evidenced by a downward deflection in the decline rate of the 17-2 well, which had been relatively stable for almost 2 years.

Other examples, including the relationship of wells that are on trend but without overlapping ellipses, show that the shape and size of the drainage ellipses developed with this model appear to be reasonable predictors of well interference.

Normal Fault Network

- Normal faults have been identified in many wells
  - Missing section
  - Occasionally faults are captured by the XRMI logs
    - Orientation

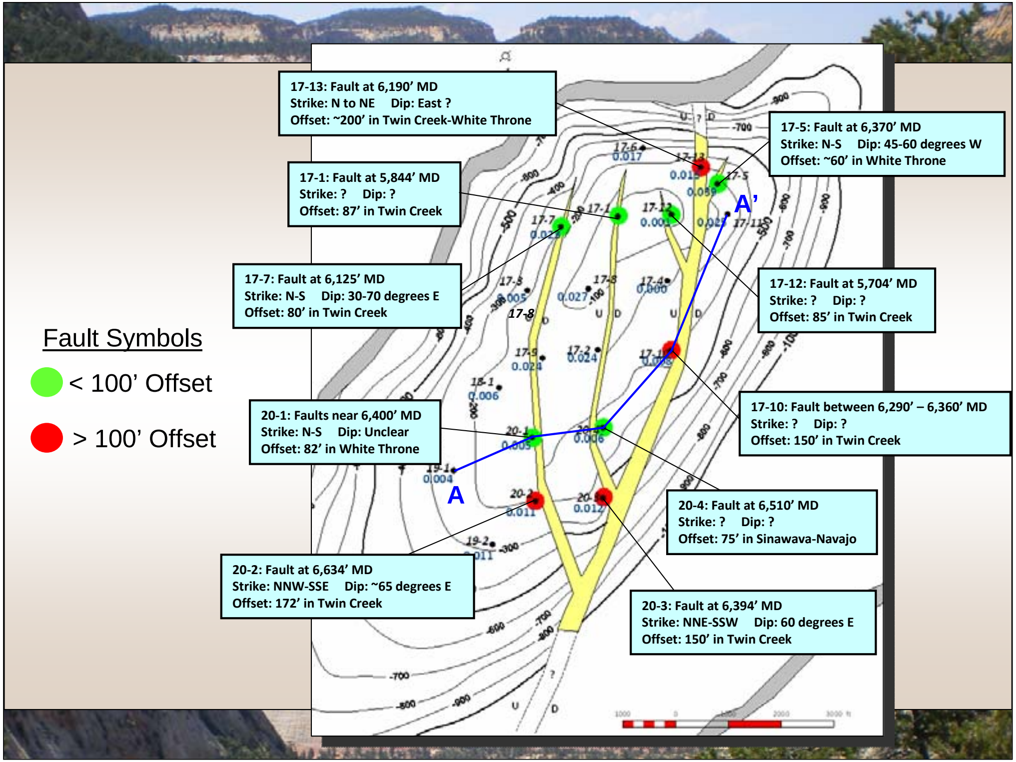
- Interference test indicates the fault network may be conductive

Presenter's Notes:

The eolian sedimentary architecture is not the only control on fluid movement within the sandstone reservoirs at Covenant Field.

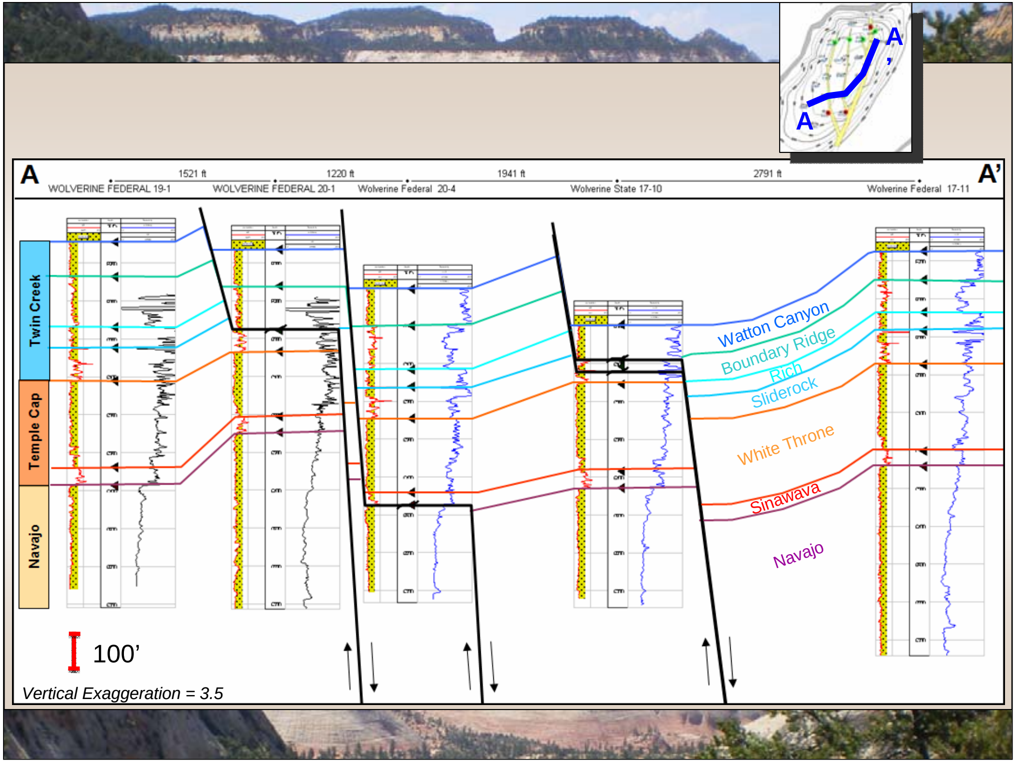
Normal faults have been identified in about one-half of the wells drilled on the basis of missing section. Occasionally the faults are recognizable on the image logs; that can give us an idea of their orientation.

Also, interference test was made between a handful of wells in the northeastern portion of the field. We shall review the results of that test in the context of the normal fault network.



Presenter's Notes:

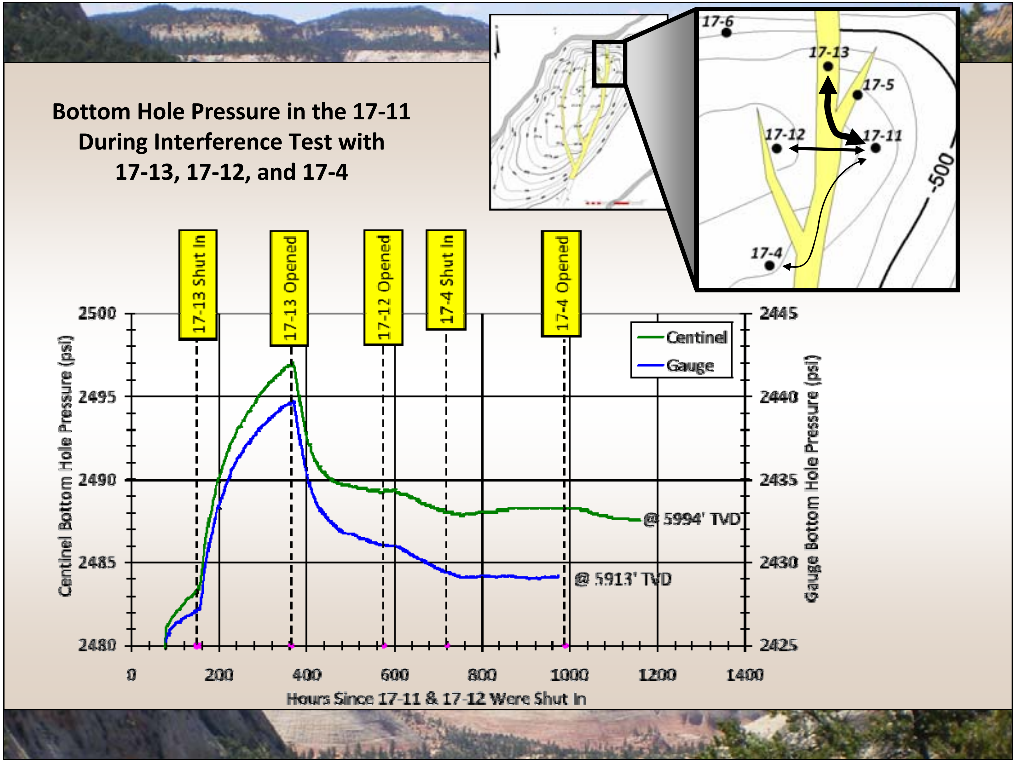
This map shows the location of normal faults that have been identified. I have used some artistic license to hypothesize a possible fault network (shown with the yellow polygon, based on what orientation data we have). Unfortunately, because these faults are below the resolution of our seismic data, there can be no guidance offered from the geophysical dataset. Cross-section A-A' is shown on the next slide.



Presenter's Notes:

This cross-section of gamma ray and resistivity logs illustrates several normal faults.

Note that with sufficient throw, these faults can juxtapose White Throne reservoir against Navajo reservoir. This is an important observation from a reservoir management standpoint. Even though the White Throne and Navajo reservoirs are separated by 50 feet of non-permeable Sinawava, the reservoirs are actually connected where these faults have breached the Sinawava horizon.



Presenter's Notes:

An interference test was conducted between 4 wells on the northeastern portion of the field in December-08 and January-09.

This graph shows the bottom hole pressure measured in the 17-11 well by two devices, a centinel and a gauge. The test began with the shutting-in of both the 17-11 and the 17-12 wells. Next, the 17-13 well was shut-in for 200 hours and then opened, resulting in a rapid increase followed by a rapid decrease in the 17-11 bottom hole pressure. Next, the 17-12 was also opened, resulting in another drop in the 17-11 bottom hole pressure. After that, the 17-4 well was shut-in; this appears to have suspended the pressure drop that was initiated with the 17-12 opening. The final stage of the test was opening the 17-4, measured by the centinel, resulting in a slight pressure drop.

The results of this test indicate that wells on opposite sides of the faults are in pressure communication, therefore the faults are conductive. Furthermore, while the 17-11, 13, and 4 wells are completed in the White Throne, the 17-12 well is completed in the Navajo. Therefore, for the 17-12 and 17-11 to be in pressure communication, the fault must be providing a conduit between the Navajo and White Throne reservoirs.

Conclusions

- The paleowind transport directions are different for the White Throne and Navajo sandstones. Both sandstones are dominated by barchanoid dune forms.
  - White Throne: southwest-trending wind
  - Navajo: south-southeast-trending wind
- The differences in wind transport directions caused unique permeability anisotropies to developed within the reservoirs.
  - Drainage ellipse mapping indicates that the sedimentary fabric of the reservoirs drives interference between existing wells.
- There is a conductive normal fault network providing Navajo-White Throne reservoir communication
- Future wells should be placed with consideration of potential drainage areas and proximity to fault to avoid unwanted interference.

Presenter's Notes:

In conclusion, we can derive some valuable information from this study that will help to shape the further development of Covenant Field.

•The paleowind transport directions are different for the White Throne and Navajo sandstones; they are both dominated by barchanoid dune forms.

•Because of the unique paleowind transport directions, the reservoirs have different permeability anisotropies. Drainage ellipse mapping shows that this sedimentary fabric is driving interference between existing wells.

•Interference tests suggest that there is also a conductive normal fault network that provides inter-well and inter-reservoir communication.

•With that understanding we can conclude that future wells should be placed with consideration of potential drainage areas and proximity to faults in order to avoid unwanted interference.

Acknowledgements & References

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  - Wolverine Gas & Oil Corporation
  - The Wolverine staff, especially Mr. John Vrona, Mr. Keith Johnson, Mr. Ed Higuera and Mr. Ellis Peterson (now of Summit Corporation) as well as consultants Dr. Rossella Sbarra at Oolithica Geoscience LTD, and Mr. Tom Zadick, P.E.
  - Mr. Doug Sprinkel of the Utah Geological Survey
  - My advisor, Dr. Chris Schmidt of Western Michigan University and the members of my committee: Mr. John Vrona, Dr. David Barnes, and Dr. Michelle Kominz

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