Interpretation of the Jurassic Entrada Sandstone Play Using 3D Seismic Attribute Analysis, Uinta Basin, Utah

by R. William Keach II, Thomas H. Morris, John H. McBride, Mike Mullen, Hannes E. Leetaru, and Ryan O'Neal

Open-File Report 493
Utah Geological Survey
a division of
Utah Department of Natural Resources
2006

Interpretation of the Jurassic Entrada Sandstone Play Using 3D Seismic Attribute Analysis, Uinta Basin, Utah

R. WILLIAM KEACH II[1]

THOMAS H. MORRIS[1]

JOHN H. MCBRIDE[1]

MIKE MULLEN[2]

HANNES E. LEETARU[3]

RYAN O'NEAL[1]

[1]*Department of Geological Sciences*
Brigham Young University
Provo, Utah

[2]*Halliburton Energy Sources*

[3]*Illinois State Geological Survey*

Open-File Report 493
Utah Geological Survey
a division of
Utah Department of Natural Resources
2006

TABLE OF CONTENTS

PREFACE

The majority of figures associated with this report are placed within four plates in poster-like fashion. The posters were created in PowerPoint and are presented herein in .pdf format. These posters allow the reader to view materials of related subjects on a single sheet. This should aid the reader in visually comparing attributes and associated geologic features.

ABSTRACT

A high quality 3D seismic survey of the North Hill Creek field located in the southeast portion of the Uinta basin, Utah has been instrumental in rejuvenating the Entrada/Curtis-Moab gas play. Seismic attribute analysis and cross sectional views of this 3D seismic survey are very effective in delineating reservoir quality dune and dune complexes which serve as the primary gas reservoirs within the Entrada/Curtis-Moab interval. Four seismic attributes were used to analyze the data set including amplitude, spectral decomposition, semblance, and phase. Amplitude extractions (maps) of the Entrada/Curtis-Moab seismic interval appear to indicate the overall geometry of dunes and dune complexes. Spectral decomposition maps are very informative in delineating lateral changes in the thickness of dunes and dune complexes. In combination, these two seismic attributes can be used to high grade exploration targets within the play. Our work suggests that, used properly, 3D seismic surveys can delineate well locations where production results of 1-4 BCF of gas can be expected from the Entrada/Curtis-Moab interval. Without a high quality 3D seismic survey, the explorationist assumes a much greater risk of missing the “sweet spots”.

Explorationists can use 3D seismic surveys to visualize several important geological phenomena associated with the Entrada/Curtis-Moab play. The J-3 unconformity lying between the Entrada Sandstone and the Curtis Formation is locally erosional and angular. This can be visualized in local areas within the survey. Also, the Entrada/Curtis-Moab seismic reflector may “split” in very localized areas. These splits potentially indicate exceptional gas production. Finally, subtle topographic or structural highs may increase the hydrocarbon trap potential in any given area.

INTRODUCTION

The North Hill Creek (NHC) 3D seismic survey was the first exploration-orientated 3D seismic survey shot in the Uinta basin, Utah and was instrumental in the discovery and development of high BTU gas-charged Jurassic-aged reservoirs (Figure 1; Eckels et al., 2005; Eckels et. al., 2006).   The relatively small NHC survey (approximately 27 square miles) has initiated a burst of 3D seismic activity in the southeastern Uinta basin which now includes more than 140 square miles of 3D coverage with approximately 100 more square miles of 3D surveys planned. The new Rock Spring 3D seismic survey, located adjacent to and southeast of the NHC field, was initially to be viewed for this study. However, because of ongoing development drilling, it remains proprietary.

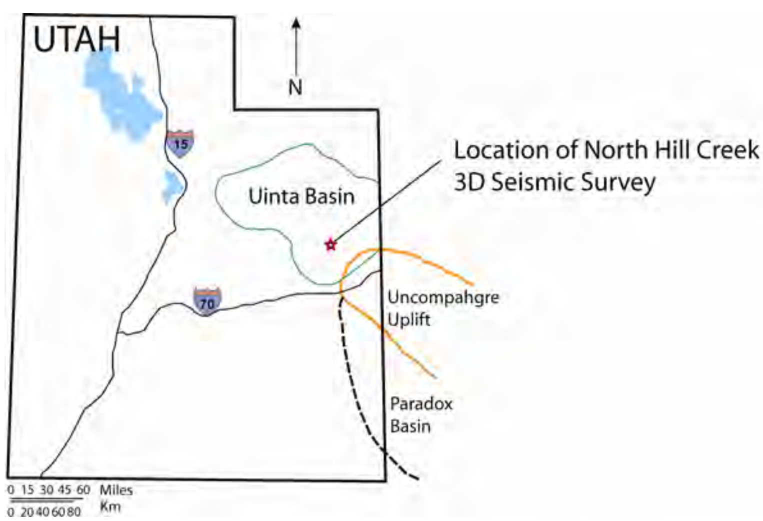


Figure 1. Map showing the location of the North Hill Creek field (NHC). The NHC field geographically overlaps the Flat Rock field.

The North Hill Creek survey helped to establish hydrocarbon production in eleven different formations, including significant gas production from the upper Middle Jurassic Entrada Sandstone. The preponderance of studies done on the Entrada Sandstone depositional system suggests that in the eastern 1/3 of the state of Utah the depositional facies are dominated by eolian dunes deposited in a coastal erg system (Figure 2). Westward these dunes transition into mudstone-dominated tidal flat deposits. The transition zone or erg-margin may be particularly important to study because of the potential for stratigraphic trapping in areas of dune complex pinchouts (Morris et.al, 2005). The overlying Moab Tongue of the Curtis Formation (Doelling, 2001) which in western Colorado appears to be stratigraphically equivalent to the Wanaka Formation (O'Sullivan, 2004) has also been interpreted to represent coastal erg dune and marine re-worked dune complexes (Allin, 2006, personal communication; Eckels et al., 2005; Kocurek, 1981;). These re-worked beds display massive to horizontal bedding along the north and northwest flanks of the Uncompagre Uplift (Figure 1) similar to those described by Vincelette and Chittum (1981) within the upper portion of the Entrada Sandstone in the San Juan basin of New Mexico. In the San Juan basin, preserved topographic relief has been interpreted to create hydrocarbon traps. The preserved relief represents drowning of eolian dunes in the deeper parts of the "lake" basin. In more shallow areas wave action reduced topographic relief.

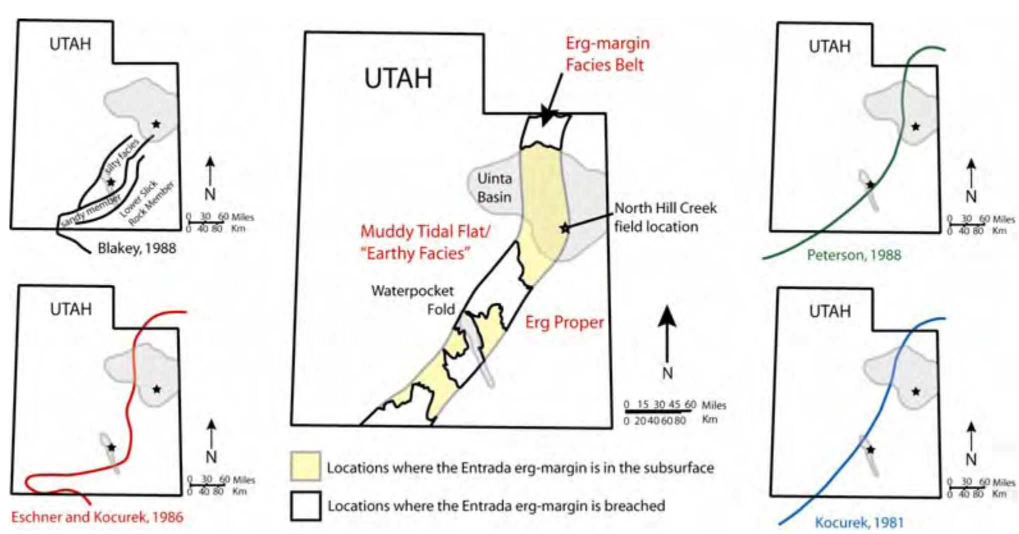


Figure 2: Compilation of past and recent studies delineating the Jurassic Entrada erg-margin. (Modified from Morris et al., 2005)

To date the Entrada/Curtis-Moab interval within the North Hill Creek field has been studied from seismic data and well log data (no whole core data). Interpretations of the seismic and well log data have suggested that the upper Entrada/Curtis-Moab interval appears to thicken locally (Eckels et al., 2005; Allin, 2006, personal communication). Further, recent field work by Morris and Monn (personal communication) demonstrate that an angular unconformity exists between the Entrada Sandstone and the Curtis Formation in the outer erg-margin area near Capitol Reef National Park. Together these interpretations leave open the possibility that dune complex relief or erosional relief was at least partially preserved in the field area. If this is true, the potential for this play to carry beyond areas of structural closure exists. More importantly, however, is that the upper portion of the Entrada/Curtis-Moab interval appears to develop the highest quality reservoir characteristics and contains the majority of the gas resource.

The purpose of this study is to further analyze the Entrada/Curtis-Moab interval using seismic attributes of the North Hill Creek 3D seismic survey. We herein provide data relative to key methods, parameters and attributes that will help the explorationist develop the best visualization of their 3D seismic data. Numerous attribute maps or images extracted from the North Hill Creek 3D seismic survey are presented. Although some interpretation and well log-based volumes are presented, the primary intent of this study is to aid the seismic interpreter in discovering and developing Entrada/Curtis-Moab reservoirs within the Uinta basin and possibly elsewhere along the erg-margin trend.

Introduction to Seismic Attribute Analysis

Included within this report are numerous seismic images and maps extracted from the North Hill Creek (NHC) 3D seismic survey. These seismic extractions include amplitude, phase, semblance, and spectral decomposition. We herein provide an introduction as to what these extractions are and what they can potentially produce in helping interpret and understand the Entrada/Curtis-Moab interval. Visualization software used to create the images was provided by Halliburton-Landmark. The software was licensed to Brigham Young University through Halliburton's Landmark University Grant Program. The grant includes a full suite of tools (e.g., ProMAX, Seisworks3D, and GeoProbe) by which seismic attribute maps can be computed in two and three dimensions. The primary reference for this introduction section comes from: *PostStack Family Reference Manual* copyright © 2004 by Landmark Graphics Corporation.

Landmark applications include a state-of-the art suite of seismic attribute computation tools for 2D and 3D seismic data sets. The use of seismic attribute analysis for seismic interpretation was first described in the context of seismic sequence analysis (Mitchum et al., 1977). The basic concept of seismic attribute analysis was outlined by Taner and Sheriff (1977). The concept is based on a set of quantitatively derived measures of a seismic waveform that can be used to improve the visual ability of an interpreter to correlate stratal reflection patterns, recognize distinctive packages of reflections with a similar character, interpret subtle bedding patterns, recognize subtle faults and other geologic features of a seismic section.

The application of seismic attribute analysis to the North Hill Creek 3D seismic survey will (1) improve the general stratigraphic and structural interpretability of the data for the Entrada/Curtis-Moab section, (2) create a consistent and quantitative basis for comparing the continuity and coherency of reflections at various levels within the section, and (3) allow us to develop a set of criteria for pattern recognition for indicating discontinuities.

Amplitude – Lithology, Facies Changes, and Fluid Contacts. By analyzing the amplitude- and phase-related interference phenomena, one can quickly and efficiently quantify and map local rock mass variability within a 3D survey.

In general, amplitude information can be useful in identifying:

- gas and fluid accumulation
- gross lithology
- gross porosity
- channel and deltaic sands
- certain types of reefs
- unconformities
- tuning effects
- changing sequence stratigraphy.

Lateral changes in amplitude have been used in stratigraphic studies to separate areas of concordant stratigraphy from chaotic or mounded beds in an interval (Figure 3). In general, beds that are concordant will have higher maximum amplitudes. Hummocky beds will have lower maximum amplitudes, and chaotic beds, the lowest. In certain

Tertiary basins, deltaic sequences prograde from sand-rich shoreline facies to shale-rich pro-delta or abyssal plane facies. Sand-rich environments often have high seismic amplitudes as indicators. Likewise, shale-rich environments often have low seismic amplitudes as indicators. These changes in the sand-shale ratio are readily detected by viewing amplitude statistics in map view.   Relative to this study, two possible scenarios exist that may make amplitude extractions helpful. First, amplitude may be used in detecting where sandy erg or erg-margin facies transition laterally to muddy intertidal facies. Second, amplitude extraction may help in detecting where sand-prone dune complexes transition laterally into finer grained interdune facies.

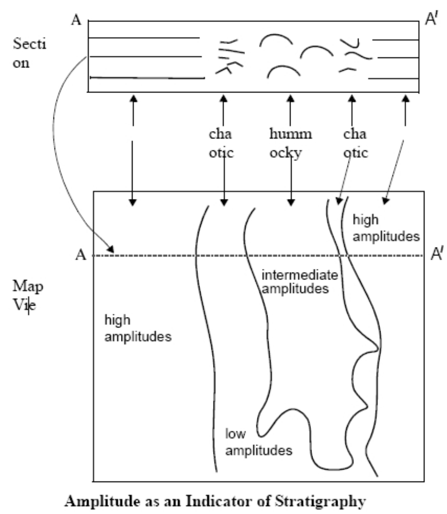


Figure 3: An idealized example of mapping amplitude variations.

Spectral Decomposition - Thickness and Thickness Variation of Seismic Events.

Spectral decomposition is used for imaging and mapping temporal bed thickness and geologic discontinuities over 3D surveys. This technology can improve prospect definition beyond seismic tuning resolution and it can often help resolve what cannot be resolved in the time domain. Spectral decomposition is a must use tool for:

•delineating facies/stratigraphic settings (such as eolian bedform thickness variation, flood plain boundaries, reef boundaries, channel sands, incised valley-fill sands, and other thin beds)

•resolving the order of deposition

•detailed mapping of structural settings involving complex fault systems (such as reservoir compartmentalization)

•mapping of near surface environmental hazards (such as expulsion features and other near surface instabilities)

•reservoir modeling (mapping fluid changes, pressure changes and changes in 4D surveys).

The frequency slice, also called a “tuning map,” is very useful because it provides visualization of thin-bed interference patterns in plan view. Drawing on experience, these tuning maps can be used to identify textures and patterns indicative of geologic processes. Animating through frequency subbands/tuning maps of the earth provides the capability to map lateral variability in the subsurface. However, the interpreter cannot collapse all the information gained by animating through a tuning cube into a single attribute map.

Spectral decomposition can be used qualitatively to reveal stratigraphic and structural edges/bodies as well as relative thickening/thinning. Quantitative use of spectral decomposition is effective at predicting reservoir thickness or intra-reservoir travel time. Whether qualitative or quantitative, spectral decomposition maps usually exhibit substantially more fidelity than full-bandwidth conventional complex trace attributes. Very rarely will the interpreter find information in conventional attributes that is unique to spectral decomposition analysis. That is to say, if the interpreter does not see an event with spectral decomposition, then he/she will not see it with traditional complex trace attributes. Furthermore, events are almost always brighter with spectral decomposition than with traditional attributes. According to most users, when compared to coherency imaging, the spectral decomposition fault definition is often superior. The current study uses spectral decomposition in a qualitative approach.

Semblance or Event Similarity Prediction (ESP) – Faults and Facies Changes.

Event Similarity Prediction (ESP) is Landmark’s version of Semblance or dissimilarity processing. The process examines the dissimilarity of an event along one trace with the same event along the adjacent trace. The advantage of dissimilarity data is that it reveals and heightens lateral seismic changes that often relate to geologic changes. These dissimilarity measurements yield the visual identification of such features as faults, facies changes, and other geologic patterns. Faults and stratigraphic changes will often stand out as prominent anomalies in otherwise homogenous data. Low similarity values may be caused by the following:

- near vertical faults or low-angle faults
- contrasts in seismic character due to stratigraphic or lithologic changes
- highly dipping events, if dip correction has not been applied
- lack of reflectors (e.g., salt)
- poor quality data

Faulting with detectable vertical throw or wavefield distortion will generally produce clearly identifiable, narrow zones of low similarity. Similarly, abrupt contrasts in seismic character due to stratigraphic or lithologic changes (such as channel sands) will also produce narrow zones of low similarity values.

Gradual stratigraphic contrasts, such as those associated with transgressive sequences, will produce broad regions of moderate similarity values. Highly dipping events, when no dip correction is applied, will result in broad regions of low similarity. Zones with poor data quality or lack of reflectors (e.g., salt structures) can also produce broad regions of low similarity. Finally, bad traces, migration "smiles," and acquisition "foot print" can also generate localized regions of low similarity.

Phase – Uniqueness of rock unit relative to its enveloping lithology (e.g. fluid content changes, bedding character). Instantaneous phase describes the angle between the phasor, which is a rotating vector formed by the real and imaginary components of the time-series, and the real axis as a function of time. Therefore, it is always a number between -180 and +180 degrees. As a result, instantaneous phase has a discontinuous, sawtooth character caused by the phase-wrapping between +180° to -180°. This character can be corrected by wrapping phase. Analysis window size is important and should be small, typically only a period or less.

PAL converts each incoming trace to instantaneous phase and then computes its mean value within the analysis window.

Because phase is sensitive to subtle perturbations in the seismic character, it is ideal for detecting lateral acoustic discontinuities often found in faulted/compartmentalized reservoirs or in areas of lateral facies changes. That is to say, if the rock mass within the analysis window is laterally stable, its phase response will likewise be stable. If a lateral discontinuity occurs, the phase response becomes unstable across the discontinuity. Once the rock mass stabilizes on the other side of the discontinuity the phase response likewise stabilizes

Average instantaneous phase provides a means of assessing the overall phase characteristics of a seismic interval. Lateral changes in phase may be related to changing fluid content of sediments or even to changes in bedding character within a sequence. Instantaneous phase should respond in a diagnostic way to amplitude tuning effects. In other words, when amplitude attributes are biased by the constructive and then destructive interference of reflectors as they come closer together, instantaneous phase can confirm that the amplitude changes are due to tuning and not to hydrocarbons or other effects.

SELECTION OF SEISMIC ATTRIBUTE PARAMETERS: BEST PRACTICES

The "art" of using seismic attribute analysis is finding images that allow the interpreter to; 1- accurately capture the geologic essence of the subsurface and 2- visualize the geology. These aspects require an understanding of the individual attribute and experience in color selection, volume orientation, mapping techniques and a variety of other methods. In the end, however, visualization is personal (i.e. one individual may see more by simply using a different color scheme than another individual). It should be noted that one needs to exercise patience and learn to "experiment" with the various attributes. A 3D data set is essentially a pile of raw data that needs to be analyzed with great care in order to extract accurate geological information.

We herein present suggestions for attribute parameters that we feel capture the essence of the geology. Plates I through III display images of extractions that use the parameters given below. Careful viewing of the images on these plates can reveal important information relative to exploration/development practices for the Entrada/Curtis-Moab gas play. For these images, we chose color schemes that are based on our own tastes for visualizing the essential geology.

Amplitude

A maximum positive amplitude extraction is presented on Plate I. This extraction uses a 28 msec window that begins 6 msec (- 6 msec) above the Entrada seismic pick and analyses a window down to 22 msec (22 msec) below the pick. This window allows the interpreter to capture the Entrada/Curtis-Moab seismic interval. When an average amplitude extraction was run through the same window, minimal differences where observed.

An average reflection strength amplitude extraction was also performed through two different windows. The first was run through the previous window (i.e. 28 msec from -6 msec to 22 msec) and the second was run through a 15 msec window (i.e from -5 msec to 10 msec). Lower amplitudes became obvious deeper in the window.

Spectral Decomposition

Spectral decomposition attribute extractions are presented on Plates I and II. The analysis window length for calculation is 40 msec. The window was centered 10 msec below the Entrada seismic pick. A cosine taper of 20% helps to focus on the middle portion of the Entrada seismic interval. The calculated tuning volume contains frequency slices from 0 Hz to 100 Hz. Plate I displays the frequency extraction at 35 Hz. Plate II displays extractions from 10 Hz to 50 Hz in 5 Hz increments.

Semblance (ESP)

A semblance attribute extraction is presented on Plate I. A semblance volume was calculated on the 3D reflection volume with a 24 msec window and a 3 trace cross correlation. The semblance values were extracted at 10 msec below the Entrada seismic pick.

Phase

Average instantaneous phase attribute for the Entrada seismic interval is presented on Plate I. The average instantaneous phase analysis also uses a 28 msec window that begins 6 msec (-6 msec) above the Entrada seismic pick and analyzes a window down to 22 msec below the pick.

SELECTION OF SEISMIC CROSS SECTIONS: BEST PRACTICES

Several images of cross sections through the 3D seismic volume are presented in Plates I and III. These cross sections were chosen in an effort to illustrate the structural surface of the Entrada/Curtis-Moab seismic interval as well as to illustrate several key geologic features that can be documented in outcrop and well logs.

The cross section presented on Plate I was designed to introduce the seismic and structural features of the North Hill Creek (NHC) field to the reader. It illustrates a structural elevation map of the top of the Entrada/Curtis-Moab interval, the North Hill Creek fault, Gamma Ray (GR) logs of several key wells in the field (displayed in lathe format), well names, and a seismic panel that illustrates the seismic character of the Mancos Shale and the general Jurassic section.

The cross sectional views on Plate III were chosen to illustrate two important geological phenomena relating to the Entrada/Curtis-Moab play: 1- the angular unconformity that is sometimes apparent between the Entrada (below) and the general Curtis Formation (above), and 2- the fact that, locally, the seismic trace picked as the Entrada – Curtis contact splits due to either apparent thickening of the upper Entrada Sandstone interval or emplacement of additional Curtis-Moab sandstone(s) on top of the Entrada Sandstone (see Results/Interpretations section below).

RESULTS/INTERPRETATIONS

For ease of viewing, all data are presented in poster format on Plates I-IV. Plates I and II display seismic attribute images from the 3D volume including images of Amplitude, Spectral Decomposition, Phase and Semblance. Plate III illustrates a number of important geologic features that are important to understand when exploring for or developing an Entrada/Curtis-Moab hydrocarbon resource. Plate IV displays a variety of log plots and isopach maps and suggests rough parameters for resource volume calculations.

Plate I

The center figure of Plate I should be used as a reference for comprehending the structural style, seismic style, the location of selected wells, relative well orientation, and well log characteristics. The structural surface is mapped on the Entrada/Curtis-Moab seismic pick. This surface shows that a relative high exists within the northern block adjacent to the North Hill Creek Fault whereas a surface adjacent to the fault in the southern block is a relative low. A fault plane map of the North Hill Creek Fault (not presented herein because the figure becomes too busy) shows that the fault has a strong high angle reverse component. The seismic style of the Mancos Shale section of the survey can be described as having weak reflectors whereas the lower Cretaceous and Jurassic through Triassic rocks appear to have much stronger reflectors. Given the nature of the lithologies in these sections, the seismic style is understandable (Mancos = homogeneous shale with weak impedance contrasts). Logs posted on this image also show the homogeneity of the Mancos Shale interval relative to the underlying section.

Amplitude. The amplitude extraction in the upper left corner of Plate I is a maximum positive amplitude extraction. Maximum amplitudes are found in the upper portion of the 28 msec window investigated. The figure illustrates numerous geologic features, some of which were previously interpreted and described by Eckles et al. (2005). Geologic features interpreted to be visible include star dune complexes, barchan dunes, and longitudinal to sinuous, seif-like dunes. The figure also illustrates that a concentration of star dune complexes can be observed in the southeast third of the 3D survey with scattered complexes in the northwest third of the survey. There appears to be few star dune complexes in the middle of the survey. Higher amplitudes may represent the general area of sandstone accumulation but do not necessarily reflect sandstone thickness or reservoir quality. Spectral decomposition may better delineate the thickness of sandstone accumulations (see interpretation on Plate II).

Spectral Decomposition. The spectral decomposition extraction in the upper right corner of Plate I is also geologically revealing. This 35 Hz extraction further defines the shapes of geologic features observed in the amplitude extraction. As the entirety of Plate

II is devoted to spectral decomposition extractions, please refer to Plate II in this section for further discussion.

Semblance. The semblance extraction in the lower right corner of Plate I assists the interpreter in defining the edges of dune complexes. Black areas are interpreted to represent interdune facies whereas light blue colors represent the dune complexes. A dark circle can be observed surrounding the well located in the northwest portion of the survey (29-6A). This circle may outline the locally thickened Entrada/Curtis-Moab section. This thickened section can be viewed in Plate III and possibly relates to either an anonymously thick Entrada or an additional Curtis Moab sandstone (dune complex?).

Phase. The image in the lower left of Plate I illustrates the average instantaneous phase. Dune complexes appear to have consistent phase values. Other features which are less easily interpreted include lineaments in the east central portion of the northern structural block and dark sinuous features visible in the northwest potion of the survey. We suggest possible interpretations of these features (see Plate I) but express little confidence in these interpretations. Phase appears to have limited value in interpreting the Entrada/Curtis-Moab interval given the other attributes available to the interpreter.

Plate II

Plate II illustrates a series of spectral decomposition images. The images are displayed at 5 Hz increments resulting in nine images from 10 Hz to 50 Hz. The 10 Hz image illustrates the areal extent of relatively thick successions whereas the 50 Hz image illustrates the areal extent of relatively thin successions. An interesting observation is that as the frequency increases, the areas in red which delineate the areal extent of a specific thickness become larger (see areas highlighted in Plate II at frequencies of 20 Hz, 35 Hz, 45 Hz and 50 Hz). This observation could be interpreted to suggest that as frequency increases we are visibly highlighting the thinner and thinner portions of dune complexes, therefore, the overall areal extent of the complex appears to expand as one moves to higher frequencies. These images appear to support the interpretation of the existence of dune complexes and, in fact, more accurately delineate sandstone body morphologies at relative thicknesses than does the amplitude extraction.

Plate III

The center image of Plate III is a basemap illustrating the orientation of the cross sections presented on the rest of the plate. The remaining images on the plate are presented in an effort to illustrate two important aspects for interpreters to comprehend when exploring the Entrada/Curtis Moab seismic interval. First, the images on the left portion of the plate examine the nature of the contact between the Entrada Sandstone and the Curtis Formation. Second, the images on the right illustrate something of a seismic anomaly in that the high amplitude Entrada/Curtis-Moab seismic pick appears to split near the 29-6A well.

Entrada – Curtis Contact. Locally, the nature of the J-3 unconformity between the Entrada Sandstone and the Curtis Formation is erosional and angular (Figure 4; Hintze, 1988; Morris et al., 2005; Monn, 2006). This angular relationship is not always present in either seismic or outcrop (see image in lower left of Plate III). However, where it can be observed seismically, it can definitively clue the interpreter into the Entrada/Curtis-Moab contact. The upper left image of Plate III illustrates this relationship in vertical section while the middle left image illustrates a side view of the same line.

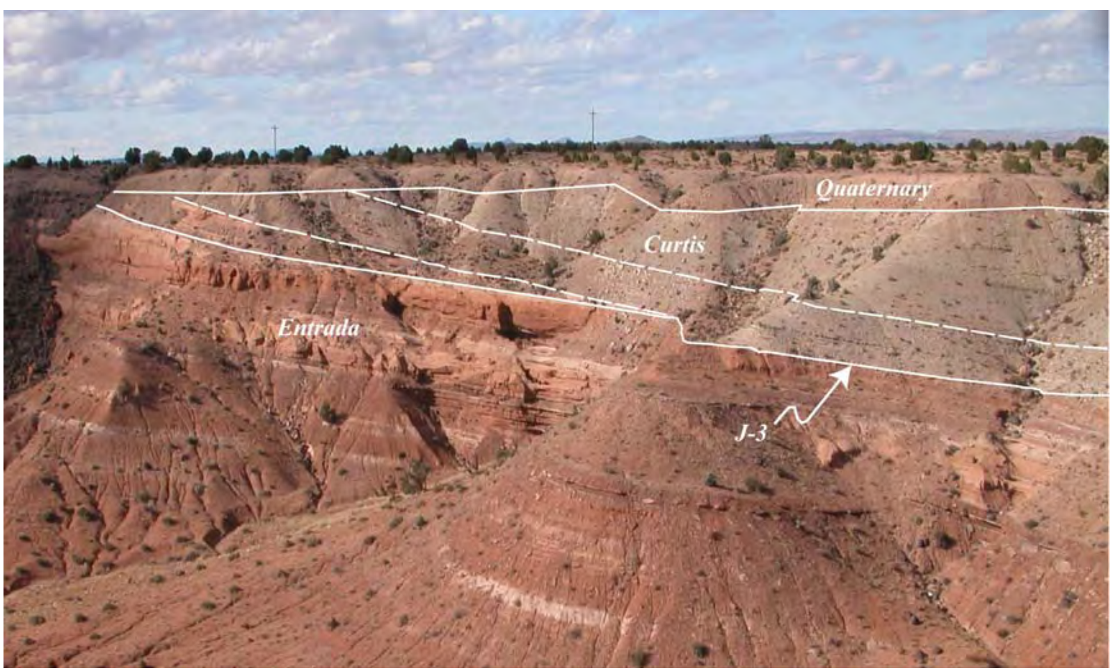


Figure 4: J-3 angular unconformity near Capitol Reef National Park.

One explanation for the localized angular unconformity at the J-3 is flowage and withdrawal of gypsum within beds of the Carmel Formation. The Carmel Formation is stratigraphically directly beneath the Entrada Sandstone. Diapir-like movement could locally create gentle antiformal folding in the overlying Entrada Sandstone. Gypsum withdrawal may cause collapse features. Collapsed features within the Entrada can be observed in outcrop on the east flank of the San Rafael Swell. In these locations it appears that the Curtis was unaffected by these collapse features. Thus, the timing of gypsum movement was previous to Curtis deposition.

Entrada/Curtis-Moab Seismic Anomalies. The images in the upper right and middle right illustrate a dramatic and very local split of the Entrada/Curtis-Moab reflector as it nears the 29-6A well. This well has been a prolific gas producer in what has been reported as the Curtis/Entrada. The interpreter is faced with carrying the reflector upward or downward. Depending on the choice, seismic attribute maps may change their character. The important point is that these types of splits should be sought after. They likely represent either an additional dune complex of the Entrada Sandstone that was locally preserved or a remnant of sandstone from the Moab Member of the Curtis Formation. It is possible that the extra sandstone created topographic relief that, in turn, enhanced the hydrocarbon trapping potential. Further, the flat nature of the reflectors immediately beneath the Entrada/Curtis Moab seismic pick, which are located in an otherwise structurally dipping environment, causes one to consider the possibility of a gas/water contact.

Plate IV

Plate IV focuses on reservoir characteristics and estimated volume calculations. The five well cross section illustrates the variability in the amount of sand within the Entrada/Curtis-Moab interval. This interval is located in the upper 200 + feet below the tie line labeled “Entrada”. The 10-10 well has been the best Entrada producer of the five wells displayed (Eckles, personal communication). The GR log signature indicates that the Entrada Sandstone is composed of a series of sandstone intervals (approximately six to eight) that are separated by significant mudstone breaks. We interpret the mudstone breaks between these six to eight intervals as a muddier interdune-complex facies associated with the groundwater table and the coastal intertidal zone. The very thin muddy breaks within sandstone intervals are associated with the finer grained facies of interdunes migrating within a given dune complex. Morris et al. (2005) demonstrate that even within a dune complex, muddier facies of the interdune facies are interbedded with sandier facies of foreset laminated, individual migrating dunes. Peak and average porosities were calculated for some of the better sand intervals in each well and are given in the table on Plate IV.

Gross and net sandstone isopach maps are also presented on Plate IV. These maps include the Carmel Formation but a quick analysis of the logs indicates that there is very little sandstone in the Carmel relative to the Entrada. Both maps indicate that the 10-10 well has penetrated a relatively sandstone-rich area. These maps, however, are very dissimilar in style to the amplitude and spectral decomposition maps given in Plates I and II. Examination of amplitude and spectral decomposition maps indicates that the 10-10 well is located within highs of the amplitude map as well as the higher frequency spectral decomposition maps relative to most of the other wells studied herein. Based on the drainage area and calculated producible reserves (MMCFG per acre – see Table on Plate IV) cumulative production is expected to reach around 4 BCF. In contrast, the 4-1 and 1-9 wells appear to miss penetrating either amplitude highs or spectral decomposition highs (at any frequency). These wells have very limited production from the Entrada interval (Eckles, personal communication). Based on the drainage area and calculated producible reserves (MMCFG per acre – see Table on Plate IV) little cumulative production is expected from these wells relative to the 10-10 well.

CONCLUSIONS

- Combined use of amplitude and spectral decomposition are very informative relative to accurately estimating the reservoir size. These two seismic attributes should be considered when calculating hydrocarbon production estimates.
- Amplitude extractions (maps) of the Entrada/Curtis-Moab seismic interval appear to indicate the overall geometry of dunes and dune complexes.
- Spectral decomposition maps are very informative in delineating lateral changes in the thickness of dunes and dune complexes. High quality 3D data sets are key in delivering high resolution spectral decomposition frequency slices. Our work indicates that 35 Hz to 50 Hz frequency slices best illustrate dune and dune complex geometries and relative thicknesses. We recommend further analysis to move this from a qualitative to a quantitative assessment.
- The explorationist should pay particular attention to reflector "splits" of the Entrada/Curtis-Moab seismic reflector. Amplitude "splits" of the Entrada/Curtis-Moab seismic reflector may indicate an additional sandstone interval (Entrada or Curtis-Moab?) that in turn may produce subtle topographic relief that would increase hydrocarbon trap potential. We speculate that the 29-6A well may also display a gas/water contact.
- Locally the J-3 unconformity between the Entrada Sandstone and the Curtis Formation can be angular. This can be observed using cross sectional views of the seismic volume. The angular discordance may aid the interpreter in picking the Entrada/Curtis-Moab seismic reflector.
- Subtle topographic relief or structural highs may be important in hydrocarbon accumulation within the Entrada/Curtis-Moab play.
- Quality 3D seismic surveys are key to the success of the Jurassic Entrada/Curtis-Moab gas play. Volume and production estimates indicate that average wells in Entrada reservoirs will produce approximately 1 BCF of gas in the North Hill Creek field whereas optimally located wells will produce on the order of 4 BCF of gas.

ACKNOWLEDGEMENTS

This research was funded through the Utah Geological Survey (UGS), Contract # 061647 under the "Characterization of Utah's Hydrocarbon Reservoirs and Potential New Reserves Program", for which we are most grateful. Additional funding was received from the College of Physical and Mathematical Sciences at Brigham Young University. We thank Marc Eckels, Wind River Resources Corporation, for providing the North Hill Creek 3D seismic survey and well logs. His continued enthusiasm, support, and feedback relative to the Entrada Sandstone play has been very helpful. David Allin, Grand Junction, CO, was instrumental in helping us develop a broader view of the Entrada and Curtis-Moab/Wanaka depositional systems. We thank him for numerous discussions and his very informative leadership on a two day field trip. Co-author Hannes E. Leetaru works with the Illinois State Geological Survey (ISGS) and the University of Illinois. 3D seismic visualization software was donated and licensed to BYU by Halliburton's Landmark University Grant Program.

REFERENCES

Doelling, H.H., 2001, Geologic map of the Moab and eastern part of the San Rafael Desert 30‘ x 60’ quadrangles, Grand and Emery Counties, Utah and Mesa County, Colorado, Utah Geological Survey, ISBN 1-55791-581-4, Map 180D, CD with GIS data, Scale: 1:100,000.

Eckels, M.T., Suek, D.H., and Harrison, P.J., 2005, New, old plays in southern Uinta basin get fresh look with 3D seismic technology, Oil and Gas Journal, v. 103, p. 32-40.

Eckels, M.T., Suek, D.H., Rawn-Schatzinger, V., Weyland, V., and Harrison, P.J., 2006, Applying 3D seismic to underexplored areas of the Uinta basin, Search and Discovery, Article # 10097, posted February 6, 2006.

Hintze, L.F., 1988, Geologic History of Utah, Brigham Young University Geology Studies, Special Publication 7, 202 p.

Kocurek, G., 1981, Erg reconstruction: the Entrada Sandstone (Jurassic) of northern Utah and Colorado, Palaeogeography, Palaeoclimatology, Palaeoecology, v. 36, p. 125-153.

Mitchum, R.M., Jr., Vail, P.R., and Thompson, III, S., 1977. Seismic stratigraphy and global changes in sea level, part 2: The depositional sequence as a basic unit for stratigraphic analysis. In: Payton, C.E. ed., Seismic Stratigraphy—Application to Hydrocarbon Exploration. AAPGMem. 26, 53-62, 1977.

Monn, W.D., 2006, A multidisciplinary approach to reservoir characterization of the coastal Entrada erg-margin gas play, Utah, Brigham Young University, MS thesis, 33 p.

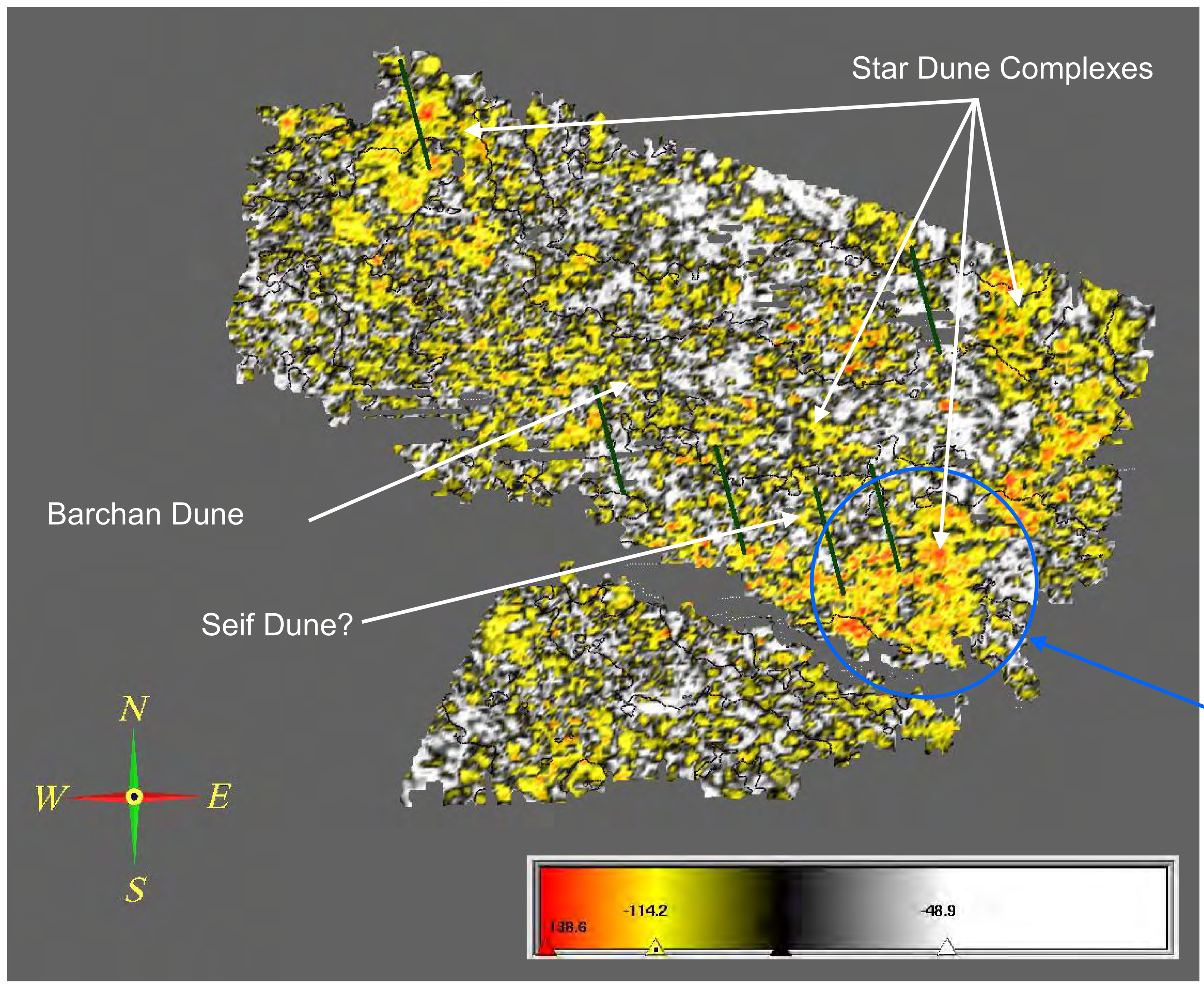
Morris, T.H., McBride, J.H., and Monn, W.D., 2005, A multidisciplinary approach to reservoir characteristics of the coastal Entrada erg-margin gas play, Utah, Utah Geologic Survey, Open-File Report 459, CD.

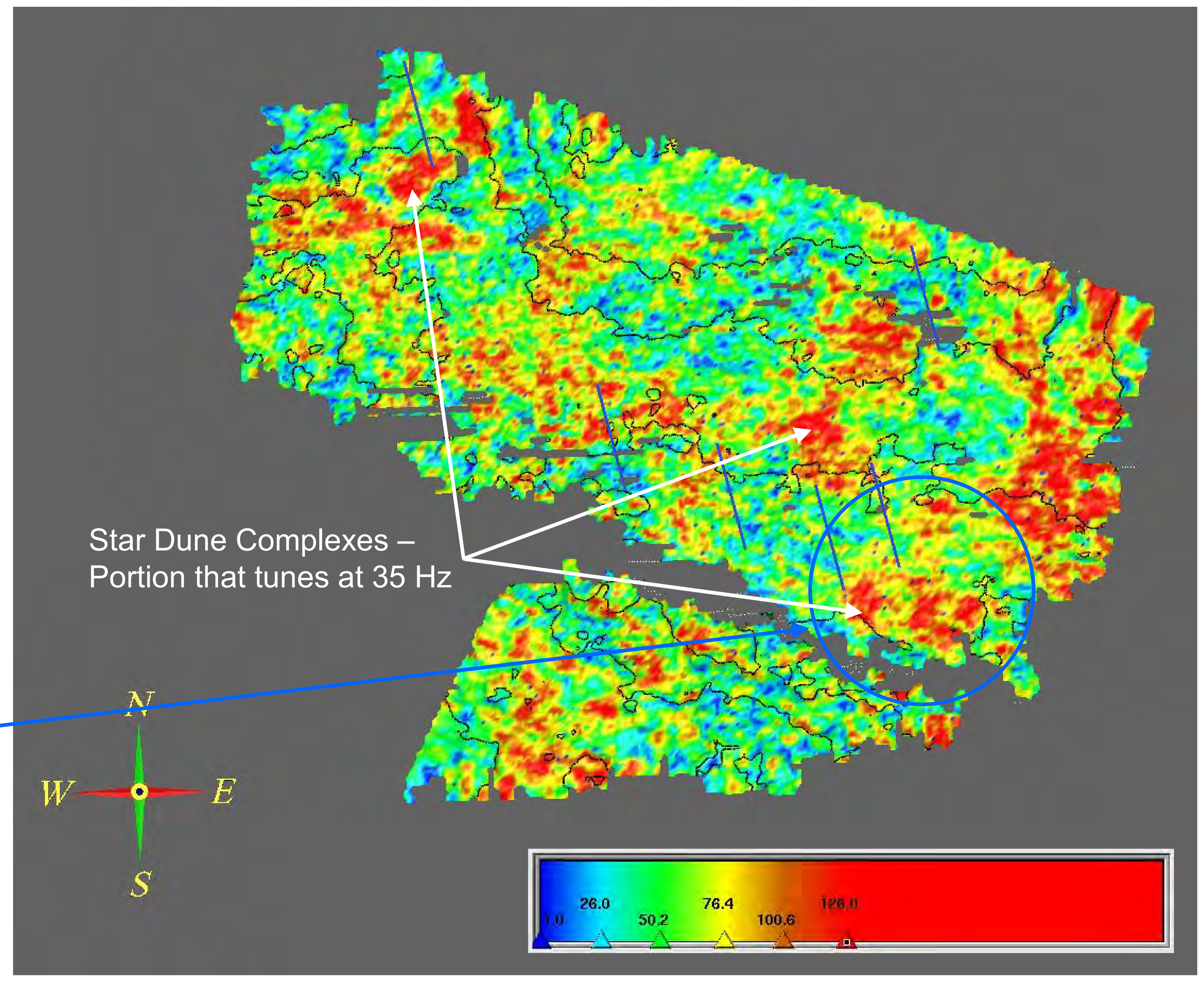
O'Sullivan, R.B., 2004, Correlation of Middle Jurassic San Rafael Group and related rocks from Bridgeport to Ouray in western Colorado, United States Geological Survey, Scientific Investigations Map, Report, SIM-2849, Sheet 1, http://pubs.usgs.gov.erl.lib.byu.edu/sim/2004/2849/.

Taner, M.T., and Sheriff, R.E., 1977, Application of amplitude, frequency, and other attributes to stratigraphic and hydrocarbon determination, In: Payton, C.E. ed., Seismic Stratigraphy-Application to Hydrocarbon Exploration. AAPG Mem. 26, 301-327.

Vincelette, R.R., and Chittum, W.E., 1981, Exploration for oil accumulations in Entrada Sandstone, San Juan basin, New Mexico, AAPG Bulletin, v. 65, p. 2546-2570.

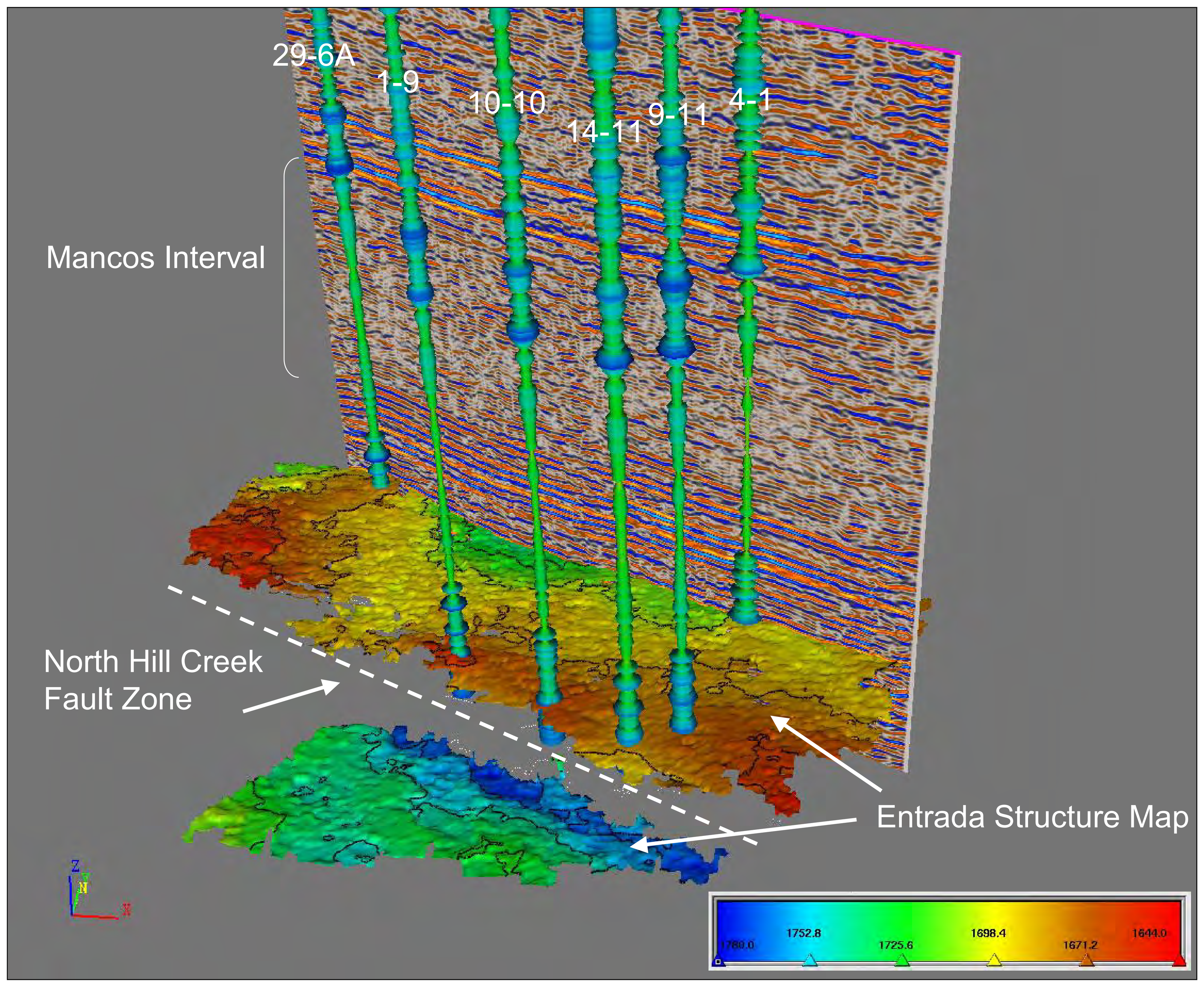
Plate I: North Hill Creek – Seismic Attributes





Amplitude seems to be an indicator of overall dune geometry but not of thickness or reservoir quality. Spectral decomposition better delineates lateral changes in thickness.
See Plate 2: 20, 35, 45 and 50 Hz.

Amplitude – Maximum Positive Amplitude extracted from the Entrada seismic interval (~28 ms). Yellow/red (higher amplitudes) correlate to dune features with the interdunes in gray/white (lower amplitudes).

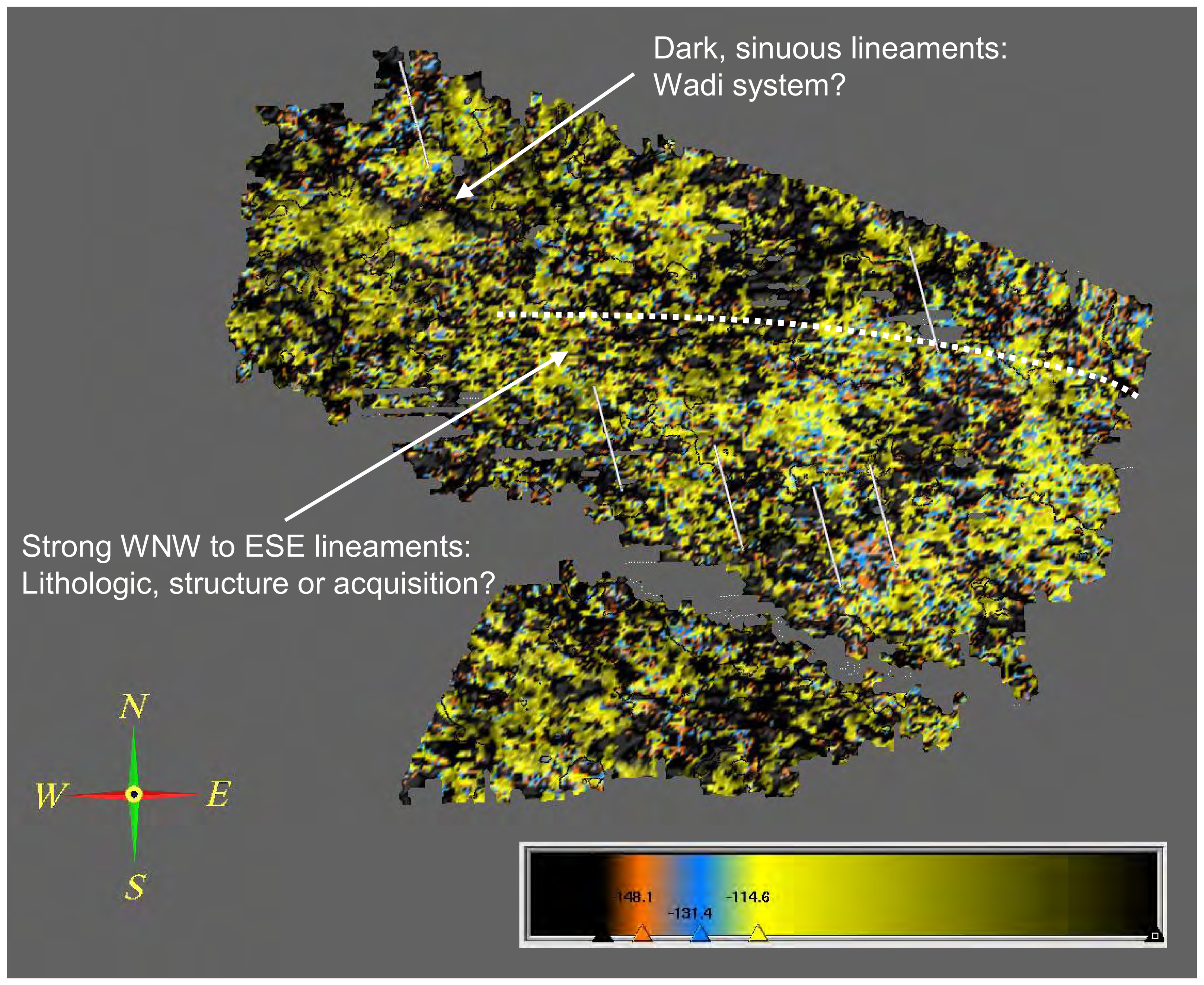


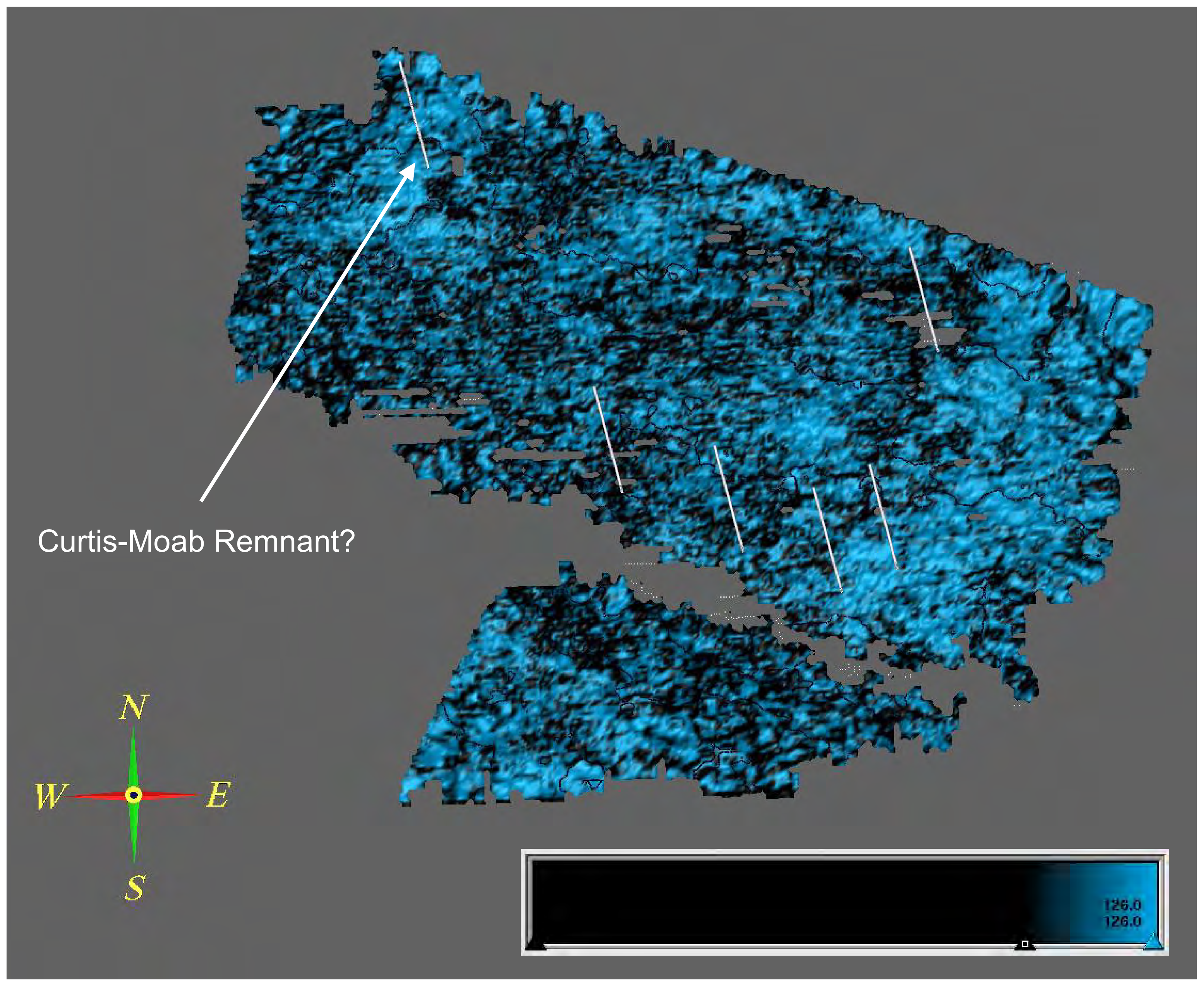
Spectral Decomposition – 35 Hz. The areas in red delineate the areal extent of a specific dune thickness. Lower frequencies show thicker sections and higher frequencies show thinner sections. See Plate 2 for the full set of derived frequencies, 10-50 Hz.

Average Instantaneous Phase – Dune complexes seem to have a consistent phase value that is distinct from the interdune areas. Features of interest are highlighted below.

Semblance – Delineates lithologic and/or structural edges. The dune edges are in black, the bright blue areas define the areal extent of the dunes.

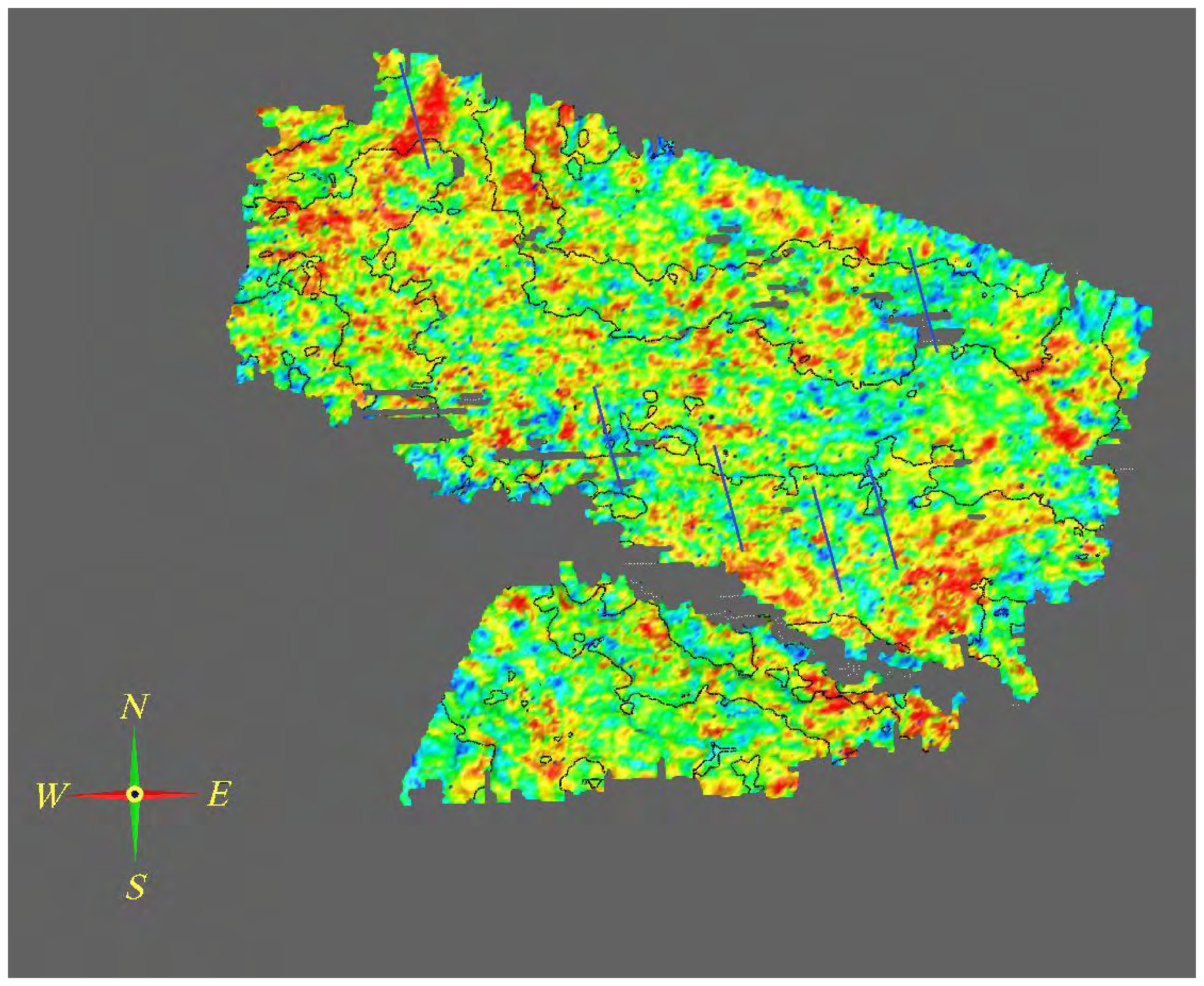
Index figure for Entrada structure, selected wells and seismic. The Gamma Ray curve is displayed as a lathe with sand in blue and shale in green to red.



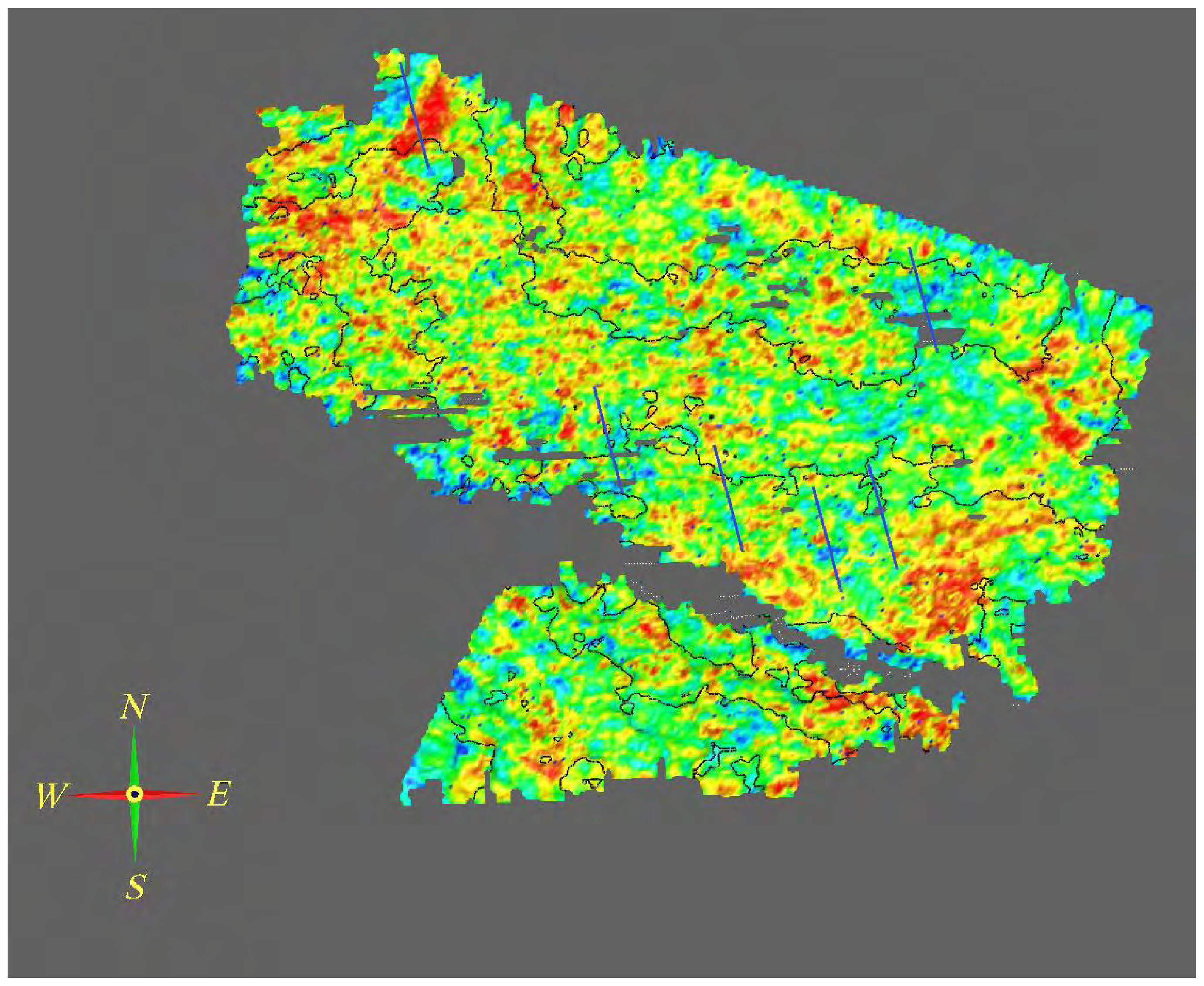


UGS Contract #061647. Keach, Morris, McBride, Mullen, Leetaru and O'Neal.

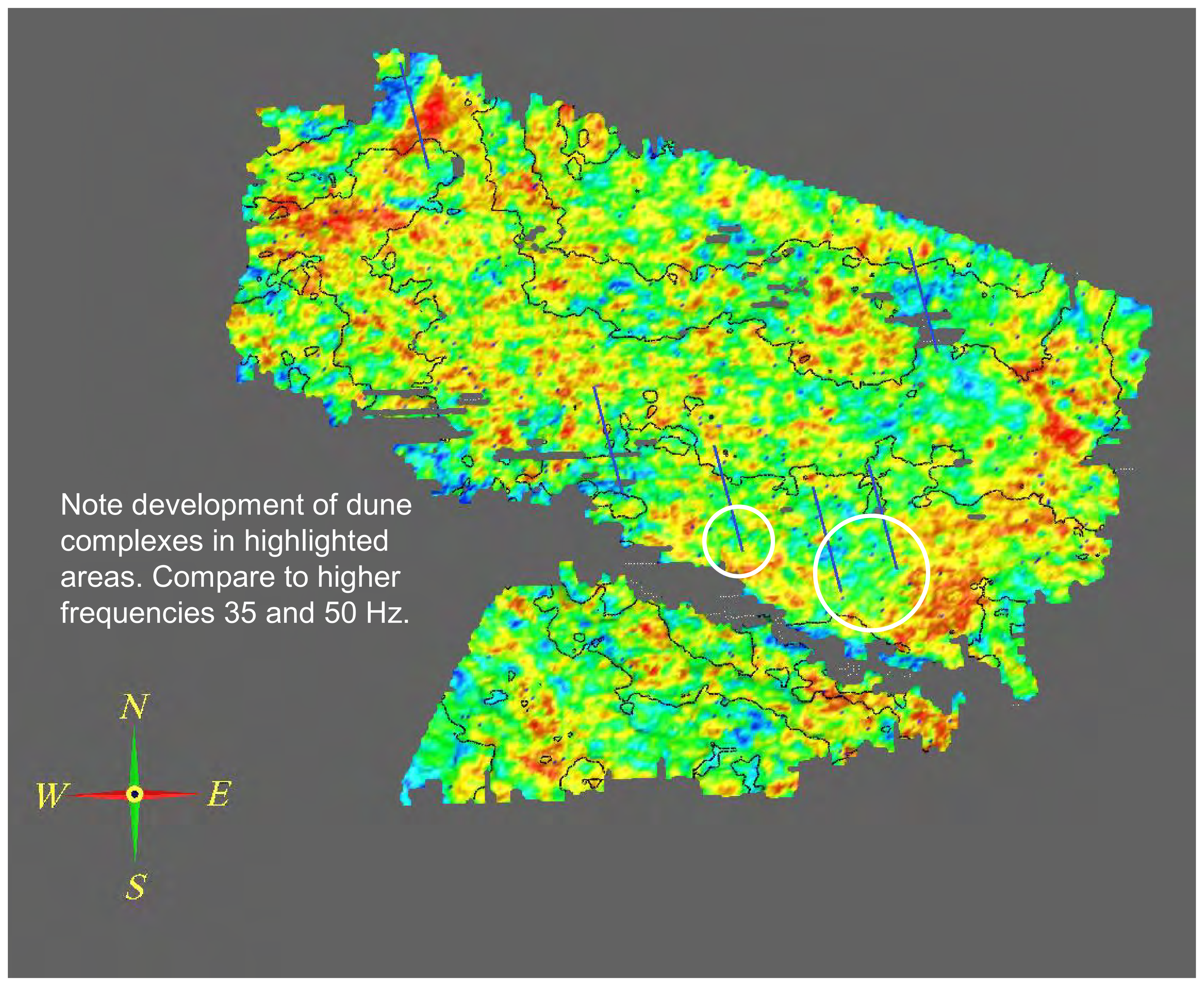
Plate II: North Hill Creek – Spectral Decomposition



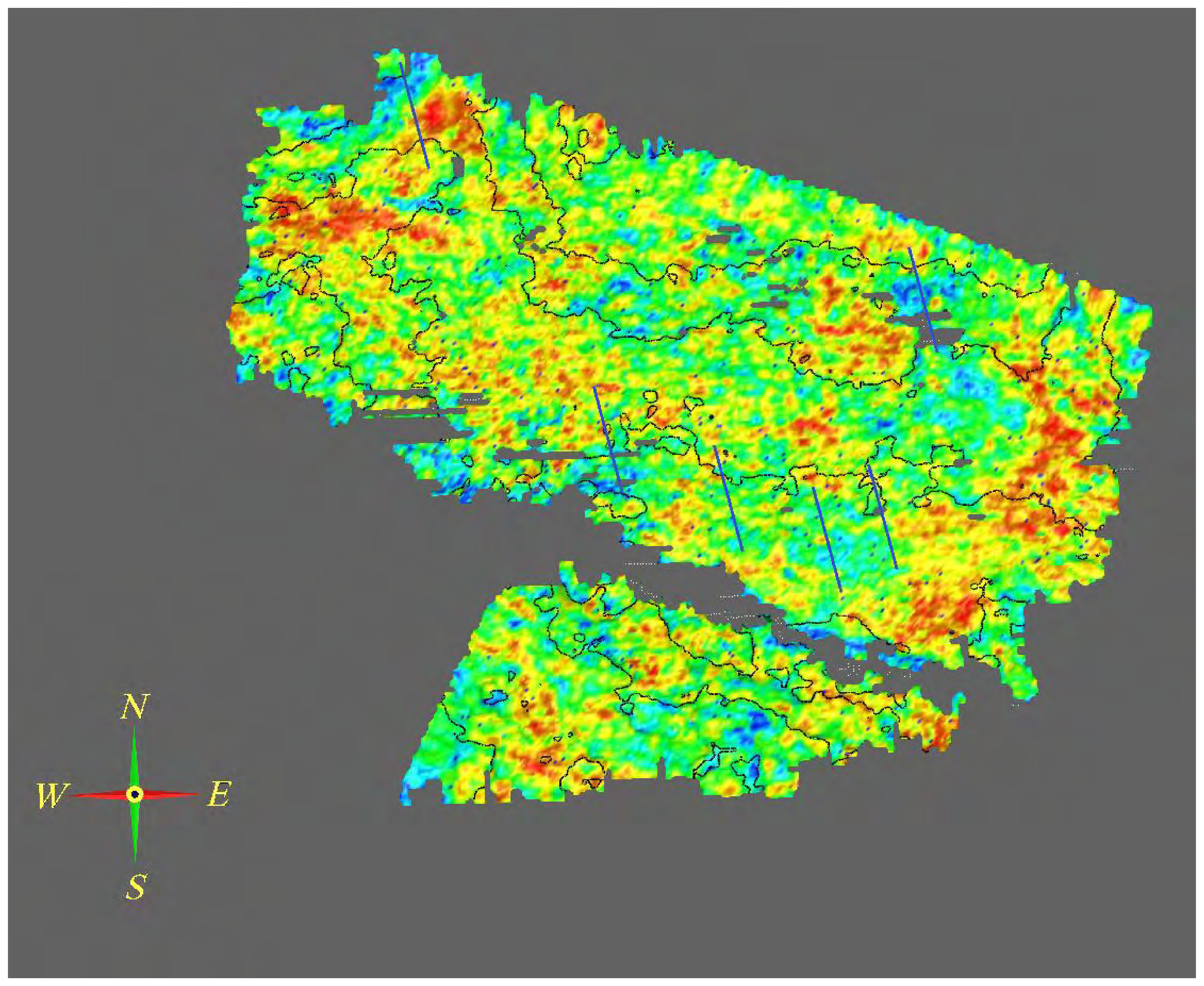
Spectral Decomposition – 10 Hz



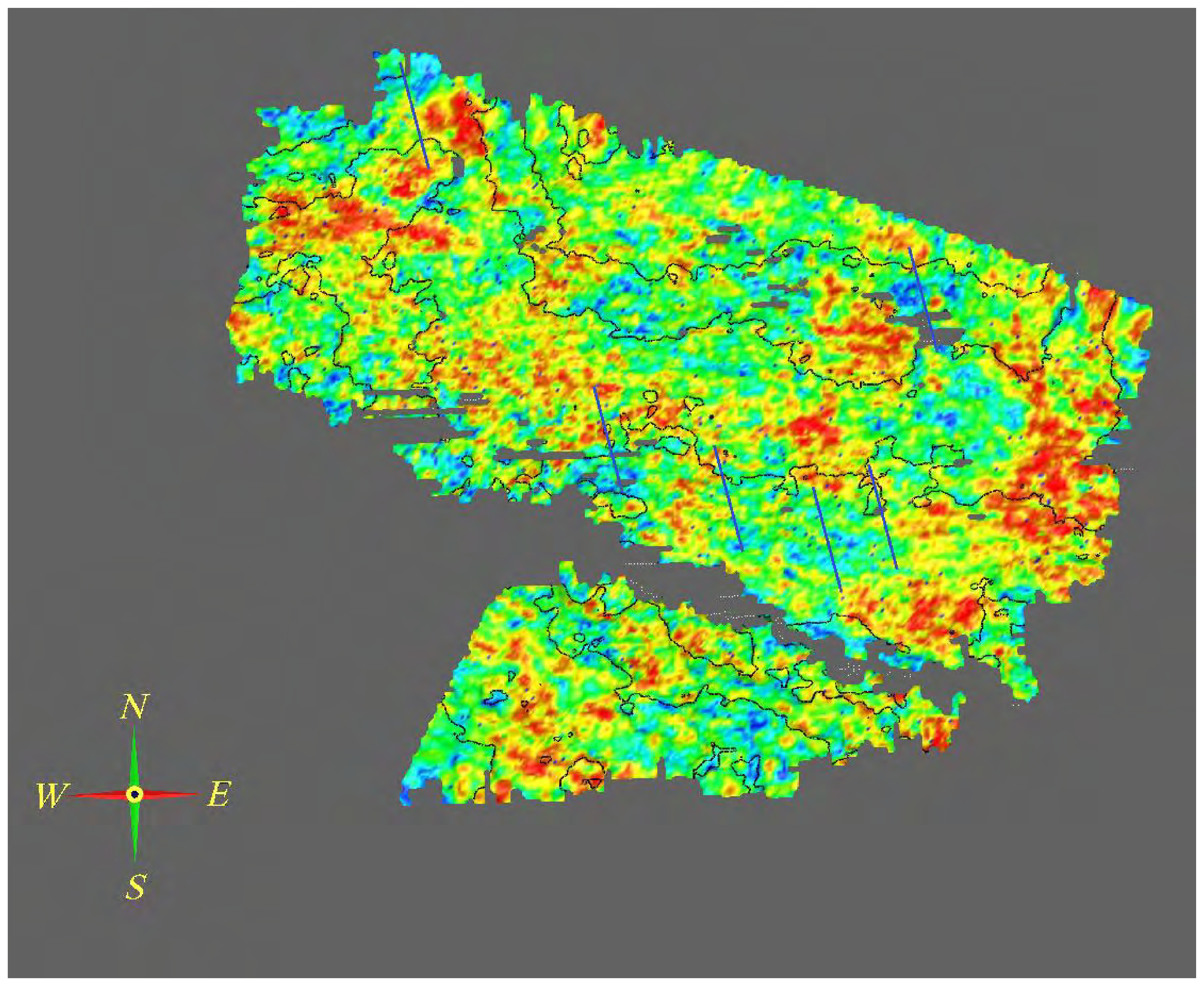
Spectral Decomposition – 15 Hz



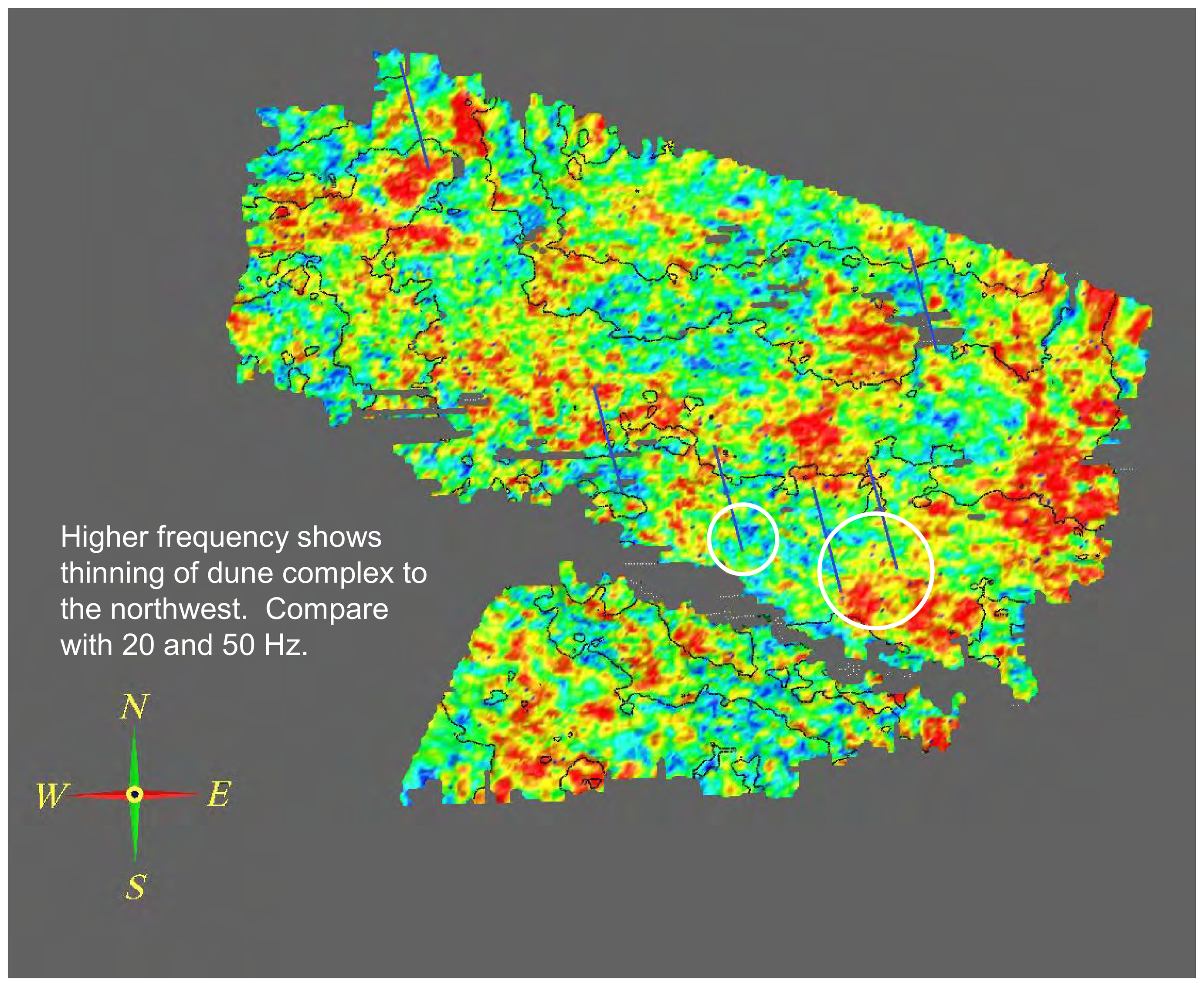
Spectral Decomposition – 20 Hz



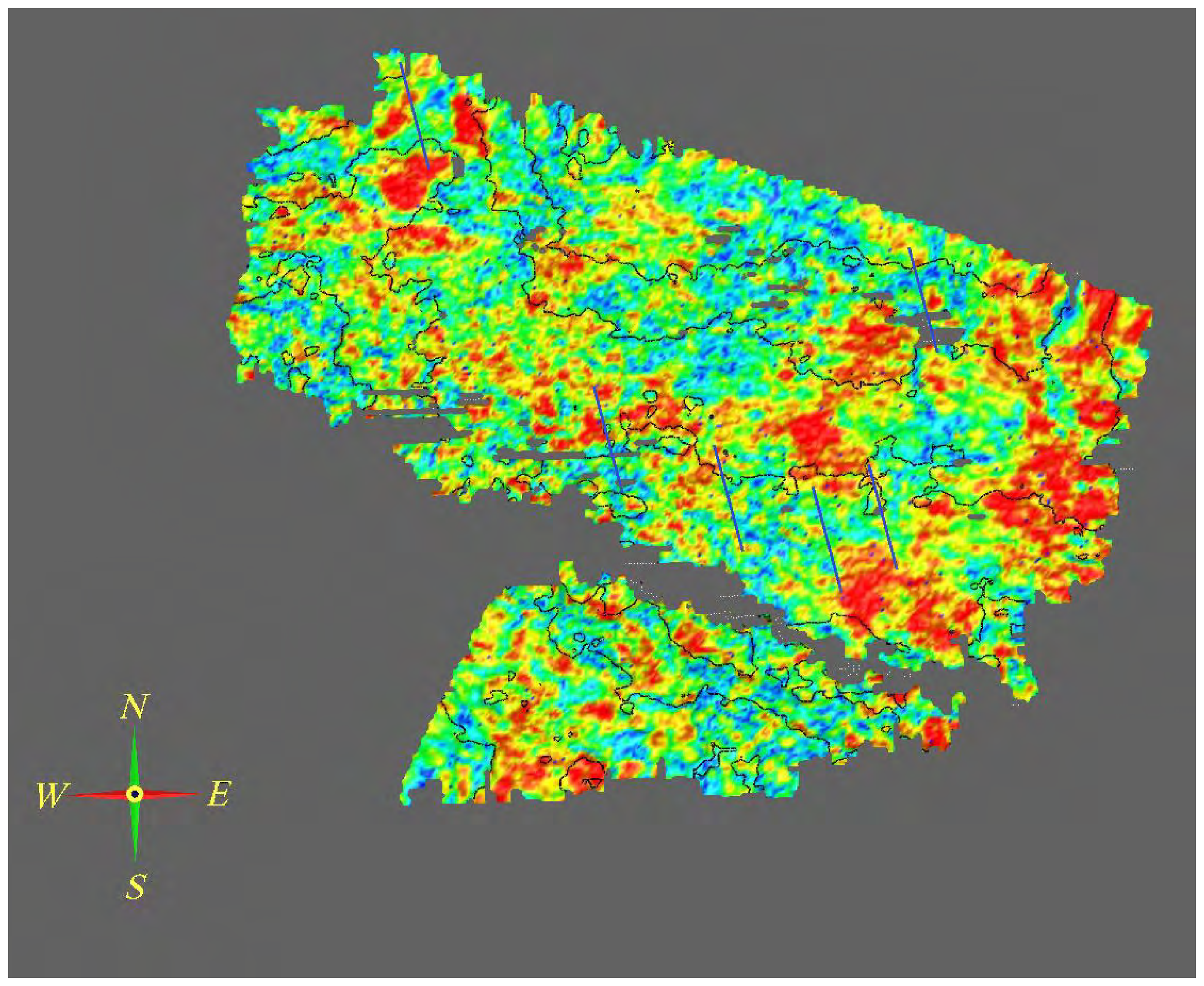
Spectral Decomposition – 25 Hz



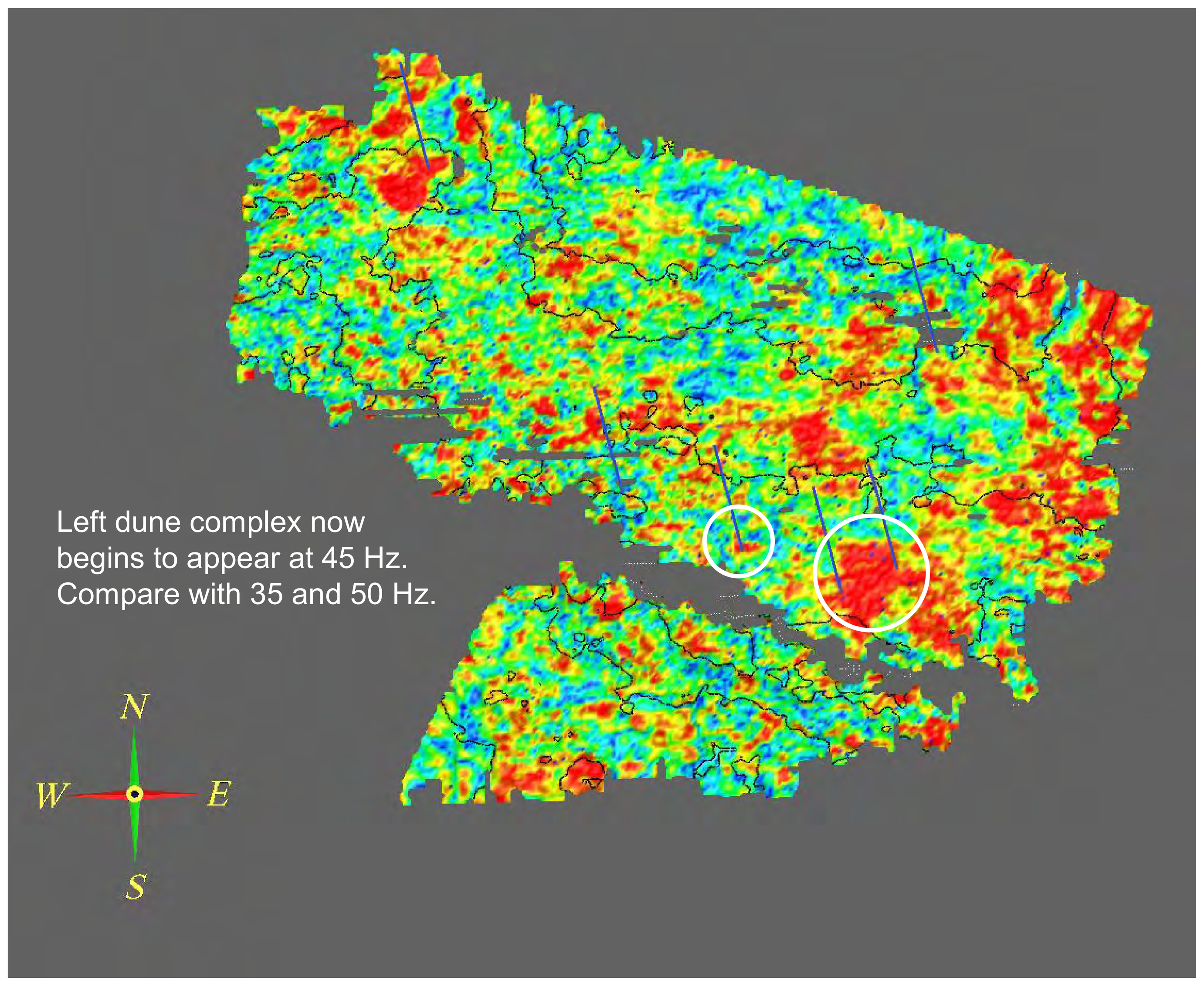
Spectral Decomposition – 30 Hz



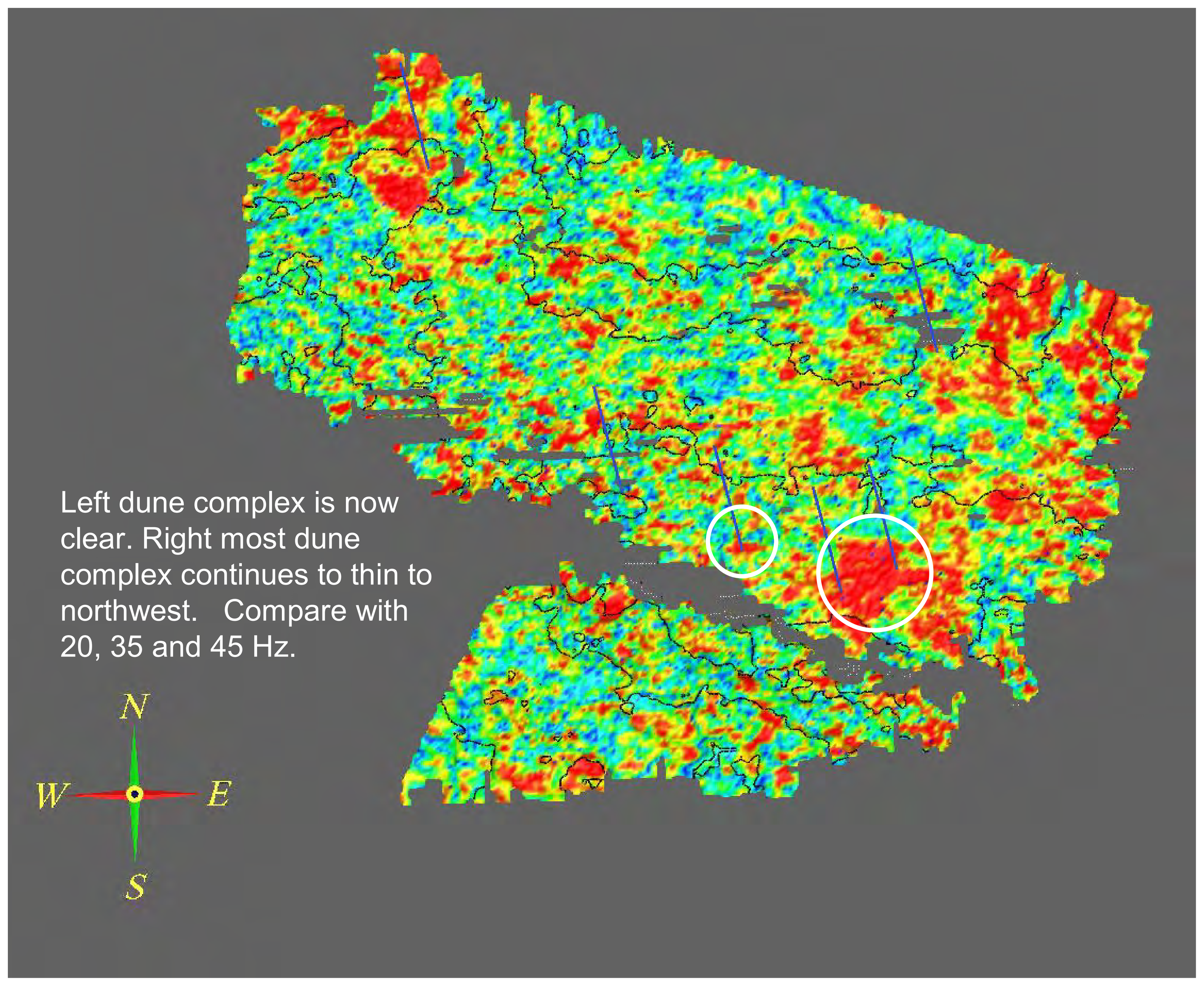
Spectral Decomposition – 35 Hz



Spectral Decomposition – 40 Hz



Spectral Decomposition – 45 Hz

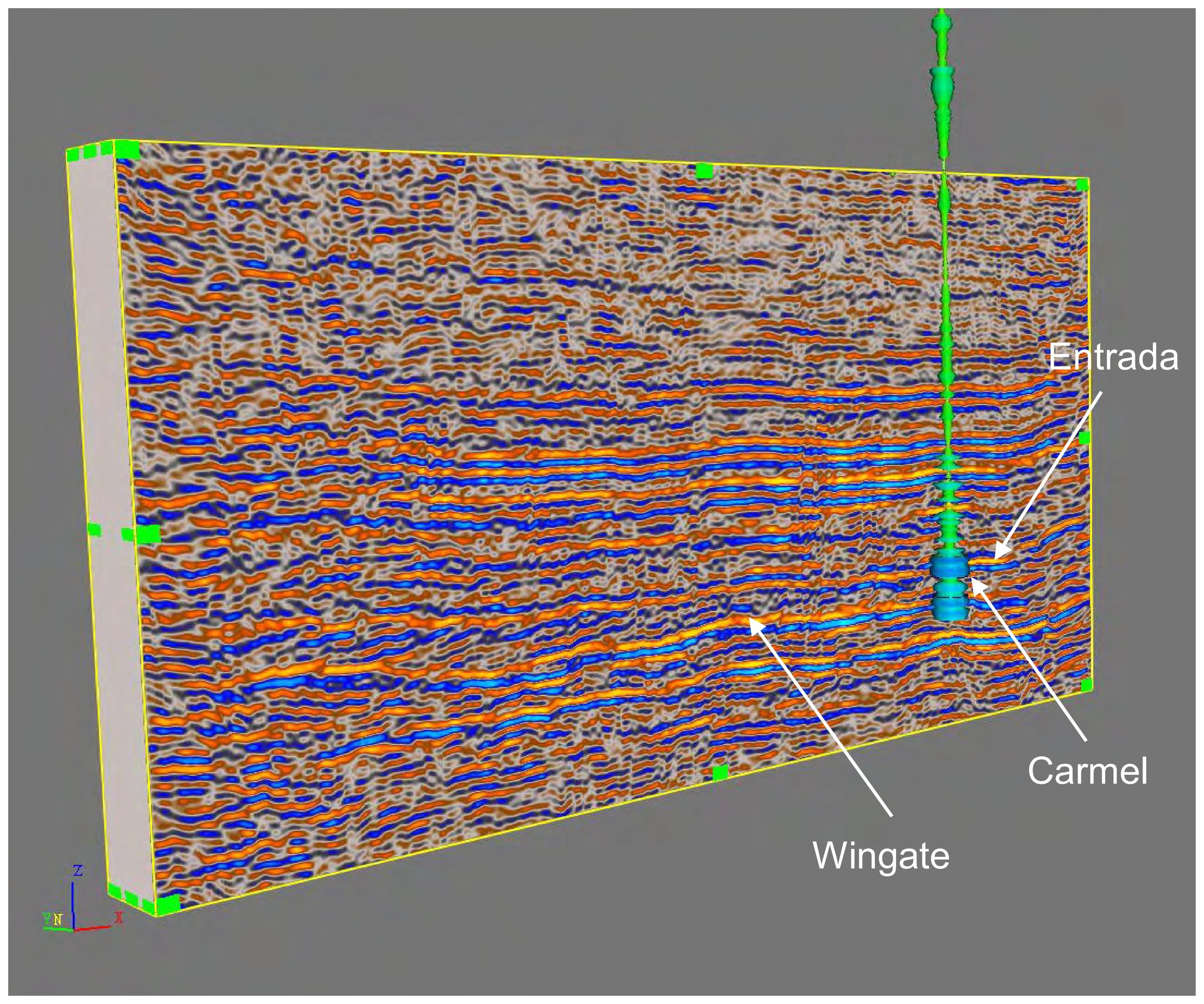


Spectral Decomposition – 50 Hz

UGS Contract #061647. Keach, Morris, McBride, Mullen, Leetaru and O'Neal.

Plate III: North Hill Creek – Seismic Character

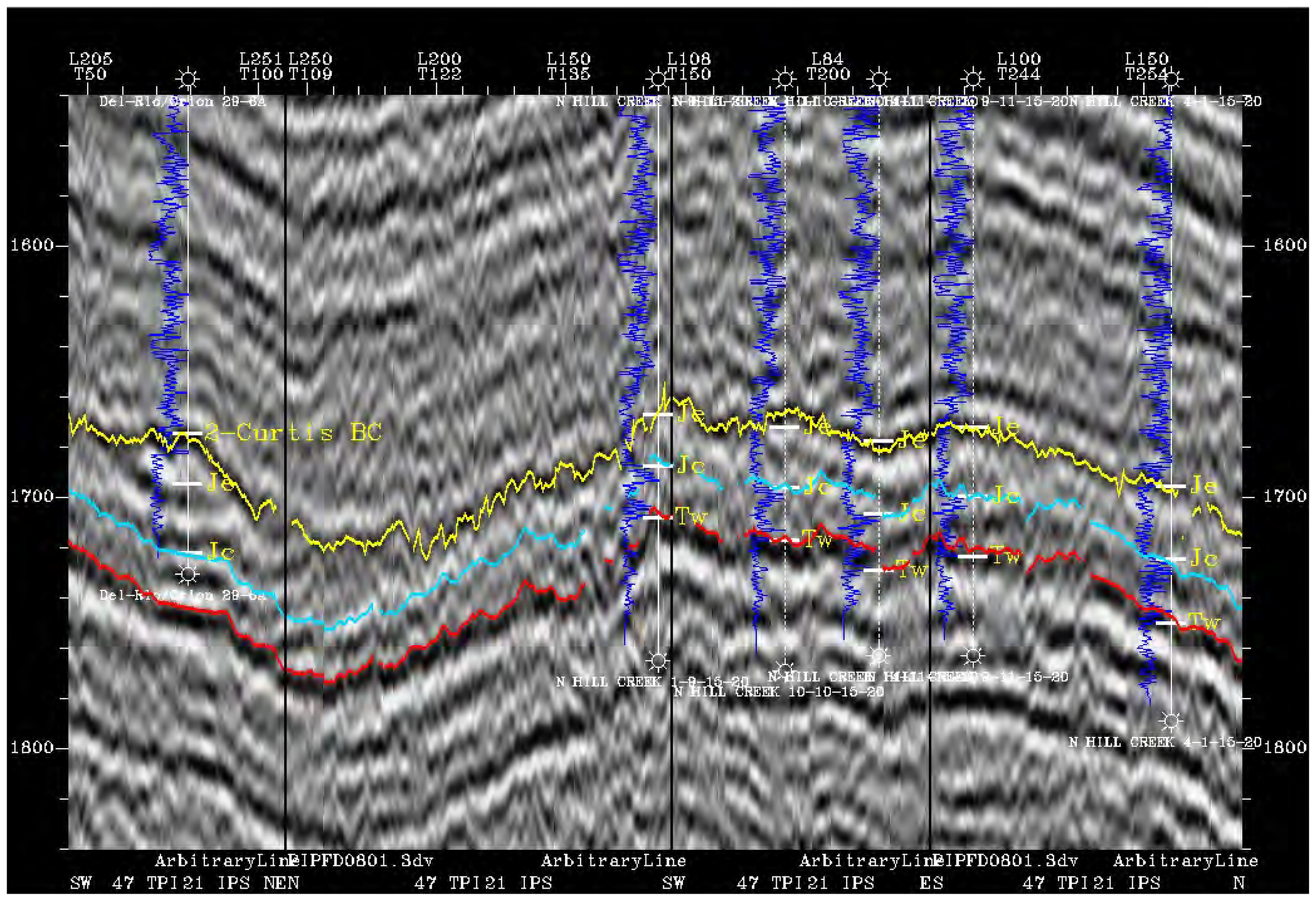
A A’



Arbitrary line through 6 wells – Gamma Ray curve is displayed (sands have highest excursion to left). Formation tops, log and seismic character are very consistent in all except the 29-6A well. The Entrada may have a remnant Curtis-Moab sandstone above it (see D – D’).

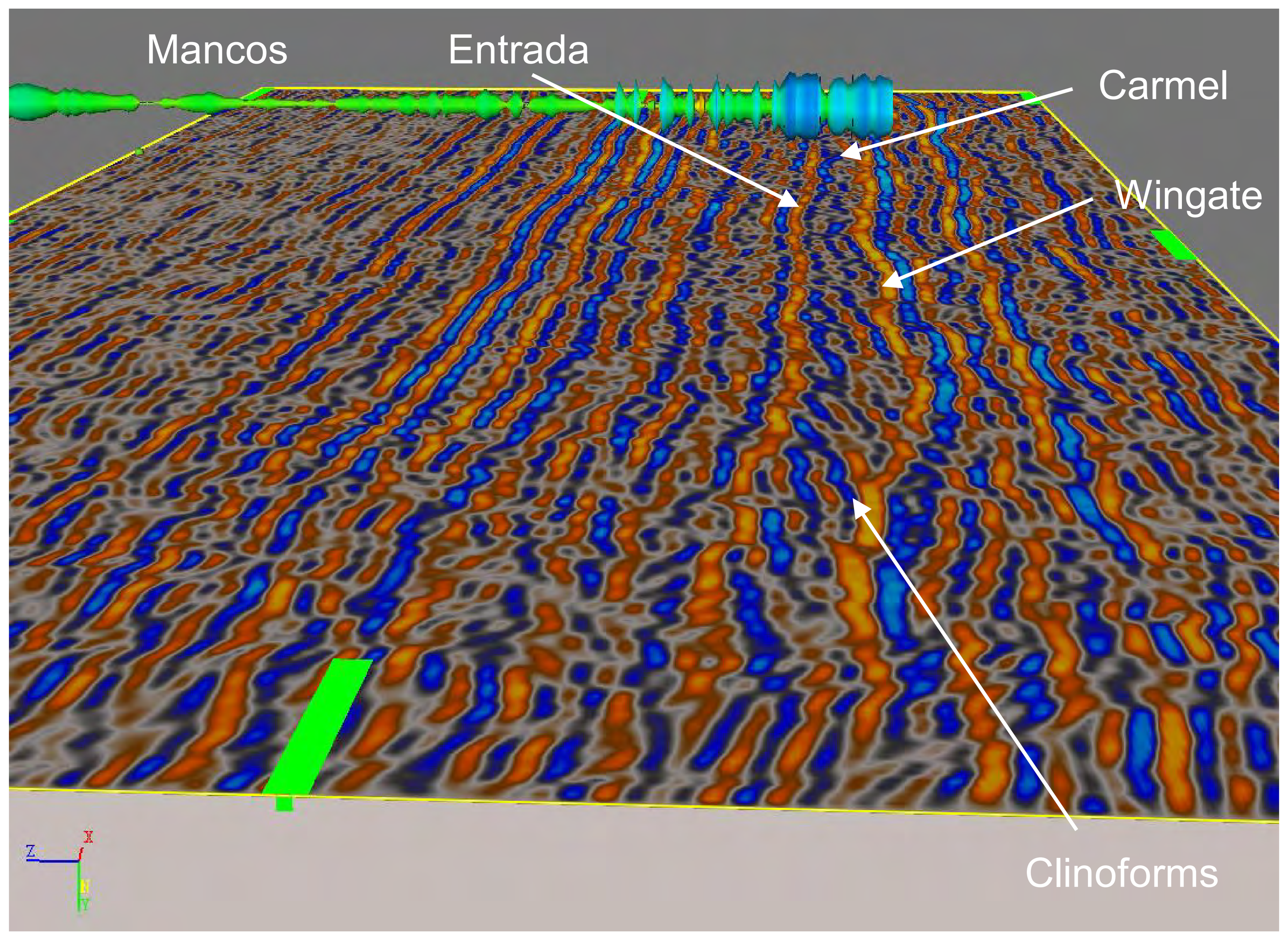
Inline 167 – Note the truncated clinoforms on west end of Entrada seismic interval and apparent stratigraphic thinning over a Wingate structure.

C C”



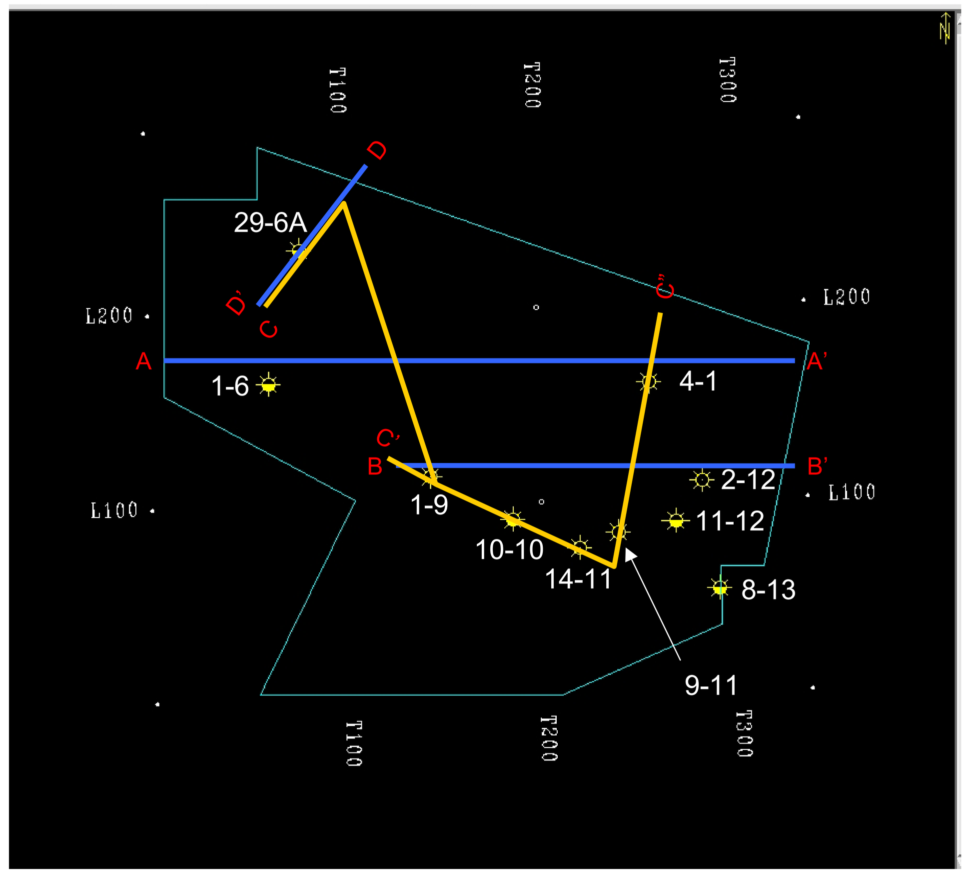
Inline 167 – Line is rotated onto its side to provide another perspective. Note the truncated clinoforms on west end of Entrada seismic interval.

A’



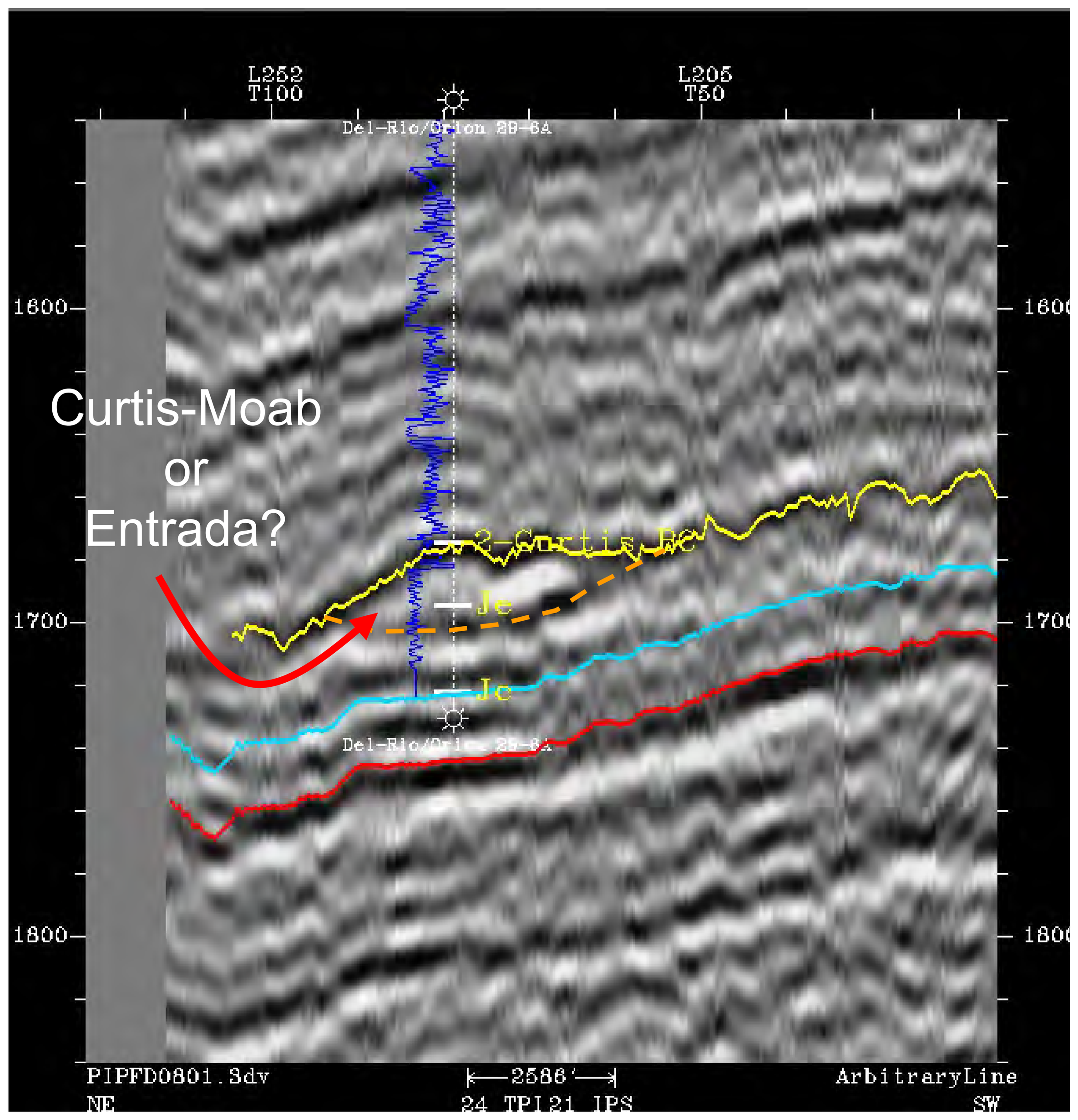
A

Arbitrary line through 29-6A –Formation tops, log and seismic character do not seem to properly correlate (time-depth issue?). Alternatively, Entrada could have been picked lower, hence supporting a remnant Curtis-Moab sandstone above it.

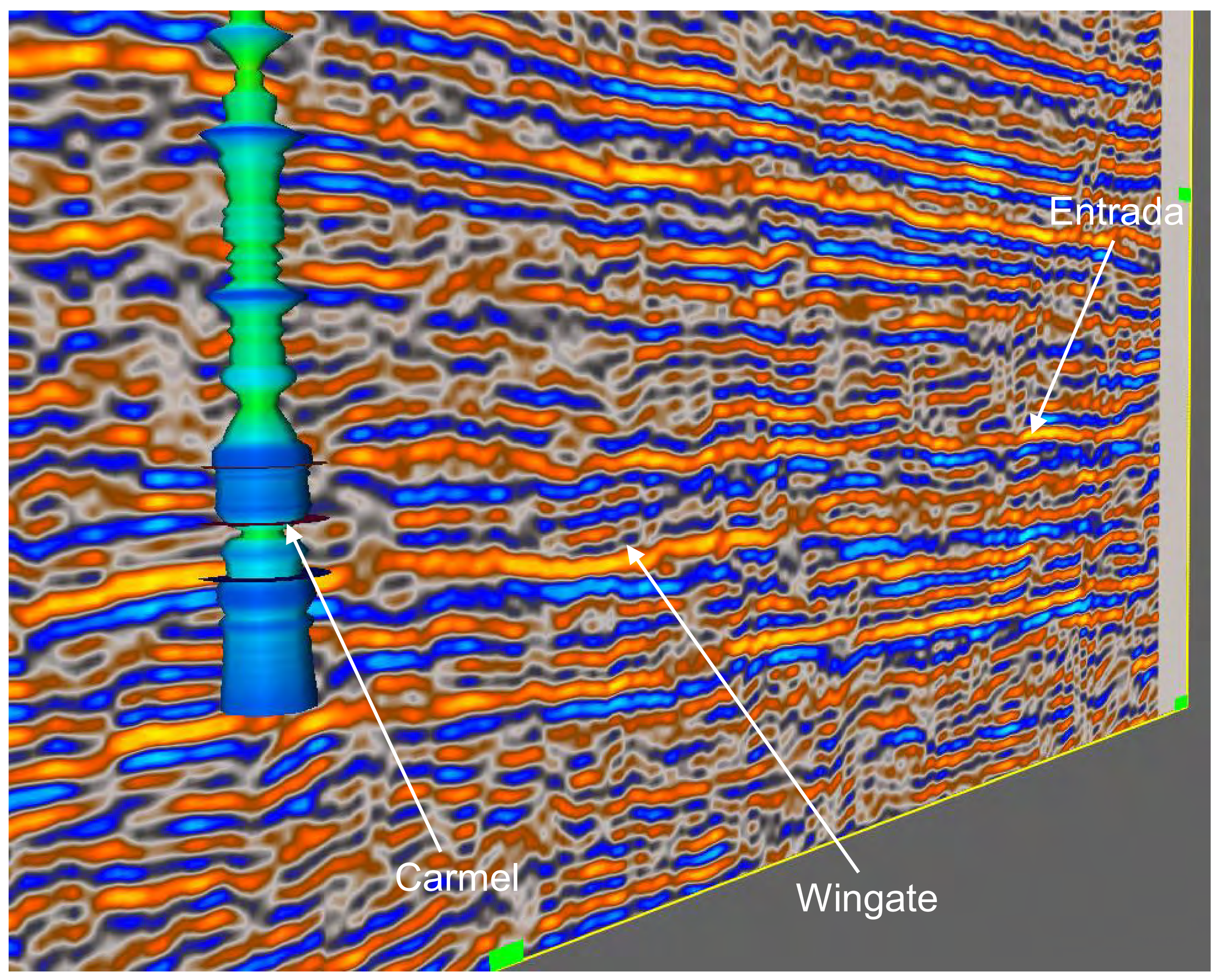


Basemap with seismic profile locations.

D D’



B B’



Expanded view of 5 North Hill Creek wells. Note the strong correlation of formation tops, log and seismic character. Both the Entrada and Wingate formation tops have a strong seismic reflector.

Inline 140 – Entrada character is different from the distinctly truncated clinoforms seen on Inline 167. Well 9-11 with Gamma Ray curve is displayed.

C’ C”

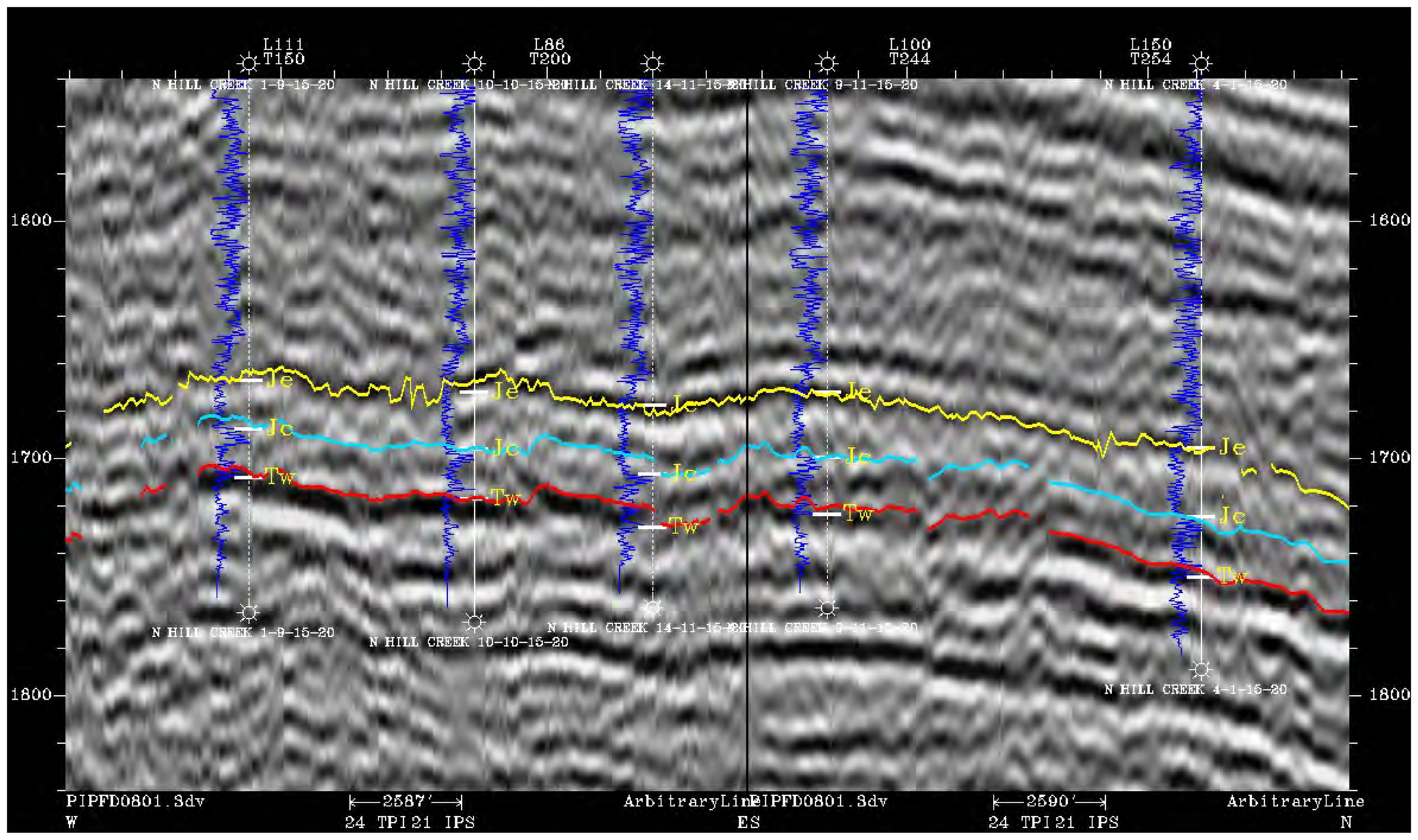
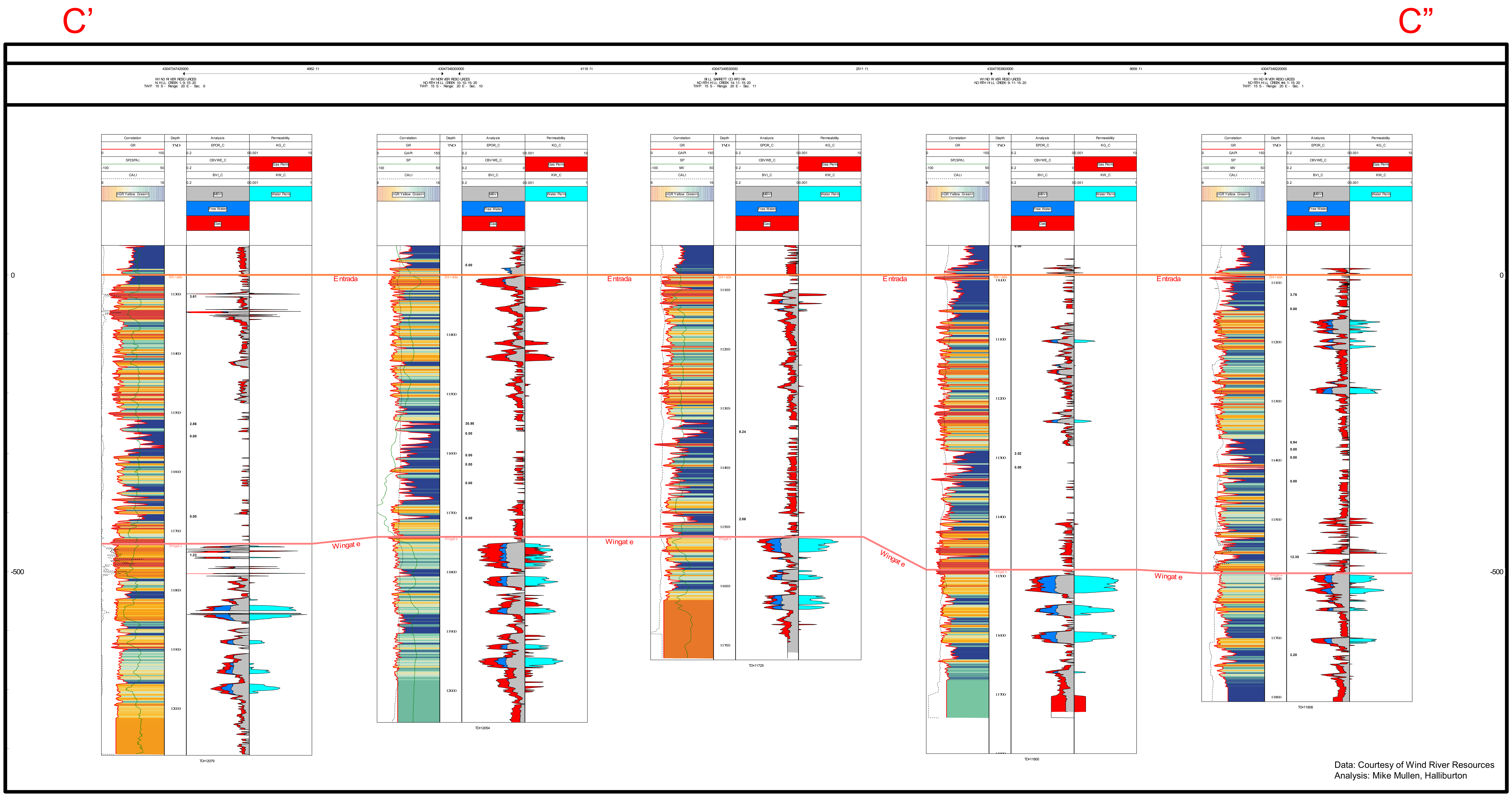
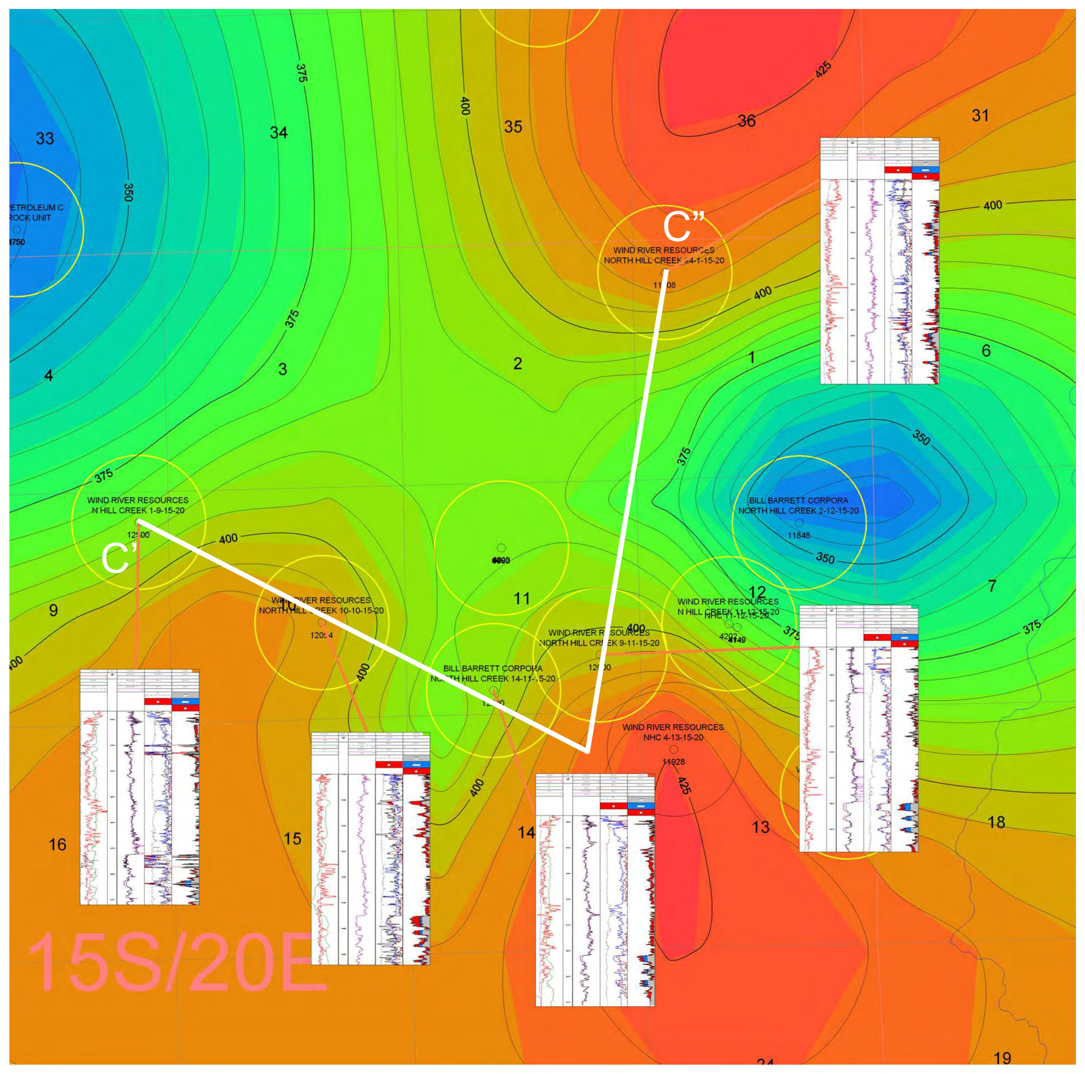


Plate IV: North Hill Creek – Reservoir Character



Gross Sand - Entrada and Carmel



Net Sand – Entrada and Carmel

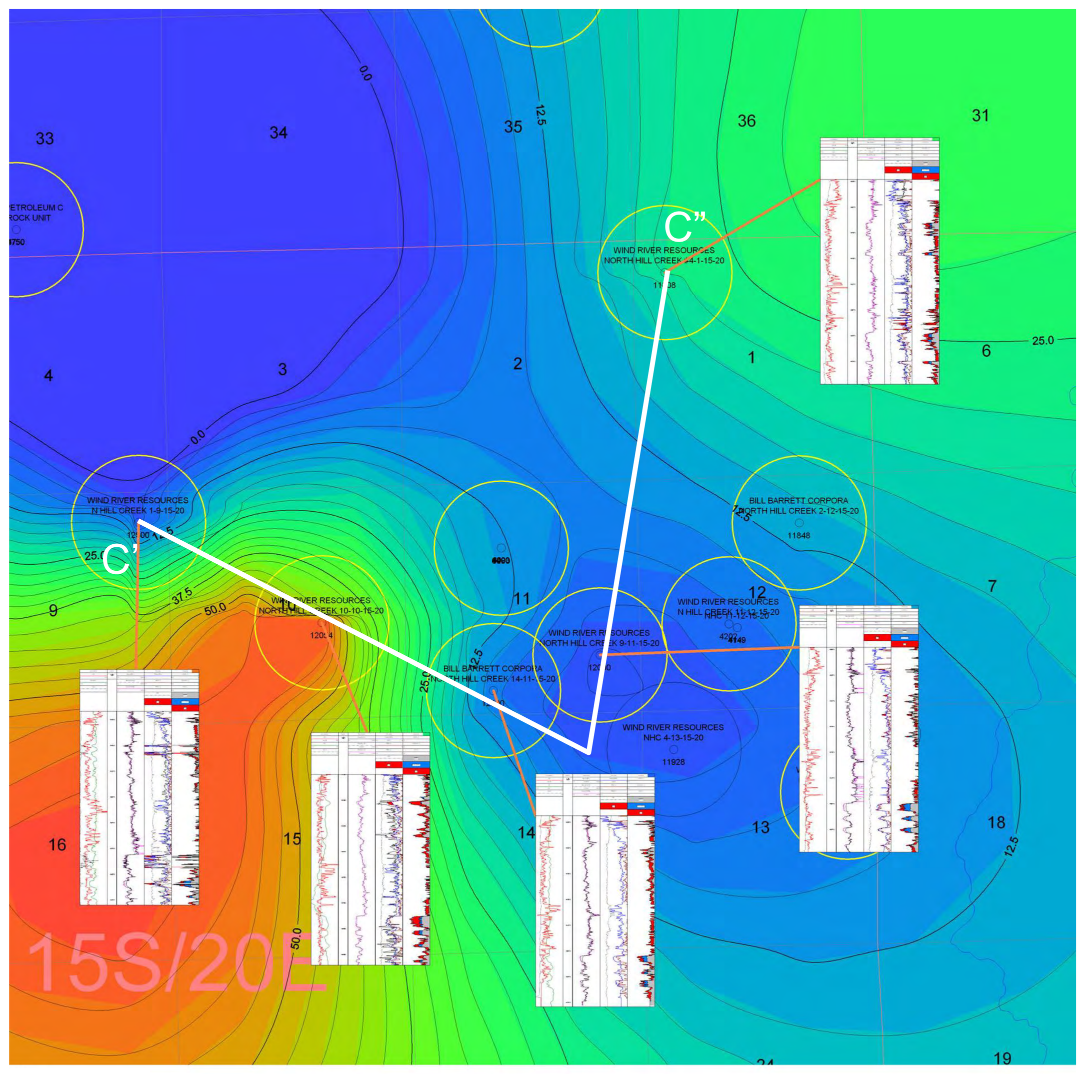


Table of Porosity and Volume Calculations

Well #	Max Por. (Avg)	Net Sand (ft)	mmcfg/Acre	Acres	Volume (mmcfg)
1 - 9	20.0 (9)	10	2.86	<10	<28.6
10 - 10	15.6 (10)	58	30.95	130	4,024
14 - 11	10.9 (8)	9	8.24	140	1,054
9 - 11	10.2 (7)	2	2.02	0*	
4 - 1	12.7 (9)	22	0.94	<10	<9.4

*9-11 produces from the northeast edge of same dune complex as 14-11, hence volume is included in the 14-11 well.

A variety of data was used to generate the volume estimates for the Entrada interval in each well. The volume estimates are based on calculated gas volume (mmcfg) per acre and estimated drainage areas. Drainage areas are based on analysis of maximum peak amplitude and spectral decomposition frequency maps.