Identifying Complex Fluvial Sandstone Reservoirs Using Core, Well Log, and 3D Seismic Data: Cretaceous Cedar Mountain and Dakota Formations, Southern Uinta Basin, Utah.

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Identifying Complex Fluvial Sandstone Reservoirs Using Core, Well Log, and 3D Seismic Data: Cretaceous Cedar Mountain and Dakota Formations, Southern Uinta Basin, Utah.

William H Hokanson

A thesis submitted to the faculty of Brigham Young University in partial fulfillment of the requirements for the degree of Master of Science

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ABSTRACT

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William H Hokanson
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Master of Science

The Cedar Mountain and Dakota Formations are significant gas producers in the southern Uinta Basin of Utah. To date, however, predicting the stratigraphic distribution and lateral extent of potential gas-bearing channel sandstone reservoirs in these fluvial units has proven difficult due to their complex architecture, and the limited spacing of wells in the region. A new strategy to correlate the Cedar Mountain and Dakota Formations has been developed using core, well-log, and 3D seismic data. The detailed stratigraphy and sedimentology of the interval were interpreted using descriptions of a near continuous core of the Dakota Formation from the study area. The gamma-ray and density-porosity log signatures of interpreted mud-dominated overbank, coal-bearing overbank, and channel sandstone intervals from the cored well were used to identify the same lithologies in nearby wells and correlate similar stratal packages across the study area. Data from three 3D seismic surveys covering approximately 140 mi² (225 km²) of the study area were utilized to generate spectral decomposition, waveform classification, and percent less-than-threshold attributes of the Dakota-Cedar Mountain interval. These individual attributes were combined to create a composite attribute that was merged with interpreted lithological data from the well-log correlations. The overall process resulted in a high-resolution correlation of the Dakota-Cedar Mountain interval that permitted the identification and mapping of fluvial-channel reservoir fairways and channel belts throughout the study area. In the future, the strategy employed in this study may result in improved well-success rates in the southern Uinta Basin and assist in more detailed reconstructions of the Cedar Mountain and Dakota Formation depositional systems.

Keywords: Cedar Mountain, Dakota, Waveform Classification, Spectral Decomposition, Percent less-than-threshold
Acknowledgements

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ABSTRACT

The Cedar Mountain and Dakota Formations are significant gas producers in the southern Uinta Basin of Utah. To date, however, predicting the stratigraphic distribution and lateral extent of potential gas-bearing channel sandstone reservoirs in these fluvial units has proven difficult due to their complex architecture, and the limited spacing of wells in the region. A new strategy to correlate the Cedar Mountain and Dakota Formations has been developed using core, well-log, and 3D seismic data. The detailed stratigraphy and sedimentology of the interval were interpreted using descriptions of a near continuous core of the Dakota Formation from the study area. The gamma-ray and density-porosity log signatures of interpreted mud-dominated overbank, coal-bearing overbank, and channel sandstone intervals from the cored well were used to identify the same lithologies in nearby wells and correlate similar stratal packages across the study area. Data from three 3D seismic surveys covering approximately 140 mi² (225 km²) of the study area were utilized to generate spectral decomposition, waveform classification, and percent less-than-threshold attributes of the Dakota-Cedar Mountain interval. These individual attributes were combined to create a composite attribute that was merged with interpreted lithological data from the well-log correlations. The overall process resulted in a high-resolution correlation of the Dakota-Cedar Mountain interval that permitted the identification and mapping of fluvial-channel reservoir fairways and channel belts throughout the study area. In the future, the strategy employed in this study may result in improved well-success rates in the southern Uinta Basin and assist in more detailed reconstructions of the Cedar Mountain and Dakota Formation depositional systems.

Keywords: Cedar Mountain, Dakota, Waveform Classification, Spectral Decomposition, Percent less-than-threshold

Introduction

An estimated 7 trillion cubic feet (200 billion cubic meters) of gas is present in the CDF (Rose et al., 2004). Only 250 billion cubic feet (7 billion cubic meters) of that has been produced (McPherson et al., 2006). Production of gas in the Cedar Mountain and Dakota Formations has primarily been from plays that contain two key elements: 1) a sandstone channel or channel complex reservoir with sufficient porosity and permeability and 2) a structural trap. The difficulty in delineating and predicting channel sandstone reservoir fairways, due to complex stratigraphy and highly variable reservoir thickness, has been a significant obstacle to achieving a high drilling success rate (Currie et al., 2008).
The Early to Late Cretaceous Cedar Mountain and Dakota Formations (CDF) in the southern Uinta Basin (Fig. 1) were deposited in a low accommodation, fluvial system that experienced increasing tidal influence through time (Currie, 1998; Currie, 2002; Currie et al., 2008; McPherson et al., 2006). These formations are characterized by a complex cut-and-fill architecture, within which the chronostratigraphic genetic relationships between individual channels and channel complexes have been difficult to resolve on a regional scale in outcrop, much less using relatively widely spaced subsurface well-log and limited core data. Subsequently, detailed correlation of geologic data from outcrop and core to geophysical well-logs within this stratigraphic interval has been performed with little success.

Early correlation of the Dakota Formation in the Uinta Basin was performed by Munger (1965). Munger (1965) used wireline logs and well cuttings from 33 wells to correlate the Dakota Formation throughout an area greater than 750 mi$^2$ (1200 km$^2$) in the southern Uinta Basin. Munger (1965) identified 3 possible paleo channels from isopach maps of the Dakota Formation. Correlation of anything other than major trends was not possible because Dakota Formation channel dimensions are much smaller than the average well spacing of 22 mi (35 km) in the 33 wells that Munger used.

Dark (2008) measured channel and amalgamated channel dimensions at outcrop along the southern boundary of the Uinta Basin for the Dakota Formation. These channel dimensions are, 25-46 ft (8-15 m) in thickness and 600-3000 ft (200-985 m) in width. Whereas amalgamated channels or channel complexes are 80-150 ft (26-50 m) in thickness and 5000 ft (1640 m) in width. McPherson et al. (2006) and Currie et al. (2008) have developed an outcrop-to-well-log correlation model that successfully correlates formation boundaries (Dakota and Cedar Mountain Formations), but does not attempt to correlate channel sandstones or channel complex systems
into the subsurface, which are of interest to understanding and predicting reservoir fairways and interpreting depositional environment.

Three 3D seismic datasets have been acquired within the southern Uinta basin for the purpose of understanding the complex relationship of the sandstone channel and channel complex reservoirs (Figure 2). In this study, we use 3D seismic imaging and attribute analysis to image these sandstone channels and channel complex reservoirs.

Recent integrated 3D seismic and well log attribute analysis in the southern Uinta Basin performed by Keach et al. (2006) demonstrated that qualitative and quantitative analysis of seismic and well log data from the North Hill Creek 3D seismic dataset (Fig. 2) allows for accurate identification of potential reservoirs in the Jurassic Entrada and Curtis Formations, which are located stratigraphically below the Cedar Mountain and Dakota Formations.

Accurate correlation and delineation of sandstone channel reservoir fairways or channel belts in this system are essential to improved drilling success in this productive hydrocarbon system in the Uinta Basin. In this study, the aim is to develop a new more detailed subsurface correlation model of channel complex systems in the CDF in the south-central Uinta Basin based on previous outcrop investigations, new sedimentary core analysis, and well-log correlation. Furthermore, attribute analysis of 3D seismic data from the Uinta Basin has made it possible to extend interpretations away from outcrop, well log, and core observations to a much broader region and greatly reduce interpretational uncertainty regarding correlation and reservoir connectivity and quality between wells.

A secondary benefit of this study is that it aims to provide a chronostratigraphic correlation scheme in the Uinta Basin that will aid in the understanding of the marine to non-
marine transition during the encroachment of the Western Interior Seaway, as recorded by the Cedar Mountain and Dakota Formations.

**Geologic Setting**

The 575 mi² (925 km²) study area is located in the south-central portion of the Uinta Basin, northeastern Utah (Figure 1). Geographically, the Uinta Basin is bordered on the north by the Uinta Mountains, on the west by the Uinta National Forest, on the south by U.S. Highway 6 and on the east by Colorado State Highway 139. The study area was defined by the location of three proprietary 3-D seismic surveys made available for this investigation.
Figure 1. Index map of study area. The state of Utah is the main outline with county lines shown within. The tan shaded area is the Unita Basin.
The CDF were deposited during the Early to Late Cretaceous, respectively, prior to the formation of the Uinta Basin. During deposition of the CDF, the Farallon plate was being subducted beneath the North American plate, causing Sevier style deformation on the western margin of the North American plate (Decelles, 2004). The associated lithospheric thickening created the Cordilleran Foreland Basin (CFB), which stretched from Northern Canada to South America (Decelles, 2004) (Figure 3). Flexural subsidence of the CFB created accommodation for the deposition of continental and marine sediments (Currie, 1998; Currie, 2002). Deposition of the Cedar Mountain and Dakota Formation was along the flexural forebulge of the CFB. The
forebulge of the CFB progressed eastward from Early-Late Cretaceous as the Western Interior Seaway progressed westward (Currie, 2002; Decelles, 2004).

Figure 3. Map of the Cordilleran Foreland Basin and associated uplift. (Decelles, 2004)
In the study area, the CDF was deposited along the forebulge of the CFB in alluvial-to-lacustrine and fluvial (fully terrestrial to tidally influenced) environments, respectively, with sediment supplied from the south-southwest and deposition to the north-northwest (Munger, 1965; Currie, 2002). Deposition of the CDF, which spanned approximately 50 million years, was strongly influenced by uplift of the Sevier Orogen to the west and the influx of the transgressive Western Interior Seaway from the east, resulting in a dynamic evolution in depositional environments through time and the formation of unconformities within the CDF between formations and intraformational members (Figure 5).

After CDF deposition, changes in the rate and angle of the Fallaron plate subduction changed the style of deformation in the CBF from “thin-skinned” Sevier-style fold and thrust belt to “thick skinned” Laramide-style pop-up structures (DeCelles, 2004; Dickinson, 1988; Dickinson, 2004). This separated the earlier CBF into many smaller basins, such as the Uinta Basin which formed during the Late Cretaceous to Early Paleocene in response to surrounding Laramide tectonism (Decelles, 2004; Dickinson 1988; Dickinson, 2004). The synclinal axis of the asymmetric basin runs east-west (Marshak, 2000). The strata in the northern portion of the basin dip steeply to the south and basinward. Strata in the southern portion dip gently to the north and basinward. Late Paleozoic NE-SW-trending high-angle reverse faults associated with the formation of the Ancestral Rockies were reactivated during the Laramide as left-lateral oblique strike-slip faults, which are featured prominently in the study area (Figure 4) (Stone, 1977).
Stratigraphy

The Cedar Mountain Formation in the southern Uinta Basin is divided into the Buckhorn Conglomerate and the upper shale members (Stokes, 1952; Young, 1960; McPherson et al., 2006). The upper shale members include the Yellow Cat Member, Poison Strip Sandstone, Ruby Ranch Member and the Mussentuchit Member. Due to the limited resolution of wireline logs, all basal sandstone in the Cedar Mountain Formation will be referred to as the Buckhorn Conglomerate and all other members will be referred to as upper shale members. The Buckhorn Conglomerate is a medium-to-very coarse grained sandstone. The Buckhorn Conglomerate lies unconformably above the Late Jurassic Morrison Formation and is only present in channels.
incised into the Morrison Formation (Currie, 1998; McPherson et al. 2006; Greenhalgh, 2007). A calcrete/secrete paleosol complex is located directly on top of the Buckhorn Conglomerate in many localities and represents a depositional hiatus of up to several million years (Currie, 1997; Currie, 1998; Currie, 2002; Greenhalgh, 2007; Greenhalgh and Britt, 2007).

The upper shale members are comprised of fluvial sandstones, overbank mudstones, lacustrine limestones, and paleosols. The lacustrine limestones and paleosols decrease and the fluvial sandstones become more laterally continuous upward (Currie, 1998; McPherson et al., 2006; Greenhalgh, 2007; Currie et al., 2008). Stratigraphic nomenclature schemes for members within the Cedar Mountain Formation vary by region and author (Fig. 5; McPherson et al., 2006; Currie et al., 2008; Greenhalgh et al., 2007), but the model defined by (McPherson et al., 2006; Currie et al., 2008) is most applicable due to its proximity to the study area.
Figure 5. Stratigraphic columns showing the Cedar Mountain and Dakota Formation members and the unconformities (gray shaded areas) within the succession (McPherson, 2006; Currie et al., 2008; Greenhalgh et al., 2007). Timescale of Gradstein et al. (2004).
In the study area, the Dakota Formation consists of two distinct stratigraphic units separated by a sequence-bounding unconformity (Ryer, 1987; Currie, 2002; Currie et al., 2008, Dark, 2008; Pierson, 2010). The lower Dakota unit, which lies unconformably above the Cedar Mountain Formation, is composed of fluvial conglomerate, sandstone, alluvial mudstone, limited occurrence of tidal facies and coal. The upper Dakota unit consists of fluvial, alluvial and more commonly occurring tidal facies with lithologies ranging from mudstone to conglomerate (Stokes, 1952; Young, 1960; Currie, 2002; Dark, 2008; Madsen, 2010; Pierson, 2010). Palynologic data constrains the upper Dakota to Late Albian-Early Cenomanian and the lower Dakota to Albian in age (Currie, 2002; Pierson, 2010,). The Dakota Formation is overlain by the Tununk Member of the Mancos Shale, an offshore marine deposit, which marks flooding and transgression of the Western Interior Seaway following the deposition of the Dakota Formation.

Methods

In order to provide an understanding of facies and establish a subsurface channel complex correlation strategy, one publicly available core was analyzed to identify correlateable facies. The Trapp Spring 13-25 core, located within the Parkridge/Main Canyon 3D seismic survey (Fig. 2) and available at the Utah core research center, captures much of the Dakota Formation allowing correlation to well log. The core was examined and described in terms of lithology, sedimentary structures, and biogenic features, such as bioturbation and fossils (Figure 6).
Figure 6. Core description of the Trapp Spring 13-25 core.

The core was used to guide the subsurface correlation throughout the study area, which covers 575 mi$^2$ (925 km$^2$) (Figure 7). A total of 82 publicly available and proprietary wells were correlated. 54 of the 82 wells propagate through the entire interval of interest, 14 wells terminate
in the Cedar Mountain Formation, and 14 wells terminate in the Dakota Formation. The Dakota Silt is a prominent silty sandstone marking the top of the Dakota Formation that can be easily picked in core, wireline logs, and seismic. The Dakota Silt was picked through all the chosen wells and was used as the datum for well correlation (Figure 7). Formation tops (Dakota, Cedar Mountain, and Morrison) were also picked, based on criteria developed by McPherson et al. (2007), Currie et al. (2008) and Dark (2008). However, for the purpose of this study, key facies and, hence, channel complex reservoir fairways were correlated, rather than formation boundaries.
Figure 7. Correlation of the Trapp-Spring core with the wireline log.
Isopach maps of total sandstone and mudrock thickness as well as sandstone and mudrock thickness for the Cedar Mountain, upper Dakota and lower Dakota Formations were created. Isopach maps were created using a 1500 m radius of influence with 500 m grid spacing. Five cross-sections (Fig. 2) were created to examine correlation of CDF across the region and compare well log data to seismic attributes.

**Facies Correlation Model**

Three distinct well log facies were identified then picked throughout the interval of interest or the interval of the CDF. These facies include a channel facies which is a sandstone-dominated package distinguished by a low gamma ray signature (low API value), an overbank facies identified by a high gamma ray signature (high API value) (mudrock dominated), and a coal-bearing facies which is identified by a high gamma ray signature (mudrock dominated) with the presence of low density anomalies in the density-porosity logs (coal).

A new correlation strategy was created by, first, selecting the interval of interest (Figure 8A). Within the interval of interest the top of the uppermost sandstone and the base of the lowermost sandstone were picked. This is termed the channel-bearing package and often included most if not all of the thickness of the CDF (Figure 8B). After the channel-bearing package was picked, then coal and overbank facies were picked within the channel-bearing package, resulting in coal, overbank, and channel complex facies (Figure 8C). This divides the interval of interest into separate channels and channel complexes.
Figure 8. Correlation method used to identify channel complexes within the interval of interest. A. Black lines represent the interval of interest. B. Yellow shaded area represents the channel-bearing package. C. Black shaded area represent the coal-bearing overbank within the interval of interest. Brown shaded area represents the overbank within the interval of interest.
Seismic attributes

3-D seismic attribute analysis was performed on three 3-D seismic surveys made available for this project: the North Hill Creek (NHC) and its extension from Wind River Resources, the Rock Spring (RS) from Wind River Resources and Flying J, and the Park Ridge/Main Canyon (PRMC) from Pioneer Natural Resources.

For the seismic analysis, we used two seismic windows hung below the Dakota Silt (DS) seismic pick (Figure 9). The Dakota Silt is easily identified on both seismic and well-log data, providing a stratigraphic tie between the two datasets. We tested several window lengths to evaluate the efficacy of seismic attribute analysis of the CDF as a whole and to the upper Dakota, lower Dakota and Cedar Mountain individually. Varying seismic windows were compared to available well data in various locations throughout the area of interest (Figure 9). The following two windows proved to be optimal in that they provide maximum stratigraphic resolution without exceeding maximum seismic resolution or the minimum separation needed between two events such that the events appears as two distinct events rather than one, upper Dakota = Window 1 = 10-30 ms below DS and the lower Dakota and Cedar Mountain = Window 2 = 30-60 ms below DS.

Vertical seismic resolution can be understood based on the Rayleigh criterion. The Rayleigh criterion states that this minimum separation is 1/4 the wavelength (λ) (Sheriff and Geldhart, 1995). If a velocity (v) of between 2 and 5 kilometers for sandstone (Sheriff and Geldhart, 1995) and a frequency (f) of 50 hertz is assumed then the equation \( \lambda = \frac{v}{f} \) can be used giving values for 1/4 the wavelength of 32.8 and 82 ft (10 and 25 m). With the expected resolution between 32.8 and 82 ft (10 and 25 m) based on reasonable velocity and frequency assumptions, identification of amalgamated channels between 80-150 ft in thickness would be
possible and even larger individual channels may also be identified. To find the wavelet period (T) at 50 hertz the equation \[ T = \frac{1}{f} \] gives the results of 0.02s or 20ms. With this resolution both window 1 and window 2 would have a full period or one wave amplitude. This provides enough data for evaluation of the upper Dakota (UD) in window 1 and the lower Dakota/Cedar Mountain (LDCM) in window 2.

Figure 9. Examples of well logs and seismic data showing the Dakota Silt pick (just above topmost white line). The white lines indicate the windows used for the seismic attribute analysis. The windows divide the upper Dakota (UD) from the lower Dakota/Cedar Mountain (LD/CM).

Three seismic attributes were chosen from the many that were tested on the UD and LD/CM intervals. These three seismic attributes were chosen based on their uniqueness. Each attribute represents geologic features and is not sensitive to small data changes (Barnes, 2007). The three attributes that were chosen are: Waveform Classification for its sensitivity to
stratigraphy, Spectral Decomposition to determine bed thickness and Percent below Threshold to
determine lateral variation. The following is a description of how each attribute was calculated
and the values/parameters used for each calculation.

ATTRIBUTE PARAMETERS

Waveform Classification

Waveform Classification works on the assumption that similar wavelets correspond to
similar stratigraphy. Wavelets are tracked with a horizon or constant time reference which
defines the threshold window. Unsupervised Standard K-Means classification provides quick
and simple classification through a k-means clustering algorithm. With the Unsupervised
Standard K-Means approach the user defines an arbitrary number of classes into which the
wavelets in the defined window are to be grouped and the neural network determines were the
character divisions should be (Anderson and Boyd, 2004). As a result of testing it was decided
that the use of 5 classes best represented the seismic and the stratigraphy as observed on the well
data for both intervals. In all three 3D surveys, classes 3 and 4 best correlated with high
sandstone content based on the comparison of cross-sections with seismic data in the UD and
LD/CM units. Based on this comparison, class 5 correlated best with areas that were mostly
mudrock. Using simple horizon calculations, the classes were reordered with 1 having the most
mudrock and 5 having the most sandstone. They were then multiplied by 20 to normalize them
0-100.
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</tr>
<tr>
<td>5 = mud</td>
<td>5 = sand</td>
<td>100 = sand</td>
</tr>
</tbody>
</table>

**Spectral Decomposition**

Spectral decomposition is frequency based attribute and is useful for imaging and mapping bed thickness and geologic variations throughout 3D surveys (Partyka et al., 1999). This is done by using a discrete Fourier transform to transform the seismic data into the frequency domain. The amplitude spectra can then be used to determine bed thickness and the phase spectra can be used to determine geologic variations (Partyka et al., 1999). In this study the spectral decomposition attribute is useful in identifying channel sands.

The analysis window length for calculation is 40 ms (21 samples). For the UD, the window was centered 20 ms below the Dakota Silt seismic pick. For the LD/CM the window was centered 45 ms below the Dakota Silt seismic pick. The calculated tuning volumes contain frequency slices from 0 Hz to 100 Hz. Each frequency slice was viewed and compared to cross-sections of well data (Plates 1-5). The frequency slices showed clear and dominant stratigraphic trends. In the Rock Spring 3D seismic data set, the frequency slice at 24 Hz exhibits a strong N-S trend and the 38 Hz slice shows a secondary SW-NE trend. An interpretation of the two is that the 24 Hz trend represents a thicker channel complex than that of the 38 Hz trend. This is based on the theory behind spectral decomposition that thicker units tune at lower frequencies and thinner units tune at relatively higher frequencies (Partyka et al., 1999). For final use, the 24 Hz frequency slice was selected because it is more sensitive to thicker beds.
**Percent less than Threshold**

Percent less than threshold is an amplitude based attribute. Unlike other amplitude attributes which average the samples or are determined by a single minimum or maximum value, percent less than threshold is based on the number of samples in a window that are below a selected amplitude threshold. This is determined by the number of samples in the window less than a selected threshold divided by the number of samples in the window. This is multiplied by 100 which gives a percentage of the samples in the window. Percent less than threshold can be sensitive to lateral variations in the seismic data which is ideal for identifying channel sands. The percent less than threshold attribute is also useful in differentiate between concordant (high amplitude), hummocky (lower amplitude) and chaotic beds (low amplitude).

The threshold value used in the percent less than threshold calculation is dependent on the amplitude scale range of each 3D seismic survey. By setting the amplitude threshold at an absolute value that is below most of the data in a window the calculations will be more sensitive to significant changes. With this in mind the amplitude threshold values that were used are:

- Parkridge 3D = 3
- North Hill Extension 3D = 4
- Rock Spring 3D = 80

In the initial maps mudrock units had percent less than threshold values close to 100 and the sandstone units had values closer to 0. In order to insure that the sandstone units had the highest values, the values were inverted making the sandstone units closer to a value of 100 and the mudrock with values closer to 0.
Integrating Seismic Attributes

Using more than one attribute to visualize the seismic data is a common procedure. The use of multiattributes or combining attributes has been around since the late 1990s (Chopra and Marfurt, 2005). The use of multiattributes typically involves a neural network, but in this study combining of attributes were performed by the interpreter so that a good correlation with the geology could be assured. Each of the three seismic attributes, waveform classification, spectral decomposition, and percent less than threshold contain unique information regarding the location and presence of sandstone-bearing channel fairways. As a predictive tool, each of these three attributes when compared with cross-sections (Plates 1-5) has a good correlation with the well data as to lithology. Individually, none of them are absolute indicators. Together, they more clearly define the geologic features (Figure 10).

The combination of the three attributes was achieved by normalizing each attribute to a value range of 0-100. The waveform classifications of 1-5 were reordered to represent an increasing value with increasing sand presence and then each value was multiplied by 20. With the spectral decomposition attribute the amplitude value was divided by 10% of the max amplitude. 100 was subtracted from the percent less than threshold initial value and then multiplied by -1 to reverse the values. Once the attributes were normalized they were then summed together into a composite attribute. Because the attributes themselves have no units, manipulation of the values does not change their significance as long as the ratios or relationship of the values to each other are preserved.
Figure 10. The four images are taken from the Park Ridge survey in the northeastern corner of the study area, upper Dakota interval (from top left to bottom right) Spectral Decomposition, Waveform Classification, Percent below Threshold and Combined attribute. The scales are unitless, but show how each attribute was given equal value.

Composite seismic attribute maps were created for the UD and LD/CM for each 3D survey area. These maps were then exported for use as a biasing parameter in the generation of isopach maps of the sandstone units (channel complexes) for each interval in the study area from the well data (picks). Biasing is a tool used to combine two or more data sets, in this case well data and seismic data. When one data source does not have the resolution to identify the desired targets then a second data source can be used to increase the resolution. This is done by designating one data source as the primary data source and another the secondary data source. When creating a isopach using the biasing tool the software first looks to the primary data to extrapolate the
contours. When there is a lack of primary data the software then uses the secondary data source to create the contours. Biasing is possible when both data sources represent the same features, as in this case. So the primary data source is biased by the secondary data source.

**Combining attributes and well data**

In order create a more complete visual representation of the CDF, the seismic attributes were combined with isopach maps of the well data. Although the values of the seismic attributes have no unit value, a comparison to cross-sections (Plates 1-5) of well log sandstone and mudstone thickness showed that the values of the seismic attributes correlated to the thickness of the sandstone. Isopach maps were created that combined the composite attribute isopach map and the well isopach map using a 500 m radius of influence and a grid spacing of 50 m to account for the better resolution of the seismic data (Figure 11, Figure 12). Using a grid function which enables the user to combine multiple isopachs using mathematical functions, the seismic isopach maps were then multiplied by the well isopachs (Figure 11B, Figure 12B). By multiplying the seismic and well isopach maps areas of compatibility were greatly exaggerated. This made it easy to see where the wells and seismic data had the greatest compatibility.

In order to provide the most accurate combination of well and seismic data, several different combinations were attempted. First, isopach maps were created using the seismic data as the primary data source and biasing it by the well data (Figure 11C, Figure 12C). Then an isopach map was created using the well data as the primary data source and the seismic as a biasing source (Figure 11D, Figure 12D). The two isopachs were then compared to determine which data should be the primary data source and which should be the biasing source.
Figure 11. Isopachs of the LD/CM showing the combination of well data and seismic data and the combination of well and seismic data.  
A. isopach of seismic data B. isopach of well and seismic data multiplied together.  C. Seismic data biased by the well data.  D. Well data biased by the seismic data.
Figure 12. Isopachs of the UD showing the application of well data and seismic data and the combination of well and seismic data.  A. isopach of seismic data B. isopach of well and seismic data multiplied together.  C. Seismic data biased by the well data.  D. Well data biased by the seismic data.
RESULTS

Lower Dakota/Cedar Mountain

Isopach maps of the combined well log and composite attribute values show distinct fluvial-estuarine channel forms. Values on the isopach maps are arranged such that warm values (yellow, orange, and red) denote sandstone with red being the thickest sandstone values. Cool colors (yellow/grey, blue) denote the presence of mudrock. In the LD/CM sandstone thickness ranges between 0-120 ft (0-40 m). Sandstone dominates in the eastern portion of the PRMC survey, while the western portion is dominated by mudrock (Figure 13). A distinct linear trend separates the eastern and western portions of the survey (Figure 13) (Plate 1). At northern end of the linear trend a fan/delta pattern extends to the southeast (Figure 13). Near continuous sandstone bodies in the southern portion of the PRMC survey become more discontinuous to the north as they approach the fan/delta (Figure 13) (Plate 2).

The RS survey has two thick sandstone bodies, one in the southeast and the other in the north central sections of the survey. The north central sandstone body may be a remnant of well data that is geographically isolated and unevenly distributed. Error in thickness values in a well or small group of wells can produce a bull’s eye feature in an isopach (Hampson, 2010). The southern sandstone body has no well data associated with it suggesting that the thick sandstone values are genuine (Figure 13).

Within the NHC survey there are thick sandstones in the northwest corner which thin and become discontinuous toward the southeast corner (Figure 13). Bounding the thick sandstone body in the northwest corner is a linear trend which separates sandstone thickness of >100 ft (33 m) to the northwest and < 75 ft (25 m) to the southeast. Another linear trend further to the
southeast parallels the first and has discontinuous sandstone and mudrock to the southeast (Figure 13) (Plate 3).

**Figure 13. Isopach map of the LD/CM well log and composite attributes combined with geologic features highlighted and labeled.**

**Upper Dakota**

Overall sandstone thickness in UD is less than that of the LCM, ranging between 0-75 ft (0-25 m). The majority of sandstone bodies are discontinuous. The PRMC survey is predominantly mudrock with a few areas of sandstone thickness greater than 60 ft (20 m) which
are located in the southern and north central regions (Figure 14) (Plates 1,4). There are no
distinguishable sandstone channel forms within the survey, yet a distinct mudrock filled channel
form is present in the north central portion of the PRMC survey, interpreted as a meander bend
and labeled as such (Figure 14). The meander bend has sharp boundaries between sandstone
bodies on the east and west.

The RS survey contains sandstone bodies greater than 75 ft (25 m) thick centered in the
southern portion of the survey. There is a series of linear sandstone bodies that are interpreted as
a channel belt (labeled channel belt in Fig. 14) (Plate 5) and trend south-north through the center
of the survey. The channel belt sandstone bodies are wider in the south and thin toward the
north. Near the southwest corner of the survey, we interpret a roughly circular sandstone body as
a crevasse splay (labeled crevasse splay in Figure 14). The crevasse splay is connected to the
channel belt (Figure 14).

Sandstone thickness in the study area is thickest in the NHC survey. A linear trend exists
in the northwest corner and along this trend are the thickest sandstones (Figure 14) (Plate 3).
Sandstone thickness decreases to the southwest grading into discontinuous sandstone bodies.
DISCUSSION

Sequence Stratigraphy

Application of terrestrial sequence stratigraphy in the Cedar Mountain Formation was performed by Currie (1997) and later by Greenhalgh (2007). In applying sequence stratigraphy to terrestrial systems it is essential to understand the processes that affect accommodation. With marine sequence stratigraphy, accommodation is controlled primarily by sediment supply and fluctuations in relative sea level (Mitchum et al., 1977). With fluvial processes, accommodation
is influenced by changes in sediment supply, tectonism (uplift or basin subsidence), and stream discharge (Shanley and McCabe, 1994; Currie, 1997). Currie (1997) established a terminology that is more applicable to terrestrial sequence stratigraphy (Table 1).

<table>
<thead>
<tr>
<th>Marine Systems Tracts</th>
<th>Terrestrial Systems Tracts</th>
<th>Architectural elements</th>
<th>Facies</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low Stand</td>
<td>Degradation</td>
<td>Valley Incision</td>
<td>Braided channels,</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Laterally continuous</td>
<td>paleosol development</td>
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<td>channels</td>
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<td>Transitional</td>
<td>Laterally continuous</td>
<td>Braided channels</td>
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<td>transition to</td>
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<td>Meandering channels</td>
</tr>
<tr>
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<td>Aggradational</td>
<td>Lenticular, isolated</td>
<td>Floodplain deposits.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>channels</td>
<td>Anastomosing channels</td>
</tr>
</tbody>
</table>

There are three identifiable sequences within the CDF interval in the study area, they are the Buckhorn Conglomerate and upper Shale member of the Cedar Mountain Formation (BCM), the lower Dakota Formation (LD) and the upper Dakota Formation (UDF) (Currie, 1997; Currie, 2002; Greenhalgh, 2007; Currie et al., 2008, Dark, 2008; Pierson, 2010) (Figure 15). Each formation within the CDF is sequence bounded. Deposition of each of the sequences began with the degradation systems tract or low stand systems tract (LST). This occurs as the underlying
sequence boundary is incised by the fluvial system as sea level or base level drops and accommodation decreases. The well log lacks an LST signature because erosion is not preserved in the log. In the composite log the LST was labeled at the sequence boundary to denote valley incision (Figure 15).

The transitional systems tract or transgressive systems tract (TST) is identified in the well log by a low gamma ray signature (low API value) that represents an amalgamated channel or channel complex (Figure 15). Though there may be variation in well log patterns, overall consistent basal sandstone marked by a low gamma ray signature (low API value) is present in each of the formations. Rising sea level or base level increases accommodation and there is aggradation in the incised valleys (Currie, 1997). Deposition begins to spill over into the floodplain where fine sediments are deposited.

As sea level or base level continues to rise the aggradational systems tract or highstand systems track (HST) is deposited. Channel movement is no longer restricted to the incised valleys and channel complexes expand laterally into discontinuous channels. This is identified with a high gamma ray signature (overbank deposits) with the occasional low gamma ray signature (individual channel) (Figure 15). In the composite log the boundary between the TST and HST is identified as an expansion surface to denote a significant increase in accommodation (Figure 15).

At the top of the CDF there is a transgressive surface that separates the CDF from the overlying Tununk member of the Mancos Formation. This transgressive surface marks the arrival of the Western Interior Seaway in the study area. In outcrop, the transgressive surface is identified as a thin conglomeratic lag deposit (Dark, 2008; Pierson; 2010). In the core the
A transgressive surface was identified at 8746 ft (2869 m) (Appendix) as a coal deposit overlain by marine sandstone. In the sequence above the CDF in the study area only the HST is preserved.

Figure 15. Composite log created from analysis of wells in the study area with a sequence stratigraphic interpretation. The log is representative of the wells in the study area.
Depositional Interpretation

The CDF was deposited during a period global eustatic sea level rise (Haq et al., 1987). Initially during the Early Cretaceous this eustatic sea level rise had little or no direct influence on the accommodation within the continent and therefore the deposition of the BCM. This interpretation is based on the concept that the amount of influence that sea level has on a fluvial system is proportional to its proximity to the shoreline (Shanley and McCabe, 1994). More downstream or coastal portions of the system respond most strongly to sea level. With the CDF the initial influence on accommodation was driven by variables from within the basin, specifically tectonism, sediment supply and discharge (Currie, 1997). As eustatic sea level rose, the distance from the study area to the shoreline decreased, increasing the influence of eustatic sea level on the deposition of the CDF. Madsen et al. (2010) suggest that tidal influence began in the LD based on marine microplankton found in the basal Dakota Formation north of the Uinta Basin. As observed in the core (Appendix) the UD expresses more tidal influence than the LD. Tidal influence in the CDF continued until the major transgression of the Western Interior occurred at the top of the Dakota Formation.

Each of the before mentioned sequences can be identified in isopach maps of the UD and LD/CM (Figures 16-18). The three sequences represent periods of transgression in the overall transgressive system of the CDF. Period 1 (P1) corresponds to deposition of the BCM. Two channel belts or fairways of thick sandstone have been identified which trend southwest-northeast which are approximately 3 mi (4.8 km) wide. These trends were identified not only by examining trends on the composite isopach maps but also by consulting the well data in order to determine the stratigraphic and geographic occurrence of the Buckhorn Conglomerate. The northwestern channel belt is only in the North Hill Creek survey and is identified by the northern
most linear trend in that survey (Figure 16). The southeastern channel is present in both the Rock Spring and Park Ridge/Main Canyon surveys and encompasses the southern sandstone body in the Rock Spring survey and is bounded on the west by the linear trend which divides the Park Ridge/Main Canyon survey (Figure 16). This is consistent with Buckhorn Conglomerate trends as stated by Currie (1998).

Figure 16. Isopach of P1 with channel belts highlighted. Solid black lines indicate channel boundaries and dashed black lines indicate channel belt boundaries inferred. Question mark (?) indicates there is not enough information to make a reliable interpretation.
Period 2 (P2) is similar to P1 in that there are two channel belts trending in the same northeastern direction. However, the channel belts broaden. Channel dimensions of P2 are significantly wider than that of P1 and range between 3-8 mi (5-12 km). The western channel belt is located within the North Hill Creek survey. It encompasses a portion of the channel belt in P1 and follows the southernmost linear trend (Figure 17). The eastern channel belt also encompasses the P1 eastern channel belt but extends further north in the RS survey to include the northern sandstone body and extends to the east in the PRMC survey to include the Fan/Delta (Figure 17). The presence of the fan/delta in the PRMC survey suggests marine influence and is consistent with several interpretations of the Dakota Formation that recognize marine, tidal, deltaic, or estuarine influence in the formation (Madsen et al., 2010; Pierson, 2010).
Figure 17. Isopach of P2 with channel belts highlighted. Solid black lines indicate channel boundaries and dashed black lines indicate channel belt boundaries inferred. Major sandstone bodies are outlined in green. Question mark (?) indicates there is not enough information to make a reliable interpretation.

Tidal influence becomes more pronounced in Period 3 (P3) with the eastern and western channel belts uniting in the PRMC survey (Figure, 18). Channel dimensions in the individual channel belts are 6 mi (9.7 km) and united channel belt dimensions are 12.5 mi (20 km). The eastern channel belt is similar to channel belts in P1 and P2 in that the boundaries are defined by linear trends in the NHC survey. The western channel belt in the RS survey is defined by the channel belt and crevasse splay identified earlier (Figure 15). The united channel belts in the PRMC are marked with relatively thin (> 60 ft) discontinuous sandstone bodies and the mudrock-filled meander bend (Figure 18).
Figure 18. Isopach of P3 with channel belts highlighted. Solid black lines indicate channel boundaries and dashed black lines indicate channel belt boundaries inferred. Major sandstone bodies are outlined in green. Question mark (?) indicates there is not enough information to make a reliable interpretation.

Channel belt dimensions in P1 and P2 exceed that of those measured by Dark (2008). There are two possible explanations for this. First, Dark (2008) gave dimension for channels and amalgamated channels or channel complexes. A channel belt would consist of multiple channel complexes, therefore a channel belt would be wider then what was measured by Dark (2008). Secondly Pierson (2010) proposes that the marine Mowry Formation north of the Uinta Basin and the fluvial upper Dakota Formation south of the Uinta Basin to be chronostratigraphically equivalent. The study area is between the outcrops used by Pierson (2010) north of the Uinta Basin and outcrops used by Dark (2008) south of the Uinta Basin. The CDF in the study area
mostly likely displays the facies transition between the marine Mowry Formation and the fluvial upper Dakota Formation during one chronostratigraphic period.

Isopach maps of the three depositional periods were compared with several depositional models of modern estuaries (Allen, 1991; Woodruffe et al., 1989; Dalrymple et al., 1992; Dalrymple et al., 1994). Dalrymple et al. (1992)’s model of a tidally dominated estuary was chosen as the best fit as it is not based on a single estuary but is a general model based on several estuaries. Similarities can be seen between features in the isopach maps and Dalrymple et al. (1992)’s model (Figure 19).

Figure 19. Map and cross-sectional view of a generic model of a tidal-dominated estuary (Redrawn from Dalrymple et al. (1992)).
Deposition of each period corresponds to a position along the model’s profile (Figure 19). P1 was deposited above the tidal limit and has narrow channel belts consisting of fluvial sediments (Figure 19). P2 with wider channel belts and a fan/delta feature was deposited along the tidal fluvial channel and sand flats and consists of tidally influence fluvial sediments (Figure 19). P3 with the broad combined channel belt is consistent with an estuarine environment, including sand flats, tidal sand bars and mud flat. Discontinuous sandstone bodies and more abundant mudrock in P3 are similar to tidal sand bars as opposed to fluvial sand.

When compared with the model, maps created from composite seismic attribute and well log data as well as the evidences discussed by Madsen et al. (2010), a tidally dominated fluvial-estuarine system is the most plausible depositional system for CDF.

CONCLUSIONS

![Workflow](image)

Figure 20. Workflow used to understand the complex nature of CDF.
Historically, the complex cut and fill architecture and poor well log resolution of CDF in the southern Unita Basin has made correlation of sandstone channels and channel complexes unreliable. With the availability of three 3D seismic datasets a workflow was created that was able to identify channel belts and interpret an environment of deposition (Figure 20). The main components of this workflow or strategy includes the following:

1) Correlation of the CDF in well logs which was performed on the basis of facies that corresponded to identifiable geology. This is a new correlation scheme in this formation that was dependent on identifying distinct log signatures based on core data and based on documented channel and channel belt dimensions from outcrop in the formation (Dark, 2008).

2) Distinct seismic attributes responded to changes in the geology unique to a fluvial-estuarine system. Spectral decomposition responded to sandstone thickness, waveform classification to stratigraphy and percent less than threshold to lateral variation. These seismic attributes were uniquely combined into a composite seismic attribute map.

3) The composite seismic attribute map was combined with well log data to give high resolution seismic the accuracy of well logs correlated to core.

This study provides a new reservoir map for increased drilling success in this region.

The Cedar Mountain and Dakota Formations within the southern Uinta Basin represent a transition from outcrops south of the Unita Basin which show no tidal influence to outcrops north of the Unita Basin with tidal influence to marine. Channel belts trend southwest-to-northeast throughout the CDF. Two distinct Channel belts are identified in the Cedar Mountain and lower Dakota which merge in the upper Dakota due the transgression of the Western Interior Seaway.
References


Chopra, S., Marfurt, K.J., 2005, Seismic attributes-A historical perspective: Geophysics, v. 70, p. 3SO-28SO.


Appendix

Core pictures, depth marked in feet.

8651 Heavily bioturbated marine sandy mudrock.
8679 Heavily bioturbated marine sandstone.
8690 Remnant wave ripples.
8703 Bentonite bed 10cm thick.
8708 Bentonite bed 3cm thick.
8720 Bioturbated muddy sandstone with shell fragments, marine.
8733 Heterolithic interlaminated siltstone and sandstone with wavy bedding.
8734-8736 Wavy lenticular bedding.
Synaeresis cracks overlain by hummocky cross stratification.
8745-8747 Coal overlain by transgressive sandstone.
8798 Mottled flood plain mudrock.
8812-8810 Coal 2 ft thick.
8824 Mottled, massive mud with a few burrows.
8834 Bioturbated coastal plain mudrock.
8838 Root traces with ripple crossbedding.
8845 Mottled mudrock.
8847 Possible paleosols.
8850 Tidal rythmites and burrows within channel sandstone.
8860 Greenish, mottled mudrock.
8866 Tidal rythmites within channel sandstone.
8867 Coarse crossbedding with mudchips.
8871-8869 Erosional channel, base unconformably overlying floodplain mudrock.
8878 Ripple cross stratification with mud drapes.
8880 Trough crossbedding.
8887 Ripple crossbedding.
8890-8887 Channel sandstone.
channel complex facies
overbank facies
coal-bearing overbank facies
channel complex facies
overbank facies
coal-bearing overbank facies
Plate 5

- channel complex facies
- overbank facies
- coal-bearing overbank facies