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Along Strike Variability of Thrust-Fault Vergence

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ABSTRACT

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The kinematic evolution and along-strike variation in contractional deformation in overthrust belts are poorly understood, especially in three dimensions. The Sevier-age Cordilleran overthrust belt of southwestern Wyoming, with its abundance of subsurface data, provides an ideal laboratory to study how this deformation varies along the strike of the belt. We have performed a detailed structural interpretation of dual vergent thrusts based on a 3D seismic survey along the Wyoming salient of the Cordilleran overthrust belt (Big Piney-LaBarge field). The complex evolution of the thrust faults that parallel the overthrust belt is demonstrated by the switching of the direction of thrust fault vergence nearly 180° from east to west. The variation in thrust-fault geometry suggests additional complexities in bulk translation, internal strains, and rotations. The thrust zone is composed of two sub-zones, each with an opposing direction of fault vergence, located on the eastern toe of the Hogsback thrust in southwestern Wyoming. The northern west-vergent thrust is a wedge thrust and forms a triangle zone between its upper thrust plane and the lower detachment that has formed in a weak shale layer (the Cretaceous K-Marker bed). Thrusts to the south have a frontal ramp geometry and are consistent with the overall thrust orientation of the Cordilleran overthrust belt located immediately to the west. The two thrust sub-zones are small, relative to the main Hogsback thrust to the west, and adjacent to each other, being separated by a transfer zone measuring in the hundreds of meters along strike. The transfer zone is relatively undisturbed by the faults (at the scale of seismic resolution), but reflections are less coherent with some very small offsets. The thrusts are thin-skinned and located above a shallow-dipping single detachment (or décollement) that is shared by faults in both sub-zones. Lateral growth of the thrust faults link along strike to form an antithetic fault linkage. Structural restoration of thrust faults shows varied amounts of shortening along strike as well as greater shortening in stratigraphic layers of the west-vergent fault to the north. Results from a waveform classification and spectral decomposition attribute analysis support our interpretations of how the variations in the detachment may govern the structural development above it. The kinematic evolution of the dual-verging thrust faults is likely controlled by local pinning within the transfer zone between the thrust-fault sub-zones as well as by changes in the competence of the strata hosting the detachment and in the thickness of the thrust sheet. The analysis and interpretation of dual-vergent thrust structures in the Cordilleran overthrust belt serve as an analog to better understand complex fold, fault, and detachment relations in other thrust belts.

Keywords: along-strike, thrust fault, vergence, 3D seismic

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TABLE OF CONTENTS

LIST OF FIGURES

INTRODUCTION

Fold-thrust belt geometries are complex and varied owing to interactions between faults and folds. Along-strike variability of thrust faults and their kinematic linkage has become a major focus of compressional settings within the past decade (Higgins et al., 2007; Higgins et al., 2009). Complex geometries and fold and fault linkages in these settings are best observed from detailed subsurface information from convergent tectonic settings. For this study, we use high-quality 3D seismic data in southwestern Wyoming to interpret thrust faults that reverse vergence along strike. The location of this survey, near Big Piney, Wyoming in the foreland of the Cretaceous Cordilleran Overthrust Belt (Figure 1), makes it ideal to investigate complicated thrust geometries. Although the kinematic evolution of the thrust belt has been well-studied (Armstrong and Oriel, 1964; Armstrong, 1968; Wiltschko and Dorr, 1983; Burchfiel and Davis, 1975; Cowan and Bruhn, 1992; DeCelles and Mitra, 1995; Guney, 1999; Knight et al., 2000; Guirigay et al., 2001; DeCelles, 2004; Dickinson, 2004; Yonkee and Weil, 2010), questions remain as to the development of foreland thrusts that propagate in directions opposite to the main thrust belt.

Three key elements dominate studies of the kinematic evolution of orogenic belts: Slip on major faults (bulk translation), rotation or large-scale folding and fault-block motion, and internal strain (Mitra, 1994; Hindle and Burkhard, 1999; Weil and Yonkee, 2012).The Sevier fold-thrust belt is an example of intraplate deformation and need not be directly related to plate tectonics. Intraplate deformation may be largely governed by nonplate-tectonic factors such as: heterogeneous strength caused by thermal weakening and the complex internal structure of continental plates and gravitational potential energy stored in thickened crust. Localization of the thrust belt is possible by paleogeographic factors and the deformation be driven by buoyancy forces within

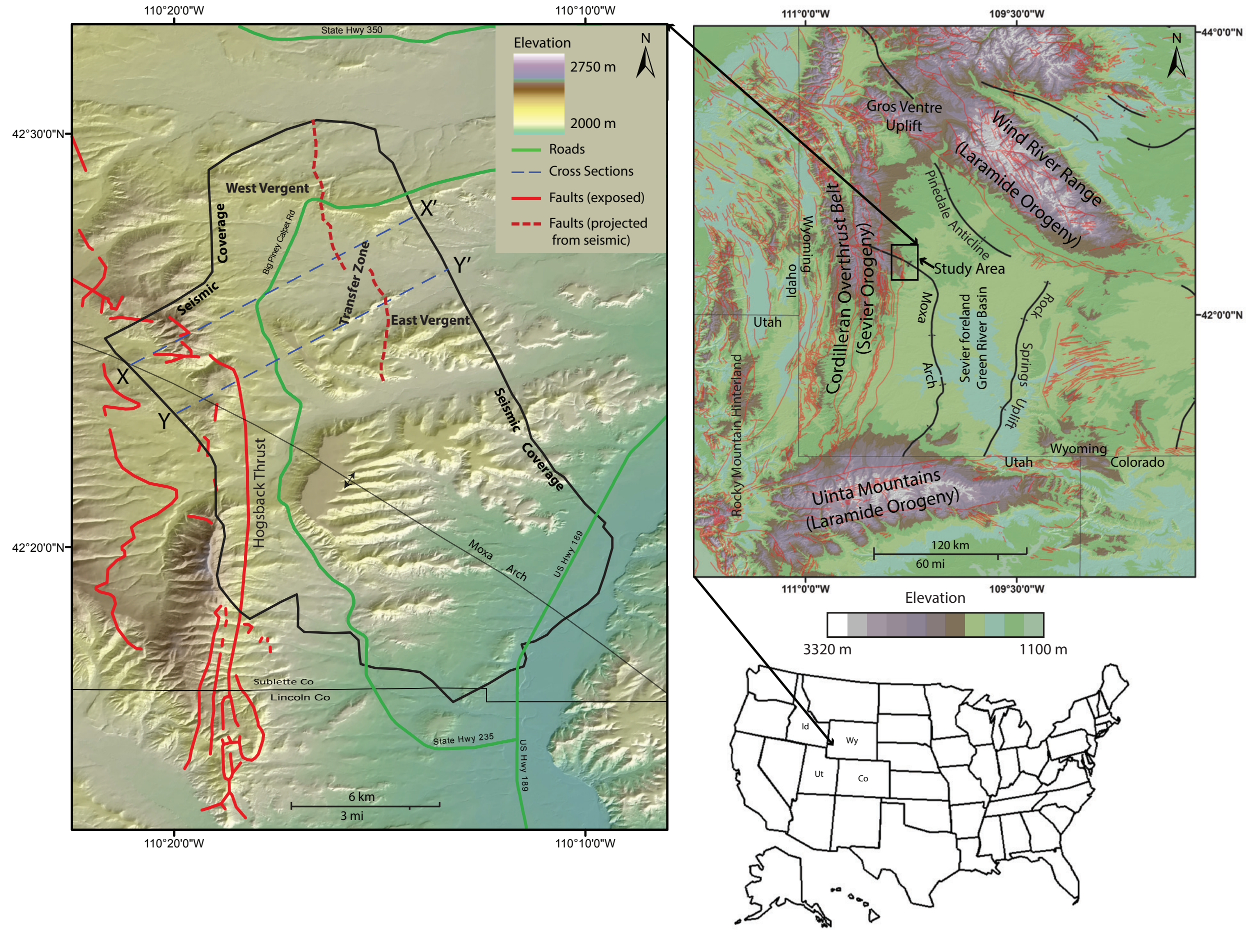

Figure 1: Index map of study area showing seismic coverage (black outline) provided to Brigham Young University, near Big Piney, Wyoming (Sublette and Lincoln Counties). Extent of seismic coverage is approximately 240 km2. Cross Sections A-A' and B-B' are illustrated in Figures 3A and 3B respectively. Dual verging thrust faults are not exposed at the surface and are vertically projected from the seismic data. West-vergent thrust dips to the east and strike is 348°. East-vergent thrust dips to the west and strike is 162°. Thrust faults (exposed), roads and the Moxa Arch axis trend from the Wyoming State Geological Survey Date accessed, February 2014

the lithosphere (Chapple, 1978; English et al., 2003; DeCelles, 2004). Evaluating the 3D interplay of these elements is challenging due to the complexity of each component (Marshak, 1988; Weil and Yonkee, 2012). Several geologic models attempt to reconstruct the kinematic evolution of the Cordilleran overthrust belt in Wyoming (DeCelles and Mitra, 1995; Guney, 1999; Guirigay et al., 2001; DeCelles, 2004; Yonkee and Weil, 2010). Each model accurately describes the onset of thrusting and only slight variations to the evolution of major thrust faults are interpreted.

Models are generally in good agreement. Fundamental questions remain as to the relationship between Sevier and Laramide structural deformation along the Cordilleran overthrust belt. Theories of interactions include the following (Weil and Yonkee, 2012): Shortening due to a lower crustal detachment from the Sevier Orogeny (Kulik and Schmidt, 1988; Oldow et al., 1989), rotation of the Colorado Plateau (Hamilton, 1988), lithospheric buckling (Tickoff and Maxson, 2001), dextral transpression from collision with the plate margin (Maxson and Tickoff, 1996), and increased basal traction from subduction (Dickinson and Snyder, 1978; Wernicke et al., 1982; English et al., 2003; Saleeby, 2003). Various studies have attempted to determine stress orientations and resulting deformation along thrust sheets and associated folds. Crosby (1969), for example, analyzed orientation data of structural elements from outcrops near the Wyoming salient to infer the horizontal components of movement and gross stress orientations. Along-strike variability of curved mountain belts is common and variable thrust fault geometries are attributed to differential shortening, translation and rotational effects (Allerton, 1998).

Thrust belt scale interactions of the Sevier and Laramide orogeny will not be specifically addressed in this study, but a local phenomenon within the Birch Creek seismic survey may provide future insight to better defining interactions in the Sevier orogenic foreland. Our study describes the geometry of a set of thrust faults that developed within a thin-skinned tectonic setting with opposing directions of vergence along the Cordilleran orogenic front and a distinct boundary that marks the reversal in vergence. Various mechanisms are evaluated and tested against our interpretation of the seismic data supported by seismic attribute analysis and balanced cross sections.

GEOLOGIC BACKGROUND

The Cordilleran overthrust belt extends nearly 6,000 km (3728 mi) across the length of North America from Alaska through western Canada and the western contiguous United States through northeastern Mexico (DeCelles 2004; Hintze and Kowallis, 2009). The Big Piney field lies in the Greater Green River Basin. The Green River Basin is bounded by the Sevier Orogenic Belt to the west and otherwise by Laramide basement uplifts that include the Gros Ventre Range to the north, the Wind River Mountains to the northeast, and the Uinta Mountains to the south (Figure 1). The Green River Basin is due to compressional tectonics, thrusting and crustal loading and is a small part of the more extensive Western Interior Cretaceous foreland (Knight et al., 2000). The Sevier orogenic belt is made up of dominantly east-vergent detachments within the sedimentary cover and their corresponding folds, which are Early Cretaceous in age (DeCelles, 2004). In southwestern Wyoming, the belt lies between the Cordilleran hinterland to the west and the foreland to the east (Heller et al.,, 1986). The timing of individual thrust sheets in Cordilleran orogenic belt and their progression from west to east has been extensively studied (DeCelles, 2004). Most authors describe the onset of thrusting to have begun during the late Jurassic and continued through early Neogene time (Armstrong and Oriel, 1964; Armstrong, 1968; Wiltschko and Dorr, 1983). Various authors have also summarized the evolution of thrust events in the larger context of western North America (Burchfiel and Davis, 1975; Cowan and Bruhn, 1992; Dickinson, 2004; DeCelles, 2004).

The Cordilleran overthrust belt is divided into several different salients (Lawton et al., 1994). The salient of interest in this study is located in southwestern Wyoming and includes the Big Piney LaBarge field, near Big Piney, Wyoming (Figure 1). The Wyoming salient is bounded by the Uinta uplift to the south and to the north by the basement-cored Gros Ventre uplift. There are several major thrust systems that progressed from east to west as subduction progressed under North America during the Early Cretaceous through the Early Paleogene (Armstrong and Oriel, 1964; Armstrong 1968; DeCelles, 2004). These thrust systems are, from east to west: the Paris-Willard, Crawford, Absaroka, and Hogsback systems (Weil et al., 2010). The Hogsback system is the closest previously mapped thrust fault in relation to the Big Piney LaBarge field and the Birch Creek 3D seismic survey used in this study. Its emplacement has been inferred to be synchronous with the Gros Ventre and Uinta uplifts (Dorr et al., 1977; Bradley and Bruhn, 1988).

The Birch Creek survey and specifically the Big Piney LaBarge field are particularly interesting locations along the overthrust belt due to the possible interaction of a basement uplift originating from the Laramide orogeny that was imposed upon the earlier thin-skinned thrusting from the Sevier orogeny. Structural features such as the Moxa Arch are described as basement-cored features that begin in the Uinta Mountains to the south and extend into the study area. The Moxa Arch is a basement uplift that transects at least 120 miles (193 km) across southwestern Wyoming (Wach, 1977). The uplift of the Moxa Arch occurred during middle Upper Cretaceous (Thomaidis, 1974). This broad arch has been associated with seismic structural closures and many high-angle reverse faults on its eastern flank (Wach, 1977). The combination of Sevier thrust propagation and basement-cored uplifts from the Laramide orogeny has produced uplifted arches and corresponding depositional basins in which synorogenic deposits have accumulated across the Rocky Mountain region (Schmidt et al., 1993). Schmidt et al. (1993) described the geometry of cover folds and arches as varying from NW-SE to E-W and forming left and right-stepping en echelon systems within the Laramide foreland.

The 3D seismic survey used in this study parallels the overthrust belt. Thrust faults are exposed at the surface and visible in outcrop along the western boundary of the survey outline. Outcrops of Ordovician rocks (Bighorn Dolomite) and other calcareous formations (Gallatin Limestone and Madison Group) of Devonian through the Carboniferous are exposed at the surface. The Hogsback thrust, associated with the Darby fault (Dorr and Gingerich, 1980), is the major thrust (Figure 1) that is visible along with some smaller scale thrusts. These easternmost faults define the furthest extent of faulting at the surface within the seismic data field. The surrounding sedimentary cover is composed of mostly Paleocene to Eocene (Wasatch Formation) sedimentary rocks of variable lithologies. Outcrops that are exposed due to thrusting also create a topographic boundary at the surface. To the west, beds and fault planes dip roughly to the west 20-40°. The Wasatch Formation on the east lacks good bedding planes but was measured in a few locations and dips gently (<2°) to the east and in most places nearly zero. These dips show that the Wasatch Formation has been almost entirely undisturbed in the study area. No visible outcrops are exposed at the surface within this formation that directly relate to the thrust faults interpreted from the seismic data. Seismically imaged stratigraphic intervals within the basin are the Wasatch Formation, Almy Formation, Mesaverde Formation, Baxter Shale, K Marker bed and the Frontier Formation. These intervals are frequently described in literature due to their hydrocarbon potential, but some also mark key unconformities within the basin. The Baxter Shale is roughly 915 m (3000 ft.) thick with some variation across the study area. Within the Baxter Shale is the K Marker bed; a shale unit that is roughly 610 m (2000 ft.) thick and provides the detachment surface for the shallow, dual-verging thrust faults.

PREVIOUS WORK

The Cordilleran overthrust belt is a classic curved fold-and-thrust belt. Studies of curved mountain belts are critical to understanding the paleogeography and the tectonic evolution of continents (Weil et al., 2010). A curved mountain belt suggests complex evolution and a three-dimensional displacement field (bulk translation, horizontal- and vertical-axis rotation, internal strain) (Macedo and Marshak, 1999; Weil et al., 2010). Orogenic curvature has been best documented by paleomagnetic analysis, which records horizontal and vertical rotational distributions along strike of a curved mountain belt (Allerton, 1998; Weil et al., 2010). Paleomagnetic data distinguish between primary curvature and secondary rotations (Yonkee and Weil, 2010; Weil and Yonkee, 2012).

The Big Piney LaBarge field, which produces mostly natural gas, has been the focus of several studies using 3D seismic data over the past 20 years. Most studies have focused on the petroleum system and the geometry of producing formations. Petroleum accumulation is by structural closures, along with stratigraphic traps. Guney (1999) created a structural model based on 3D seismic data over the field, along with balanced cross sections, demonstrating that one of the major structures was a backthrust anticline and documenting its relation to hydrocarbon production. Guney (1999) concluded that a north-south oriented, east dipping thrust fault-cored anticline is the main hydrocarbon trap and that the amount of tectonic shortening was greater within formations at greater depths. Guirigay et al. (2001) produced a 3-D seismic-geologic model of the field and concluded that an east-dipping (west-vergent) thrust fault and the associated anticline structurally trapped an elongated sand body in the hanging wall that is the main producing interval. Schroer (1999) proposed an east-verging La Barge fault and a west-verging Calpet fault that forms a triangle zone from which a significant amount of gas has been produced.

These previous studies have described the subsurface structural complexity, mapped various stratigraphic units, and documented the petroleum system. The present study is focused on understanding the dual-verging thrust faults that detach within a single stratigraphic unit, but with perhaps some along-strike variability in the detachment surface. The stratigraphic unit hosting the detachment is the Cretaceous Baxter Shale. The detachment bed within the shale is called the K-Marker bed in previous studies (Guney, 1999). Along with describing the interpreted thrusts and their respective geometries, it is equally important to describe the transfer zone between the faults as it marks an abrupt change in the direction of vergence and structural style. We explore 4 possibilities for mechanism(s) that produced the reversal in vergence based on our interpretation of the seismic data, attribute analysis, and limited field exposures.

METHODS

The primary method used in this study is the interpretation, attribute analysis, and modeling of 3D seismic reflection data. Because thrust faults interpreted from the seismic data appear to extend upward to very shallow depths, field reconnaissance was conducted in order to locate any faults that were exposed in outcrop at the surface. We were unable to find evidence of any surface faulting and thus all further methods are based on the seismic data alone.

Depth Conversion

Seismic data is recorded in two-way travel time and our conversions to depth are based on formation tops from a limited selection of wells in the area. Previous studies of the area used well log data to produce synthetic seismograms and build reliable velocity models that give fairly uniform velocity values for the shallow section down to 6500 feet (Schroer et al., 1999; Guney, 1999). Our results compare favorably with previous studies and give a sufficiently accurate aver

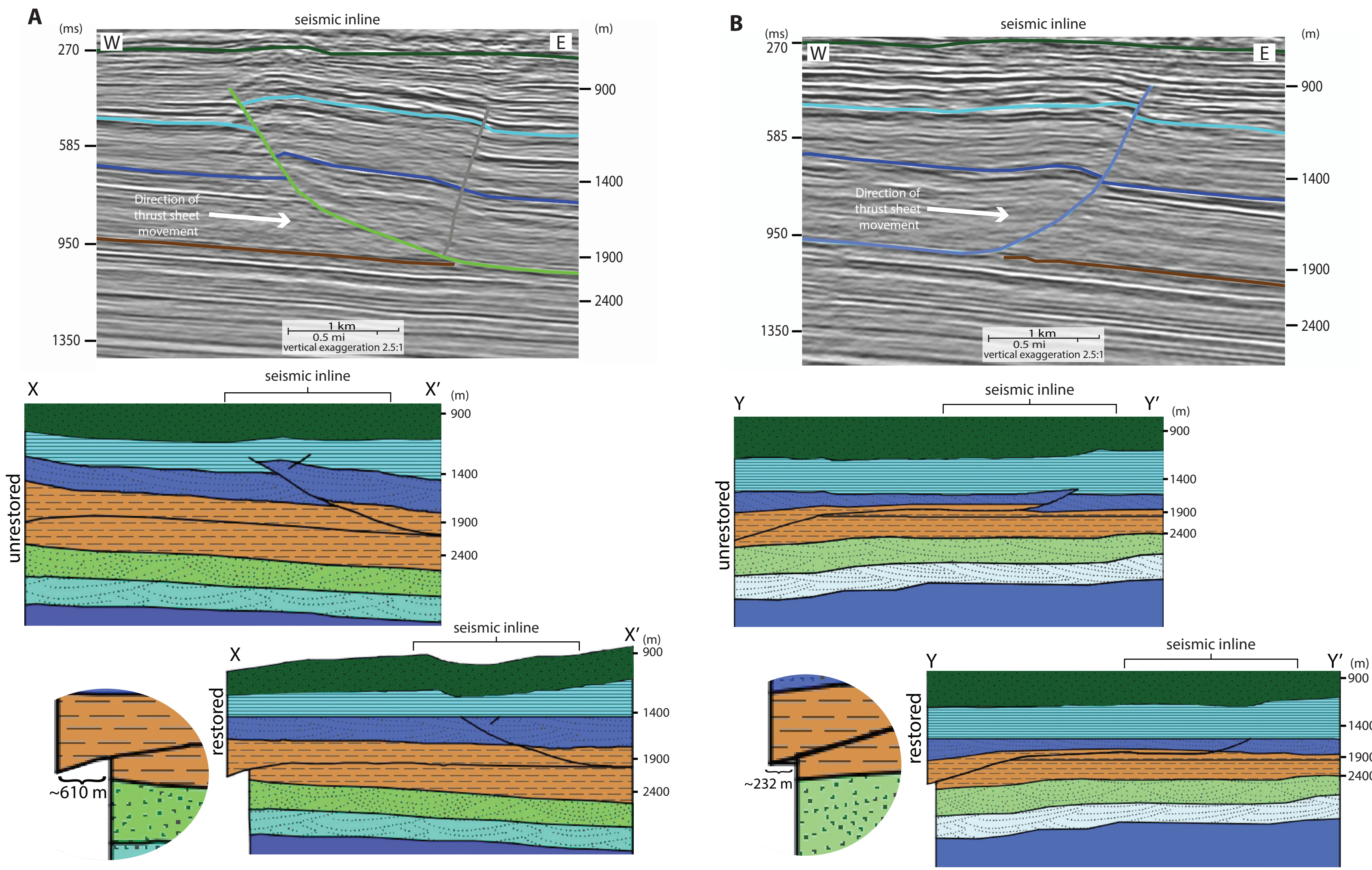

Figure 2: Figure 2. Restored cross sections from individual inline traces associated with each fault that switch vergence along strike. A) Thrust A-A'is a west-vergent hinterland-propagated wedge backthrust and the amount of shortening on the west-vergent thrust fault is ~610 m. B)Thrust B-B'is an east-vergent foreland propagated forethrust and the amount of shortening is ~232 m. Balancing and restoration techniques include: flexural slip, vertical/oblique slip, Trishear and forward modeling to validate balancing and final restoration.

age velocity (3,658 m/s or 12,000 ft/s). All depths in our figures are based on a uniform velocity to the depth of the décollement.

Interpretation and Mapping of 3D Seismic Data

Stratagraphic horizons identified: Wasatch Formation, Almy Formation, Mesaverde Formation, Baxter Shale, K Marker bed and the Frontier Formation. These horizons were selected for interpretation based on previous studies in the area and because they are easy to identify from prominent reflections within the data. These stratigraphic intervals represent Late Cretaceous sediments of the Frontier Formation to the Eocene (tertiary) Wasatch Formation. Horizons were interpreted using various methods from user drawn lines and then computer based algorithms to track along the seismic event to create time and depth contoured structure maps (e.g. see Figure 5A). These interpreted horizons were then used as the basis for structural restoration modeling, attribute analysis, and our overall tectonic interpretation of the dual-vergent thrust faults.

Structural Restoration & Balancing

In order to perform structural restoration, balancing, and forward modeling based on the interpretations of the seismic data, we used the following kinematic modeling assumptions: 1) Flexural slip (slip parallel to layer boundary; 2) slip line (slip parallel to fault); 3) vertical slip (vertical slip); 4) oblique slip (inclined slip); and 5) rigid block (rigid body translations/rotations following Geiser et al. (1988) and Marshak and Mitra (1988). The most applicable model assumption for our data is a combination of flexural and vertical/oblique slip. Oblique slip is useful in compressional settings where fault and stratigraphic dips are $< 30°$ and when performing a contractional restoration based on defined regions from the seismic data (separated by the thrust fault) (Geiser et al., 1988; Bob Ratliff, personal communication, 2014).

Fault Prediction, Forward Modeling & Trishear

Fault prediction is a software based tool that will predict further movement along a fault based on its interpreted geometry in its modern or restored state. It was used to interpret faults through data gaps and allows the software to project the proper location of a fault based on the balanced state of the adjacent rocks in their pre-faulted state (Woodward et al., 1989). This can be a useful tool in the beginning stages of balancing and restoration to verify the correct initial interpretation has been made by visual inspection of the seismic data.

Forward modeling, of the interpreted faults, was used to verify the correct restoration and recreate the present-day position of faults and strata based on the seismic data. Trishear modeling was developed by Erslev (1991) and is a kinematic model that evaluates fault propagation folding where displacement decreases along a fault plane and is accommodated by heterogeneous shear from the tip line of the fault (Hardy and Allmendinger, 2011). Trishear modeling improves on the parallel kink-fold concept of fault propagation folding and is capable of determining strain distributions at the tips of propagated faults (Zehnder and Allmendinger, 2000). We used this technique to forward model and predict fault tip terminations based on the geometry of the overlying seismic reflectors. This method allowed us to recreate the slip or movement of the thrust fault along its interpreted fault plane and watch the undeformed rocks deform and verify the deformation based on direct observation from the seismic data.

Attribute Analysis

A variety of attributes were used in both volume and horizon analysis. Using a suite of 3D seismic attributes (instead of any single attribute) maximizes the interpreter’s ability to detect and identify geologic anomalies and/or discontinuities (structural or stratigraphic) (McBride et al., 2014). Using multiple attributes also enhances the viability of the interpretation by showing repeatability of the geologic anomalies. Geometrical attributes (e.g., azimuth, semblance, structure) are useful to identify structural characteristics and to blend with physical attributes (e.g., amplitude, phase, frequency) to delineate structural trends and discontinuities along the dual verging fault network. Horizon attributes (waveform classification and spectral decomposition) were used to identify any changes in stratigraphy along the detachment surface for each fault.

Attribute calculations for horizons average information from the seismic data based on the interpreted horizon. The averaging method looks at a user-defined time interval or "gate" above and below the horizon. We used a centered gate to average above and below the horizon that corresponds to the interpreted detachment.

Volume attributes were used to visualize structural patterns from a horizontal time slice. These attributes differ from the above mentioned horizon attributes, in that they are not centered over a stratigraphic unit determined by the interpreter. This is useful as it removes any bias from the interpreter (McBride et al., 2014). Visualization tools that enhance both structural and physical attributes were used to overlay one attribute on another, giving it an enhanced three-dimensionality, or overlaying/blending two different attributes for a combination that enhances visualization. We found this to be most useful when looking at geometrical attributes as it highlights faults and other small discontinuities around the area of interest. Chopra and Marfurt (2005) provide a detailed mathematical development of seismic attributes and usage.

Waveform classification is a horizon computed attribute that assumes similar wavelets correspond to similar stratigraphy based on measures of frequency and phase (Andersen and Boyd, 2004). An arbitrary number of classes are used in order to best define variations.

Spectral decomposition is a frequency based attribute from which one can infer bed thickness and stratigraphic variations (Partyka et al., 1999; Andersen and Boyd, 2004). The tech-

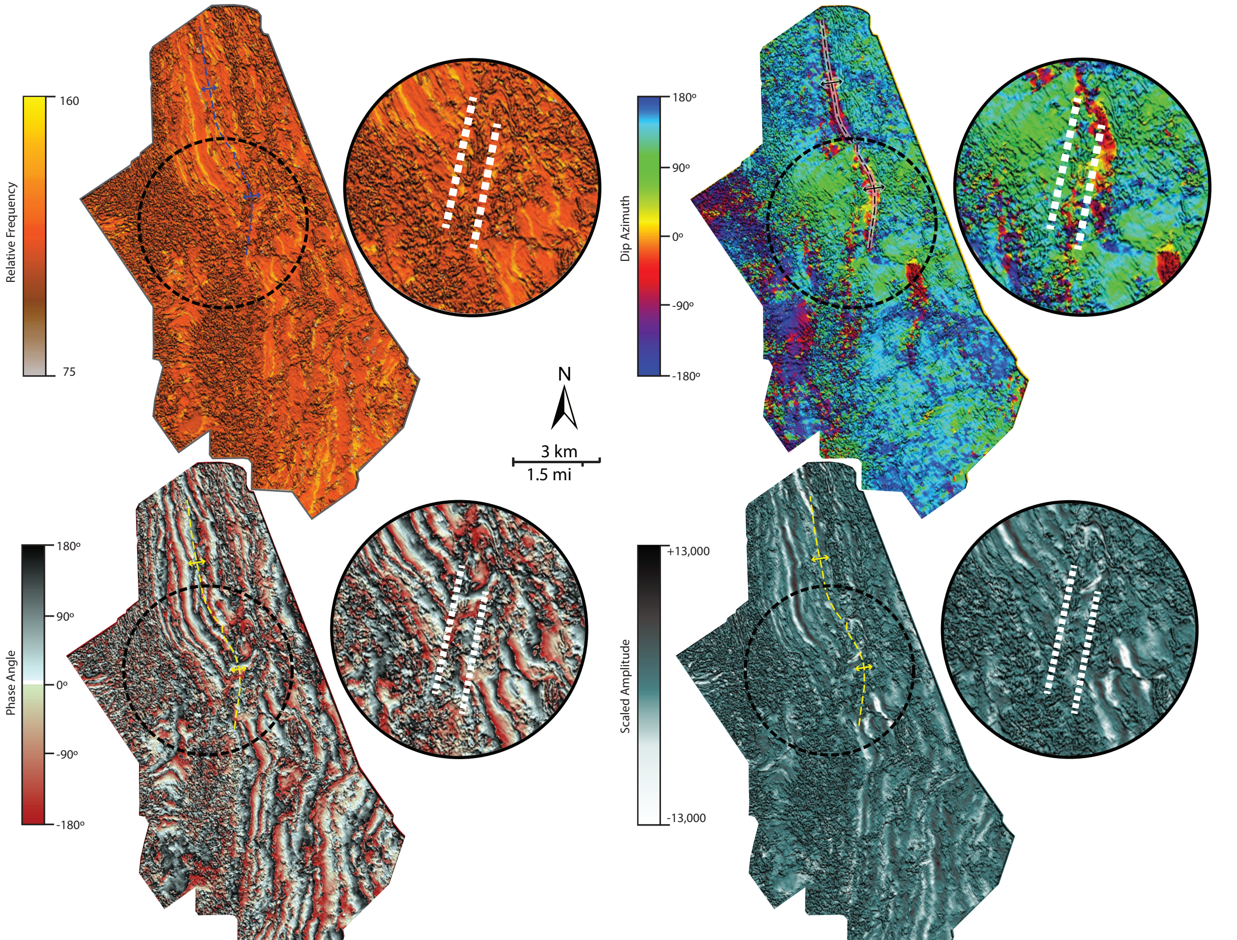

Figure 3: Volume attributes (992 ms) that highlight the transfer zone between opposite verging thrust faults. Each attribute is a combination of the labeled description co-rendered with a semblance volume to add a structural and textural aspect. Colored axial trace arrows highlight the fold anticline axis of the west and east vergent directed thrust fault. Zoomed areas of the transfer zone show a consistent interpretation of the edges of the transfer zone and all attributes are in general agreement.

nique is based on observing "tuning" (i.e., constructive interference) effects for different wavelet frequencies just above and below the zone of interest. We use spectral decomposition in order to track variation along the detachment interval. Spectral variations from this interval may indicate the preferred direction of vergence for thrust faults emerging up from the detachment.

RESULTS

Our seismic horizon mapping reveals a complex zone of thrust faulting within the Early Cretaceous age and the Baxter Shale Formation(s) in the Big Piney La Barge field (Figure 1).

These faults vary along strike in their amount of horizontal and vertical displacement. Further, the direction of fault propagation (vergence) is reversed by approximately 180° and separated by a "transfer zone" (defined herein to mean….the zone along strike where the faults switch vergence). Asymmetric anticlines are associated with each fault and are not linked across the transfer zone. Displacement along the faults is transferred along strike, and deformation would be expected to appear in the transfer zone; however, it is relatively undisturbed and appears to

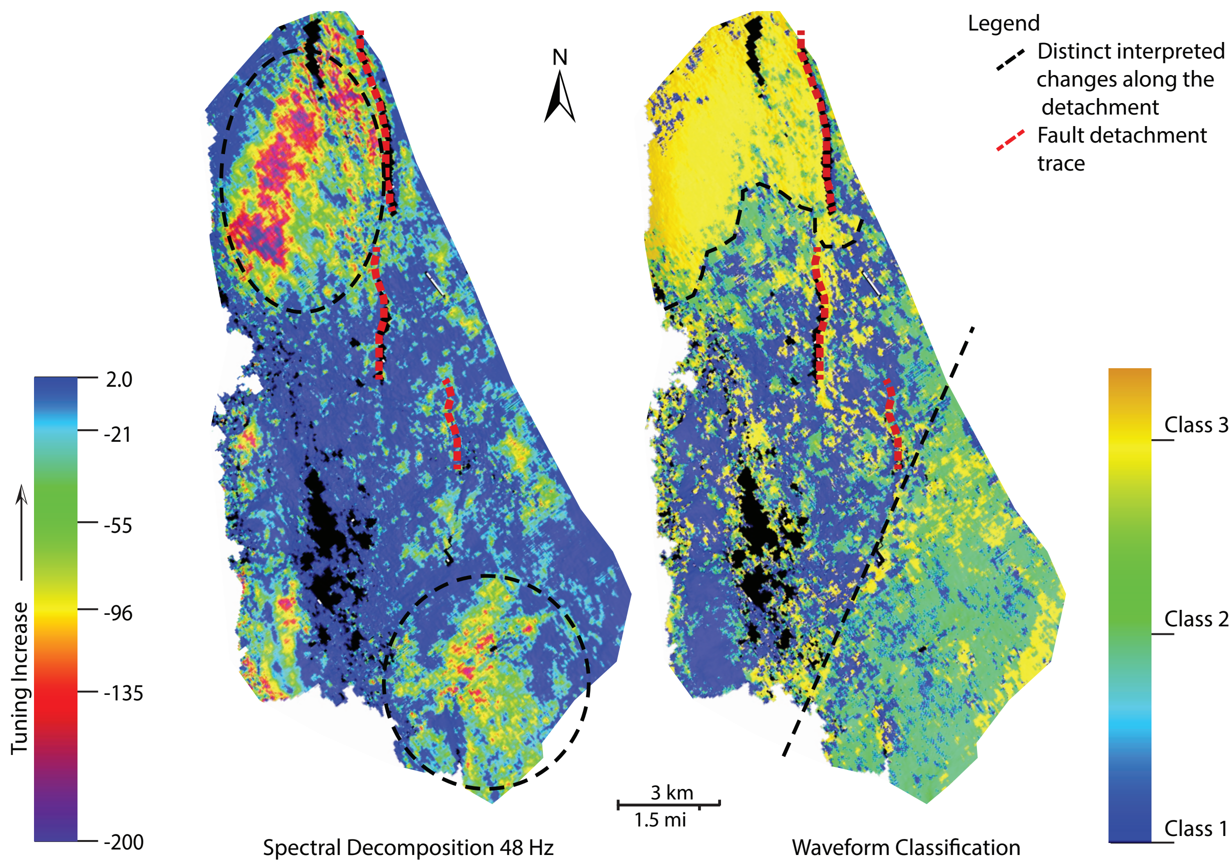

Figure 4: Spectral decomposition and waveform classification for the detachment horizon. Both fault detachment horizons are within the Baxter Shale. This is an interpreted horizon from the seismic and the location of each fault in the detachment surface is highlighted by red dashed lines. The best tuning results for the detachment horizon were at 48 Hz. Positive values represent high tuning, which suggest thinning and areas with a negative value are low tuning associated with thickening. Three classes were chosen for the waveform classification attribute. Each zone is separated by black dashed lines that highlight major physical changes in the detachment. Three classes is the best fit to highlight similar boundaries in the spectral decomposition.

be unaffected by the reversal in vergence (Figure 6). We might expect to see some small offsets related to strike-slip or en echelon tear faults, but such features may be below the resolution of the seismic data. The thrust faults are observed to detach from a single horizon within the Baxter Shale termed the K-Marker bed in previous studies. The detachment horizon is approximately 1900-2000 m deep based on an average interval velocity of 3,658 m/s (12,000 ft/s) and restored cross sections demonstrate that each thrust fault differs in its magnitude of horizontal and vertical displacement (Figure 2). Volume attributes delineate boundaries associated with the transfer zone (Figure 3) and horizon attributes better define stratigraphic variations in the detachment horizon (Figure 4). Thrusts of opposing vergence link (referring to the geometric linkage of the fault plane as they grow laterally from Higgins et al., (2007)) along strike and the anticline associated with each fault is not continuous or linked in the transfer zone. Since the folds are not continuous, lateral gradients of the fault propagated fold reduce to zero abruptly at the edge of the transfer zone as seen in Figure 5A of the west-vergent fault. Thrusts that link along strike and have dual vergence are referred to as antithetic fault linkages (Higgins et al., 2007) (Figure 7). Due to the observed fault linkage across the transfer zone and the steep lateral gradient of the west-vergent fault propagated fold, we suggest local pinning of the transfer zone and rotations about the transfer zone, combined with lateral variations (e.g. stratigraphic, thickness, fluid content) in the detachment horizon has facilitated the switch in vergence.

Two results emerged from analyzing seismic attributes: 1) volume attributes delineate the edges (edges, referring to a change from coherent to incoherent reflections) of the transfer zone and the axial trace of the anticlines associated with each fault; semblance, structure, phase, and azimuth were the most useful to visualize the shallow thin-skinned thrust faults. 2) Waveform classification and spectral decomposition indicate a change in physical properties (e.g. thickness, facies variations, pore fluid pressure or fluid type) laterally along the detachment horizon. The best tuning (spectral decomposition) occurs at 48 Hz and we infer that the thickness of the thrust sheet varies along strike. Three classes (waveform classification) were sufficient to highlight any lateral variations or stratigraphic discontinuities along the detachment associated with the physical properties listed above. These three classes corresponded well with the tuning effects at 48 Hz from the spectral decomposition. For example, black dashed lines in Figure 4 represent areas that correspond in lateral changes between the two attribute. These zones may affect the competency of the surface due possibly to overpressure zones, changes in facies, or changes in the thickness of the wedge. Attributes associated with the east-vergent fault demonstrate thinner beds as seen in the increased tuning affect from Figure 4 of the spectral decomposition. Similar patterns are in general agreement with thrust faults that propagate to the east along the seismic data.

DISCUSSION

The Wyoming salient of the Cordilleran overthrust belt is a curved fold-and-thrust belt with varying thrust-fault geometries and magnitudes of horizontal shortening and vertical displacement (Figure 2) along strike. Macedo and Marshak (1999) describe several factors that influence salient geometry. According to these authors, factors that govern the along-strike variability of fold-and-thrust belts are: type of salient, variations in pre-deformational sedimentary thickness, indenter shape, convergence direction, and variations in strength of the strata that host the detachment. Detachment-controlled thrusts (such as the faults seen in the Big Piney La Barge field) typically occur above a glide horizon whose strength varies laterally along strike (Macedo and Marshak, 1999). Davis and Engelder (1985) showed how the detachment horizon can influence the geometry of a fold-and-thrust belt and that a weak basal detachment underlying a thrust fault does not necessarily favor a dominant vergence. Therefore, forethrusts and backthrusts may be equally possible. Other conditions to consider for backthrust development are boundary conditions (limiting factors that control the distribution of fault slip within finite models), material strength and layering, fault strength, and overburden or surface pressure against the fault due to the overlying stratigraphy (Erickson, 1995). Finite-element models have been used to study conditions that favor backthrust development in triangle zones. For example, Erickson (1995) concluded that a foreland buttress, which is analogous to a pin line between the cover and footwall of a balanced cross section, is essential for backthrust displacement. Foreland buttressing in our study area could correspond to a stratigraphic pinchout or strong sedimentary cover in the foreland. Other causes of varying thrust fault geometries are presented by Allerton (1998): differing geometries, or shape, of the fault and fold, variations or curved axial traces of folds (due to refolding), refolding and deviation of regional trends may all be results of thrust-sheet rotations. Thus, the effect of along-strike changes in vergence may be significantly influenced by rotational effects.

Two distinct fault geometries (frontal ramp and wedge) are represented by the set of dual verging thrust faults presented in this paper (Figure 2). The southern, east-verging thrust fault has a frontal ramp geometry that coincides well with the overall direction of strain and vergence from the exposed thrust faults in the Cordilleran thrust belt located immediately to the west. As the direction of vergence changes to the north, a backthrust develops, approximately along strike, by wedge faulting (referring to a wedge of allochtonous material propagating toward the foreland (MacKay et al. 1996)) due to its wedge-like shape termed a triangle zone (Figure 6). Some confusion exists in the literature surrounding thrust fault triangle terminology. MacKay et al. (1996) gives an introduction to triangle zones and tectonic wedges that clarifies the terminology and demonstrates the importance of studying these frontal thrust geometries. A unique definition of a triangle zone is difficult to find in literature because of the variability in triangle zone thrust geometries (Barnes and Nicol, 2004). Triangle zone models have been developed by various authors to mean: tectonic wedges inserted between opposite vergent thrusts that are linked (Banks and Warburton, 1986, Lawton et al., 1994), a basal detachment with opposite vergent thrusts (Couzens et al., 2003) and zones, triangular in shape, between thick- and thin-skinned thrusts that are independent and dual-vergent (Zapata and Allmendinger, 1996). Our definition follows closest to that proposed by Couzens et al., (2003) of a basal detachment with opposite vergent thrusts.

Whether thrust faults propagate independently or if their growth history is linked by mechanical processes or timing of emplacement is difficult to interpret from the seismic data alone due to the complexities described above. However, it can be useful to describe the boundaries between faults and define any overlap or linkages between faults. Similar dual-vergent thrusts that switch vergence along strike and link to form continuous folds have been studied in the Niger Delta and are referred to as "antithetic fault linkages" (Higgins et al., 2007). The study by Higgins et al. (2007) involved classifying the various fault-fold relationships that can occur along strike as faults grow laterally and overlap (Figure 7). Thrusts in this study link together in a similar manner to a Type 1 antithetic linkage (Figure 7) and unlike the classification proposed by Higgins et al. (2007), the fold associated with the thrusts is not continuous through the transfer zone (Figure 6). Our structure map (Figure 5A) indicates that each fold is a direct result of its adjacent fault and that the growth of each fault-anticline are completely independent of the dual vergence (no deformation within the transfer zone). Thus, any overlap (lateral growth) of the dual vergent faults would be coincidental. In Figure 5C, we see the lateral growth of the west-vergent fault to the south becomes connected with a backthrust of the east-vergent fault.

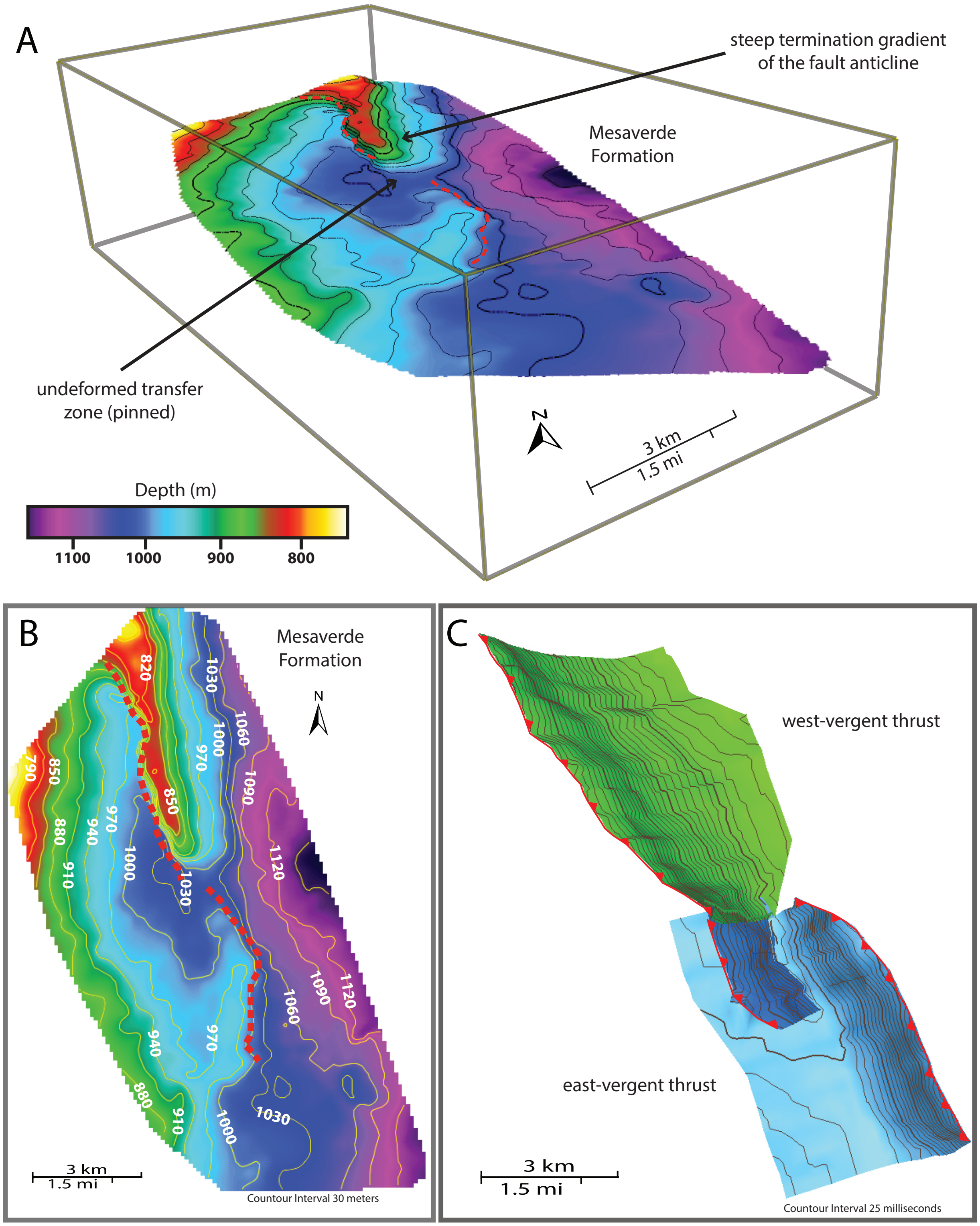

Figure 5: Profiles and 3D views of the anticline associated with the west-vergent thrust. A) Depth contoured structural map of the Mesaverde Formation. B) Angled view of the Mesaverde Formation showing the steep gradient at the fault tip. C) 3D view of the thrust fault and an outline to show the abrupt termination and steep gradient taper of the fault tip. The small portion to the left of the main fault links to the main thrust, but there is no associated anticline and only minor offsets.

The anticline associated with the west-vergent fault is the best evidence for pinning within the transfer zone. The relief on the southern end of the anticline quickly reduces to zero, resulting in a steep termination gradient, as it approaches the transfer zone (Figure 5B-C).

The northern west-vergent anticline in this study is of particular interest due to its steep lateral gradient and abrupt termination near the transfer zone (Figure 5). The continuation of the fault to the north is undefined as it extends outside the limits of the seismic data, but as the fault terminates southward against the transfer zone, the lateral displacement on the fold anticline quickly reduces to zero. This steep gradient is inconsistent with the idea of faults gradually

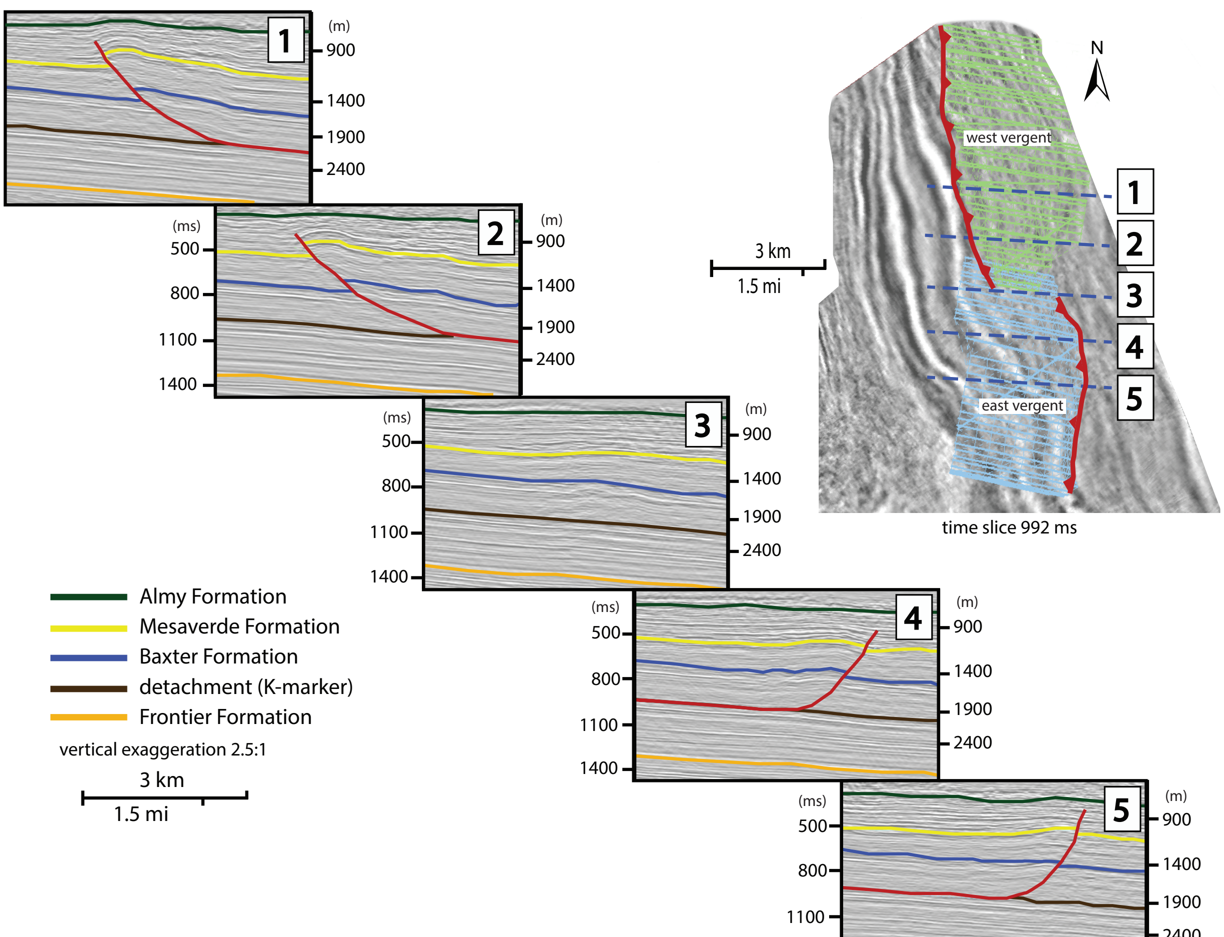

Figure 6: Along strike profiles of dual verging thrust faults. Profiles 1 and 2 are the wedge geometry of the west vergent thrust and profiles 4 and 5 are a frontal ramp geometry of the foreland propagated, east vergent thrust. Profile 3 represents the transfer zone where there is little disruption from either fault.

tapering along strike until the gradient is reduced to zero at the fault tip. Such a steep gradient would indicate that the displacement is being taken up by adjacent structures within the foreland and the transfer zone is acting to pin and limit the extent of the fault tip. Armstrong and Bartley (1993) suggest that faults propagation initiates quickly with very little slip until they reach a location that impedes further expansion. This idea is consistent with other studies that suggest faults become pinned when only small displacement has occurred and structures near the fault tip become further deformed by differential growth along the fault surface (Julian and Wiltschko

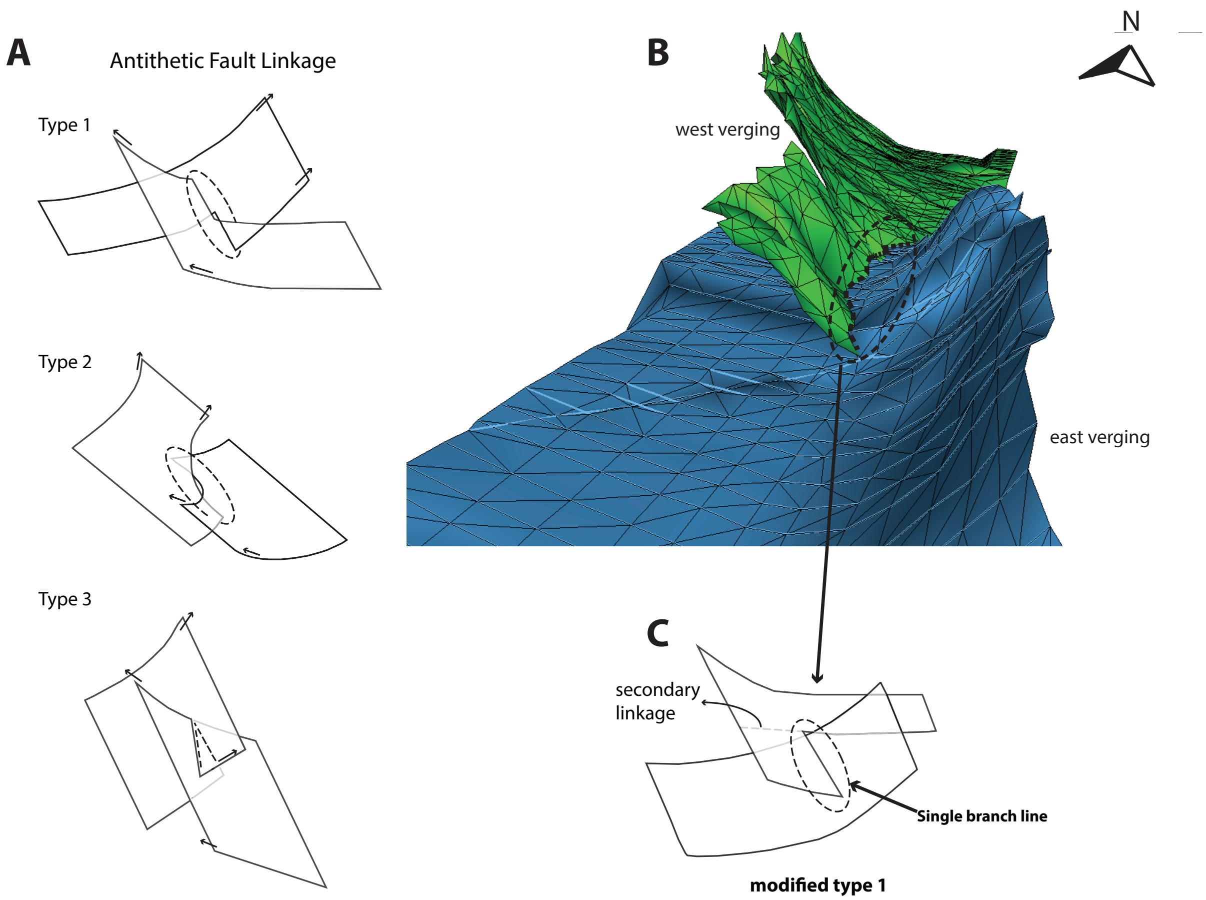

Figure 7: Antithetic thrust fault linkage. A) Antithetic fault linkage classification as defined by Higgins et al. (2007). B) Wireframe model of dual verging faults (see Figure 1 for location). C) Modified Type 1 antithetic fault linkage. Type 1 linkage shows both verging faults overlapping and a structural high in the transfer that links each anticline of the opposite verging faults. Faults in the study area only overlap in a type 1 linkage as the branch line from the west-vergent thrust fault (north) overlaps and terminates against the east-vergent thrust fault (south) and no structural high associated in the transfer zone.

1983; Fischer et al., 1989). As a result, faulting must precede folding and the pinning may be due to a change in facies and competency within the rock (Armstrong and Bartley, 1993).

Antithetic fault linkages, as described by Higgins et al. (2007), were proposed to form as dual vergent faults (Figure 7) developed along strike as a result of folding. This model requires that folding precede faulting and that each thrust fault grew laterally until faults overlapped with a low lateral gradient. For our study, we observe an antithetic fault linkage similar to a Type 1 linkage, but the displacement in the hanging wall of the east-vergent fault is small and no folding has occurred (Figure 7).

CONCLUSION

Thrust faults in the subsurface of the Big Piney LaBarge field switch vergence along strike resulting in two opposing thrust geometries. The northern west-vergent thrust is a wedge thrust and forms a triangle zone between its upper thrust plane and the lower detachment along the K-Marker bed. Thrusts to the south have a frontal ramp geometry and are consistent with the overall thrusts of the Cordilleran overthrust belt to the west. We interpret the Big Piney field thrust faults to be a result of unaccommodated displacement left over from the Hogsback thrust. Mechanically it became easier to transfer displacement further east to the foreland rather than continue displacement on the Hogsback thrust.

Lateral gradients of the faulted anticlines are steep near the transfer zone, where displacement is likely accommodated by other structures (e.g. faults, folds, and fractures); however, no major structure can be mapped in the transfer zone and accommodating structures may be present outside the seismic survey area. The transfer zone shows only small anticlinal expressions. Other structure may be present are not seismically imageable due to its complexity.

Balanced cross sections (Figure 2) demonstrate that east and west-vergent faults differs in their magnitudes of shortening along strike and that the vertical offset is different for each fault. Forward modeling defined the vertical extent of the fault tip, based on fault prediction and trishear methodology, in such a way that the overlying Almy and Wasatch formations are only slightly deformed by the fault propagation. The west-vergent backthrust anticline has a steep lateral gradient and suggests that pinning occurs in the transfer zone, and impeding ability of the underlying fault to propagate laterally. Anticlines are a result of fault propagation. Further growth of the anticlines continued after the initial slip of the fault.

Why do these thrusts switch vergence along strike? This question continues to be the subject of studies of fold and thrust belts around the world. Our study suggests the following as possible keys to understanding what affects the direction of vergence: Lateral change in detachment competency, pinning of the thrust sheet distally in the foreland or by local pinning within the transfer zone, and vertical axis rotation of the thrust sheet due to local curvature of the overthrust belt. While each of these components or a combination of them may influence the change in vergence, the direction of propagating thrusts in the foreland of an overthrust belt appears not to be dominated by a particular preferred direction of vergence and it is equally probable to propagate thrusts into the foreland or toward the hinterland.

This study exemplifies the complexity of propagating thrusts into a foreland basin; effects of discontinuities on thrust variability; use of integrated methods (seismic interpretation, restoration modeling, seismic attribute analysis, etc.) to understand the complexity of contractional deformation in foreland basin margins where high-quality 3D data are available.

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