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3D Seismic Mapping of Probable Tripolitic Chert Bodies in Osage County, Oklahoma

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3D Seismic Mapping of Probable Tripolitic Chert Bodies in Osage County, Oklahoma

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A thesis submitted in partial
fulfillment of the requirements for the degree of
Master of Science in Geology

by

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The University of Texas at Dallas
Bachelor of Science in Geoscience, 2011

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ABSTRACT

The Mississippi Lime play is an important recent oil and gas development in the mid-continent of the United States. In April of 2007, Chesapeake Energy Corporation used horizontal drilling and multistage fracing to bring the Howell 1-33H well online. This well revitalized the Mississippi Lime play, expanding exploration with potential Mississippian reservoirs.

The Mississippian section is a complex carbonate reservoir containing several distinct lithologies. An important Mississippian lithology known from outcrops in Arkansas and Missouri is tripolitic chert, or tripolite; a bleached, highly diagenetically altered, silica rock with high porosity, low density, and high permeability. Tripolite is an important reservoir target with the broader Mississippi dense lime play, but should not be confused with Mississippi Chat reservoirs found in Kansas or Oklahoma which commonly are described as cherty paleosols, chert breccia or conglomerates. Acoustic impedance of tripolite is quite low, leading to a characteristic strong negative amplitude anomaly in 3D seismic data (i.e., a lithology bright spot).

This study presents techniques and results for seismic mapping of probable tripolite occurrences in the Wild Creek 3D seismic survey of Osage County, Oklahoma. Resolution estimates are also presented, along with preliminary reflection coefficient calculations indicating observed amplitude anomalies represent tripolite embedded in dense Mississippian limestone, a stratigraphic relationship in agreement with recent outcrop observations.

ACKNOWLEDGEMENTS

I would like to thank my committee: Dr. Christopher Liner, Dr. Matt Covington, and Mr. Steve Millagan for all their edits and support. I would like to mention Dr. Van Brahana, Dr. Walt Manger, Dr. Ralph Davis, and Dr. Doy Zachry for their excellent support as well. I would also like to thank my family Dad, Mom, and especially my sister Krista for always giving great advice: I would not be here today without them. Additionally, I would like to thank my friends and peers for a great two years! It certainly has been a ride.

I would like to sincerely express my appreciation to the Osage Nation Minerals Council for access to data on tribal lands.

This thesis is a product of the Multiscale Arkansas Unconventionals Project (MArkUP) established in 2012 and directed by Professor Christopher Liner.

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1. INTRODUCTION

The Mississippi Lime play is an important recent oil and gas development in the mid-continent of the United States. It covers thirty million acres across north and northeastern Oklahoma, central to west Kansas, and southern Nebraska. Historically, the Mississippi Lime has produced over 278 million bbl of oil and 2.4 tcf of natural gas in south-central Kansas (Wantey et al., 2001) and 105 million bbl and 1 tcf of gas in Oklahoma (Rogers, 2001), as well as production from Pennsylvanian sandstone deposits (Sands, 1927) and Arbuckle Group reservoirs (Elebiju et al., 2001). In April of 2007, Chesapeake Energy Corporation used horizontal drilling and multistate fracing to bring the Howell 1-33H well online, producing initially 441 bbl/day and 55 mdfd. This well revitalized the Mississippi Lime play, expanding exploration within potential Mississippian dense lime, and tripolite reservoirs from south Kansas and north central Oklahoma. The cost of drilling a well in the Mississippi Lime play is low due to shallow target depths (3,000 to 6,000 feet) resulting in a typical well cost of 3-3.5 million (Cross et al., 2014; Evans and Newell, 2013).

Mississippian rocks outcrop in four states: Oklahoma, Arkansas, Missouri, and Kansas. The bulk of outcrops occur in northwest Arkansas, with Missouri second, and then Oklahoma third. There are minor Mississippian outcrops in far southeast Kansas.

Unfortunately, the stratigraphic zonation and nomenclature of the Mississippian is not agreed upon, resulting in three different stratigraphic columns (Figure 1). Kansas surface nomenclature is omitted from this study. This stratigraphic naming variability is an indication of how heterogeneous the Mississippian can be over short distances.

In my study, the uppermost Mississippian is often termed “chat,” but the term “chat” is a misnomer and is not a formally recognized geologic term (Mazzullo and Wilhite, 2010b). It only has meaning locally within the mid-continent as early drillers described how the drill rig would chatter while drilling through the zone containing large chert fragments. Watney et al. (2001) defines chat as “... an informal name for high porosity, low resistivity producing chert reservoirs in the mid-continent.”

Another type of Mississippian chert reservoir is tripolite: a lightweight, very porous, siliceous rock that has a white, almost chalky appearance (Pettijohn, 1975; Mazzullo and Wilhite, 2010a and 2010b; Manger and Evans, 2014). It is porous enough that a sizeable piece can stick on the tongue and not fall off. Tripolite has been termed ‘cotton rock’ (McKnight and Fischer, 1970) and is a lithology distinct from the informal chat.

Chat typically resides below the Mississippian-Pennsylvanian unconformity and consists of a paleosol or brecciated chert that developed as the Mississippian was exposed to weathering before Pennsylvanian time (Rogers, 2001). Tripolite does not fit this depositional model as it seems unrelated to exposure, it is most likely a limestone diagenetically altered by leeching via groundwaters or aquifers (Manger, 2014).

The tripolite is important as an excellent reservoir target within the broader Mississippi dense lime play. Current models propose horizontal drilling of multiple tripolite targets to maximize productivity (Dowdell, et al., 2012). Due to tripolite’s low density and velocity, it has a significant impedance contrast with encasing rock which shows in 3D seismic data as a strong amplitude anomaly. Unlike the fluid (gas) bright spots of the Gulf of Mexico, tripolite forms a lithology bright spot against the otherwise dense Mississippian limestone. This study will map and quantify these tripolite bright spots using the Wild Creek 3D seismic data, located in southwest Osage County, Oklahoma (Figure 2).

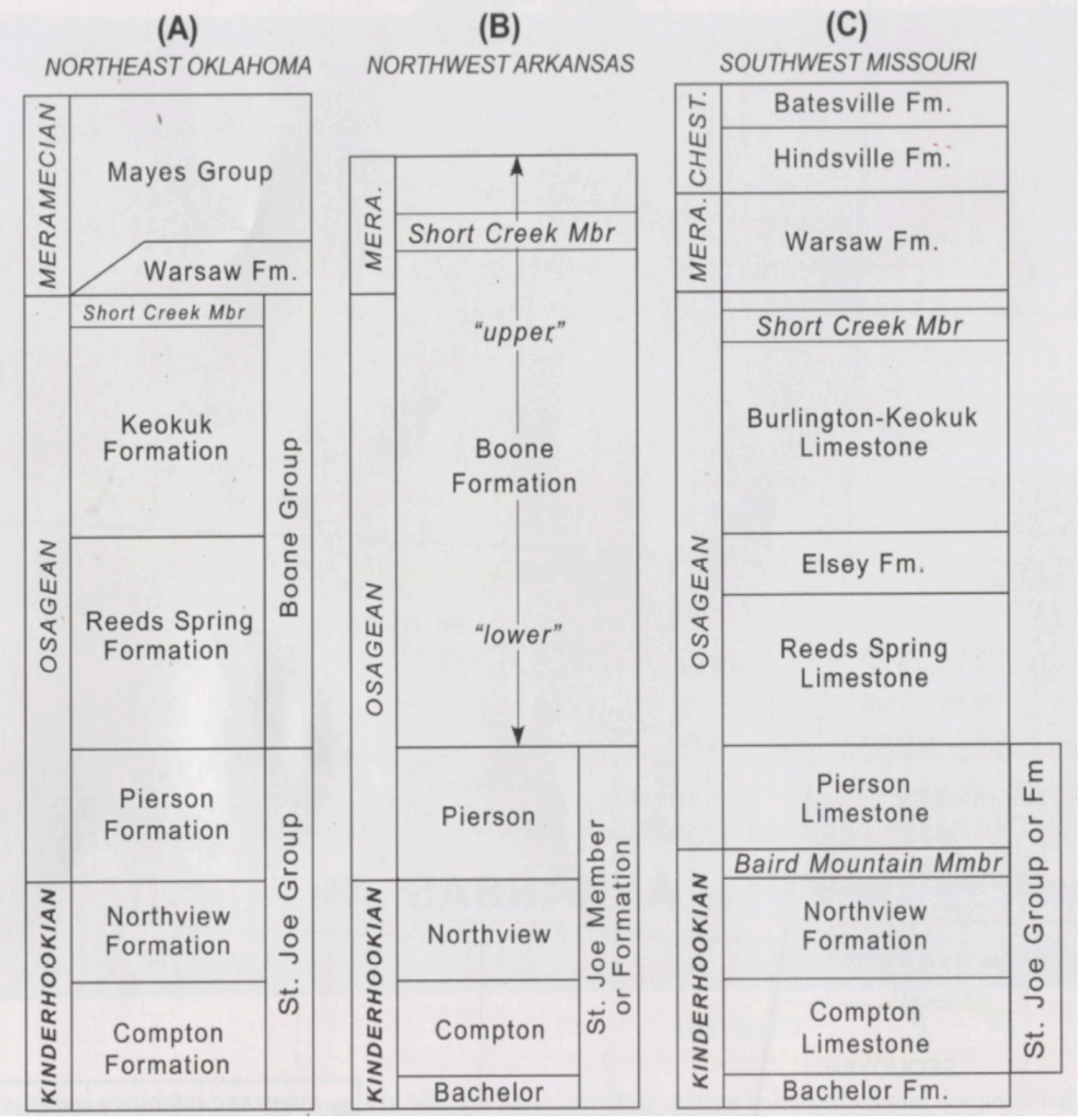


Figure 1: Three stratigraphic columns from the tri-state area (Mazzullo et al., 2013).

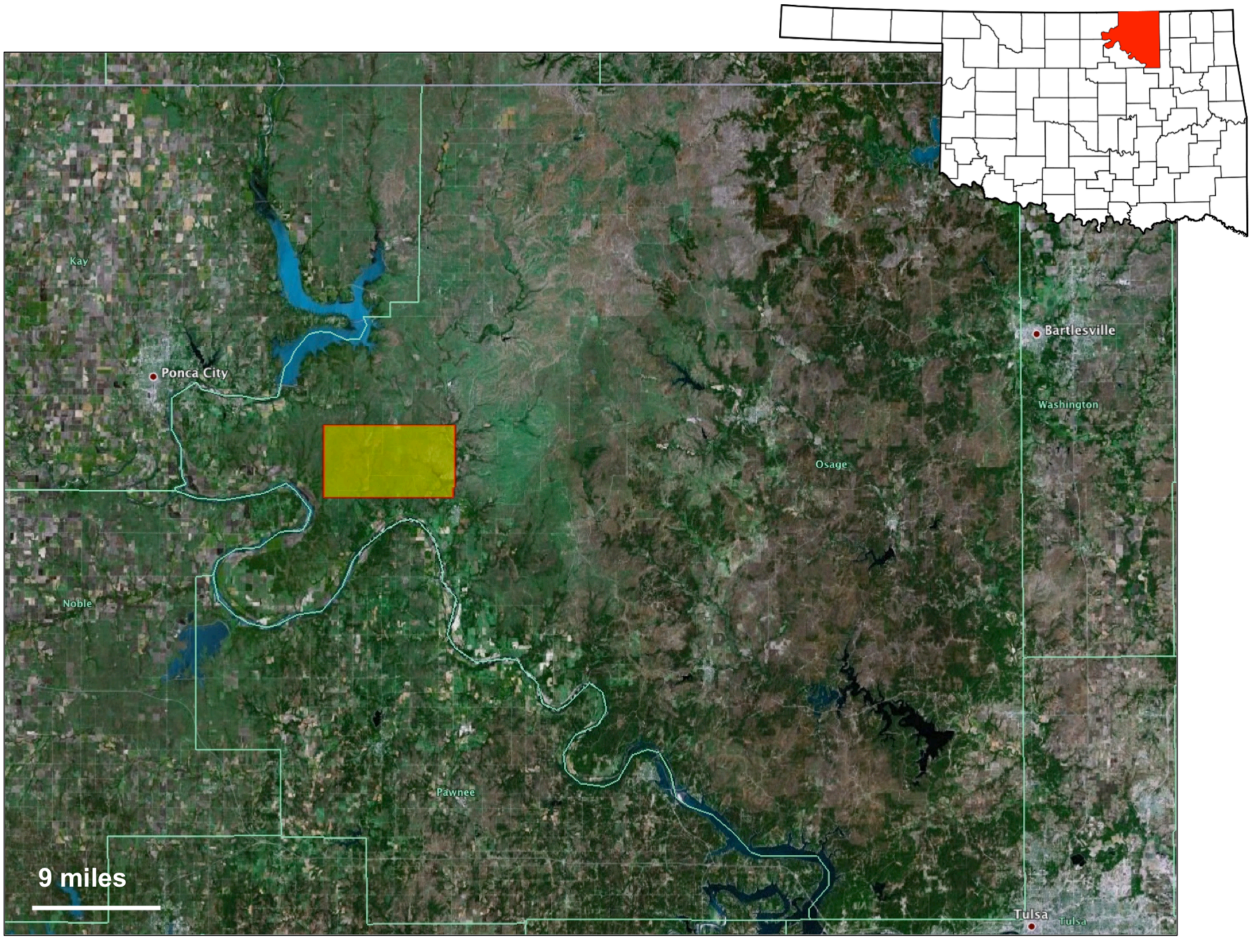


Figure 2: Osage County with the Wild Creek 3D seismic survey highlighted.

1.1 Study Area

The study data consists of the Wild Creek 3D seismic survey acquired and processed by Chevron in the mid 1990s. It has an area of 44.89 square miles in Osage County, Oklahoma in the township 25N R4E, with a bin size of 66 x 66 feet, 287280 migrated seismic traces, nominal CMP fold of 70, and 2 seconds of data at 2 ms time sample rate. The traces have a frequency of 15-100 Hz, with a dominant frequency of 57.5 Hz (Figure 3). Wild Creek is located in the eastern part of the Mississippi Lime play and east of the Nemaha Ridge and there was no synthetic available.

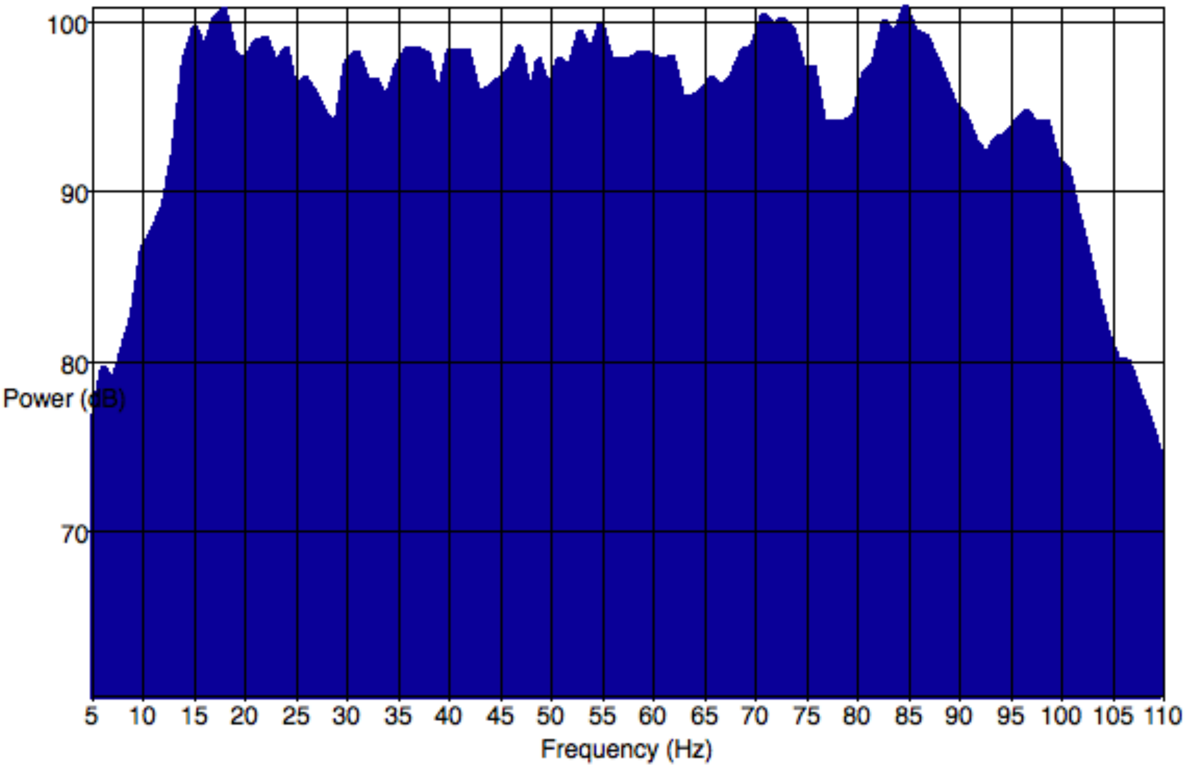


Figure 3: Histogram frequency spectrumct values, generated by OpendTect, taken from Inline 3800 of the Wild Creek 3D survey.

1.2 Previous Investigations

The Mississippian in the mid-continental United States has been studied in Arkansas for over 100 years since the identification of the Boone Formation by J.C Branner (1891). The Boone contains significant chert that workers have been trying to explain since the early part of the century.

Bass et al. (1942) conducted a detailed investigation of the stratigraphy, structure, and oil resources of Osage County for the USGS

In-depth analysis of the Mississippian was conducted by the US geological Survey in Pitcher County, northeast Oklahoma (McKnight and Fischer, 1970). This report provides an in depth study of the hydrothermally invaded Mississippian containing heavy minerals, such as zinc and lead, and has proved invaluable to all proceeding investigations of the Mississippian for its stratigraphic, petrologic, and diagenetic analysis.

Montgomery (1998) highlights that most chat fields in Kansas were discovered in the early half of the century and that new depositional models conclude that oil entrapment within the chat is stratigraphic and not structurally controlled.

Thomasson et al. (1989) investigated the chat using seismic data and well logs associated with active chat fields. He demonstrated that two studied chat fields had different seismic responses and different cap rocks. One field is a collapse breccia chat reservoir capped by porous dolomite. The higher velocity dolomite caused a peak reflection between basal Pennsylvanian and Mississippian chat. The second field is a collapse breccia chat reservoir directly at the Miss-Penn unconformity with Pennsylvanian shale acting as cap rock. With no dolomite between the two units, no peak reflection developed.

Dowdell et al. (2012) used seismic attributes, such as impedance inversion and coherence and curvature, to map tripolitic, high porosity sweet spots.

Rogers (2001) conducted an investigation of Mississippian chat reservoirs in north-central Oklahoma and created a depositional and diagenetic model for chat deposits. She concluded that uplift and erosion controlled where silica replaced limestone in the Upper Boone and that porous chat deposits are found most often as weathering products on the flanks of structural highs. Additionally, she drew heavily on the accepted view in Kansas that the source for the chert in the Upper Boone is sponge spicules.

Manger et al. (2002) investigated the regolith sitting on top of the upper Boone formation and found "…composite grains of platy minerals that resemble, and presumably represent, volcanic ash." Niem, (1977) concludes that the source of volcanic ash came from the south or southeast during Mississippian time and alludes to a volcanic arc behind the Ouachitas as a possible source.

Manger and Evans (2014) have created a yet unpublished field guide to northwestern Arkansas on the Mississippian's depositional history, stratigraphy, and structure.

Other investigations conducted on tripolite include Tarr (1938), which gave a definition of tripolite. More recent investigations by Mazzullo et al. (2010a and 2013) focused on the stratigraphic zonation of the tripolite and Mazzullo and Wilhite (2010b) differentiates between chert, tripolite, and chat. The tripolite, and chert in the Mississippian in general, has seen a renewed interest with University of Arkansas theses by Whitman (2013), Minor (2013), Johnson (2014), Cahill (2014), Kremin (2011), Freisenhahn (2011), and Jennings (2014).

1.3 Statement of Purpose

The Mississippi ‘chat’ is an informal drillers term used to describe a unit with a high amount of chert. As early drillers went through the formation, chert would tap on the drill pipe causing the pipe to ‘chat’ or chatter. In northeast Oklahoma, the term is commonly used to describe cherty paleosols, chert breccia or conglomerates, and tripolite. One goal of this paper is to distinguish tripolite separate from the generic ‘chat’ designation.

Although tripolite has long been known in outcrop, there has been little attention given to recognition and mapping in 3D seismic. Two previous studies have used seismic data to investigate the Miss/Penn unconformity and associated rock facies. Thomasson et al. (1989) used 2D seismic to investigate two chat fields in Kansas and Dowdell et al. (2012) emphasized 3D seismic attributes. The current work differs from Thamsson et al (1989) in using 3D seismic data and focusing on probable tripolite response; and differs from Dowdell et al. (2012) in the application of traditional horizon tracking and geobody extraction, rather than seismic attribute analysis, as well as focusing on tripolite. The current study presents techniques for 3D seismic mapping of the tripolite. This will provide information on the morphology and orientation of the tripolite, which may assist with further interpretation in 3D seismic volumes, develop more accurate diagenetic models, and aid outcrop studies.

Additionally, to characterize the Mississippian-Pennsylvanian unconformity, this paper presents reflection and resolution data of the tripolite within a 3D seismic survey using neutron density logs and sonic velocity logs.

2. STRATIGRAPHY

2.1 Stratigraphy of Osage County, Oklahoma

This paper uses a general stratigraphic column for Osage County, Oklahoma adapted from Arkansas surface exposures (Liner, Zachry, and Manger, 2013) (Figure 4). The Precambrian base in Osage County, Oklahoma is at least 540 million years old (Bass et al., 1942). Above the Precambrian are the Cambrian Reagan Sandstone and the lower Arbuckle and Simpson of Cambro-Ordovician age overlain by the Chattanooga Shale of Devonian and Mississippian age. The Mississippian section consists of Kinderhookian, the Osagean, the Meramecian, and the Chester series. Overlaying the Chesterian series are Pennsylvanian age rocks of Desmonian and Missourian age. Within these series are numerous subdivisions of Groups and Formations further subdivided into numerous members. The total thickness of the Paleozoic section in Osage County above the Precambrian varies from 2,000 feet over basement highs in the southeast to 5,000 feet in the west (Bass et al., 1942; Reeves, 1995)

The Precambrian basement of Osage County is composed of igneous and/or metamorphic rocks that occur at depths beginning at 2,200 feet below surface to 4,600 feet at the deepest. The shallowest occurs on domes in (T20N, R12E) that have considerable topography; some locations have Precambrian occurring 40 feet below the Mississippian (Bass et al., 1942).

The Reagan Sandstone was deposited on the Precambrian by a late Cambrian transgressive sea. It is interpreted to be a fine granitic wash of the basement and can be either quartzose, arkosic, or feldspathic with a range between fine to coarse grained (Thorman and Hibpshman, 1979; Newell et al., 1987). The average Reagan thickness is 40 feet (Newell et al., 1987; Goebel, 1968) and in some areas can be an oil producer.

The Arbuckle Group is up to 700 feet thick and composed of light gray to white vuggy, sometimes cherty, limestone and dolomite (Newell et al., 1987). Interbedded between the carbonates are thin beds of sandstones and greenish shale (Bass et al., 1942). In some locations the Arbuckle forms the unconformable contact with the Precambrian basement (Elebiju et al., 2011) and it is difficult to distinguish Ordovician from Cambrian Arbuckle. The Arbuckle is an oil-producing zone in some localities.

The Simpson Group was deposited by a regression in the Middle Ordovician (Elebiju et al., 2011) and is dominated by sandstones, a number of shales, and a few carbonates (Newell et al., 1987). The Simpson is split into three members, which are the Burgen Sandstone, the Tyner (a combination of shales and sandstones), and the Fite Limestone (Bass et al., 1942). Simpson sandstones are light gray, quartz rich, fine to medium grained, and subrounded to subangular with few rounded grains. The sandstones are oil producers in southern Kansas (Newell et al., 1987) and are stratigraphically equivalent to the St. Peter Sandstone in Arkansas (Ireland, 1965). The thickness of the Simpson ranges from 100 to 140 feet (Bass et al., 1942).

The Viola Limestone and Sylvan Shale are Upper Ordovician formations that show oil but are not major oil producers (Newell et al., 1987). The Sylvan Shale is known as the Maquoketa in Kansas. The Viola is a cherty fine to coarse-grained limestone/dolomite and the Sylvan Shale is a nondescript gray-green shale (Newell et al., 1987).

The Chattanooga Shale is part Devonian and part Mississippian in age. It is a black, deepwater, fissile organic shale that serves as a marker bed to distinguish the Ordovician limestones below with the Mississippian limestones above (Bass et al., 1942). The Chattanooga (also known as the Woodford Shale) is a major oil and gas producer, occurs irregularly with thicknesses between zero and 75 feet (Thorman and Hibpshman, 1987), and contains small nodules and disks of pyrite that are interpreted to be plant spores (Bass et al., 1942). At the base of the Devonian Chattanooga is the Misener Sandstone that resulted from seas transgressing from the east and reworking the Simpson sandstones; maximum thickness is 20 feet (Thorman and Hibpshman, 1979).

During Mississippian time a shallow sea covered much of Oklahoma resulting in deposition of the Kinderhookian and Osagean series. The formations that belong to these series are collectively called the Mississippi Lime for their thick, dense limestone successions up to 400 feet thick. The St. Joe member (upper Kinderhookian and lower Osagean) is a succession of hard coarse-grained crinoidal limestone that formed on a paleo-shelf, is no more than a few tens of feet thick, relatively chert-free, and is light gray to nearly white with a greenish tinge (McKnight and Fischer, 1970). One of the most distinguishing characteristics between the St. Joe and the overlaying Boone is how the formation weathers. Commonly, the St. Joe weathers back into parallel niches giving the formation in outcrop the appearance of individual slabs.

The Osagean Boone Formation is characterized by a succession of cherty limestone up to 300 feet thick that formed on a paleo-shelf. The top of the Boone is an unconformable surface to overlaying Pennsylvanian sediments. Multiple types of chert occur within the Boone. The Boone is an increasingly important reservoir in the mid-continent (Whittman, 2013). The dense lime itself can be a reservoir with tripolite acting as sweet spots within the formation. The Boone is the stratigraphic unit of focus for this paper. The Meramecian and Chesterian, which overlay the Osagean series elsewhere in Oklahoma and Kansas are absent due to erosion in Osage County.

The Pennsylvanian unconformably overlies the Upper Mississippian Boone Formation and is divided into two series: the older Desmonian and younger Missourian (which forms the surface in Osage County). The Desmonian is divided between the lower Cherokee and upper Marmaton Group and forms productive reservoirs in the mid-continent (Newell et al., 1987). The Missourian is split into the older Skiatook and younger Ochelata (which is at the surface). In Pennsylvanian time Osage County was part of a stable shelf system sloping towards the Arkoma Basin with seas transgressing and regressing (Thorman and Hibpshman, 1979; Clinton, 1957).

The Cherokee is a succession of numerous sandstones and limestones. It is divided into the Burgess Sandstone, Bartlesville Sandstone, Inola Limestone, Red Fork or Burbank Sandstone, Pink Limestone, Skinner Sandstone, Verdigris Limestone, and the Prue Sandstone. Oil producing units from the Cherokee are the Bartlesville, Burbank, Skinner, and the Prue (Clinton, 1957; Bass et al., 1942).

The Marmaton forms the Upper Desmoines and has four members: the Oswego Limestone, the Labette Shale, the Big Lime, and the lower Cleveland Sandstone. The Oswego and Big Lime are thin units no more than 50 to 70 feet thick with the Big Lime as a minor oil producer (Bass et al., 1942). The Labette is a "... silty shale with thin limestones and sandstones" (Bennison, 1972). In Kansas, the shales are gray to yellow and sandy (Jewett et al., 1968). The Cleveland Sandstone is partially in the Marmaton but will be described in the Skiatook.

The Skiatook is the basal Missourian formation and is composed of the Cleveland, Upper Cleveland, Checkerboard Limestone, Layton Sandstone, and Hogshooter Limestone. The Cleveland is 200 feet thick oil producer and the Layton is a minor shaley sandstone producer (Bass et al., 1942). The Hogshooter is a massive crinoidal limestone with maximum thickness of 50 feet (Schweitzer, 2009).

The Ochelata is the shallowest formation of the Pennsylvanian and forms the surface in Osage County. Its divisions include the basal Cottage Grove, the Osage Layton Sandstone, the Avant Limestone, the Perry Gas Sandstone, and the Okesa Sandstone.

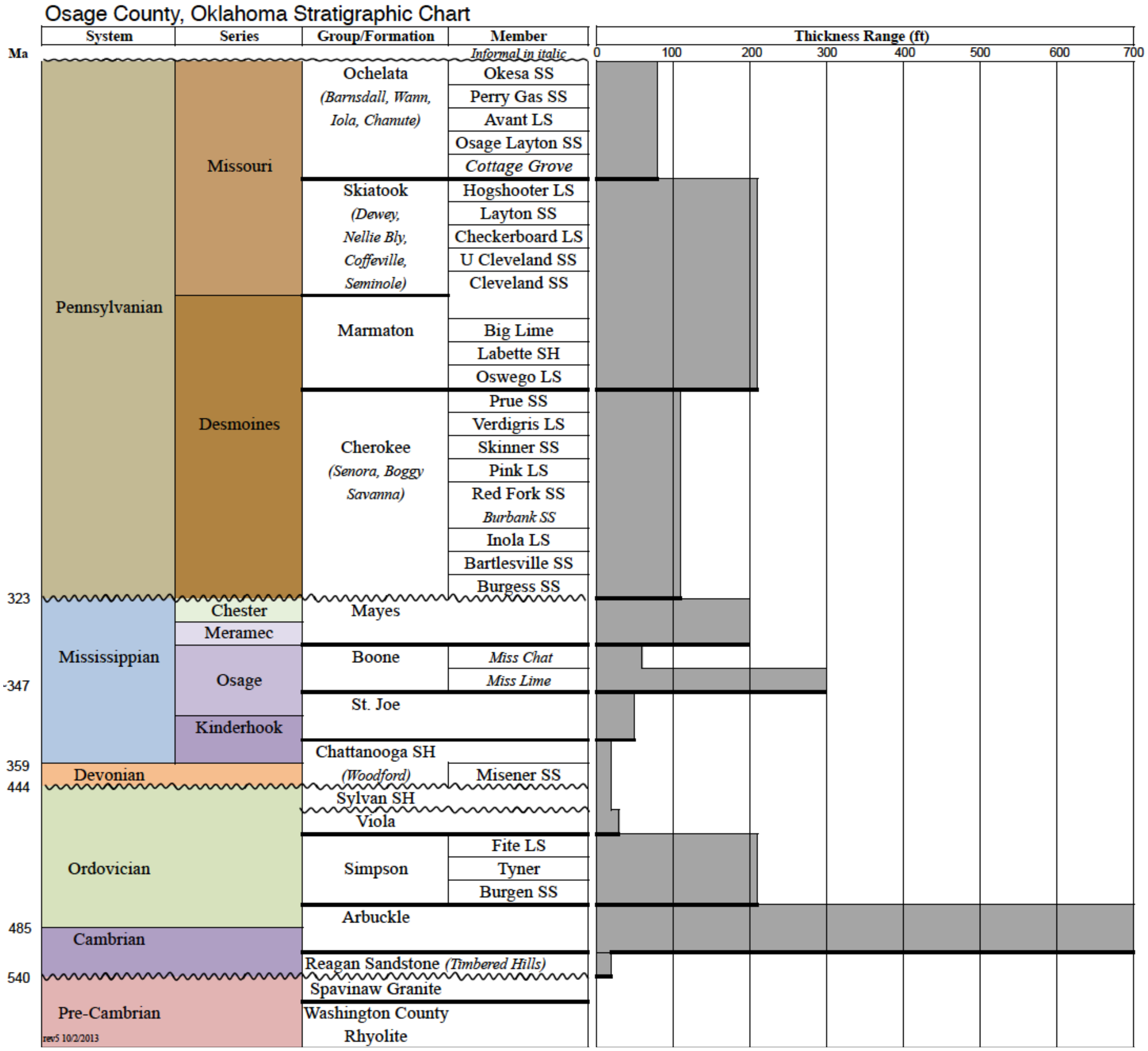


Figure 4: Stratigraphic column adapted from Arkansas surface exposures to Osage County, Oklahoma (Liner, Zachry and Manger, 2013)

2.2 The Mississippian and the Boone

The Mississippian is broken down into further subdivisions in Figure 5 as proposed by Mazzullo et al. (2013).

The St. Joe Limestone underlies the Boone and is a condensed limestone (Figure 6) containing very little to no chert. The contact between the St. Joe and the Boone is unconformable and represents a regression to transgressive contact. Additionally, when examined closely, the limestones of the St. Joe are divided by thin beds of terrigenous units (Shelby, 1986). The units in ascending order are the Bachelor, Compton (Figure 7), Northview, and Pierson (Manger and Evans, 2014) (Figure 8). The Bachelor is usually a thin gray shale and the Northview is a calcareous siltstone or shaley siltstone (Whittman, 2013). The Bachelor and Northview are most likely absent in Osage County.

The Boone Formation is the oldest designation for the Osagean section and is split into Upper and Lower Boone. It has been interpreted as a regression of a third order eustatic cycle (Minor, 2013), part of the "…Kaskaskia II second order super sequence…" (Whittman, 2013) (Figure 9). The Lower Boone is equivalent with the Reeds Spring Formation in Missouri and represents the maximum flooding interval when seas were at their peak (Manger, 2014).

The maximum flooding interval is composed of nodular or bedded penecontemporaneous chert which is described by Manger (2014) as being "… black to dark grey, vitreous luster, compaction phenomena/disruption of bedding, shrinkage fractures, lack of macrofossils, low carbonate content" (Figure 10). Penecontemporaneous chert was formed out of seawater solution syndepositionally, perhaps as a gel, with the limestone (Twenhofel, 1932; Minor, 2013). The Upper Boone Formation is equivalent to the Elsey and Burlington-Keokuk Formations in Missouri (Mazzullo et al, 2013; Manger and Evans, 2014) (Figure 1). It is characterized by later diagenetic chert, likely a result of groundwater invasion, that has replaced the lime-mud matrix of the carbonates along bedding planes (Minor 2013) (Figure 11). This diagenetic chert appears to favor high carbonate limestones that are commonly finer grained and fossiliferous (Manger, 2014).

There is a transition zone between the black penecontemporaneous chert of the Lower Boone and the later diagenetic chert of the Upper Boone. This transition zone is comprised of white, nodular chert (Manger, 2014). An important point to make is that much of the Boone Formation did not form in place; they were sourced from the carbonate shelves to the north and northeast and rolled down a ramp to be deposited in their current location (Mazzullo et al, 2009). This ramp is designated as the Burlington Shelf by Lane (1978).

The source for the abundant penecontemporaneous chert of the Lower Boone formation has been a topic of debate for almost a hundred years. Although there is a presence of silica sponge-spicules seen in the matrix of the chert, the strongest evidence points to a volcanic ash source (McKnight and Fischer, 1970; Neim, 1977; Manger et al., 2002). In early Mississippian-late Devonian time there was a prolific volcanic arc caused by a subduction zone to the south (Figure 18). These volcanoes spewed high amounts of ash into the atmosphere, landing in silica-poor seawaters, and rapidly dissolved (McKnight and Fischer, 1970).

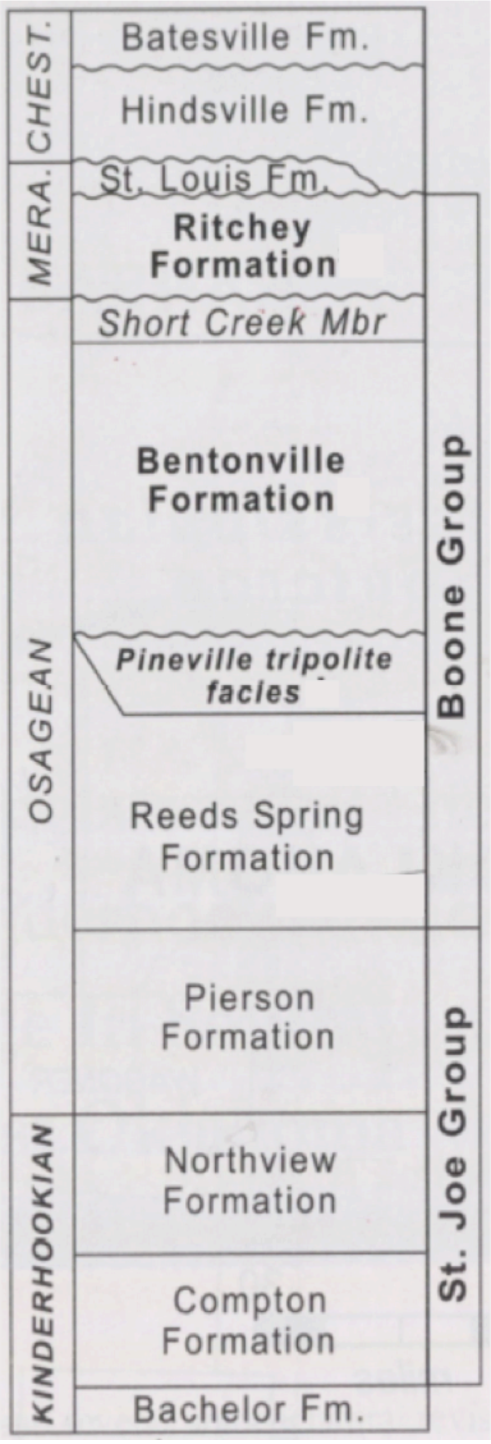


Figure 5: Stratigraphic column showing divisions of the Mississippian with the location of the tripolite (Mazzullo et al., 2013)

Figure 6: Outcrop of the St. Joe with typical weathering into slabs (photo by John Gist, 2013).

Figure 7: Outcrop of the Compton member of the St. Joe overlaying the Chattanooga (photo by John Gist, 2013).

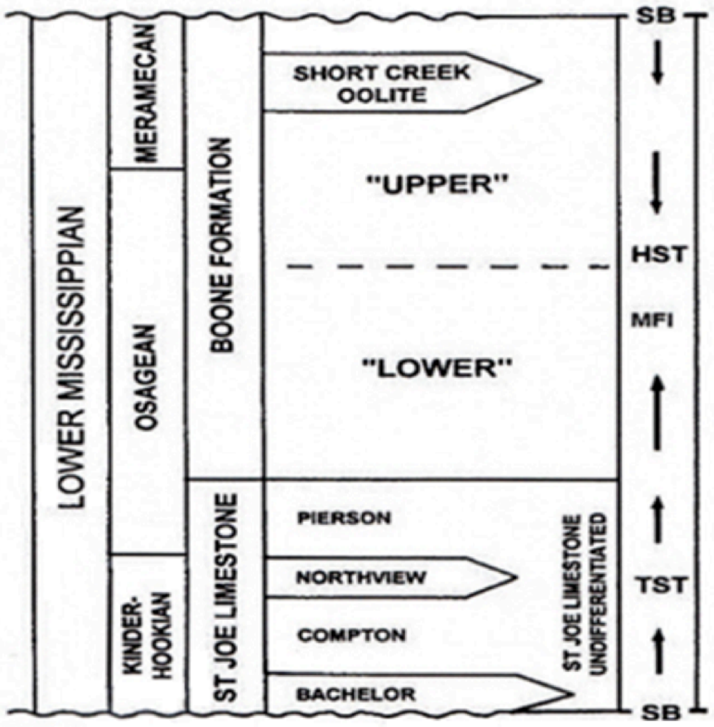


Figure 8: Stratigraphic column showing the members of the St. Joe (Manger and Evans, 2014).

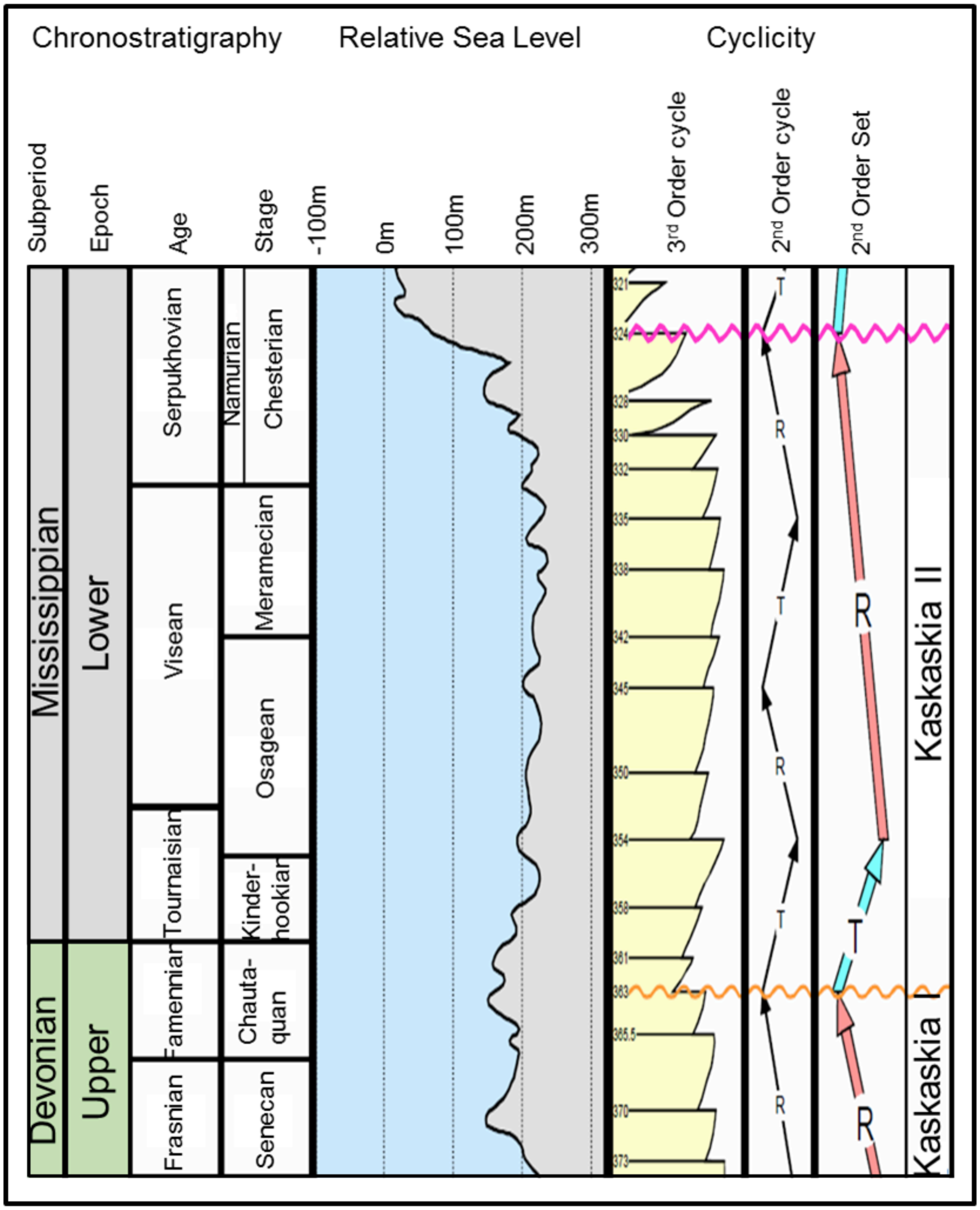


Figure 9: Late Paleozoic cyclicity (Cahill, 2014).

Figure 10: Outcrop of the Lower Boone displaying limestone (light gray) and the nodular penecontemporaneous chert (dark) (photo by John Gist, 2013).

Figure 11: Outcrop of the Upper Boone displaying limestone (light gray) the characteristic later diagenetic chert (tan color) (photo by John Gist, 2013).

2.3 Tripolite

The exact locations of tripolite in the Boone stratigraphic section are still debated. Tripolite is mostly found in basal Upper Boone and is a white to grey, red to yellow, sometimes pink, lightweight porous rock. Tripolite is reported directly above the Reeds Spring facies on highway 412, heading west out of Siloam Springs, Arkansas towards Tulsa, Oklahoma (Mazzullo et al. 2013 and 2010b; Liner personal communication, 2014). However, Manger and Evans (2014) report "… tripolitic chert is confined to the upper portion of the Boone Formation and its' equivalents – Elsey, Burlington, Keokuk of Missouri. The maximum flooding interval = Reeds Spring in Missouri and lower Boone in Arkansas, has not experienced this alteration because of the crystalline texture of the penecontemporaneous chert. Consequently, there is no tripolitic chert development… except at the immediate contact with the… Elsey = upper Boone." Furthermore, Manger (2014) states "There is not a high enough percentage of carbonate in typical Reeds Spring penecontemporaneous chert or in the transition zone to produce tripolitic chert; in the Lower Mississippian succession of the southern midcontinent, the only chert that contains enough carbonate to be leached and form tripolitic chert is found in the Upper Boone Formation…"

The high porosity of the tripolite causes a seismic amplitude anomaly due to low density and low acoustic velocity (Figure 12) and makes a potential reservoir for hydrocarbons. Following Mazzullo et al. (2013), the tripolite that is the most stratigraphically persistent throughout northwest Arkansas will be referred to as the Pinesville Tripolite. It is found sitting on the Lower Boone inside the Upper Boone sequence (Figure 13). It forms a sharp contact that at some localities can be slightly gradational. However, tripolite can be found in multiple stratigraphic positions inside the Upper Boone but typically not as thick (Figure 14).

The Pinesville is most easily interpreted as the result of an unconfined aquifer system with multiple, thinner tripolites further up-section the result of perched aquifers (Manger, 2014). In this interpretation, the Pinesville Tripolite marks the location of a paleo-water table where the vadose and phreatic zones made contact. The phreatic comprised the Lower Boone section that is dense lime, which acted as an aquitard, and the vadose zone comprised the non-tripolitic, later diagenetic chert in the Upper Boone (Manger, 2014).

The tripolite in northwest Arkansas did not just experience diagenetic decalcification, but also an invasion of silica rich hydrothermal waters that caused growth of euhedral quartz crystals in voids (Minor, 2013). It is most likely that the hydrothermal waters that are responsible for the large zinc deposits of northeast Oklahoma are the same that invaded the tripolite.

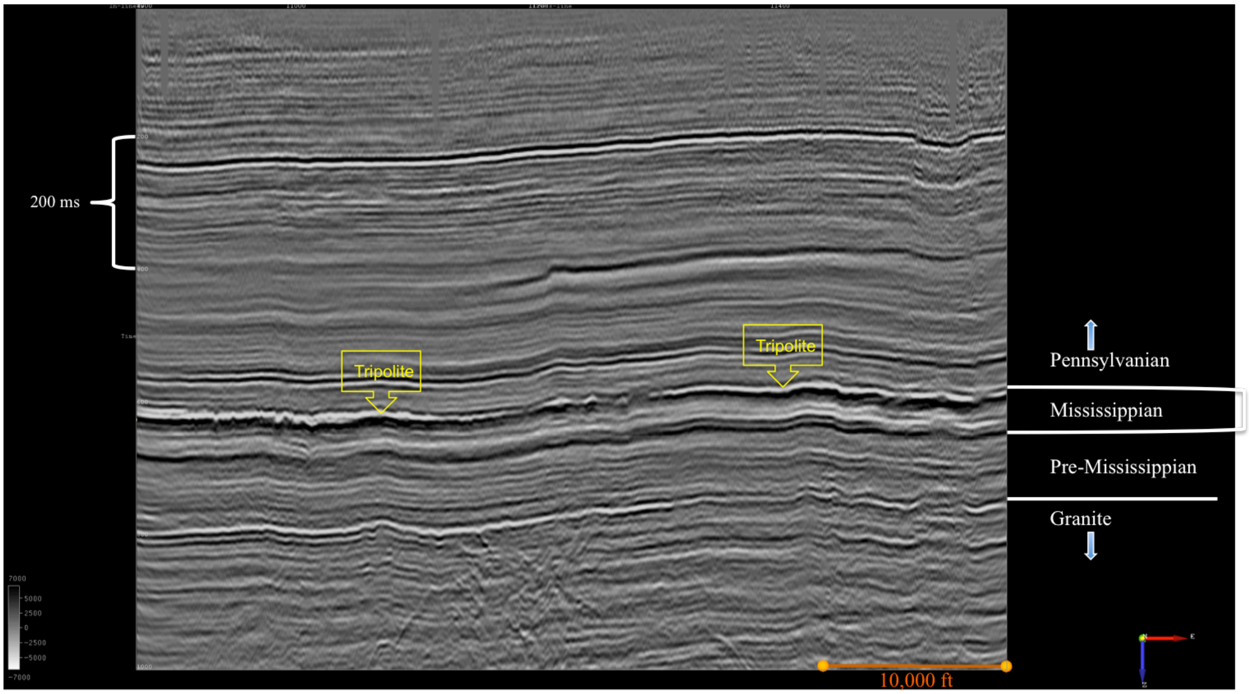


Figure 12: Representative Wild Creek east-west inline 4000 showing negative amplitude anomalies in Mississippian section. These are presumed to represent the tripolite facies. Note the irregular surface associated with the Pennsylvanian-Mississippian unconformity and ariable amplitude associated with it.

Figure 13: Outcrop of the Pinseville Tripolite overlaying the Lower Boone between Bella Vista, Arkansas and Pinesville, Missouri (photo John Gist, 2013).

Figure 14: Close up view of white tripolite in outcrop on I-540 south of Bella Vista, Arkansas (photo by John Gist, 2013).

3. TECTONIC HISTORY

In Oklahoma, most tectonic activity has occurred in the southern portion leaving northeastern Oklahoma tectonically stable. This zone of tectonic stability is called the Cherokee Platform and contains 37 counties across Missouri, Kansas, and Oklahoma including Osage County. Some major geologic provinces of Oklahoma are the Ozark Uplift, the Arkoma Basin, the Ouachita Uplift, the Arbuckle Uplift, the Wichita Uplift, the Anadarko and Ardmore Basins, the Anadarko Shelf, and the Nemaha Uplift (Figure 15). Osage County is bounded by the Ozark uplift to the east and the Nemaha uplift to the west, which divides the Anadarko Shelf from the Cherokee Platform. Structures in the Cherokee Platform are generally broad anticlines and domes, compared to larger-scale structures in the south. Other minor structures en echelon normal faults that trend northeast and both faults and folds were slowly active through Paleozoic time (Thorman and Hibpshman, 1979; Rogers, 2001).

Little literature exists on how or when the en echelon faults occurred. It is speculation that these faults are very old structures associated with the Precambrian basement. The Grenville orogeny occurred 1.1 billion years ago and was a collision between the Yavapai-Mazatzal-Superior and the Grenville Precambrian provinces (Keller, 2012). The orogenic compression trended to the northwest and could be a suitable candidate to create north-northeast trending faults suitable for reactivation (Figures 16 and 17).

Major deformation occurred in Pennsylvanian time as Oklahoma transitioned from a passive margin to an active one. This transition began in the very late Mississippian with gentle flexure in southern Oklahoma causing subsidence associated with the future Anadarko and Arkoma basins. This gentle subsidence is the precursor to Wichita, Arbuckle, and Ouachita orogenies that were soon to follow. By Late Mississippian time, the Appalachian orogeny was well underway as North America and Gondwana collided (Figure 16 and 17). The Wichita, Arbuckle, and Ouachita orogenies all started roughly at the same time and are an extension of the Appalachian orogeny as Gondwana wrapped around to southern North America.

The Wichita orogeny resulted in uplift of the Wichita Mountains in early Pennsylvanian time (Clinton, 1957). It is responsible for the formation of the foreland Anadarko and Ardmore basins, as well as the Nemaha Uplift (Johnson, 2008). The Nemaha Uplift borders the Cherokee platform and Osage County to the west.

Following the Wichita Uplift, the Ouachita orogeny created the Ouachita uplift and the foreland Arkoma Basin, as well as uplift in northwest Arkansas. Evidence suggests that this major orogenic even in the early Pennsylvanian occurred in pulses ending in the Desmoinesian and resulted in an estimated 50 miles of crustal shortening (Johnson, 2008).

The Arbuckle orogeny occurred in Pennsylvanian-Virgilian time causing significant foldings in the Ardmore and Anadarko Basins (Johnson, 2008). The Arbuckle uplift is geographically located between the Wichita and Ouachita uplift (Figure 15). The orogeny likely ended in the Virgillian and left the structure in southern Oklahoma as we see it today (Figures 19-21).

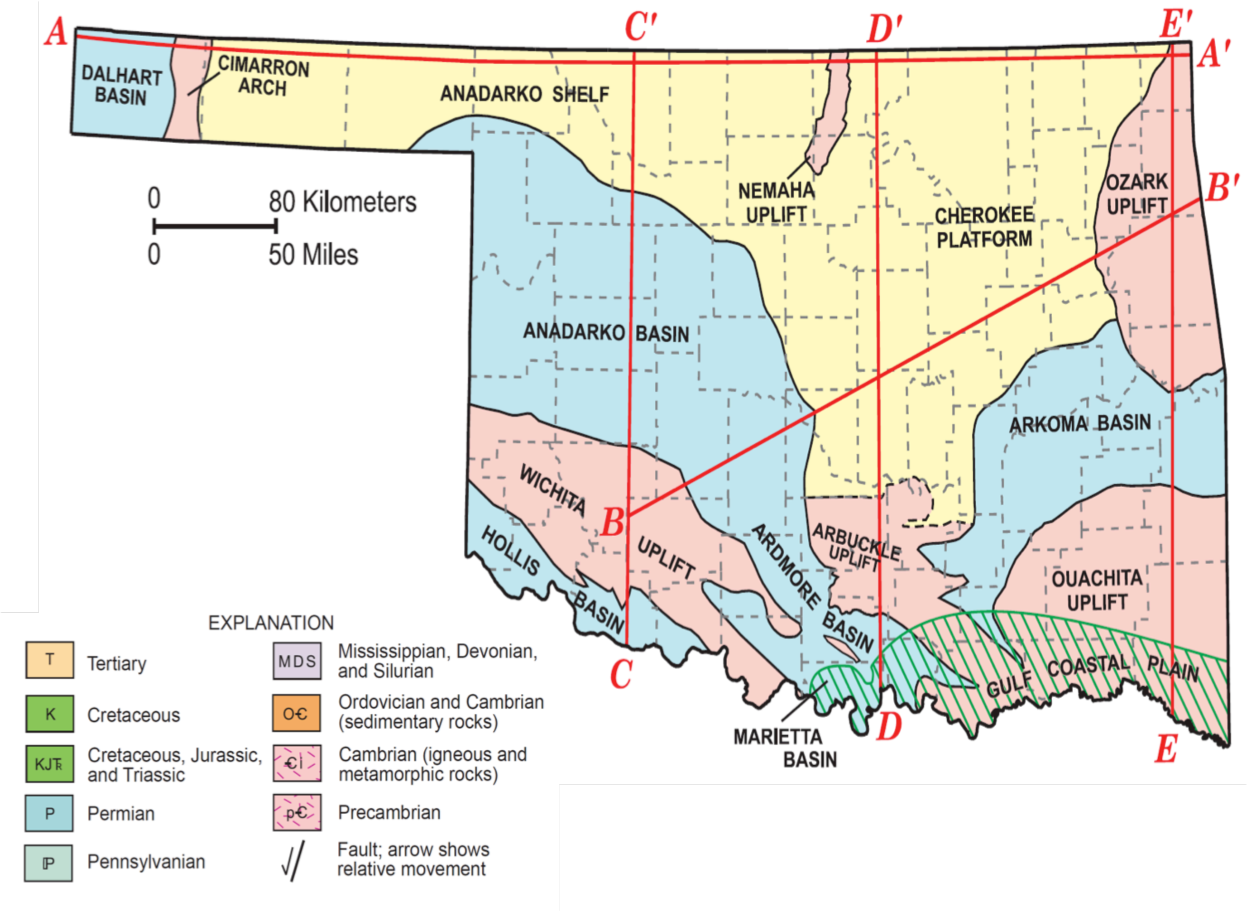


Figure 15: Map of the geological provinces of Oklahoma with cross section lines (Johnson, 2008).

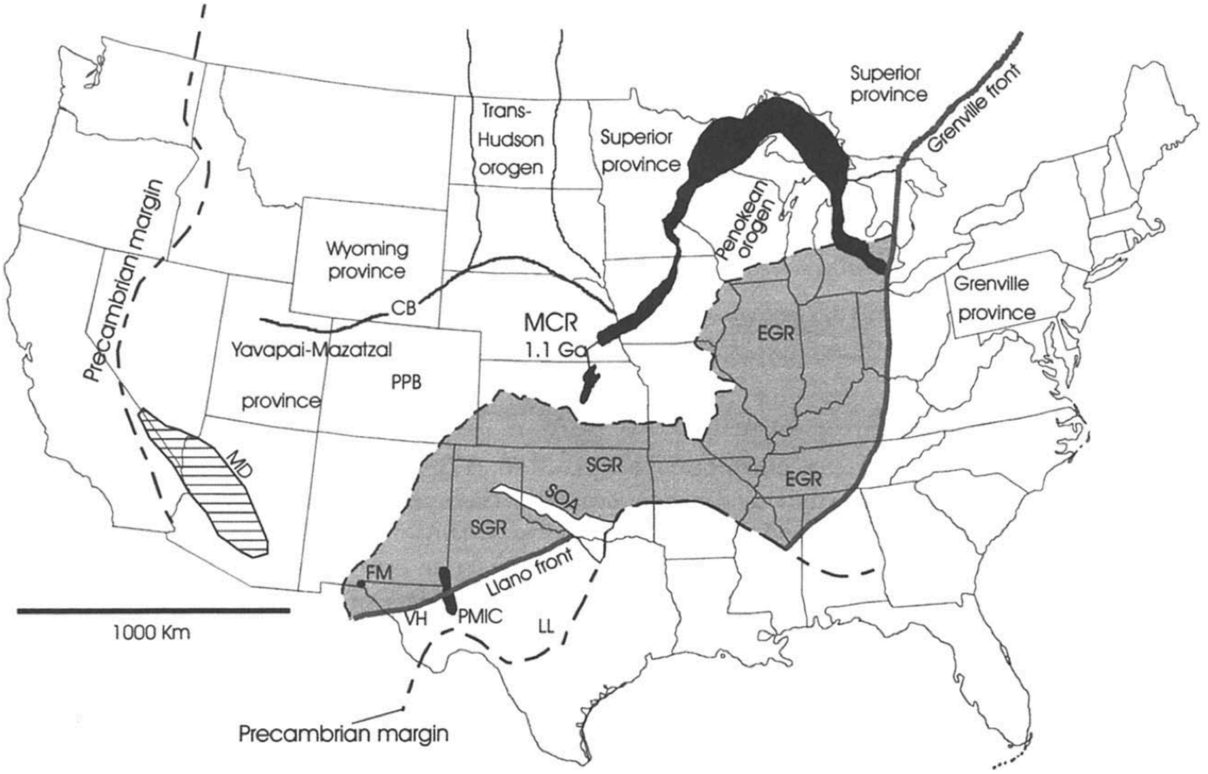


Figure 16: Precambrian geologic provinces with the Grenville, Yavaoai-Mazatzal, and Superior Provinces with the location of the Grenville Orogeny. Acronyms on the map are as follows: Pikes Peak batholith (PPB), Pecos mafic instrusive complex (PMIC), Franklin Mountains (FM), southern granite-rhyolite province (SGR), eastern granite-rhyolite province (EGR) (Barnes et al., 1999).

Figure 17: Gondwana and Laurassia collision that formed the Appalachian Mountains (KGS, 2006)

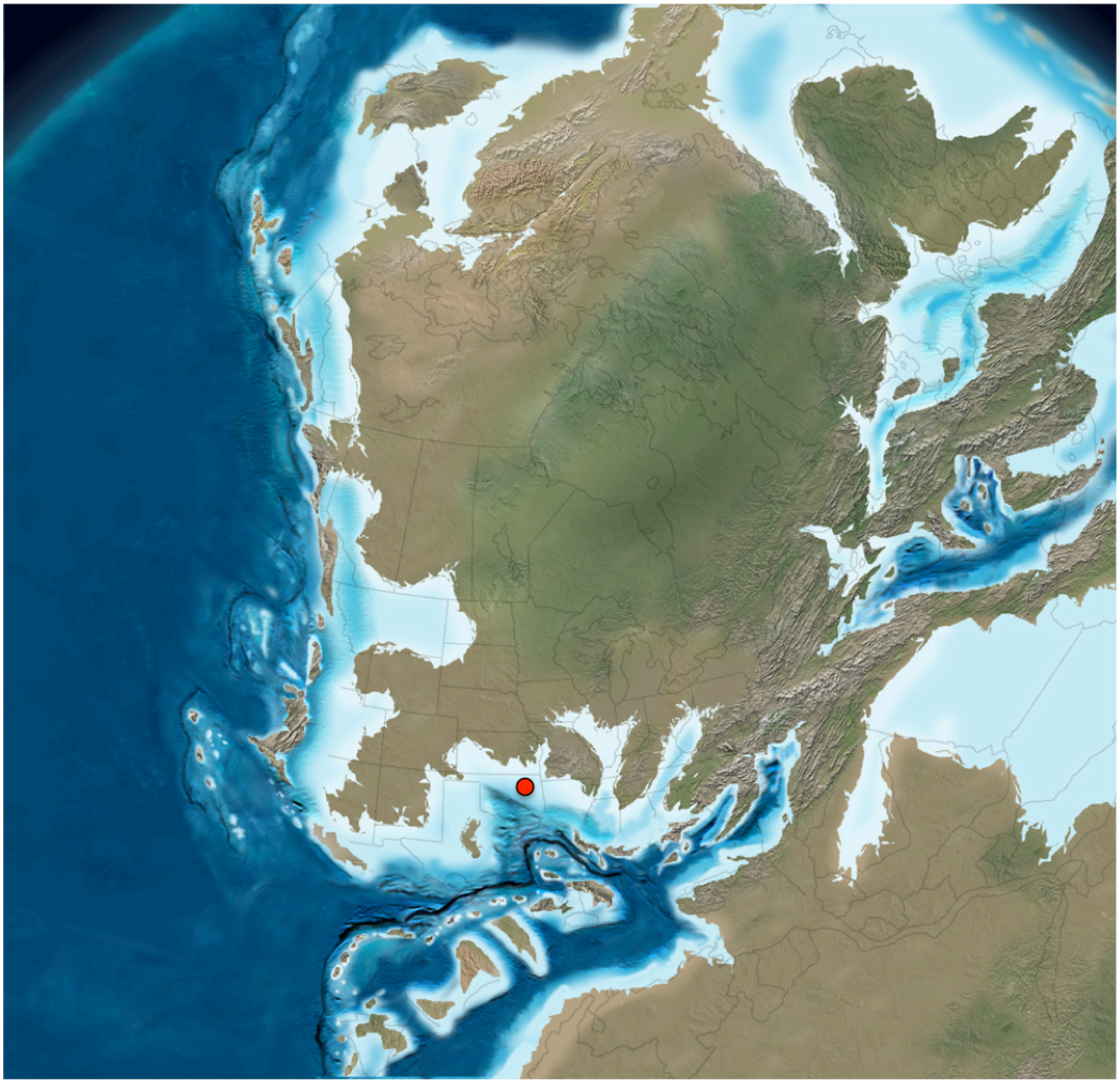


Figure 18: Paleogeography of North America during the Late Mississippian showing the trench and associated volcanic arc to the south of study area (red dot). At this time, the Ouachita, Arbuckle, and Wichita orogenies are occurring (Blakey, 2013), and the island arc is though to be the source of silica-rich ashfalls that generated chert in the Mississippian section of northeast Oklahoma.

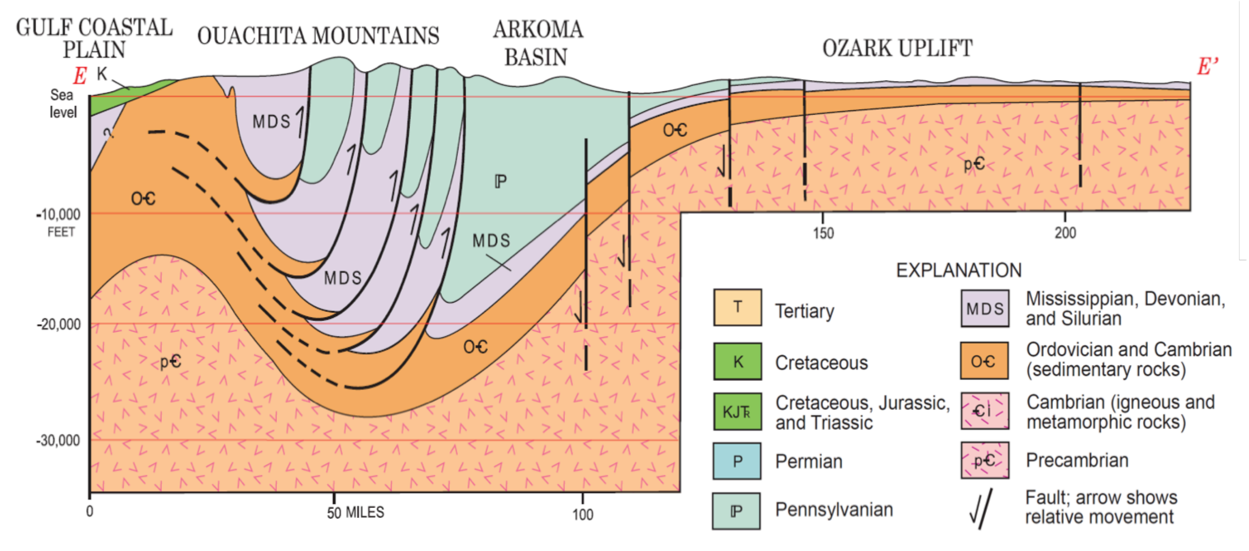


Figure 19: Cross section of Oklahoma from E to E’ of Figure 15 showing the Ouachita Uplift, Arkoma Basin, and Ozark Uplift with possible associated faults (Johnson 2008).

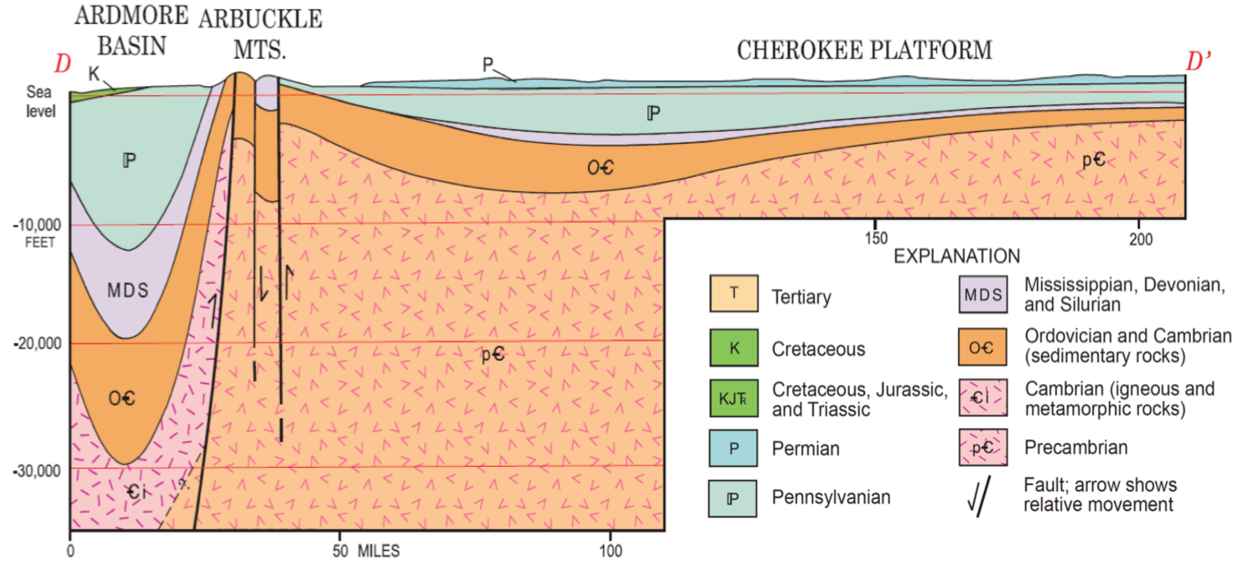


Figure 20: Cross section of Oklahoma from D to D’ of Figure 15 showing the Ardmore Basin, Arbuckle Uplift, and Cherokee Platform with possible associated faults (Johnson, 2008).

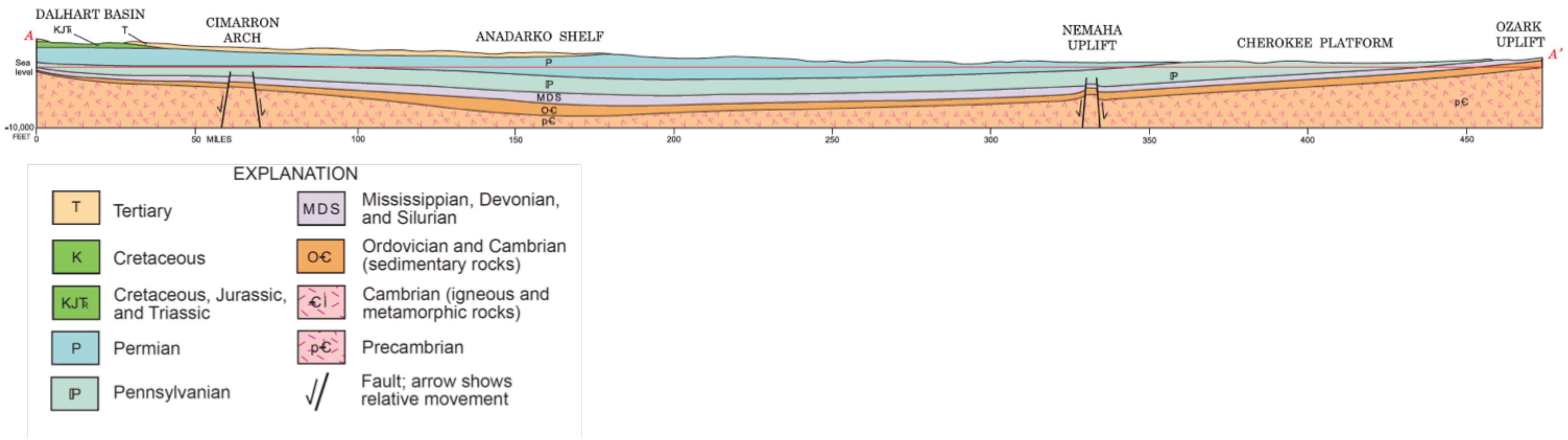


Figure 21: Cross section of Oklahoma from A to A’ of Figure 15 showing the Anadarko Shelf, Nemaha Uplift, Cherokee Platform, and Ozark Uplift among other geological provinces (Johnson, 2008)

4. METHODS

4.1 Workflow

Figure 23 illustrates a generalized workflow for the project. It begins with literature review.

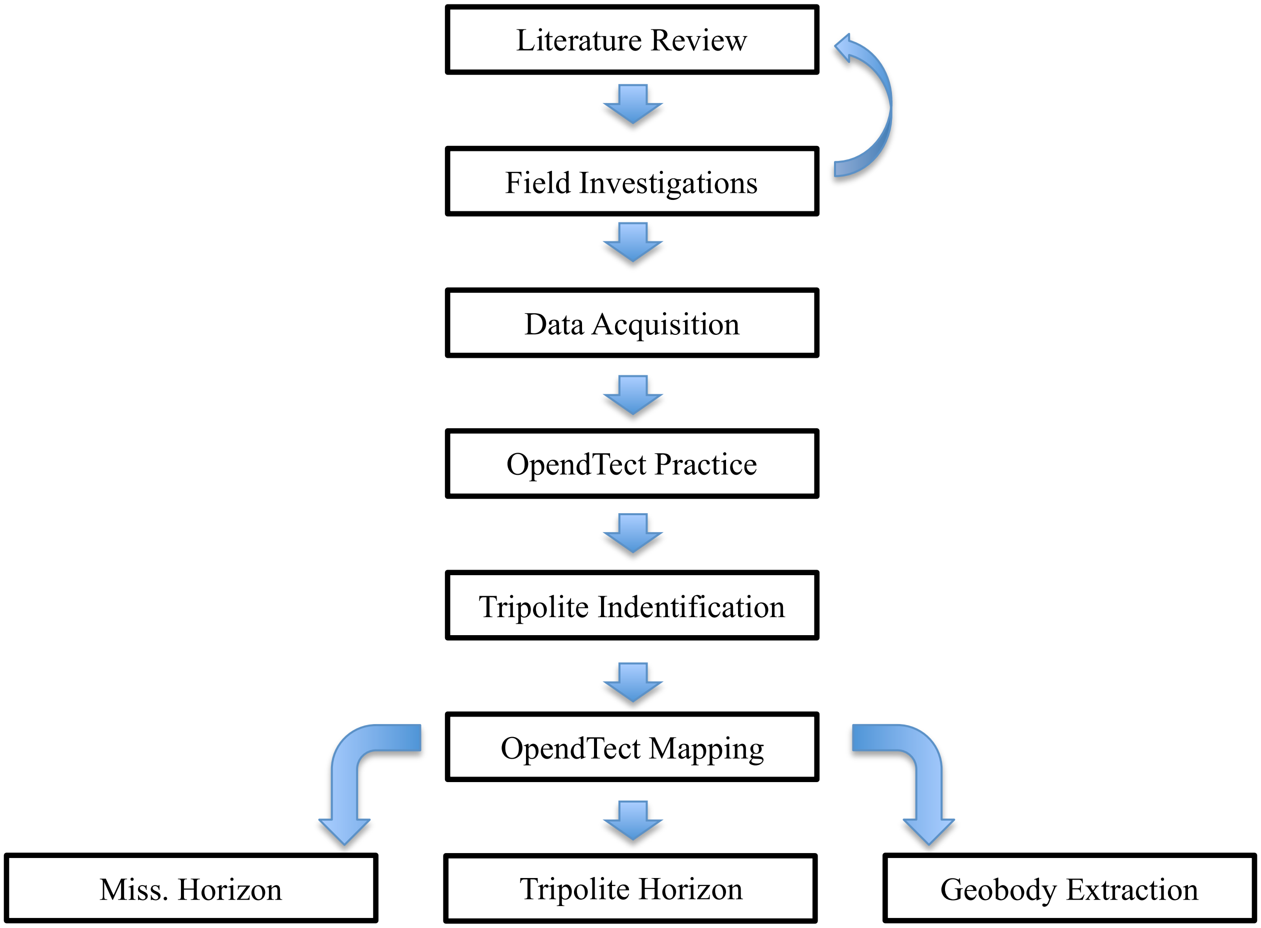


Figure 22: Work flow of the present work

4.2 Outcrop Work

Outcrop study in Arkansas was necessary understand the nature of the Mississippian with the abundance of chert. I am unaware of any other carbonate sequence in the world that is like the mid-continent Mississippian, implying special circumstances occurred leading to development of the Mississippian as we see it. By visiting outcrops, one can begin to imagine how the Mississippian behaves in 3D seismic. Figure 23 shows the scope of the outcrop work by the University of Arkansas.

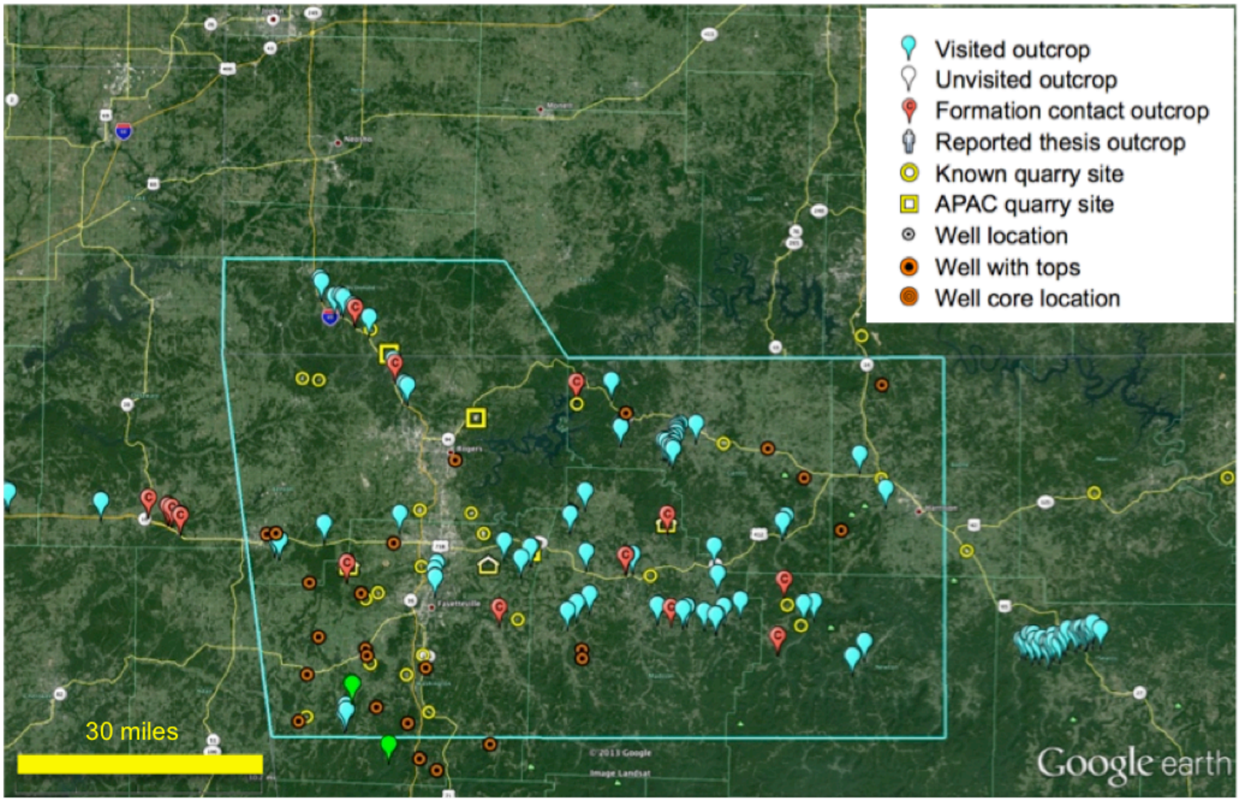


Figure 23: Study area in NW Arkansas and SW Missouri (blue outline) and outcrop sites (blue balloons).

4.3 OpendTect and Wild Creek

The Wild Creek 3D seismic survey was donated by the Osage Mineral Council. OpendTect was selected as the program of choice for interpretation because it is open source and has a quick learning curve. Figures 24 and 25 show the OpendTect user interface and example data from the Wild Creek Survey

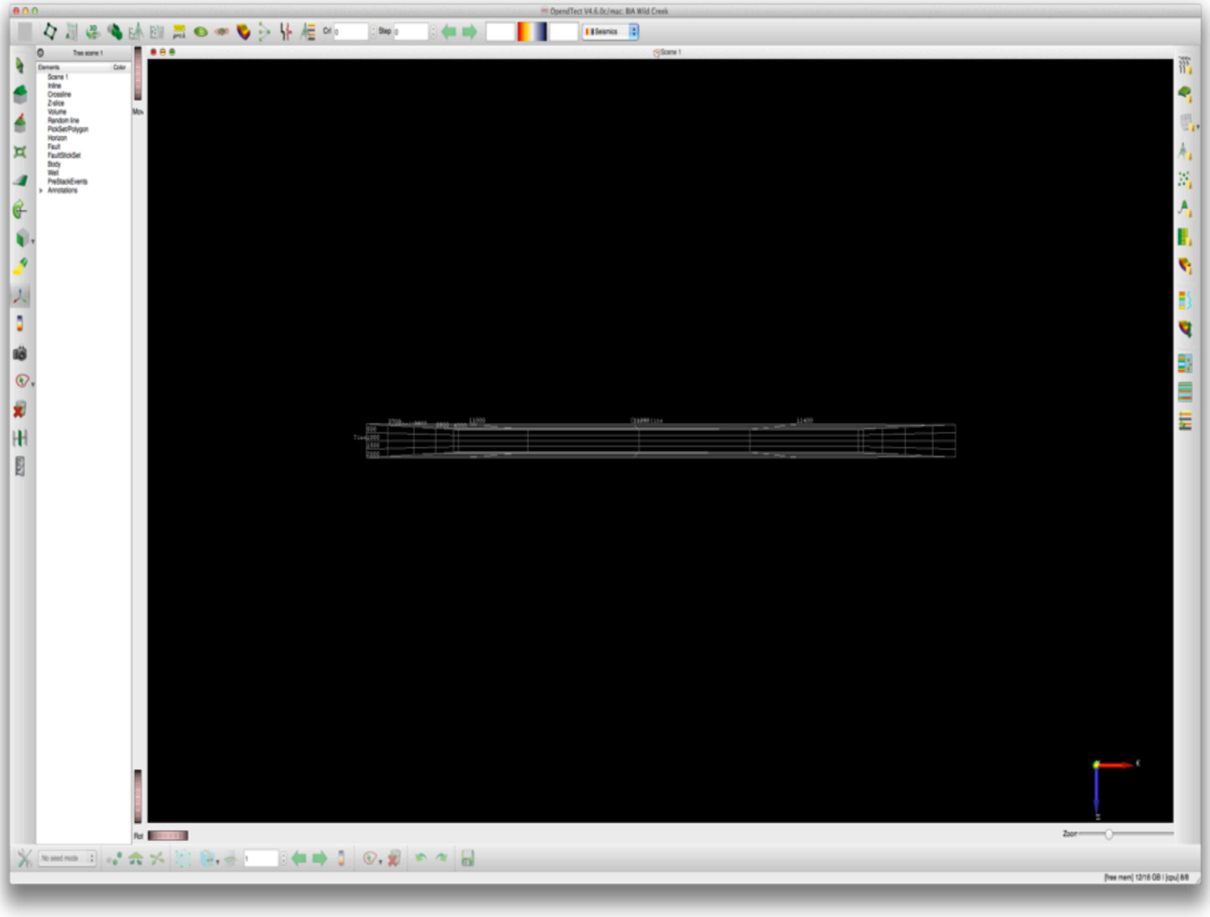


Figure 24: User interface of OpendTect on Mac OS system

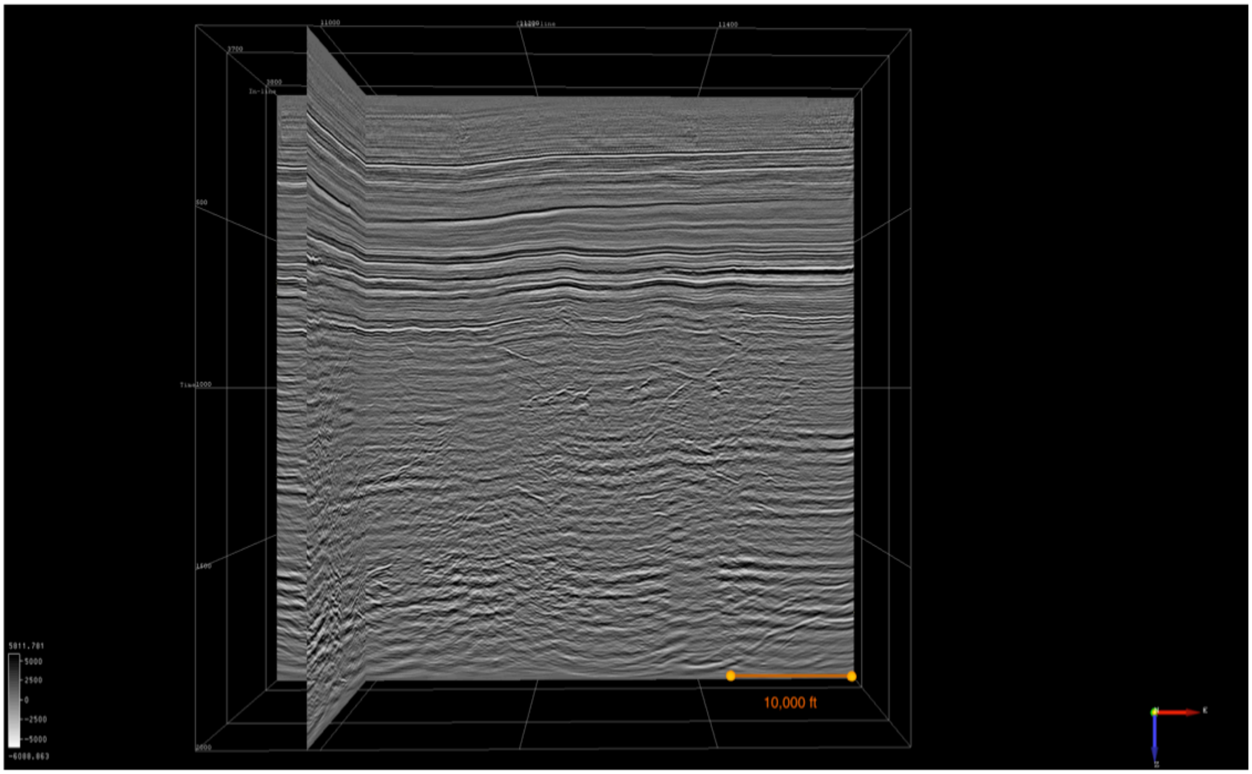


Figure 25: Wild Creek in OpendTect with a crossline and inline.

4.4 Mapping the Top of the Mississippian

Using data from Jennings (2014), it was calculated that the top of the Mississippian is roughly 630 milliseconds (3500 feet) deep. It is known that the top of the Mississippian at the unconformity is highly weathered and karsted. The karstification at the unconformity allows for visual identification as an erratic reflection event in 3D seismic data. Using this information it is possible to identify the unconformity with a high a degree of certainty (Figure 26 and 27).

At an interval of every 10 inlines, seeds were picked following the unconformity as closely as possible. It is difficult in many situations due to the irregular nature of the unconformity, so multiple updates were needed to get a satisfactory end product. Figure 28 shows the parameters that were used while picking the unconformity, and Figure 29 is a map view of all seed points picked (green dots). Using the similarity tracking parameter gives a more robust result for highly variable for the top of the Mississippian.

After going through the volume, OpendTect auto-track was used to create a horizon from the seeds. This process was accomplished in small areas by using user defined tracking box. Amplitude values were added to the horizon and then the green tracking box was moved. Figures 30 to 33 show the process of mapping the unconformity. The unconformity is extremely difficult to map in the southwest section of the survey as evident with abundant tracking busts. The structure that looks like a fault or graben also causes tracking problems resulting in a few busts. For the purposes of this paper, the process of picking seeds every 10 lines and using auto-tracking will be referred to as: the traditional method. Figure 34 shows the completed time-structure and amplitude map of the top of the Mississippian in 3D.

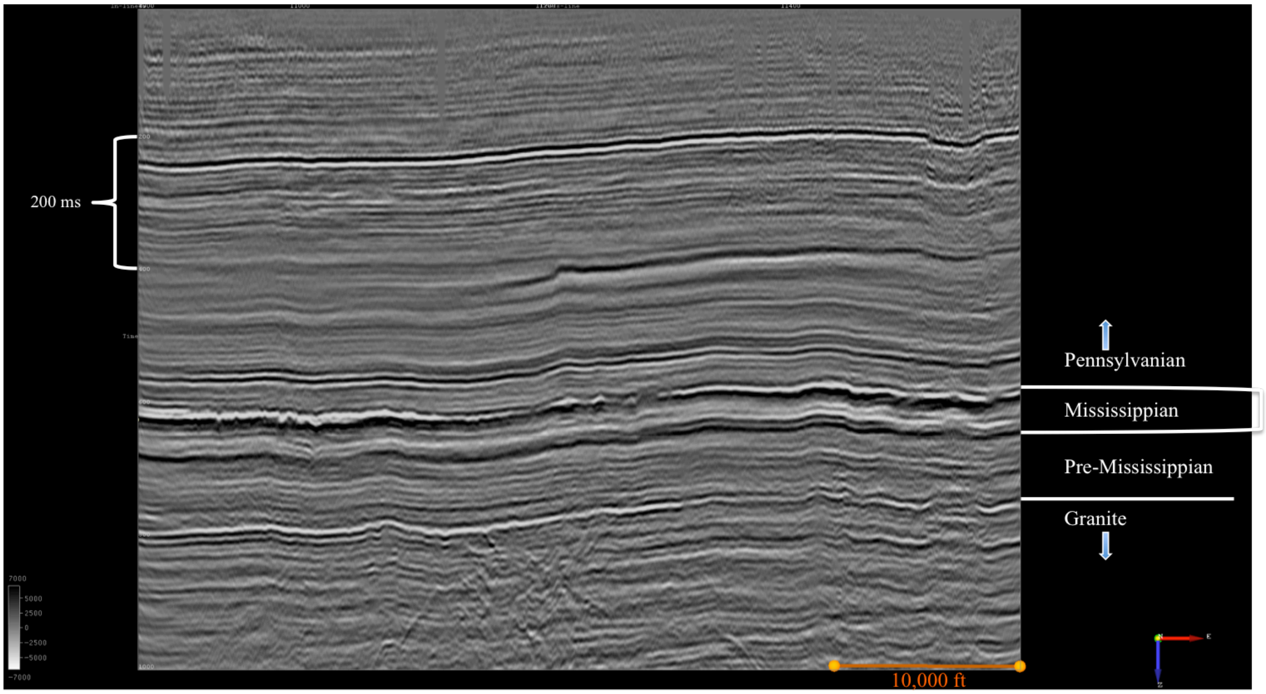


Figure 26: Uninterpreted inline 4000 with main geological intervals.

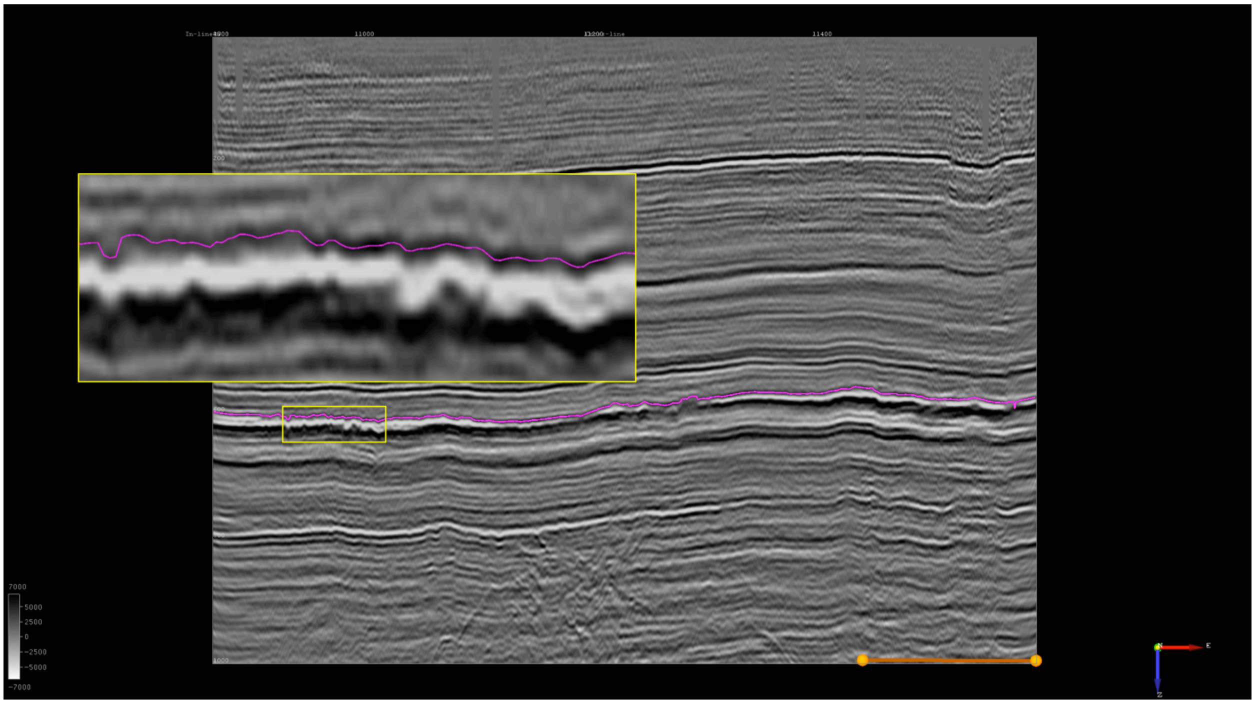
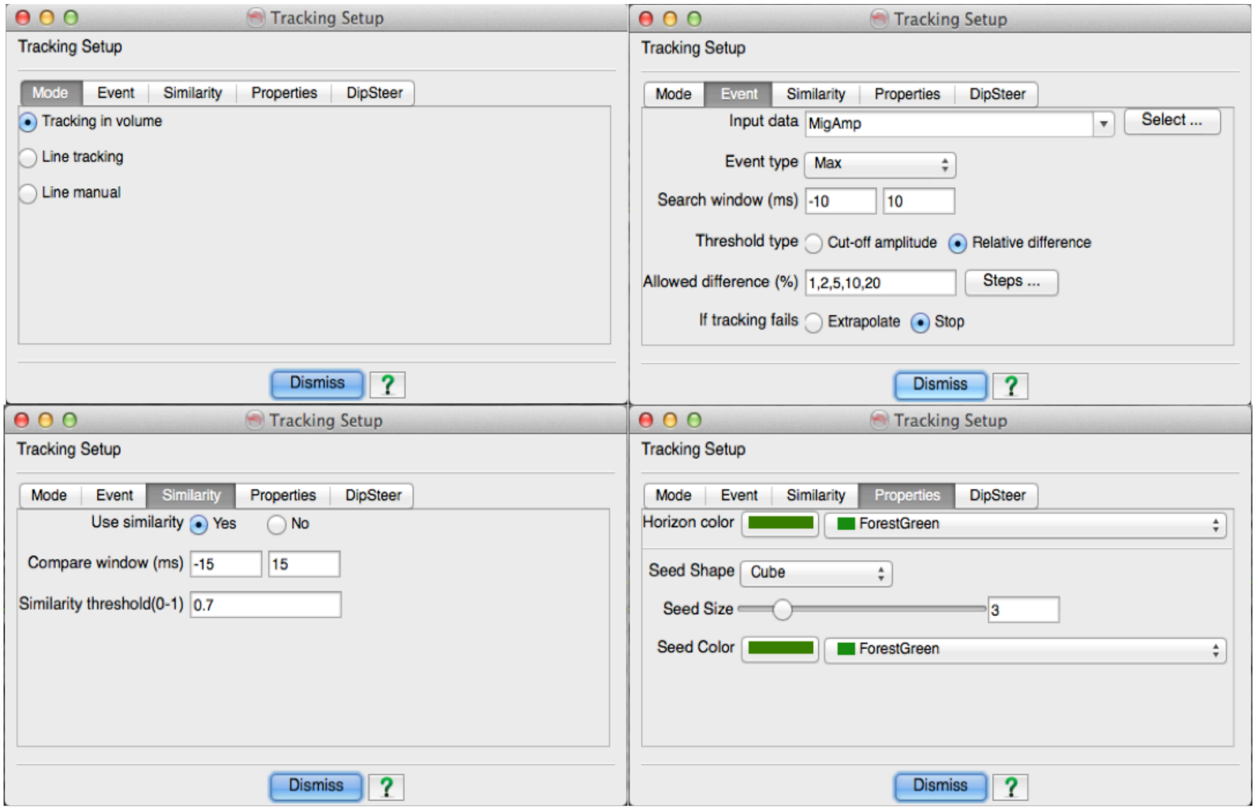


Figure 27: Interpreted Mississippian-Pennsylvanian unconformity on inline 4000.



Tracking Setup

Mode | Event | Similarity | Properties | DipSteer

● Tracking in volume
○ Line tracking
○ Line manual

Tracking Setup

Mode | Event | Similarity | Properties | DipSteer

Input data: MigAmp
Event type: Max
Search window (ms): -10 10
Threshold type: ○ Cut-off amplitude ● Relative difference
Allowed difference (%): 1,2,5,10,20
If tracking fails: ○ Extrapolate ● Stop

Tracking Setup

Mode | Event | Similarity | Properties | DipSteer

Use similarity: ● Yes ○ No
Compare window (ms): -15 15
Similarity threshold(0-1): 0.7

Tracking Setup

Mode | Event | Similarity | Properties | DipSteer

Horizon color: 🟩 ForestGreen
Seed Shape: Cube
Seed Size: 3
Seed Color: 🟩 ForestGreen

Figure 28: Parameters for tracking the Mississippian horizon.

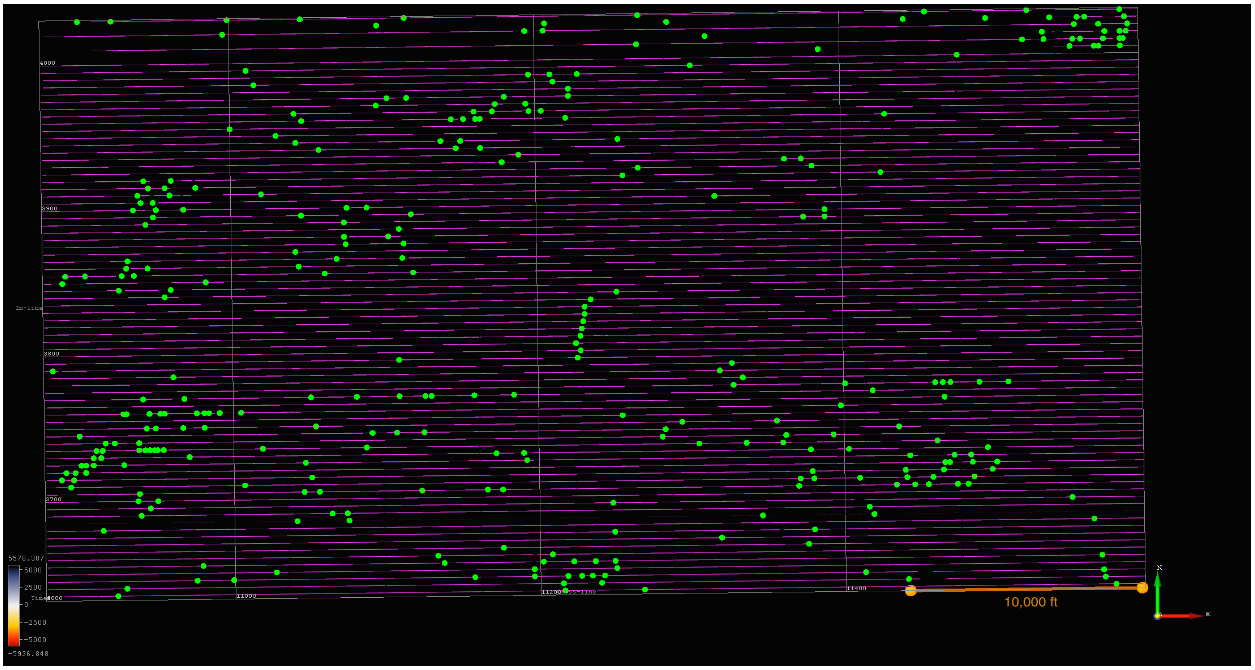


Figure 29: Picked seed points (green dots) with tracked associated inlines (purple lines).

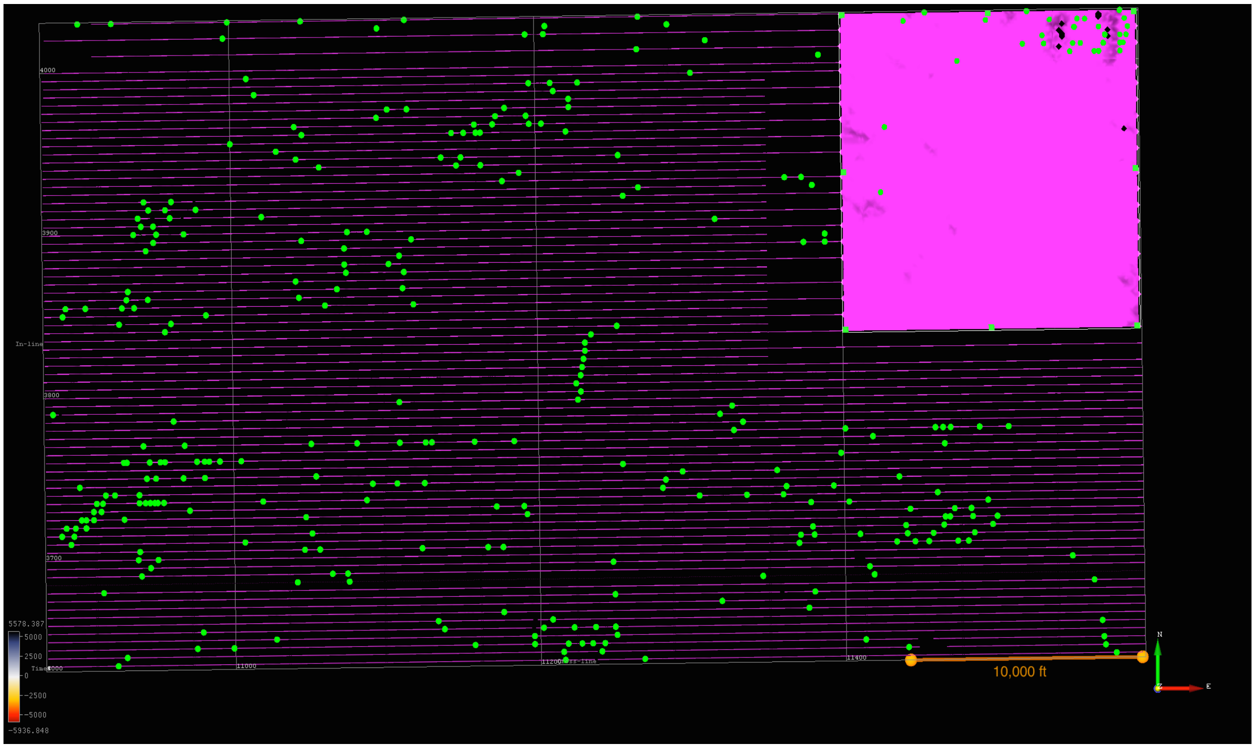


Figure 30: Green tracking box in the upper right hand corner with a tracked surface in purple.

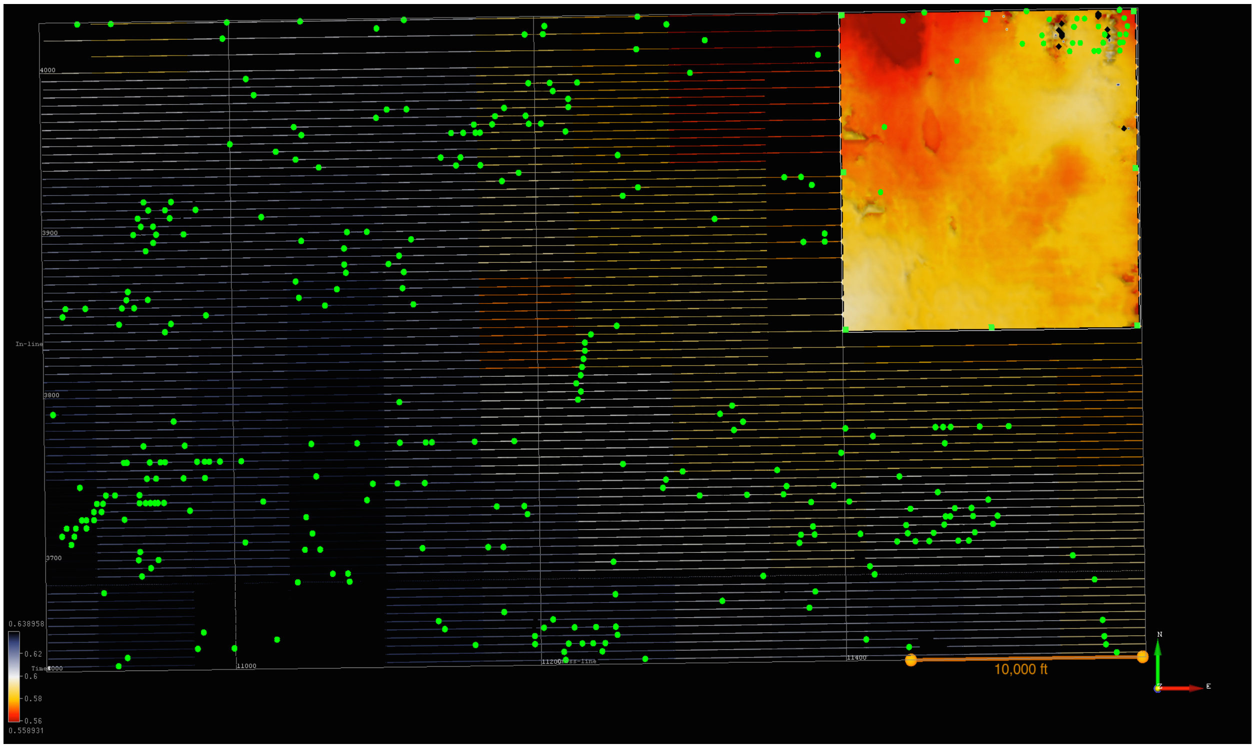


Figure 31: Mississippian surface partly tracked with z-values (time) assigned showing structure.

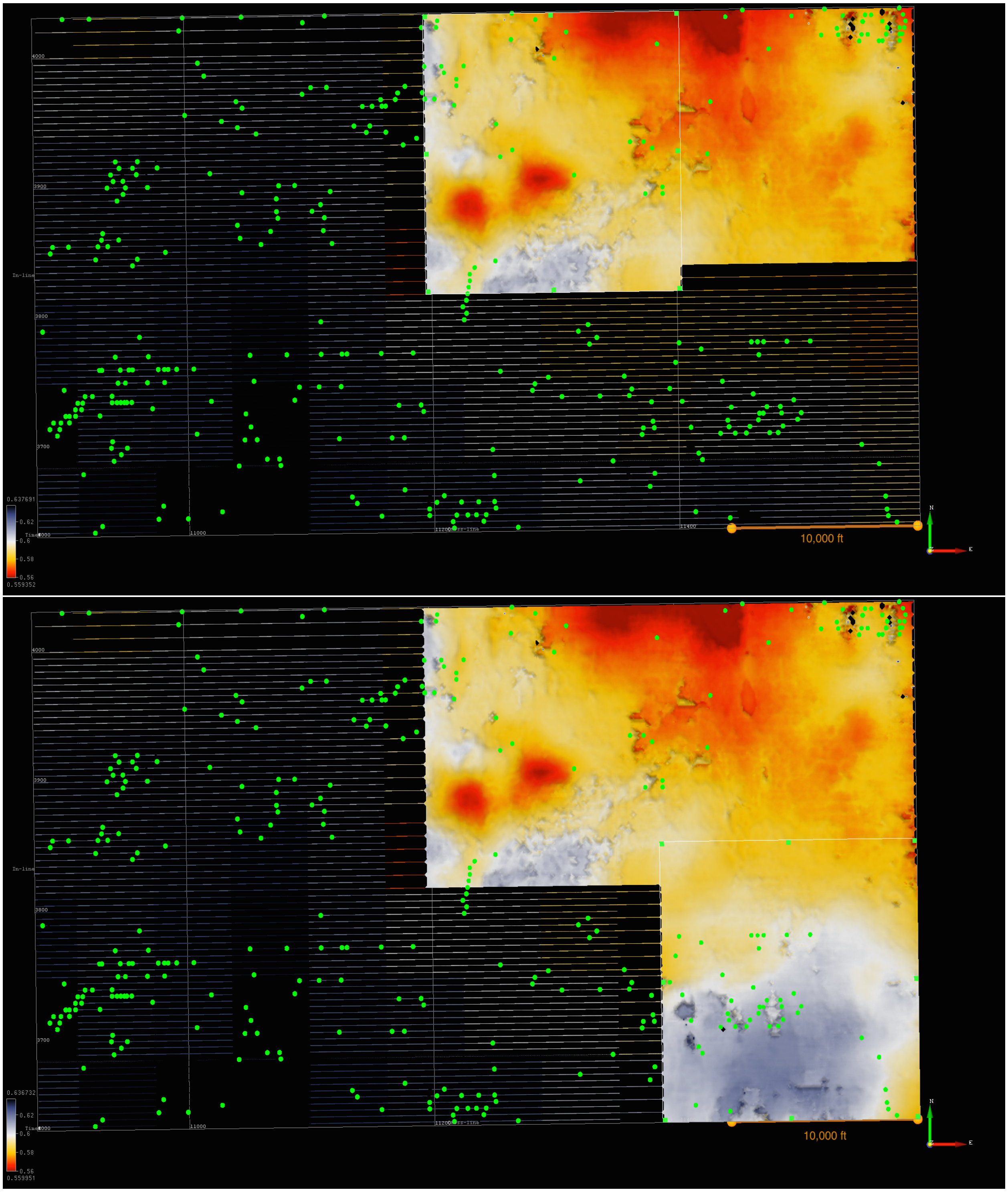


Figure 32: Progressive 3D autotracking of the Mississippian-Pennsylvanian unconformity with z-values shown.

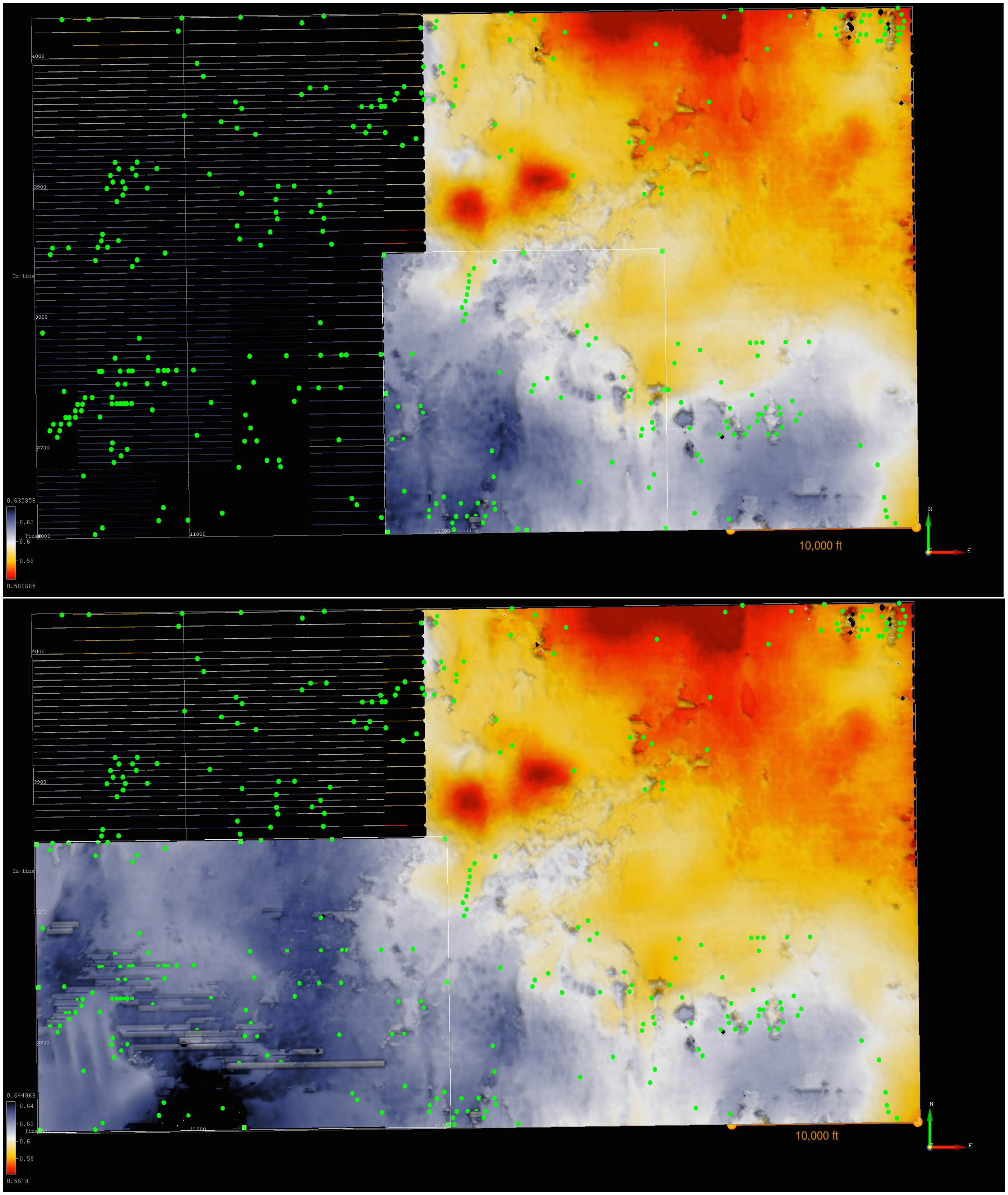


Figure 33: Continued mapping of the unconformity as a horizon. Note small tracking errors in lower left area likely due to inconsistent amplitude.

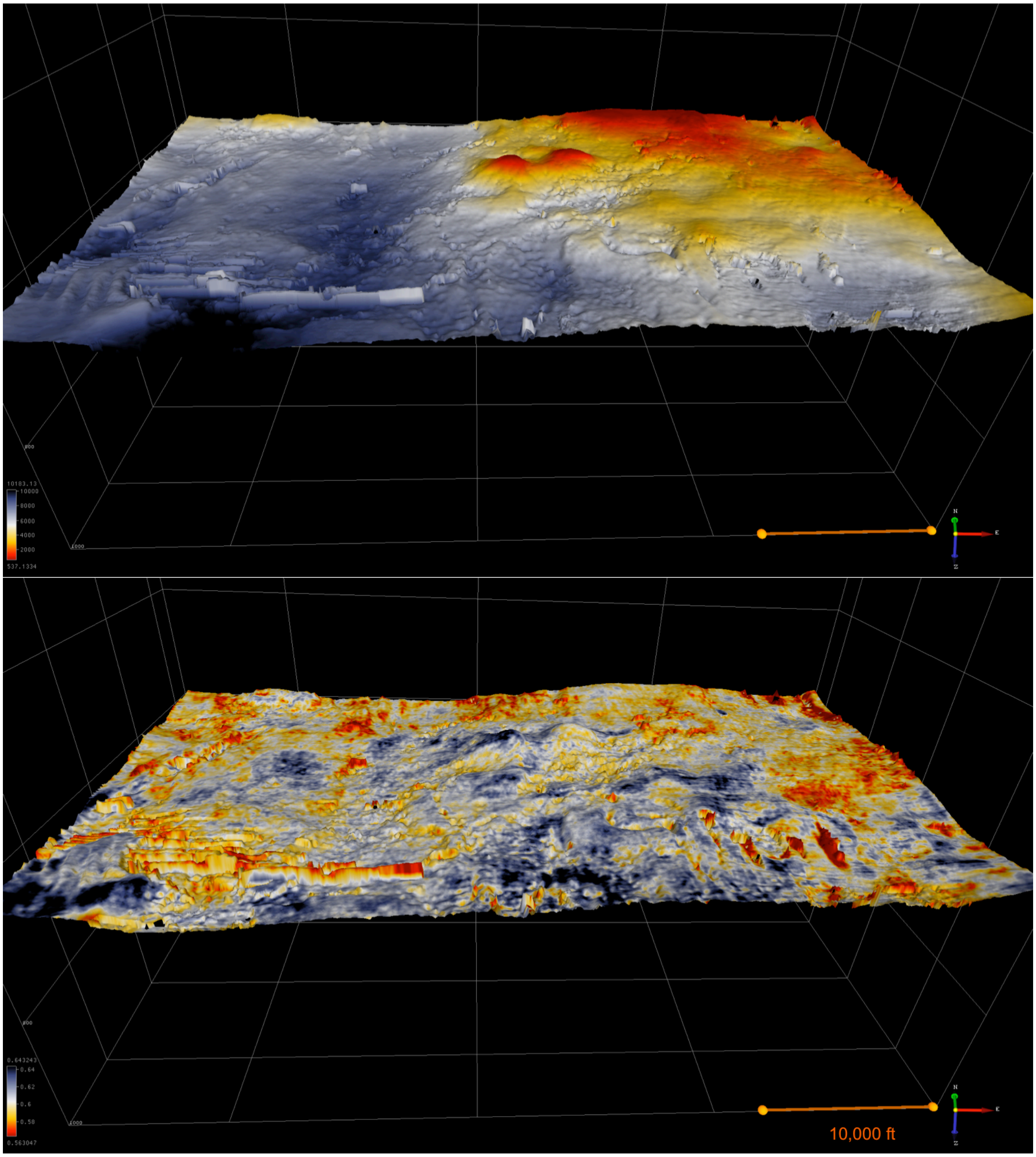


Figure 34: 3D time structure and amplitude map of the top of the entire Mississippian event.

4.5 Mapping the Tripolite with a Horizon

The previous section detailed traditional horizon tracking of the Mississippian – Pennsylvanian unconformity. From a 3D seismic viewpoint, tripolite occurs, and is discontinuous, at an unknown depth into the Mississippian requiring a different mapping approach. The tripolite has a very low density and velocity, yielding low acoustic impedance that shows up in 3D seismic data as a bright negative amplitude anomaly. The tripolite in many ways is similar in appearance to a direct hydrocarbon indicator such as a gas bright spot. Two methods were employed and compared for mapping the tripolite.

The first method used for mapping the tripolite is single point extraction. The seismic data were scanned for negative amplitude anomalies. Once an anomaly was identified it was viewed in time-slice and crossline. A new horizon was created and a single seed point was picked at the most negative value. The view was changed to top-down view where the process becomes similar to horizon mapping of the Mississippian – Pennsylvanian unconformity as described earlier, exept the single seed point always remained in the auto-tracking box to provide the program with a reference point. This means that the auto-tracking box merely increased in size after every successful auto-track (Figure 36-38). The end result of the mapping is a time-structure map and an amplitude map (Figure 40). One tripolite body flanks a structural anticline and one is amorphous around a structure that zzappears to be a fault or graben. This structure made it necessary for two seed points to be used to accurately map it (Figure 35).

The second method used for mapping the tripolite was a traditional approach similar to picking the unconformity: picking seeds every 10 inlines through the 3D volume and using OpendTect's auto-tracking to create a horizon (Figure 39). Figures 40 and 41 show the resultant time-structure and amplitude maps that make it possible to compare and judge which technique is better.

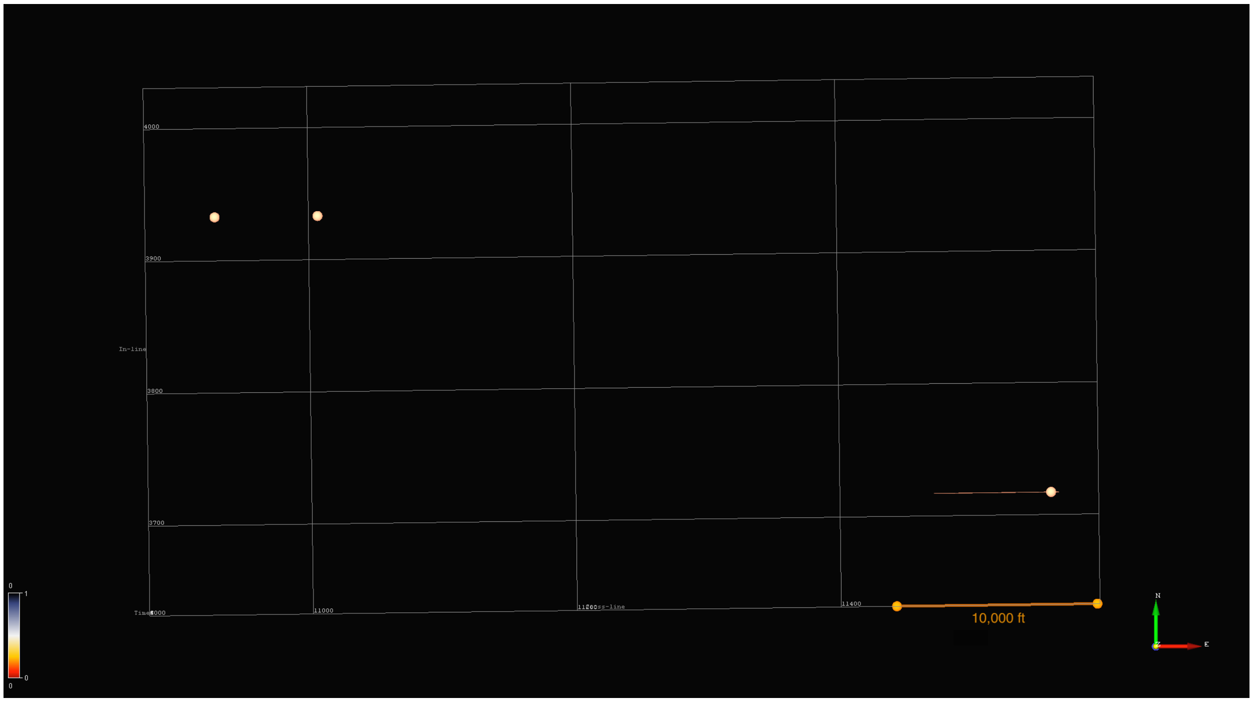


Figure 35: Map view of three tripolite seed points.

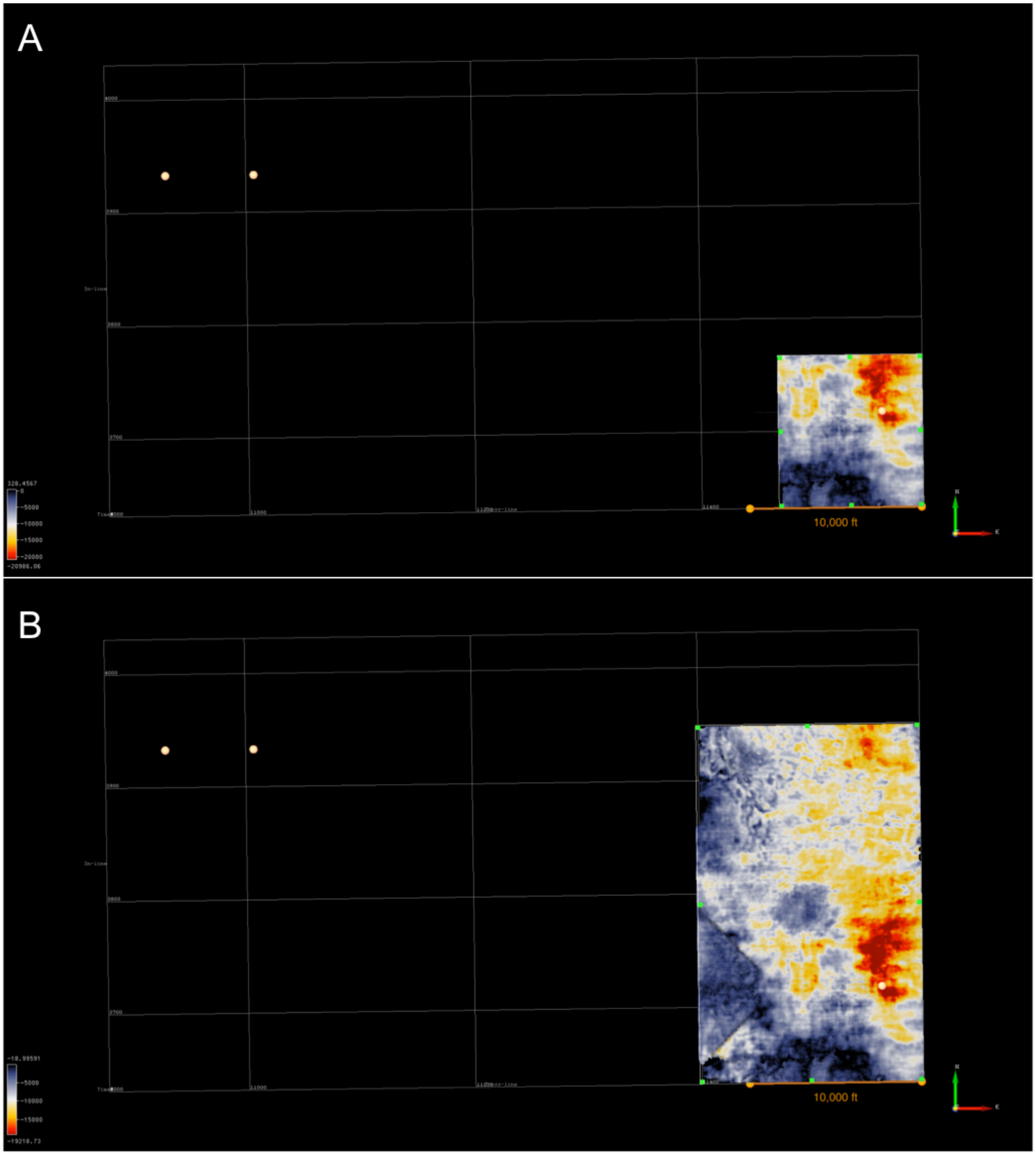


Figure 36: Map view of the tripolite seed point and tracking box with a partial tracked horizon showing amplitude. A) Stage 1 tracking from single seed point. B) Expanded tracking box used to define limits of probable tripolite anomaly.

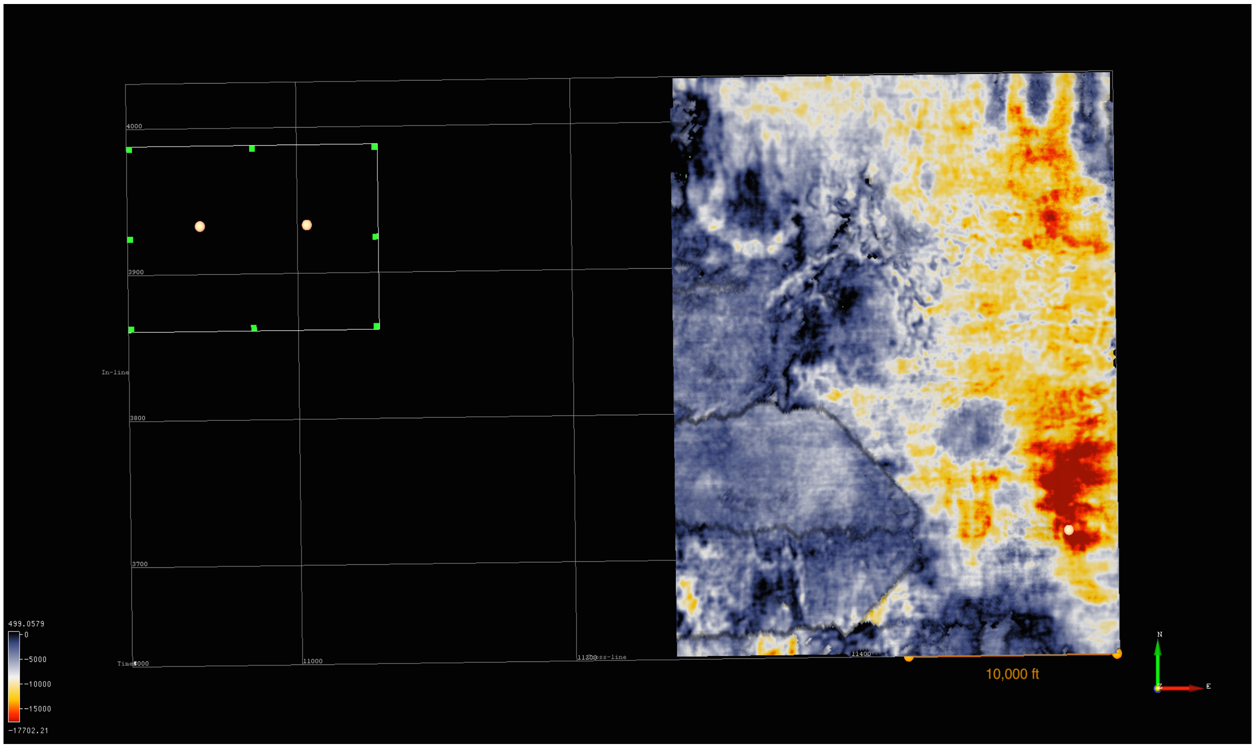


Figure 37: Extent of the eastern tripolite mapped. Green tracking box is hovering over the western two seed points.

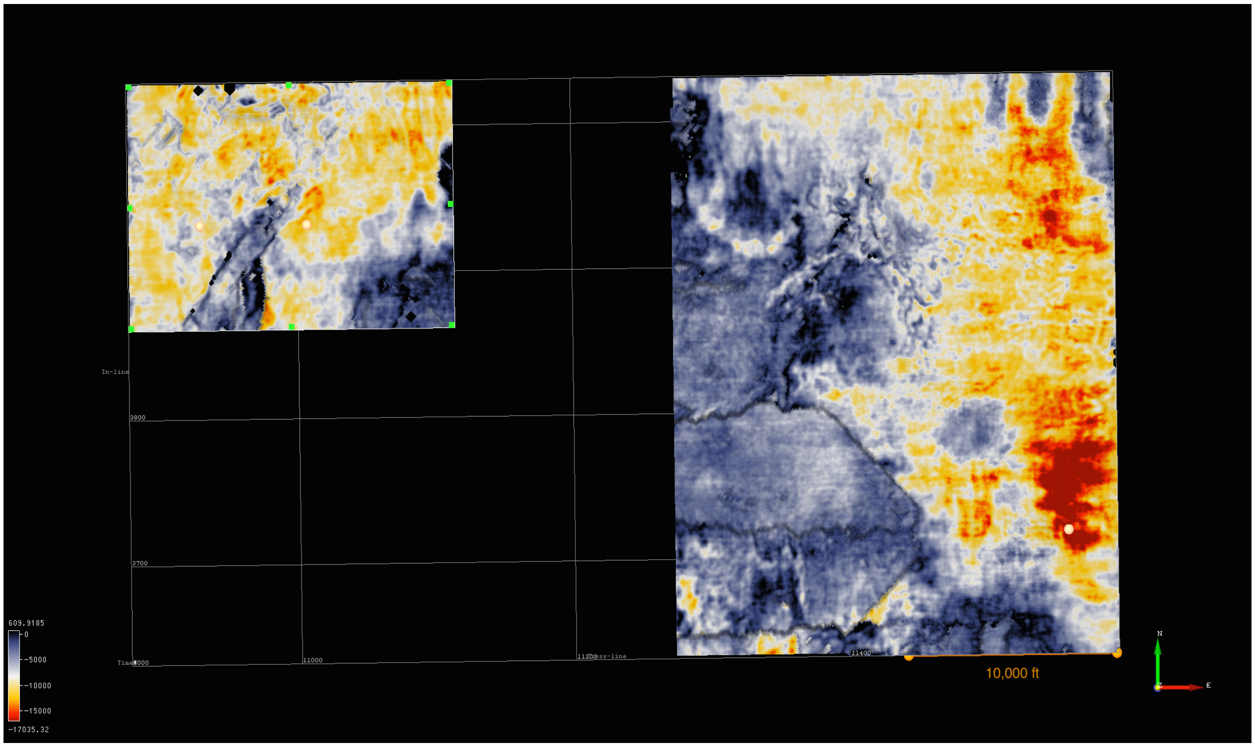


Figure 38: Tracking the western tripolite body with amplitude values.

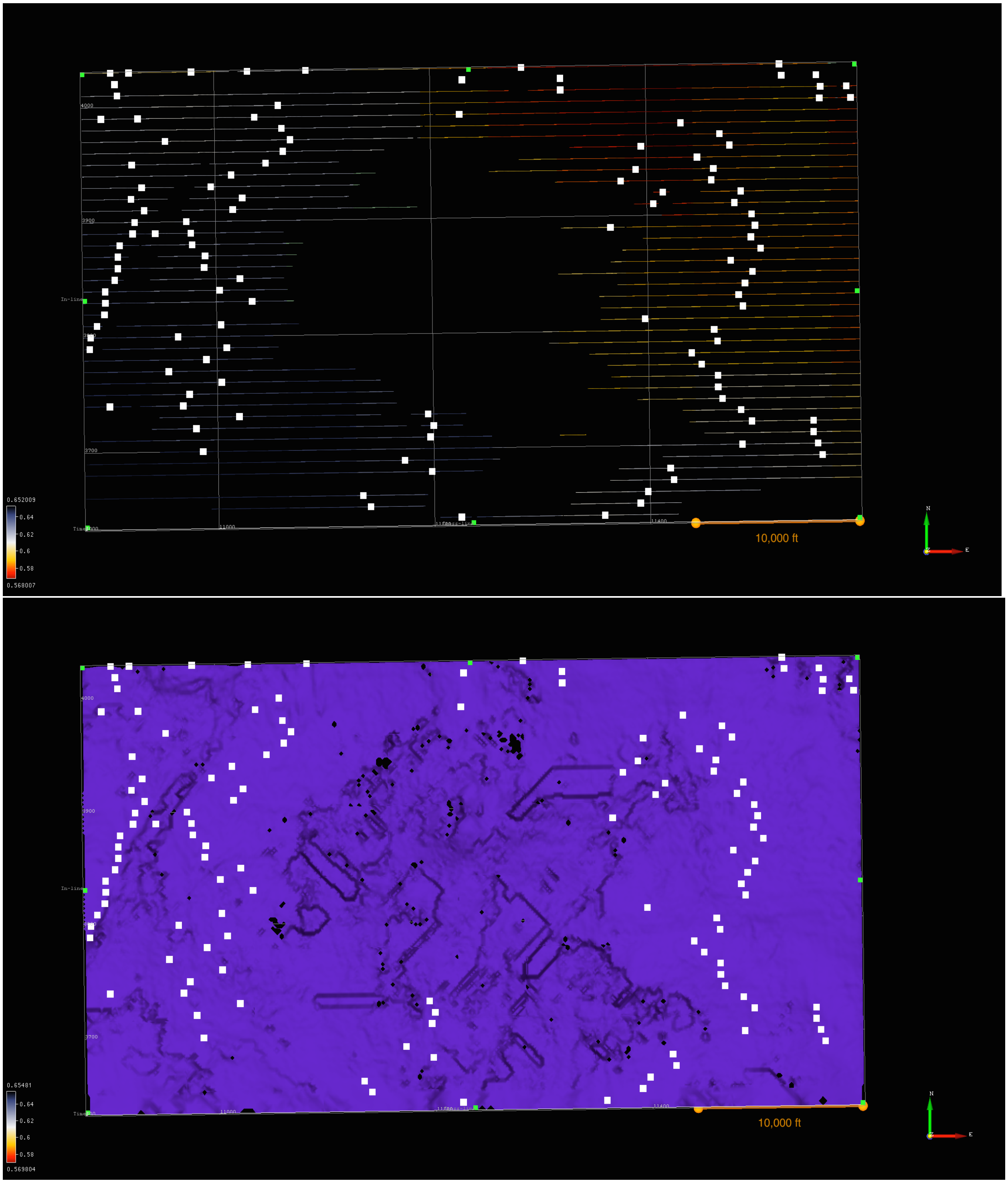


Figure 39: Traditional tracked lines with seeds going through the tripolite and green tracking box and mapped horizon of tripolite with no attribute yet assigned.

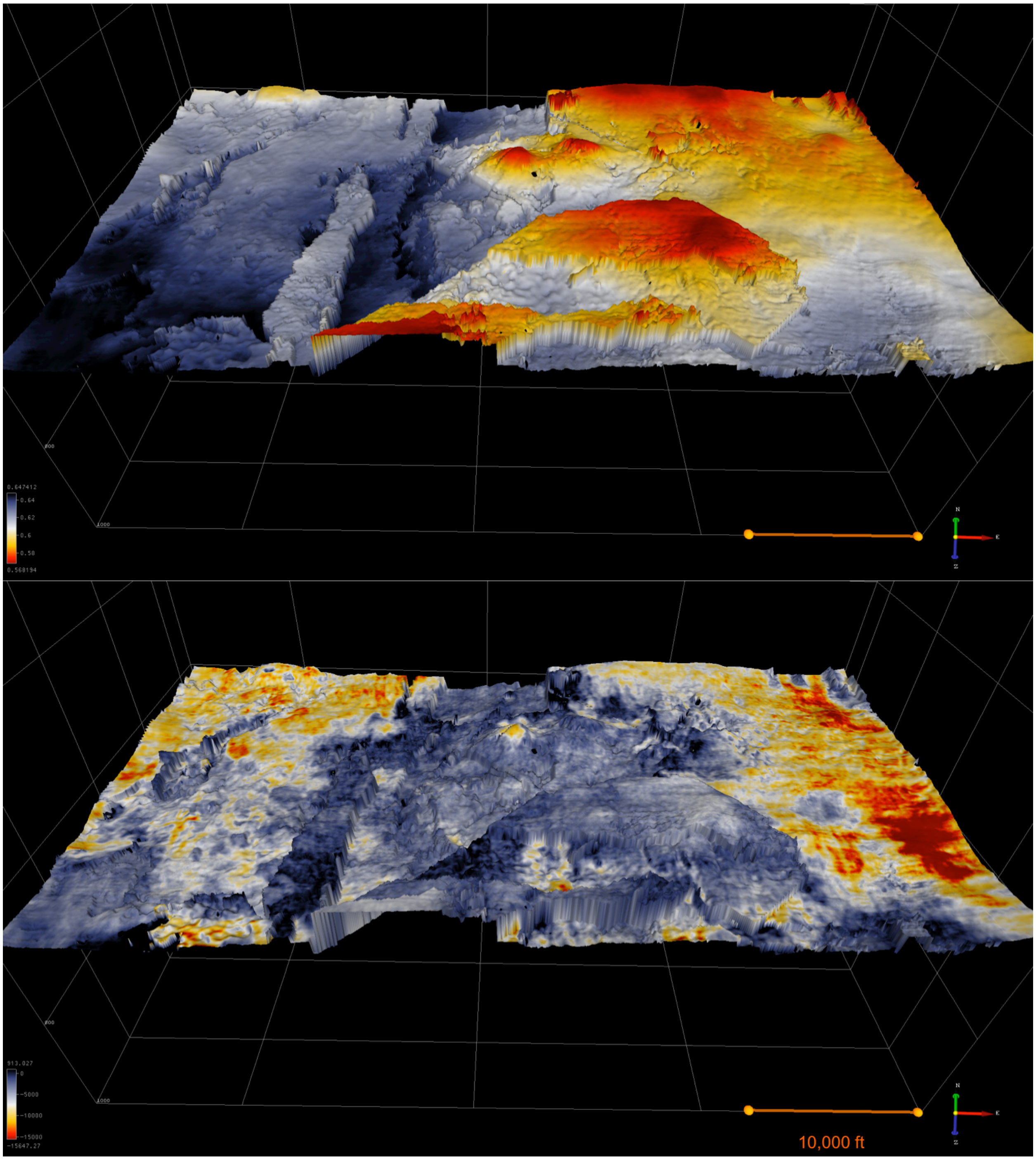


Figure 40: 3D view of resultant time-structure and amplitude maps from method 1. Notice the large tracking busts that occur where the discontinuous event dies out.

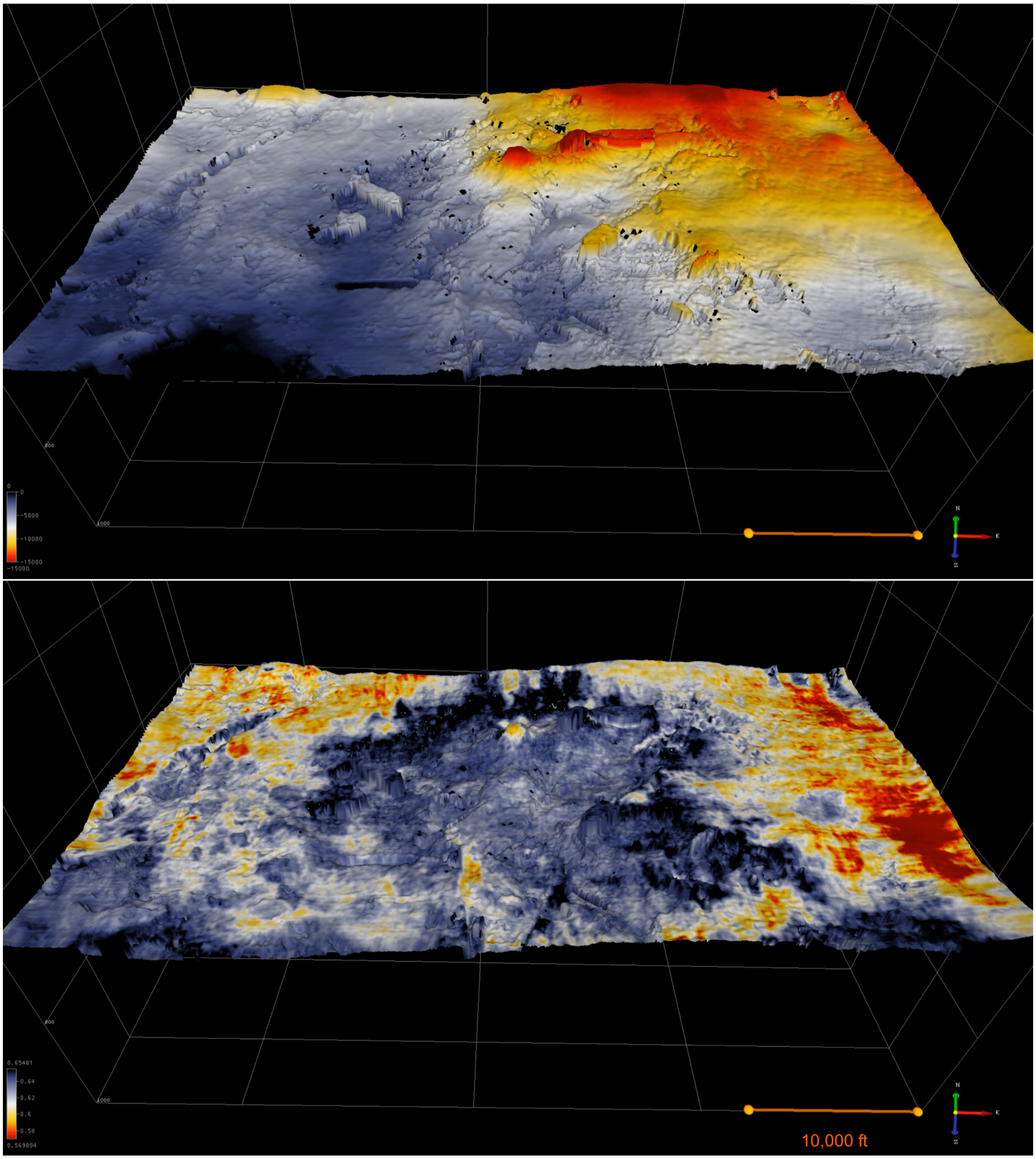


Figure 41: 3D view of resultant time-structure and amplitude maps for method 2. Note improved continuity of time structure and amplitude.

4.6 Geobody Extraction of the Tripolite

The tripolite horizon provides a good idea of the shape and strength of the amplitude anomaly. However, the resolution of the tripolite can be raised and the full expanse be mapped by completing a geobody extraction. This process ironically is the least complicated and provides the best 3D view of the tripolite.

Creating a geobody of the tripolite is represented by Figures 42-46. The first step is to create what OpendTect calls a PickSet/Polygon. The PickSet/Polygon allows you to put picks inside the tripolite pod similar to the seeds that are used when creating a new horizon. Picks were made on inlines stepping every 10 resulting in a ‘point’ cloud’. It is possible to only use one pick per inline but more picks provide additional reference points that improve results.

After creating a point cloud, a new volume box (OpendTect volren cube), is created. This cube is similar to the green auto-tracking box for creating horizons seen in the previous sections. The volume box binds the program to look for amplitude values inside it while using the point cloud as a reference. Selecting ‘MigAmp’ (seismic amplitude data type), then ‘Display’, ‘Add’, and ‘Iso Surface’, brings up a histogram showing amplitude values. Next to Mode, select ‘Seed based’ and next to Seeds value, select ‘Below is-value’. These options tell the program to search for amplitude values below a threshold using the Picks as reference points. The time it takes for the program to compile the geobody can take time ranging from 5 to 20 seconds on a 3.6 GHz Mac with OpendTect version 4.4. After trial and error, the threshold value that looked most geological to the author is -8000.

Geobody extraction not only allows for increased resolution and shape of the tripolite but also allows for the identification of the amplitude extreme associated with tripolite. By changing the threshold maximum values to -10000, -12000, -14000, and -16000, it is possible to find the most anomalous tripolite (Figures 47-51).

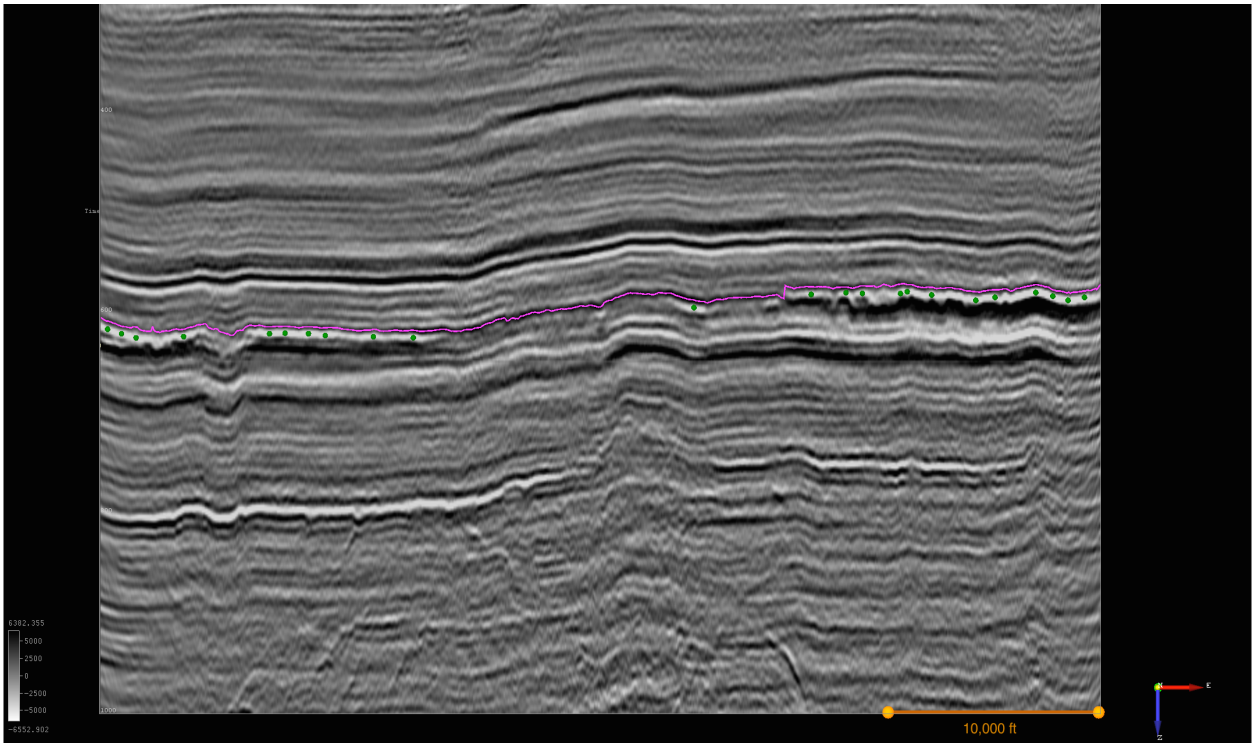


Figure 42: Using a pick set to pick seeds for the point cloud on inline 3930.

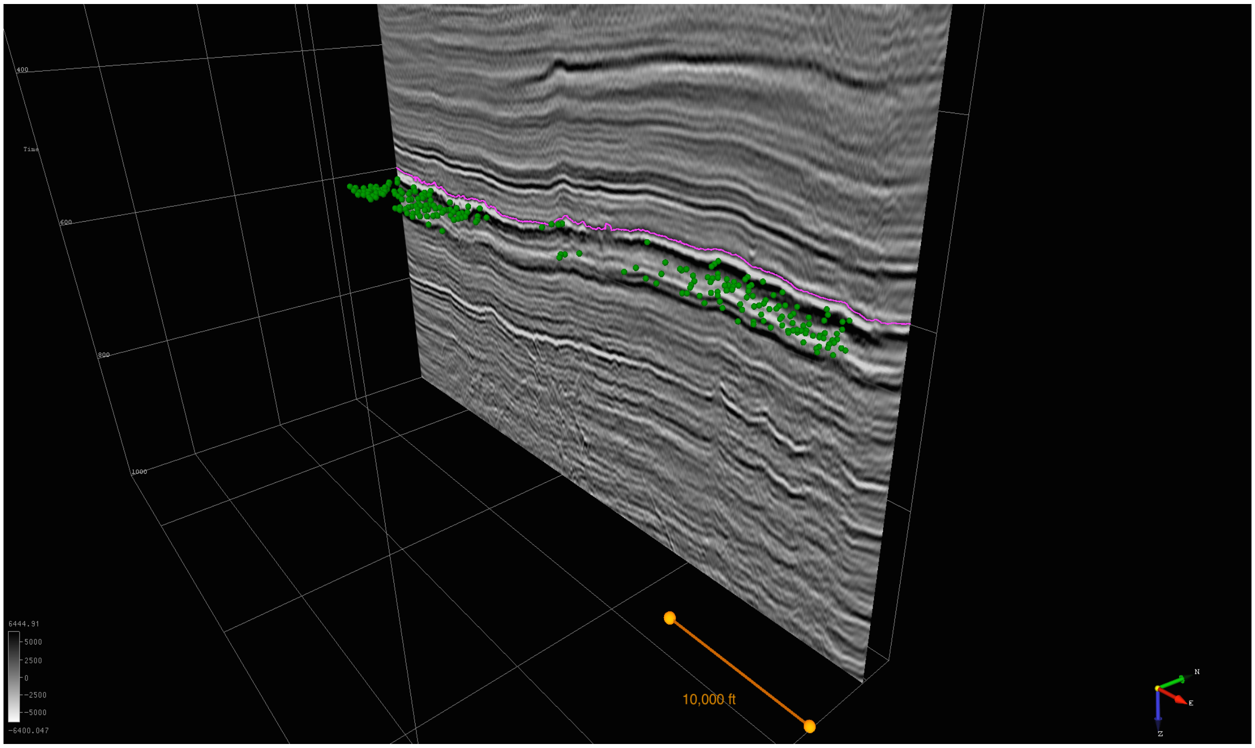


Figure 43: 3D view of Wild Creek with a small point cloud made up of seed picks (picks are in orange).

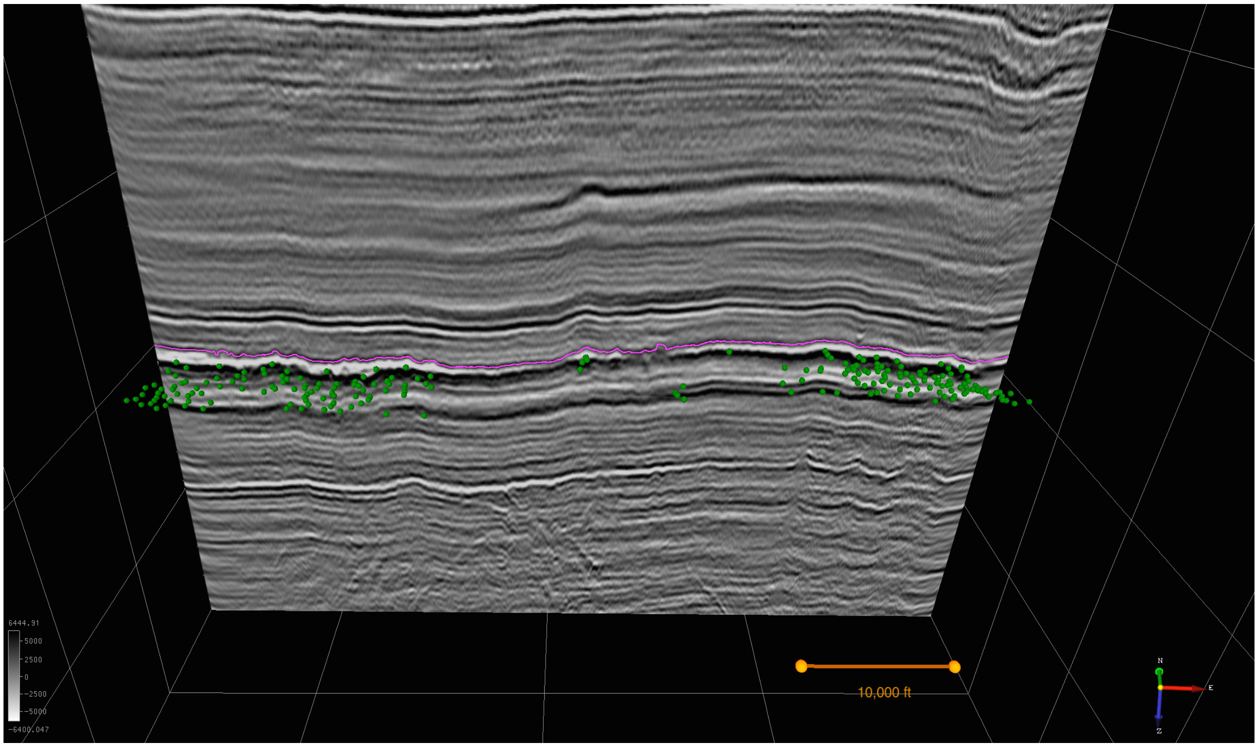


Figure 44: 3D view facing north of the small point cloud.

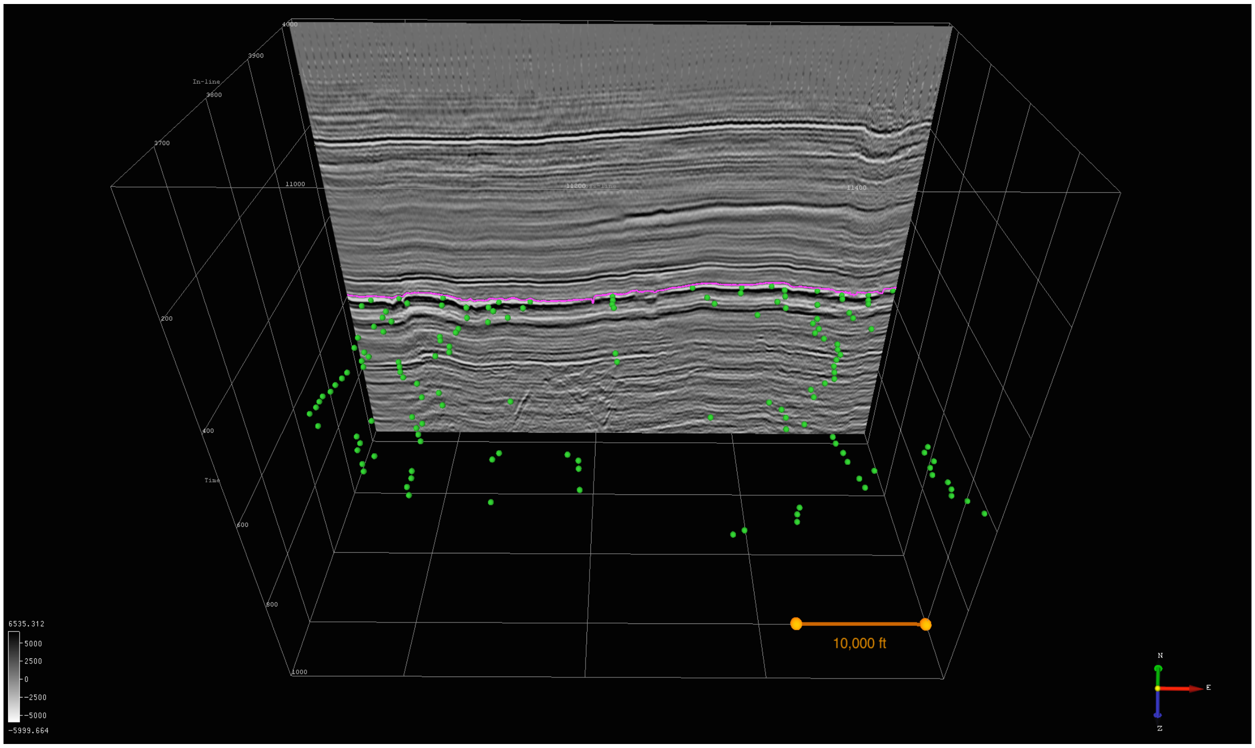


Figure 45: A complete point cloud used for geobody extraction.

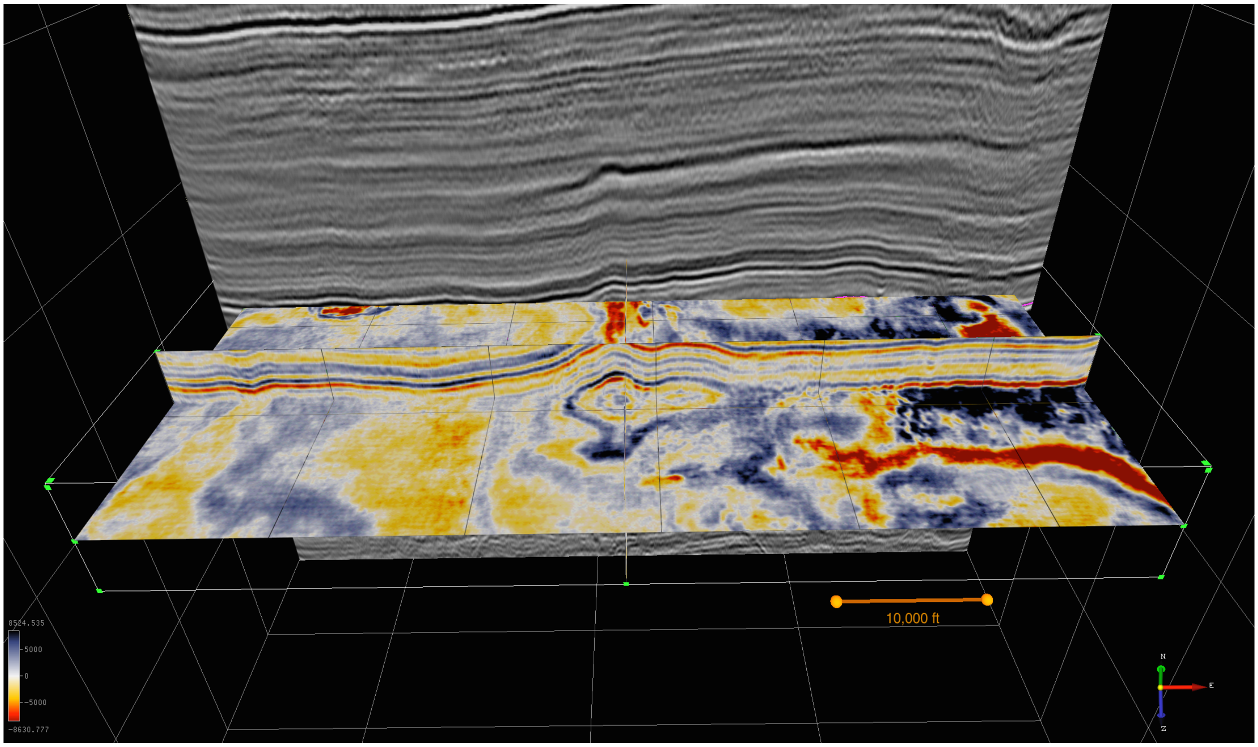


Figure 46: 3D view of the volume cube, used to create the geobodies, overprinted on the seed picks.

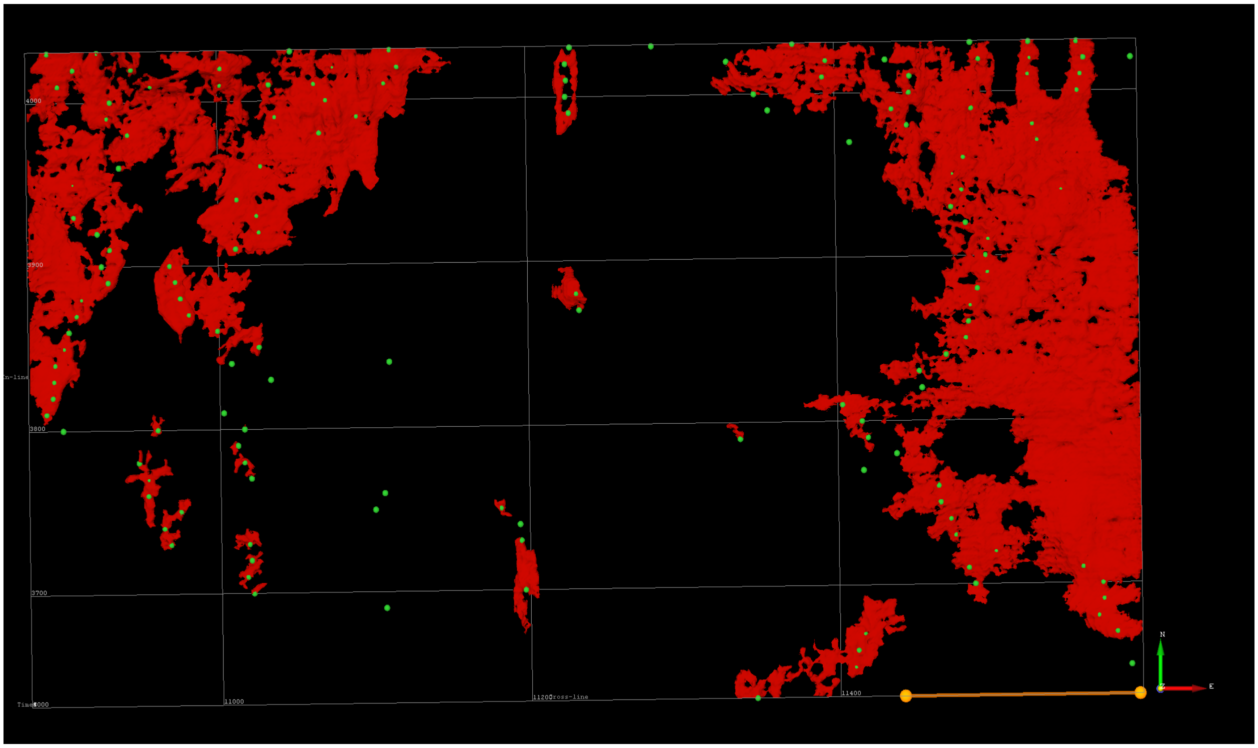


Figure 47: Geobody of the tripolite with seed picks with threshold maximum set to -8000; the geobody looks the most geological at this value.

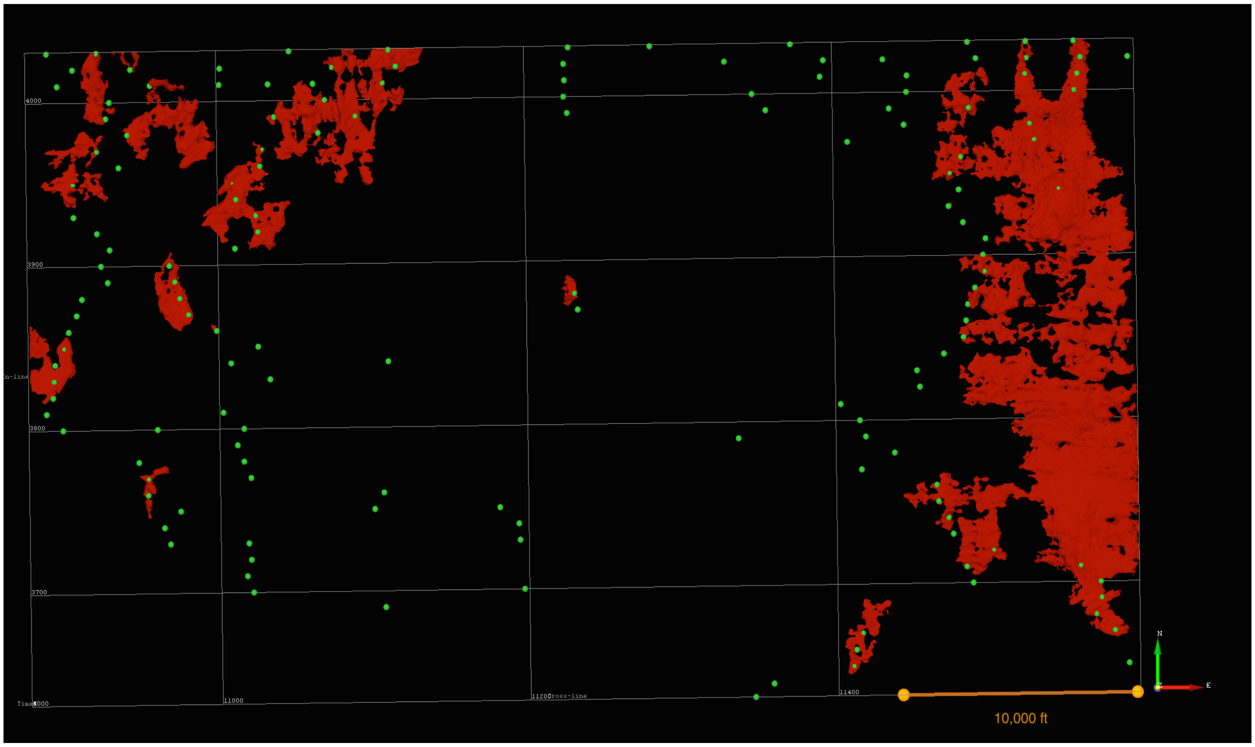


Figure 48: Less dense tripolite with threshold maximum value set to -10000.

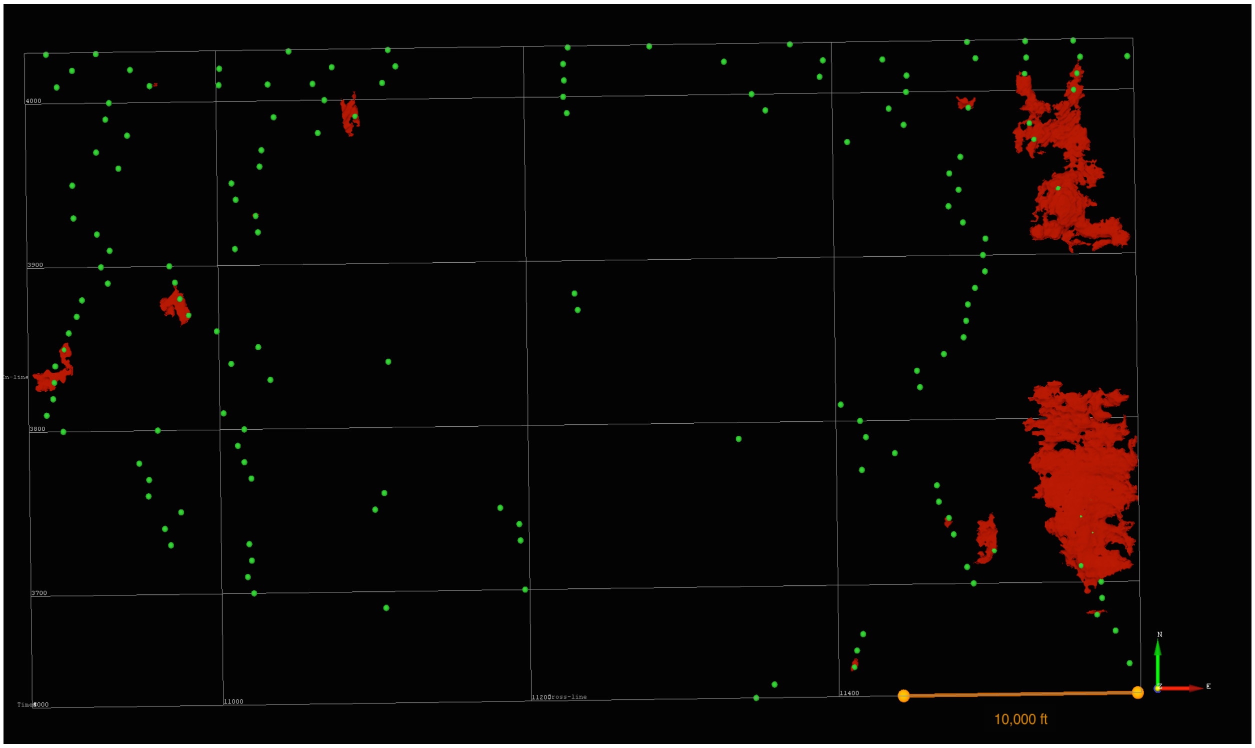


Figure 49: Less dense tripolite with threshold maximum value set to -12000.

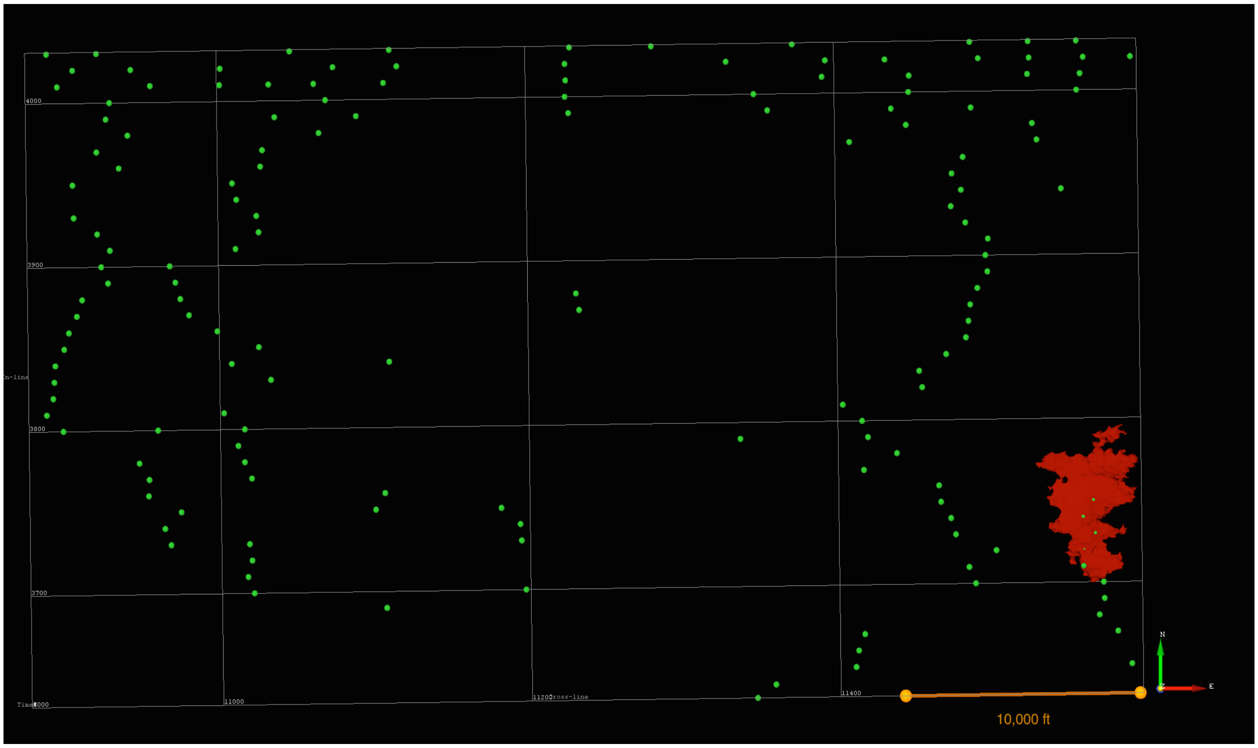


Figure 50: Less dense tripolite with threshold maximum set to -14000.

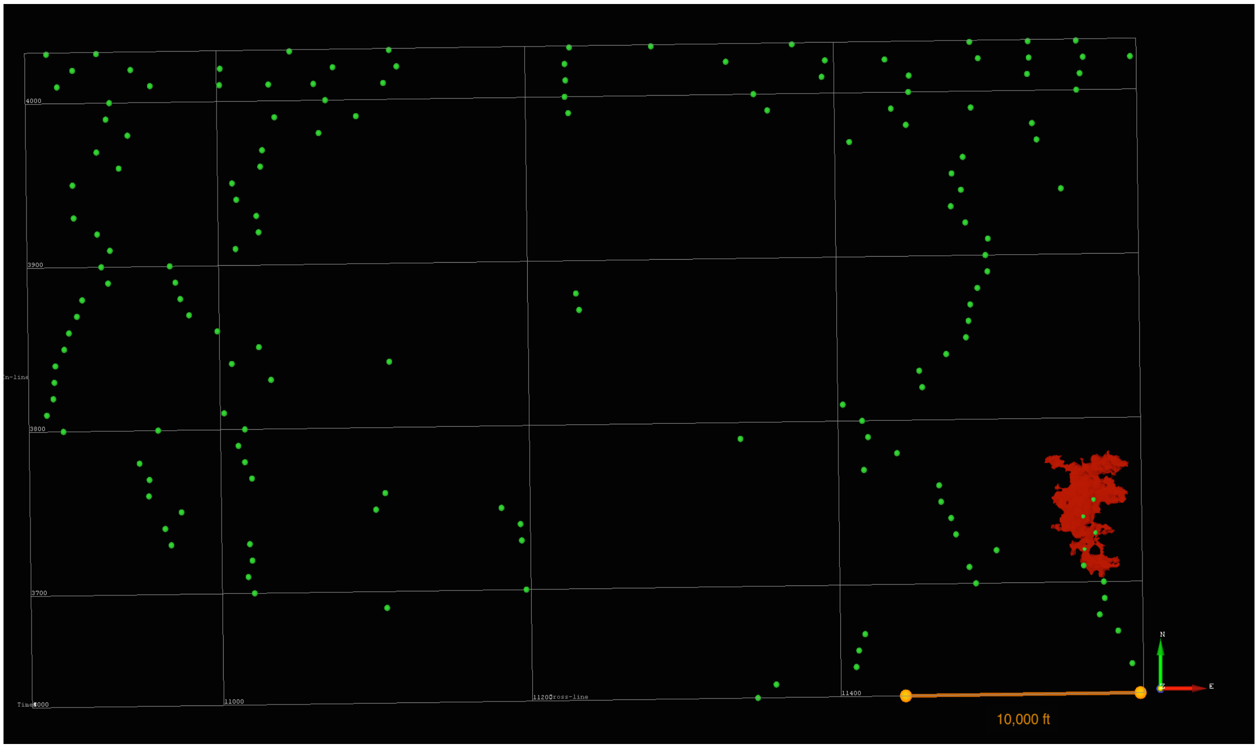


Figure 51: Core of the tripolite with threshold maximum set to -16000. Max anomaly may be associated with lowest tripolite acoustic impedance and/or thickest occurrence.

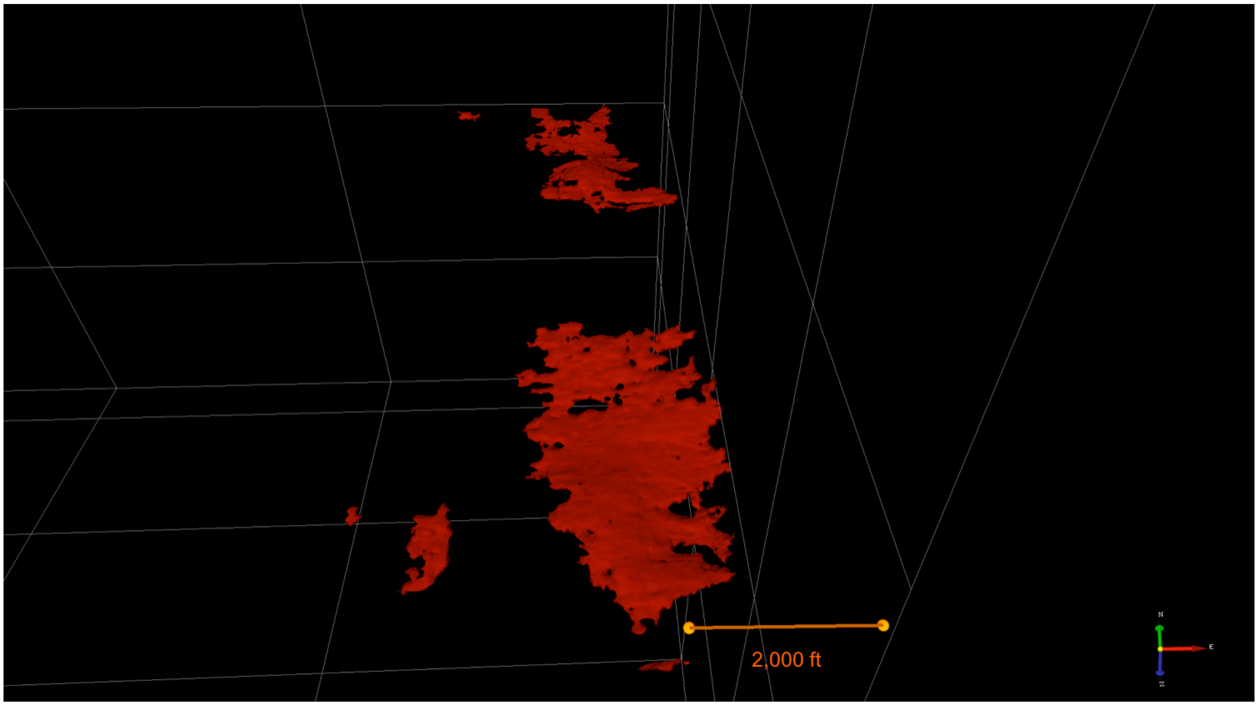


Figure 52: 3D close up view of southeastern geobody in Figure 49 (threshold -12000).

4.7 Resolution and Reflection Coefficients of the Mississippian

The purpose of this section was to calculate resolution and reflection coefficients of the Mississippian. An important value to calculate is the vertically resolved thickness of the tripolite. This is accomplished with the equation:

$$(1) \qquad \mathrm{Z}_{tripolite} = \frac{\lambda_{tripolite}}{4} = \frac{240\,ft}{4} = 60 \text{ feet}$$

Where the wavelength can be calculated:

$$(2) \qquad \lambda_{tripolite} = \frac{v_{MT}}{\mathcal{F}_{MT}} = \frac{13{,}819\,ft/s}{57.5\,Hz} = 240 \text{ feet}$$

Where the dominant frequency can be calculated:

$$(3) \qquad \mathcal{F}_{dom} = \frac{f_{high} + f_{low}}{2} = \frac{100\,Hz + 15\,Hz}{2} = 57.5 \text{ Hz}$$

Where $\lambda_{tripolite}$ is the acoustic wavelength going through the tripolite, $\mathrm{Z}_{tripolite}$ is the acoustic resolution of the tripolite, and $\mathcal{F}_{dom}$ is the dominant frequency of Wild Creek survey.

Taking into consideration of the actual stratigraphy in Osage County, there are only two possibilities to simulate the negative anomaly (Figures 53 and 54). First, the unconformity is a contact between basal Pennsylvanian and Mississippian tripolite. Secondly, the unconformity is a contact between basal Pennsylvanian and Mississippi dense lime with a tripolitic chert layer at some depth to the unconformity.

Symbol	Definition
ρ, v, I	Density, acoustic velocity, acoustic impedance
$\rho_P, v_P, \mathrm{I}_P$	Basal Pennsylvanian sediment parameters
$\rho_{MT}, v_{MT}, \mathrm{I}_{MT}$	Mississippian tripolite parameters
$\rho_{MD}, v_{MD}, \mathrm{I}_{MD}$	Mississippian dense lime parameters

Table 1: Definition of mathematical symbols used for reflection coefficient calculations

	Density	Velocity	Acoustic Impedance
Basal Pennsylvanian	2.577 g/cc	3731 m/s (12241 ft/s)	9614787 $\frac{kg}{m^2 s}$
Mississippian Tripolite	2.489 g/cc	4212 m/s (13819 ft/s)	10483668 $\frac{kg}{m^2 s}$
Mississippian Dense	2.635 g/cc	5472 m/s (17953 ft/s)	14418720 $\frac{kg}{m^2 s}$

Table 2: Parameter values for rock units of interest for this study

Figure 53: Stratigraphic case 1

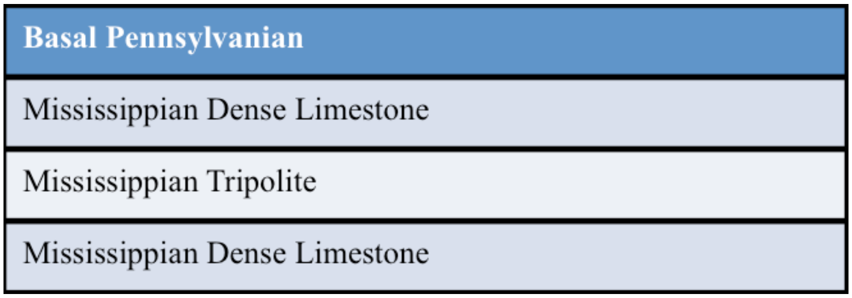


Figure 54: Stratigraphic case 2

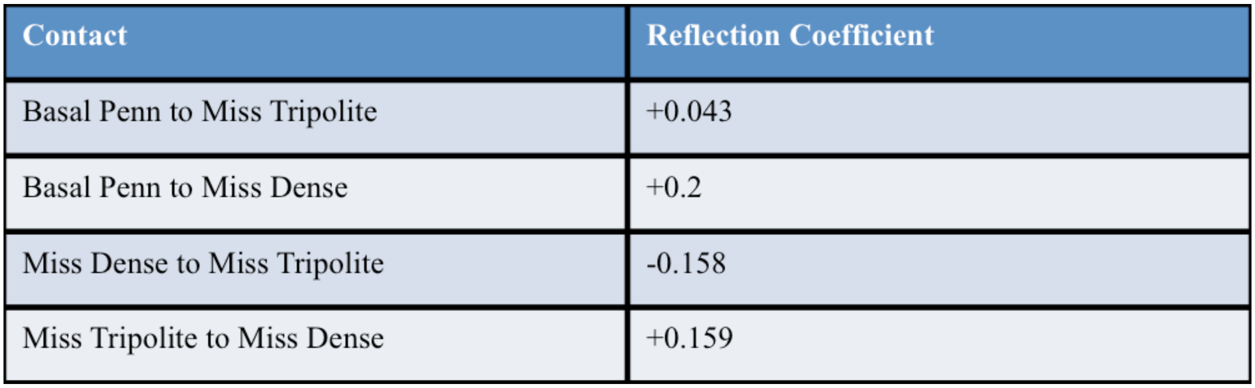
Reflection coefficients for the stratigraphic cases can be calculated to examine the negative anomaly identified to be tripolite (Figure 55). The goal of these calculations is to understand the cause of the strong negative anomalies. Specifically, which configuration of rock units will result in the observed behavior. The normal incidence reflection coefficient (Liner, 2004) is defined as:

$$(4) \qquad R_0 = \frac{I_2 - I_1}{I_2 + I_1}$$

where R_0 is the reflection coefficient, I_1 is the impedance of the overlaying units, and I_2 is the impedance of the underlying rock unit, and impedance is calculated using this equation:

$$(5) \qquad I = \rho v$$

Density values are available from neutron density logs, and velocity comes from sonic log data. Results reported use data from the Shaw 1A-8 plot well (Jennings, 2014) (Table 2).



Contact	Reflection Coefficient
Basal Penn to Miss Tripolite	+0.043
Basal Penn to Miss Dense	+0.2
Miss Dense to Miss Tripolite	-0.158
Miss Tripolite to Miss Dense	+0.159

Figure 55: Reflection coefficient results. Note the only large negative reflection is associated with Miss Dense overlying Miss Tripolite.

4.8 Estimation of Tripolite Thickness

If tripolite is thicker than the seismic vertical resolution limit, it is possible to directly estimate tripolite thickness. To calculate the thickness you need to measure the difference in time between a trace's trough and peak (Figure 57), on the assumption that the trough represents the top of the tripolite and the next peak is the base of the tripolite. This assumption appears justified for the data in Figure 56 and 57.

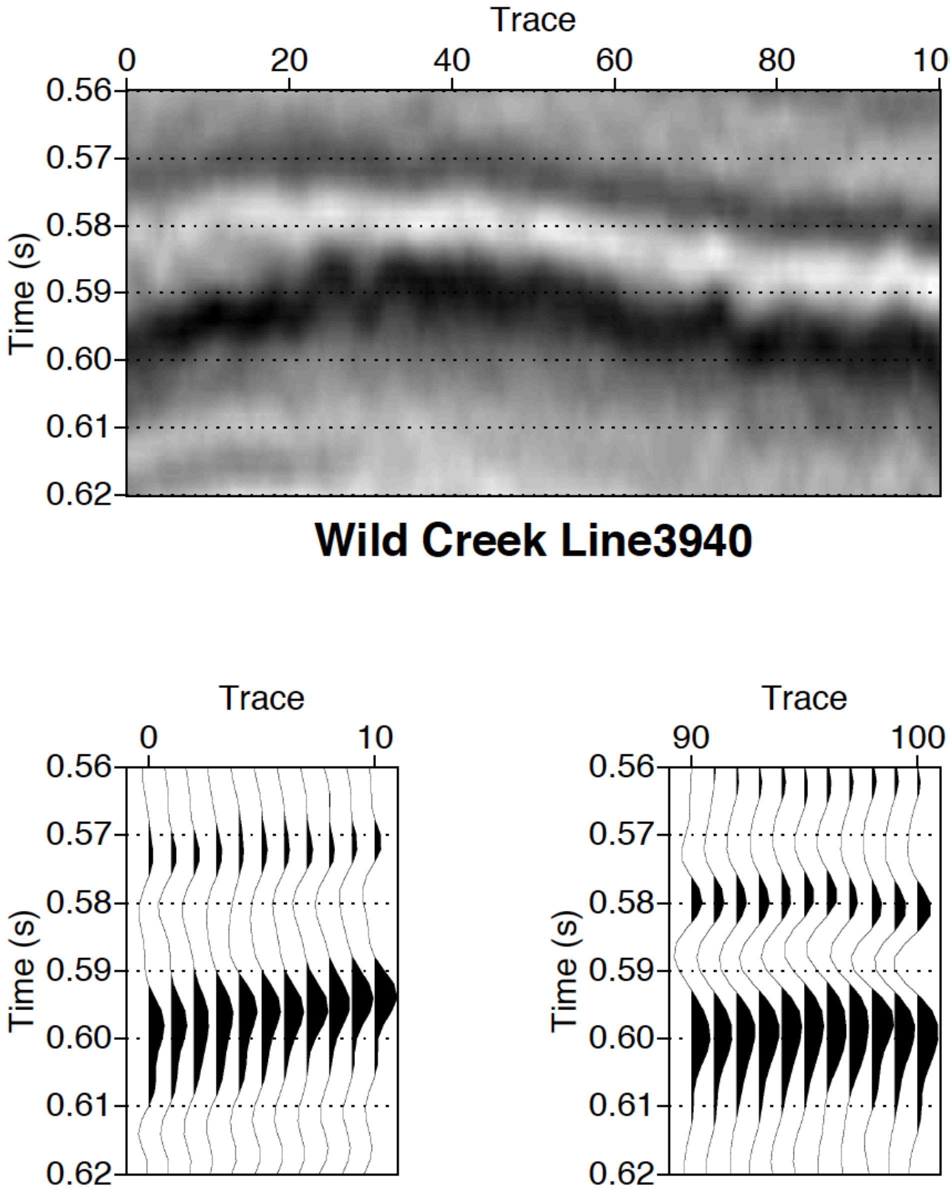


Figure 56: A close up of tripolite traces on inline 3940 from the Wild Creek survey (Liner, 2014)

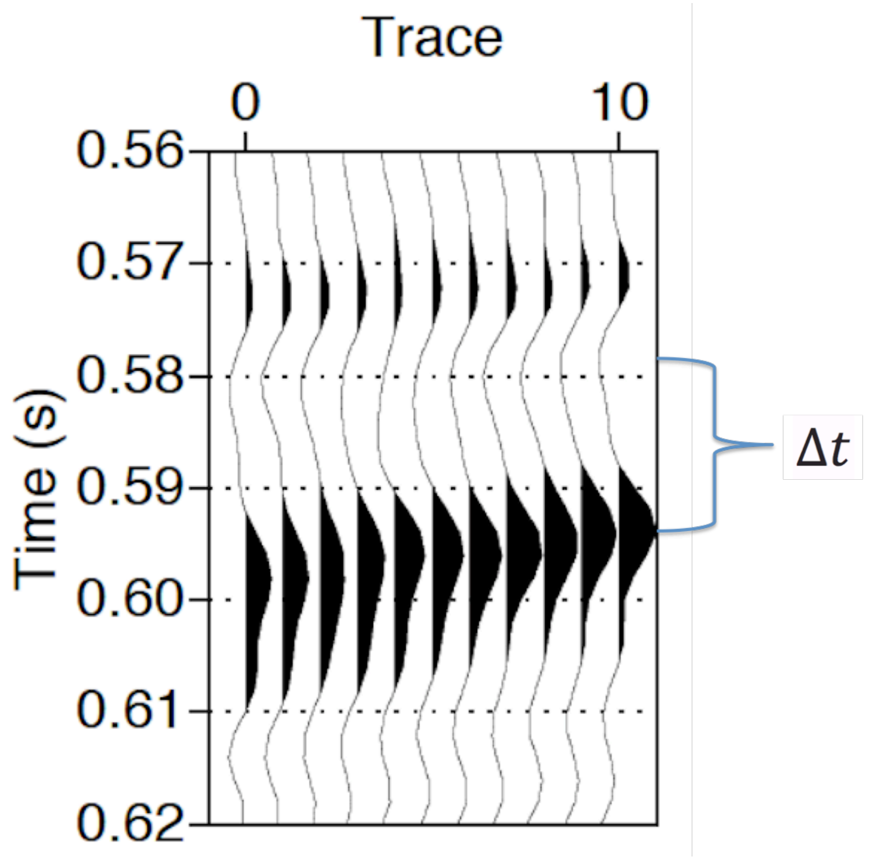


Figure 57: How to measure the difference in time between a traces trough and peak. Data is from inline 3940 of Wild Creek survey (modified from Liner, 2014).

Average tripolite velocity (V_T) is needed from the previous section's calculations. This value will allow for the use of the following equation to calculate the thickness of the tripolite if greater than the vertical resolution:

(6) $h_T = \frac{V_T \Delta t}{2}$

For the case shown in Figure 57 (trace 10) we find:

(7) $h_T = \frac{V_T \Delta t}{2} = \frac{(13{,}819\ ft/s)(0.016)}{2} = 159$ feet

Reflection time separation associated with the vertical resolution limit of tripolite is:

(8) $\Delta t_{tripolite} = \frac{2Z_{MT}}{v_{MT}} = \frac{2(60\ ft)}{13{,}819\ ft/s} = 0.0086\ \text{s} = 8.6\ \text{ms}$

In other words, when the tripolite trough/peak pair are separated by 8.6 milliseconds or more, the tripolite is vertically resolved and thickness can be robustly estimated. For thinner tripolite cases, thin bed effects dominate and higher risk amplitude analysis would be required (Liner, 2004)

5. RESULTS

In Osage County, the Mississippian was subaerially exposed resulting in the karstified Mississippian-Pennsylvanian unconformity. This unconformity is identifiable in seismic data due to the karstification and weathered lithology contrast. Complete 3D seismic mapping of the unconformity yields an amplitude and time structure map of the top of the Mississippian (Figures 58 and 59) that has surprising detail of the karst in the central to northeast sectors of the survey. This resolution is lost to the southwest where conventional tracking methods fail (Figure 59) where there is a noticeable graben or fault like structure to the west trending to the northeast (Figure 59). This is particularly interesting because northeast trending faults are common in the mid-continent (Figure 60). The unconformity dips to the southwest.

Two techniques were utilized in mapping the tripolite event to detmerine which one performed better: single point amplitude extraction or traditional horizon tracking. These two techniques result in time-structure and amplitude maps, which can be compared (Figures 61 and 62).

The geobody extraction gives the best view of the tripolite, takes less time, and is easier to execute. Furthermore, the geobody provides insight to the structure as well as location of the tripolite chert that is likely the best reservoir rock (lowest acoustic impedance and/or thickest occurrence) (Figure 51). The total area of tripolite in the Wild Creek 3D survey area is roughly 11.6 square miles (Figure 65).

Calculating reflection coefficient (Equation 4) characteristics at the Mississippian-Pennsylvanian unconformity allows us to understand the cause of the strong negative anomaly, specifically, which configuration of rock units will result in the observed behavior. Density values and velocity values come from the Shaw 1A-8 pilot well (Jennings, 2014) allowing us to calculate impedances (Table 2) for each stratigraphic unit (Equation 5) (Table 2). The reflection coefficients from cases 1 and 2 (Figures 53 and 54) are shown in Figures 66 and 67. The only scenario that produces a strong negative anomaly is transitioning from Mississippian dense lime to Mississippian tripolite (R_0= -0.158).

The minimum time thickness needed for the tripolite in the Wild Creek survey to vertically resolve is estimated at 8.6 milliseconds (Equation 8). Table 3 shows the thickness and Δt of traces 0-10 and 90-100 from Figure 56. The average thickness of the tripolite shows to be about 88 feet and is graphed in Figure 68.

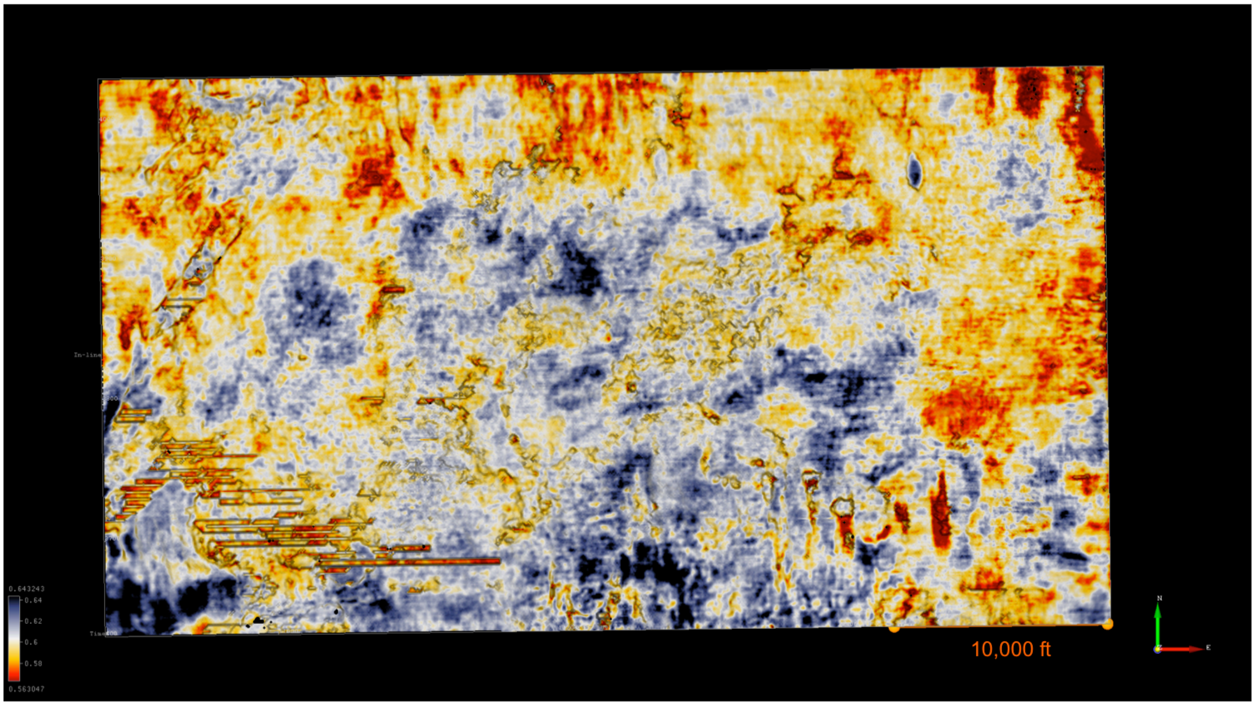


Figure 58: Map view amplitude map of the top of the Mississippian. Recall from the methods section that the tracked seismic event was a peak.

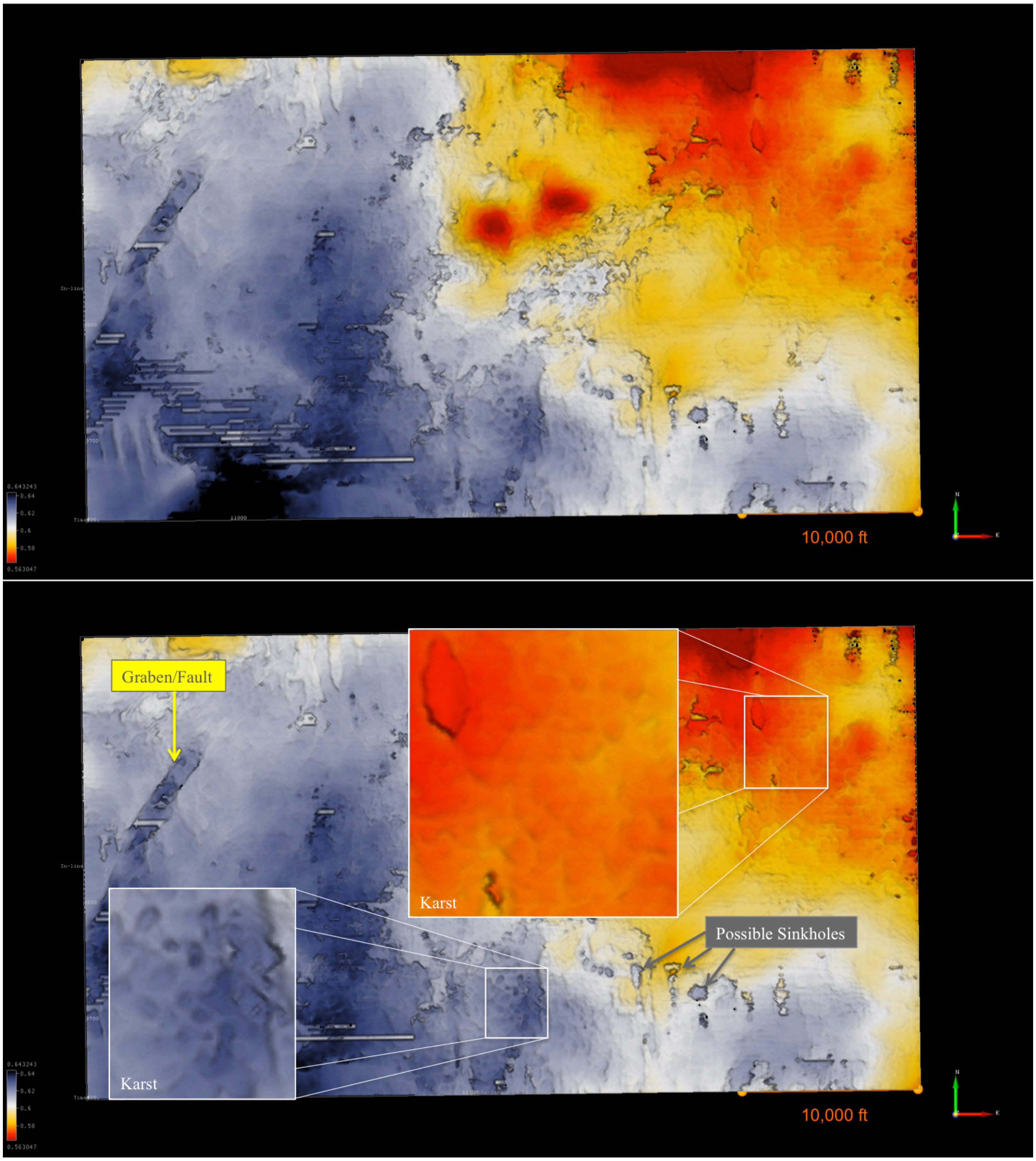


Figure 59: High-resolution time structure map (upper) and interpretation (lower) of the top of the Mississippian. Hot colors are shallow areas while deeper areas are cool colors.

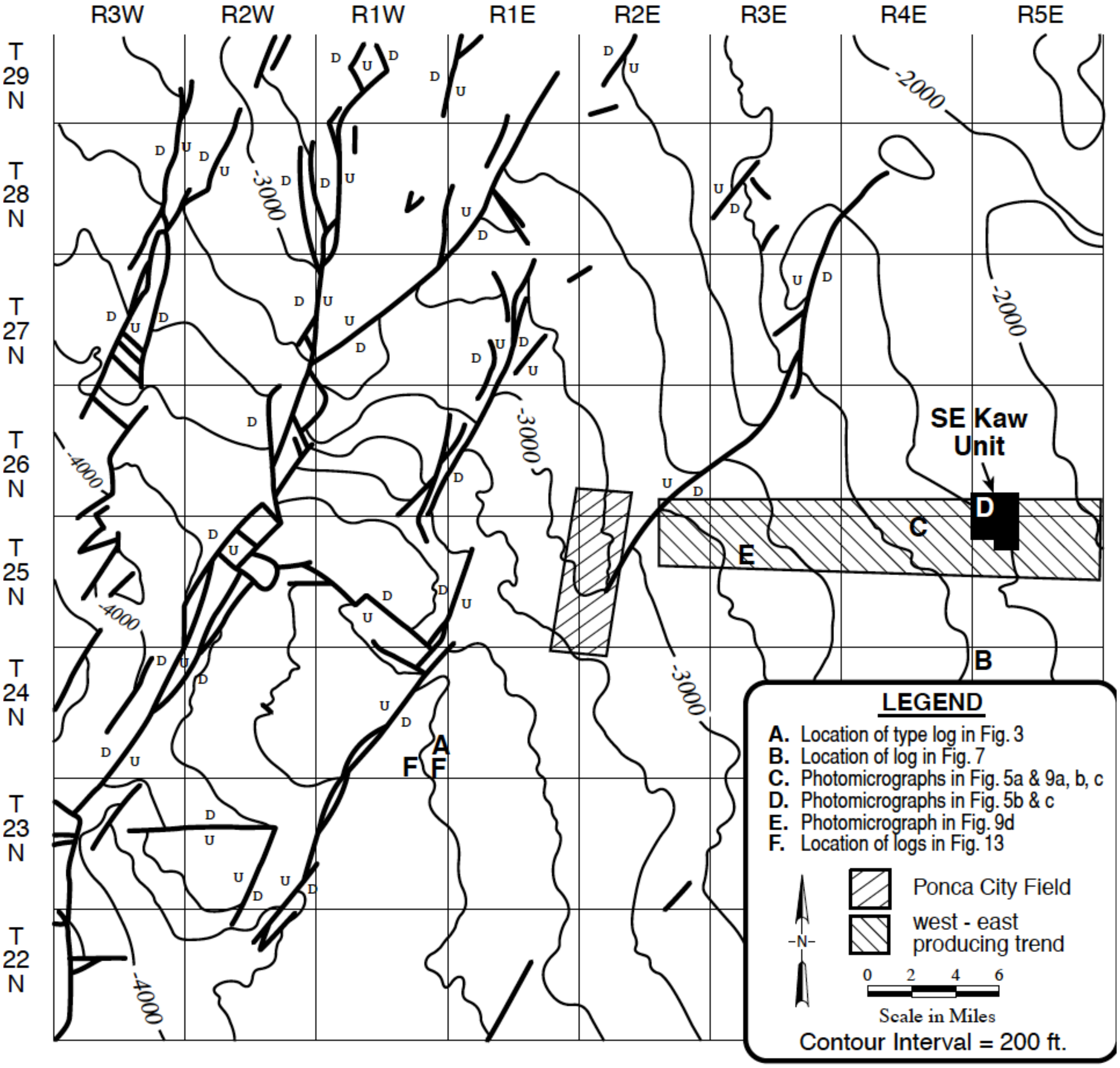


Figure 60: Regional northeast trending faults in Kay County, Oklahoma (Rogers, 2001).

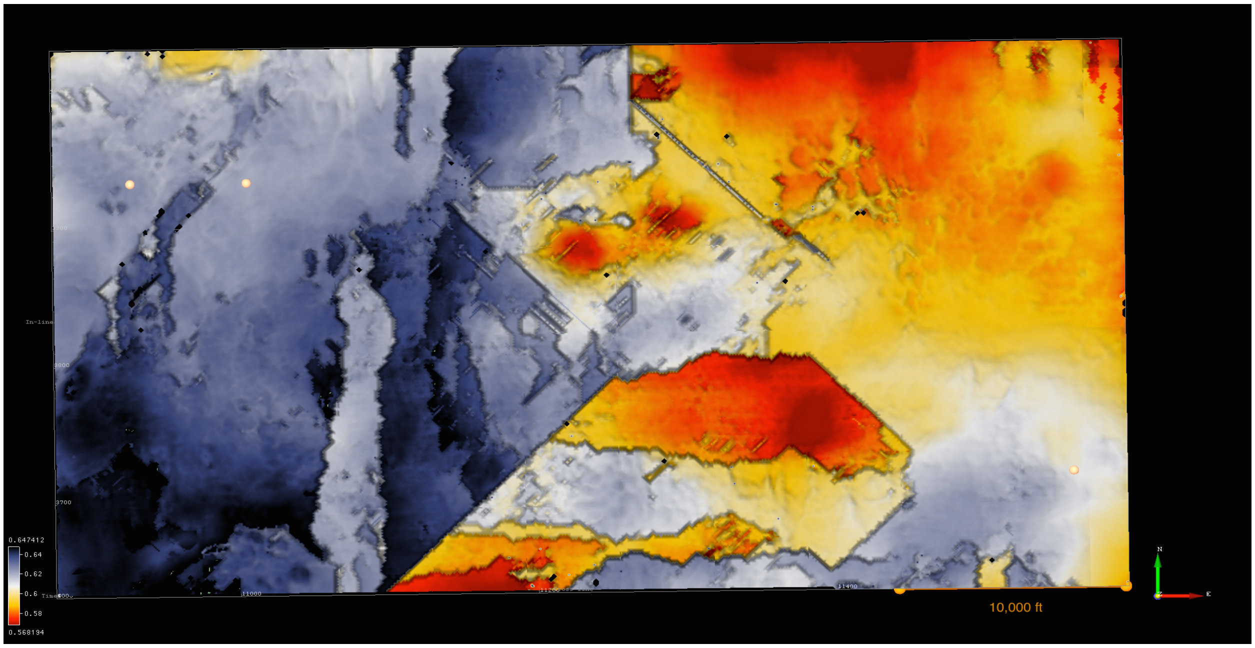


Figure 61: Time-structure map of tripolite horizon from single point extraction (method 1).

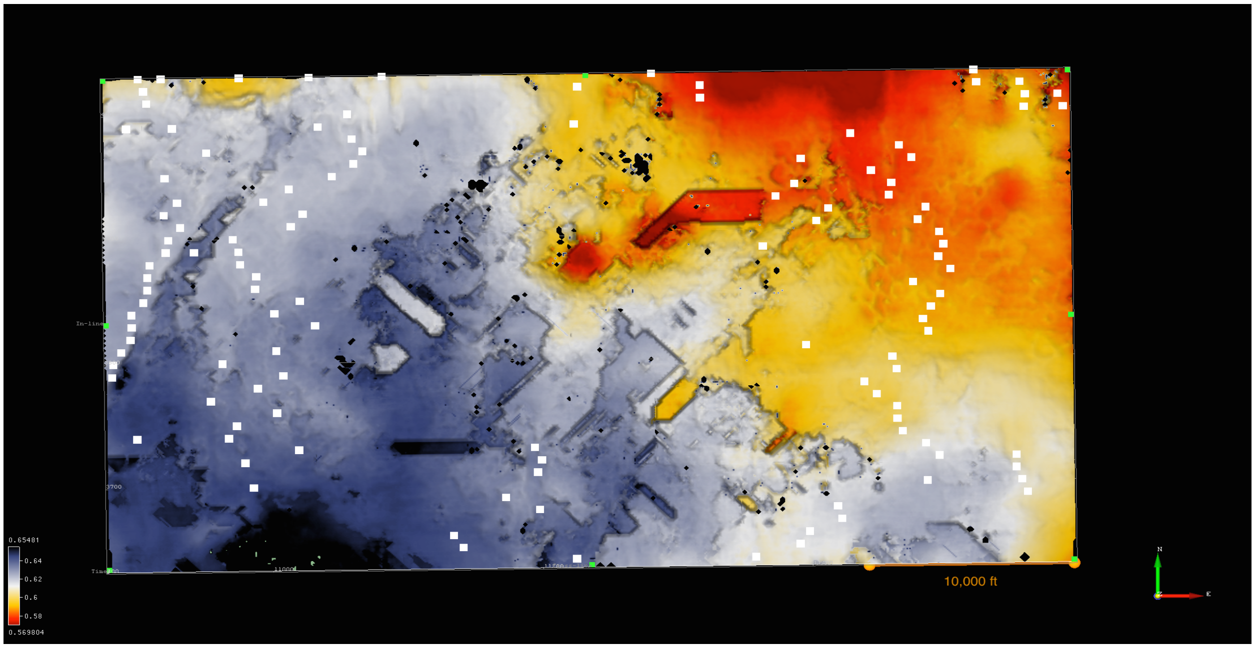


Figure 62: Time structure map of tripolite horizon from traditional mapping (method 2).

Table 3: Table showing thicknesses of tripolite in traces 0-10 and 90-100 with associated delta (change) in time.

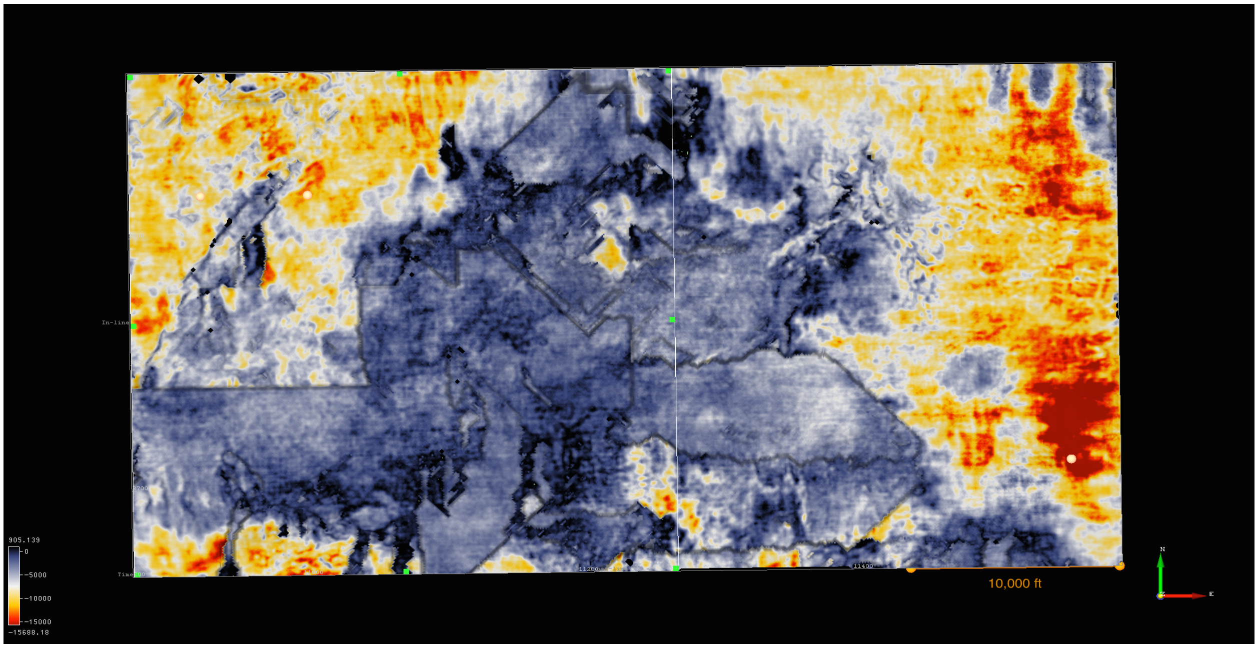


Figure 63: Amplitude map of tripolite horizon from single point extraction (method 1).

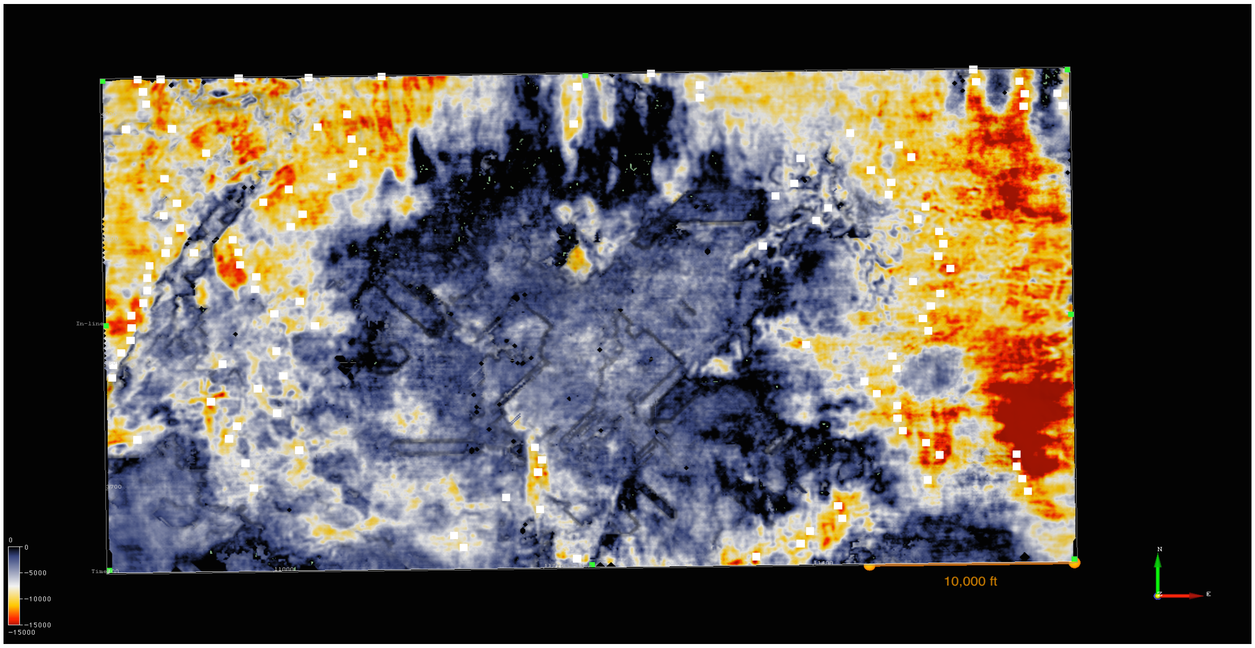


Figure 64: Amplitude map of tripolite horizon from traditional mapping (method 2).

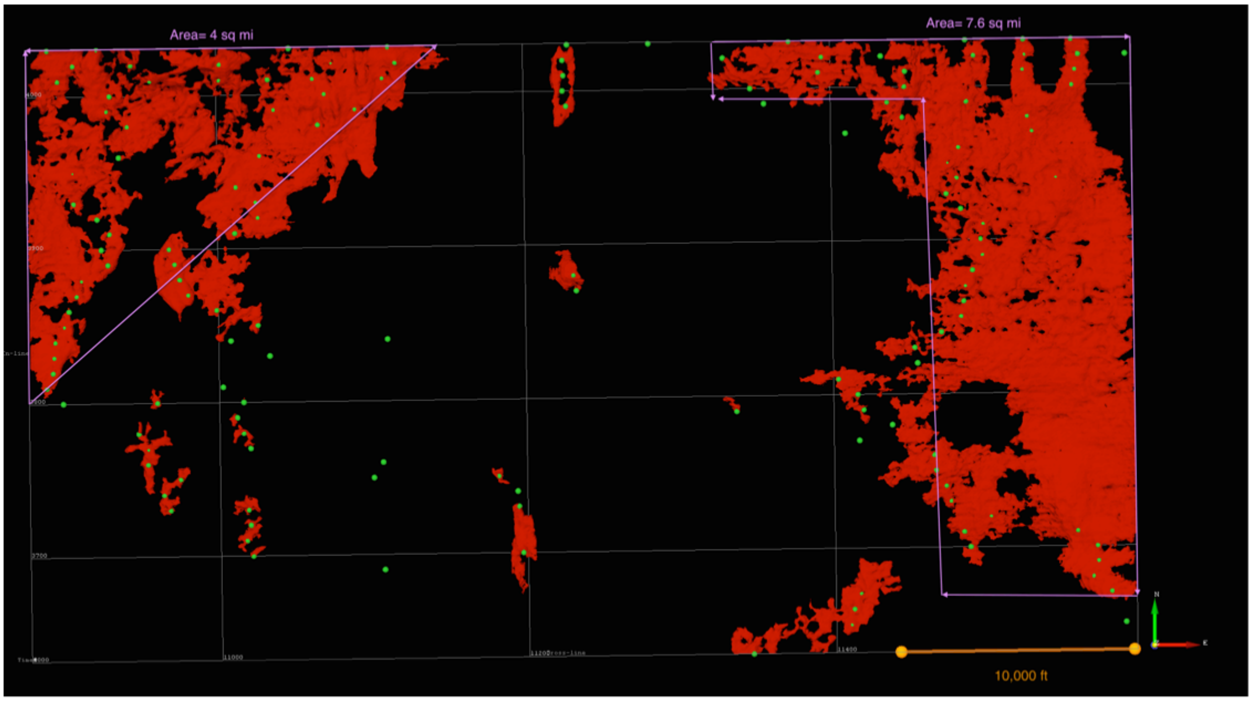


Figure 65: Measured size of the tripolite bodies.

Contact	Reflection Coefficient
Basal Penn to Miss Tripolite	+0.043
Miss Tripolite to Miss Dense	+0.159

Figure 66: Case 1 scenario using reflection coefficient estimates from Figure 55

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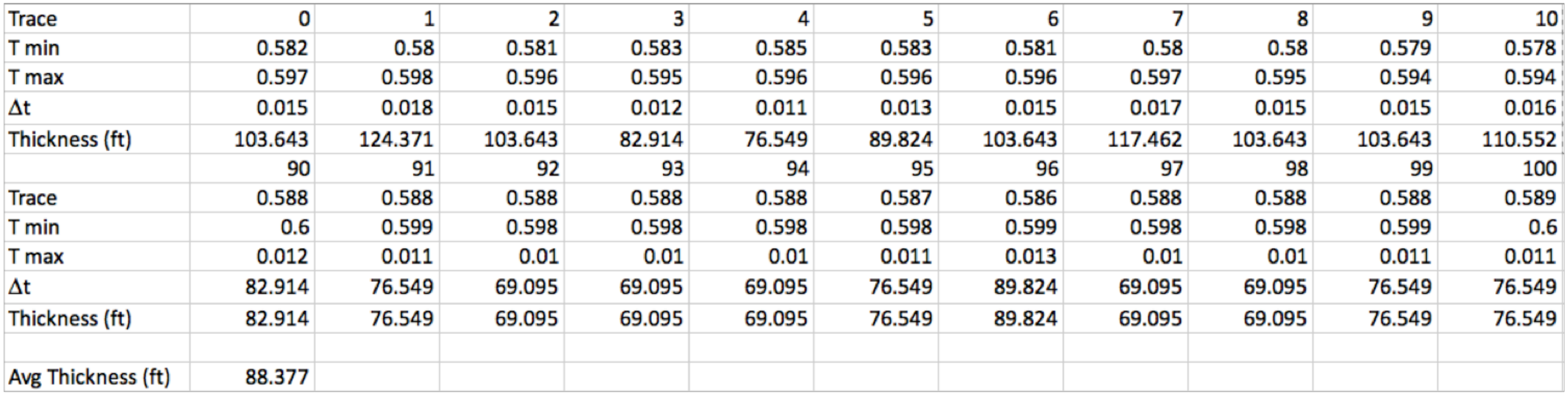
Contact	Reflection Coefficient
Basal Penn to Miss Dense	+0.2
Miss Dense to Tripolite	-0.158
Miss Tripolite to Miss Dense	+0.159

Figure 67: Case 2 scenario that yields large, negative reflection coefficient consistent with field data observations.



Trace	0	1	2	3	4	5	6	7	8	9	10
T min	0.582	0.58	0.581	0.583	0.585	0.583	0.581	0.58	0.58	0.579	0.578
T max	0.597	0.598	0.596	0.595	0.596	0.596	0.596	0.597	0.595	0.594	0.594
Δt	0.015	0.018	0.015	0.012	0.011	0.013	0.015	0.017	0.015	0.015	0.016
Thickness (ft)	103.643	124.371	103.643	82.914	76.549	89.824	103.643	117.462	103.643	103.643	110.552
	90	91	92	93	94	95	96	97	98	99	100
Trace	0.588	0.588	0.588	0.588	0.588	0.587	0.586	0.588	0.588	0.588	0.589
T min	0.6	0.599	0.598	0.598	0.598	0.598	0.599	0.598	0.598	0.599	0.6
T max	0.012	0.011	0.01	0.01	0.01	0.011	0.013	0.01	0.01	0.011	0.011
Δt	82.914	76.549	69.095	69.095	69.095	76.549	89.824	69.095	69.095	76.549	76.549
Thickness (ft)	82.914	76.549	69.095	69.095	69.095	76.549	89.824	69.095	69.095	76.549	76.549
Avg Thickness (ft)	88.377										

Table 3: Table showing thicknesses of tripolite in traces 0-10 and 90-100 with associated delta (change) in time.

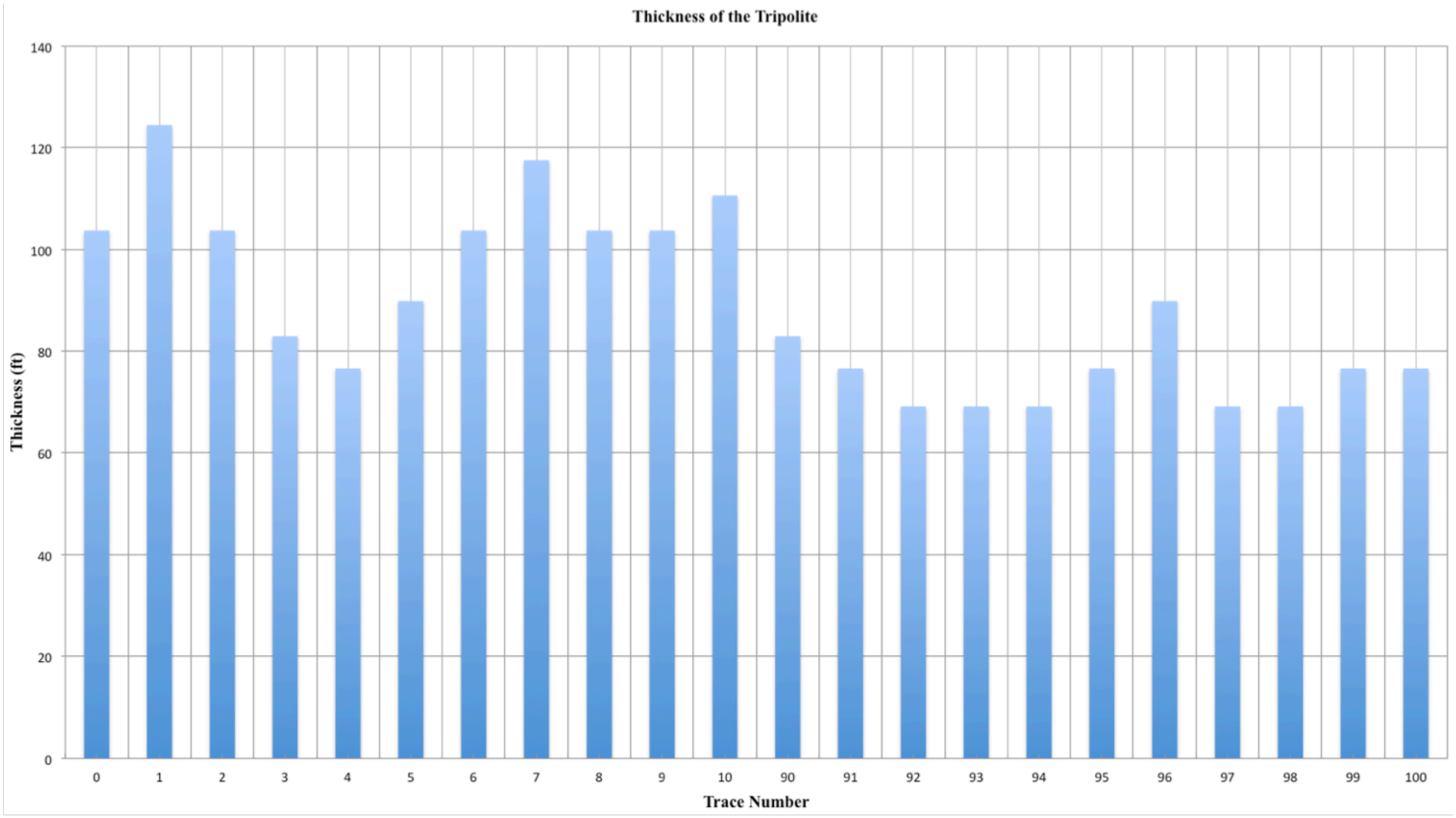


Figure 68: Graph of the thickness of the tripolite from Table 3. Average thickness is 88 feet.

6. CONCLUSIONS

Three methods of 3D seismic tripolite mapping have been presented. When mapping the tripolite with horizons, the traditional method performs the best results because it lacks the large tracking errors associated with the single point extraction method (Figures 62 and 64). This allows for more accurate tripolite representation and interpretation.

The geobody extraction technique is the more efficient way of imaging the tripolite. The geobody extraction allows us to image the 'core' of the tripolite where the max anomaly occurs that might be associated with the lowest tripolite impedance and/or thickest occurrence.

The regional northeast trending faults of the mid-continent may have had control over the diegenesis of the tripolite (Figure 64). The eastern tripolite body is seen sitting around a northeast trending fault/graben of not inconsiderable size. This fault/graben may have acted as a conduit for hydrothermal waters to invade the tripolite. It is well known that hydrothermal activity has occurred in northeastern Oklahoma.

The current study presents resolution and reflection coefficient calculations that support the claim that the negative anomaly is indeed tripolite. With a vertical resolution of 8.6 milliseconds (55 feet), the tripolite is often resolved by the Wild Creek 3D seismic data. Additionally, the average thickness calculated from the seismic data is about 88 feet and the only scenario that yields a negative amplitude anomaly is when tripolite is overlain by Mississippian dense lime. This data supports outcrop observations that the tripolite occurs deeper in the Mississippian section and is separate from the Mississippi chat at the unconformity surface.

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