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Mapping Middle Paleozoic Erosional and Karstic Patterns with 3-D Seismic Attributes and Well Data in the Arkoma Basin, Oklahoma

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MAPPING MIDDLE PALEOZOIC EROSIONAL AND KARSTIC PATTERNS
WITH 3-D SEISMIC ATTRIBUTES AND WELL DATA IN THE
ARKOMA BASIN, OKLAHOMA

by

Alonzo Riley Brinkerhoff

A thesis submitted to the faculty of
Brigham Young University
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Masters of Science

Department of Geological Sciences
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ABSTRACT

MAPPING MIDDLE PALEozoIC EROSIONAL AND KARSTIC PATTERNS WITH 3-D SEISMIC ATTRIBUTES AND WELL DATA IN THE ARKOMA BASIN, OKLAHOMA

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Department of Geological Sciences
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Newly available industry well data and seismic attribute analysis reveal that late Ordovician-early Devonian Hunton Group strata are more widespread (i.e., not removed by mid-Devonian erosion) in the central and southern portions of the Arkoma Basin in eastern Oklahoma than previously thought. This study demonstrates the value of applying seismic attribute analysis to problems of quantifying and mapping stratigraphic features caused by erosions and/or karstification. Well and seismic isochron data in the Red Oak petroleum field for the Viola-Woodford interval (the units that lie stratigraphically beneath and above, respectively, the Hunton Group) show isolated ~40-m thick lenses of Hunton rocks, on average measuring 3 km in diameter, with a surrounding halo of karsted rock. This distribution can be explained in two different ways: 1) Hunton occurrences could represent isolated erosional remnants reflecting incomplete removal of the Hunton Group during Middle Devonian time (pre-Woodford unconformity) or 2) due to karsting and collapse of stratigraphically lower units (Viola or Bromide carbonates), lenses of
Hunton rocks would have sagged into sinkholes where they were preserved beneath regional base level.

Using formation tops from a well data set correlated with attribute and structure maps from a proprietary 3-D seismic data set, we identify three seismic characteristics in the middle Paleozoic interval that correlate well with: 1) absent Hunton seismic markers, indicating that Hunton rocks were completely removed, 2) the Hunton contacts, indicating where a seismically visible section of Hunton rocks remains, 3) absent Hunton but with a thin horizon included within lower carbonate strata that is interpreted to be an incipient karst zone, which is consistently adjacent to areas containing Hunton rocks.

The base of the Sylvan Shale and the top of the Woodford Shale, the respective lower and upper adjoining units, form significant chronostratigraphic surfaces. As such, anomalous thicknesses of these units are depositionally related; thick Woodford sections often correlate to thin or absent Hunton rocks, possibly indicating back-filled pre-Woodford channels eroded into or through the Hunton Group. Conversely, when there is little or no Woodford thickening over Hunton lenses and when adjacent areas show thinning and partially karsted Viola rocks, we propose that karstic collapse of Viola strata was responsible for the Hunton rocks preservation. A combination of these models may be necessary to account for areas where we see thinning both in the Woodford and Viola, suggesting that a Hunton lens is structurally lowered due to karsting, but due to its erosionally resistive nature, the lens forms a depositional high, causing the Woodford to thin over it. The 3-D approach is absolutely necessary to reveal the subtle waveform details that illustrate the karstic and erosional processes involved in the preservation of the Hunton wedges.
These findings were interpolated, constrained by well data, over the entire Oklahoma portion of the Arkoma basin in order to produce a new Hunton isopach map and 20 separate cross-sections (two shown herein). These show a broad linear region of absent Hunton. Eustatic sea levels rose throughout the middle and late Devonian, so this large area of eroded Hunton is interpreted as a post-Hunton, pre-Woodford structural uplift. Other Hunton wedges, similar in size and extant to that seismically imaged in this study, were also found in the well data. The karstic collapse of the Viola and subsequent preservation of Hunton rocks occurred on both limbs of the arch.
I wish to thank my coauthors, John McBride, Bill Keach, Scott Ritter, Tom Morris and Vince Felt, all of whom contributed so much of their time and expertise to this project. Each of them was always willing to answer my endless string of questions and help keep me on course.

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# TABLE OF CONTENTS

Abstract ................................................................. iv

Introduction ............................................................. 1

Purpose of Study ....................................................... 2

Geologic Setting ......................................................... 4
  Structure and Tectonics ............................................. 4
  Stratigraphy and Depositional Environment ................. 6

Methodology .......................................................... 7

Data Interpretation ................................................... 11
  Seismic Character of the Hunton ............................. 11
  Imaging Collapse Features within the Viola Group ....... 13
  Using Amplitude Extractions to Characterize the Hunton Wedges .......... 15
  Using Waveform Classification to Differentiate Hunton Rocks from Viola... 17
  Modeling Hunton Preservation .................................. 18

Regional View ......................................................... 19

Geological Mechanism for Collapse Structures .............. 21

Potential for Solution Collapse within the Viola .......... 22

Conclusions .......................................................... 24

References ............................................................ 26

Figures ................................................................. 30
  Figure 1 Structure-Depth Map of the Hunton Group ....... 30
  Figure 2 Isopach of the Hunton Group ....................... 31
  Figure 3 Location Map of the Study Area within the Arkoma Basin ......... 32
Figure 4  Strat Column with Estimated Sea Level Curve………………………..33
Figure 5  Interpreted and Annotated Seismic Section through Hunton Rocks…..34
Figure 6  Isochron of the Hunton Group Overlying a Time-Structure Map of the
        Top of the Viola………………………………………………………..35
Figure 7  Isochron of the Woodford Shale……………………………………….36
Figure 8  Total Amplitude Map of the Hunton Overlying a Time-Structure Map of
        the Top of the Viola……………………………………………………37
Figure 9  Seismic Section Relating Hunton Filled Sinkholes to a Total Amplitude
        Attribute Map…………………………………………………………...38
Figure 10 Six Part Waveform Classifier Map……………………………………39
Figure 11  Arc Length Map……………………………………………………....40
Figure 12  ESP 3-D Map…………………………………………………………41
Figure 13  Interpreted Lithology Log Correlation in the Red Oak Gas Field……42
Figure 14  Interpreted East-West Lithology Log Correlation 1 through the
        Oklahoma Portion of the Arkoma Basin……………………………….43
Figure 15  Interpreted East-West Lithology Log Correlation 2 through the
        Oklahoma Portion of the Arkoma Basin……………………………….44
Figure 16 Models Relating Hunton Preservation to Local Changes in Woodford
        Shale Thickness………………………………………………………..45
Figure 17  Correlation of Woodford Models to the Woodford Isochron………..46
Figure 18  A Model Demonstrating the Rapid Removal of Hunton Rocks from
        Non-Karstic Area………………………………………………………..46
Figure 19  Woodford Shale Isopach Map of the Oklahoma Portion of the Arkoma Basin
Figure 20 Schematic Diagram Showing the Stages of Collapse of the Viola
Figure 21  Photograph of a Sinkhole Filled with Carbonate Debris
Figure 22  Photograph of a Core Containing Collapse Breccia
Figure 23  Photograph of a Core Containing Collapse Features
Figure 24  Interpreted and Uninterpreted Photographs of the Great McKelligon Sag, an Analogy of the Viola Collapse
Figure 25  Correlation of the Six Part Waveform Map with the Schematic Model of Figure 20
Appendices
Appendix A  Parameters of the Combined 3-D Seismic Survey
Appendix B  Explanations of the Arc Length Extraction
Introduction

The Hunton Group is an Ordovician-Devonian heterolithic succession of carbonates and shales deposited on a south-dipping ramp. It is currently ranked first in daily oil production and third in daily gas production in Oklahoma. However, in the Arkoma Basin of eastern Oklahoma, relatively few wells have penetrated the Hunton Group, and little is known about its stratigraphic character and distribution. It is present, although mostly in the subsurface, from the Texas Panhandle through most of Oklahoma and into western Arkansas (Shannon, 1962; Amsden, 1980). Oil was first discovered in the Hunton Group in 1921 in eastern Oklahoma (Northcutt, 2000). Since then it has produced enormous quantities of oil and natural gas, most notably in the Anadarko Basin of western Oklahoma. In the period stretching from Jan. 1977 to Sept. 1999, the Hunton Group produced 157,118,000 barrels of oil and 46,759,666 million cubic feet of natural gas (Northcutt, 2000).

Previous studies of the Hunton include its description, naming and designation as a formation by Taff in 1902, stratigraphic and paleontologic studies by Reeds (1911, 1927), Maxwell (1936), Christian (1953), Amsden (1957, 1960, 1961, 1973, 1975, 1980, 1984 and 1989), Maxwell (1959), England (1961), Shannon (1962), Hollrah (1978), and Amsden and Barrick (1988). It was raised to group status by Amsden in 1980. The Hunton Play in Oklahoma, a special publication compiled by the Oklahoma Geological Survey in 2000, is the most recent large-scale work available. Most of these works have concentrated on the Hunton in regions where it is close to the surface and has historically been a major producer, such as the southern Anadarko Basin and Cherokee Platform. The southern portion of the Arkoma Basin in eastern Oklahoma has received scant
attention because here the Hunton is deep, averaging about 12,000-16,000 ft (3600-4900 m) (Fig. 1), and in many places is relatively thin. In a broad, ~ 25 mile (32 km) wide, 100 mile (128 km) long belt, (Fig. 2), it was completely eroded away during Devonian time.

Many different subcrop isopach maps have been produced of the Hunton over the last century (Tarr, 1955; Maxwell, 1959; Shannon, 1962; England, 1961; Amsden, 1980; Rottmann, 2000). All of these maps show the Hunton pinching out to the south in the central Arkoma Basin. In light of new data and interpretations presented in this paper, we will conclude that Hunton rocks are found much farther to the south than was previously thought. New drilling has encountered Hunton rocks in areas where it was previously thought to be absent. The Hunton Group is becoming the focus of petroleum exploration, making a study of the Hunton in the Arkoma Basin very relevant at the present time.

**Purpose of Study**

The primary objective of this study is to examine the ability of seismic attribute mapping to accurately present erosional and karstic features. An ancillary objective is to determine the regional extent and thickness of the Hunton Group in the Arkoma Basin. Hunton strata were mapped on two scales: a large regional scale that includes the entire Oklahoma portion of the Arkoma basin, and on a seismic scale to better understand stratigraphic problems associated with the newly recognized southern erosional edge of the Hunton. To accomplish this goal, we determined how best to seismically resolve and map the erosional edge using 2-D and 3-D seismic and well data sets, utilizing state of the art seismic attribute analysis to differentiate the Hunton rocks from surrounding strata. This was difficult because of the variability of the rocks directly above the
Hunton, ranging from thin conglomerates to cherty shales to sandstones. As the Hunton erosional pinchout is not a simple feather edge, but instead is found scattered into progressively thinner lenses, it was also imperative that we used the adjacent stratigraphy to model its depositional and preservational history. We first mapped the Hunton carefully within a producing gas field using a high quality 3-D seismic survey, modeled the coeval karstic and erosional processes involved in the preservation of the Hunton in the area and then extended our model throughout the Oklahoma portion of the Arkoma Basin by correlating data from 1,569 well penetrations.

The 3-D seismic survey used for this study comes from the Red Oak gas field of the triangle zone between the Ouachita Mountains and the southern Arkoma Basin. The study area consists of a rectangle about 4 mi (6.4 km) north of the Choctaw Fault, in Latimer, Haskell and Le Flore counties, about 20 miles (32 km) west of the town of Poteau (Fig. 3). Hunton rocks are completely absent along most of the northern and eastern parts of the area, and where present comprise thinly lenticular bodies of sedimentary strata.

We focused on the interval ranging from the top of the Woodford Shale to the base of the Viola Group, which underlies the Hunton (Fig. 4). This interval was chosen because of the depositional relationship these rocks share with the Hunton. The base of the Sylvan Shale and the top of the Woodford Shale, the respective lower and upper adjoining units, form chronostratigraphic surfaces (Rottmann, 2000). As such, anomalous thicknesses of these units are inversely related: the Woodford Shale is thickest where the Hunton Group is thin or completely absent, possibly indicating back-filled pre-Woodford channels or some other geologic mechanism causing relief (i.e., karsting). Conversely,
when there is little or no Woodford thickening over Hunton lenses and when adjacent areas show partially karsted Viola rocks, we propose that karst-induced collapse of Viola strata lowered Hunton rocks below the paleo-regional base level and thereby preserved them. We will show that a combination of these models may apply wherein a Hunton lens is structurally lowered due to karsting, but due to its resistive nature, the lens forms a depositional high, causing the Woodford to thin over it.

Geologic Setting

Structure and Tectonics

The Arkoma basin is a foreland basin underlying much of eastern Oklahoma and western Arkansas, and extending south to the Choctaw Fault, which experienced maximum displacement during the Early Permian time (Whitaker, 2006) (Fig.3). This fault forms the boundary of the frontal zone of the Ouachita Mountains, which stretches the length of the southern portion of the basin. In general, the basin deepens and thickens toward the south, into the Choctaw Fault (Amsden, 1984). The Ouachita Mountains are part of a mostly buried late Paleozoic fold-and-thrust belt that extends from Alabama to northern Mexico. In Oklahoma, the Ouachita Mountains and the Arkoma basin can be divided into four tectonic provinces (Fig. 3) on the basis of different structural styles (Arbenz, 1989; Suneson and Campbell, 1990). From north to south they are (1) the Arkoma foreland basin, a mildly compressed fold belt of Pennsylvanian and older strata, (2) the frontal thrust zone, which lies between the Choctaw and Windingstair faults and consists of severely shortened, north- and northwest-vergent imbricated thrusts and tight folds of mainly Pennsylvanian strata, (3) the central thrust zone, characterized by broad open synclines separated by tight, typically thrust-cored anticlines of mainly
Mississippian and Lower Pennsylvanian turbidites, and (4) the Broken Bow uplift, which consists of isoclinally folded and faulted Lower Ordovician to Lower Mississippian strata (Lillie et al., 1983; Thomas and Viele, 1983).

The tectonic history of the Oklahoma portion of the Ouachita orogen can be summarized as follows. During the late Precambrian and Early Cambrian, opening of the Iapetus Ocean produced an irregular rifted margin of the North American craton (Thomas, 1991). Subsequently, a broad, southward dipping continental shelf formed on the south end of North America, becoming a prolific carbonate ramp from Late Cambrian to Early Devonian time (Amsden, 1984). These sediments are represented by a succession of widespread, thin carbonate units, separated from one another by thin shale units and unconformities. These are interpreted as representing terrigenous input and lowstands, as a fall in sea level would rejuvenate fluvial systems, causing not only a hiatus in carbonate deposition, but also providing energy to transport siliceous material.

Continental convergence began in the Late Mississippian between North America and the colliding tectonic terranes (collectively called the Sabine plate) along a southward-dipping subduction zone (Whitaker, 2006). In Atokan (middle Pennsylvanian) time, before the study area experienced large-scale thrusting, the shelf was broken by mostly down-to-the-south normal faulting, apparently induced by obduction of the approaching Ouachita accretionary prism and related loading of the continental margin (Houseknecht, 1986; Sutherland, 1988). The subsequent orogeny culminated in the Early Permian (Whitaker, 2006). Regional tectonic transport in the Ouachita fold-and-thrust belt was north-northwestward, approximately perpendicular to present orientations of fold axes and fault traces (Lillie et al., 1983).
Stratigraphy and Depositional Environment

The Hunton Group consists of organo-detrital limestones and related dolomites, and shales (Fig. 4) deposited in a warm shallow sea on a gently south-dipping ramp during Late Ordovician through Early Devonian time (Al-Shaieb, 2000). In the study area it ranges from completely absent to over 300 ft (~110 m) thick. The Hunton Group is the topmost member of the Tippecanoe Sequence (Sloss, 1959) in the southern mid-continent. Throughout the basin Hunton strata generally dip to the south (Fig. 1) into the Choctaw Fault Zone, the deepest Hunton penetration in the Arkoma basin is approximately 18,000-ft (5500m).

Hunton deposition was not continuous, however, with unconformities occurring in the Early Silurian, Middle Silurian, and Early Devonian (Amsden, 1980). Several major unconformities occur in the study area, the most important for this project being the post-Upper Silurian Henryhouse pre-Lower Devonian Frisco erosional unconformity, defined as a third order regional unconformity, and the post-Hunton, pre-Woodford erosional unconformity, defined as a second order unconformity (Fritz and Medlock, 1995). The pre-Frisco unconformity stretches from Ludovian to Helderbergian time during which the Henryhouse Formation was stripped away over most of eastern Oklahoma, (Amsden 1980; Rottmann, 2000). The subaerially exposed surface (almost entirely Llandoverian-Wenlockian Chimneyhill Subgroup) was subjected to dissolution, producing in places up to 3 ft (1 m) of relief (Amsden, 1980). The resulting unconformity was followed by the deposition of the Frisco and Sallisaw Formations, separated by a small, fourth order unconformity.
The post-Hunton, pre-Woodford erosional unconformity occupies all of the Middle Devonian (Emsian-Givetian). The present-day extent of the Hunton is largely controlled by erosion that occurred during the time of this unconformity (Fig. 2) (Hollrah, 1978; Amsden, 1980). Because eustatic sea level rose through the Devonian, (Fig. 4), this unconformity is usually thought to represent a period of substantial uplift (Tarr, 1955; Amsden, 1980), although some workers believe the unconformity instead represents a major lowstand and that the time represented may have been relatively short, based on the absence of dolomite and karst in the Frisco (Kuykendall and Fritz, 1993). The model linking the Middle Devonian unconformity to moderate uplift of the region is supported by the Hunton Group isopach map constructed during the course of this study. A major transgression followed Middle Devonian erosion during which the Misener Sandstone (the basal member of the Woodford, composed of a cherty, fluvial lain lag), as well as the Woodford (Fig. 4), were deposited. Dissolution of the pre-Woodford surface during this unconformity produced a network of relatively deep crevices and caverns in many of the Ordovician-Devonian carbonates, some of which measure 50 ft (~ 18 m) across (Amsden, 1961; Matthews, 1994; Sykes, 1997). Where the Hunton was not removed by this unconformity, its surface was often etched by fluvial erosion, with the extent of the erosion ranging from very little to complete removal. Previous workers have built isopach maps of the Misener member (Fig. 4), which show an overall down to the south dendritic stream pattern, modified by faulting and fracturing along the north-south Nemaha Ridge (Kuykendall and Fritz, 1993, Rottman, 2000).
Methodology

The 3-D seismic survey used in this study is actually two separate surveys, the first of which was recorded in 1999 and the second in 2001. These two surveys were merged in reprocessing and represent the data set used in this study. Of interest is that the 2001 survey was, at the time, one of the most densely sampled land data sets in the world. It had over 1 million prestack traces per square mile (1.6 km), and because of its 55 ft (16.74 m) bin size (common depth point), its nominal fold of cover was over 700. It was shot so densely in an effort to overcome very strong surface wave contamination (ground roll) that obscures so much reflection data in the lower Pennsylvanian Red Oak Sandstone (the greatest producing interval in the Red Oak gas field). The high fold data helped to, but did not completely overcome the ground roll issue in the Pennsylvanian section. However, it is not an issue in the much deeper carbonate rocks involved in this study. This high nominal fold of cover ultimately provided us with very high quality data in areas of interest relating to Hunton stratigraphy.

The combined migrated data set has 866 east-west in-line profiles and 1415 north-south cross-line profiles, for a total of 1,225,390 bins (common cell gathers). The source line orientation was north-south and the receiver line orientation was east-west in both surveys. The length in the cross-line direction is 12 mi (19.31 km) and in the in-line direction 8 mi (12.87 km), for a total of 103 mi² (266.77 km²). The quality of the data varies according to the fold coverage. Because our data set represents two merged data sets, maximum fold reached in the central part of the data was 288 and decreased toward the edges of the survey. The data were recorded in the field by SEG (Society of
Exploration Geophysicist) standards, meaning that an upward motion of the earth creates negative amplitudes on the geophones.

The surface consistent deconvolution, a process to remove undesired filtering by the earth (Biggs, 2004), assumed a minimum phase source (i.e., dynamite). The vibroseis data were converted from zero phase (where the wavelet is symmetrical about zero time) to minimum phase (where the wavelet has a causal relationship with real world geology) before deconvolution so that it would be consistent with the dynamite data and a single deconvolution algorithm could be performed on the entire combined survey. Zero phase is preferred over minimum phase because zero-phase data tend to provide sharper definition and less distortion between stratigraphic features in the subsurface (Addison, 2002), in this case helping us define the Woodford-Hunton contact. Application of deconvolution ensures that the data are near zero phase. Special care had to be taken with phase consistency because this is a merged survey and because of the detailed stratigraphic interpretations extracted from the waveform. No other subsequent data processing was applied that might alter the phase of the data. Further information on the acquisition and processing parameters can be found in the Appendix.

We seismically mapped the following five horizons: top and base of the Woodford Shale, top and base of the Viola Group, and a weak, interrupted horizon within the Viola (Fig. 5). Areas where the Hunton is absent were defined as zones where the base of the Woodford Shale coincided with the top of the Viola Group. In Hunton zones, we could subtract the base of the Woodford from the top of the Viola in order to obtain a Hunton isochron map. The Sylvan Shale was not resolvable in our seismic data and so was grouped with the Hunton. Travel time-structure maps were created by mapping
these horizons in every fifth section, in both in-line and cross-line directions. Areas with Hunton rocks present were mapped even tighter, ranging from every third line to every line, due to their weak amplitudes, which were difficult for interpolation mapping algorithms (auto pickers) to track. Fault heaves, the horizontal offset distance that a once continuous formation is separated by a normal fault, are represented by gaps in the horizons. Control polygon maps were drawn by connecting the gaps representing the fault heaves. These maps end up being a series of polygons that outline each fault heaves. The control maps were used with an interpolation algorithm to build a complete horizon from the interpreted lines. The control maps kept the algorithm from building the horizons across the faults. We then used these horizons to build accurate isochron maps of the Woodford, Hunton/Sylvan, and Viola intervals through subtractive computations (Figs. 6 and 7).

As we began to understand how these units related to one another, we were able to choose which seismic attribute extractions would best illustrate the erosional and depositional relationships that these rocks share. Seismic attributes are a name given to any number of mathematical extractions from the seismic data set (Brown, 2004). Attributes are used to isolate particular features of the seismic response that have geologic significance, such as an amplitude extraction showing a high amplitude fluvial channel against a low amplitude backdrop representing overbank muds (Brown, 2004). The attribute extractions we performed imaged the zones of interest using three different extraction processes; direct extraction through a total amplitude algorithm (Figs. 8 and 9), a statistical analysis of the wavelet (to mathematically identify relevant trends in the different frequency components of the waveform) over the zone of interest through a
waveform extraction (Fig. 10), and the isolation of wavelet components through
certainty and phase extractions (Figures 11 and 12). Some extractions imaged Hunton
rocks better than others; many tended to clump Hunton rocks with unrelated deeper Viola
phenomena. We quality checked the attribute extractions by carefully building an
isochron of the Hunton (Fig. 6) and comparing them with the attribute extractions.
Many, like the arc length extraction (explained in the Appendix) of Figure 11, map the
Hunton, but clump them with the Viola phenomena (compare Fig. 11 to Fig. 6).
Clumping of Hunton and Viola phenomena tended to occur in the frequency dominated
extractions like arc length, energy halftime, effective bandwidth and dominant frequency
series. The extractions that we used for this study are explained in the Data Interpretation
section.

Having mapped the Hunton in some detail on the northern tip of its southern
erosional edge in the Red Oak area, we extrapolated our Hunton preservation model
across the entire Oklahoma portion of the Arkoma basin (Fig. 2). We mapped
occurrences of the Hunton using 1569 well formation tops, first penetration depths from
sample logs and scout tickets of wells that penetrated to Ordovician-age strata, similar to
what Amseden did for his 1980 Hunton subcrop map, but with more wells than what he
had available. In the Oklahoma portion of the Arkoma basin, isopach maps of both the
Hunton and Woodford Shale and a depth map for the Hunton were built using a least
squares gridding algorithm. Cross-sections were created using with wells providing the
stratigraphic control (Figs. 13, 14, and 15).

Data Interpretation

Seismic Character of the Hunton
We began our interpretation of the data set by using synthetic seismograms from six separate wells to correlate formation tops from the well data to stratigraphically relevant horizons in the seismic sections. A first-order observation are the low amplitude doublets (Fig. 9) that lie between the easily interpreted, high amplitude Woodford base and the top of the Viola Group, also a high amplitude horizon. A 2005 well in the Red Oak gas field established that these low amplitude doublets are Hunton rocks (Fig. 9). Within the Hunton wedge perforated by the well, the base Woodford surface (top of the Hunton Group) was found to be 165 ft (~50 m) above the Viola surface, separated by 102 ft (~31 m) of Hunton rocks and another 63 ft (~19 m) of Sylvan Shale (Fig. 9).

A synthetic seismogram was constructed by convolving the 2005 well’s density log with its sonic log. This was then used to tie the well stratigraphic picks to the seismic data and to define the seismic character of the Woodford Shale, Hunton Group and the Viola Group. The top of the Woodford Shale is a high amplitude, very continuous, seismic minimum, and the base is the following maxima, which would be a very low amplitude in the presence of Hunton rocks, but substantially higher if lying directly on the Viola Group (Fig. 9). The Hunton interval was defined as a discontinuous, low amplitude doublet, 20 to 30 ms in width. The Sylvan shale is not distinguishable from the Hunton, being a shale with a slower seismic velocity. This is the reason that the base of the Hunton/Sylvan interval is a maxima. This same high amplitude, continuous maximum is defined as the top of the Viola. The interpreted Viola horizon includes the underlying Bromide Dense Member of the Bromide Group, as they are also not seismically distinguishable. The base of this interval is defined on the following high amplitude, continuous minimum (Fig. 9).
The seismic reflection response in each wedge of Hunton differs significantly from the reflection response in areas of absent Hunton. This difference in seismic behavior is well illustrated in our data when the amplitude of the Hunton doublet is displayed across the interpreted Viola surface (Fig. 8). On it are irregular amplitude lows that match the Hunton wedges, as seen in comparison of this figure with the Hunton isochron map on Fig. 6. This isochron surface was constructed so that it followed the apex of a reflection trough located between the interpreted base of the Woodford Shale and the top of the Viola Group.

Imaging Collapse Features within the Viola Group

One unique aspect of the Arkoma basin stratigraphy that was revealed during the course of this study was the manner in which Hunton rocks have been influenced by solution collapse that originated in rocks of the deeper Ordovician-age Viola Group, and how these complicated Woodford depositional thickness as it covered the area. This is illustrated in a well lithology log correlation in the Red Oak Gas Field (Fig. 13). Accurately mapping the Hunton wedges’ effect on Woodford thickening (Fig. 7) and the wedges’ geometries (Fig. 6) is currently only possible using 3-D seismic data. The seismic-interpreted Viola surface developed in this study is displayed in Figure 6. An important observation is that these Viola depressions are positioned directly below equivalent lenses of Hunton rocks approximately 100 ft (~30 m) thick, supporting the interpretation that there is a genetic relationship between the wedges of Hunton rocks and the underlying Viola depressions.

These structural collapse zones occur at a high spatial density, with adjacent collapses often separated by only 1 mi (1,600 m) or less (see Fig. 6). Because of the
severe topographic disruption that these collapses caused on the Hunton surface, these Viola collapses were a significant influence on Mississippian sedimentation, and thus should be considered when trying to understand sedimentation patterns over karst-prone carbonates.

This karsting phenomenon is further illustrated by inspecting the sinkholes on a seismic-derived calculated event similarity prediction (ESP 3D) map extracted from the Viola interval (Fig. 12), from which location, size, shape, and orientation of the Hunton lenses and the sinkholes in Viola group rocks (near the Hunton base) can be derived. ESP volumes are essentially a measure of trace-to trace similarity, so discontinuities in the seismic data are enhanced (Haber and Wilk, 2006). Inspection of the ESP map (Figure 12) shows that ovoid disruptions (appearing as white areas) occur across the top Viola horizon. Correlating this disruption pattern with the Hunton isochron map (Fig. 6) confirms that each of these anomalies in the seismic reflection response corresponds to a depression in the Viola surface topography. ESP 3D computes local trace to trace dissimilarity. The advantage of dissimilarity data is that it reveals and heightens lateral seismic changes that often relate to geologic changes. These dissimilarity measurements yield the visual identification of such features as faults, facies changes, and other geologic patterns. Faults and stratigraphic changes (such as the collapse features within the Viola) will often stand out as prominent anomalies in otherwise apparently homogenous data displays (Hagdo and Johnson, 2006). Conceptually, you would expect high similarity values from trace to trace when the strata are flat and continuous, lower values when they are dipping and continuous, and anomalous values when they are discontinuous. The ESP map (Fig. 12) was calculated along the top of the Viola horizon.
and revealed strong circular and ovoid anomalies that correspond with mapped Hunton wedges. We interpret these anomalies as an edge effect, meaning a line where continuous strata is cut by some geologic feature, of the previously discussed solution sinkholes in Viola Group rocks.

Inspection of the total amplitude maps and Viola ESP, (Figures 8, 9 and 12, the former two both being derived from total amplitude extractions, which is described in the following section) shows that several depressions occur in a line sub-parallel to the normal fault system cutting across the Viola surface, perhaps suggesting that the same stress field that eventually caused the normal faulting existed during the pre-Woodford unconformity. This is to be expected in a karsted terrain because the same stress fields that are causing the normal faulting will often open fractures in a parallel direction to the faulting, allowing meteoric waters to travel through and begin the dissolution process. These depressions tend to be oval in shape, with the long axis parallel to the normal faults, with diameters ranging from about 500 ft (~150 m) to about 5,000 ft (~1500 m). These groups of collapse features, which occur along linear northeast-southwest trends, support the idea that there may be a genetic relationship between these structural depressions and the later Pennsylvanian faulting (Fig. 9).

In the northern portion of the Red Oak gas field, which we have interpreted as being devoid of Hunton wedges, the thickness of the Viola, as measured from well data, is similar to that under the Hunton intervals. Perhaps the soluble portion of the Viola responsible for the karsting has been removed (Welling Member?) (Fig. 4) from both areas, leaving the more insoluble Viola Springs Member (Mairs, 1966).

Using Amplitude Extractions to Characterize the Hunton Wedges
The areas directly above the interpreted sinkholes within the Viola interval contain a distinct seismic amplitude character that is interpreted as disrupted Hunton rocks. This behavior of Hunton wedges is best illustrated when this interval is displayed as an amplitude map. Figure 8 was created using total amplitude attribute extraction, which was then overlaid on a time-structure map of the top of the Viola Group. Lateral changes in amplitude have been previously used in stratigraphic studies to separate areas of concordant stratigraphy from chaotic or mounded beds in an interval (Brown, 2004). In general, beds that are concordant will have higher maximum amplitudes because the reflected energy is not being scattered. Hummocky beds will have lower maximum amplitudes; and chaotic beds the lowest as many of the contained reflectors are scattering energy in various directions. To better understand a discreet horizon, one might make the window extremely small (as we did in Fig. 8, defining the interval as only the wavelet containing the Viola Group). Focusing on a single wavelet provides information on the average characteristics of the contained bed to bed interfaces, meaning that we get an idea of how ordered the contained horizon is. For each trace, the total amplitude attribute computes the integration of amplitude for samples within the interval. In the resulting map we see the ovoid and circular shapes of the Hunton lenses, with the negative amplitude anomaly confirming the chaotic nature of the collapsed rocks within the sinkhole. The low amplitude character becomes larger and better defined as it approaches the edges of the collapsed intervals. We believe this is an indicator of the chaotic nature of the beds within the Hunton wedges. As they sagged, we would expect some brecciation and fracturing, so it follows that we would expect these to be amplitude lows. An important observation is that these low amplitude anomalies occur in the thickest
preserved sections of the Viola. This response is interpreted as incipient but arrested karsting that did not develop sufficiently to allow Hunton rocks to be lowered and thereby preserved.

The location of profile ABCD shown in Figure 9 was chosen so that it traversed four of these interpreted sinkholes into the Viola surface. A section view of the seismic behavior along this profile is provided as Figure 9, and in this view the consistently near-vertical attitude and the height of these stratigraphic disruptions are striking, although one should keep in mind that this view is vertically exaggerated. Each structural disruption begins in the Viola interval (not far below 2 s), and extends vertically into the Hunton Group wedge causing the vertical extent of these disrupted zones to be as much as 200 to 250 ft (60 m to 76 m) throughout the 3-D seismic grid.

Using Waveform Classification to Differentiate Hunton Rocks from Viola

Another example of the seismic reflection sensitivity to these surface depressions is shown in Figure 10, which is a display of a six-part waveform classifier in a window stretching from the base of the Woodford through the Viola. Waveform-classifier is a seismic attribute extraction that allowed us to automatically cluster similar waveforms into classes (Andersen et. al., 2004). The output classes are ordered by similarity. The members of class 1 more closely resemble each other than they do of members of class 2 and so on. In this study a group of six classes was chosen. Figure 10 uses an unsupervised waveform algorithm to create a map consisting of groups of 6 waveform types, with each waveform type corresponding to different features in the search window, which we defined as top of the Viola Group and the base of the Bromide Dense Formation. Three classes were particularly relevant in connection to the Hunton wedges,
with one class corresponding to very thin to absent Viola rocks beneath Hunton wedges, another class corresponding to a very thick Viola section with only incipient or no karsting, and the third class corresponding to Viola rocks that did not develop karsting sufficient to allow the preservation of a Hunton wedge. Hunton wedges are delineated by the thin Viola waveform class in this figure.

Modeling Hunton Preservation

An important observation in the isochron map of the Woodford Shale (Fig. 4), the unit that overlies the Hunton Group, is that the areas of thinnest Woodford rocks are directly above Hunton lenses and surrounding the Hunton rocks are thick moats of Woodford Shale, while further away from the Hunton wedges a more constant Woodford thickness is found. The “moats” are areas of unusually thick Woodford near the Hunton wedges, could be sinkholes in areas where Hunton rocks had already been removed, providing the accommodation space necessary for an especially thick Woodford section to be deposited (Fig. 16). We built three stratigraphic models (Figures 16 and 17) that account for these changes, with Model A of Figure 16 showing the normal Woodford case and Models B and C of Figure 16 showing the Woodford thin and thick cases, respectively. The average difference between the thickness of the Woodford covering the Hunton wedges is 250 ft (76 m) to 300 ft (91 m) in the moat, implying that Hunton rocks formed a paleo-high at least 50 ft (15 m) high that Woodford seas drowned and eventually buried (Model B, Fig. 16). A seismic section next to an isochron of the Woodford (Fig. 17) illustrates this thinning of the Woodford where it overlies a Hunton wedge and also the thinning of the Viola under this same Hunton wedge. We can account for the presence of the Hunton wedges with geometries that match a sinkhole
developed into the underlying Viola with a model that allows the Hunton to sag into these sinkholes as the Viola collapses (Fig. 6). The Hunton wedges are preserved largely because they are beneath the regional base level as the whole area is eroded in Middle Devonian time. But since the Woodford thins over these Hunton wedges, we must allow for these wedges to still form paleo-highs (Model B, Fig 16).

The fact that Hunton wedges formed highs during Woodford sedimentation can perhaps be explained by examining where the Sylvan Shale occurs with respect to base level. The Chimneyhill Subgroup of the Hunton Group is generally erosionally resistive, much more so than the much weaker Sylvan Shale. The Sylvan Shale unit is stratigraphically sandwiched by the Hunton and Viola, and so sagged into the sinkholes with the Hunton during the Viola collapse. So while unkarsted areas had their Sylvan sections above base level and thereby subject to erosion and removal (Fig. 18), some areas that sagged downward into the karst sinkholes only had their Hunton rocks exposed (Fig. Model B, Fig. 16). They could not thus be undercut and weakened by eroding Sylvan Shale. These wedges could therefore form depositional highs as the Woodford Sea advanced and eventually drowned the region. The resulting Woodford Shale would thin over these Hunton paleo-highs. Figure 17 show on a Woodford isochron map where these models fit with respect to one another. That the Woodford Shale locally thins over Hunton wedges is an important observation because they could indicate areas of possible Hunton wedges. However, as a basin wide isopach map of the Woodford Shale shows (Fig. 19), these changes in Woodford thickness are high resolution features that do not show up on a basin scale isopach map of the Woodford.

**Regional View**
After analysis and interpretation of Hunton Group rocks in the Red Oak gas field (Fig. 2) area, we applied our approach over the entire southern erosional edge of the Hunton in the Arkoma basin. We found that these karsting episodes and resultant wedges typify the southern pre-Woodford erosional edge in at least two places, the Red Oak field of this study, and an area west of the Wilburton field (Fig. 2). Further to the south, scattered well data show gradually thickening Hunton strata that eventually include not only the Chimneyhill Subgroup but also the Henryhouse and Sallisaw Formations. Because none of these wells show absent Hunton strata, and all have the Hunton gradually thickening southward, we conclude that the isolated wedges to the north become a continuous section of Hunton rock as we move down dip on the flank of a mid-Devonian antiform (Fig. 2).

As we built a regional isopach map of the Hunton Group, it became apparent that it is dominated by two extensive bodies of Hunton rocks separated by a 20 mile (32 km) eroded area (Fig. 2). This suggests that a post-Hunton, pre-Woodford arch may be responsible for the area of thin and absent Hunton. Indeed, well log correlations flattened on the top Woodford (Figs. 14 and 15) indicate that uplift did occur along a broad zone (~100 miles (160 km) long by 30 miles (48 km) wide) running the length of the Oklahoma portion of the basin, with the Hunton being eroded off the top of the arch, but preserved on both limbs. The opposing dips (with the northern limb dipping to the north, and the southern limb dipping to the south) of Hunton and older rocks supports a post-Hunton, pre-Woodford arch. The arch continues into Arkansas; however, building an isopach map of the Hunton into Arkansas was beyond the scope of this study. We propose naming the
arch the Allen-Poteau Arch because these towns bracket the arch’s western and eastern extents, excluding the Arkansas portion.

An isopach of the Woodford Shale (Fig. 19) throughout the basin does not show any visible effect from this arch, suggesting that the structure was completely beveled by the pre-Woodford unconformity. Rising eustatic sea levels throughout the Devonian Period (Johnson, 1985) provide further evidence for an arch, as the southern mid-continent experienced a large-scale regression and erosion (Amsden, 1980), suggesting regional uplift. West of the Arkoma basin, other post-Hunton, pre-Woodford uplifts have been recognized (Tarr, 1955, Maxwell, 1959), the most relevant to this study being the Guthrie-Holdenville Arch. The geometry of the areas of absent Hunton in the Arkoma basin matches that of a breached arch, with the long axis of the arch trending parallel to subsequent Ouachita structures.

Geological Mechanism for Collapse Structures

The extensive vertical collapse zones are interpreted to be the result of post-Viola carbonate dissolution beneath the Hunton, which occurred during the pre-Woodford exposure, when the entire section was uplifted and possibly in the vadose zone (Fig. 20). This karst model is supported by karst-generated vertical collapse zones that can be observed in Viola outcrops in the Arbuckle Mountains in Garvin County (Fig. 21) (Sykes, 1997). Indeed Viola karst exploration targets are pursued throughout southern Oklahoma (Al-Shaieb, 1994) (Figs. 22 and 23).

Preservation of sediments by sagging into karst related collapse features has been documented previously from outcrop and other 3-D seismic data sets. Large karst-generated vertical collapse zones can also be observed in Ellenburger outcrops (roughly
age and compositionally equivalent to the Viola Group) in the Franklin Mountains near El Paso, Texas (Fig. 24) (Hardage et al., 1996). The Ellenburger outcrop collapse features also have extensive vertical dimensions, with some of these outcrop collapses extending vertically for at least 1,200 ft (365 m) in the larger outcrop exposures. In Meade County, Kansas, subsurface lenses of St. Peterburg Sandstone age are thought to have been preserved in Ordovician-age sinkholes (Merriam and Atkinson, 1956), by much the same mechanism described by us for the Hunton. These sinkholes were developed in Arbuckle Group carbonates. Another example is Sanders and Steel (1982) who used 3-D seismic data to document that karst features much like those outlined above, have been observed in the Gippsland basin offshore southeastern Australia. These features from the Gippsland basin have become classic geological examples of karsting (Brown, 1991).

**Potential for Solution Collapse within the Viola**

In a study of the Upper to Middle Ordovician (Black Riverien to Richmondian) Viola cores in south-central Oklahoma, Sykes et al. (1997) found paleokarstic features, such as collapse and crackle breccias, focused flow features, cave parabreccias, sediment infill, and solution enhanced fractures (Figs. 21-23). Solution-enlarged joints and bedding planes, karren, and small caves represent active dissolution of the Viola. These features are common in outcrops of the Arbuckle Mountains, 25 miles (40 km) from the study area. Paleokarstic features recognized in the Viola cores and outcrops include 1) cavern-fill parabreccia, 2) collapse breccia, 3) crackle breccia, 4) solution-enlarged fractures and vugs, sediment infill, and 6) conduits and channels. These features all
indicate volumetrically destructive processes, supporting a model that would allow the Hunton to subside at the expense of the Viola.

We propose that solution weathering during the Middle Devonian unconformity led to widespread Viola karsting and collapse in the study area, similar to what Sykes (1997) observed in south-central Oklahoma. Using a six-part waveform-classifier (Fig. 11) we can correlate karsting models (Fig. 25) with separate portions of the Viola Group interval, with the classifier dividing the Viola into areas of incipient karst, well-developed karst, and areas where the Viola has been completely removed by dissolution. The geometries of the interpreted collapse zones are consistent with what would be expected in a karst terrain (White, 1988).

Although no Viola cores are available within the project area, the aforementioned seismic images allow the following karst/erosional-related hypothesis to be put forward regarding the genesis of the collapse structures:

1. Post-Viola/pre-Woodford fracture sets formed (trending east-northeast) in the study area, perhaps in response to regional uplift in Middle Devonian time.

2. Karst solution weathering occurred in post Hunton, pre-Woodford time, particularly along vertical fractures trending northeast where water seepage was enhanced, and this process produced large caverns in some carbonate units, particularly the Welling Member of the Viola Group.

3. As the area continued to be uplifted and the regional water table fell, large-scale collapse occurred.

4. The resultant collapse structures lowered (sagged) Hunton rocks below the paleo-regional base level and thereby preserved them from the widespread erosion.
5. Episodes of collapse probably continued until the majority of the solution caverns had collapsed and filled from above, resulting in sagging displacement of overlying strata. 
6. Due to the erosionally resistive nature of most of the Hunton Group and that weaker Sylvian Shale had sagged into the sinkholes far enough that it could not be eroded and thereby undercut Hunton rocks, the collapsed Hunton lenses formed depositional highs as the Woodford Sea advanced and eventually drowned the region, causing the resulting Woodford Shale to thin over them.

Conclusions

A 3-D seismic approach, especially the use of attribute extractions, has allowed us to document karsting features and subtle stratigraphic changes that would be impossible to map using 2-D technology. The seismic data, along with previously unavailable well data has allowed us to create a regional map that shows the Hunton Group as being far more extensive than previously believed. This map shows that mid-Devonian karsting episodes and resultant wedges typify the southern Hunton Group erosional edge. Similar wedges are seen between the Red Oak and Wilburton fields and within and west of the Wilburton field itself. Further to the south, these isolated wedges become a continuous section of gradually thickening Hunton strata that eventually includes not only the Chimneyhill Subgroup but also the Henryhouse and Sallisaw Formations. Because these formations terminate in an erosional pinchout and dip to the south with a source rock (the Woodford Shale) that directly overlies them, they form ideal hydrocarbon targets.

The broad zone of absent Hunton to the north of the Red Oak and Wilburton fields we interpret as the crest of a post-Hunton, pre-Woodford arch (named herein, the Allen-Poteau Arch), based on the following evidence;
1. Eustatic sea level was rising worldwide throughout the Devonian, yet the southern mid-continent experienced a large-scale regression and erosion, suggesting regional uplift.

2. West of the Arkoma basin, other post-Hunton, pre-Woodford arches have been recognized, the most relevant to this study being the Guthrie-Holdenville Arch (Tarr 1955).

3. The geometry of the areas of absent Hunton in the Arkoma basin matches that of a breached arch (Fig. 2).

We envision a broad uplift that allows the newly deposited Hunton rocks to be eroded off the crest, and, on the southern portion of the arch, pulling the Hunton through Viola section into the vadose zone. This allows large-scale solution weathering and karsting, eventually producing the Hunton wedge geometries we find today in the Red Oak and Wilburton gas fields.
References


Sykes, M., 1997, Paleokarst Characteristics of the Surface and Subsurface in the Viola Limestone (Ordovician), Arbuckle Mountains, Oklahoma, Shale Shaker, March-April, p. 107-121.


Tarr, R.S., 1955, Palogeologic map at base of Woodford, and Hunton isopachous map of Oklahoma; AAPG Bulletin, v. 39, no. 9, p. 1851-1858.
Whitaker, A.E, and Engelder, T., 2006, Plate-scale stress fields driving the tectonic evolution of the central Ouachita salient, Oklahoma and Arkansas, GSA Bulletin; May/June 2006; v. 118; no. 5/6; p. 710–723.
Figure 1  Structure depth map measuring from a sub-sea datum (tvdss).  Note that the Arkoma basin generally dips to the south, and that the great depth of the Hunton interval, together with the generally greater structural complexity of the overlying sediments, has limited exploration wells in the southern portion of the basin.  Data is constrained by well data (black dots).  The red square in the center-right outlines the 3-D seismic data set.
Figure 2  Generalized isopach map of the Hunton in the Arkoma basin, new in this article. Map was built using a least squares gridding algorithm with data from 1569 wells that penetrate the Woodford through Viola interval. Note that all strata less than 10 ft were plotted as zero Hunton due to the difficulty in distinguishing these thin Hunton intervals from widespread rubble zones related to the pre-Woodford unconformity. The green lines running from the south-west to the north-east are the cross-sections in Figures 14 and 15, with Figure 14 being the northern cross-section and Figure 15 being the southern cross-section. The red square in the center-right outlines the 3-D seismic data set.
Figure 3 Location map showing the study area. Red area represent outcrops of crystalline basement, the gray area uplifted, pre orogenic sediments, and brown area signify synorogenic sediments (after Valderrama et al 1996). Of particular note are the down to the south normal faults within the basin, which cut the intervals involved in this study. The outline of the coverage of the 3-D data set is given in very general terms.
Figure 4 Stratigraphy involved in this study. The blue areas signify the missing time associated with unconformities. The red line is a eustatic sea level curve. Note that globally, sea levels were rising throughout the pre-Woodford unconformity (middle Devonian), suggesting that structural uplift of the affected region is responsible for this unconformity. Figure modified from Rottman, 2000.
Figure 5 Interpreted seismic section showing the stratigraphy involved in this study. The blue lines are gamma ray curves of two wells that were used to tie the seismic survey to the units involved. The well on the left is the 2004 well that first confirmed the existence of Hunton wedges in the area. Note the Hunton log signature in this well. Also note the low amplitude character of the Hunton wedges, the thickened Woodford ‘moats,’ and how the Viola thickens in non-Hunton areas that are also probably non-karsted.
Figure 6 Time-structure map of the top of the Viola limestone, with an isochron map of the Hunton-Sylvan interval overlaid on top of it. Notice the large depressions show up in the structure map, and show up in reds, greens and yellows in the Hunton Isochron map. The reds are about 200 ft thick, the greens about 100 ft.
Figure 7 Isochron of the Woodford Shale, constructed by subtracting the top Woodford pick from the base Woodford (the green and blue lines in Fig. 9, respectively). Note that the Woodford thins over the Hunton wedges (yellows), and thickens dramatically in “moats” around the Hunton wedges (reds). The purples represent unaffected Woodford sedimentation. The green dot and line in the upper right is the 2004 well that first penetrated a Hunton wedge. Compare to figures 16 and 17.
Figure 8 Time-structure map of the top of the Viola limestone, with a total amplitude map of the Hunton-Viola interval overlaid on top of it. Reds represent areas of negative amplitude anomalies, the greens and blues representing areas of much higher amplitudes. Notice that the red areas coincide with large depressions in the time-structure map. We interpret these depressions as sinkholes developed in the Viola interval, filled with Hunton debris, which, due to their broken nature, shown up as negative amplitude anomalies in the total amplitude extraction. Hunton wedges show up as amplitude lows because their chaotic nature scatters the seismic energy.
Figure 9 Seismic section relating Hunton filled Viola sinkholes to a Total Amplitude attribute extraction. The yellow areas of the amplitude maps are negative amplitude anomalies interpreted as the previously mentioned sinkholes. The blue gamma ray curve on the seismic section is the 2004 well that first penetrated Hunton rocks. Note that it is well within a negative amplitude anomaly zone. Also note how the trend of the sinkholes parallels the Pennsylvanian age normal faults (the red lines).
Figure 10 Six part waveform classifier with areas of Hunton rocks in blue, demonstrating the uniqueness of the Hunton waveform. The dark blue zones represent areas that the waveform classifier isolated the Hunton character. The lighter blue pole is the 2004 well that first penetrated Hunton rocks. Note that it is squarely within a blue zone interpreted as a Hunton wedge. The green, pink and light blue zones are areas of varying Viola thickness and character. See Fig. 25 for more information on this varying Viola character. Compare the areas interpreted as Hunton here to those on Fig. 6.
Figure 11 Arc length attribute extraction. Notice that many of the lower arc length anomalies (the bright spots) coincide with the Hunton wedges in the isochron map of Figure 6, but that many, especially near the southern edge, do not. This is because this attribute tended to clump the Hunton phenomenen with Viola thickening, making this attribute a good example of attribute extractions unsuitable for mapping Hunton wedges.
Figure 12 ESP extraction at the top of the Viola, showing the edges of the sinkholes filled with Hunton debris. In order to more accurately interpret the karstic collapse and determine their sizes and orientations, an Event Similarity Prediction (ESP) attribute extraction was calculated in a window defined as the top of the Viola to the base Bromide. The ESP attribute essentially measures trace-to-trace dis-similarity. In the above figure, regions of high dis-similarity are represented by white, and regions of relatively low dis-similarity (more uniform geology) are represented by black. The ESP attribute window clearly delineates the major collapse trends and is a significant improvement in aiding subtle collapse feature interpretation compared to conventional 3D seismic data in time-slice view.
Figure 13 Interpreted gamma ray well log correlation through the Red Oak gas field, flattened on the top of the Woodford shale. This correlation shows a thick Hunton wedge with an abnormally thin Viola interval beneath in the 2004 well previously shown in Fig. 9.
Figure 14 Interpreted gamma ray well log correlation through the Arkoma basin, running from the southwest to northeast. It is flattened on the top of the Woodford shale. Notice that a structural arch was planed off during the pre-Woodford unconformity, forming the Hunton absent zone. The cross-section is the northern green line in Figure 2.
Figure 15 Another interpreted gamma ray well log correlation through the Arkoma basin, running from the southwest to northeast, shown to confirm the geometries of the structure. It is flattened on the top of the Woodford shale. The line is located in the southern green line in Figure 2.
Figure 16 Models showing possible variations of Woodford Shale thickness and their seismic correlatives. The seismic sections are flattened on the top of the Woodford Shale. Model A shows normal Woodford and Viola thickness in an absent Hunton area and how this absent Hunton stratigraphy is expressed on seismic. The middle shows a model of a Hunton wedge with karsted underlying Viola limestone. Note that the underlying Sylvan shale is no longer exposed to erosion, allowing the more resistant Hunton rocks to form topographic relief and eventually cause the Woodford shale to thin over these Hunton wedges. Also note its seismic expression. The bottom model is of the thick Woodford “moats” and their seismic representation. We postulate that these perhaps represent areas where the Hunton was removed (as in the top model) before the Viola collapse.
Figure 17 A demonstration of how the models of Fig. 16 are represented in the Woodford isopach map of Fig. 7.

Figure 18 A model demonstrating the possible rapid removal of the Hunton from non-karstic areas due to rapid removal of the weak Sylvan shale, which would thereby undercut the overlying Hunton rocks. The resulting rubble would then be quickly carried away.
Figure 19 Woodford isopach map. Compare to the Hunton isopach map (Fig. 2). Note that the Woodford is relatively thick through the center of the basin where the Hunton has been completely removed. The red square in the center-right outlines the 3-D seismic data set.
Figure 20 Schematic diagram showing the stages of development of a coalesced, collapsed paleocave system. Multiple cave-system development at a composite unconformity may be necessary to produce a high density of passages. As the multiple-episode cave system subsides into the deeper subsurface, wall and ceiling rocks adjoining open passages collapse and form breccias that radiate out from the passage and intersect with fractures from other collapsed passages and older breccias in the system. The strata above the collapsed system are characterized by faults and sags termed “suprastratal deformation” by Loucks (2003). The collapsed paleocave systems are the prime exploration targets. Modified from Loucks (1999) by Loucks et al. (2004).
Figure 21 Collapse feature (sinkhole) filled with fine carbonate debris, mud, and large clasts. Note near-horizontal stratification that contrasts with apparent dip of host beds. Large ceiling block (above hammer) rotated into the cavern. I-35 road cut. Hammer for scale. From Sykes (1997).

Figure 22 Collapse breccia containing angular clasts with mud infill. Mobil No. 21-19 EFU. Depth, 3,906 ft. From Sykes (1997).
Figure 23 Cavern-fill parabreccia composed of angular to subrounded clasts in a mud-rich matrix. Fractures terminating at clasts margins suggest pre-depositional origins. Mobile No. 21-19 East Fitss Unit (EFU). Depth, 3,825 ft. From Sykes (1997).
Figure 24 Uninterpreted photograph of The Great McKelligon Sag (Lucia, 1995). (b) Interpreted photograph of The Great McKelligon Sag in McKelligon Canyon along the east face of the southern Franklin Mountains, showing the distribution of collapse breccia and the collapse of the Ordovician Montoya Group into the Ranger Peak Formation. B = breccia, C = blocks of Cindy Formation, M = blocks of Montoya Group (Lucia, 1995).
Figure 25 The six part waveform attribute map (figure 13) and how it corresponds to figure 20. Hunton wedges show up as dark blue, non-collapsed areas show up as light blue and areas of the proposed incipient karst show up as greens and pinks.
**Appendix**

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<td>Tape format and media</td>
<td>Seg-D 3480</td>
<td>Seg-Y 3590</td>
</tr>
</tbody>
</table>

**Basic Processing Sequence for Merged Survey**

Reformat & resample field data to internal format at 4 ms. sample interval
<table>
<thead>
<tr>
<th>Step</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Geometry initialization and elevation statics calculation</td>
<td></td>
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<tr>
<td>Verify geometry and statics</td>
<td></td>
</tr>
<tr>
<td>Pre-stack ground roll/linear noise attenuation</td>
<td></td>
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<tr>
<td>Trace edit / spike elimination</td>
<td></td>
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<tr>
<td>Spherical divergence and exponential gain</td>
<td></td>
</tr>
<tr>
<td>3D common midpoint binning to 55 feet inline by 55 feet crossline</td>
<td></td>
</tr>
<tr>
<td>Phase correction for receivers and instruments</td>
<td></td>
</tr>
<tr>
<td>Deconvolution (surface consistent, source and receiver)</td>
<td></td>
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<tr>
<td>Surface consistent amplitude scaling</td>
<td></td>
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<tr>
<td>Velocity analysis (on a one mile grid)</td>
<td></td>
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<tr>
<td>3D surface consistent residual statics (1st iteration)</td>
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<tr>
<td>Velocity analysis (on a one mile grid)</td>
<td></td>
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<tr>
<td>3D surface consistent residual statics (2nd iteration)</td>
<td></td>
</tr>
<tr>
<td>Velocity analysis for migration velocity field generation using Kirchhoff 3D</td>
<td></td>
</tr>
<tr>
<td>pre-stack DMO (half mile grid)</td>
<td></td>
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<tr>
<td>Kirchhoff 3D pre-stack DMO</td>
<td></td>
</tr>
<tr>
<td>Velocity analysis for post DMO stacking velocity field (half mile grid)</td>
<td></td>
</tr>
<tr>
<td>Stack</td>
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<tr>
<td>Post Stack Finite Difference Migration</td>
<td></td>
</tr>
<tr>
<td>Time variant filter and scaling</td>
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</tr>
<tr>
<td>Post stack signal enhancement</td>
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</tbody>
</table>
Arc Length (Figure11)

Arc Length is defined as the trace wiggle length. It is a scaled measure of the total excursion of a seismic trace in a window. To illustrate, imagine a seismic trace plotted in wiggle-trace format. Then imagine that a string is placed on the trace such that the string follows every wiggle. The Arc Length of the trace is then defined as the total length of the string stretched out. The length does not account for any smooth wiggle appearance. It only measures the distance from sample to sample. Arc Length is used to differentiate between high amplitude/high frequency and high amplitude/low frequency and between low amplitude/high frequency and low amplitude/low frequency events. (Schultz et. al, 1994)