EVIDENCE OF SYNDEPOSITIONAL SUBSIDENCE AND THE EVOLUTION OF MULTIPLE COAL SPLITS IN THE HARTSHORNE FORMATION, WESTERN ARKOMA BASIN, OKLAHOMA

By

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geologist, mentor and friend.

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INTRODUCTION

The Pennsylvanian (Desmoinesian) Hartshorne Formation is an important gas producing lithostratigraphic unit in the Arkoma Basin. Sandstone reservoirs in the Hartshorne, which are called the upper and lower Hartshorne sandstones, produce large volumes of conventionally trapped natural gas. Exploratory drilling for coal-bed methane is now the focus of the oil and gas industry. Wire-line logs provide a wealth of information regarding the distribution of the upper and lower Hartshorne sandstones and coals in the subsurface. The interpretation of the depositional environment and mapping of the distribution of the coal and sandstones in the Hartshorne Formation is the focus of this study. The results of this study will be used by exploration geologists to develop conceptual depositional models for these units. The conceptual models will help predict the distribution patterns of coals and sandstone, thus increasing the probability of successful exploration and development drilling.

Purpose and Objectives

The purpose of this study is to examine evidence obtained from wells drilled for gas exploration and interpret the depositional environments and stratigraphy of the Hartshorne Formation. The objectives are: (1) to delineate the thickness trends of the Hartshorne coals and sandstone, (2) to interpret the depositional environments of the Hartshorne Formation, and (3) refine the depositional model to explain multiple coal splitting in the study area.

Location

The Pennsylvanian Hartshorne Formation is recognized in the Arkoma Basin, which is located in the central and western part of Arkansas and the southeastern part of Oklahoma. The basin covers approximately 33,800 square miles (Perry, 1995). The maximum width from north to south is 175 miles, and the maximum length from east to west is about 315 miles (Perry, 1995). The Arkoma Basin is bounded by the Cherokee Platform and Ozark Uplift to the north, the Arbuckles to the west, and the Ouachita Mountains to the south (Cemen, 2004). The post-Atoka structural style of the Arkoma Basin is dominated by narrow anticlines that separate broad synclines. Normal faults dominate the pre-Atoka structure of the basin, which include the strata from the Precambrian basement to the base of the Atoka (Houseknecht, 1986). The study area (Figure 1) is located in parts of Haskell, Latimer, McIntosh and Pittsburg Counties, Oklahoma.

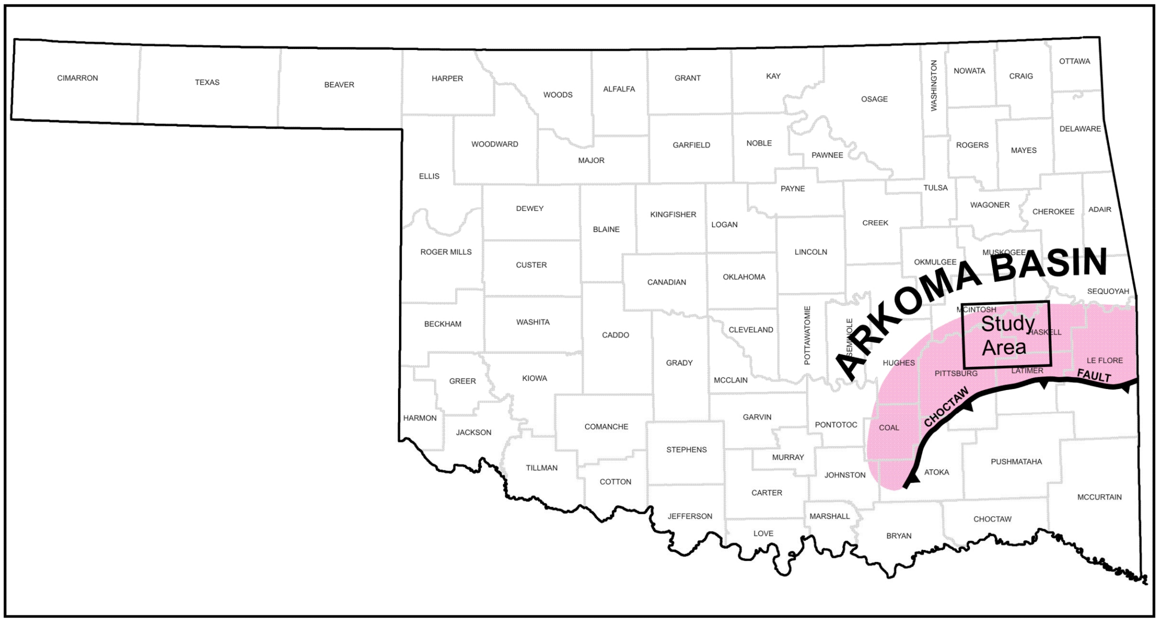


Figure 1. Index map of the Arkoma basin showing the general location of the study area. Deering (2005).

Methodology

The study area is located north of the Choctaw Fault in a portion of the Arkoma Basin that has experienced widespread drilling for conventionally trapped natural gas. An extensive data set is available as a result of drilling of a large number of wells. Recent drilling in the area to produce coal bed methane (CBM) from the Hartshorne Coal has produced numerous modern wire-line logs to augment the existing data set. The new logs provide resistivity, gamma-ray, neutron-density, bulk density and sonic log signatures that were used to distinguish the Hartshorne Coal from sandstone, and establish the Hartshorne stratigraphic framework and electrofacies. Log signatures were correlated to published outcrop descriptions, and depositional electrofacies were established using sedimentary structures, distribution patterns and curve forms. Isopach maps were constructed for the upper coal and upper sandstone bodies to establish distribution patterns.

Tectonic History

The Hartshorne sediments were deposited near the end of the tectonic evolution of the Arkoma Basin. The Arkoma basin is an arcuate synclinorium that lies directly north of the Ouachita orogenic belt (Houseknecht, 1986). Arkoma Basin evolution began with the major rifting event that caused the opening of the Iapetus (Atlantic Ocean) during the late Pre-Cambrian and into the Cambrian (Figure 2) (Houseknecht and Kacena, 1983). Due to this rifting event, the southern part of North America evolved to an Atlantic type passive margin with miogeoclinal deposits. This rifting lasted well into the Mid-Paleozoic. Sediment accumulating during this phase includes shelf facies (carbonates, shale, and sandstone) and off-the-shelf facies (limestone, sandstone, and bedded chert) (Houseknecht, 1986).

The Iapetus Sea began closing in the Devonian and Mississippian because of a southward dipping subduction zone. The subduction occurred when the North American plate collided with a southern plate. Wright (2002) describes the southern plate's identity unknown, "but is generally believed to have been a subductional accretionary thrust front with one of the following four bodies as the colliding object: 1) Gondwana, 2) a mid-oceanic volcanic arc, 3) an unknown foreign terrane, or 4) a former piece of North America which had been removed from the craton during Cambrian rifting."

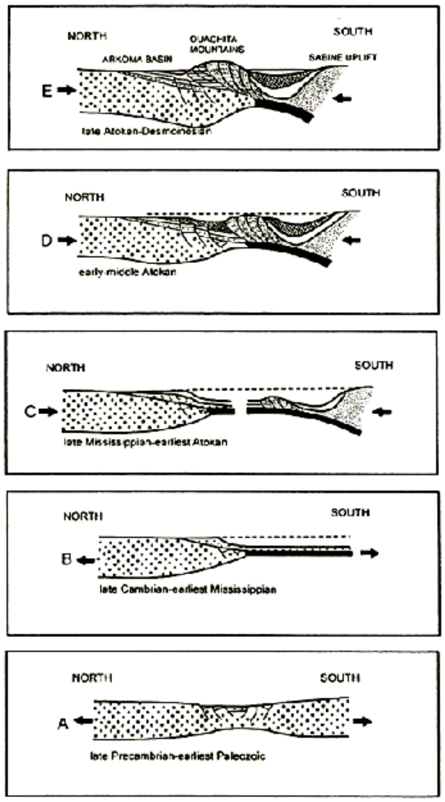
Houseknecht (1986) points out that the evidence for subduction lies in the abundant volcanic tuffs and volcaniclastic sandstones. These tuffs and sandstones are indicative of orogenic processes (like the Ouachita Orogeny). The Sabine Uplift, found on the northern flanks of the unidentified southern plate, contains carboniferous volcanic rocks representing the magmatic arc that developed there.

Slow sedimentation, which ultimately formed shales, sandstones and carbonates continued from the Mississippian to early Atokan time (about 1.5 km of sediment according to Houseknecht and McGilvery, 1990). Continued convergence resulted in an uplift along the Ouachitas, and the area became a site of the rapid deposition of flysch sediments. These sediments poured into the remnant ocean basin and accumulated to more than 5.5 km (18,000 feet) (Houseknecht and McGilvery, 1990).

By the beginning of Atokan time, the remnant ocean basin was subducted, and the other parts of the subduction complex were pushed on to the rifted continental margin of North America. As a result of this mass being pushed up, flexural bending occurred.

Normal faults, striking parallel to the Ouachitas, developed from the flexural bending. Concurrent with faulting, Atokan muds and sands were being deposited by a series of submarine fans. This change in depositional style reflects the change of the basin from a passive margin to a foreland basin (Houseknecht, 1986).

Foreland-style thrusting dominated during the late Atokan time period while the subduction complex continued pushing northward. The consequential uplift continued in the frontal thrust belt of the Ouachita region creating the peripheral foreland basin observed today. Shallow marine, deltaic and fluvial sediments were deposited throughout the Atokan. From the upper Atokan through the Desmoinesian, abundant peat-bearing molasse were deposited (Houseknecht, 1986).



Houseknecht, D.W., and Kacena, J.A., 1983, Tectonic-Sedimentary evolution of the Arkoma Basin: Soc. Econ. Paleontologists and Mineralogists, Mid-Continent Section, v. 1, p. 119

Figure 2. Tectonic Evolution of the Arkoma Basin (Houseknecht and Kacena, 1983).

Previous Investigations

As a result of its economic importance, the Hartshorne Formation has been the topic of study for over one hundred years. According to Hemish and Suneson (1997), a number of field geologists were responsible for the defining studies on the Hartshorne Formation. These studies include the work of Chance (1890), Taff (1899), Taff and Adams (1900), Oakes and Knechtel (1948), Branson (1956) and McDaniel (1961). These field investigations defined the stratigraphic nomenclature, lithology and geometry, and lead to the development of models to explain the depositional environments.

No extensive studies of the Hartshorne Formation using subsurface data were conducted until 1968. McDaniel (1968) used wireline logs to map the subsurface geology of the Hartshorne. This study was the foundation for the development of the fluvial-deltaic depositional models for the Hartshorne.

A number of theses, at various institutions, have been completed that address various aspects of the Hartshorne Formation. Agbe-Davies (1978) examined the structure and stratigraphy of the Hartshorne Formation in Le Flore County as well as the quality of the coals. Using well-log data, Agbe-Davies (1978) constructed structure maps, isopach maps and cross sections. He concluded that the Hartshorne exhibits characteristics of a fluvial-deltaic deposition system and that structural deformation did not influence the rank of the coals. Additionally, Donica (1978) examined the geology of the Hartshorne Formation in Le Flore County. The main objective was to accurately interpret the stratigraphic position of the coals for future exploration and production. Donica (1978) noted that the sediments for the Hartshorne Formation were deposited by a prograding deltaic plain environment. The environment included a distributary channel flowing to the southwest and interdistributary marshes with overbank deposits (site of peat deposition). Donica (1978) also found a localized middle coal in the Hartshorne Formation in Le Flore County.

Matteo (1981) studied the Hartshorne in the western Arkoma basin. Similar to other theses, Matteo constructed cross sections and isomaps from wireline well-log information. Matteo focused on defining the stratigraphy of the upper and lower coals in the subsurface, while creating a depositional model for the Hartshorne Formation. Descriptions of the depositional models created for the Hartshorne will be discussed later.

STRATIGRAPHY

The Hartshorne Formation is the basal unit of the Krebs Group (Pennsylvanian Desmoinesian Series), which also includes the McAlester, Savanna and Boggy Formations (Figure 3). The Hartshorne Formation overlies the Atoka Formation (Pennsylvanian Atokan Series).

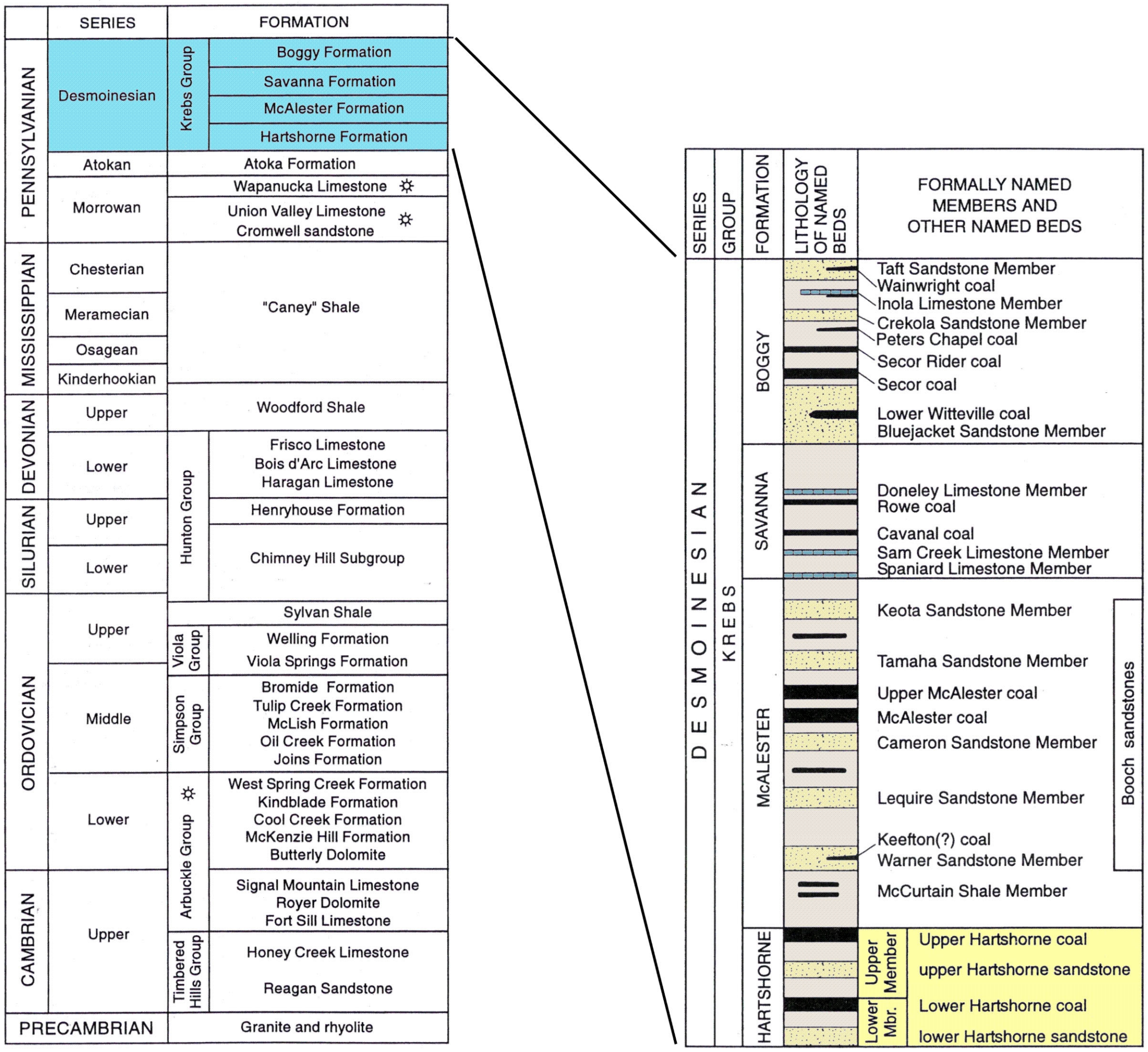


Figure 3. Stratigraphic nomenclature for the Arkoma Basin and Desmoinesian Series (modified from Suneson, 1998, Fig. 2 and 3).

“The Atoka Formation is overlain throughout the axial part of the Arkoma Basin by the Hartshorne Sandstone…of Desmoinesian age” (Zachry and Sutherland, 1984). The Atoka Formation and Hartshorne Formation are separated by an unconformity (Suneson, 1998), which is not apparent on wireline logs. The mapable contact used in this study was interpreted from resistivity logs (induction and laterolog) and was recognized throughout the study area. The contact was defined as the position where the resistivity curves in the lower Hartshorne shale shift left to approximately 10 ohms or less. This shift defines the change in electrofacies signatures from the overlying Hartshorne shale whose resistivity signature reads between 10 ohms and 300 ohms. For this study, the point of the shift corresponds to the “contact” between base of the Hartshorne sandy shales, shale, and siltstones and the underlying Atoka (Figure 4).

According to Al-Shaieb (2000), the Atokan interval is dominated by shale, but contains numerous sandstones that are vertically and laterally distributed throughout the interval. The sandstones are assigned various names by the petroleum industry and in ascending order include: Spiro, Paul Barton, Dunn, Jenkins, Sells, Vernon, and Casey (Al-Shaieb, 2000). The thickness of the Atoka Formation within the study area ranges in thickness from less than 3,000 feet to an excess of 9,000 feet in Haskell County (Donica, 1978).

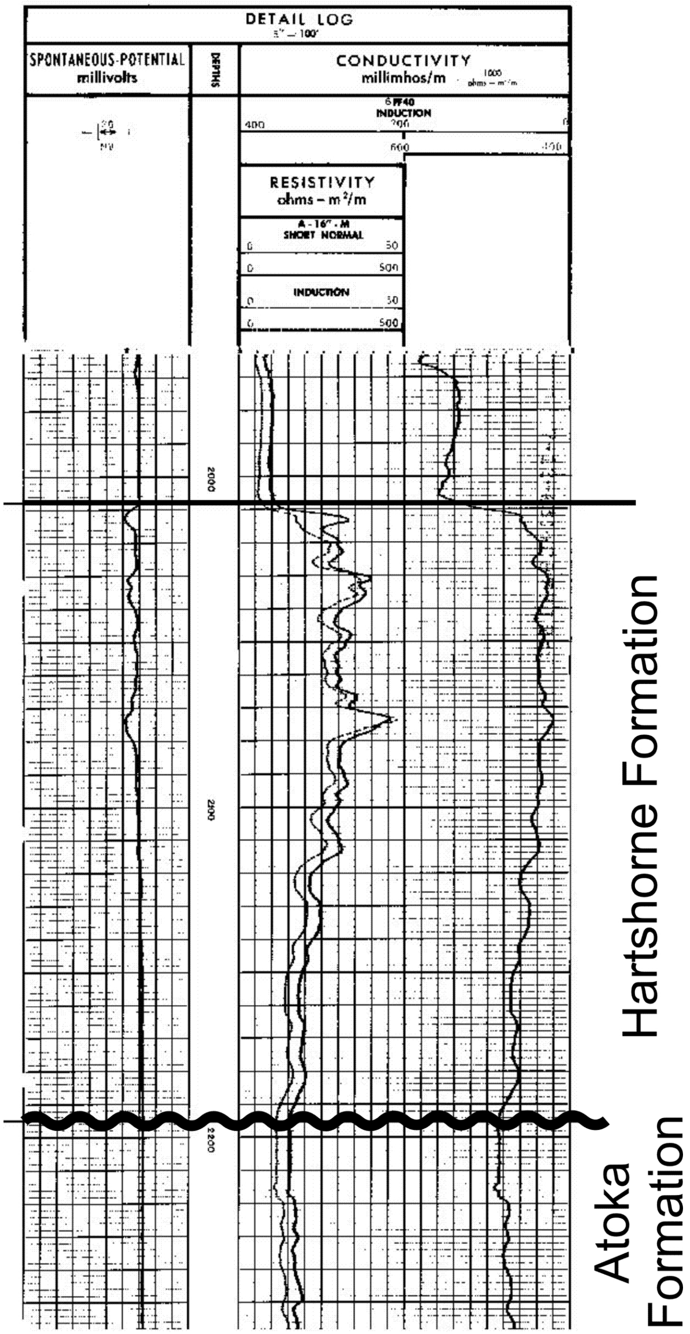


Figure 4. Well log showing top of Hartshorne Formation and top of Atoka Formation.

For this study, the top of the Hartshorne Formation was selected at the top of the upper Hartshorne Coal. This boundary is easily recognized on wireline logs as a sharp gamma ray deflection to the left to a value of less than 75 API units. This sharp deflection gives the coal a "clean" signature compared to the overlying and underlying shales. In addition, the porosity curves (sonic, density, and bulk density) deflect strongly toward the depth track and often go off scale (Figure 5). In wells that penetrate sections where the Hartshorne Coal is missing, the top of the Hartshorne was picked at the top of the first mapable sandstone (Figure 6). The thickness of the Hartshorne Formation is between 100 to 800 feet thick. Suneson (1998) notes that the thickness in Pittsburg County ranges from zero to approximately 1000 feet thick. This range in thickness is likely due to the increase in sediment load toward the southern part of the basin. The thickness of the upper Hartshorne sandstone ranges from 100 feet to 400 feet thick.

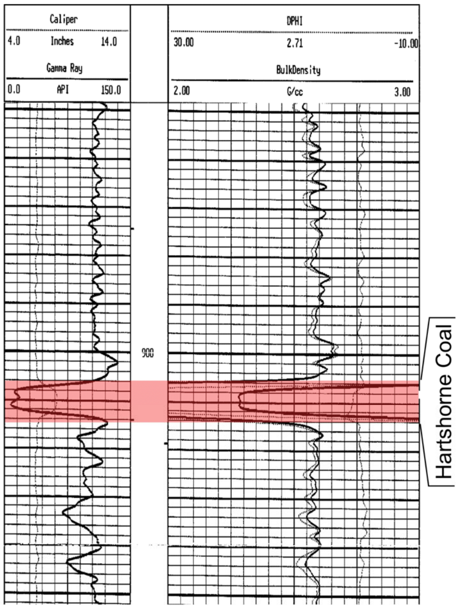


Figure 5. A portion of the wireline log curves showing distinctive log signature for the Hartshorne Coal (shaded pink). The Hartshorne Coal is characterized by a "clean" gamma ray signature (less than 75 API units) and high density porosity (greater than 40%).

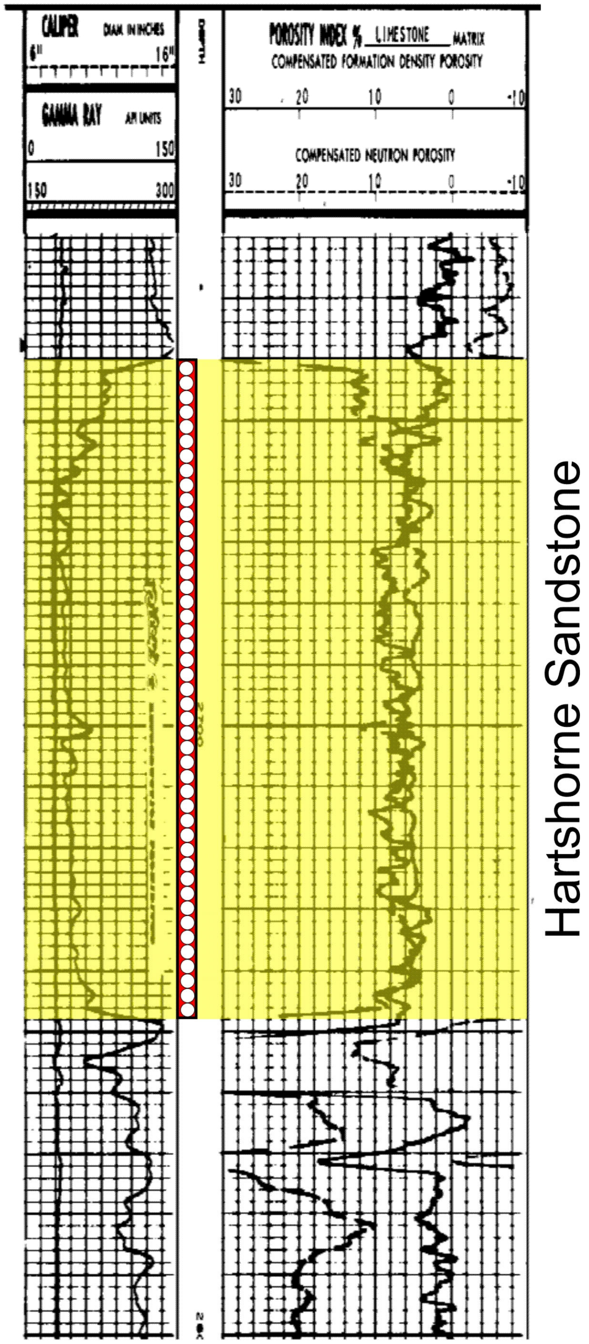


Figure 6. The wireline log signature of an interval that does not contain Hartshorne Coal. The Hartshorne sandstone (shaded yellow) is characterized by a gamma ray deflection of less than 75 API units and density porosity of 10% to 20%. Neutron porosity, which reads approximately 30% in the shale decreases to approximately 10% in the sandstones.

History of Hartshorne Formation Nomenclature

The section now recognized as containing the Hartshorne Formation was first studied by Chance in 1890. Chance originally named the coal the Grady Coal Group and called the sandstone the Tobucksy Sandstone (Suneson, 1998). In 1899, Taff renamed the unit using the terms Hartshorne Coal and Hartshorne Sandstone. The Hartshorne is named for the community of Hartshorne, which is located east of the area where Taff studied the Hartshorne outcrops (Suneson, 1998).

Taff and Adams (1900) recognized two distinct coal beds, one above the sandstone and one below. The coal above the sandstone was called the upper Hartshorne Coal; the one below was called the lower Hartshorne Coal. However, Taff and Adams (1900) included the Upper Hartshorne Coal in the lower part of the McAlester Shale instead of grouping it with the other Hartshorne units (Suneson, 1998).

Oakes and Knechtel (1948) mapped the northern part of the Arkoma basin and determined that the upper and lower coals joined into one coal. Oakes and Knechtel recommended that the Upper Hartshorne Coal be placed in the Hartshorne and not the McAlester (Suneson, 1998).

Branson (1956) did not approve of using the term Hartshorne for the lower sandstone, and changed the name back to its original, the Tobucksy Sandstone. Branson also chose to name the unit the Hartshorne Formation instead of the Hartshorne Sandstone (Suneson, 1998).

The Oklahoma Geological Survey (OGS) acknowledges the definition (Figure 7) of the Hartshorne Formation reported by McDaniel (1961) (Suneson, 1998). McDaniel suggests that the Hartshorne Formation be divided into two members after Oakes and

Knechtel's work. The lower Hartshorne member consists of sandstone (Tobucksy sandstone originally recognized by Chance in 1890), shale and the lower Hartshorne Coal. Suneson (1998) also notes that a chert-pebble conglomerate is found at the base of the Hartshorne at several outcrops located in the southwestern part of the basin. The upper Hartshorne member consists of sandstone, siltstone, shale and the Upper Hartshorne Coal (Suneson, 1998).

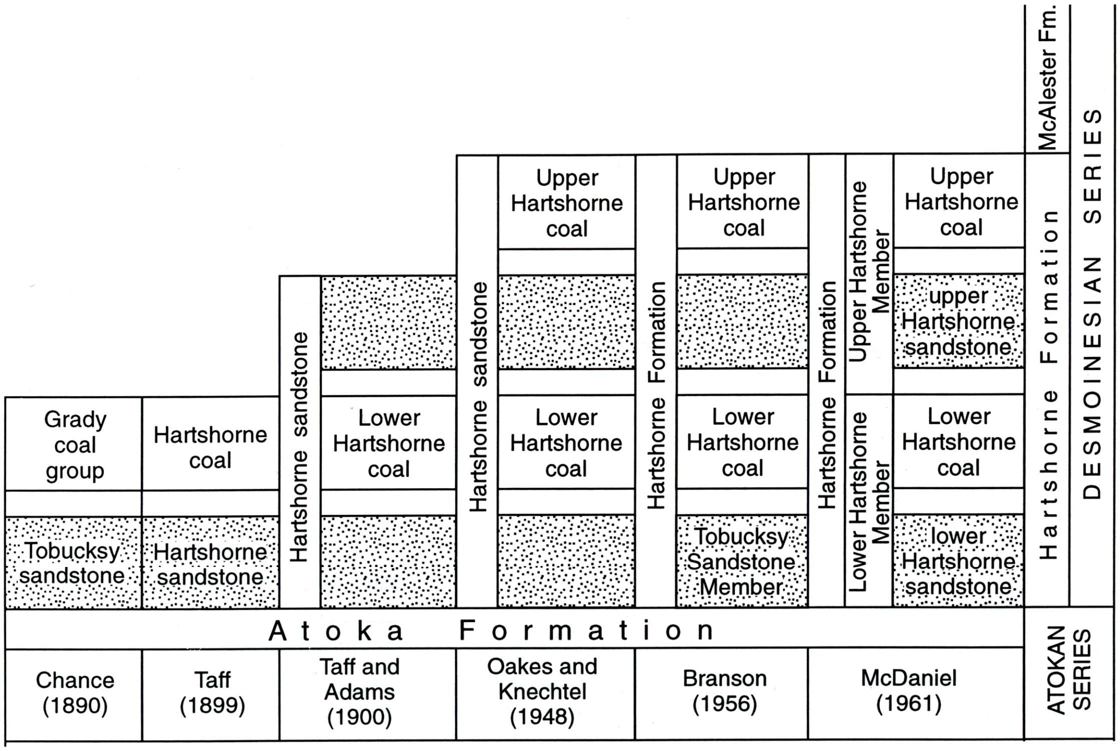


Figure 7. History of Hartshorne nomenclature (From Suneson, 1998, fig. 5)

The McAlester Formation, which overlies the Hartshorne Formation, is poorly exposed in outcrop. The base of the McAlester is superjacent to the Upper Hartshorne Coal. The McAlester is divided into six members separated by shale intervals: McCurtain Shale, Warner Sandstone, Lequire Sandstone, Cameron Sandstone, Tamaha Sandstone and the Keota Sandstone (Hemish, 1997). The McAlester Formation contains three coal beds of significant thickness: Keefton Coal within the Warner Sandstone Member, McAlester (Stigler) Coal above the Cameron Sandstone, and the Upper McAlester (Stigler Rider) Coal, which is immediately over the McAlester Coal (Hemish, 1997).

The McAlester sandstone units in outcrop correlate to the subsurface units named by the petroleum industry as the lower Booch, middle Booch, and upper Booch sandstones. The sandstones in the Booch interval produce significant volumes of oil and gas and reach thicknesses of several hundred feet.

The McCurtain Shale Member (lower Booch) overlies the upper Hartshorne Coal. The contact between the two intervals is characterized by wireline logs exhibiting a change in gamma ray signatures. Above the "clean" Hartshorne Coal signature (less than 75 API units), the gamma ray curve stays closer to the shale baseline (approximately 140 to 160 API units) indicating the base of the McCurtain Shale Member. In certain instances, the gamma ray curve exhibits lower readings (50-120 API units) in the McCurtain Shale indicating a silty sandstone above the upper Hartshorne Coal (Figure 8)

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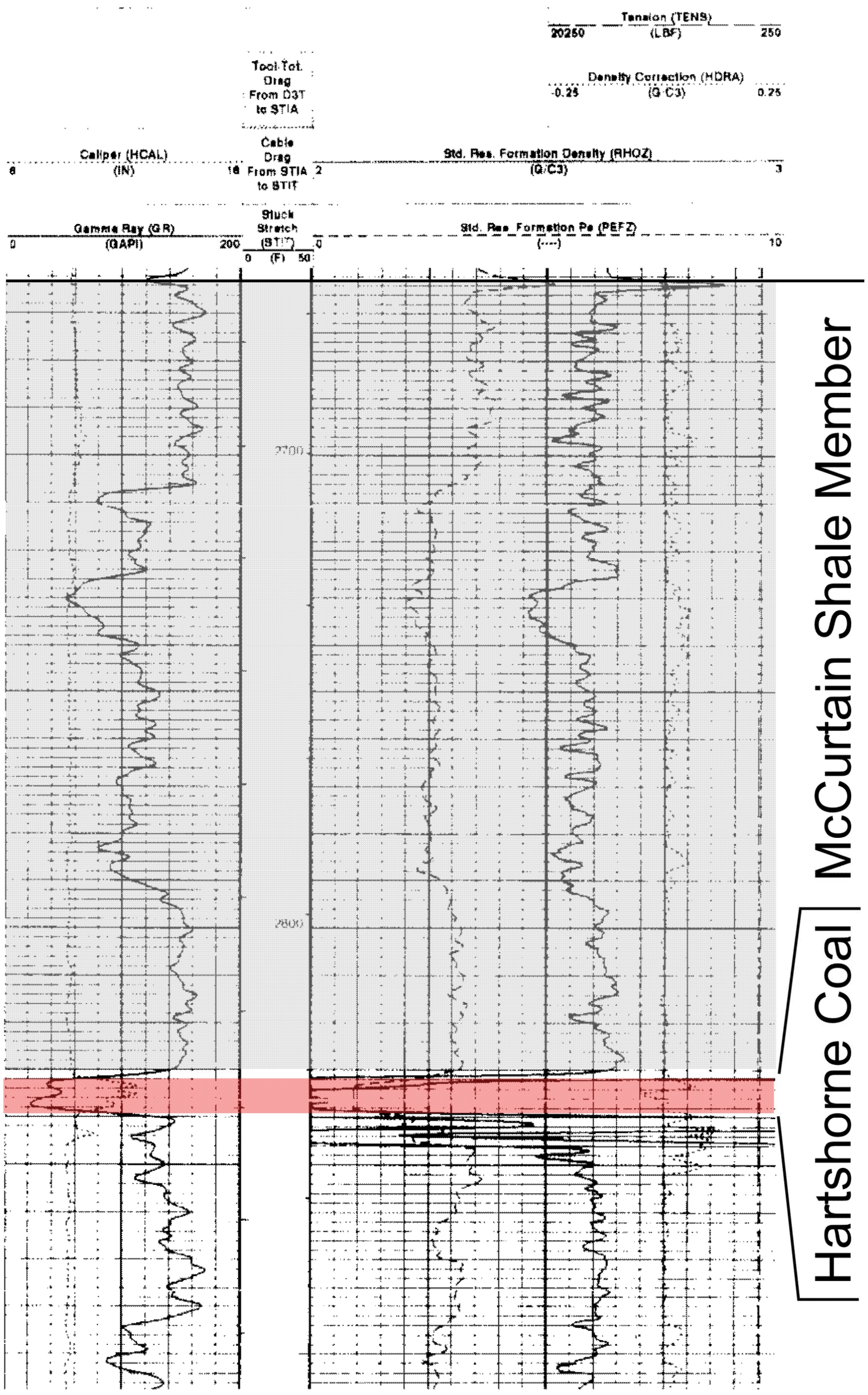

Figure 8. Portion of bulk density porosity wireline log for an interval containing sandstone in the McCurtain Shale Member of the McAlester Formation (shaded gray). The clean upper Hartshorne Coal (shaded pink) has greater than 40% density porosity while the McCurtain Shale Member has 10% to 20% density porosity.

DEPOSITIONAL ENVIRONMENTS OF THE HARTSHORNE FORMATION

In order to determine the depositional environment of the Hartshorne Formation, abundant well log data was correlated. Over 2800 wireline logs for wells were analyzed within the study area. Gamma ray and resistivity signatures were the principal curves used to interpret electrofacies. Most of the interpretation was based on the work of Weber (1986) who developed a facies recognition diagram using gamma ray signatures (Figure 9). Many of the characteristic profiles described by Weber (1986) were similar to ones in the Hartshorne interval.

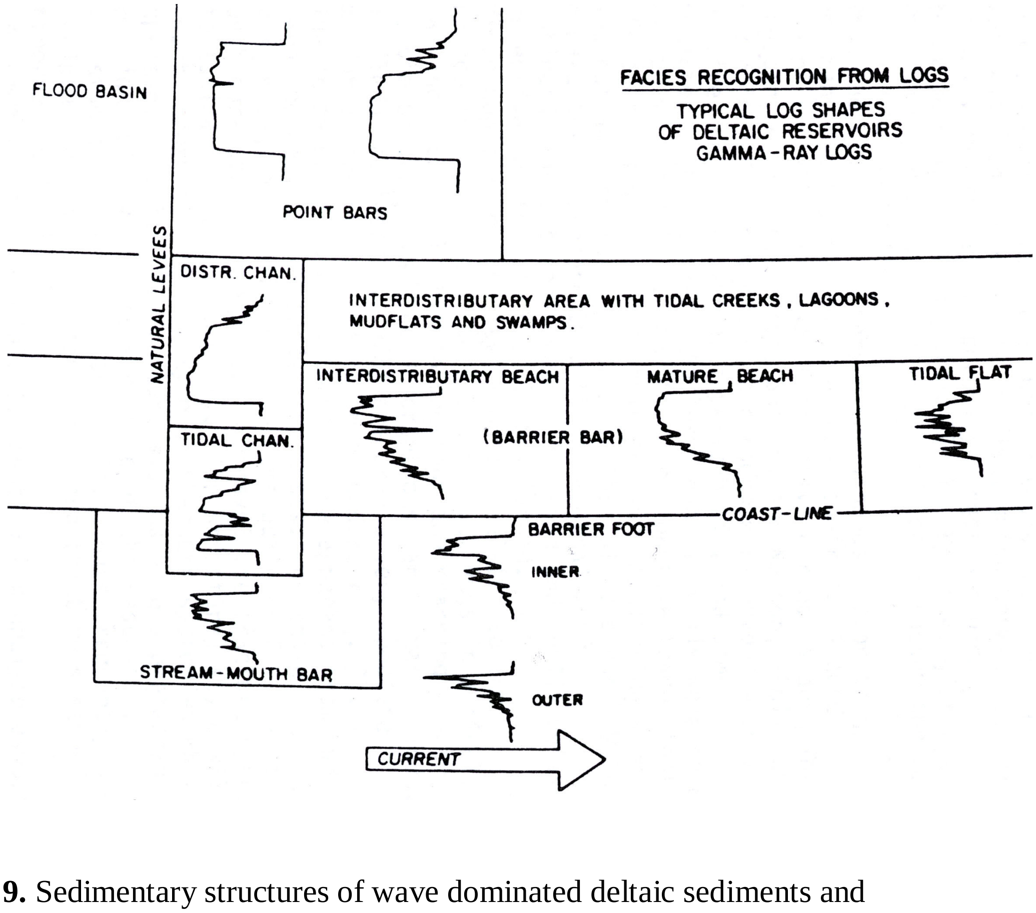

Figure 9. Sedimentary structures of wave dominated deltaic sediments and corresponding shapes of the natural gamma-ray log (From Weber, 1986, fig. 6).

Multiple environments are interpreted for the Hartshorne based upon varying gamma ray and resistivity signatures and previous investigations, especially Andrews and Suneson (1999). These environments include distributary channels, incised valleys, interdistributary bays, the delta margin/shallow marine, and peat bogs. The distributary channels have a bell shaped gamma ray signature with a sharp base that becomes more clay rich (fining upwards sequence) towards the top. The sandstone tends to be thinner (less than 100 thick) in distributary channels. The incised valley fills display standard channel fill shapes and also have a sharp base on the gamma ray signature. These channel fills tend to have API gamma ray readings of less than 60 units for 100 feet to 400 feet. The interdistributary bay shows a gamma ray signature that stays close to the shale base line (135 API) and deviates back and forth from 135 API to 105 API (indicating possible tidal influenced areas). The delta margin/shallow marine setting can be determined by the classic coarsening upwards sequence on the gamma ray that displays a funnel-shaped curve. The peat bog shows the "cleanest" gamma ray signature, which is often less than 75 API units.

In the fluvial system, two channel systems have been identified. The first channel system is a large east to west trending area of thick sandstone that reflects valley fill deposition. This trend supports the position of a depocenter in the west (Godwin, 2005). The valley fill sandstones range from 100 to 300 feet in thickness (Figure 10) and often consist of standard fining upwards sandstone units. A second channel system contains smaller, northwest to southeast trending distributaries. The distributary channels are generally less than 100 feet thick (Figure 11). Cross-section C-C' and D-D' (Plates 4 and 5) show characteristic distributary channels (10 to 20 feet thick) on either side of a thick (valley fill) sandstone package. It is apparent that the thick sandstone package identified (100 to 300 feet thick) fills a valley eroded into older material that is comprised of distributary channels, associated lower coal, shales and siltstones.

There are also several areas that are interpreted as interdistributary bay deposits, delta front/shallow marine and peat bogs. These areas contain rocks that exhibit a gamma ray signature that deviates back and forth at the shale baseline, coarsens upwards, and then deflects lower than 75 API units (Figure 12). The very clean gamma ray signature that usually caps the interdistributary bay/shallow marine area is laterally continuous throughout the northern part of the Arkoma basin, and is indicative of widespread peat bog deposition.

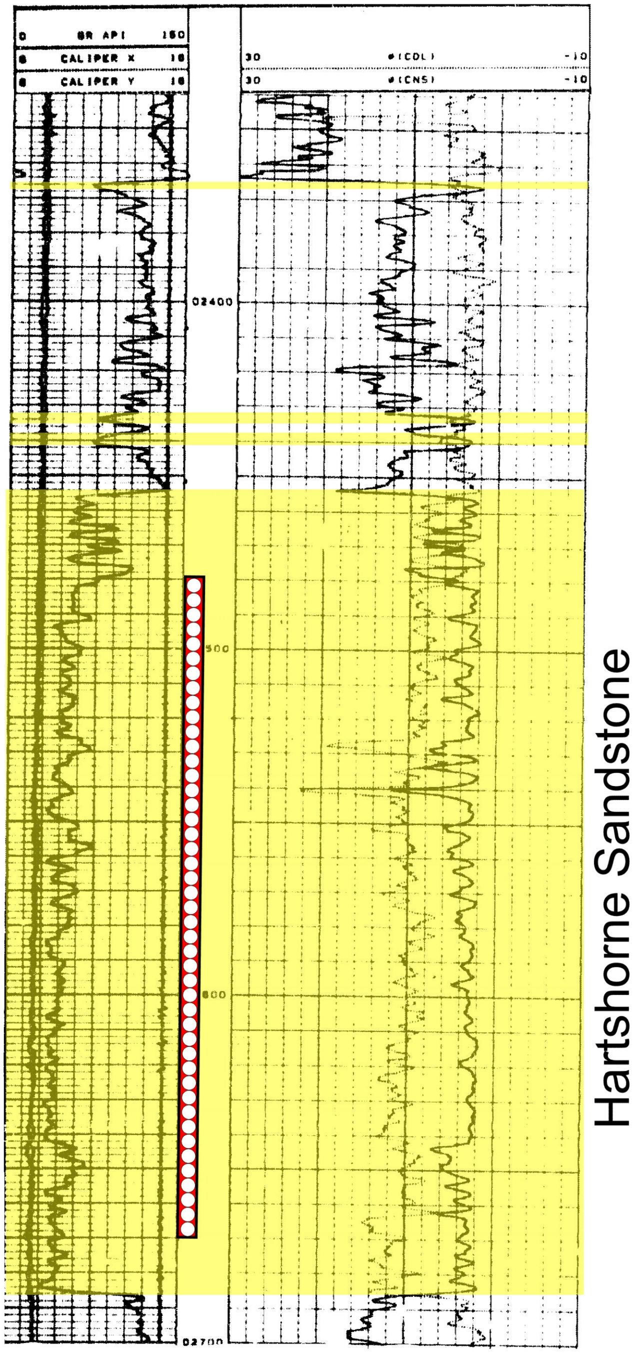

Figure 10. Wireline log interpretation: Incised valley fill sandstone (shaded yellow for over 200 feet) overlain by a low energy tide influenced (deltaic) shale and sandstone. Channel fill is indicated by the sharp base on the clean (less than 75 API) gamma ray signature. Interpreted low energy environment has a profile close to the shale baseline (120 API) with variable, but low magnitude deviation from the baseline.

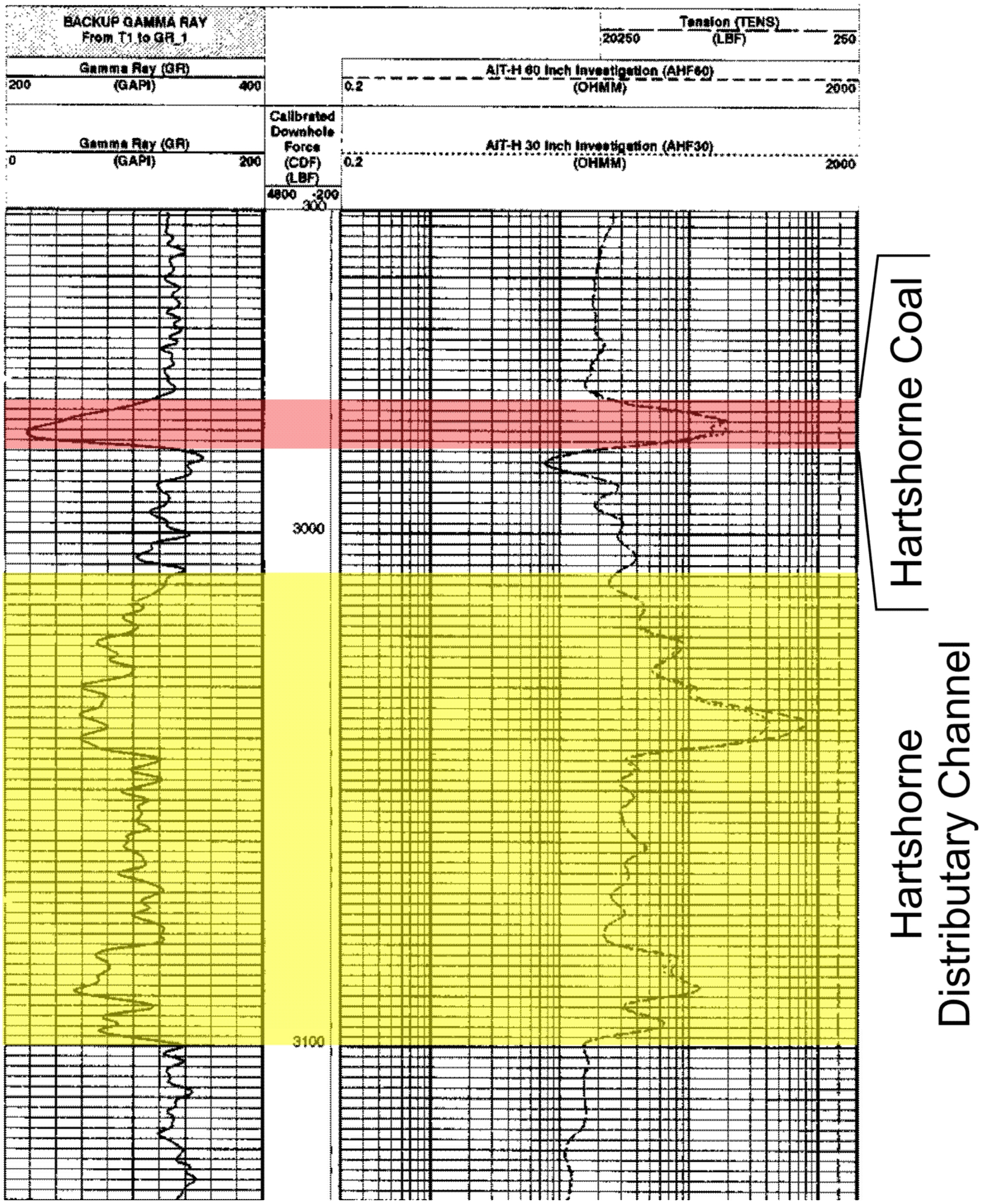

Figure 11. Wireline log interpretation: Distributary channel sandstones that are overlain by a low energy deltaic environment. Coal (shaded pink) is approximately 6 feet thick, and exhibits a clean gamma ray signature (less than 75 API). The distributary channel sequence (shaded yellow) shows a sharp base with clean sandstone overlying shale. The sandstone has a bell-shaped, fining-upward signature. A second sandstone exhibits similar fining-upwards signature before reaching the low energy environment (140 to 120 API) immediately below the coal.

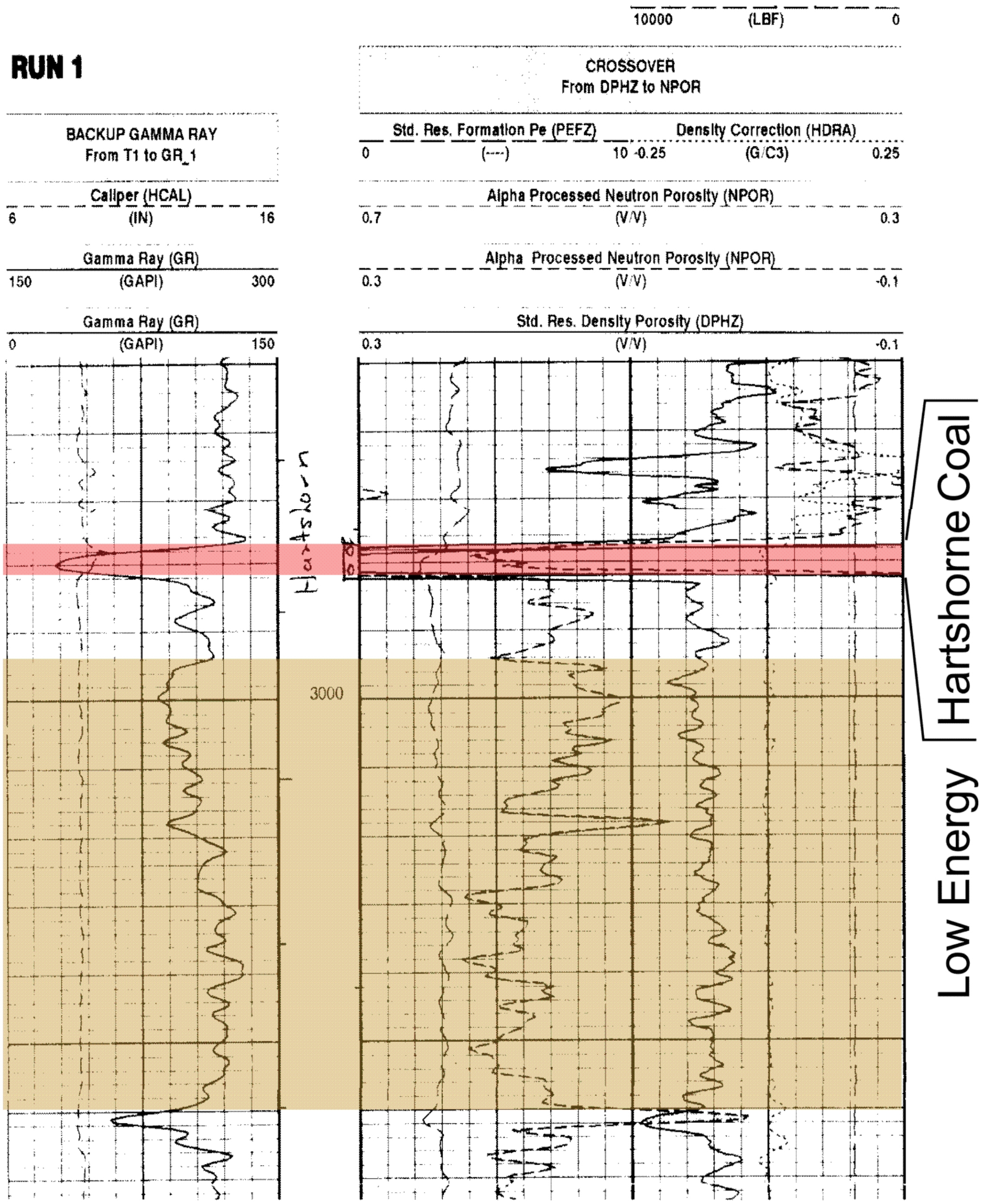

Figure 12. Wireline log interpretation: Low energy deltaic environment. No log signatures characteristic of fluvial systems are present. Above a sandstone at 3060 feet is a coarsening upward sequence for approximately 55 feet (3060' to 2994'). Four feet thick coal caps the sequences (shaded pink).

Distribution of Hartshorne Coal and Sandstone

Isopach maps were constructed for the upper Hartshorne coal and sandstone encompassing most of the western Arkoma Basin in Oklahoma (approximately 6000 wells in 128 townships). A smaller study area of 15 townships was chosen for detailed examination. In this area, color coding was used to delineate coal thickness (Plate 1). Areas colored yellow contain less than one foot of coal. In most areas where coal is thin, the underlying sandstone is thick. Areas containing coal that is one to four feet thick are colored light green to dark green. Brown color indicates coal thicknesses that exceed four feet. Four feet was chosen as a cutoff point because it is the informal petroleum industry standard for the thickness required to drill horizontal wells.

Certain inferences regarding the relationship between coal thickness and underlying sandstone thickness were discovered. These inferences, which are tested via the construction of cross sections (Plates 2, 3, 4 and 5) through the area, include:

1. Yellow shaded areas, which contains thin coals or no coal, are underlain by thick sandstone.
2. Brown areas represent single, undifferentiated coals, and are also underlain by shale dominated sections.
3. Coal splits on either side of the brown colored areas south of the primary valley trend.
4. The northern coal split line is shown on the map by a red dotted line (from literature) that follows the northern margin of the channel.
5. Green shaded areas have variable thickness of sandstone and both coals.

Evolution of Coal Split Lines

The Oklahoma Geological Survey reports that the Hartshorne Formation is comprised of a lower member in the northern part of the Arkoma Basin and an upper and lower member in the southern part of the basin (Suneson, 1998, Figure 3). The previous widely accepted deposition model for the Hartshorne Formation is best explained by Matteo (1981). Matteo states that the Lower Hartshorne Member was deposited during the progradation of the delta-lobe after the transition from a marine to non-marine environment. The peat accumulation from the swamp-marsh caps that sequence. Matteo maintains that the Upper Hartshorne Member was restricted to the south. Peat accumulation also topped the second package (i.e. Upper Hartshorne Coal). The merging of these two coals identifies the location of the coal split line. This coal-split definition is accepted by many geologists (Hemish, 2001). Matteo (1981) gives a detailed account of a mechanism that explains the splitting of the coal units.

> “In cross section these coal beds merge northward into one coal bed; the upper member, concomitantly, pinches out the north. A line may be drawn areally defining this coal merger or coal-split. North of the coal-split line only the lower Hartshorne member is present, and above the coal, by definition, is the McAlester Formation. South of the line, the upper member is superjacent to the Lower coal, and the McAlester Formation lies above the Upper Hartshorne coal, which caps the upper member.” (p.39)

The previous model for the depositional environment for the Hartshorne Formation and genesis of the coal split line is partially supported by the evidence gathered in this study. The general depositional setting (fluvial-deltaic) is substantiated by the collective evidence. However, the proposed single coal-split line for the entire Arkoma Basin should be modified as several splits were identified. In the focus area, the coal splits and re-merges more than once. Mapping evidence supports an undifferentiated coal north and west of a regional incised valley fill sandstone trend that follows the current coal-split line. Another split is present along the south margin of the valley trend. Continuing in a southerly direction, the coals merge back into one coal and split again (Cross section

A-A’ {Plate 2} illustrates this relationship). The additional well data also shows that the upper Hartshorne Coal is traceable from the southern undifferentiated area northward toward the valley fill. The upper Hartshorne coal thins over the thick valley fill sandstone and is absent over the crest of the valley fill. The upper Hartshorne coal thickens again toward the northern split line and undifferentiated coal area (brown). The undifferentiated coal is likely composed of both upper and lower Hartshorne coal (Figure 13). There is a thin (less than 1 foot to 1 foot thick) “bony” coal in the middle of the thicker undifferentiated coal. This bony coal appears to correlate to the shale section in most wells on the opposite side of the split line.

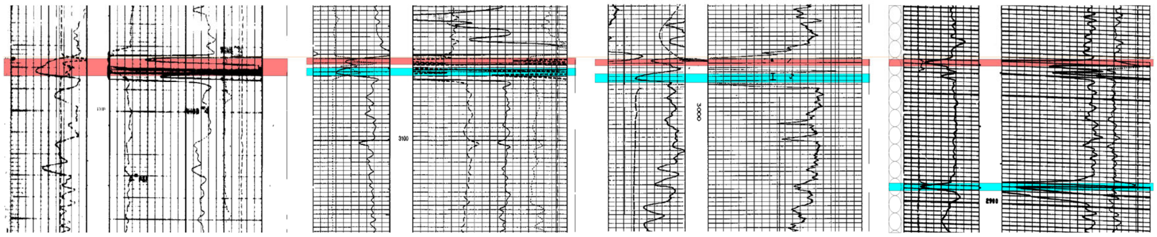

Figure 13. Evolution of single upper Hartshorne Coal (shaded pink) splitting into Upper and Lower Hartshorne Coal (shaded blue). Gamma ray signature is high in intervals between coals (greater than 75 API) which indicates shale/muds.

This transition from a single coal to separate upper and lower coals is similar in both the southern and northern part of the study. However, the northern coal split line appears to be absent along the northern “bend” in the thick valley trend. This may be the result of increased erosion against the cut bank of the meander. Throughout the western part of the basin, the thick channel follows the northern coal split line (Godwin, 2005) (Matteo, 1981). The second coal split line follows the southern margin of the thick, valley fill sandstone. This relationship infers a connection between the thick valley fill sandstones and coal split lines.

Depositional Model for Multiple Coal Splits

The connection between thick valley fills and coal splits implies paleotopographic influence on both. The cross sectional evidence (A-A’ and B-B’) supports the following depositional history:

Stage 1

Upper Atoka sediments are deposited and subsequently eroded to form an unconformable surface (Suneson, 1998).

Stage 2

Lower Hartshorne deltas prograde over the Atokan surface. The lower Hartshorne distributary channel system is evident by wireline log data (Cross section A-A’). Delta front/shallow marine deposition is also evident (Cross section B-B’).

Stage 3

Deposition in lower Hartshorne culminates with the formation of extensive peat bogs.

Stage 4

Subsidence induced by outside factors (possible differential compaction or faulting in the Atokan) created topographic lows throughout the area.

Stage 5

Topographic lows in-filled with low-energy, mud-rich sediments. Peat bogs to the north and south of the topographic lows continued to accumulate.

Stage 6

As a result of the lowering of sea level, a major fluvial system cut through the area, following the topographic low. This system eroded older sediments, including the lower coal and older deltaic deposits (Cross section C-C’).

Stage 7

During a subsequent rise in sea level, the incised valley filled with sand and muddy sediments.

Stage 8

The southern and northern peat bogs which were not significantly affected by the incision began to spread laterally over the valley fill deposits. In areas of thick sand accumulation, differential compaction formed topographic high areas. The peat bogs thin toward the crests of these features. Peat was never deposited or it was eroded from the crests.

Stage 9

The Hartshorne interval was flooded by the sea responsible for the deposition of the sediment that became the McCurtain Shale Member of the McAlester Formation.

Summary

This depositional model (Figure 14) offers an explanation for the stratigraphic relationship in the study area. The previous model depicts the lower Hartshorne Sandstone and coal in the northern part of the basin. The evidence presented in this study suggests the upper and lower Hartshorne Coals are present in the northern part of the basin and in the undifferentiated area in the south. The lower Hartshorne Coal is not present where it was completely eroded by the incised valley fill. The cross sections illustrate how the upper Hartshorne Coal thins over the thick valley fill trends. The presence of “bony” coal in the middle of some thick coal sections may identify the boundary between the upper and lower coal. Detailed geochemical or palynological studies may resolve the issue of the composition of the thick, undifferentiated coals.

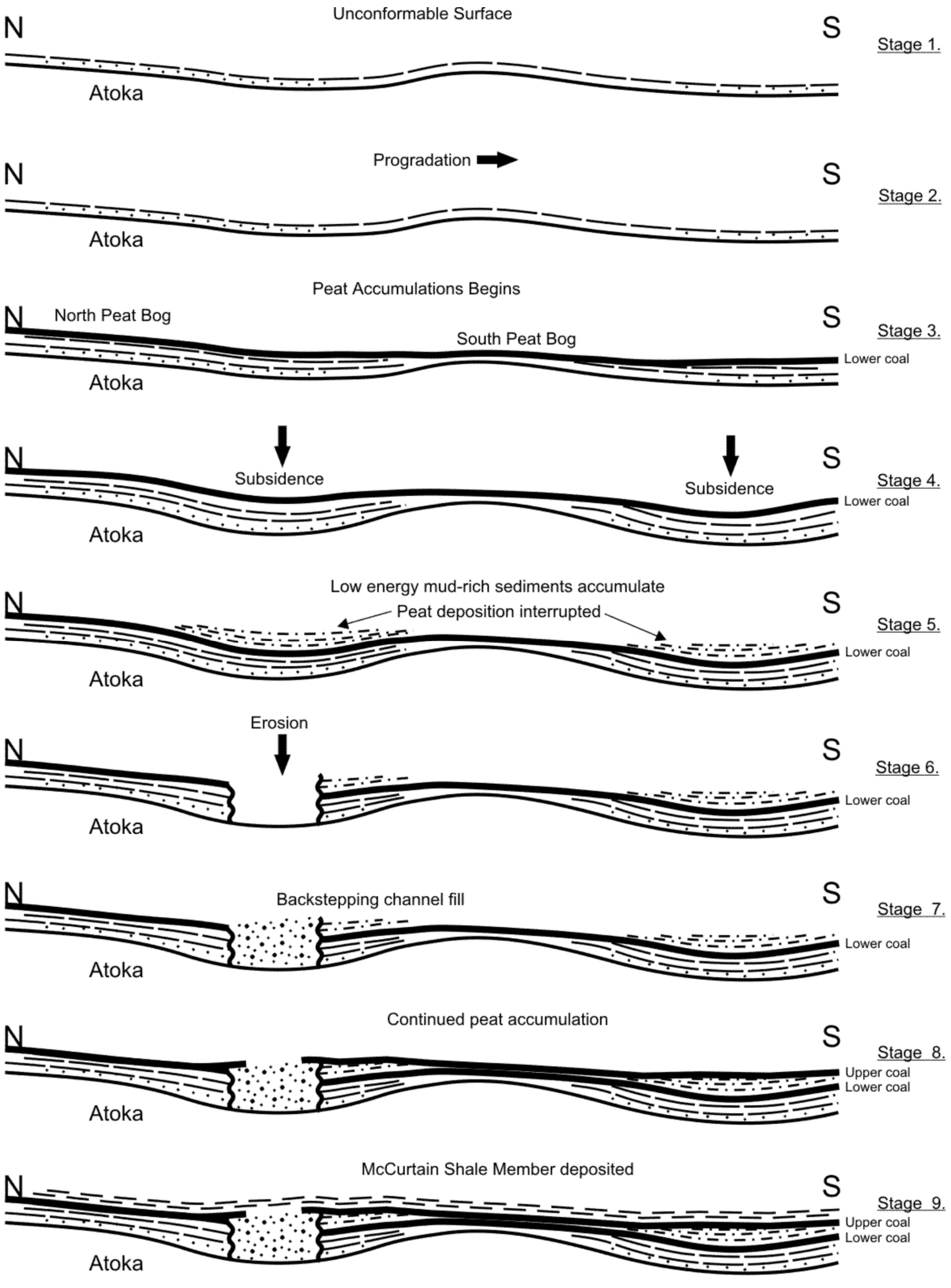

Figure 14. Model for multiple coal splits (vertically exaggerated). Refer to text for descriptions of stages.

3-D SEISMIC EXAMPLE FOR COAL

3-D seismic interpretation is a vital exploration tool for the oil and gas industry. In areas where well control is sparse, interpretation based on well logs alone can be problematic. Faulting or valley incision can disrupt coal continuity and localized folding can create anomalous dips that may impact exploration success or production efficiency. 3-D seismic not only improves interpretation in structurally deformed areas, but it also aids in determining horizontal well bore paths. For successful coal-bed methane exploration, it is important to understand the stratigraphy, lateral extent of coal beds and the structure of the subsurface. 3-D Seismic data provides an image that can be interpreted to determine the placement of faults, structural dip and most importantly, coal continuity. Lateral coal continuity is crucial to the successful drilling of horizontal wells.

Integrating cross sections from well log data with 3-D seismic was used to interpret the Hartshorne stratigraphy of the Arkoma Basin. Examining and interpreting well-log data allows the identification of electrofacies and the construction of cross sections that are key to understanding lateral continuity of the upper Hartshorne Coal. Maps based on wireline log data allow the representation of the structure. The cross sections combined with the 3-D seismic verify the subsurface geology.

Mercer Seismic was contracted by Devon Energy to perform the first part of the seismic 3-D survey over approximately four square miles of the thesis area (Figure 15).

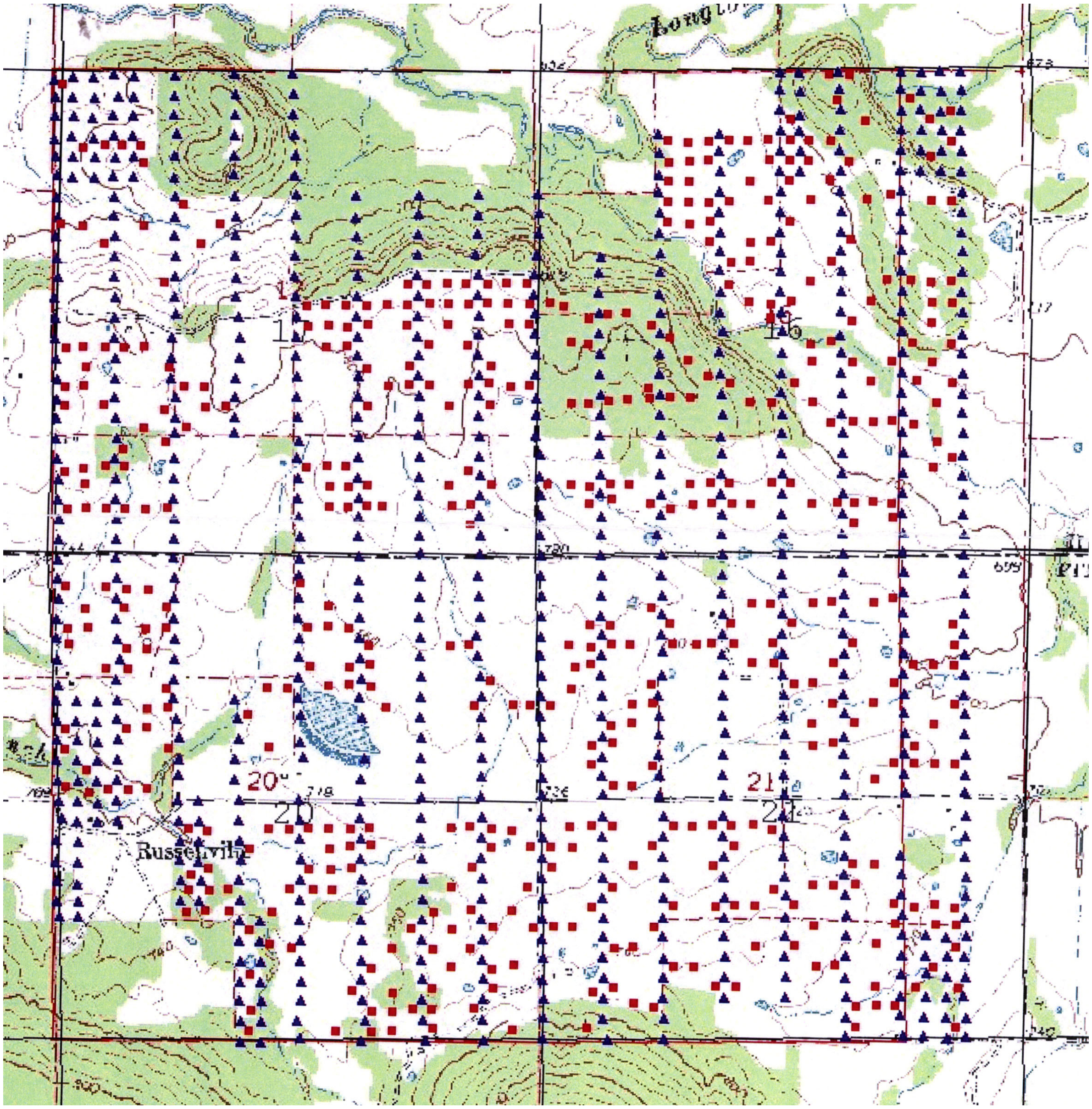

Figure 15. Topographic map showing location of seismic survey. Red squares indicate sources, and blue triangles are the receiver points (courtesy of Devon Energy).

Using dynamite as the energy source, Mercer Seismic was responsible for drilling twenty foot deep holes and loading them with two and a half pounds of dynamite. The sediments and rock column from the surface to the base of the hole included clay, shale, limestone, and sandstone. Clay was usually present from the surface to a depth of five to ten feet. Geophone arrays were set up in six foot circular patches to act as receivers for the source. The sources and receivers were set up perpendicular to each other using 220 foot interval spacing.

There were two major problems in the field area that impacted seismic data acquisition. The first was that the terrain in the northern part of the area is steep. As a result of the rough terrain, no source holes were drilled, and only receiver lines were laid out. The second problem involved obtaining the rights to “shoot” in the area. Several local residents refused to grant approval for shooting the survey on their property. As a result, there were areas where the ideal arrangement of sources and receivers was not possible. As an example, certain areas did not have the preferred perpendicular configuration between sources and receivers. These problems resulted in the poor seismic data in part of the field area.

After the sources, receivers and geophones were laid out, Devon Energy contracted Tidelands Geophysical Company, Inc. to perform the seismic 3-D survey. Tidelands was responsible for charging the dynamite, observing the surface 100 feet from the holes, and recording the subsurface data. After the dynamite was charged, observers watched the surface of the location where the hole was dug. There is usually a generic informal ranking for the way the surface sediment behaves when the dynamite is charged. If the sediment stays in the hole and does not move, it is considered a “good” shot. If the sediment in the hole is disrupted in any way, it was regarded as an “okay” shot. If the sediment explodes out of the hole and into the air (called a blowout), it is a “bad” shot. Approximately 54% of the holes experienced a blowout (Figure 16) during this process.

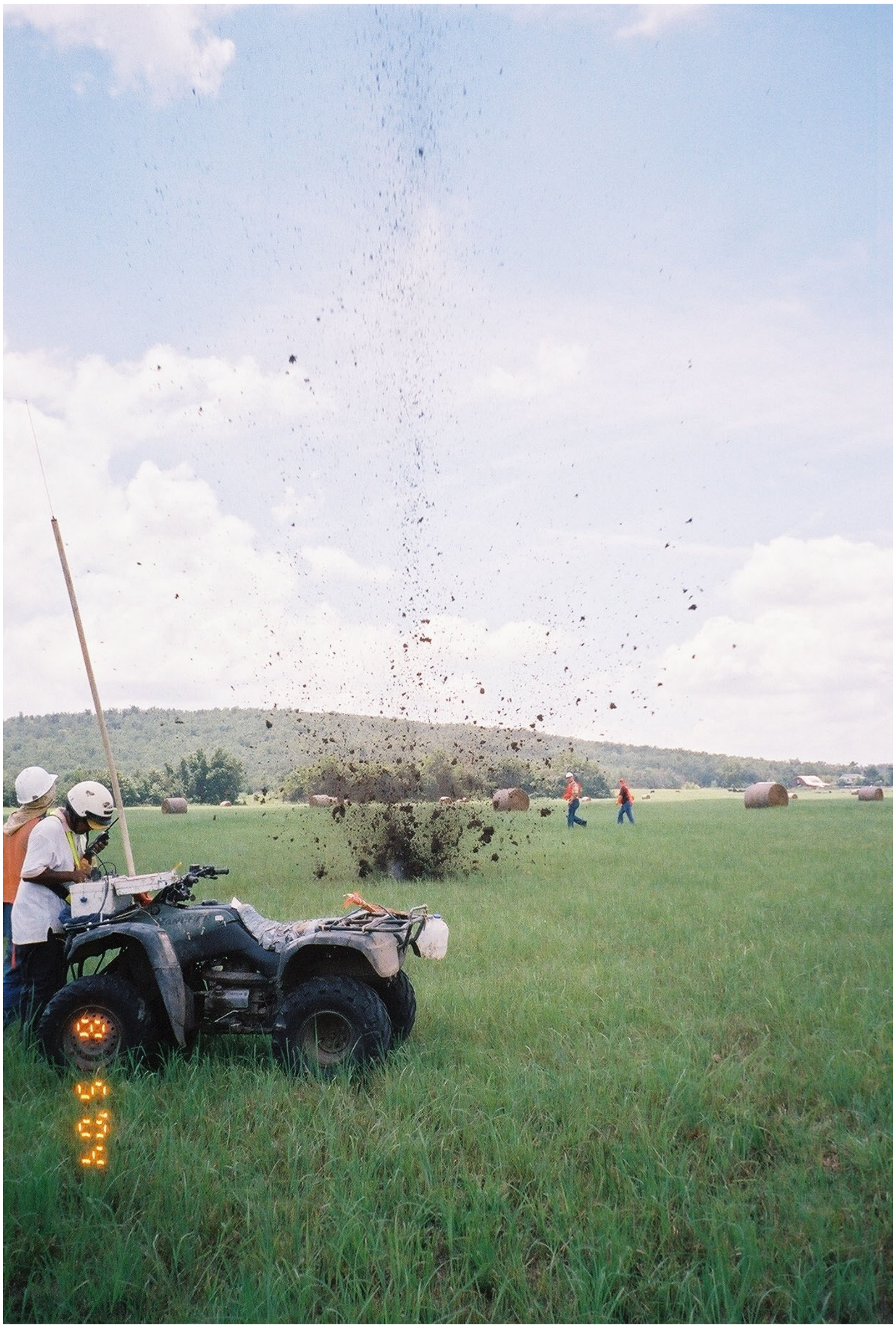

Figure 16. Blowout of seismic shot (courtesy of Lori Nelson).

This created additional problems for data collection. When a blowout occurs, energy travels to the surface instead of traveling down into the subsurface. If too much energy expected to travel down into the subsurface is lost, the geophones will receive weak signals.

Following dynamite charging, the signal detected by the receivers is sent to the "doghouse" where the data for each individual shot is printed. There are many components to each printout of a shot point. They are listed under the header and include the remote seismic parameters and plot parameters. This information provides the time and date, length of shot, filters, time intervals and frequency. The information recovered in the field was sent to Dawson Geophysical Company for processing. The seismic data was processed using standard statics, filters, common depth point stacks, and migration. Using standards in the processing, it is possible for a geophysicist to change the parameters to ones they prefer. After Dawson processed the data, it was sent to Devon Energy, where it was analyzed by geophysicists and geologists.

Three components were utilized to identify the Hartshorne Formation, including (1) a time structure map, (2) arbitrary lines, and (3) synthetic modeling. The time structure map (Plate 6) is constructed based on time intervals from approximately 330 milliseconds (ms) to 390 ms. It is a fundamental map that depicts the attitude of subsurface units. The time structure map indicates that the Hartshorne Formation is dipping in a southerly direction.

The arbitrary lines are the main constituents of the 3-D seismic interpretation. The lines can be oriented in multiple directions around the seismic survey area to help depict the subsurface geology. The line chosen for this study is oriented diagonally through the 3-D survey block and trends southwest to northeast. Time interval values are shown instead of feet values. Time values reflect the time (velocity in feet per second) it takes for a signal to reach a certain horizon (lithology) and return to the surface. The signal traveling in the subsurface travels through different lithologies at different velocities. These velocity changes exhibit peak and trough curves in the data (black vs. white lines).

The 3-D arbitrary line (Plate 7) contains peaks and troughs from the surface (zero ms) to approximately 600 ms. The Booch Sandstone is the first solid black peak seen at approximately 340 ms (traced by the green line). The trough below is likely shale. The Hartshorne Sandstone is indicated by the next solid black peak at 390 ms, which is traced by the yellow line. The continuity of this reflector shows that the Hartshorne Sandstone is laterally extensive and can be traced for approximately two miles. The attitude of the reflector indicates that the bed is dipping southward. The bed also bends upward slightly and is not planar. No major faulting (greater than 30 feet of offset) is present in this arbitrary line. However, there could be minor faulting that is not resolved by the image.

The last component is the synthetic modeling of well log data (Plate 8). Well logs in this area show the Hartshorne Coal thickness ranging from three feet to eight feet. However, seismic 3-D surveys cannot resolve beds that thin. In order to find the coal in the subsurface, well log data has to be correlated to time (velocity) intervals. The sonic porosity log is preferred because it measures velocity. Well “A” has the only sonic log in the seismic survey area. Velocity can be calculated for well logs without the sonic curve. In this case, a synthetic curve must be generated from bulk density or induction logs using the Faust equation. Synthetics can then be correlated to sonic logs.

The sonic or synthetic logs are correlated to the arbitrary lines in the seismic profile. The Hartshorne Sandstone is approximately 50 feet or 10 ms thick (outlined by yellow on Plate 7). The known stratigraphy of the area, combined with the well log data, shows that the Hartshorne Coal rests above the Hartshorne Sandstone. With that, the geophysicist was able to pick the upper Hartshorne Coal horizon indicated by the pink line in the trough.

Drilling horizontal wells in coal beds to produce coal bed methane is a high priority in the study area. To support a horizontal well, the coal bed needs to extensive and continuous. The arbitrary line (Plate 7) indicates that the coal bed is laterally extensive for approximately two miles (10,000 feet). This makes the area an excellent candidate for drilling horizontal wells. Since the Hartshorne Coal shows a very clean gamma ray signature, a gamma ray tool is connected to the end of the drill bit in order to "read" the lithology. The combination of seismic data and gamma ray signatures allows the drilling engineer to better maintain a horizontal path in the coal seam.

CONCLUSIONS

The evidence accumulated through the examination and correlation of over 2800 wireline well logs allows the formulation of the following conclusions. These conclusions challenge some existing ideas regarding the existence of a single coal split line, the classification of all coal north of the coal split line as the lower Hartshorne coal, and offer a plausible model to explain the spatial relationship between coals and sandstones of the Hartshorne Formation.

1. Both the upper and lower Hartshorne Coals can be correlated in the areas of "undifferentiated" thick coal. This evidence suggests that the areas of single thick coal contains upper and lower coal equivalents. The "bony" coal or "shaly zone" near the center of the thick undifferentiated coal may correlate to the "split" interval that is well defined by mudrocks that separate the two coals south of the incised valley fill.
2. Coal splits occur on either side of the incised valley fill. The presence of thicker coal north and south of the trend of the thick valley fill sandstone suggests a genetic relationship between valley fills and coal splits.
3. Another coal split is identified south of the southern margin of the incised valley fill area (south peat bog). Coal splits are found on all sides of the south peat bog.
4. Each coal split is believed to be the result of localized subsidence. Following the deposition of the lower Hartshorne peat, an accumulation of muddy sediments interrupted the peat production.

5. Outside of the area of subsidence, peat production continued uninterrupted and thicker peat accumulated.
6. During a drop in sea level, a fluvial paleodrainage system followed the topographic lows, creating a valley that in some cases eroded through the lower Hartshorne Coal and the underlying deltaic/marginal marine deposits.
7. After the valley filled with sediment, the Hartshorne peat bog extended back over the valley fill, depositing peat that ultimately became the upper Hartshorne Coal. In areas where sediments separated lower Hartshorne peat from the upper Hartshorne peat, a “coal split” developed.
8. As a result of differential compaction over sand in the valley fill, topographical highs developed that were only thinly covered by the peat bog. An alternate explanation is that the thinner peat was removed by erosion in these areas. As a result, the upper Hartshorne Coal is thin to absent over the thick channel fill sandstones.
9. Following deposition of the uppermost peat, the area was flooded and covered by mud-dominated sediments that ultimately became the McCurtain Shale of the McAlester Formation.

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Plate 1

THESIS AREA

Stefos,2005

Stratigraphic Cross Section "MMS_Thesis_A-A'" : Equally Spaced Logs
Datum = BOCHL
Vertical Scale = 2 in per 100 ft

Plate 2
Stratigraphic Cross section A-A’
M. Stefos, 2005

GRAVES 1-D
10820 ft
WINTERS 1-20
7615 ft
MADDEN 1-28
4476 ft
ZARTMAN 1-33
2783 ft
ZARTMAN 1
2151 ft
MACKEY 1-34
2004 ft
HUDSON HEIRS UNIT 1
2338 ft
ETCHISON UNIT 1
2149 ft
ETCHISON 1
5482 ft
AHERN-COBLENTZ UNIT 1
7907 ft
NOBLIN 1
7950 ft
PANTHER 1-24
10015 ft
INTEX 13-35
4439 ft
MIDWAY PREMIER 3
2846 ft
WEAVER 3-6
6200 ft
DEPT OF WILDL 3
2852 ft
DEPT WILDLIFE CONSE 5-7
5820 ft
ROBBERS CAVE 1
9352 ft
HACKNEY 2
BOCHL
HRSR

Stratigraphic Cross Section "MMS_Thesis_B-B'" : Equally Spaced Logs
Datum = BOCHL
Vertical Scale = 1 in per 100 ft

Plate 3
Stratigraphic Cross Section B-B’
M. Stefos, 2005

ORBISON 3-1
6115 ft
MONCRIEF 12-1
13238 ft
LAKE EUFAULA 1-30
21114 ft
PHILLIP 1-3
5408 ft
BROWN 1-10
3448 ft
NANCY 1-10
6726 ft
BROWNE /J/ 1
19954 ft
RUBY FETHRSTON 1
11430 ft
LEFLORE 1
16110 ft
W ERLE WHITE `A` UN 2
8043 ft
WHITE 3-C
9809 ft
WHITE `B` 5
2520 ft
WILDLIFE 1
5380 ft
STATE 4
11041 ft
ROBBERS CAVE 1
13102 ft
YOUNG RANCH 1-28
6792 ft
YOUNG RANCH 1-27
6107 ft
ARKANSAS KRAFT 1-26
BOCHL

Stratigraphic Cross Section "MMS_Thesis_C-C'" : Equally Spaced Logs
Datum = BOCHL
Vertical Scale = 1 in per 100 ft

Plate 4
Stratigraphic Cross Section C-C'
M. Stefos, 2005

ADAMSON 1-7807
8358 ft
WILDLIFE 3-14
9036 ft
WHITE RANCH 1
4590 ft
EMMA WHITE 3
12385 ft
WERLE WHITE 'A' UN 2
11853 ft
CHRISTOPHER 1
16547 ft
NOBLIN 1-13
5347 ft
LAKE 1
7953 ft
RUTH 1
7845 ft
ARY 1
14190 ft
BEA 4-13
0
-500
BOCHL
HRSR
3500
4000
3000
2500
2000
1500
TD=6121
TD=3300
TD=3000
TD=10654
TD=3000
TD=2639
TD=2800
TD=2444
TD=2700
TD=7282
TD=1996

Stratigraphic Cross Section "MMS_Thesis_D-D'" : Equally Spaced Logs
Datum = BOCHL
Vertical Scale = 1 in per 100 ft

Plate 5
Stratigraphic Cross Section D-D'
M. Stefos, 2005

W F BADSEN 1
1972 ft
BASDEN 1
5281 ft
STARR 2-15
10552 ft
BENNIGHT 1
5270 ft
M O ROBERTS 1-34
5372 ft
ROBERTS 3-3
8330 ft
C M TAYLOR 1
5381 ft
FEATHERSTON 2-22
2946 ft
MCFALL 2-22
5026 ft
O A PRUITT 3
8284 ft
ERLE 1
2712 ft
ERLE 4
7464 ft
WILDLIFE 2-15
3475 ft
WILDLIFE 3-15
7920 ft
ADAMSON 1-7807
CALIPER
FORMATION DENSITY LOG
GAMMA RAY
BULK DENSITY
POROSITY
CORRECTION
BOCHL
HRSR
0
-500
TD=6714
TD=2601
TD=2365
TD=2800
TD=2810
TD=2960
TD=2925
TD=2700
TD=2680
TD=3203
TD=8151
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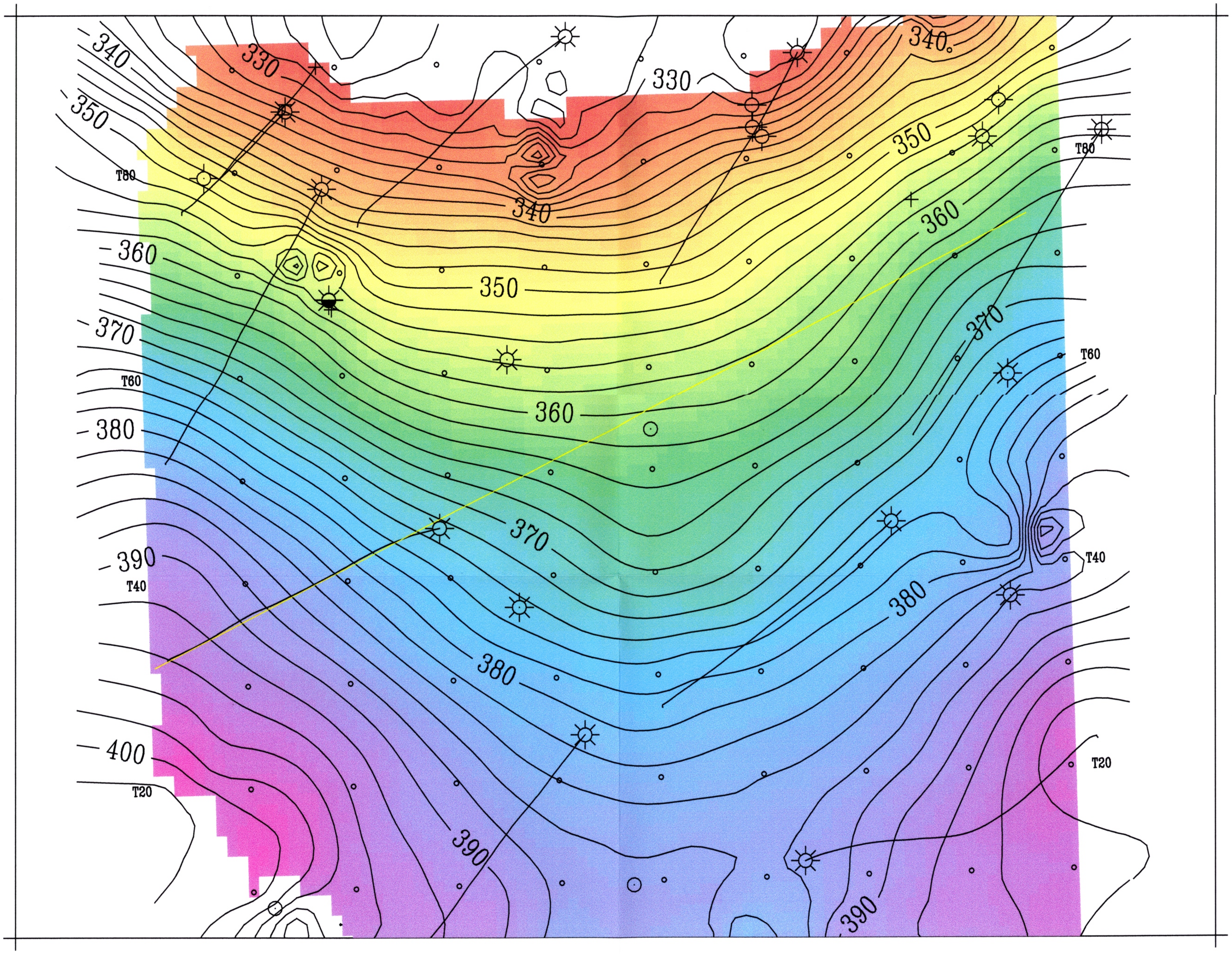
TD=2569
TD=3110
TD=8121

Plate 6
Time Structure Map
M. Stefos, 2005



HRZ:(327.12,402.35) JW_HartshrnIntSm

JW_HartshrnIntSm

TIME STRUCTURE MAP
HARTSHORNE

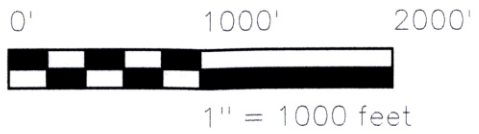


Plate 7
Arbitrary Seismic Line
M. Stefos, 2005

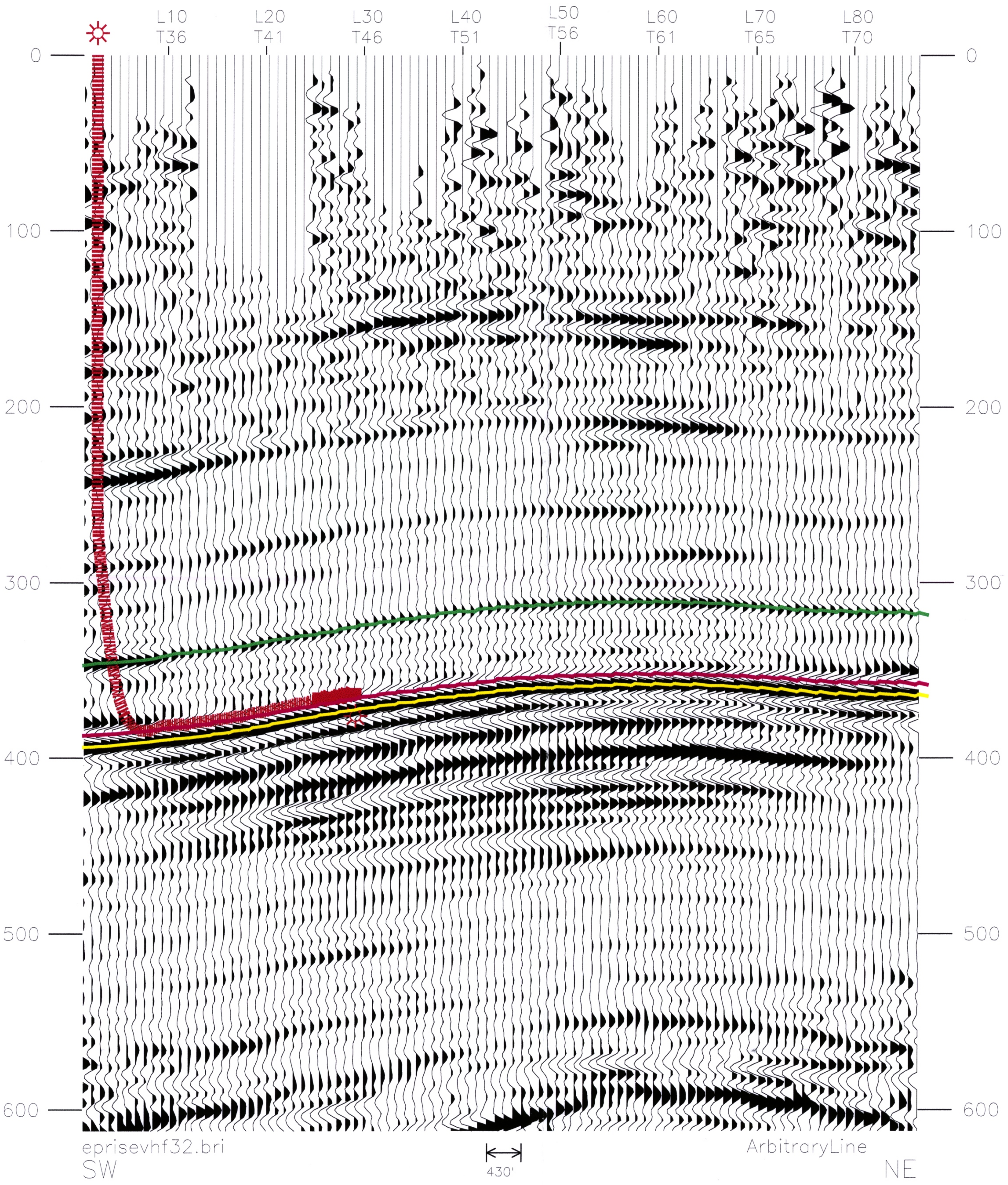
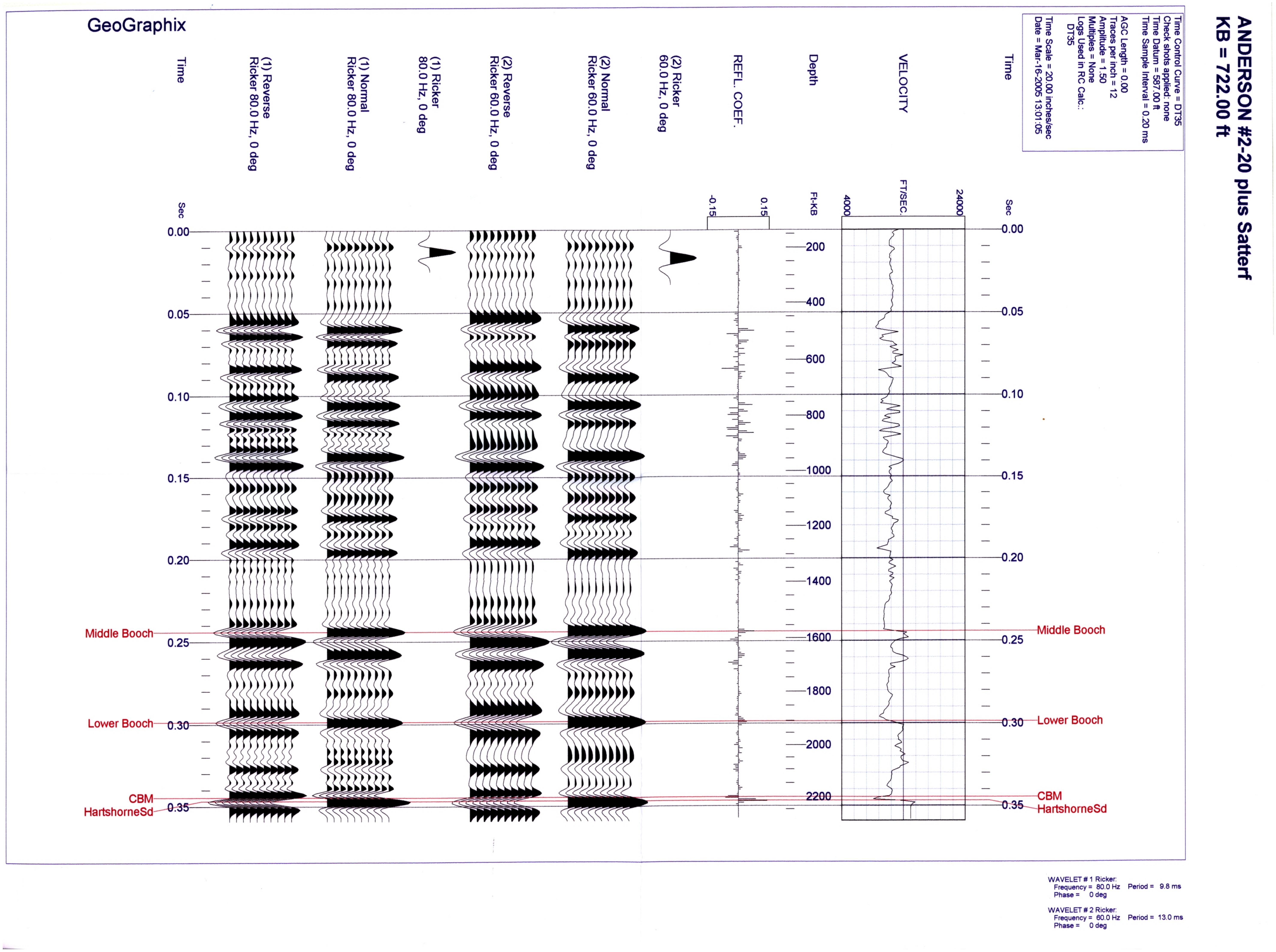


Plate 8
Synthetic
M. Stefos, 2005



VITA

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Thesis: Depositional Environments of the Hartshorne Formation, Western Arkoma Basin, Oklahoma

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Education: Graduated from Amos Alonzo Stagg High School, Palos Hills, Illinois in June 1999; received Bachelor of Science degree with a major in Geology and minor in Geography from Eastern Illinois University, Charleston, Illinois in May 2003. Completed the requirements for the Master of Science degree with a major in Geology at Oklahoma State University, Stillwater, Oklahoma in May 2005.

Experience at Eastern Illinois University:

- Geology tutor and teaching assistant
- Geology in the Schools program teacher (worked under Dr. Kathy Bower)
- Geoscience Club
    - Member 1999- 2003
    - Treasurer 2000- 2001
    - President 2001- 2002
- Sigma Gamma Epsilon (Earth Science Honors Society)
    - Member 2000-2003
    - President 2001- 2002
- Gamma Theta Upsilon (Geography Honors Society)
    - Member 2000-2003
    - Secretary 2002-2003
- College of Sciences Student Advisory Board 2002

continued

Research and Awards at Eastern Illinois University:

Water quality and assessment of the Town Branch Stream with Dr. Kathy Bower and Dr. John Stimac from 2000-2001

Palynology studies on Yellowstone National Park with Dr. Robert Jorstad from 2001-2003

Scholars in Undergraduate Research at Eastern (SURE) Award in 2001
Dewey H. Amos Geology Earth Science Award in 2001-2002
Annie E. Weller Scholarship in 2002-2003

Experience at Oklahoma State University:
Geology teaching assistant 2003-2004
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Pages in Study: 40 Candidate for the Degree of Master of Science

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Scope and Methodology: The Pennsylvanian (Desmoinesian) Hartshorne Formation of the Krebs Group was studied in Haskell, Latimer, McIntosh and Pittsburg Counties, Oklahoma. The purpose of this study was to examine evidence obtained from gas exploration wells to develop an interpretation of the depositional environments and stratigraphy of the Hartshorne Formation. Data from over 2800 well logs, cross sections, isomaps, and a seismic survey were integrated to complete this work.

Findings and Conclusions: The Hartshorne Formation is divided into two coal-bearing members: the upper and lower. Previous depositional models interpreted the Hartshorne as a fluvial-deltaic complex that contains a single coal-split line.

Multiple coal splits were recognized in this study. Both the upper and lower coals are present in many parts of the study area, not just south of the previously identified single coal split line. Coal splits are associated with thick valley fill deposits. Thicker, undifferentiated single coals found north and south of the incised valley fill appear to contain the upper and lower Hartshorne coals. Coal splits converge toward the thicker, single undifferentiated coals. “Bony coal” or the shale zone in the middle of the undifferentiated coal may correlate to the split. The upper coal thins toward and is absent over the thickest valley fill sandstones.

A modified depositional model for the Hartshorne was developed that incorporates the new findings. This model suggests that localized subsidence and deposition are responsible for the coal split. Fluvial drainage followed and eroded the subsided areas, establishing the association of coal split with the incised valley. The cause of subsidence was not established, but it could relate to deeper faulting or differential compaction in the underlying Atokan section.

ADVISOR’S APPROVAL: Dr. James Puckette