SEQUENCE STRATIGRAPHY AND RESERVOIR CHARACTERIZATION OF THE UPPER MORROW SANDSTONE, TEXAS COUNTY, OKLAHOMA

By

ERIN ELIZABETH VAN EVERA

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Thesis Approved:

Zuhair al-Shaieb

Thesis Adviser

Jim Puckette

Stanley T. Paxton

Timothy J. Pettibone

Dean of the Graduate College

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CHAPTER I

INTRODUCTION

This study of the Upper Morrow Sandstone is part of an extended research program at Oklahoma State University. The program was originally instituted in 1995 by Dr. Zuhair Al-Shaieb and Dr. James Puckette. Their work on the Morrow sandstone has proven to aid in the development of hydrocarbon exploration in the Panhandle of Oklahoma and surrounding regions.

Exploration and development of upper Morrowan fields is particularly difficult because the sandstone is a channel fill (Sonnenberg, 1985). The channels are erratic in distribution and pattern (Barrett, 1964) and are susceptible to geographic irregularities due to tectonic influences. One of the main tasks of exploration is locating the channels. However, within the channel fill, which has been deposited during transgressions and regressions of sea level, there are various lithofacies present. It is within certain lithofacies that the better porosity and permeability are located, which would therefore qualify as being the significant reservoirs. The distribution of these depositional environments is highly dependent on tectonic setting, rate of sediment supply, and sea level changes (Vail,1977). A lack of vertically continuity of the sandstone, variation in grain size, rapid facies changes, and diagenesis all contribute to channel fill heterogeneity. The complex genetic composition of the rock obscures exploration for upper Morrowan fields. In order to better understand the geometry of the sandstone reservoirs, which has influenced the positioning of sequence boundaries and stacking patterns, facies changes have been concentrated upon in this study and will determine which should be target zones for hydrocarbon reservoirs in the upper Morrow sandstones.

Location

This study pertains to the sequence stratigraphy and reservoir characterization of the Upper Morrow interval within the Carthage, Northeast Hardesty, Northwest Eva, and Southwest Rice fields. These fields are located on the northwestern shelf of the Anadarko Basin in Texas County within the Oklahoma Panhandle (fig 1.) and are present in townships 2, 3, 4, & 5 and ranges 10, 11, 12, 13, and 18 ECM. The fields that were investigated have reported oil and gas production from the upper Morrowan reservoirs, but also have large potential for further field development. These fields have been chosen because of relative proximity to one another as well as the possibility of potential future field development with upper Morrow sandstone drilling in their respective areas.

Purpose

The purpose of this study is to compare the lithologies, depositional environments, petrology, and reservoir characteristics of the Southwest Rice field in Texas County, Oklahoma with previously completed work in other Texas County fields. This knowledge may aid in the exploration and development of these and future upper Morrow reservoir fields.

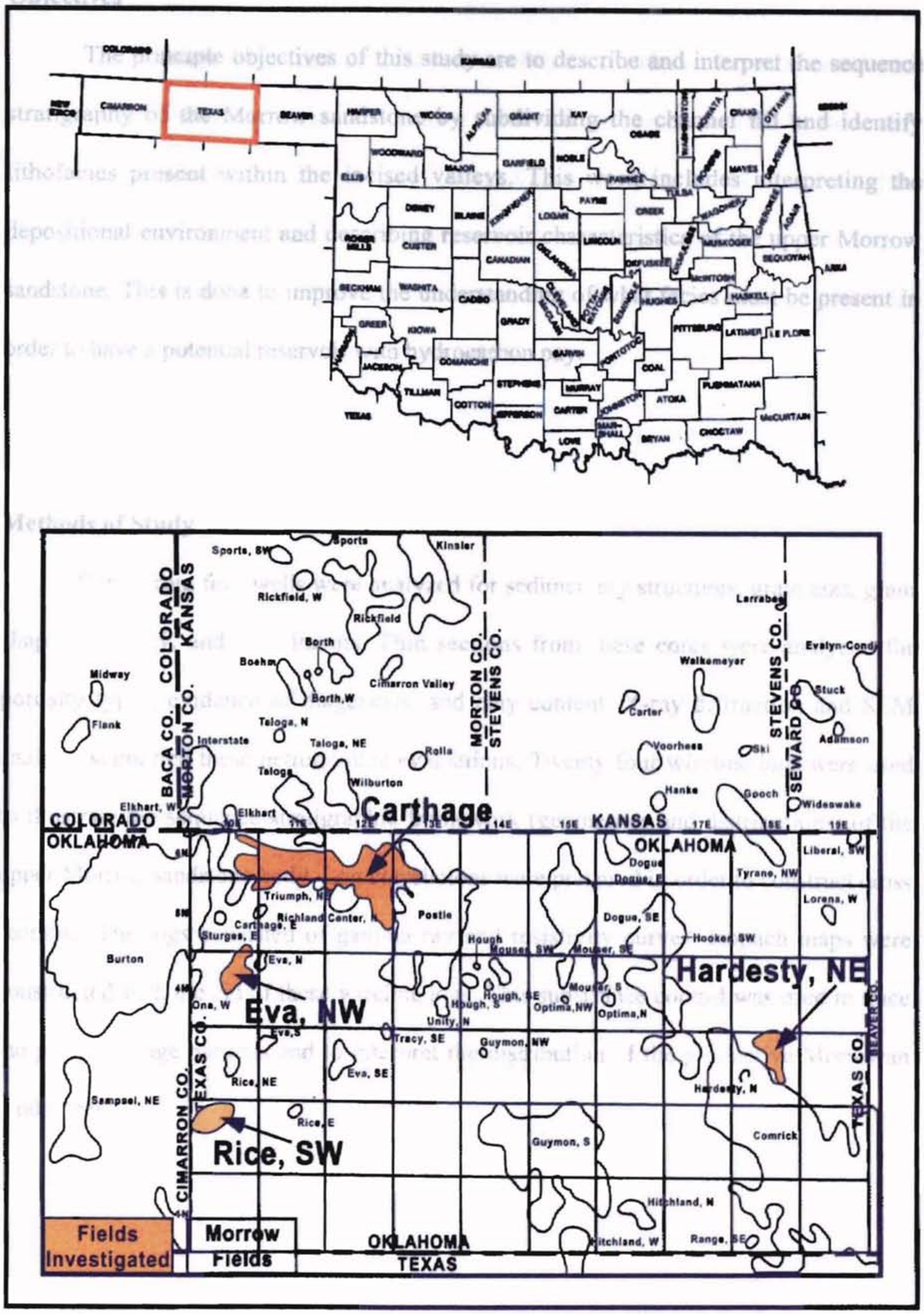


Figure 1. Location of study area in the Panhandle of Oklahoma, Texas County.

Objectives

The principle objectives of this study are to describe and interpret the sequence stratigraphy of the Morrow sandstone by subdividing the channel fill and identify lithofacies present within the incised valleys. This work includes interpreting the depositional environment and describing reservoir characteristics of the upper Morrow sandstone. This is done to improve the understanding of what facies must be present in order to have a potential reservoir with hydrocarbon pay.

Methods of Study

Cores from four wells were analyzed for sedimentary structures, grain size, grain shape, lithology, and constituents. Thin sections from these cores were analyzed for porosity types, evidence of diagenesis, and clay content. X-ray diffraction and SEM analysis supported these petrographic evaluations. Twenty four wireline logs were used to illustrate the sequence stratigraphic framework (geometries and distributions) of the upper Morrow sandstone body. Log correlations were prepared in order to construct cross sections. The logs consisted of gamma ray and resistivity curves. Isopach maps were constructed with the aid of these wireline logs. This subsurface control was used to trace the paleodrainage patterns and to interpret the distribution of the productive Morrowan sandstones.

Geologic Setting

The study area is bounded to the southeast by the Anadarko Basin, thus the study area is on the shelf of the basin. The Dalhart Basin is to the direct south of the study area, as is the Amarillo-Wichita Uplift. The Central Kansas Uplift is to the northeast of the study area, as is the Hugoton Embayment. To the west the Ancestral Frontal Range, Apishapa Uplift, and Sierra Grande Uplift trend northwest- south southeast. The study area is on the Keyes Dome formation in the Oklahoma panhandle. (See fig. 2)

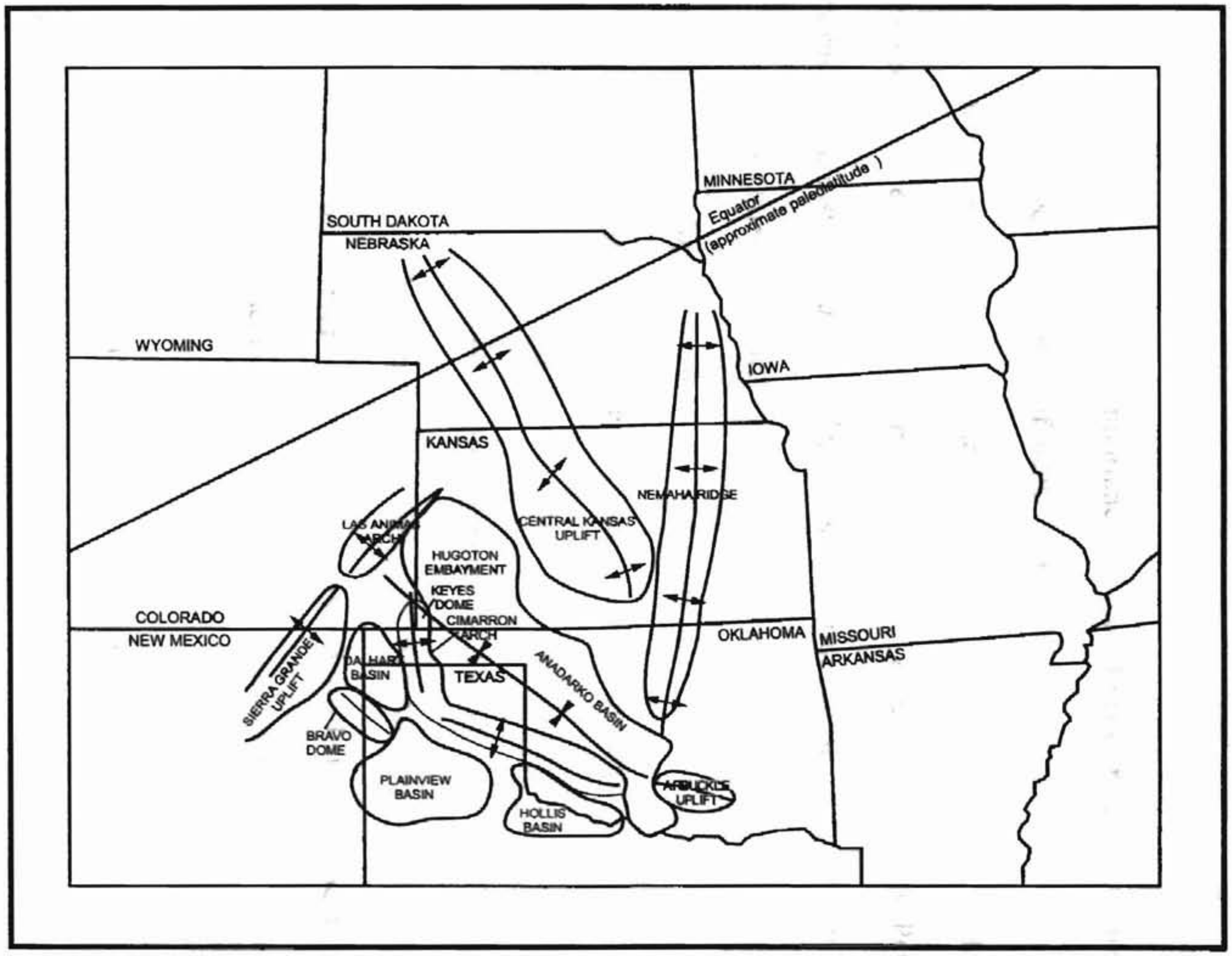


Figure 2. Paleogeographic map of the early Pennsylvanian time (modified from Jorgensen, 1989 and Khaiwka, 1968).

CHAPTER II

PREVIOUS INVESTIGATIONS

Due to the economic importance of the Morrow reservoirs, the Oklahoma Panhandle has been the location of many studies.

During the regression of the Mississippian sea, fluvial drainage channels were incised into the Mississippian limestone surface. Later, cyclic Early Pennsylvanian marine transgressions caused the deposition of marine sandstone. Clark, (1987) proposed the greatest thicknesses of Early Pennsylvanian (Morrow) sands were concentrated in low areas in well-developed drainage patterns on the eroded Mississippian topography, where there are excellent stratigraphic traps for petroleum accumulations.

Barrett (1965) noted that the Morrow contains a variety of stratigraphic reservoirs resulting from facies changes, porosity pinch-outs, the overlapping of porous sands, as well as minor faulting. Forgotson (1969) identified Morrow sandstone oil and gas production to be primarily stratigraphically controlled. This occurred because topographically high structures developed contemporaneously with deposition of sand on the flanks of structures rather than on crests.

Khaiwka (1968) characterized the depositional types of the Morrow as small, localized deltas and were depocenters for shore sands along the northeastern shelf of the Anadarko basin during periods of shoreline stillstand. Inferences regarding energy levels were determined by studying textural differences within sediments.

Benton (1970) determined the probable environments in which the Morrow sediments were deposited and indicated that structural activity was a strong influence. This knowledge of paleostructure determining deposition patterns allowed for more accurate predictions of sandstone body geometries.

Simon (1979) recognized different environments for the upper and lower Morrow sandstones. The lower Morrow was described as being a marginal marine-transgressive system. Lower Morrow sandstones were subdivided into high and low energy environments. Simon (1979) suggested that regressive fluvial/deltaic depositional systems existed during deposition of upper Morrow sandstones.

Swanson (1979) described reservoir sandstones as ranging from distributary mouth bars to fluvial point bars. Swanson (1979) also proposed a fluvial deltaic model for upper the Morrow, and that sand bodies were deposited in deltaic conditions. This interpretation was based on progradational channel sequences, which consisted of marine shale with fluvial sediments deposited on top of it. However, no sea level changes were needed for this model, as deltaic lobes build basinward into a shallow marine environment and accumulate vertically through deposition. Swanson believed that the deposition of fluvial sediments in the upper Morrow were controlled by a series of incised drainage systems trending NW-SE. In some areas the deposition rates may have exceeded sea level rise, which would be evidence of deltaic areas. Other areas may have had insufficient sediment load to overcome the effects of sea level rise, which would have been equivalent to flood plain conditions. Altogether, the fluvial deposits of point bars and braided river deposits may have been reworked by tides in coastal inlets by transgression.

Orchard and Kidwell (1984) proposed that channel sands were deposited within a non-incised fluvial meander belt that was laterally confined by levees and flood plain deposits. This would allow the Morrow sandstones to be point bar deposits associated with non-incised fluvial meander belts. This was demonstrated as Morrow reservoir sands on top of marine regressive sequence and overlain by transgressive marine sequence including marine shale. Delta sediments were capped by floodplain deposits as channel facies were deposited within them which were capped by transgressive marine shales.

In 1985, Sonnenberg contrasted with Orchard & Kidwell s idea with an incised valley-fill model such that fluvial deposits were implaced within a pre-existing incised valley and that no time equivalent facies to the valley-fill deposits are present in the valley margin. Sonnenberg thought that fluctuating sea level was responsible for deposition and preservation of the Morrow sands. During sea level lowstands, narrow valleys were incised into which exposed lower marine shales. As sea level rose, the valleys back filled with fluvial sediments and were eventually transgressed and preserved by the overlying marine shales. Basement faulting was responsible for creating paleotopographic lows which influenced drainage patterns and valley development during deposition of the Morrow.

Walker (1986) interpreted the upper Morrow sandstones to be delta processes with NNE and WNW sources. Sedimentary structures that indicated delta deposition included cross-bedding, such as in the Cimarron River in Oklahoma, penecontemperaneous deformation, and minor bioturbation. This was characterized by fine sand and sharp basal contacts. The sands fine upward with an increase in clay. Diagnostic constituents included interclasts of clay and siderite, carbonaceous matter, and some glauconite. Delta sandstones were characterized by basal channel conglomerates. Primary delta depositional facies included delta fringe deposits, distributary channels, interdistributary bays, and levee/splay deposits.

Bolyard (1989) divided the upper Morrow into five units. These were primary reservoir sands at the base of valley-fill deposits with a series of fluvial point bars with associated oxbow and floodplain deposits. There were estuarine facies present in upper valley-fill sequence, transgression and inundation, covered by marine shales to preserve valley-fill sequence. These sequences were evidence of fluctuating sea level.

Keighin and Flores (1989) identified fluvial-incised coastal and tidal-influenced nearshore lithofacies in the Panhandle. These lithofacies consisted of lower delta-plain deposits with associated tidal and intertidal lithofacies. The tidal and brackish water influences suggest that the Anadarko basin was an embayment that was affected by sea level fluctuations.

Wheeler (1990) proposed a valley-fill model that consisted of fluvial fill deposited on an erosional surface that formed as sea level dropped. Evidence for this was marine fossils and trace fossils that were found in sediments above channel deposits. The distribution of upper Morrow was controlled by the locations of paleo-valleys and marine influences during high sea level which may have been tidal or estuarine conditions. Complete marine inundation would have occurred as marine transgression continued and facies development would be related to sea level position.

Harrison (1990) found valley-fill sequences, including point bars, completely surrounded by marine shale. Wheeler (1990) came to the same conclusion as Harrison (1990), that during sea level lowstand, incisement into exposed shelf (preexisting

Morrow shale) would occur and an extension of fluvial processes would develop during sea level transgression. Harrison found that upper Morrow sands held most oil production, as the middle and lower Morrow sandstone bodies had e-log characteristics of fluvial channels and were most apt to produce gas. It was also believed that Morrow deltas were small and tide-dominated.

Puckette and others (1996) described the upper Morrow sandstone to have been deposited within two distinct depositional settings, one being southward-flowing fluvial-dominated tracts on the Anadarko shelf and the other being northward-prograding fan-delta complexes adjacent to the Wichita-Amarillo uplift. Puckette and others (1996) also concluded that after channel incision into shelf muds occurred during sea-level lowstands, the channels were filled with fluvial, estuarine, and flood-plain sediments during sea-level transgressions.

CHAPTER III

TECTONISM & STRUCTURAL FRAMEWORK

Geologic History

At the end of the Mississippian, sea level regressed and the northern shelf of the Anadarko Basin was subaerially exposed to erosion. This transpired shortly after uplifting in the Mid-continent area occurred and the pre-Pennsylvanian unconformity developed. Fluvial drainage systems and thus canyon cutting initiated by lowering sea level (Vail, 1977) began to develop during early Pennsylvanian time. This ensued in the vicinity of the flanks of the Ancestral Rocky Mountains, from the Sierra arch and the Apishapa uplift, and the northern shelf of the Anadarko Basin as sediment was eroded and transported into the area.

Paleostructure influenced Morrow depositional patterns. Morrow sandstone accumulated in paleostructural low areas created by movement on basal fault bocks (Sonnenberg, 1984). Because of the structurally weak zone of the Anadarko Basin axis, more rapid subsidence occurred in this area than in the surrounding vicinities (Benton, 1970). Drainage followed this axis and thus channels were developed on the adjacent shelf. Marine transgression into the area during Morrowan time resulted in the deposition of conglomeratic basal sands and marine mud that filled these channels. Several transgressive-regressive cycles influenced deposition of the sporadically distributed lower and middle Morrowan sandstones which were areally restricted some sequences to basin centers (and continental margins). Early Pennsylvanian depositional units are examples of areally restricted sequences that resulted from major global unconformities such as the pre-Pennsylvanian unconformity (324 Ma) (Vail & Mitchum, 1977). Because of uplift, the Anadarko Basin became the major area for drainage and stream erosion. This caused channels to be cut into the Lower Morrowan deposits. Coarse clastic sediments derived from the northwest were carried through these channels (see fig. 3). Because of subsidence and thus a rise in base level, the rivers that had formed began to be filled with these sedimentary deposits. Once the channels were filled, an extensive flood plain developed, over which rivers meandered. With the continued subsidence, clastic sediments were deposited in a more landward position, thus converting the area into swamp and marsh environments. It is in these localities that fine-grained clastics and peats were deposited (Benton, 1970). Afterwards, the uppermost Morrowan sands were deposited during the final marine transgressive phases (Clark 1987).

Tectonism During Pennsylvanian Time

The midcontinent of the U.S. was very unstable during Pennsylvanian time. Collisions between Laurasia and Gondwana resulted in large compressional stresses developed in general north-south trending directions (Jorgensen, 1989). Features such as the Nemaha Ridge, which is a discontinuous series of block-faulted uplifts, formed. This collision caused regional folding, faulting, uplifting, and downwarping to transpire in the mid-continental area. No igneous or metamorphic activity accompanied the tectonism (Johnson, 1989). The Wichita-Amarillo block was uplifted along WNW-trending reverse faults. This uplift caused faulting to occur at the southeast end of the Anadarko basin in

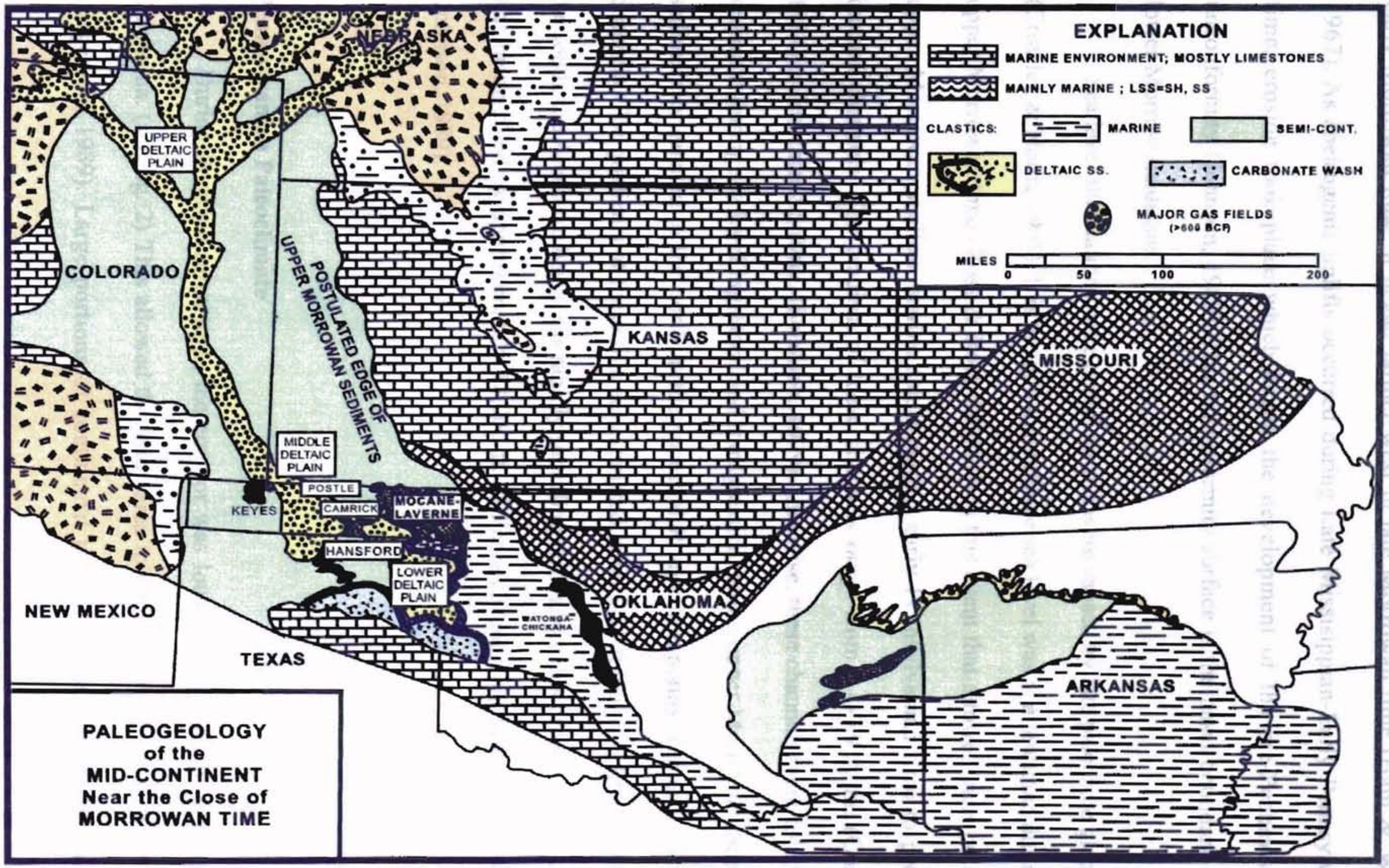


Figure 3. Paleogeologic map during lower Pennsylvanian time (modified from Rascoe and Adler, 1983).

early Morrowan time; it began farther west in late Morrowan time (Ham & Wilson, 1967). As epeirogenic uplifts occurred during Late Missisippian-Early Pennsylvanian time, erosion took place which began the development of the pre-Pennsylvanian unconformity (Johnson, 1989). This unconformity surface is the basal boundary of the lower Morrow sandstone.

Sea level fluctuations were prevalent and were caused by late paleozoic glaciation (Crowley & North, 1991). It is thought that relative sea level was at a lowstand during the upper Morrowan time (Ross & Ross, 1985). It is this event that allowed incision of the upper Morrowan shallow marine shales during early Pennsylvanian time to produce incised channels. The gradient of these channels range from 0.4-0.9 ft/mi. (Cornish, 1984) to less than 2.5 ft/mi. (Swanson, 1979). Likewise, these channels were filled with sediment during sea level highstand and transgression during upper Morrowan time. The sediment originated to the north in the ancestral Rocky Mountains, filling the incised channels. The gradients of these fills are estimated to be 1-35 ft./mi. (Luchtel, 1999). To the south, the Anadarko basin was rapidly subsiding throughout this orogenic activity and was being filled by approximately 18,000 ft. of Pennsylvanian clastics and carbonates (Johnson, 1989).

Pennsylvanian Paleoclimate

During Pennsylvanian time, the equator was located just north of present-day Oklahoma. (see fig. 2) This allowed the study area to be in a warm, wet climatic zone (Jorgensen, 1989). Large portions of continental interiors were covered by shallow epeiric seas, as the sea level was generally advancing (Crowley and North, 1991). Having this sea level rise cyclic transgressions and regressions occurred. Land plants evolved during this time, which increased the amount of organic material present and thus a tropical belt of coal swamps developed from the mid-western U.S. through Europe during the non-marine phase of sea level oscillation (Crowley and North, 1991).

Regional Structure

The study area is located on the western end of the Anadarko Basin. Most of the tectonic features in the area developed as a result of structural deformation lasting from Late Mississippian through Early Pennsylvanian time. The regional structure was modified by the Laramide Orogeny during Late Cretaceous and Early Tertiary time (Benton, 1970). The Keyes Dome is located to the west of the study area (see fig. 2) and influenced the dip rate of 100-150 feet per mile on its eastern flank. Trending east across Texas County, the dip decreases to approximately 20 feet per mile. In the eastern portion of the Oklahoma panhandle the dip once again increases to over 100 feet per mile.

CHAPTER IV

DEPOSITIONAL ENVIRONMENTS

Introduction

The Lower Morrowan sequence is interpreted to have been deposited in a shallow marine environment (Benton, 1970). The uppermost productive Morrowan sandstones in the panhandle of Oklahoma are interpreted as being fluvial valley-fill deposits, mainly channel sandstones deposited during the transgression of the sea. These sandstones are approximately greater or equal to 10 ft. thick and the porosity is best preserved within the former fluvial channels due to differential compaction during deposition. Deposition of the sands on Mississippian highs outside the channels resulted in thin, (approximately less than 5 ft. thick), tight sandstone. The valley-fill sands were covered and encased by marine mud as transgression continued.

Fluvial Systems

Fluvial systems typically consist of a drainage basin with a sediment and water source, a river by which to remove the debris from the drainage area, and a location or site for sediment deposition such as a coastal environment (Schumm, 1981).

The sinuosity of channel systems commonly progresses from low to high. There is relatively continuous lateral migration and the individual channel courses are close in distance such that they are not resolvable in cross section and are very subtle in seismic sections (Kolla et al., 2001). In a meander loop, the top of the point bar deposit is relatively flat with no significant aggradation. Channel width remains relatively constant during the evolution of sinuosity. When the meander bend becomes highly sinuous with high-volume flows and low floodplain aggradation rates, compared to lateral migration rates, neck cutoffs occur (Peakall et al., 2000). Otherwise, river channels may avulse, after which the sinuosity evolution may begin again.

Braided Fluvial Systems

Braided fluvial systems occur near the source in alluvial plain environments. They are signatures of high stream gradient as coarse material is found within the systems. The sand bodies are sheetlike or elongated, straight lenticular deposits. Fining upward sequences are common, as channel-lags, cross-bedding, accretionary, and laminated surfaces are present (Prothero, & Schwab, 1996). The sheet sandstones or conglomerates contain thin lenses or beds of shale and are enclosed within thicker sediments. The systems are ephemeral and constantly shifting position within the channel which account for lateral channel migration and aggradation (Boggs, 1995). In the proximal realms of the provenance, gravels are common; whereas distally more sand is present. Ripple marks and dunes are evidence of low flow velocities, as bar sands are evidence of higher flow velocities. Fossil evidence of root casts and burrows on vegetated sand flats may be present (Prothero, & Schwab, 1996).

Meandering Fluvial Systems

Meandering fluvial systems are associated with floodplains and are present in downdropping basins or in aggrading coastal sequences. They grade downstream into a deltaic system and upstream into a braided system. The channels may form elongated ribbon-like bodies of sand that are composed within thick shale sequences. They are confined within narrow, sandy meander belts of stream floodplains and create a shoestring appearance of sand bodies that are oriented parallel to the course of the river (Cant, 1982). Typically, the channel-fill sequences fine upward from basal channel-lag gravel into sandy point-bars. The point bars are denoted by the presence of planar beds, trough crossbeds, and ripple drift. Finely laminated floodplain muds overlie the sequence and may vertically accrete. Organic matter and fossil wood are common, predominantly in the floodplain (Prothero, & Schwab, 1996).

Fluvial Point Bars

Point bars are defined as being one of a series of low, arcuate ridges of sand and gravel developed on the inside of a growing meander by the slow addition of individual accretions accompanying migration of the channel toward the outer bank.

Most common reservoirs in coastal flood plain environments occur in channel deposits such as point bars and braided river deposits. Point bars are common components of fluvial systems in Oklahoma (Andrews, Campbell, & Northcutt).

Distributary Channels

Distributary channels form as current velocity slows down on the surface of a delta. As a result, sediment accumulates on the channel bottom as cross-bedded sands and muds, causing the river channel to branch repeatedly into smaller channels that radiate outward from the mainland. Sands then spill out from the channel mouths to form shoals and sheetlike sand bodies along the delta front (Stanley, 1989).

Deltas

Deltas are formed by a series of rivers that drained southeast out of the eroding ancestral Rocky Mountains toward the Anadarko Basin in Oklahoma and Texas. Generally, deltas form where rivers carry more sediment into the sea than marine erosion can carry away. Diagnostic features of deltas include their occurrence along coastal plains of passive margins or in broadly downwarping cratonic basins. They are associated with meandering fluvial deposits and shallow marine shelf deposits. A typical deltaic facies profile includes coarsening upward sequence of prodelta muds and clays that is overlain by distributary bar finger or delta front sands. These are overlain by muds and coals of interdistributary marshes and levees. Sedimentologically, there is a wide range of grain sizes which varies from coarse sand to fine mud, generally becoming finer distally. Organic material is very common in the interdistributary areas, where thick layers of peat or coal can form. Organic material can be trapped in the distributary sands, which are less common. Prodelta muds have lower amounts of organic debris but can contain abundant shells and bioturbation (Prothero & Schwab, 1996).

As deltas prograde into such shallow seas, they would be composed almost entirely of delta-plain beds. The sloping delta front, like the one that produces the delta-front beds in deltas like the Mississippi Delta, is not present. Ancient deltas that grow into shallow epicontinental seas probably consist largely of delta-front beds as well. (Stanley, 1989) Because of this low regional gradient, it is possible for channels to display meandering patterns. This results because river-dominated deltas project farther out into the ocean and their construction prevails over the destructive forces of the sea (Stanley, 1993).

Estuaries

An estuary is a relatively small, semi-enclosed coastal embayment that is present in the area where the lower course of a river opens up to the ocean. This inlet to the sea may extend into a river valley as far as the upper limit of tidal rise (Fairbridge, 1980) and head to the seaward limit of coastal facies at its mouth.

An estuary differs from a delta in that the seaward portion of the submerged valley system would receive sediments from both fluvial and marine sources. (Dalrymple et al., 1992) These sediment facies may be influenced by fluvial, tidal, and wave processes. Estuaries form when there is a relative rise in sea level, such as a transgression. During times of regression, or progradation, the estuaries may fill up with sediment and thus become delta environments.

Estuaries thus provide important information relative to shoreline conditions and environments. Because much organic material is present in estuary settings, there is evidence for potential hydrocarbon source material. Also, the interlayering and juxtapositioning of the sandy and muddy facies, may provide favorable settings for hydrocarbon stratigraphic trapping (Boggs, 1995).

Marine

In marine environments, typical deposition may consist of shelf muds such as clay with occasional layers of clean silt deposited by storms. Lower, middle, and upper shoreface deposits such as slightly muddy sand with some burrowing, clean sand with low angle cross-bedding, and clean sand with cross-bedding caused by ripple migration may also be present. At shallow ocean depths, strong wave movements produce cross-bedding and exclude most bottom-dwelling animals. At greater ocean depths, wave action does not have any effect on the deposited sediments although burrowing animals may disrupt most sediment layers.

Evidence of marine depositional environments may also be present as flooding surfaces. These flooding surfaces represent episodes of sea level rise and transgression. As seas transgressed, there was a landward shift of the shoreline, which flooded the valley terrain and mud was deposited. These muddy deposits may be meters to tens of meters in thickness and act as sequence boundaries between correlative conformities amongst regional deposits.

Facies Descriptions and Characterizations

Various facies, or areally restricted lithostratigraphic bodies that represent different depositional environments, are present within the Upper Morrow sandstone channel fill. The facies in the Upper Morrow sandstone represent marine, fluvial, and estuarine environments. The criteria for boundaries, or sequence boundaries within the channel fill is defined as the having a sharp basal contact, incisement into the underlying marine muds and shales of the Upper Morrow shift of facies, the presence of complex facies which include fluvial, estuarine, and marine lithofacies that backstep in the landward direction which reflects sea level rise, and patterns of specific grain size changes such as fining upward sequences. Walther s Law describes facies changes and correlation as laterally continuous, regional environments shift with time in response to variations in shorelines because of fluxing sea level or other geologic conditions, the facies boundaries also change so that the deposits of one environment may lie above those of another environment (Boggs, 1995).

Marine Facies

The M1 facies is characterized by the presence of shale in core samples and also by the presence of trace fossils, macroinvertebrates, and glauconite in thin section analysis (fig. 4).

The glauconite signature indicates very slow sedimentation rates. It is a diagenetic iron silicate found in marine sedimentary rocks from the Cambrian to the present. Because shale is composed primarily of clay, silt, and mica, the small grain sizes reflect the low porosity values that would be present in a sample. Fossiliferous sandstone is also present in portions of the upper marine facies and is classified as M2.

Lithofacies	Sedimentary Structures and Depositional Facies	Reservoir Characteristics
Fluvial (F)		
F-1	Matrix-supported paraconglomerate *High current-energy stream*	Generally poor-quality. Low porosity and permeability are due to abundant cement and pseudomatrix.
F-2	Coarse-grained sandstone to conglomerate. This package is characterized by trough and tabular cross-bedding and containing stacked fining-upward sequences. *High energy braided stream of middle to lower channel complex.*	Generally fair to good-quality. Primary and enlarged intergranular porosities are common.
F-3	Ripple to low angle cross-bedded fine to coarse-grained sandstone with occasional clay clast and carbonaceous material and gradded bedding. *Point bar of upper channel complex.*	Generally fair to good-quality. Porosity reduction as a result of cementation and/or pore filling authigenic kaolinite.
F-4	Fine-grained sandstone occasionally interbedded/interlaminated with silty, shaly and coaly intervals. *Channel abandonment.*	Generally poor to fair-quality. Significant pore space is filled with matrix.
Estuarine (E)		
E-1	Interbedded fine to medium grained sandstone and shale containing abundant trace fossils. *Mid-Estuarine environment: Low energy*	Generally poor-quality. Low porosity and permeability are due to abundant cement and pseudomatrix.
E-2	Fine to medium-grained, burrowed sandstone and dark shale that is interbedded with thin coarse-grained sandstones. *Upper-Estuarine environment: Tidally influenced with variable energy and possible fluvial input.*	Generally fair-quality. Primary and enlarged intergranular porosities are common.
Marine (M)		
M-1	Thinly laminated black shales and claystone. Calcareous interval contains abundant fossils. *Low-energy environment: Anoxic, offshore shelf setting.*	
M-2	Fine to coarse-grained, calcite-cemented and fossiliferous sandstone. *High-energy environment: shallow marine.*	Poor-quality reservoir rock due to extensive calcite cement.

Figure 4. Order of lithofacies present in study area of Texas County, Oklahoma (modified from Luchtel, 1999).

F1 Facies

The Fluvial 1 facies contains paraconglomerate sediment that was deposited at a time of mass transport. A paraconglomerate is in the conglomerate family, but is not deposited by normal aqueous flow. The samples have a disrupted gravel framework that is not stratified and often contains more matrix than the gravel-sized fragments. Conglomerates are evidence for sea level lowstand. They represent channel lag deposits that remain after the channel was carved out by high-current streams during a time of incision (fig. 4). Channel lags often contain slightly filled pore space, which would occlude porosity and therefore hinder permeability.

F2 Facies

The Fluvial 2 facies is characterized by braided stream deposits. Gradded bedding is present in core samples (fig. 4). Because of these structures, it can be justified that the F2 facies was deposited during a rise of sea level or a transgressional time during which as sea level rose, backstepping of the sea occurred, which caused the previously incised channels to begin being filled with fluvial sediments that were being carried basinward. The F2 facies contains open pore space, which allows the sandstone to have relatively higher permeability.

F3 Facies

The Fluvial 3 facies is characterized by low angle cross stratification. This facies is typical of point bar depositions and sand accumulation that would develop on the inside of a growing meander by the slow addition of small accretions that accompany migration of the channel toward the outer bank (fig. 4). The F3 facies often contains open pores.

F4 Facies

The Fluvial 4 facies is characterized by evaluations as being an abandoned channel or oxbow lake (fig. 4). In order to have an abandoned channel, the slope must be near vertical such that the stream would form a cutoff across a narrow meander neck. The ends of the original bed eventually become silted up, thus in core samples there are very fine grain sands present. The pore space is partially filled, which results in relatively lower porosity and permeability.

Estuarine Facies

The E1 facies contains fine-grained sediments of clay and silt size that are of marine and fluvial origin. They contain trace fossils that are mixed with a proportion of decomposed terrestrial organic matter (fig. 4). Because of small grain sizes, the amount of porosity that is present is relatively small. Some glauconite was also present in thin section analysis, being an indicator of an aqueous, possibly partially marine, environment.

CHAPTER V

STRATIGRAPHY

Depositional History

As eustatic sea level changes cause alternating periods of subaerial exposure, flooding, or progradation at the shelf-slope boundary, the falls of sea level that are more rapid than subsidence cause subaerial exposure and canyon cutting (Vail & Hardenbol, 1981). During this lowering of base level, or sea level regression, fluvial systems incise and create paleovalleys which develop by upstream-migrating knickpoint erosion as the slope to base level changes.

During base-level lowering and early base-level rise, valleys fill with multistory braided-stream sands. During the middle session of base-level rise, deposition occurs in the upper parts of the valleys on the alluvial plain. During the late phase of base-level rise, there is predominately muddy alluvial plain, or floodplain deposits. This cycle is repetitious and begins again with another base level drop (Van Wagoner & Hill, 1994).

The occurrence of sea level rise and subsidence at the same time commonly cause flooding of the shelf margin, marine transgression, and sediment starvation of the middle and outer shelf (Vail & Hardenbol, 1981).

The fill of incised valley systems may be described in three subdivisions. The distal sections of the incised valley are closest to the sea and include transgressive or backstepping fluvial and estuarine deposits. These may contain marine sands with shelf muds deposited on top of them. The middle areas of the incised valley include estuarine complexes that were deposited during marine transgression and overlie lowstand and transgressive sequences of fluvial and estuarine deposits. The innermost reaches of the incised valley contain fluvial deposits that are deposited beyond the reaches of the transgressive marine limit where base level does not control the fluvial style (Boyd & others, 1994).

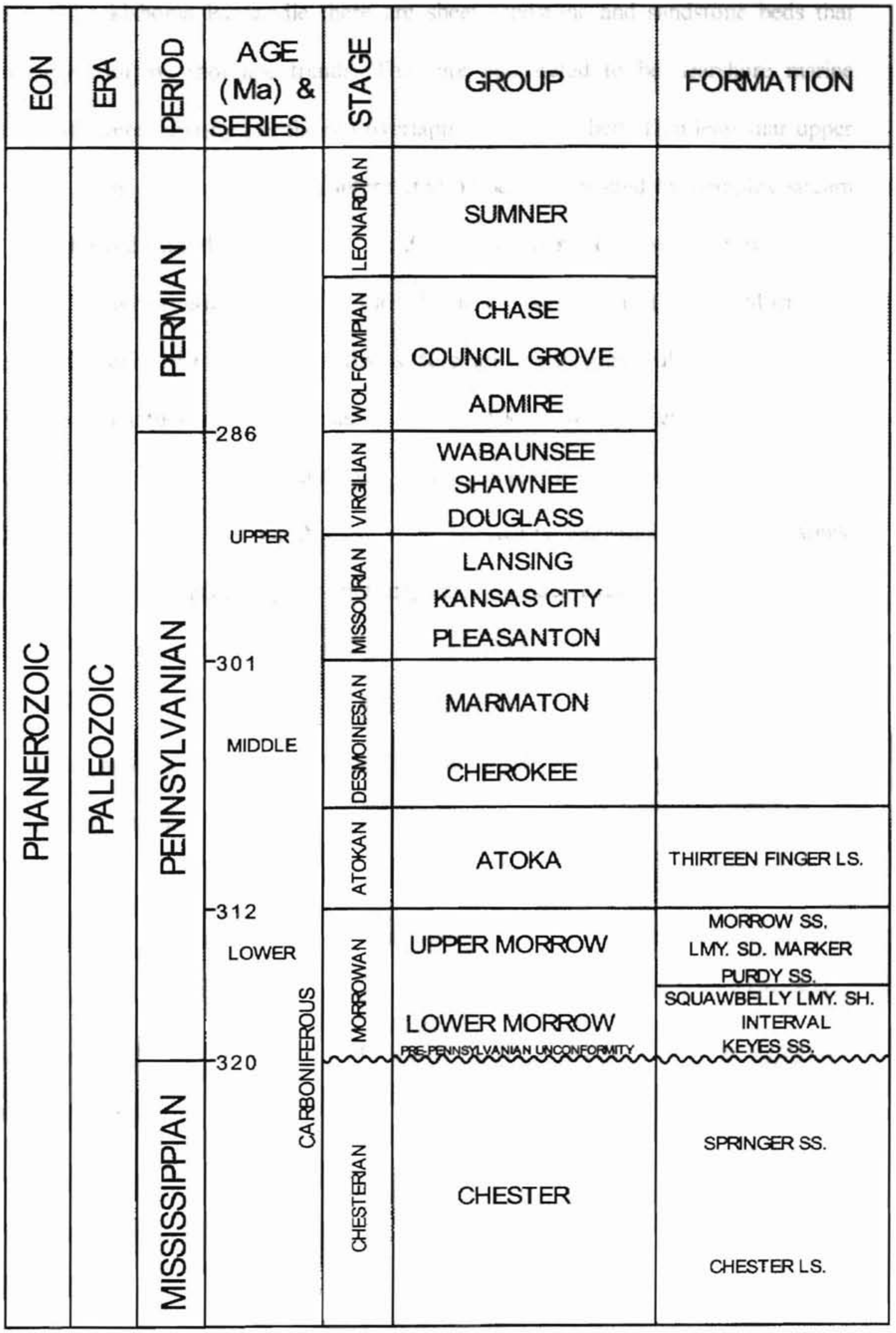
Stratigraphy of the Morrow Sandstone

The Morrowan Series is defined as being the interval between the base of the Atokan Thirteen Finger Limestone and the top of the Pre-Pennsylvanian Unconformity, which is the top of the Mississippian Chester Limestone. This stratigraphic unit known as the Morrow Formation consists of various lithofacies including sandstones and shales. The name itself is a subsurface term used by the oil and gas industry in northwestern Oklahoma, although it is a formal stage and formation name that originates in western Arkansas (Andrews, 1995).

The Morrow Formation has been divided into two units, the Upper Morrow Sandstone and the Lower Morrow Sandstone. The lower Morrow stratigraphic unit are characterized by features that were formed by marine processes with sandstones trending NW-SE. Busch (1959) interpreted these sandstones as beach deposits that parallel ancient shorelines. Simon (1979) interpreted the sandstones to possibly be delta deposits that were reworked by longshore currents and were re-deposited as offshore bars. Walker (1986) interpreted the lower Morrow to be primary shallow marine depositional facies and could be classified as tidal ridge/shoal deposits, offshore bars, tidal flat, and transgressive deposits. Gerken (1992) interpreted the lower Morrow to be transgressive valley-fill sandstones, as Puckette and others (1996) interpreted the lower Morrow to consist primarily of marine sandstones that were deposited on the eroded Mississippian surface.

The upper Morrow stratigraphic unit consists of fluvial sediment that was deposited as channel fill in the lows on the underlying eroded Mississippian surface. The division between the upper and lower Morrow units occurs at the Squawbelly Limestone interval, commonly referred to as the middle Morrow, being that the upper Morrow is above the Squawbelly limestone and the lower Morrow includes the interval which contains the Squawbelly limestone and the Keyes sandstone (fig. 5). An erosional unconformity is present beneath the lower Morrowan Keyes sandstone and underlying Chesterian marine limestones and shales. This would indicate that the unconformity existed before or developed during the deposition of the Morrow units (Forgotson, 1969). The Keyes sandstone is interpreted to be transgressive beach or shoreline sandstones (Curtis and Ostergard, 1979).

The upper Morrowan marine sandstones generally trend northwest-southeast. It is approximately 200-400 ft. thick on the Anadarko shelf and thickens towards the basinward depocenter to over 4000 ft. in western Oklahoma (Andrews, 1995). Where these sandstone trends and topographic lows or channels on the eroded Mississippian surface intersect, reservoir quality stratigraphic traps were developed (Clark, 1987).



EON	ERA	PERIOD	AGE (Ma) & SERIES	STAGE	GROUP	FORMATION
PHANEROZOIC	PALEOZOIC	PERMIAN		LEONARDIAN	SUMNER	
				WOLFCAMPIAN	CHASE COUNCIL GROVE ADMIRE	
		PENNSYLVANIAN	286 UPPER	VIRGILIAN	WABAUNSEE SHAWNEE DOUGLASS	
				MISSOURIAN	LANSING KANSAS CITY PLEASANTON	
			301 MIDDLE	DESMOINESIAN	MARMATON CHEROKEE	
				ATOKAN	ATOKA	THIRTEEN FINGER LS.
			312 LOWER	MORROWAN	UPPER MORROW	MORROW SS. LMY. SD. MARKER PURDY SS.
					LOWER MORROW PRE-PENNSYLVANIAN UNCONFORMITY	SQUAWBELLY LMY. SH. INTERVAL KEYES SS.
		MISSISSIPPIAN	320 CARBONIFEROUS	CHESTERIAN	CHESTER	SPRINGER SS. CHESTER LS.

Figure 5. Stratigraphic column

In the Oklahoma Panhandle there are sheet sandstone and sandstone beds that parallel early Morrow shoreline trends. They are interpreted to be nearshore marine sediments that were deposited as the sea overlapped onto the shelf. Thin lenticular upper Morrow sandstone bodies have been interpreted as being deposited by complex stream systems that flowed from the northwest towards the basin axis (Forgotson, 1969).

In the southeastern portion of Colorado, it has been found that the Morrow is composed of a series of multistory, northwest to southeast trending valley-fill complexes that have incised into marine limestone and shale. The scoured valleys are filled with coarse, trough cross-stratified sandstone that grades upward and is capped by transgressive, burrowed sandstone that advances into marine mudstone (fig. 6) (Krystinik and others, 1987). The geometry of such deposits includes laterally migrating stacked channels. These channel deposits may be interconnected reservoirs that are continuous along valley axes.

By examining electric log signatures of the Upper Morrow interval, patterns are well established, particularly within the gamma-ray and resistivity logs that indicate boundaries for sequences and various facies within the valley fill. This electrofacies interpretation is based on correlating log signatures to core samples from field wells. This comparison of wireline logs and core is imperative for determining electrofacies lithofacies correlation within a given field study. Figure 7 demonstrates log signatures with facies relationships within the Upper Morrow interval.

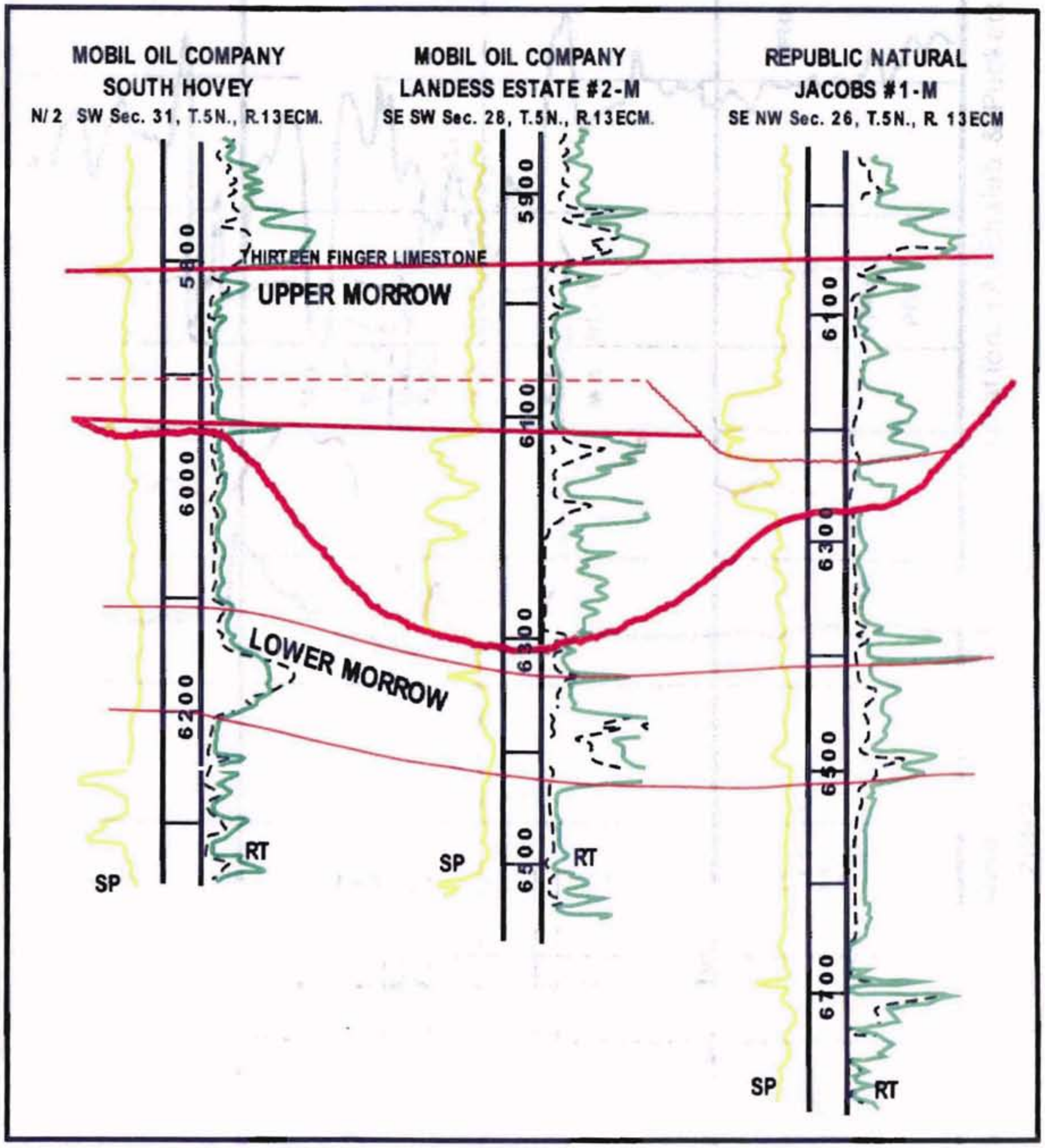


Figure 6. Stratigraphic cross section showing the incised valley profile in Postle Field, Texas County, Oklahoma (Puckette and others, 1996).

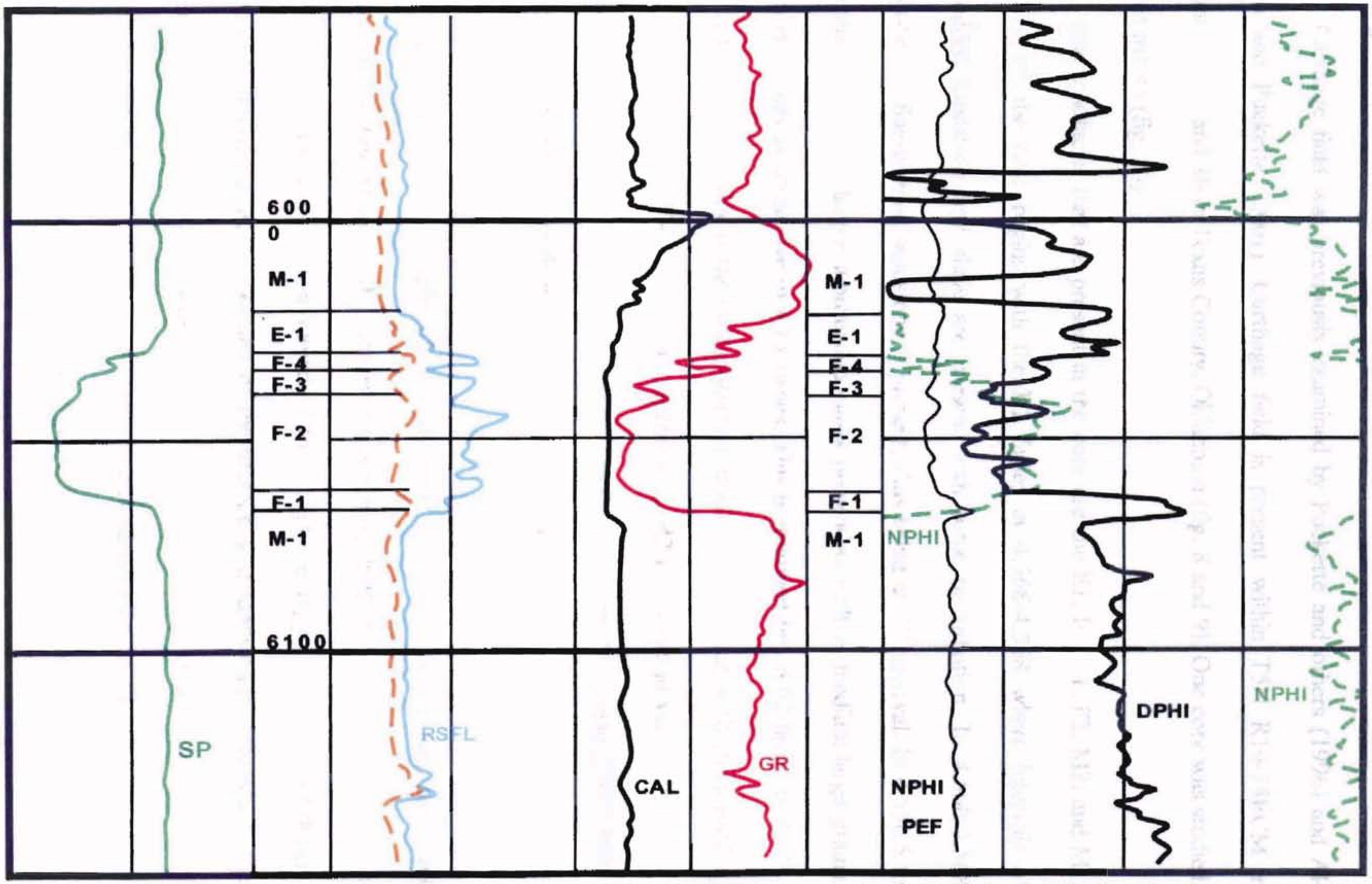


Figure 7. Wireline log showing depositional facies interpretation. (Al-Shaieb & Puckette personal communication, 2002)

Carthage Field

Carthage field was previously examined by Puckette and others (1996) and Al-Shaieb and Puckette (2001). Carthage field is present within T5N R10-13ECM in sections 24, 25, and 30 in Texas County, Oklahoma (fig. 8 and 9). One core was studied, the Hendrix #3 (fig. 10).

The lithofacies that are present in the core are the E1, E2, F1, F2, M2, and M1. The base of the core begins with the E1 facies at 4,568-4,568 where intervals of interbedded sandstone and shale are present with some bioturbation. In 4,560-4,568 grayish-brown fine-grained sandstone is present, thus being an E2 interval. In 4,556.5 to 4,560 there are a few larger subrounded clasts present as well as medium-large grains. This mixture may be indicative of a F1 facies. This is followed by an F2 facies in 4,538-4,556.5. Evidence for this is the coarse-grained sand that is present with cross-bedding structures. The interval of 4,527.5-4,538 represents a M2 facies in that very low porosity is present because of high amount of calcite cement with fine to coarse grains being present. The top of the core from 4,525-4,527.5 contains an M1 facies with black shales and claystones being present.

This is a prime example of a shallowing upward sequence and sea level transgression by first studying the estuarine successions both in core and log, being a low-energy estuarine environment moving into a higher energy estuarine environment with possible fluvial interaction because of the presences of sandstones. Afterwhich, the gradation of transgressive sequences of fluvial environments with cross-bedding present followed by and high-energy and low-energy marine deposition as the shales that are present change from coarser-grained to fine-grained claystones. Also, the black shale is

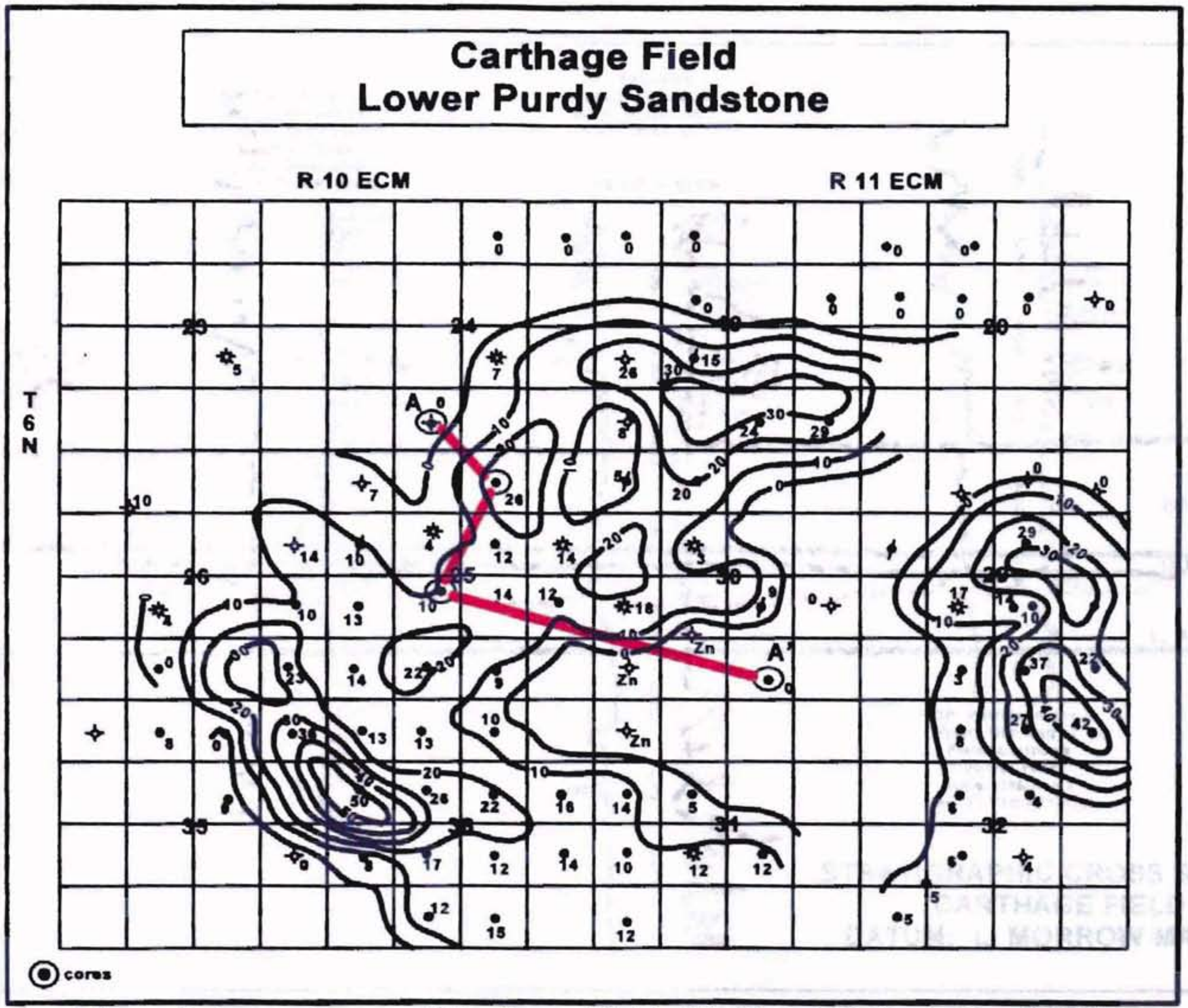


Figure 8. Isopach map of Carthage Field. (Al-Shaieb & Puckette , 2002)

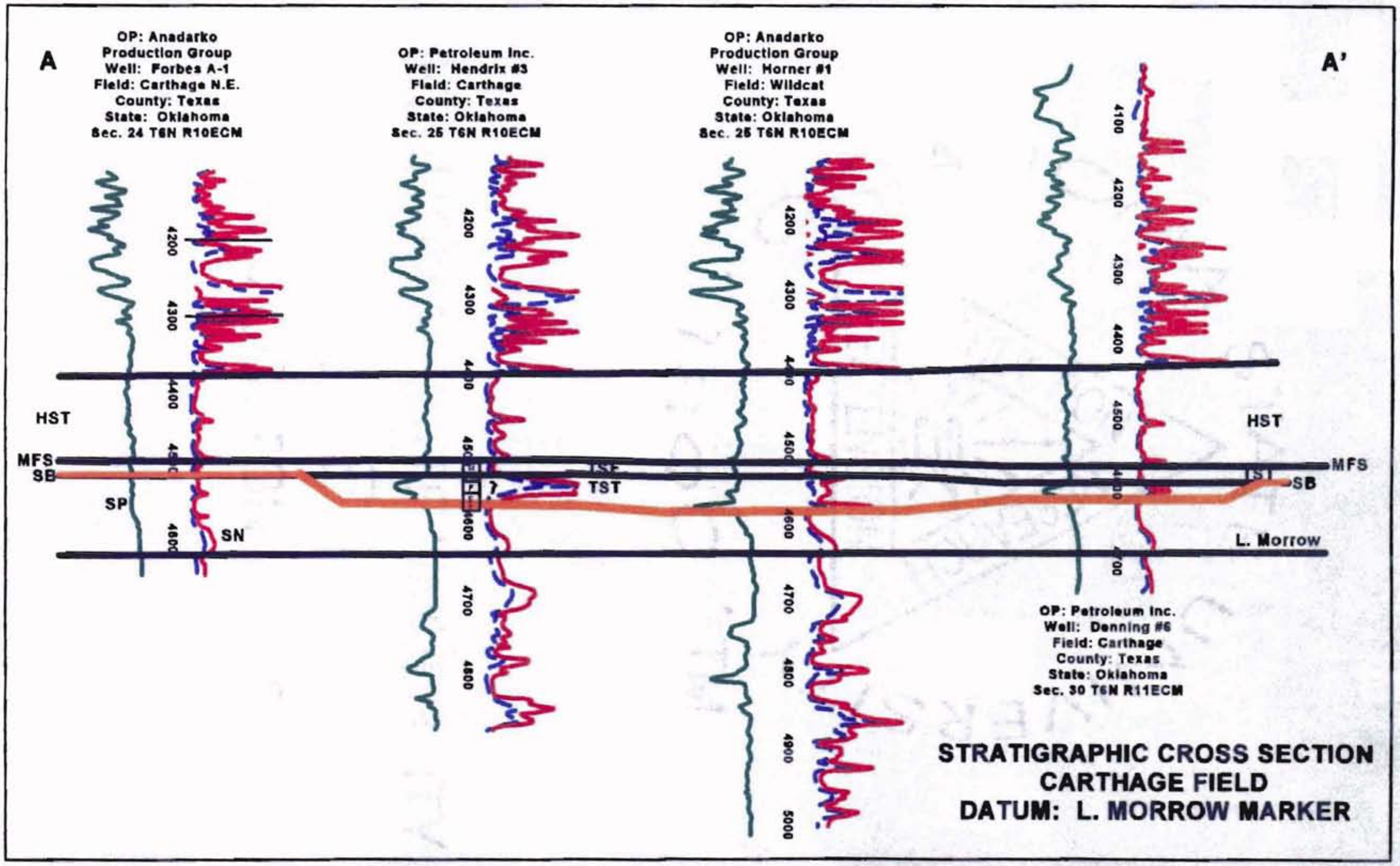


Figure 9. Stratigraphic cross section of the Carthage Field. (Al-Shaieb and Puckette , 2001)

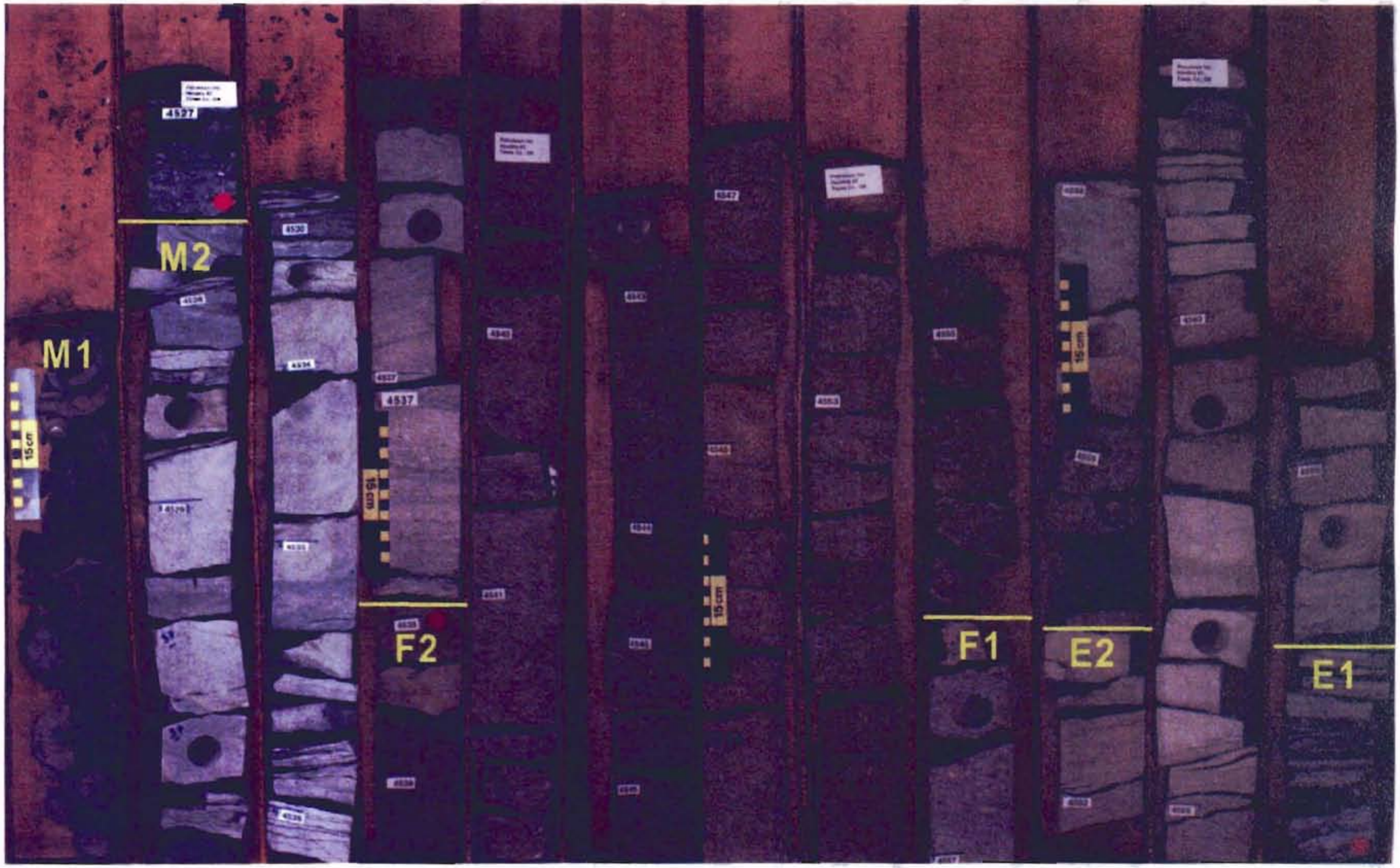


Fig. 10. Hendrix #3 core photo from Carthage Field. (Al-Shaieb & Puckette , 2001)

indicative of anoxic environments, being a deep marine setting. This core is represented as a lowstand followed by a transgressive deposition (see fig. 11, 12, and 13).

Northeast Hardesty Field

The Northeast Hardesty field was previously examined by Al-Shaieb and Puckette, 2001. Northeast Hardesty is located within T3N R18ECM in sections 3, 4, 10, 11, and 12 in Texas County, Oklahoma (fig. 14 and 15). One core was studied, the Hardesty #11-2 (fig. 16).

The lithofacies that are present in the core are the M1, F1, F2, F3, and F4. At the base of the core the interval from 6366-6367.5 black shales and claystones are present, being an M1 facies. This is followed by a F1 facies consisting of paraconglomerate sandstones in the interval of 6362-6366. In 6333.5-6362 the F2 facies is present with cross-bedded sandstone structures and graded bedding within the sandstone consisting of coarse-grained sands. The interval of 6328-6333.5 the F3 facies is present with fine to coarse-grained sediment in graded bedding structures. The top of the core from 6324-6328 is evidence for F4 deposition. Silty and shaley interbedded intervals are present in this top section.

With these sequences of events, it is interpreted that the initial shale that was deposited was marine in origin, since the shale and claystone is black, which is indicative of low-energy, anoxic marine environments. A drop in sea level then took place as channels were eroded down to base level to meet with the new shoreline that was moving seaward. Because of this regression, clay-clast conglomerates or paraconglomerates were deposited in the recently eroded channels under high-energy stream current conditions. A

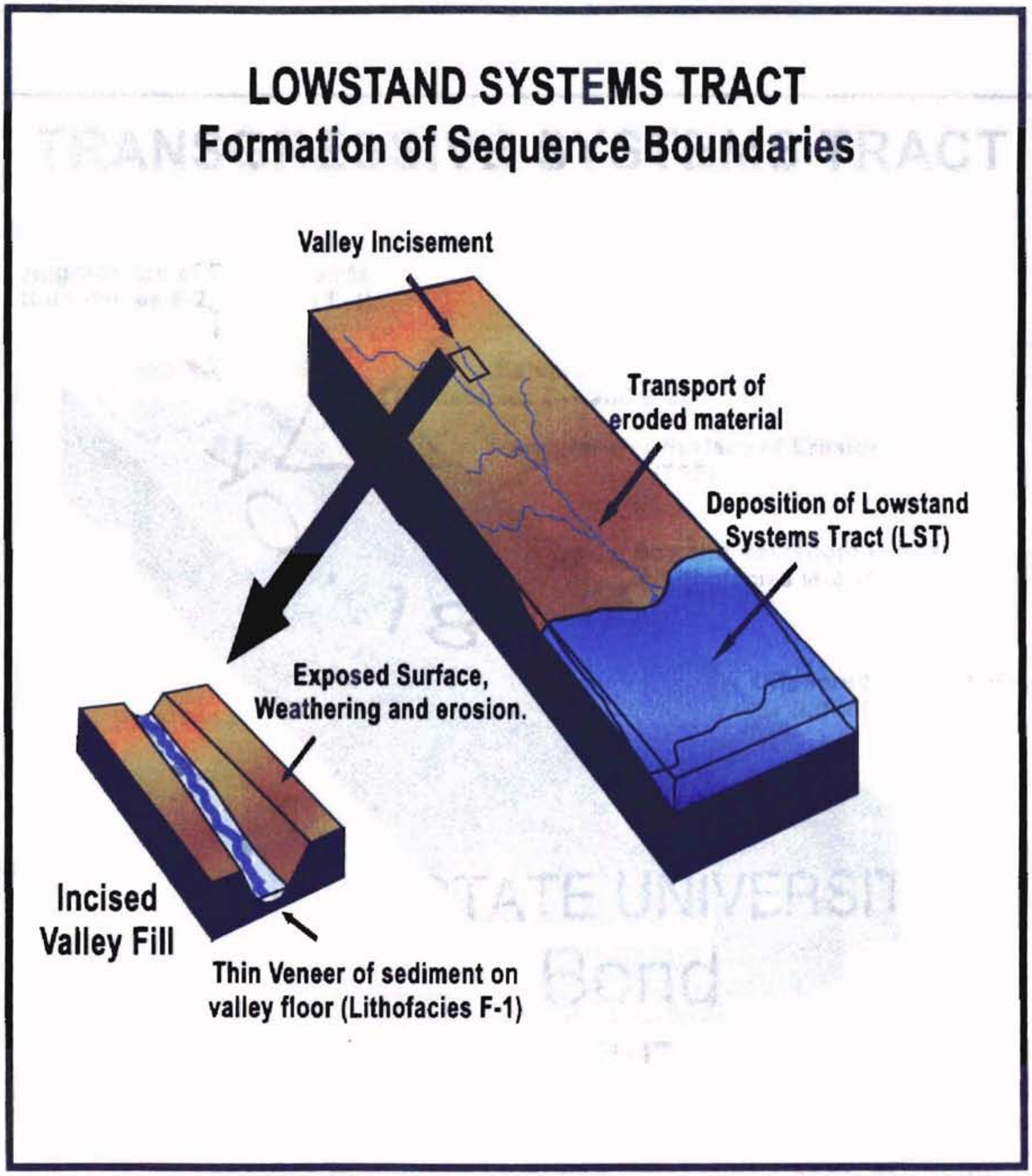


Figure 11. Lowstand systems tract demonstrating valley incision during sea level lowering (after Wheeler et. al. 1990).

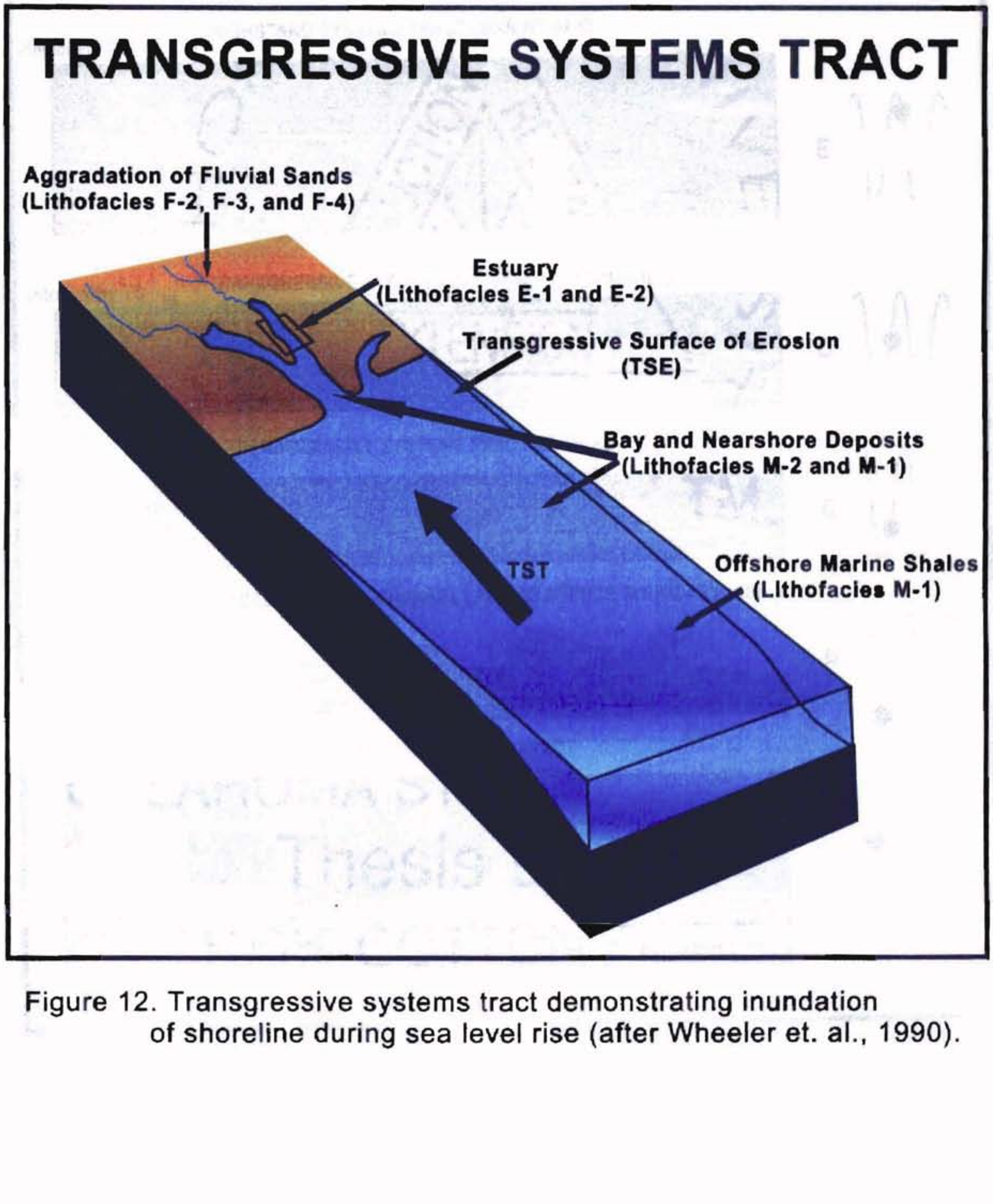


Figure 12. Transgressive systems tract demonstrating inundation of shoreline during sea level rise (after Wheeler et. al., 1990).

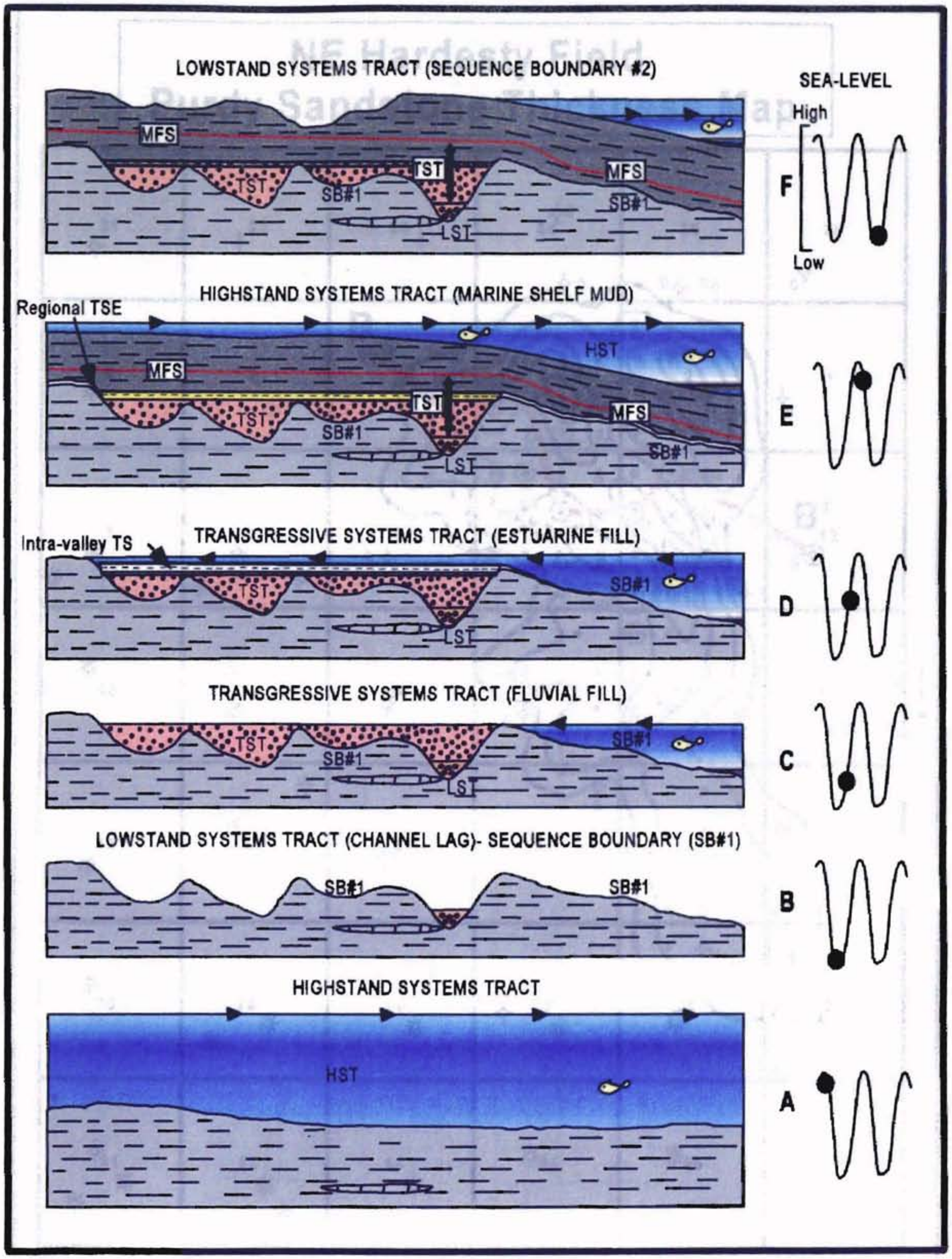


Figure 13. Evolution of upper Morrowan successions of systems tracts in study area (modified from Luchtel, 1999).

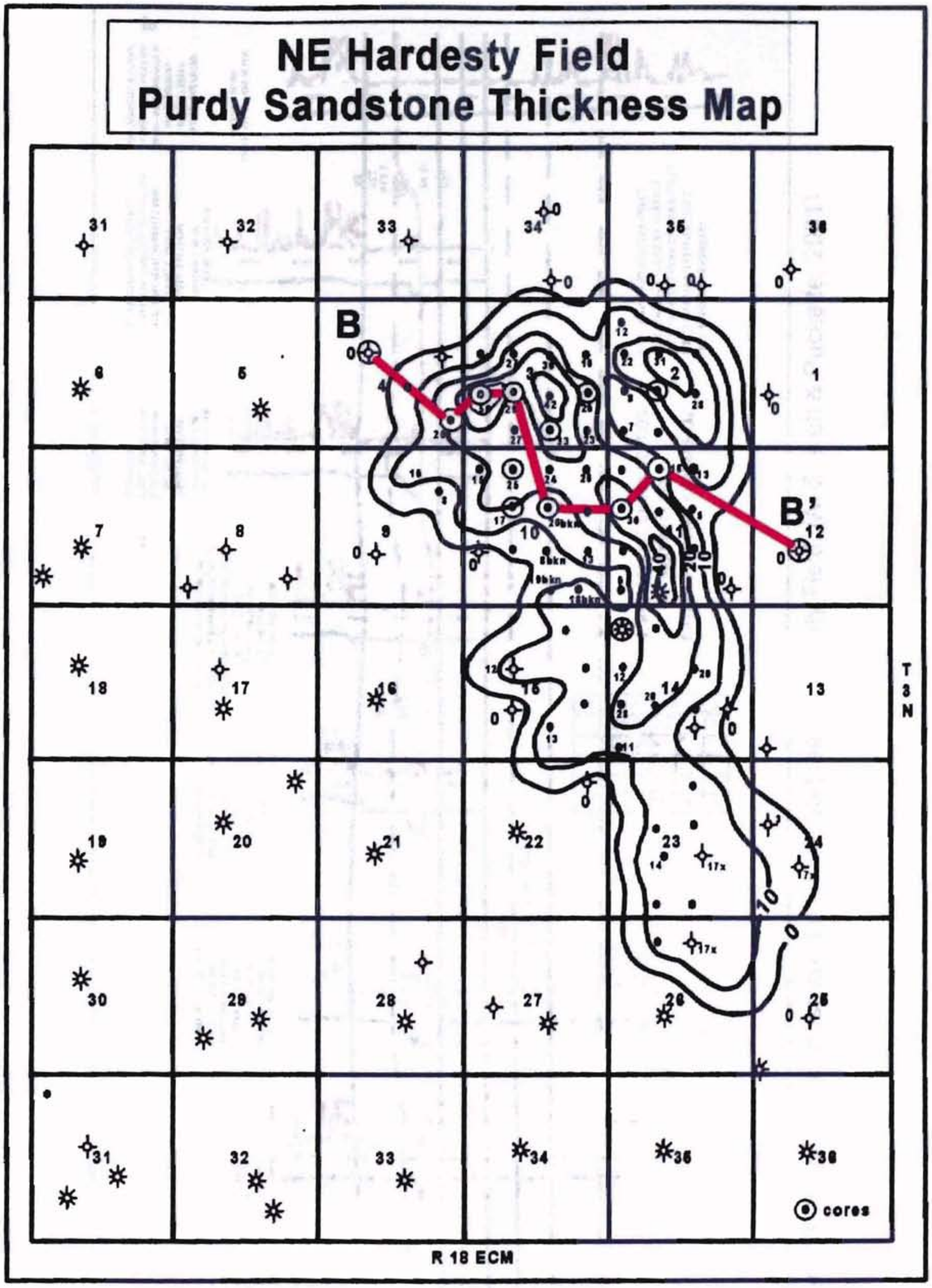


Figure 14. Isopach map of the Northeast Hardesty Field Purdy sandstone. (Al-Shaieb and Puckette, 2001)

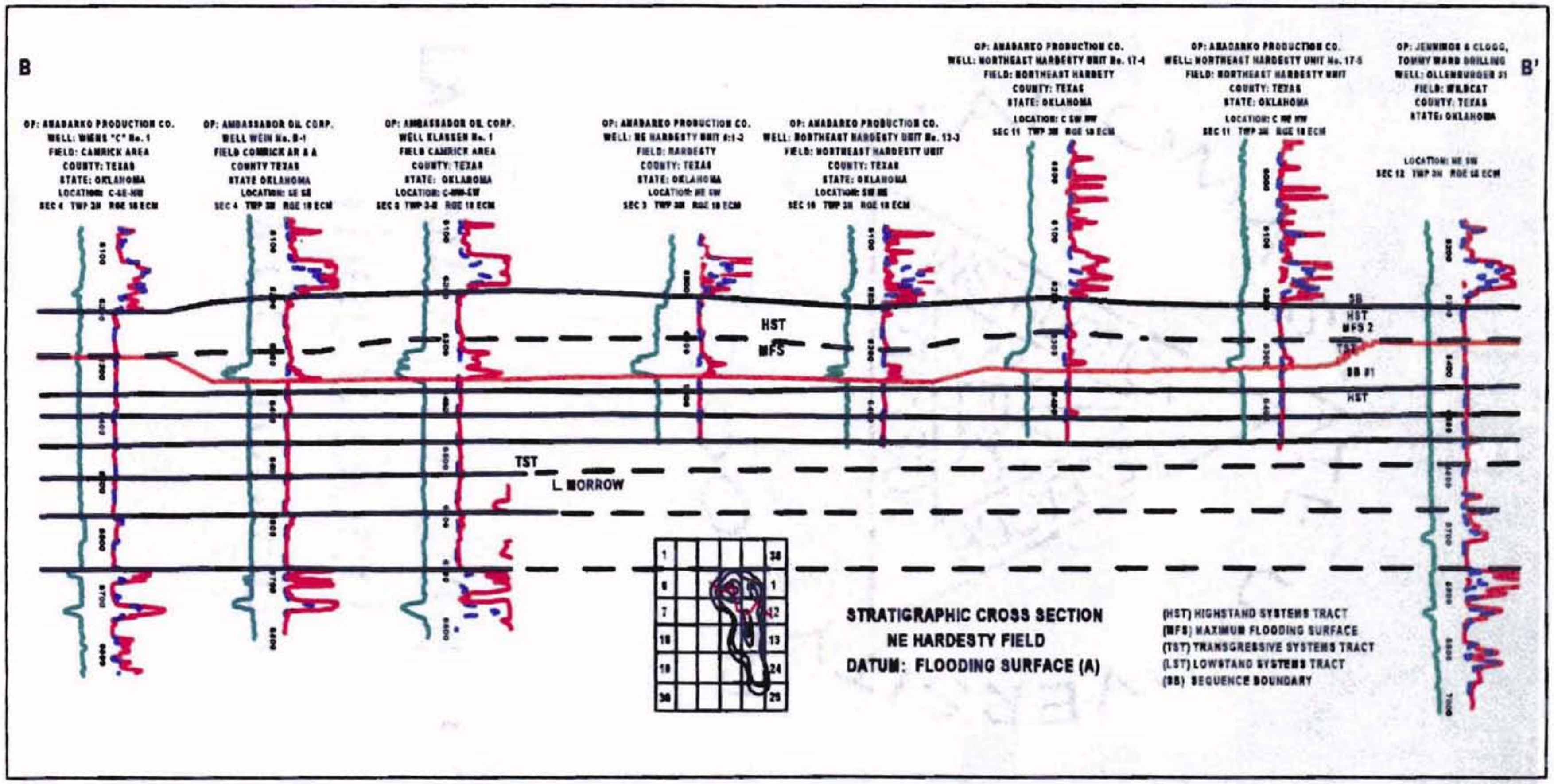


Figure 15. Stratigraphic cross section of the Northeast Hardesty Field. (Al-Shaieb & Puckette, 2001)

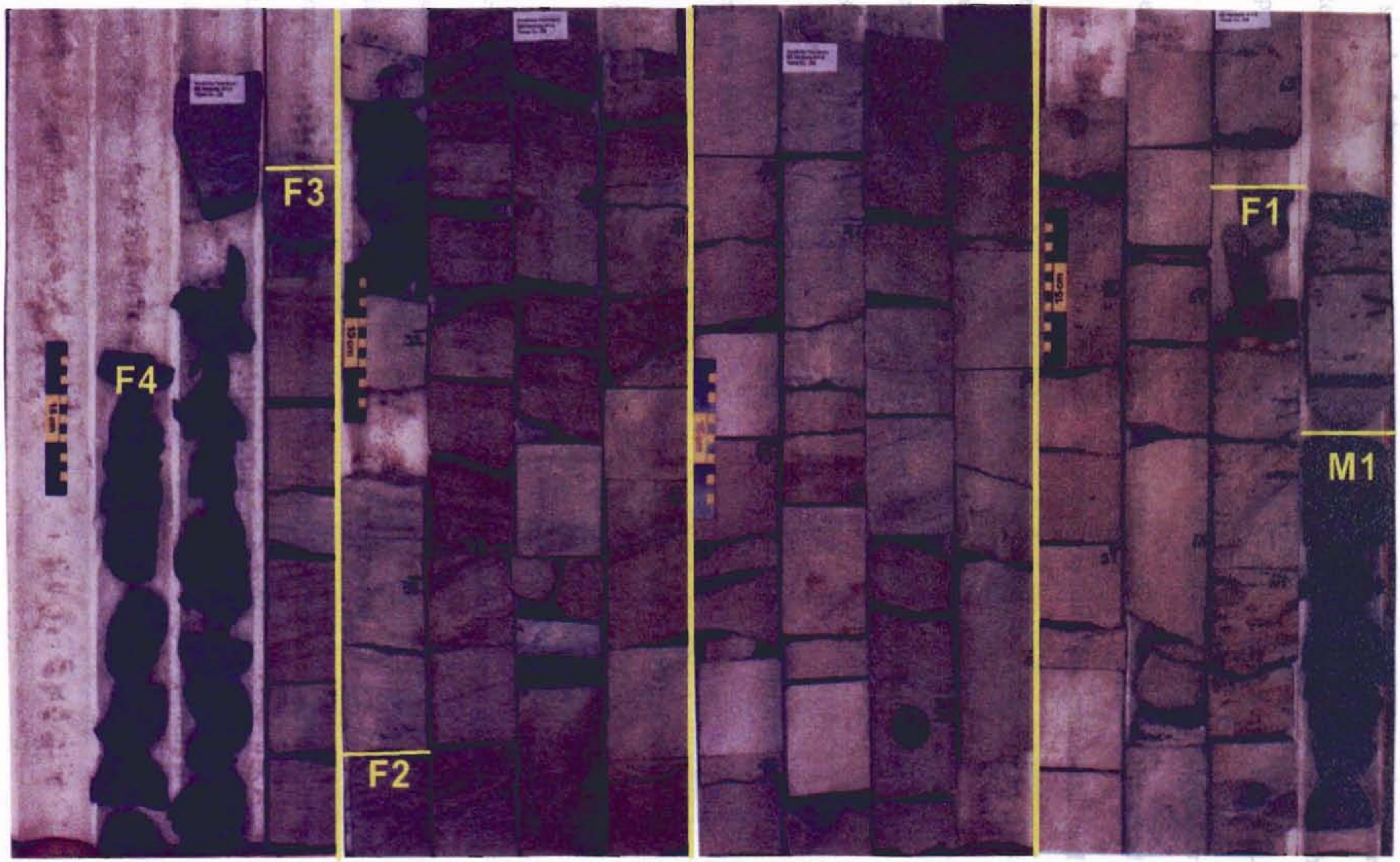


Fig. 16. Hardesty #11-2 core photo, Northeast Hardesty field. (Al-Shaieb & Puckette, 2001)

rise in sea level then occurred, which deposited the successions of fluvial sandstone facies to be deposited. This transpired as the shoreline moved landward in which backstepping and thus channel filling of sands occurred. Evidence for this was the cross-bedding structures of braided stream deposits and the graded bedding of point bar sequences that were deposited. The transgressional event ends at the top of the cored interval as an abandoned channel environment is present as very fine-grained silt and shale intervals are present with some evidence of carbonaceous material possible. This core is an example of a highstand event, being the marine shale, followed by a regression in sea level downcutting the channel and depositing the paraconglomerates and then a transgressional event of fluvial sands being deposited.

Northwest Eva Field

Northwest Eva field was previously studied by Harrison (1990), Puckette and others (1996), and Al-Shaieb and Puckette (2001). Northwest Eva field is present within T4N and T5N R10ECM in sections 1, 2, and 4 in Texas County, Oklahoma (fig. 17 and 18). Core was not employed in this study, thus facies interpretations were inferred from electrologs.

The lithofacies that are present in log signatures are the M1, F1, F2, E2, and E2 (see Appendix A). The log signatures were studied within the interval of 4270-4600 by cross-sectional mapping. In the interval of 4510-4600 there is a M1 signature, being that of the presence of shale. This is followed by 4500-4510 with a F1 signature with a slight show of sand presence. The 4470-4500 shows another shale signature, possibly evidence

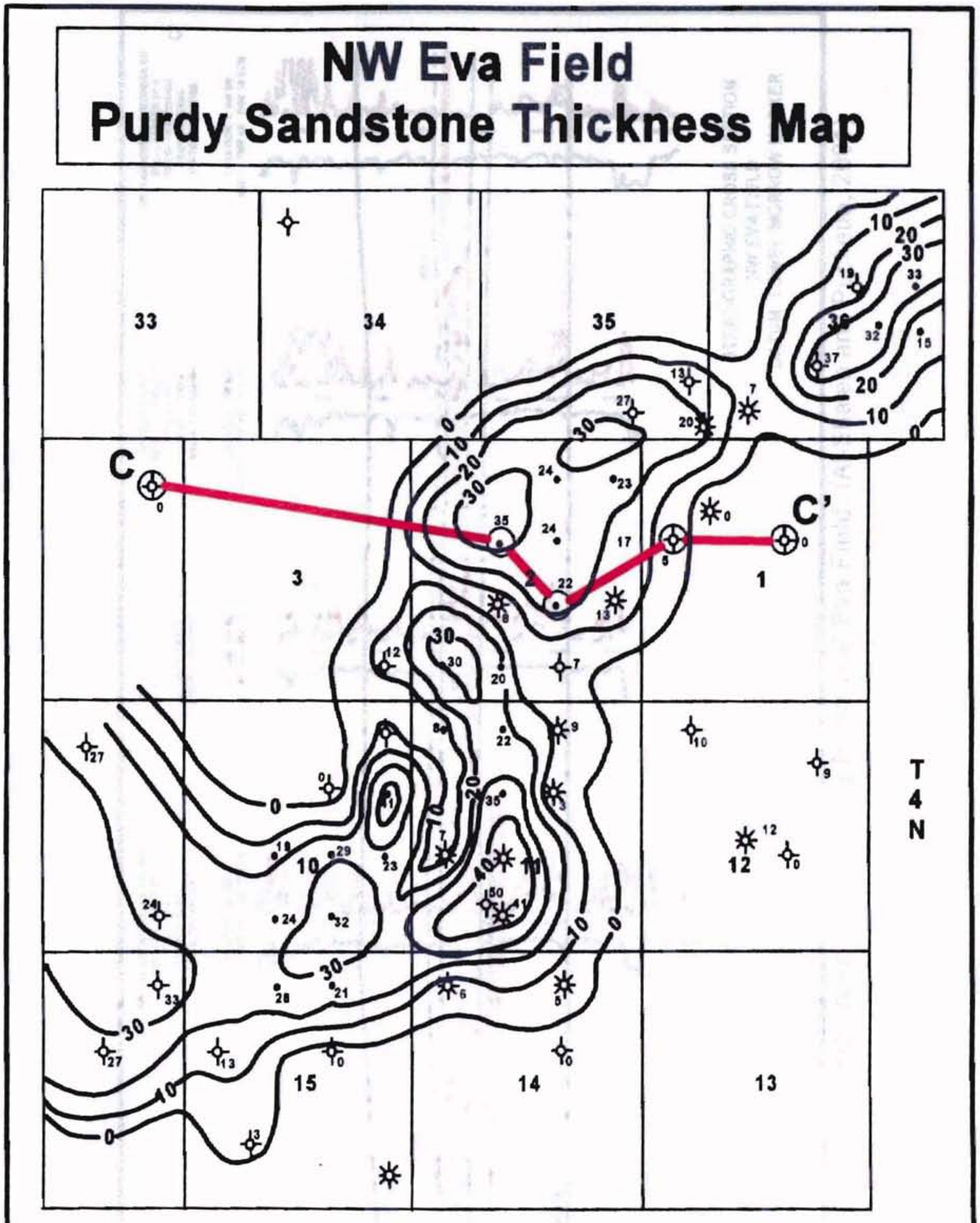


Figure 17. Isopach map of the Northwest Eva Field Purdy sandstone (from Harrison, 1990).

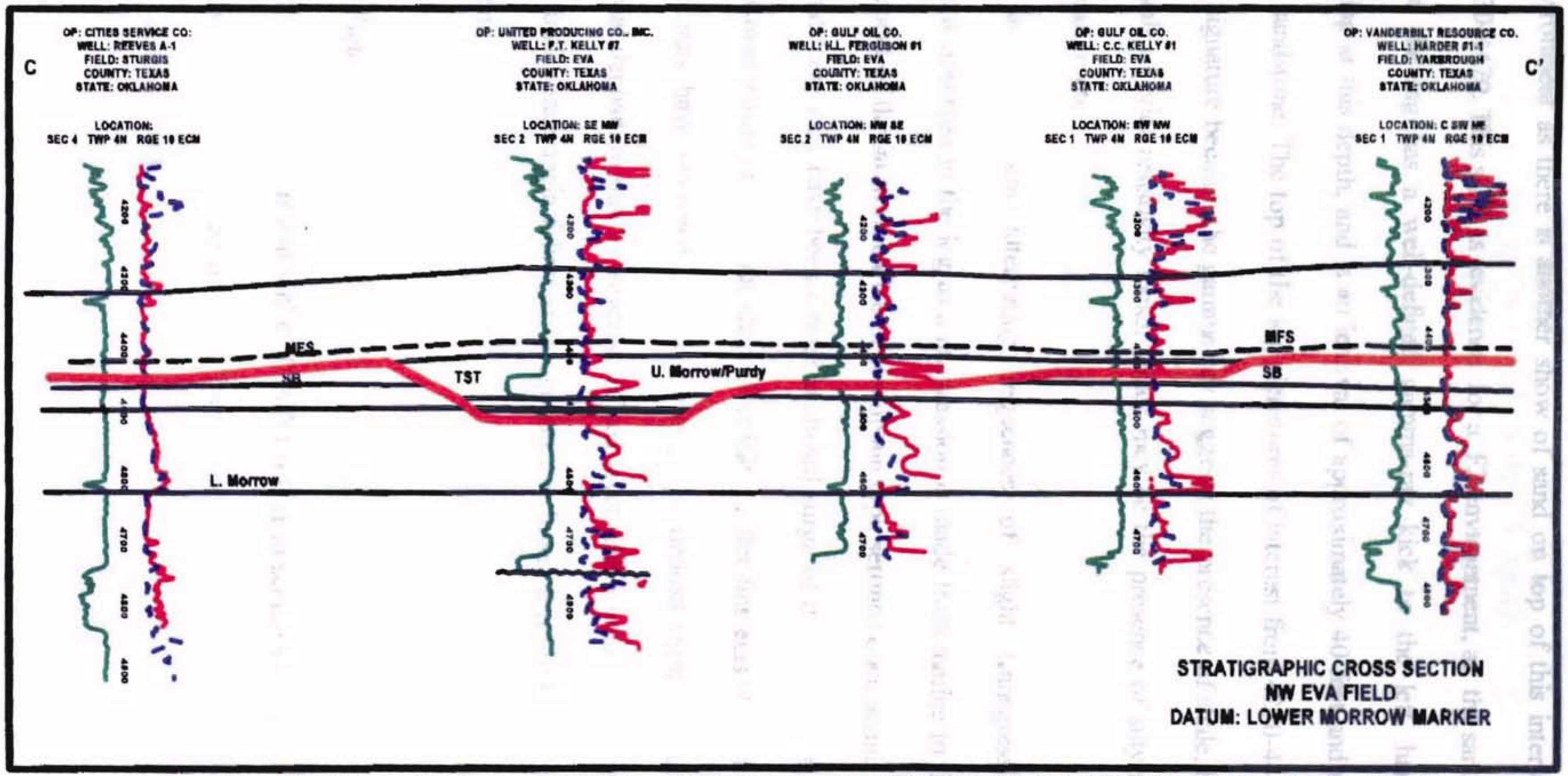


Figure 18. Stratigraphic cross section of the Northwest Eva Field. (Al-Shaieb and Puckette, 2001)

for an E2 environment as there is another show of sand on top of this interval, being present at 4430-4470. This sand is evidence for a F2 environment, as the sand that is represented on the log has a well-defined gamma-ray kick to the left, has a high resistivity reading at this depth, and is an interval of approximately 40 feet and may be a coarse-grained sandstone. The top of the log signatures of interest from 4270-4430 show more of an E2 signature because the gamma-ray suggests the presence of shale, but there are small intervals of brief resistivity kicks, which may be the presence of silty material, carbonaceous matter, etc.

These facies represent alternating sequences of slight transgression and regression. This is observed in the log as a progression is made from marine to fluvial to estuarine to a repeat of fluvial to estuarine or floodplain type settings once again. The log data suggests that there may have been a brief landward surge of the sea, only to have a sea level drop, which would bring about channel incision. After this episode, yet another rise in sea level may have occurred, but only enough to deposit estuarine sediments, followed by fluvial deposition due to lowering of sea level which would have deposited coarser-grained sands, once again followed by another rise in sea level to bring about the estuarine environment.

Southwest Rice Field

Southwest Rice field is present within T2N R10ECM in sections 4, 5, 8, and 9 in Texas County, Oklahoma (fig. 19, 20, and 21). Two cores were used in this study, being the RMU #6 and the RMU #13.

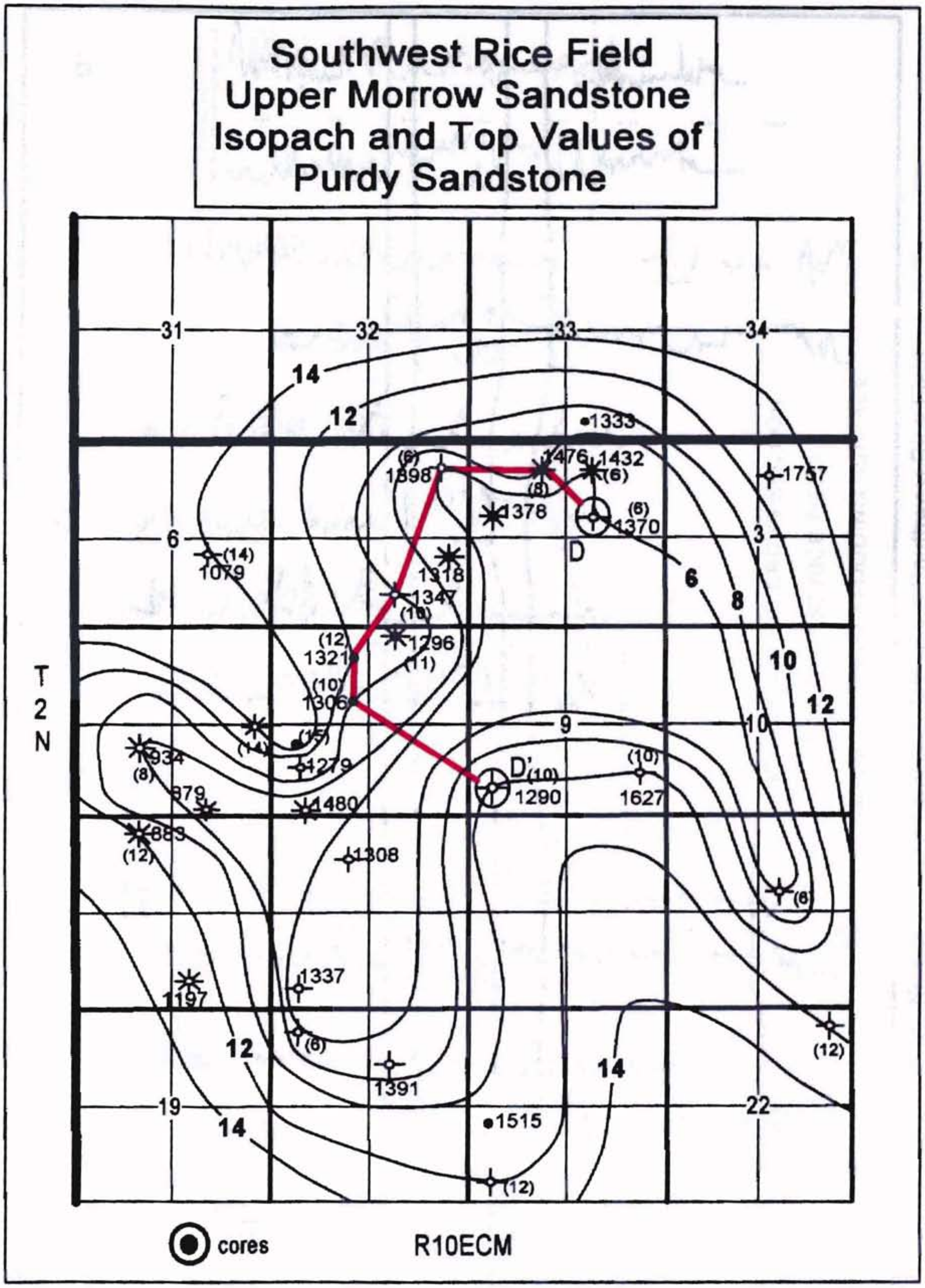


Figure 19. Upper Morrow Sandstone mapped tops and Purdy Sandstone (Upper Morrow) thicknesses, Southwest Rice field.

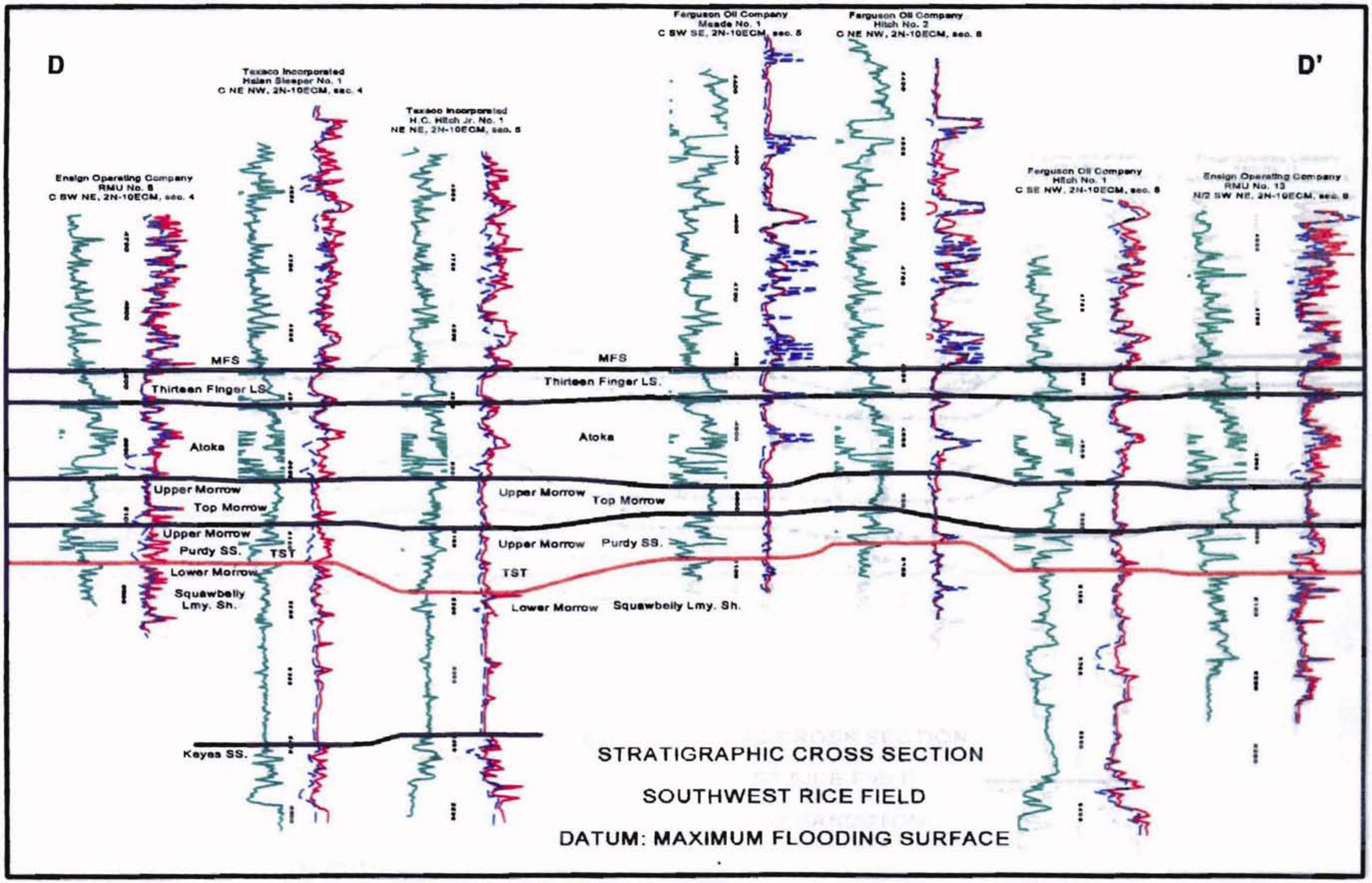


Fig. 20. Stratigraphic Cross Section of the Southwest Rice Field.

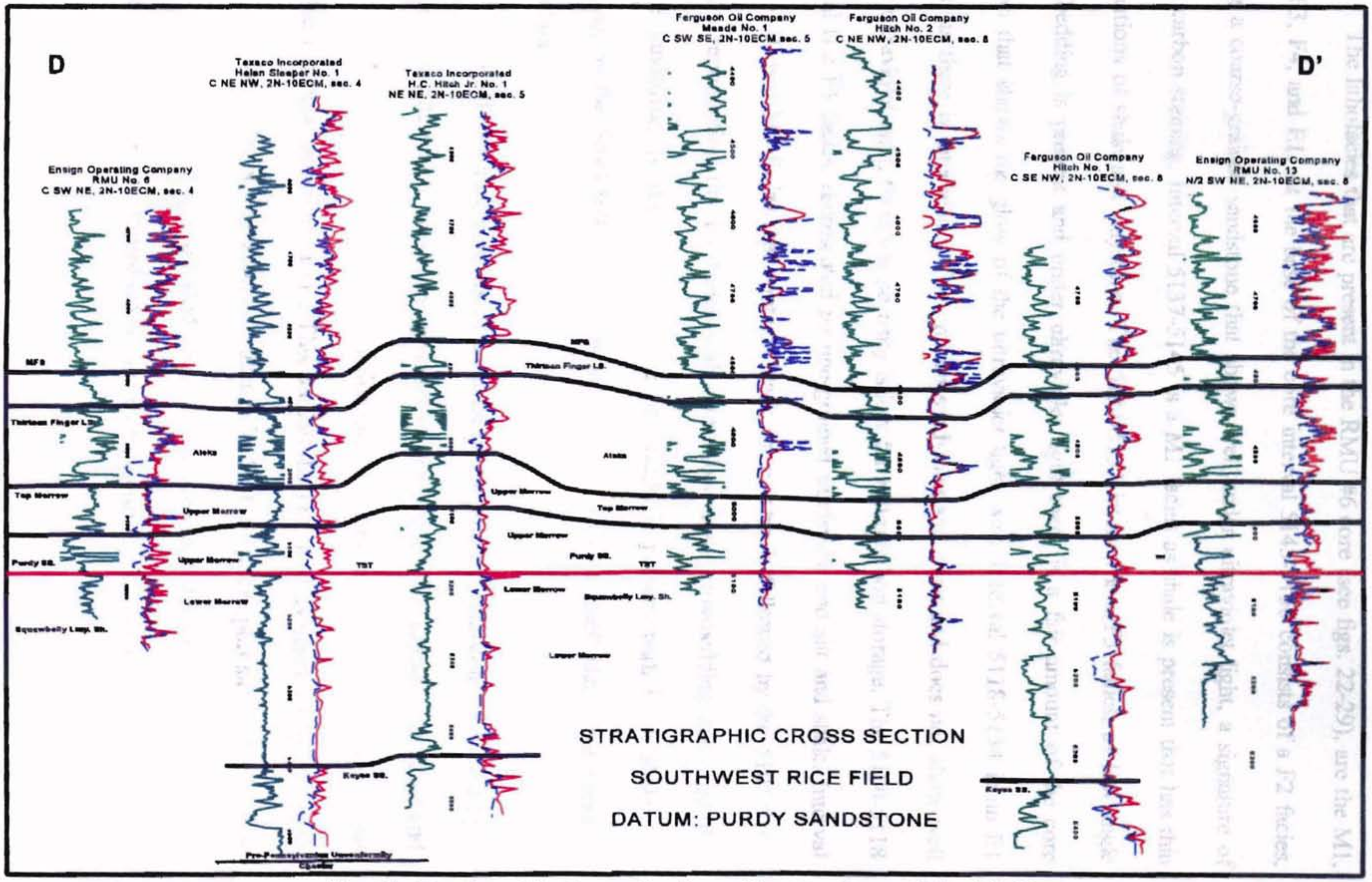


Fig. 21. Stratigraphic Cross Section of the Southwest Rice Field.

The lithofacies that are present in the RMU #6 core (see figs. 22-29), are the M1, F2, F3, F4, and E1. At the base of the core interval 5145-5150 consists of a F2 facies, being a coarse-grained sandstone that shows well under ultraviolet light, a signature of hydrocarbon staining. Interval 5137-5145 is a M1 facies as shale is present that has thin laminations of shale and claystone. The 5134-5137 interval is a F3 facies, as low angle crossbedding is present and under ultraviolet light there is a fair amount of the core section that shows the glow of the ultraviolet light well. Interval 5118-5134 is an E1 facies, as there is interbedded fine-grained sandstone and shale and does not show well under ultraviolet light, therefore porosity is low for hydrocarbon storage. The 5100-5118 interval is a F4 facies, represented by fine-grained sandstone and silt and shale. Interval 5108-5110 is a M1 facies that contains black shale. This is followed by the 5105-5108 interval, representing the F3 facies with some low-angle crossbedding and medium-grained sandstone. In the 5098-5105 the M1 facies is present with black shale and claystone, as the 5090-5098 interval is also a M1 facies of black shale, but contains mostly intact brachiopod fossils.

The RMU #6 core consists of a fluvial coarse-grained sandstone, followed by a shale interval, afterwhich, two more episodes of interbedded fine-grained sandstone and shale were deposited in fluvial and estuarine environments and small shale layers were deposited amongst sandstone layers. This section did not have evidence of hydrocarbon presence as there was not a response to ultraviolet light, therefore porosity in this section is very low because of the small sand grains and interbedded shale that are present. An episode of medium-grained fluvial sands were then deposited with low porosity showing

Figure 22. RMU #6 Well. Core Depth: 5142-5150, plane light and uv light.

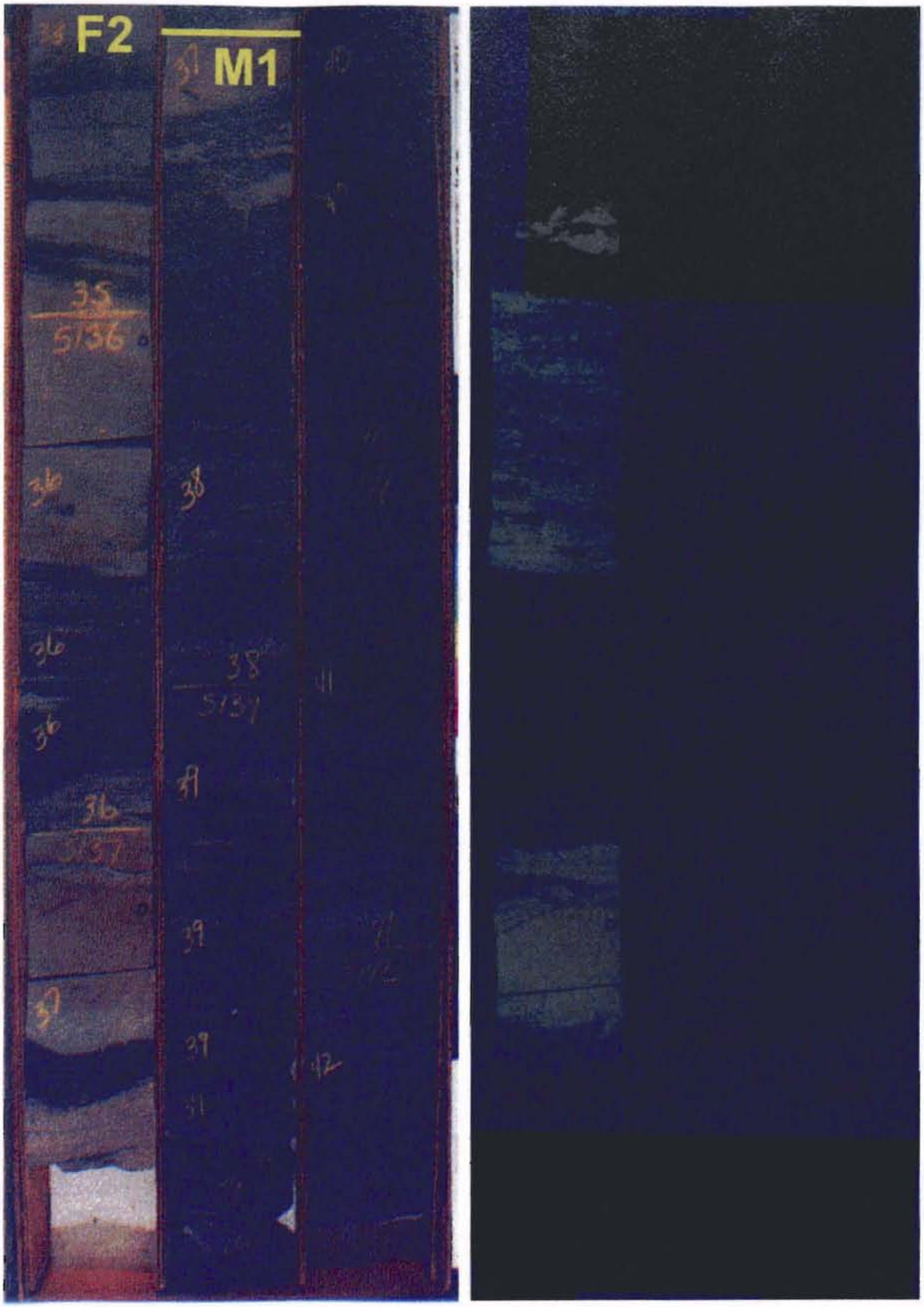


Figure 23. RMU #6 Well. Core Depth: 5135-5142, plain light and UV light.

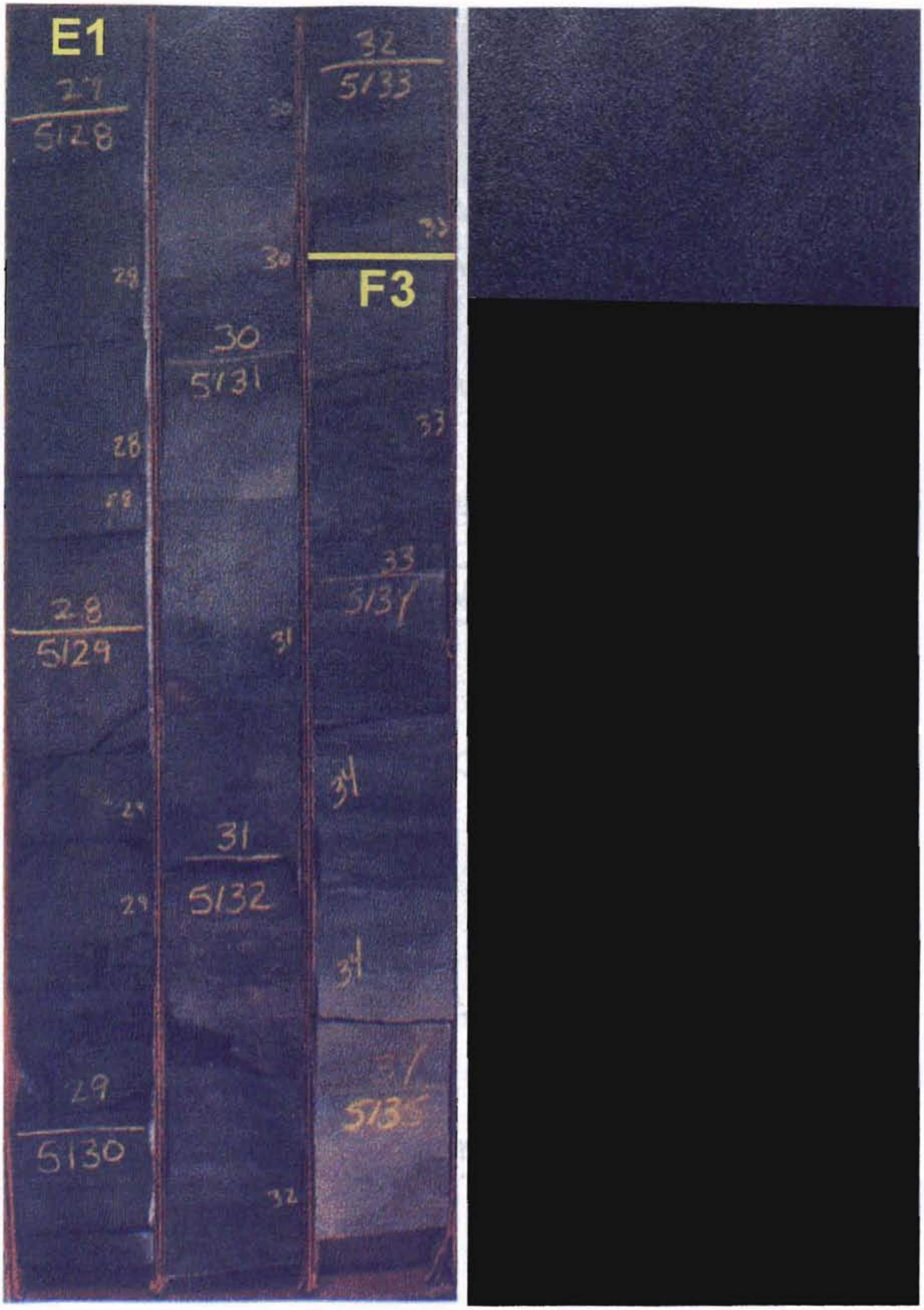


Figure 24. RMU #6 Well. Core Depth: 5127-5135, plain light and UV light.

Figure 25. **RMU #6 Well.** Core Depth: 5120-5127, plain light.

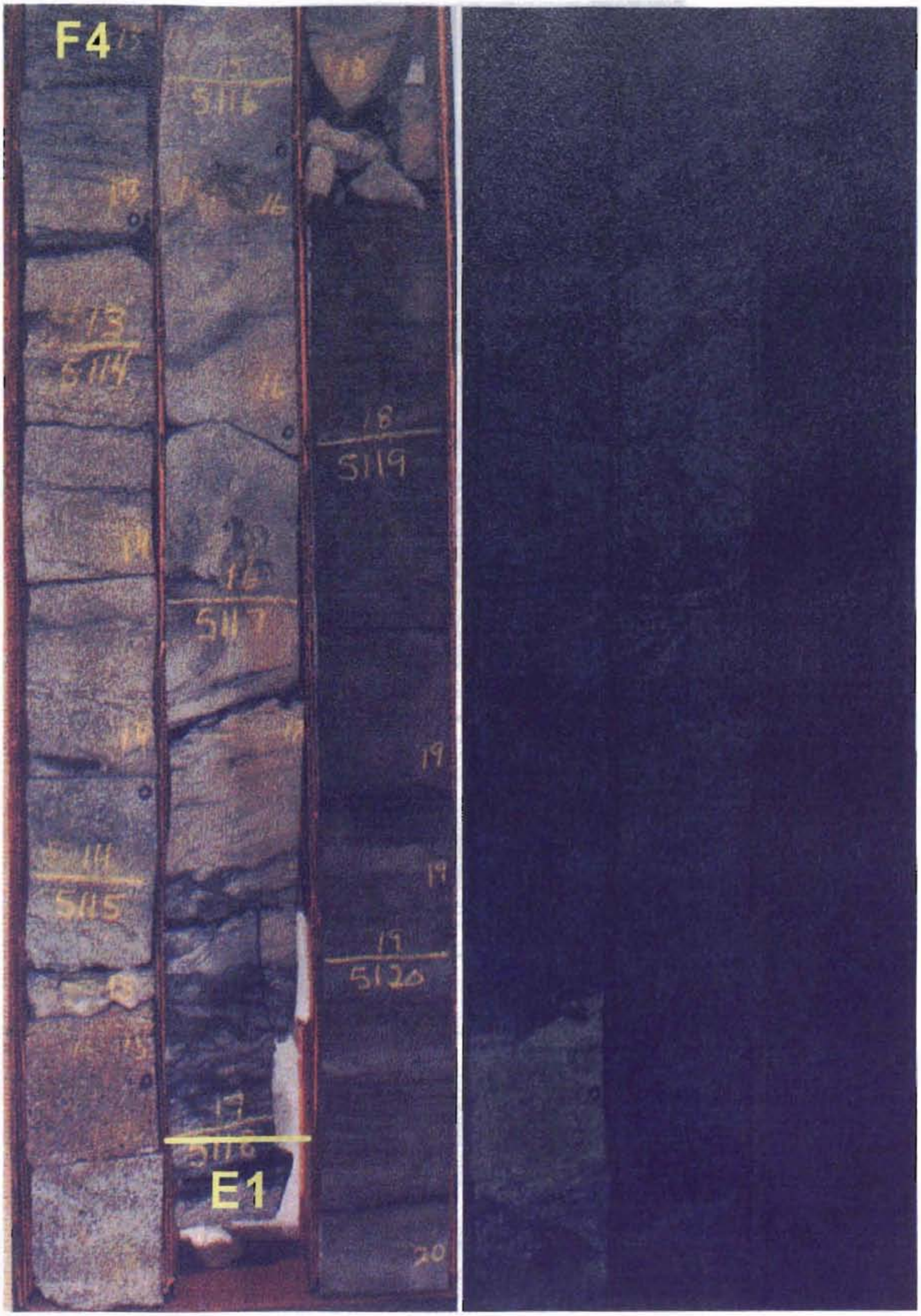


Figure 26. RMU #6 Well. Core Depth: 5113-5120, plain light and UV light.

Figure 27. RMU #6 Well. Core Depth: 5105-5113, plain light.

Figure 28. RMU #6 Well. Core Depth: 5098-5105, plain light.

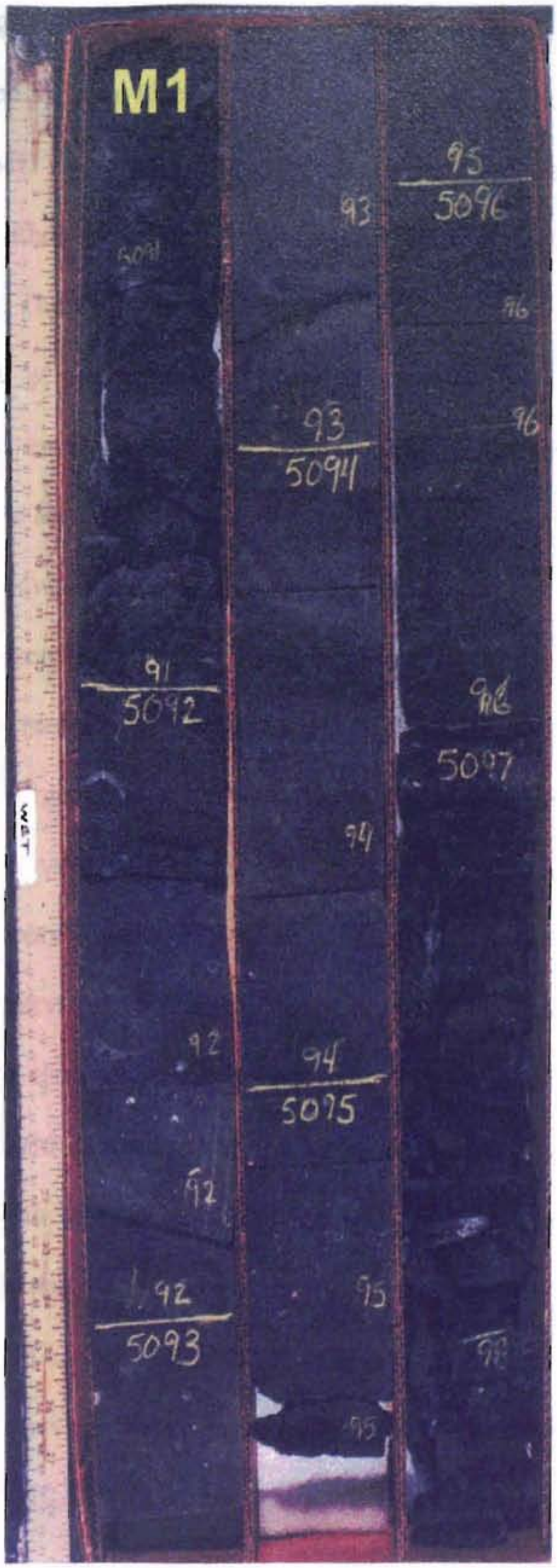


Figure 29. RMU #6 Well. Core Depth: 5090-5098, plain light.

under ultraviolet light. Black shale and claystone was then deposited in a marine environment, followed by more black shale that contains brachiopods.

The core, RMU #6, is an example of alternating fluvial and estuarine influences, being that the main lithology is a sandy mudstone. The fluvial influences being that of sandstone deposition. The estuarine influences being that of shale deposition, particularly the black shale that is present with interbedded sandstone. Because of fluvial and estuarine depositional environments, this core suggests that there were many past sea level fluctuations in the area of this core. The ocean would have risen, or transgressed, to provide an estuarine environment, while a sea level decrease, or regression, would have provided a fluvial environment. There may have been tidal influences as well, as the core has evidence of much interbedded sandstone and shale throughout. As the cored interval is finally capped by a surge of the sea level, a deep marine environment would have to be present in order to preserve the almost completely intact brachiopod fossils.

The RMU #13 core (figs. 30-40) consists of the M1, F2, and E1 lithofacies. At the bottom of the cored interval at 5059 a M1 facies is present as it contains black shale and does not have any light show under ultraviolet light. The interval of 5037.5-5059 is a F2 facies, as medium-grained sandstone with crossbedding is followed by coarse-grained sandstone is present with several fining-upward sequences. Under ultraviolet light, this interval shows hydrocarbon staining as well as some small areas where porosity has been occluded. The 5032-5037.5 interval is an E1 facies as there are interbedded fine to medium-grained sandstones and shales present and does not have any show of light under ultraviolet light. The 5010.5-5032 interval is a F2 facies, as this is another section of coarse-grained sandstone with several fining-upward sequences and also has very bright

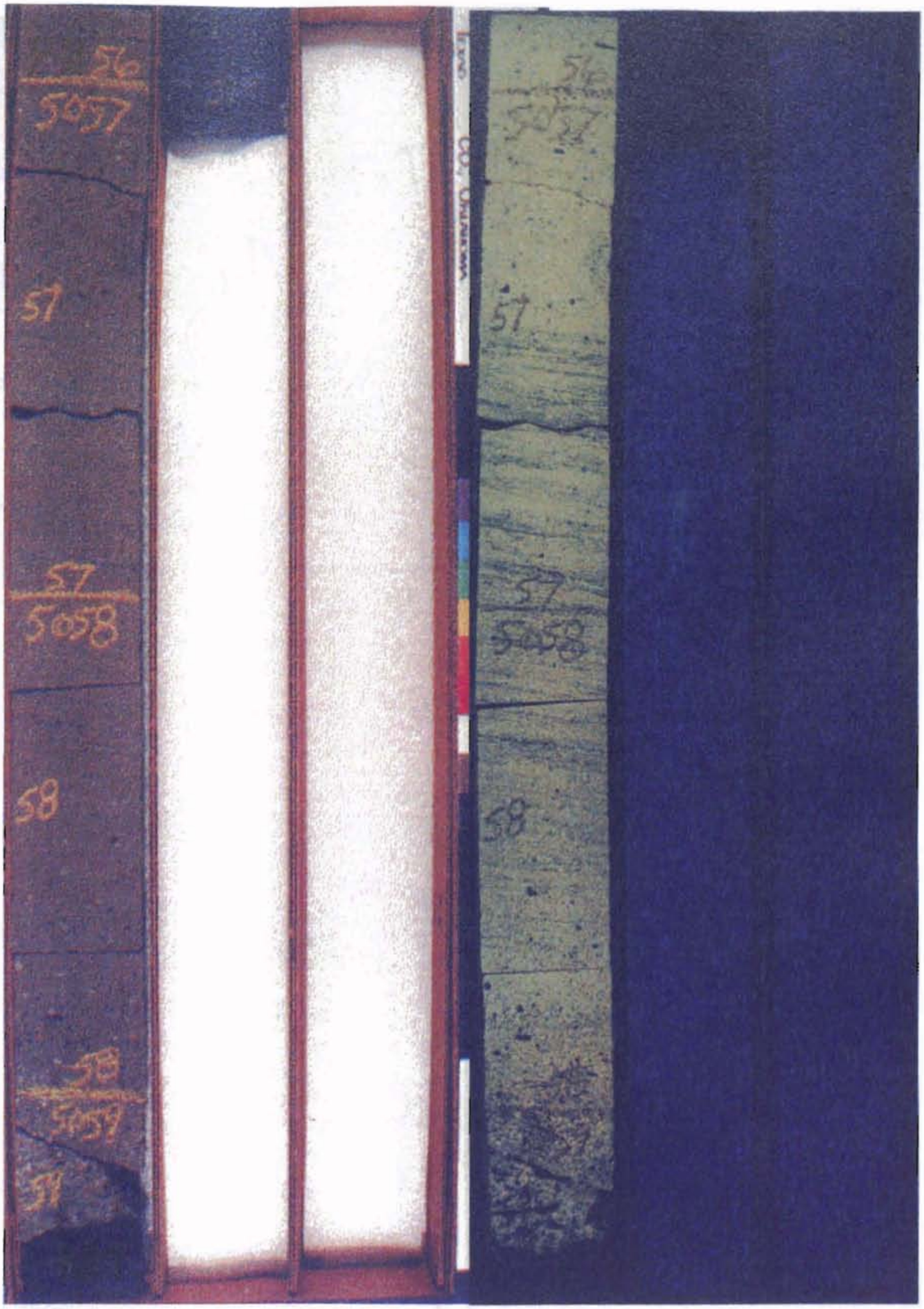


Figure 30. RMU #13 Well. Core Depth: 5056-5059, plain light and UV light.

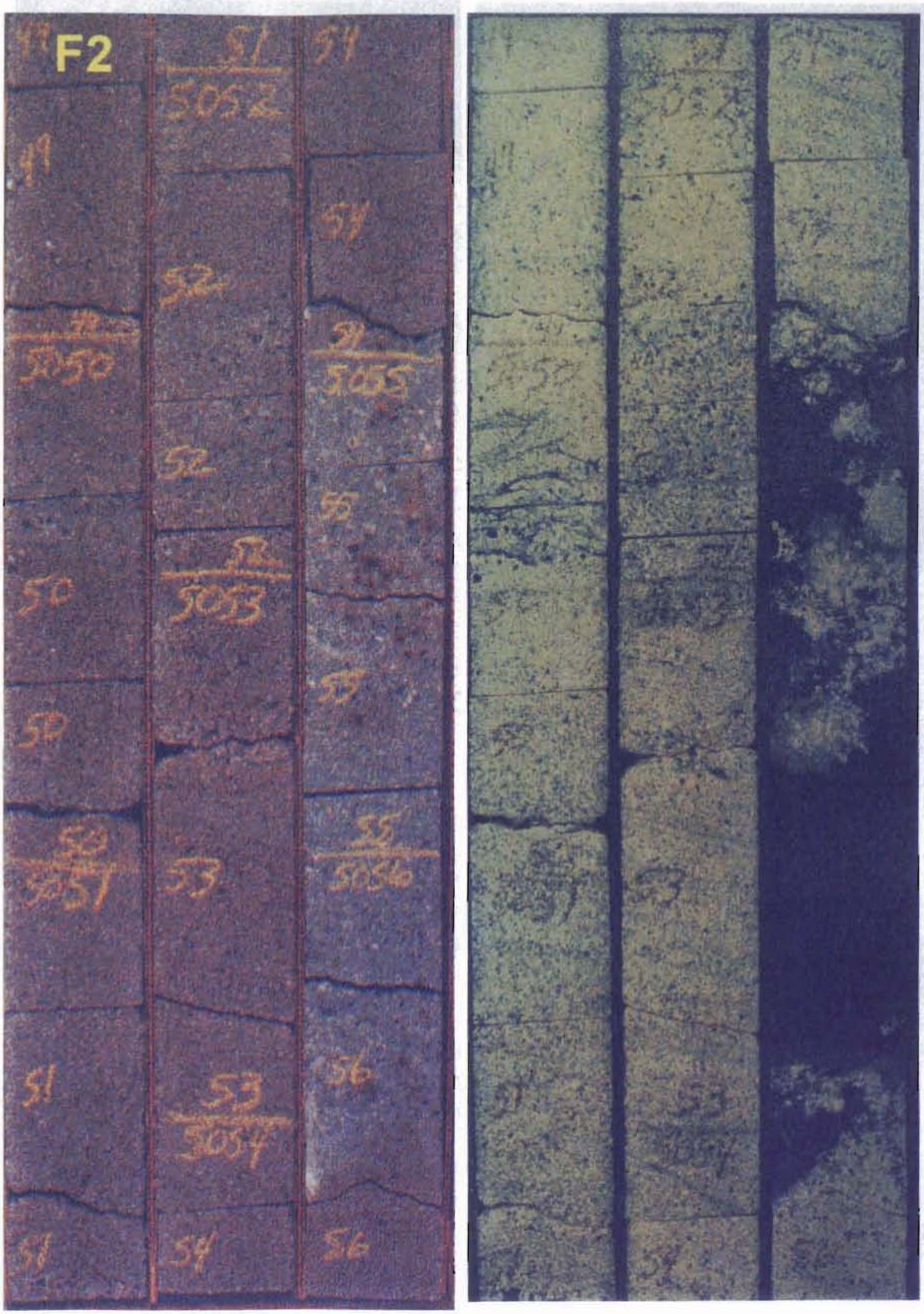


Figure 31. RMU #13 Well. Core Depth: 5049-5056, plain light and UV light.

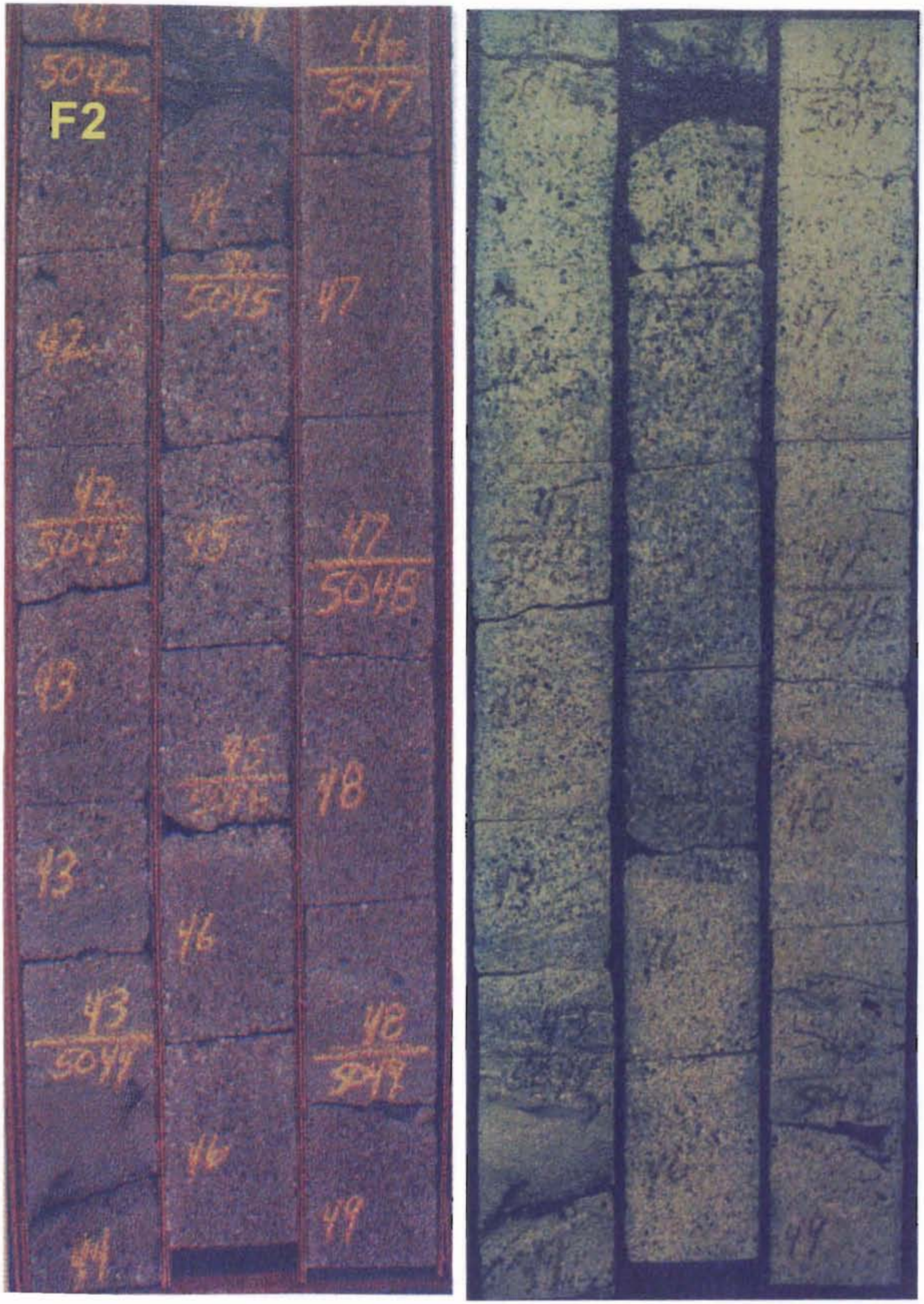


Figure 32. RMU #13 Well. Core Depth: 5041-5049, plane light and UV light.

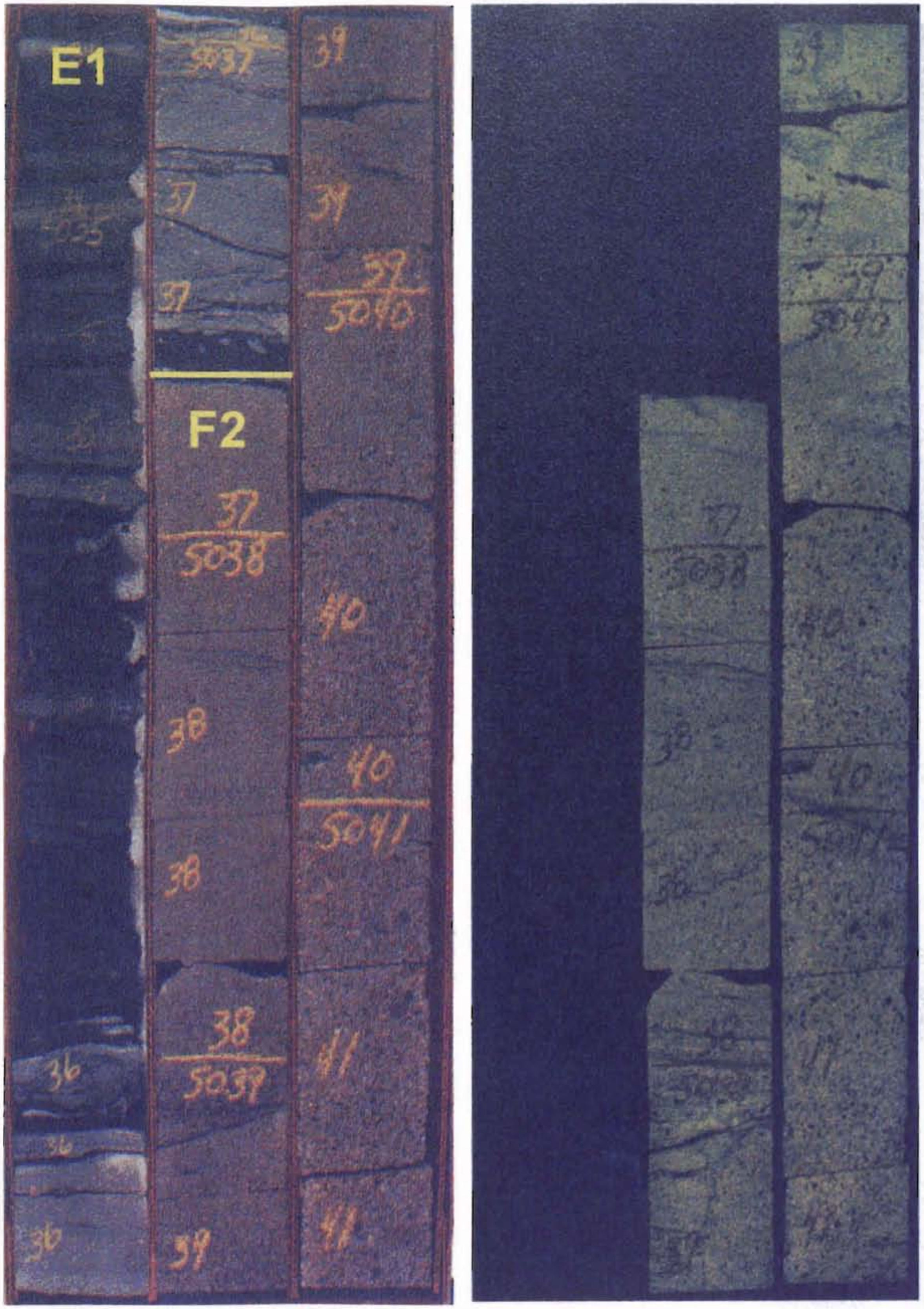


Figure 33. RMU #13 Well. Core Depth: 5034-5041, plain light and UV light.

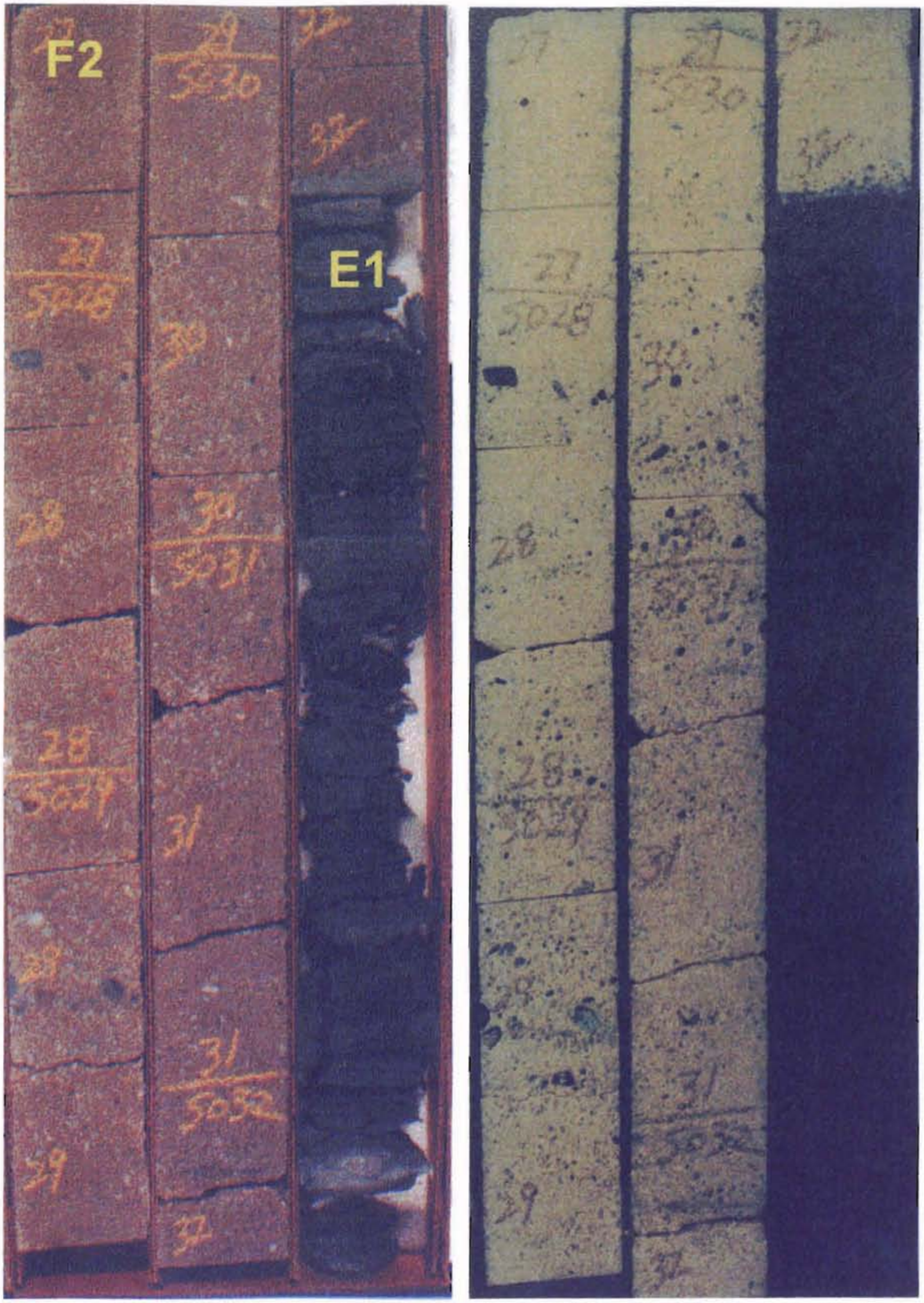


Figure 34. RMU #13 Well. Core Depth: 5027-5034, plane light and UV light.

Figure 35. RMU #13 Well. Core Depth: 5020-5027, plane light and UV light.

Figure 36. RMU #13 Well. Core Depth: 5012-5020, plane light and UV light.

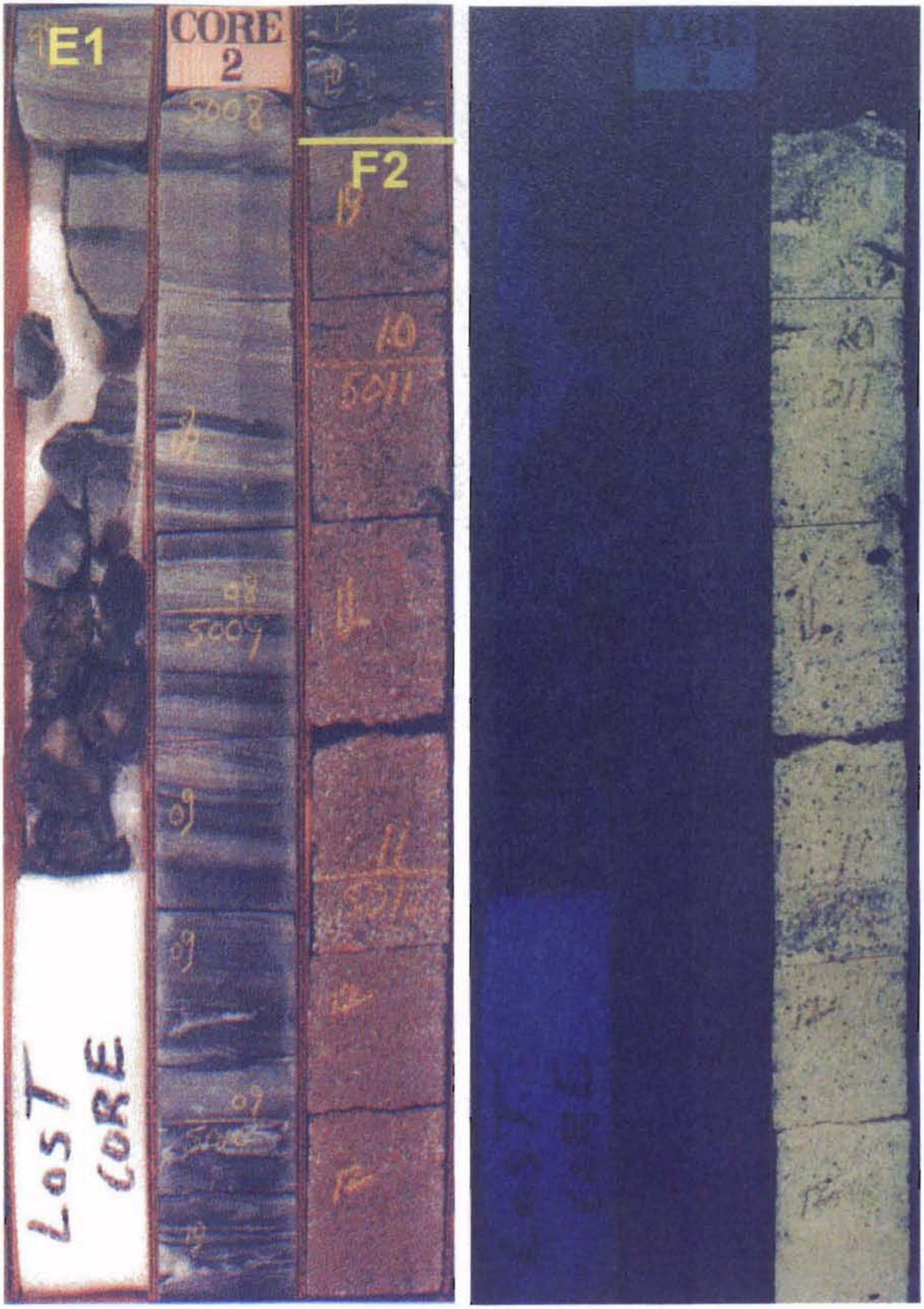


Figure 37. RMU #13 Well. Core Depth: 4999-5012, plain light and UV light.

Figure 38. RMU #13 Well. Core Depth: 4991-4999, plain light.

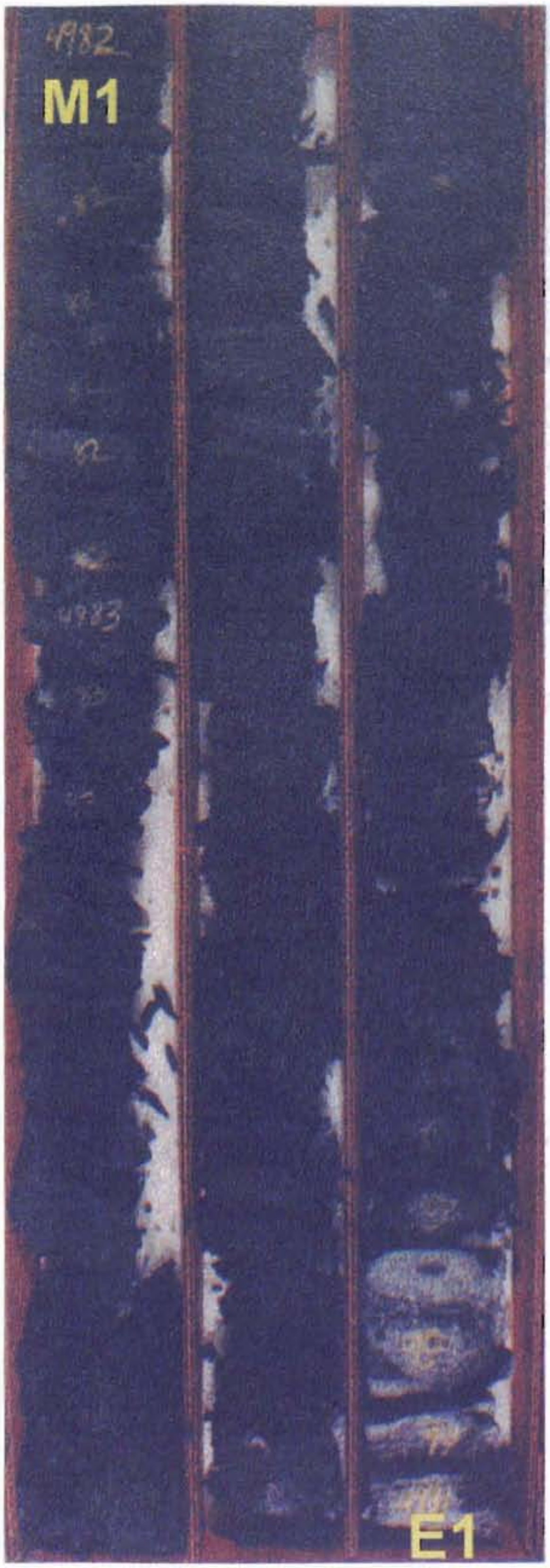


Figure 39. RMU #13 Well. Core Depth: 4982-4991, plain light.

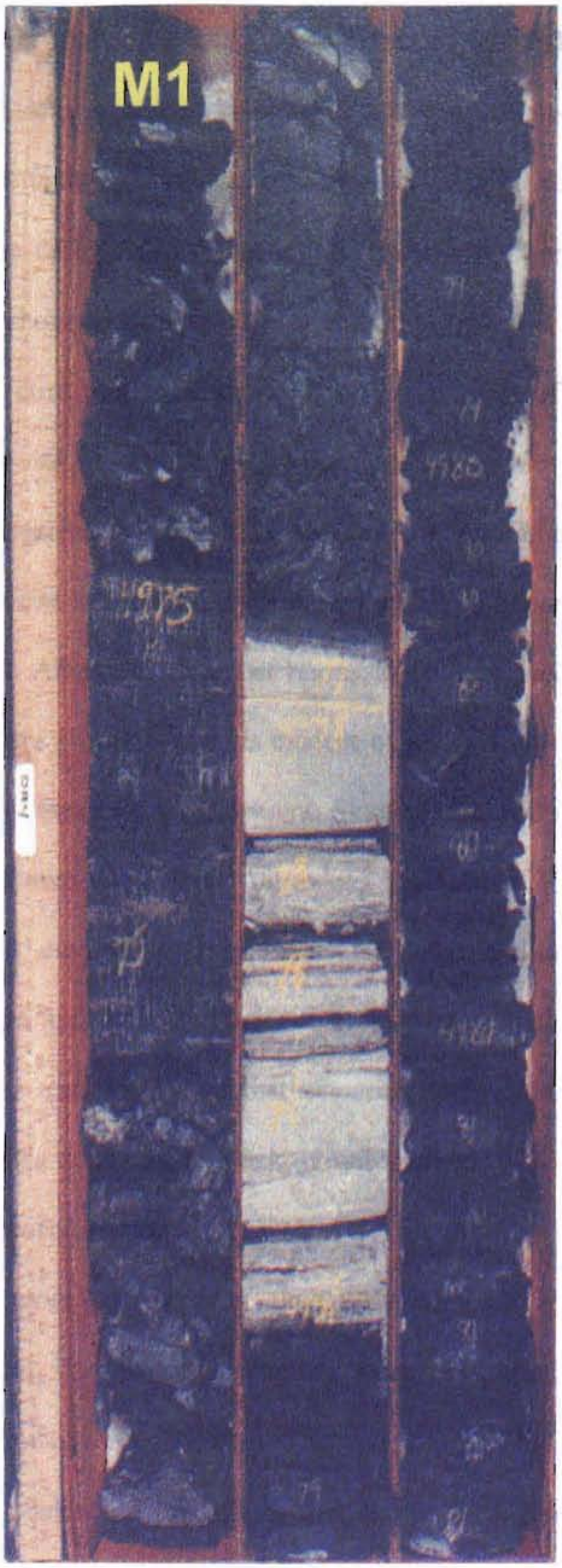


Figure 40. RMU #13 Well. Core Depth: 4974-4981, plain light.

hydrocarbon shows under ultraviolet light. The interval of 4990-5010.5 is an E1 facies as it contains interbedded sandstone and shale that is fine to medium-grained and does not have any show of light under ultraviolet light. The top interval of 4974-4990 is a M1 facies and contains very dark, black shales and claystones that are thinly laminated and does not have any light show under ultraviolet light.

This RMU #13 core is representative of slight episodes of sea level regression. This is evident by the initial deposition of black marine shale and then the fluvial deposition of the coarse-grained sand from braided stream deposits as sea level regressed. There was then a slight rise in sea level as estuarine sediment deposits were present in a low-energy environment. Afterwards, another regression of sea level occurred, as coarse-grained fluvial deposits are present, which is evident of braided stream deposits as fining-upward and crossbedded sequences were present. Since the braided stream deposits in the fluvial environments showed well under ultraviolet light, than it may be that those deposits show the best environments by which to have hydrocarbon reservoirs in comparison to the marine and estuarine facies that are present within this core. The sea level then rose again, or transgressed so that estuarine sedimentation could occur and marine sediments were also deposited as black, possibly anoxic, shales and claystones are present at the top of the cored section.

The RMU #13 core represents a fluvial environment as well as a marine environment being present. The fluvial environment occurred during a relatively low sea level, in which the sandstones were deposited. This was followed by a rise of sea level, as evidenced by the black shales and mudstones that are present. Because the shales are primarily at the top of the core and the sandstones are present at the bottom of the core, it can be surmised that this core is evidence of a sea level transgression as the fluvial area was flooded by immediate episodes of water inundation, thus depositing the shales. (See fig. 41)

The cores that were studied within the Southwest Rice field show similar facies relationships to the field studies of Carthage, Northeast Hardesty, and Northwest Eva fields. These field studies demonstrate evidence for sea level transgression and regression within Texas County, Oklahoma and also demonstrate similar successions of facies development within the incised channels in the Morrow interval.

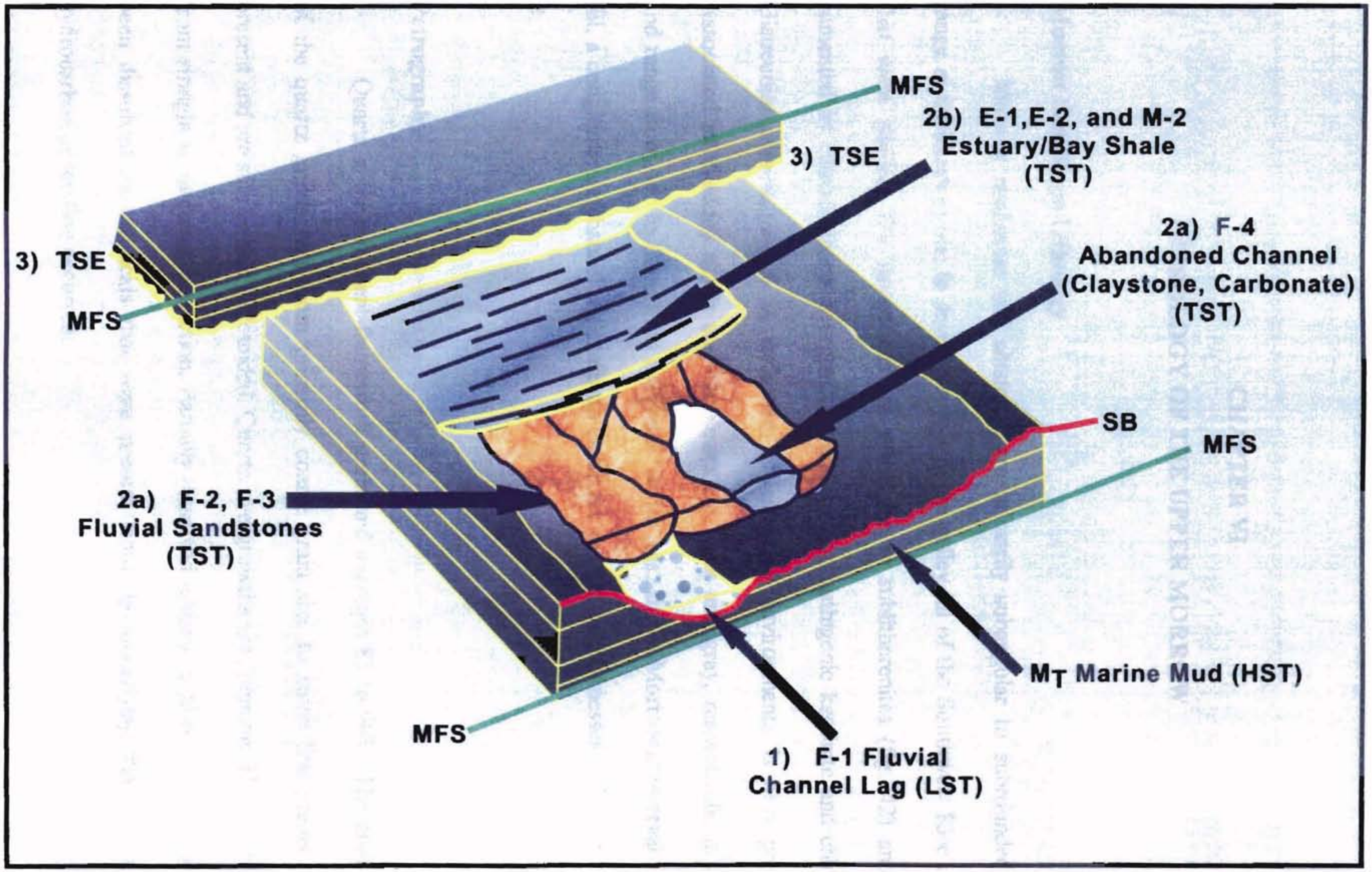


Figure 41. Depositional model of incised valley fill during various sea level stages (from Wheeler et al., 1990)

CHAPTER VI

PETROLOGY OF THE UPPER MORROW

Morrow Sandstone Lithology

Morrow sandstone and siltstones are primarily subangular to subrounded and range in thickness of one to seventeen feet in the valley fill of the Southwest Rice cores that were studied. The sandstones are subarkose to sublitharenites (fig. 42) and are cemented by calcite, quartz overgrowths, and contain authigenic kaolinite and chlorite. Glauconite cement, which is indicative of estuarine environments is also present. Associated interbedded shales and claystones are black and gray, respectively, in color and range from one to three ft. in thickness. At the base of the Morrowan interval valley fill, a conglomerate channel lag or rip-up clasts are present in thicknesses of less than one ft.

Petrography

Quartz is the dominant framework grain and averages 85 to 90%. The grain size of the quartz grains vary from primarily coarse grain size to some fine grains being present and are subrounded to rounded. Quartz overgrowths are common. The grains vary from straight to undulose extinction. Partially dissolved feldspar is also common and has been dissolved by the acids that were present from the underlying shales in which hydrocarbon generation occurred.

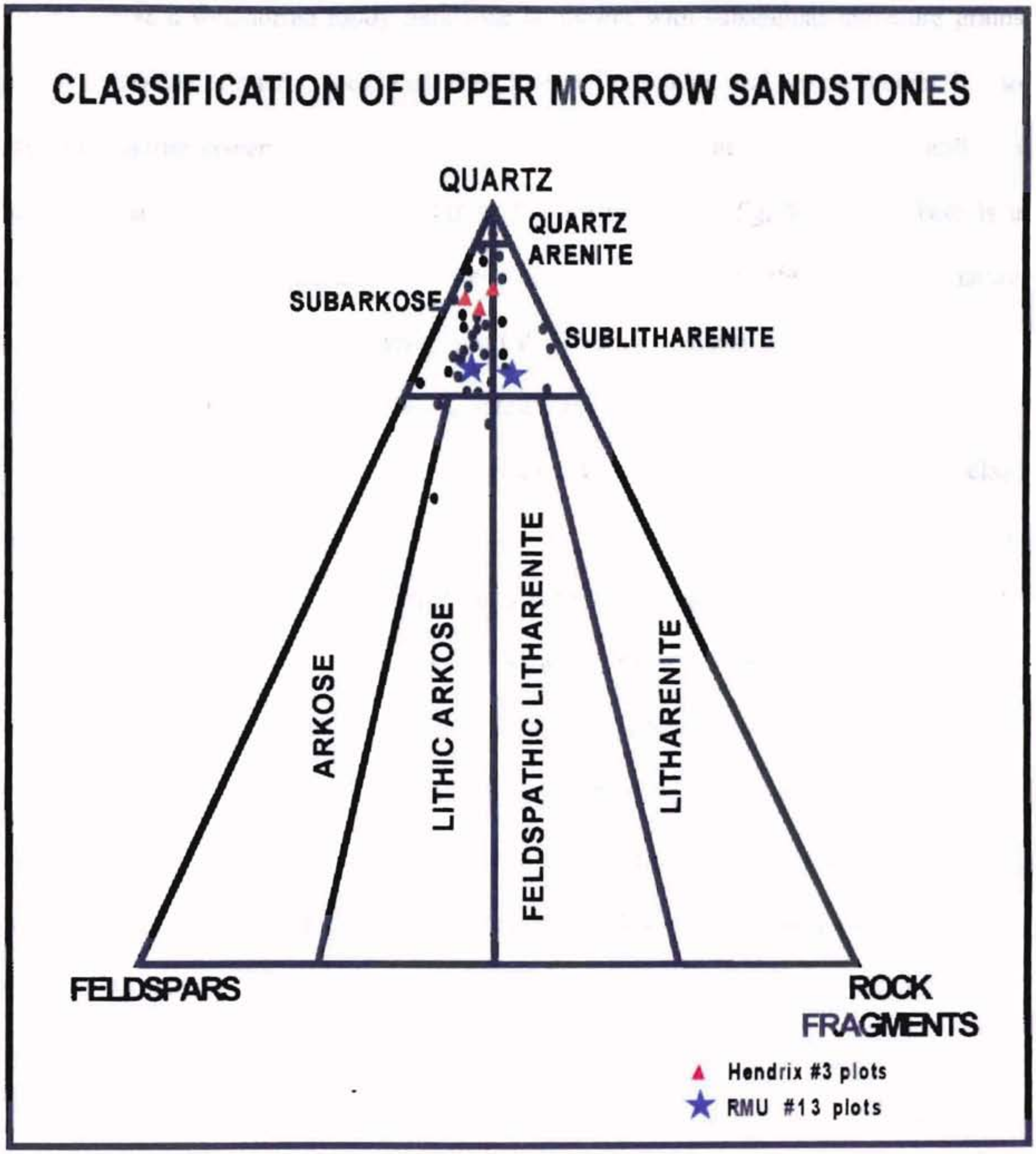


Figure 42. QRF diagram of the Hendrix #3 well in Carthage field and RMU #13 in Southwest Rice field demonstrating the abundance of quartz minerals present (after Gerken,1992, Harrison, 1990, Munson, 1989, and Al-Shaieb & Puckette, 2001).

Several types of rock fragments are present within the sandstones and are rounded to subrounded, are various spherical shapes, and are pebble to granule in size such as in fig. 43 where a well-sorted sandy mudstone is present with subangular immature grains mostly consisting of quartz, rock fragments, muscovite, biotite, and organic debris. It also contains chlorite cement, illitic and chlorite clay, and microfractures that are parallel to bedding. Large igneous rock fragments grains are present in fig. 44 where there is a subarkose/lithic arkose sample that is very poorly sorted with subrounded, submature grains mostly consisting of quartz, partially dissolved feldspar, and igneous rock fragments. Kaolinite, chlorite, and quartz overgrowths are also present.

Muscovite, biotite, organic debris with chlorite cement, illite and chlorite clay, and structures such as microfractures that are parallel to bedding are present in petrographic analysis. In figure 45 there is a subarkose/lithic arkose that is very poorly sorted with subrounded, submature grains, however, there are some minor grain-moldic pores present with some minor stylolites as well as chlorite cement and bits of pyrite. Figure 46 contains lithic arkose/feldspathic litharenite that consists of partially dissolved feldspar, igneous rock fragments, dolomite and kaolinite cement. Figure 47 is a SEM (scanning electron microscope) photomicrograph that contains microporous mudstone amongst detrital clay and silt. The silt includes muscovite, quartz, and potassium feldspar grains. The sand grains consist of muscovite, potassium feldspar, and biotite/chlorite.

Some fossil fragments are present within the Morrow sandstone and are mostly found in trace percentages. The fossil types that are present include brachipods, bryozoans, and gastropods. The fragments range in size from small pebble to medium sand such as in figure 48 with interbedded sandstone and shale with trace fossils as well

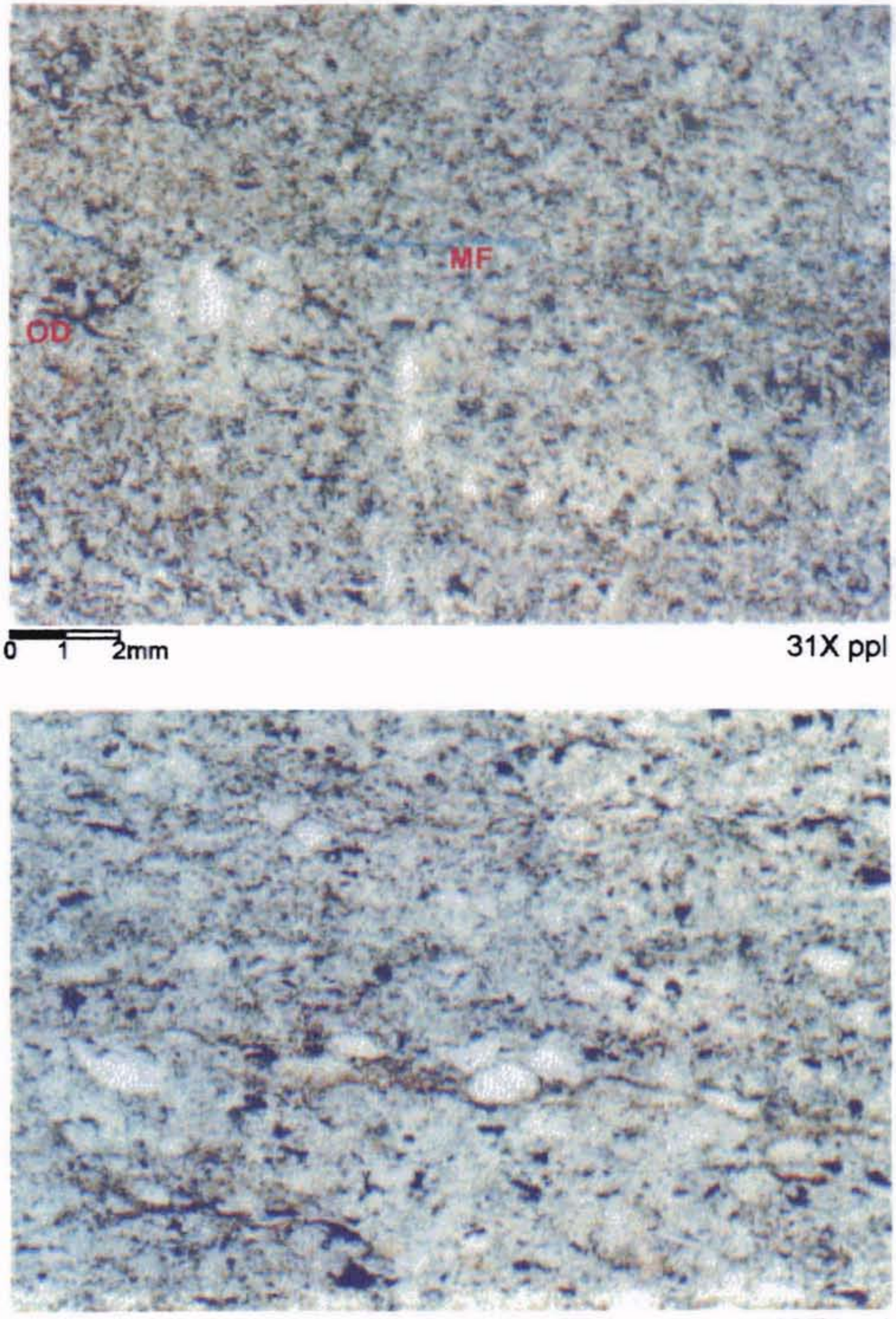
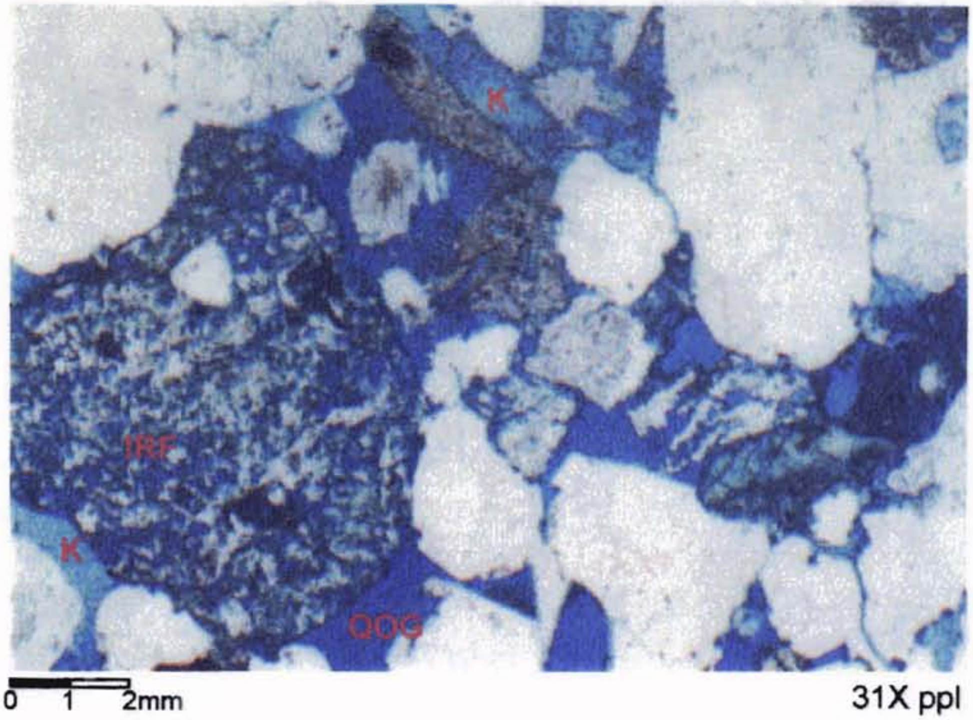
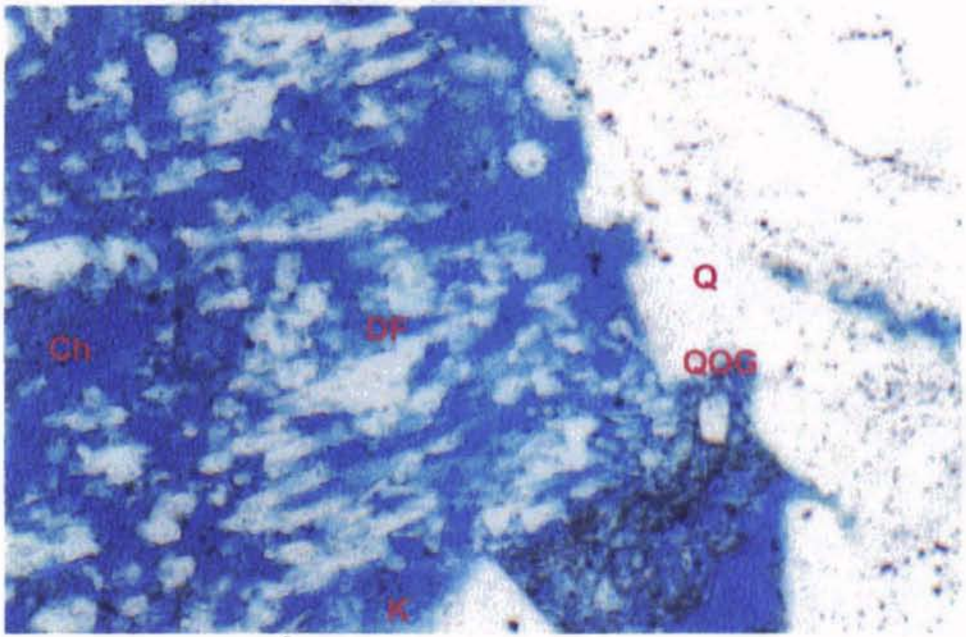


Figure 43. RMU #6 Well. Sample Depth: 5124.6 ft. Sandy Mudstone photomicrograph. MF= microfracture; OD= organic debris



31X ppl



125X ppl

Figure 44. RMU #13 Well. Sample Depth: 5011.9 ft. Subarkose/lithic arkose photomicrograph. K= kaolinite, QOG= quartz overgrowth, Ch= chlorite, IRF= igneous rock fragment, Q= quartz DF= dissolved feldspar.

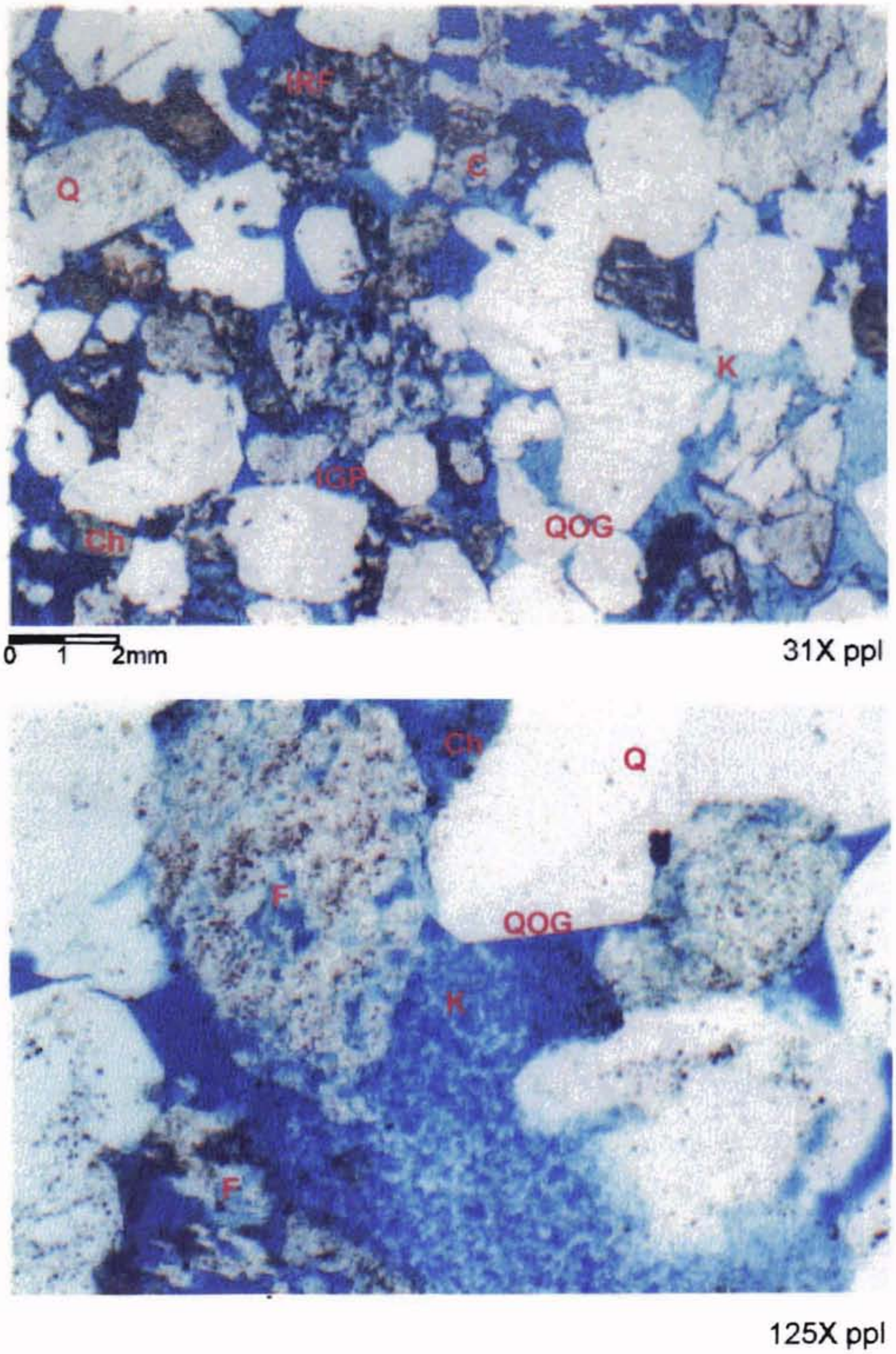


Figure 45. RMU #13 Well. Sample Depth: 5031.8 ft. Subarkose/lithic arkose photomicrograph. F= feldspar, K= kaolinite, QOG= quartz overgrowth, Q= quartz, Ch= chlorite, C= calcite, IGP= intergranular porosity, IRF= igneous rock fragment.

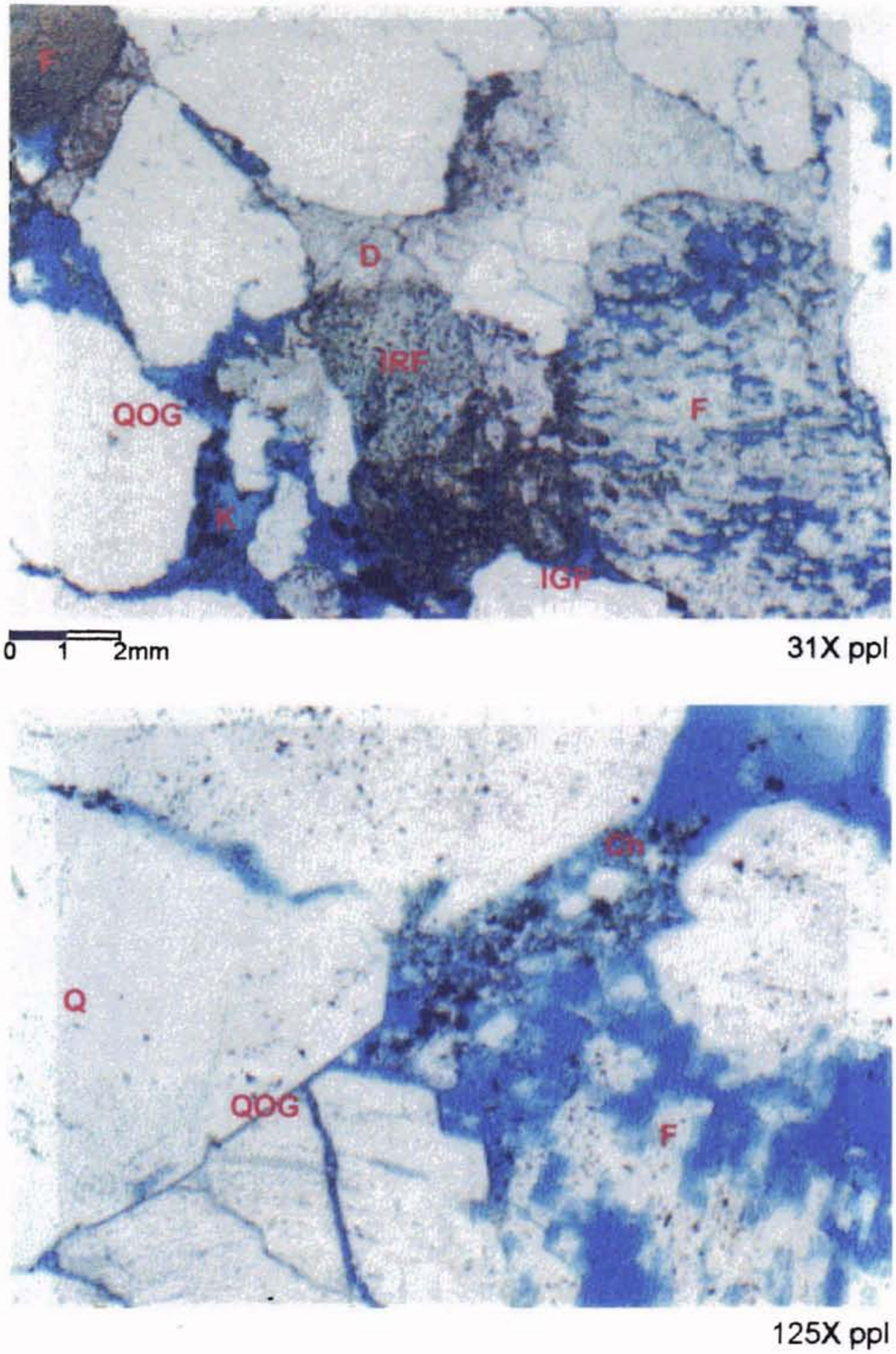
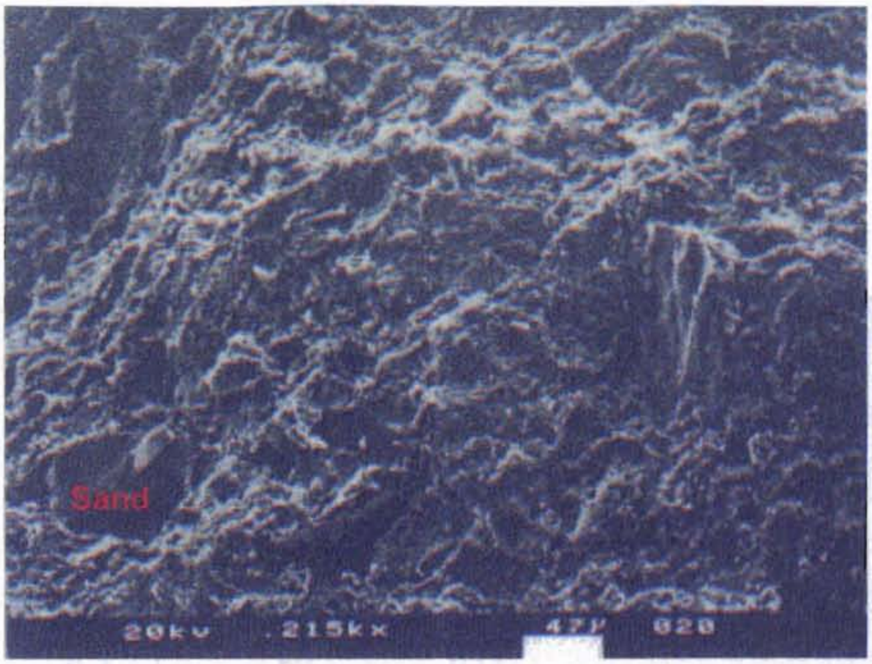


Figure 46. RMU #13 Well. Sample Depth: 5042.1 ft. Lithic arkose/ feldspathic litharenite photomicrograph. F= feldspar, QOG= quartz overgrowth, Ch= chlorite, IGP= intergranular porosity, K= kaolinite, D= dolomite, Q= quartz.



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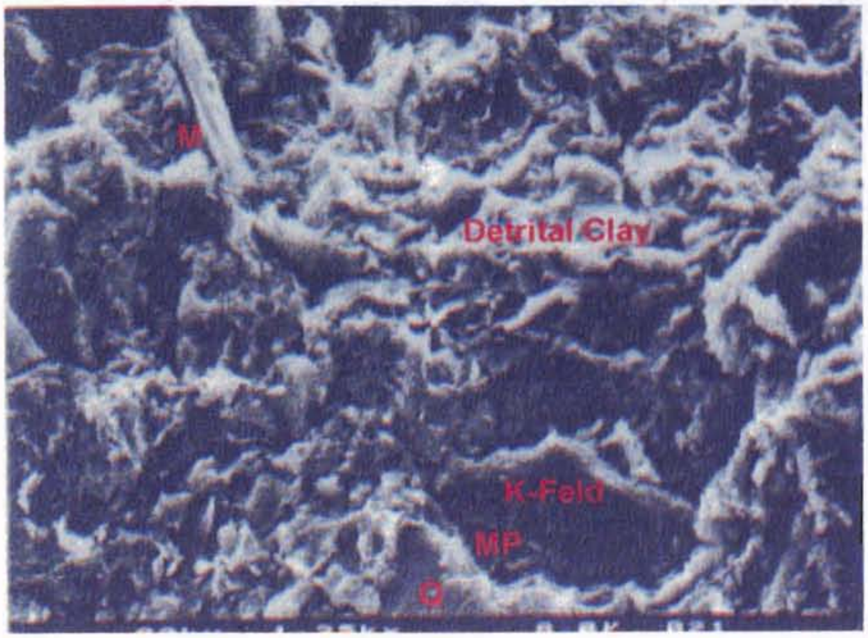


1250X

Figure 47. RMU #6 Well. Sample Depth: 5124.6 ft. SEM Photomicrograph. Microporous mudstone amongst detrital clay and silt. M= muscovite, MP= microporosity, Q= quartz, K-Feld= Potassium Feldspar.

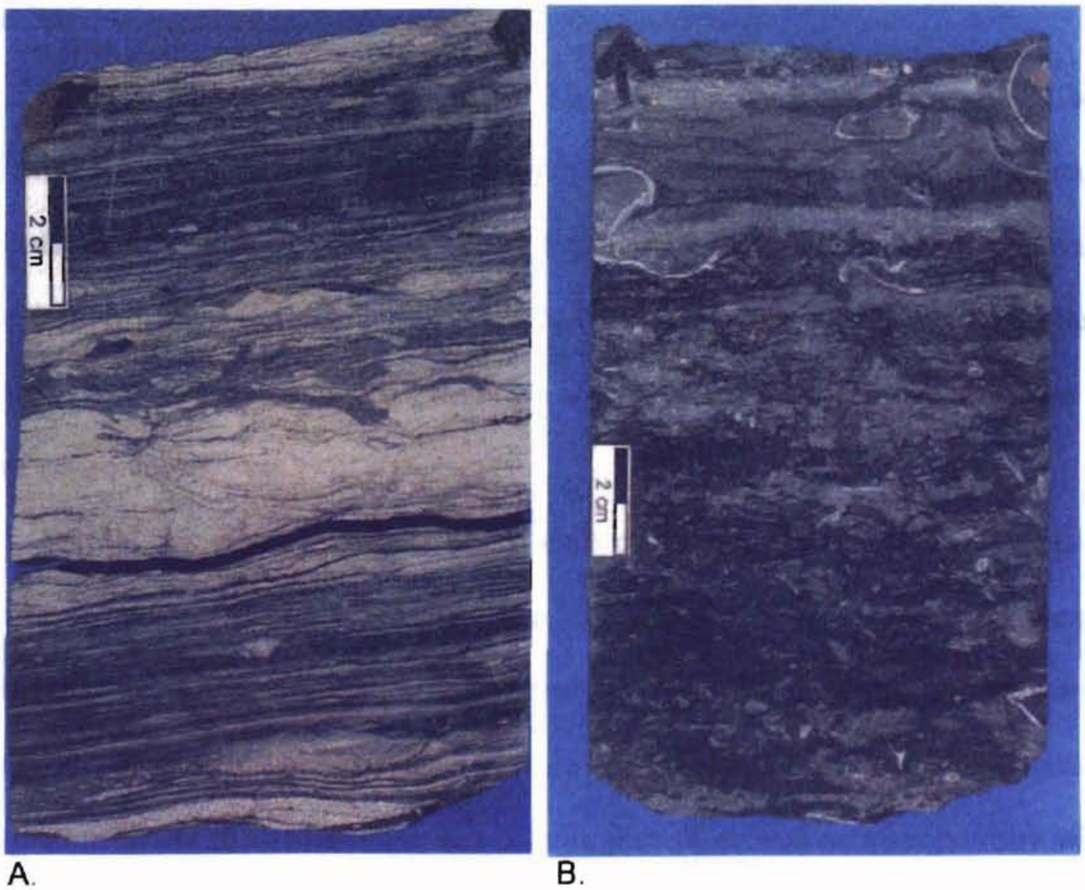


Figure 48. A. Core sample of interbedded sandstone and shale with trace fossils. B. Core sample of dark gray shale with abundant bioclasts. (Al-Shaieb and Puckette, 2001)

as a dark gray shale sample with abundant bioclasts. These fossils would indicate that a low energy marine environment was once present and therefore the fossil fragments would be present in marine facies. These specific fossil fragments were not identified in the Southwest Rice field area, however, brachiopod fossils are present in the top portion of the RMU #6 core in fig. 29.

Shale is present within the upper Morrow unit in the Carthage Field and Southwest Rice Field areas and is formed by the consolidation of clay and silt, or mud. Laminated structures are formed and allows for the rock to be fissile and have cleavage approximately parallel to the bedding plain. The shale is of a light gray color and contains silt, clay, and chemical or authigenic materials and are present in high energy estuarine or marine environments.

Detrital clay matrix is present within most of the samples and primarily contains kaolinite and chlorite. In figure 49 there is a lithic arkose/feldspathic litharenite sample that is poorly sorted and has subrounded, submature grains that mostly consist of quartz, partially dissolved feldspar, and igneous rock fragments with kaolinite and quartz overgrowths. There is also dolomite and chlorite present as well as microporosity with some faint cross-bedding features apparent. In figure 50, the SEM photomicrograph shows a very poorly sorted sandstone that consists of authigenic clays, kaolinite, chlorite, and quartz overgrowths. Significant microporosity is present in the clay masses.

X-ray diffraction was used to determine the most prominent clays present in the cores that were studied. It was discovered that kaolinite was present in the largest quantity within the studied sections (fig. 51). Kaolinite is associated with the hydrothermal alteration of aluminum silicates such as feldspar grains. Since feldspar is

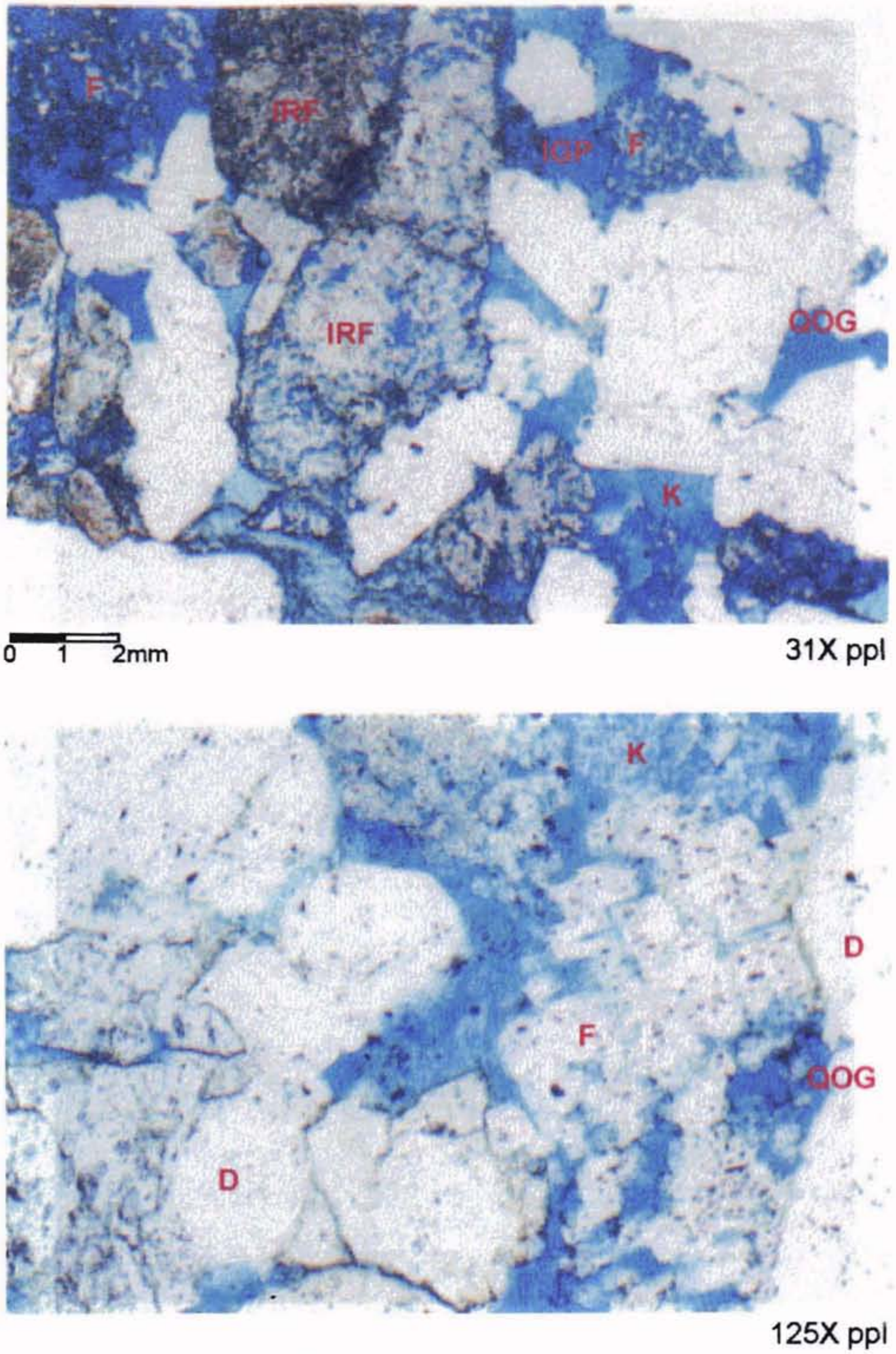
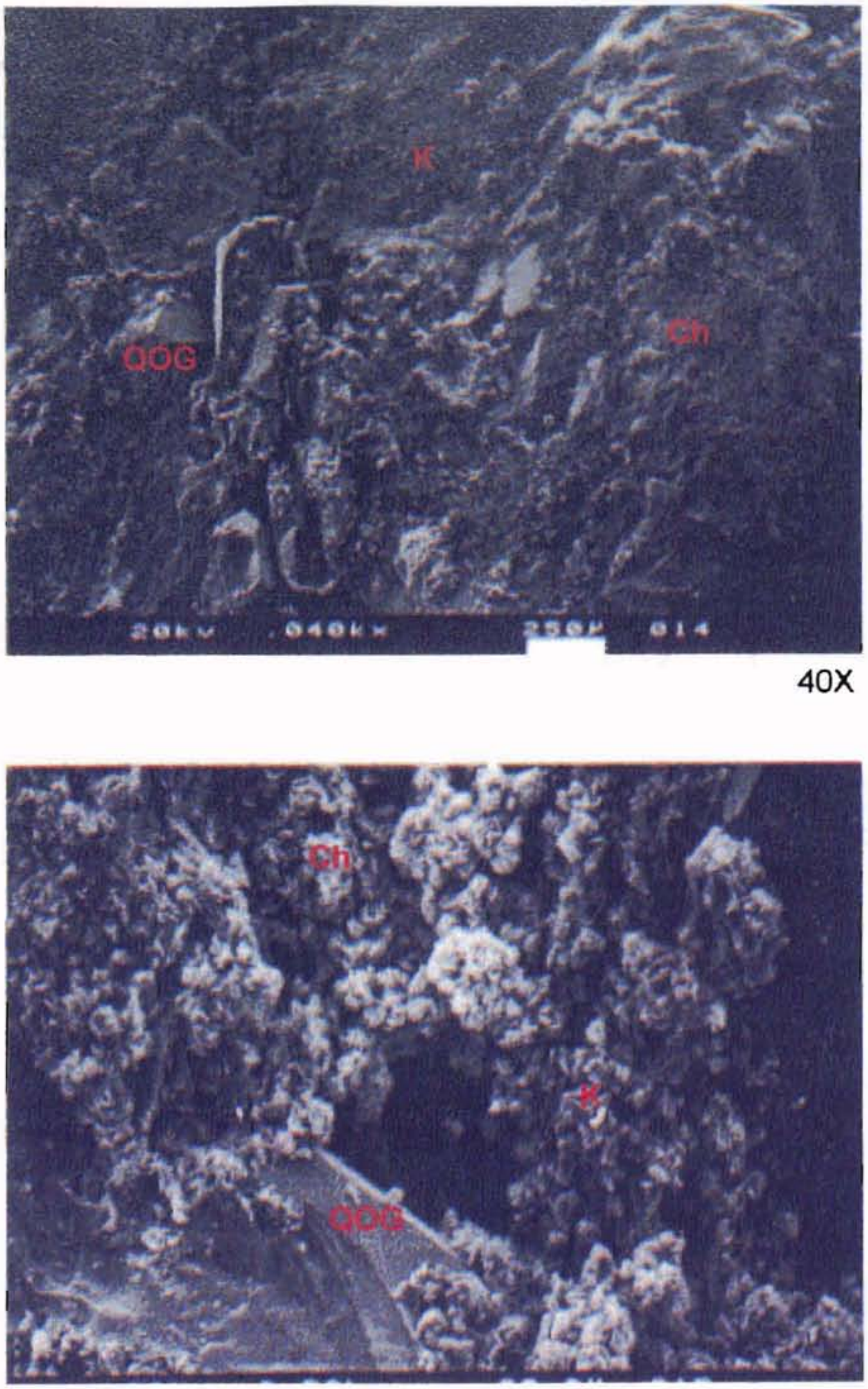


Figure 49. RMU #13 Well. Sample Depth: 5047.8 ft. Lithic arkose/ feldspathic litharenite photomicrograph. D= dolomite, K= kaolinite, F= feldspar, QOG= quartz overgrowth, IRF= igneous rock fragment, IGP= intergranular porosity.



40X

500X

Figure 50. RMU #13 Well. Sample Depth: 5031.8 ft. SEM Photomicrograph. QOG= quartz overgrowth, K= kaolinite, Ch= chlorite

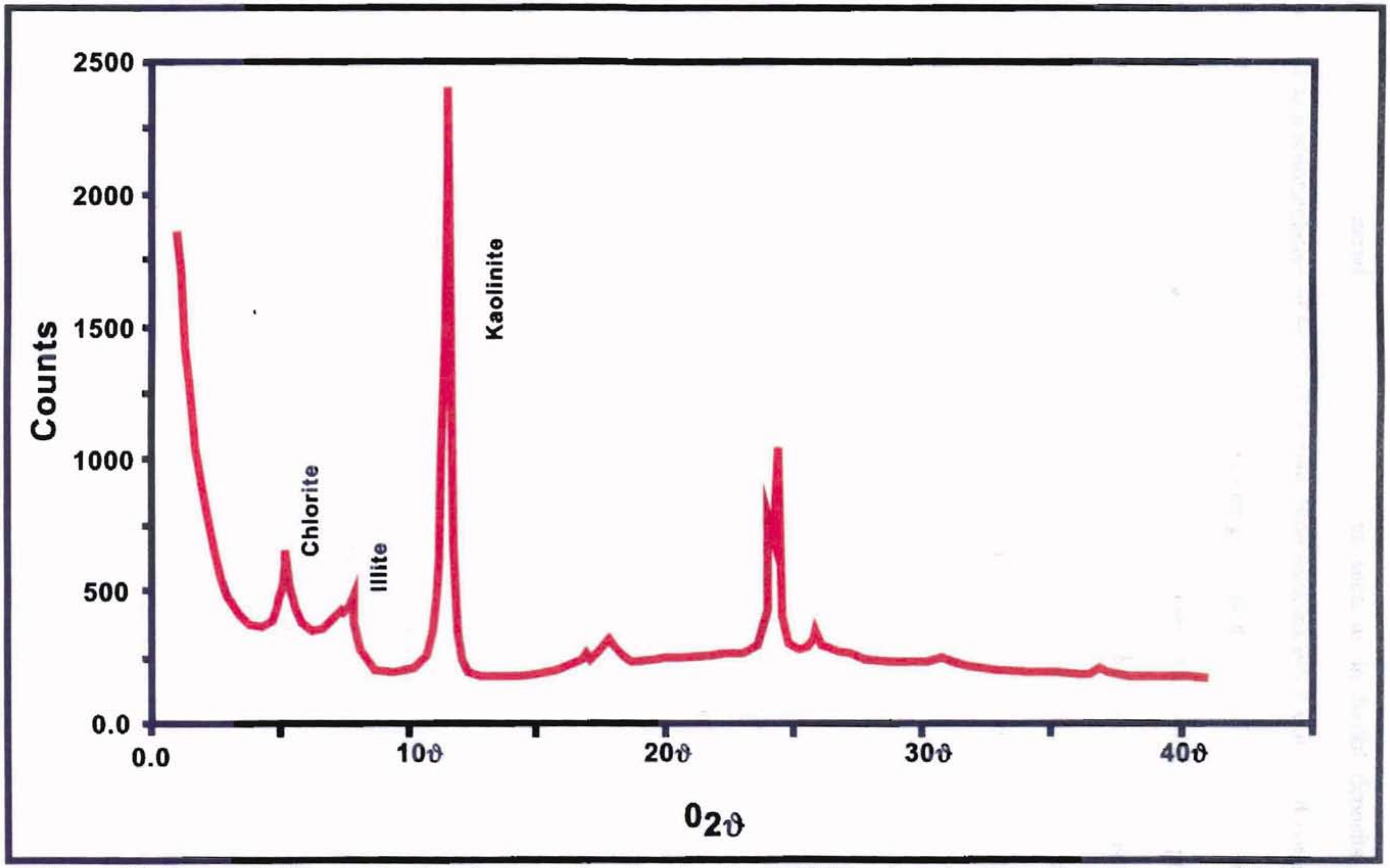


Figure 55. Composite X-ray diffraction demonstrating the abundance of clay minerals present in core sampes. (Al-Shaieb and Puckette, 2001)

found in many terrestrial sediment accumulations such as in fluvial deposits, then kaolinite is a representative of terrestrial origin. Illite contains much water and potassium while the potassium is replaced by calcium and magnesium, it is associated with a setting consisting of bioturbation and flowage, and is present in many shales and is thus present in marine environments. Chlorite is often associated with the alteration of igneous rocks to magnesium-iron silicates such as biotite, amphibole, and pyroxene. It is present as grain coatings to partially dissolved feldspar grains and is thus also a representative of terrestrial origin.

Porosity

The porosity type that is dominantly present in the Morrow is secondary porosity, which occurs as a result of diagenetic processes. (Schmidt and McDonald, 1979) During early diagenesis the primary intergranular porosity was reduced as a result of silica precipitation and occlusion of pore space by clays. The predominant types of secondary porosity in the Upper Morrow sandstone include dissolution of granitic constituents, feldspar, and dolomite. The maximum amount of secondary porosity occurs in the quartz-dominated sandstones and in the Southwest Rice field is greater than 12%.

The dissolution of matrix is common in the Morrow sandstones. This dissolution, the results in enlarged intergranular porosity such as that in figure 52 where the SEM photomicrograph shows quartz and quartz overgrowth that is present along with partially dissolved plagioclase that is covered by authigenic chlorite, as authigenic kaolinite is also present. Here it is also observed that intragranular dissolution of the pores may aid the effectiveness of the porosity in the sandstone. An example of dissolving matrix is the

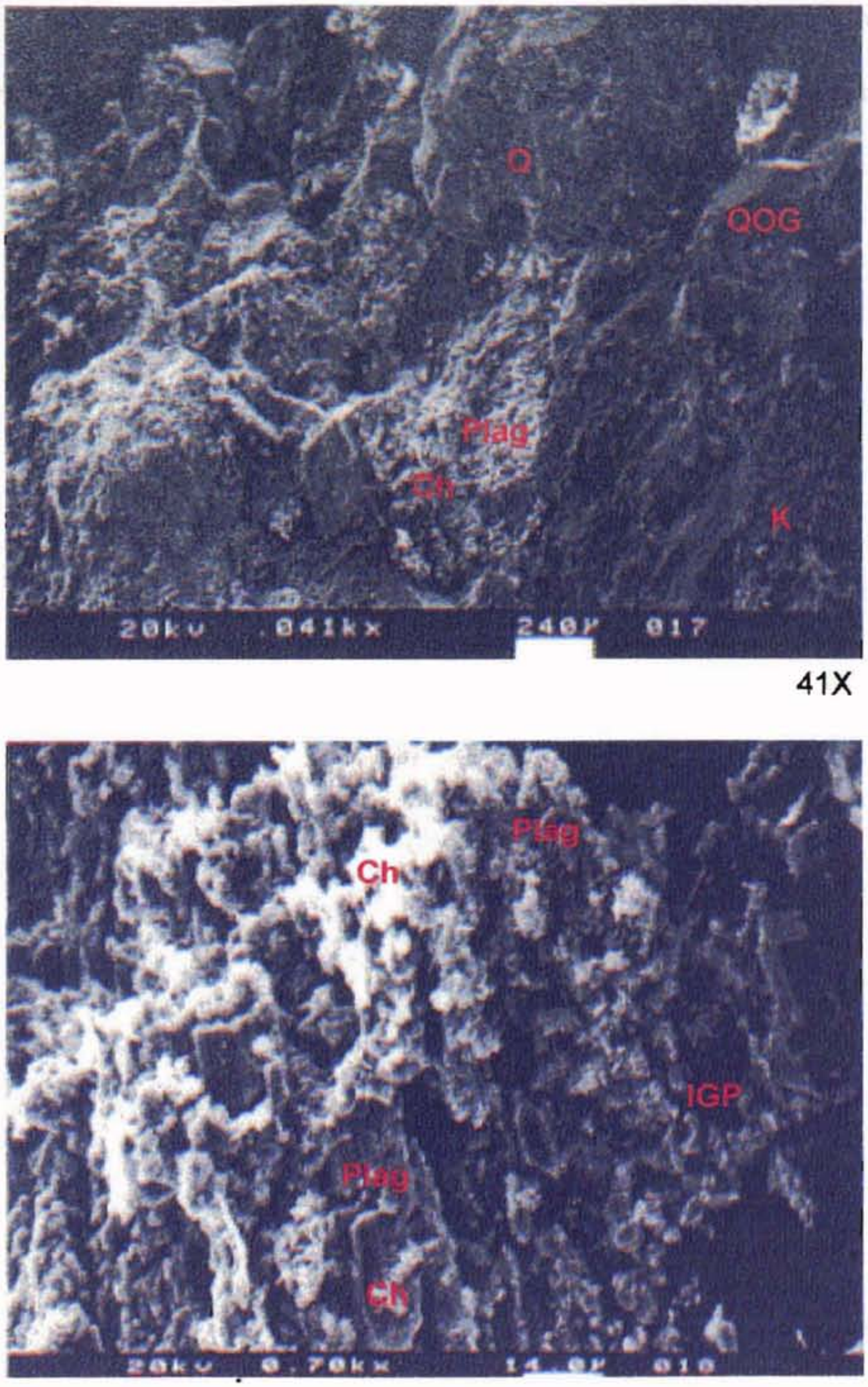


Figure 52. RMU #13 Well. Sample Depth: 5047.8 ft. SEM Photomicrograph. Plag.= Plagioclase Feldspar, IGP= intergranular porosity, Ch= chlorite, Q= quartz, K= kaolinite.

leaching of pseudomatrix such as deformed glauconite or detrital silty matrix that produces enlarged intergranular pores. Residue of the clay matrix is present rimming pore spaces and as isolated patches within pore spaces where dissolution occurred. Some secondary porosity may also be attributed to silica dissolution such as quartz, chert, and even pyrite that is associated with the over pressuring characteristic of stylolites (fig. 49).

CHAPTER VII

RESERVOIR CHARACTERISTICS

Introduction

As the depositional sequence began, shales were deposited in marine environments that were present to the south. Ultimately, sea level dropped, which caused a lowstand to occur. Throughout this time, channels were carved out of the existing shale during incision. The sediments that were left were paraconglomerate deposits that are known as channel lag that were present in the bottom of these incised channels. Eventually sea level rose and it imposed upon the shoreline as a transgressional event. The sediments that were deposited were coarser-grained sandstone that are observed as being braided stream deposits, point bar sequences, and abandoned channel deposits. With the continuous rise in sea level, estuaries formed, in which fined-grained sediment was deposited as well as the deposition of highly organic material.

Production

Pennsylvanian Morrow valley-filled sandstone reservoirs have variable production that is caused by complex facies relationships. The reservoirs were created when a coarse, permeable valley sequence scoured into and filled in a preexisting valley which contained fine, low permeability sandstones (Krystinik, 1989).

Most production comes from the coarse-grained, younger fluvial deposit, which scoured into the older, more estuarine valley fill (Krystinik, 1989). Production ranges from depths of approximately 4,500 feet in the Panhandle to nearly 17,000 feet in the deep southeast portion of the Anadarko Basin (Keighin & Flores, 1989).

Morrow Distribution

The depositional environment must be determined in order to identify trends of reservoir sands, thickness and extent of intervals, clay content, and reservoir quality. The Morrow sandstones are highly variable in thickness, lateral extension, depositional origin, grain size, and sorting of grains. Having the occurrence of fluvial sandstones interbedded with marine sediments and limestone of close proximity to one another indicate an unstable geologic setting with several depositional environments. Shorelines fluctuate significantly and depositional environments of sandstones are interactive. Short durations of time and short episodes of sand deposition prevented widespread occurrences of uniform depositional sequences. Individual sandstone beds are less than 50 feet, as total sandstone in a depositional cycle is less than 150 feet (Andrews, 1995). Therefore sediments that are in close proximity to each other both stratigraphically and laterally may also include sandstone horizons that were affected by sea level changes.

The Morrow is composed of sediments that have fluvial or fluvial-dominated deltaic origin which gives it good reservoir properties. The sand is coarser grained than tight marine sands that produce gas. Oil and gas production is stratigraphically controlled and is not related to structural features (Andrews, 1995). Therefore reservoir properties are related to depositional environment and not directly to structure.

The lower Morrow is composed of marine shale, shallow marine sand, subaerially exposed sediments consisting of fluvial point bars, marsh, and carbonaceous material. Sandstone beds have fluvial geometry but contain marine constituents such as shell fragments or glauconite. These elements may indicate a redistribution of preexisting marine sediments during transgression or extension of a channel into a marine environment, such as with a distributary channel. Fluctuating shorelines or tidal currents may also be responsible for this incorporation of marine sediments, such as sea level changes (Andrews, 1995). After inundation by marine conditions by which existing sand was redistributed and shale and discontinuous sand bodies were deposited, the newly deposited sand was interpreted to be the upper Morrow interval.

In Texas County, Oklahoma, the lower Morrow is composed of marine shale that overlies basal marine sands. East of Texas County, the environment is interpreted to be marine or semi-marine. Southeast of these sediments elements of coarse-grained clastics become apparent. Because of this distribution, there must be a clastic source area to the north-northeast. The regional extent of the Morrow to the northeast is a depositional limit and Morrow seaway was deeper to the southwest.

The upper Morrow is composed of marine shale with discontinuous sand bodies scattered throughout. These sand bodies are elongate or in sinuous patterns that originate from fluvial channels (Andrews, 1995).

Diagenesis

Diagenesis helps to play an important role in the development of secondary porosity. Within this new void area, potential reservoirs for hydrocarbons within the upper Morrow sandstone became present. The diagenetic history of the upper Morrowan sandstone is summarized in figure 53. The diagenetic events and thus the evolution of secondary porosity are related to the hydrogen ions that are produced directly from the organic material maturation process of Morrow shales (Al-Shaieb and Walker, 1987).

One of the first stages of diagenesis was silica occuring as quartz overgrowths, which completely encase the original grain and completely infringe upon the intergranular pore space. Some dust rims that contain clay separate the overgrowths from the detrital grain, but are not always present. Because the advanced stages of quartz overgrowths are present in the relatively clean subarkose/sublitharenite sandstones in the Southwest Rice field, the alteration of adjacent shales could be the possible source of silica for the overgrowths (Hower et al., 1976).

After the dissolution of granitic rock fragments, calcite filled in much of the void space. Silicious fragments such as chert and quartz were also dissolved, thus leaving room for more calcite to precipitate. Hydrocarbon migration into the upper Morrow sandstone occurred, during which feldspar was dissolved from acids that were released during hydrocarbon generation, leaving room for kaolinite and chlorite to take the place of the dissolved feldspar.

Moderate post-depositional compaction has occurred in the upper Morrow sandstone. This is evident by long grain-to-grain contacts and slight suturing along some grain contacts, which lead to stylolite formation.

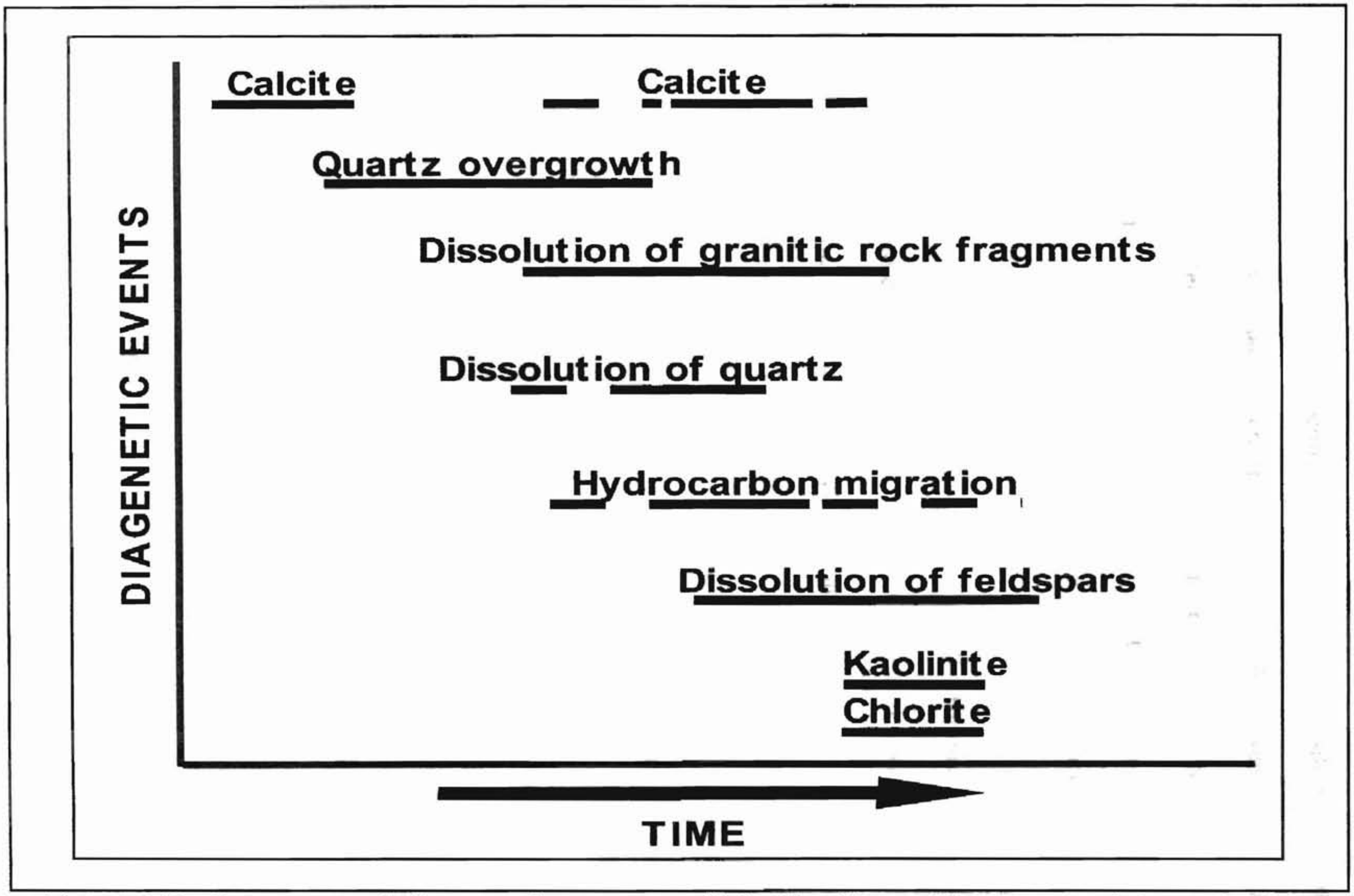


Figure 53. Sequence of diagenetic events within the Upper Morrow sandstone in the Texas County, OK study area. (Al-Shaieb personal communication, 2002)

Reservoirs

The most favorable hydrocarbon reservoirs tend to contain high porosity by which to house hydrocarbons as well as high permeability. This serves to easily transmit the fluid to the well bore under unequal pressure (figs. 54 and 55). With given porosity and deep resistivity values, water saturation can be estimated, which is based on wet resistivity and true resistivity (fig. 56). This allows for a quantification of hydrocarbons that may be present within a zone, as the lower the water saturation, the more likely the chance of hydrocarbon presence.

Within this study of the upper Morrow sandstone and the various facies that it contains, the facies themselves are the intervals by which reservoirs may be characterized. The facies that show the highest porosity and permeability are the F2 and F3 facies, otherwise known as the braided stream and point bar deposits (fig. 57). Because the F1, F4, E1, and M1 facies, representing the paraconglomerate, abandoned channel, estuarine, and marine facies, respectively, do not contain as favorable porosity and permeability, they are not the prime areas for hydrocarbon reservoirs to form. Because of this, when drilling for hydrocarbons in the upper Morrow sandstone, the braided stream and point bar deposits should be the target areas to drill, if these facies are present at all in the field under investigation.

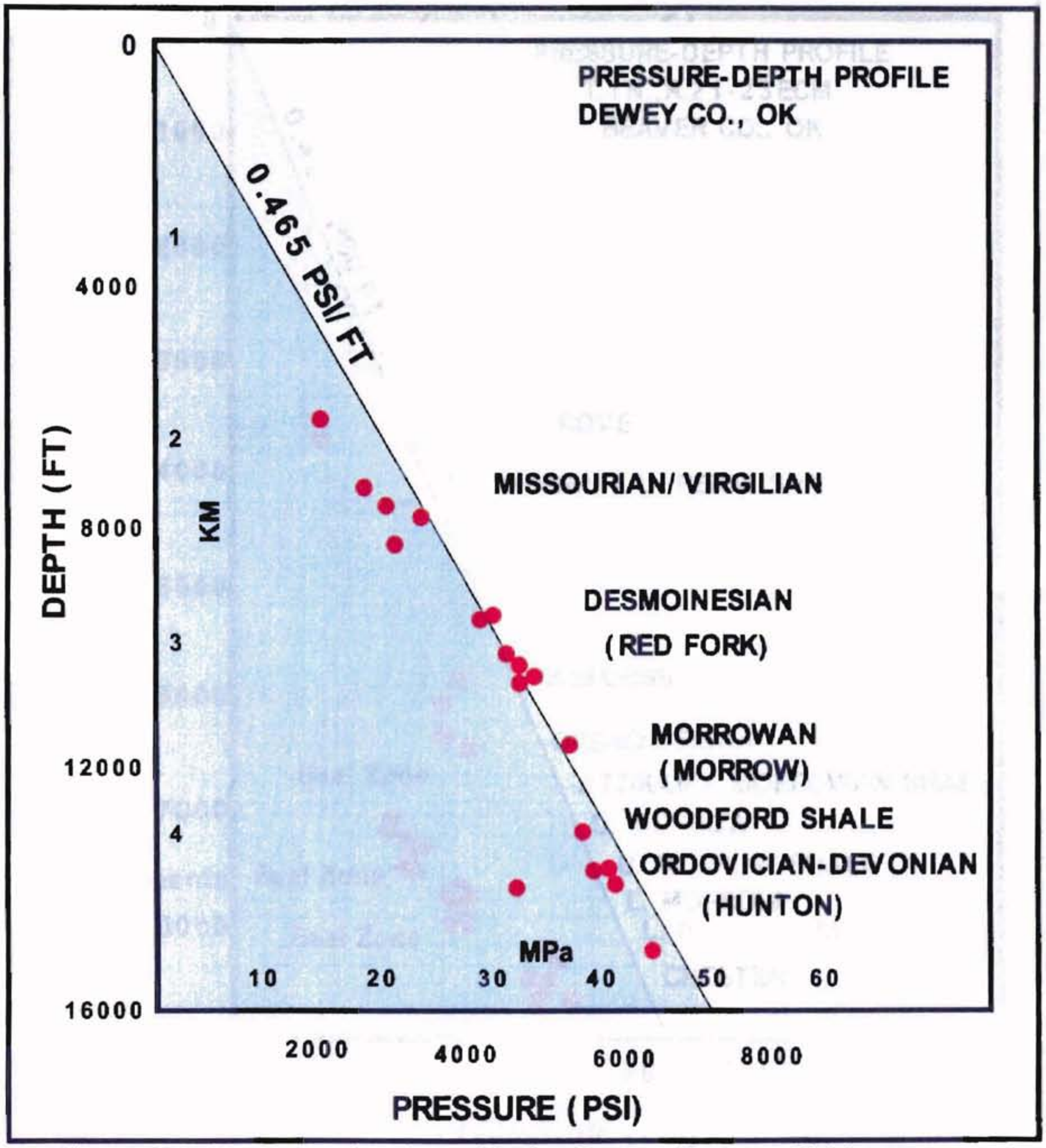


Figure 54. Pressure-depth profile for Dewey County, Oklahoma. (Al-Shaieb and Puckette, 2001)

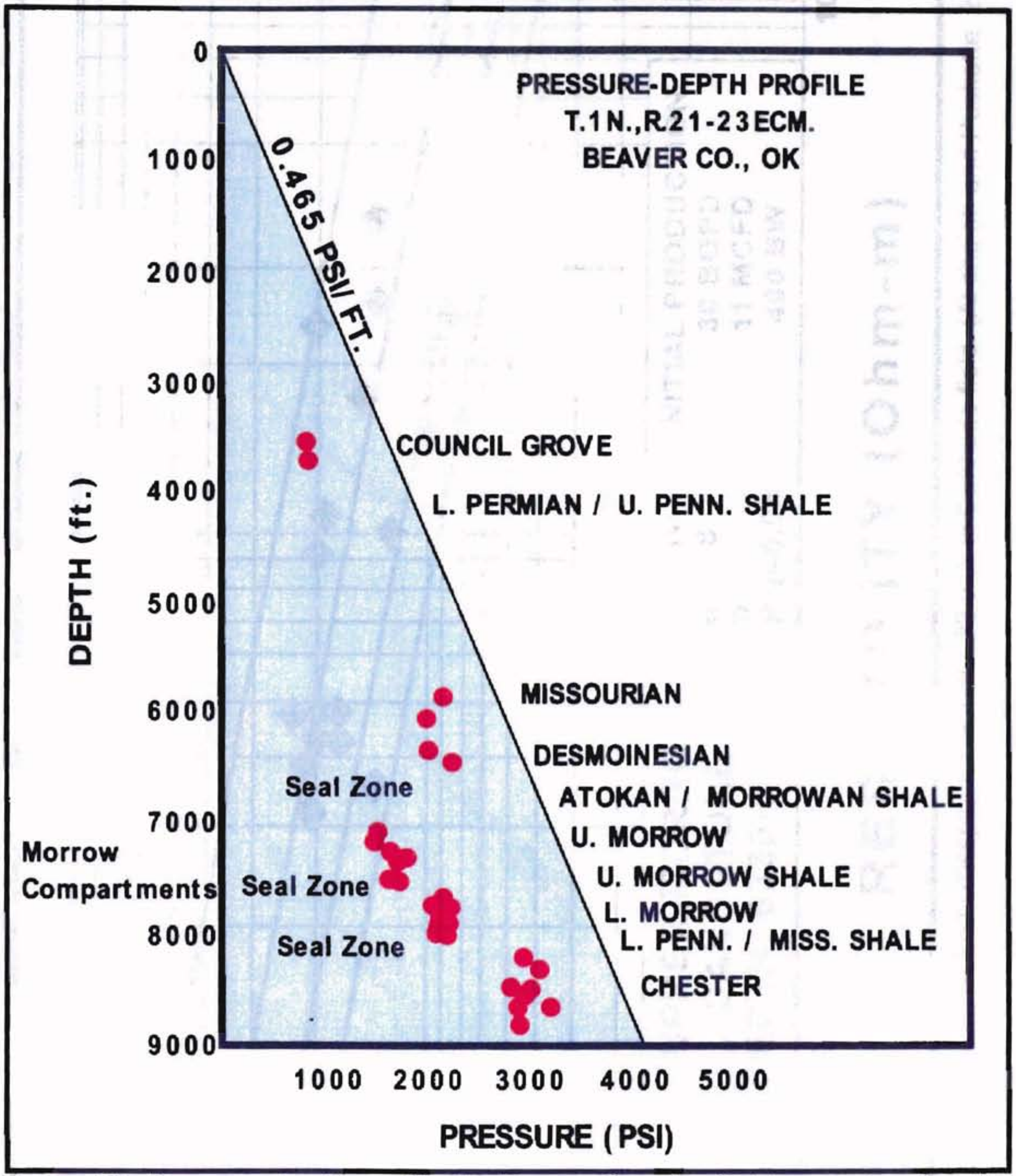


Figure 55. Pressure-depth profile for Beaver County, Oklahoma showing the compartmentalization for the Morrow intervals. (Al-Shaieb and Puckette, 2001)

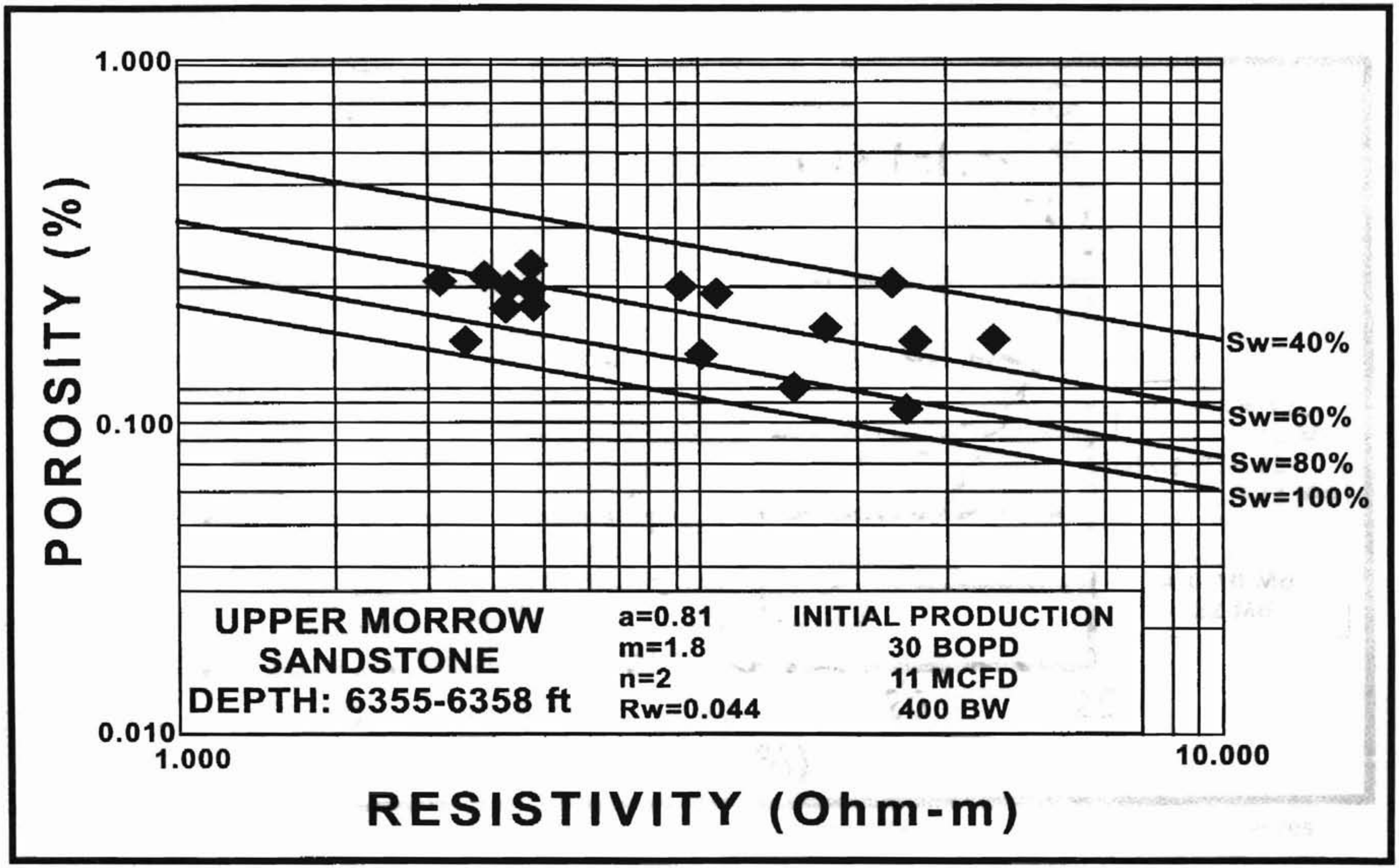


Figure 56. Pickett crossplot for Hendrix #3 well in Carthage field. (Al-shaieb and Puckette, 2001)

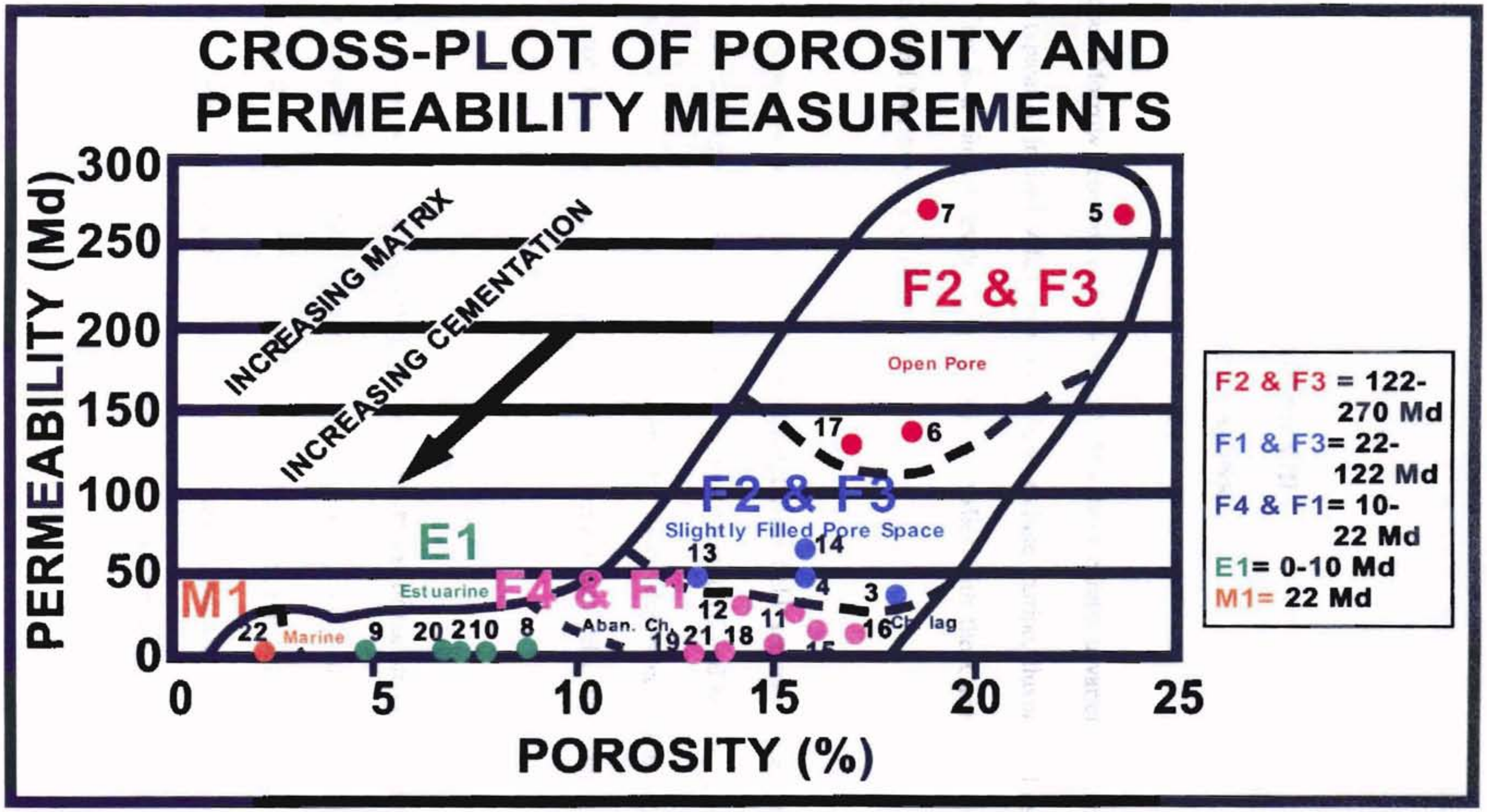


Figure 57. Porosity and permeability cross-plot showing the distinction between the four depositional sequences. (Al-Shaieb and Puckette, 2001)

CHAPTER VIII

CONCLUSIONS

1. The upper Morrow reservoirs in Southwest Rice field exhibit a variety of lithofacies that are typical of incised valley systems. These include marine, fluvial, and estuarine facies. This is a similar result of the previous studies with the Carthage, Northeast Hardesty, and Northwest Eva fields.

2. The upper Morrow sandstones in the Southwest Rice field are interpreted as being incised valley fill deposits. This consists of vertically restricted and laterally persistent non-marine sandstones, siltstones, and shales that were deposited within erosional channels that were incised into marine shales. These valley fills were deposited in response to fluctuating relative sea levels.

3. The source of the sandstones was from the west-northwest of the study area, being the mountain terrains of the Sierra Grande Arch, Apishapa Uplift, and Ancestral Front Range of the Rocky Mountains. From these locations, arkosic detritus was shed and flowed down slope toward and into the Anadarko Basin. Evidence for this is present in the QRF diagram from RMU #6 and RMU #13. Therefore, the channels trend Northwest to Southeast.

4. Using textural, structural, sedimentological, and depositional parameters, each major lithofacies is subdivided into several parasequences.

5. The depositional environment of the upper Morrow sandstone in the Southwest Rice field is a fluvial system that consists of paraconglomerate rocks, braided streams, point bar sequences including meandering streams, and abandoned channels.

6. The differences of facies distribution are a function of the change of regional structure during deposition of the sediment.

7. The incision of these channels occurred during sea level fall, which would be classified as a lowstand systems tract (LST) occurrence/phenomenon. Mostly clay clast conglomerates or paraconglomerates were deposited at this time.

8. The fill of the channels, which decreased the accommodation space, occurred during sea level transgression and thus deposition of the sandstone transpired during backstepping; the landward migration of the shoreline with rising sea level. This is known as the transgressive systems tract (TST) and is also in the time span of when the fluvial and estuarine lithofacies were deposited.

9. Petrographic, petrophysical, and core measured porosity and permeability data indicate that the braided stream and point bar fluvial facies represents the best quality reservoirs in the Southwest Rice field and thus would yield the highest potential for

bearing hydrocarbons from the upper Morrow sandstones. This is because the facies contain relatively high porosity and permeability.

10. Primary and secondary porosity occur in the sandstones of the Southwest Rice field. Primary porosity is reduced intergranular porosity due to the precipitation of diagenetic minerals. Secondary porosity developed as a result of partial or complete dissolution of feldspar and quartz.

11. The upper Morrow sandstone reservoir of Southwest Rice field consists of four stages of fluvial deposition. Erosional paraconglomerates deposited during a lowstand occurrence is followed by transgressive episodes of braided stream deposits with point bar sequences once again followed by abandoned channel lithofacies. These are deposited before estuarine lithofacies and finally marine shales are deposited.

12. Authigenic kaolinite and chlorite clay drastically affect porosity and permeability of various lithofacies by filling in void space that could potentially be utilized for hydrocarbon reserves.

13. The RMU #6 and RMU #13 cores from the Southwest Rice field are evidence of alternating transgressional events, or rises and falls of sea level. The well sorted sands, the abundance of secondary porosity, and the presence of clays suggest that this may be a good reservoir rock from which to produce hydrocarbons from.

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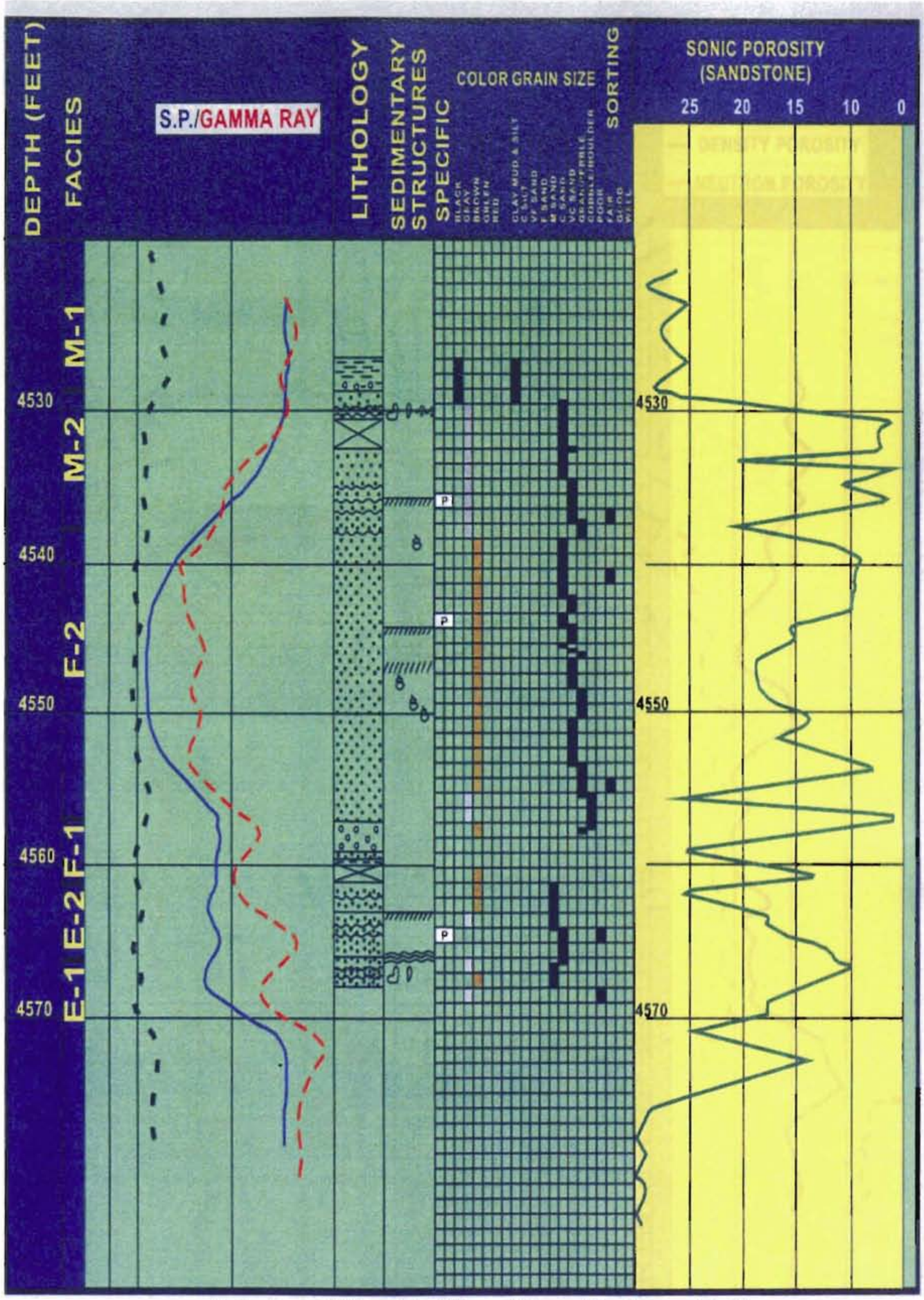
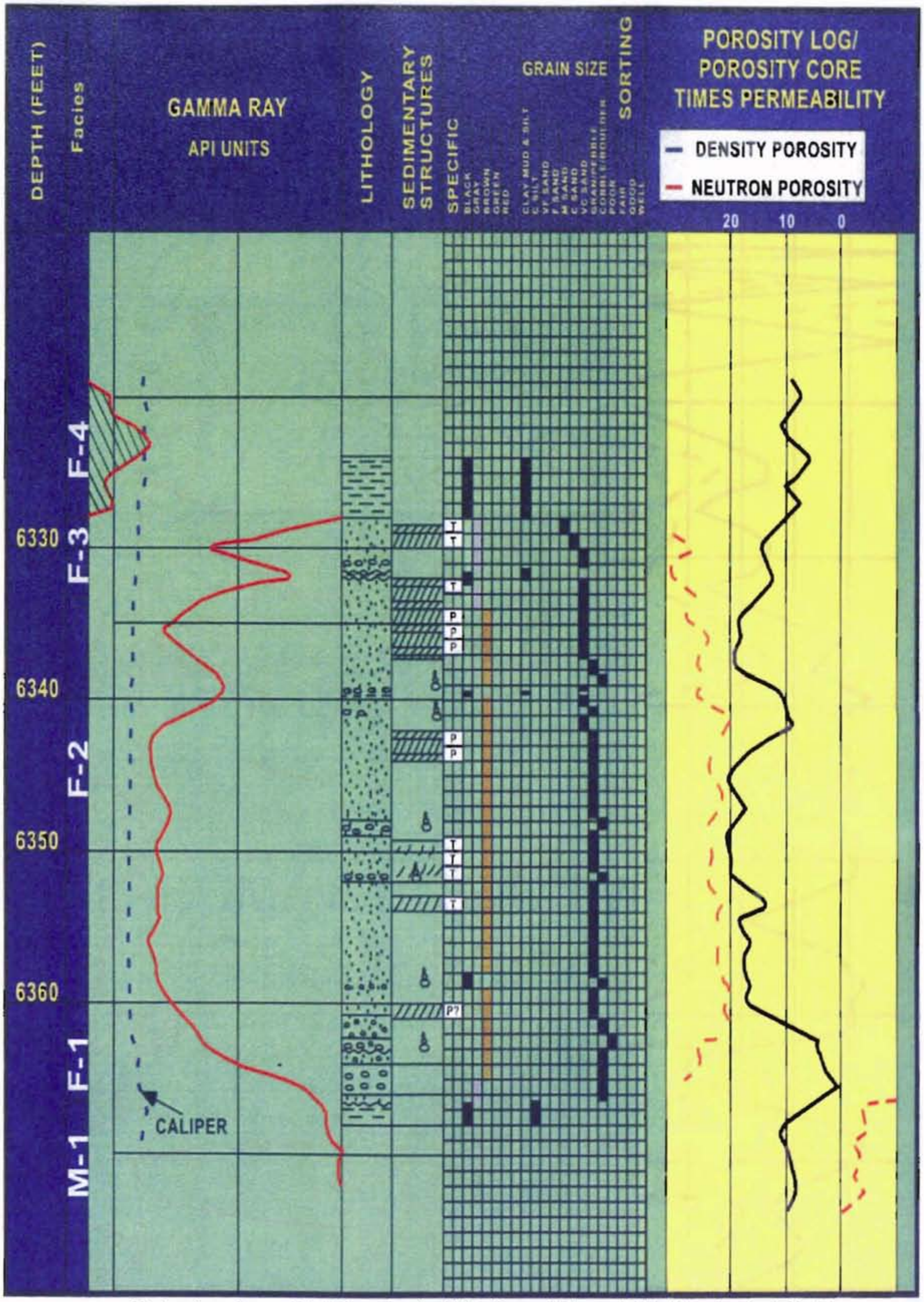
APPENDIX A

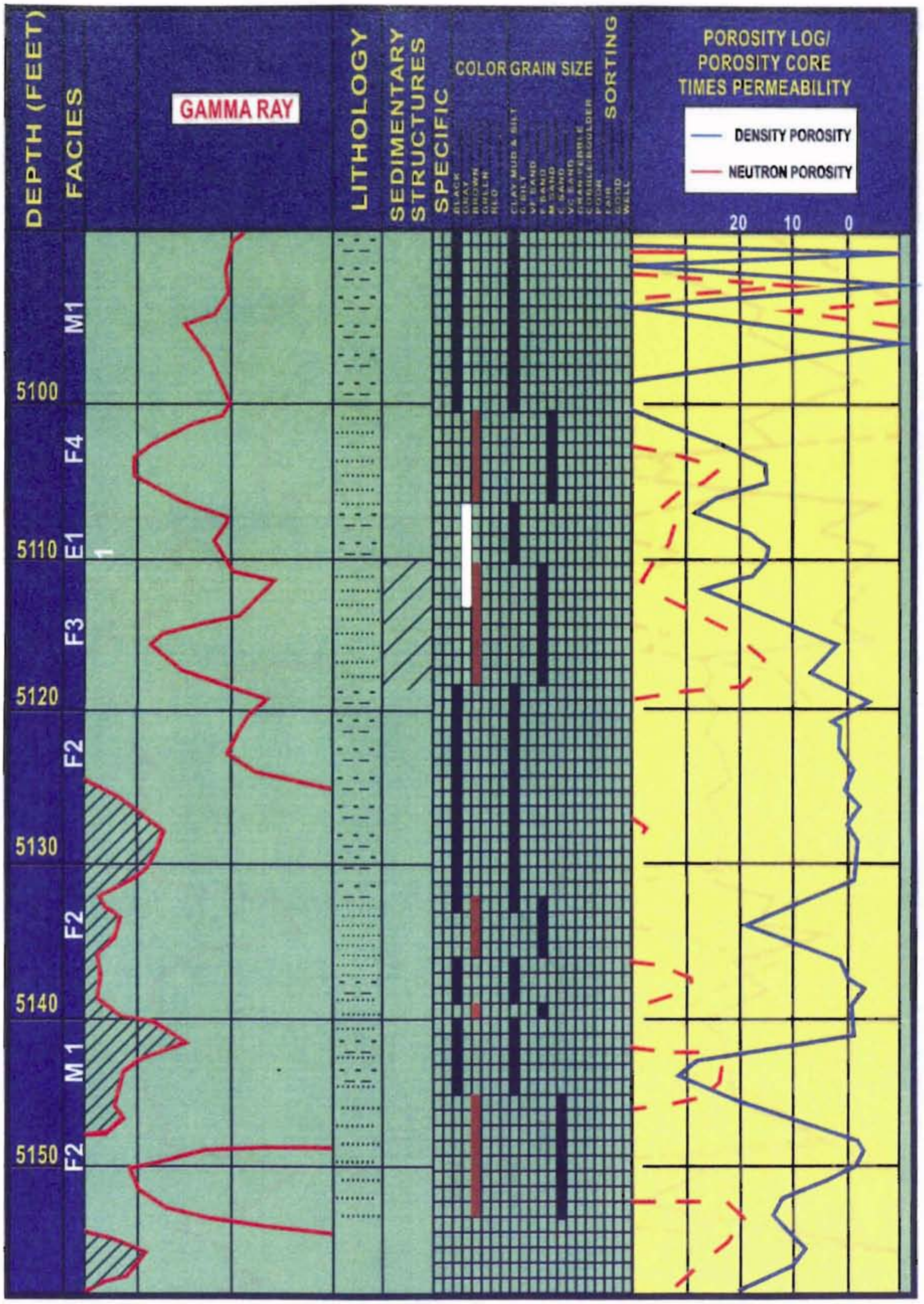
PETROLOGS OF STUDIED CORES



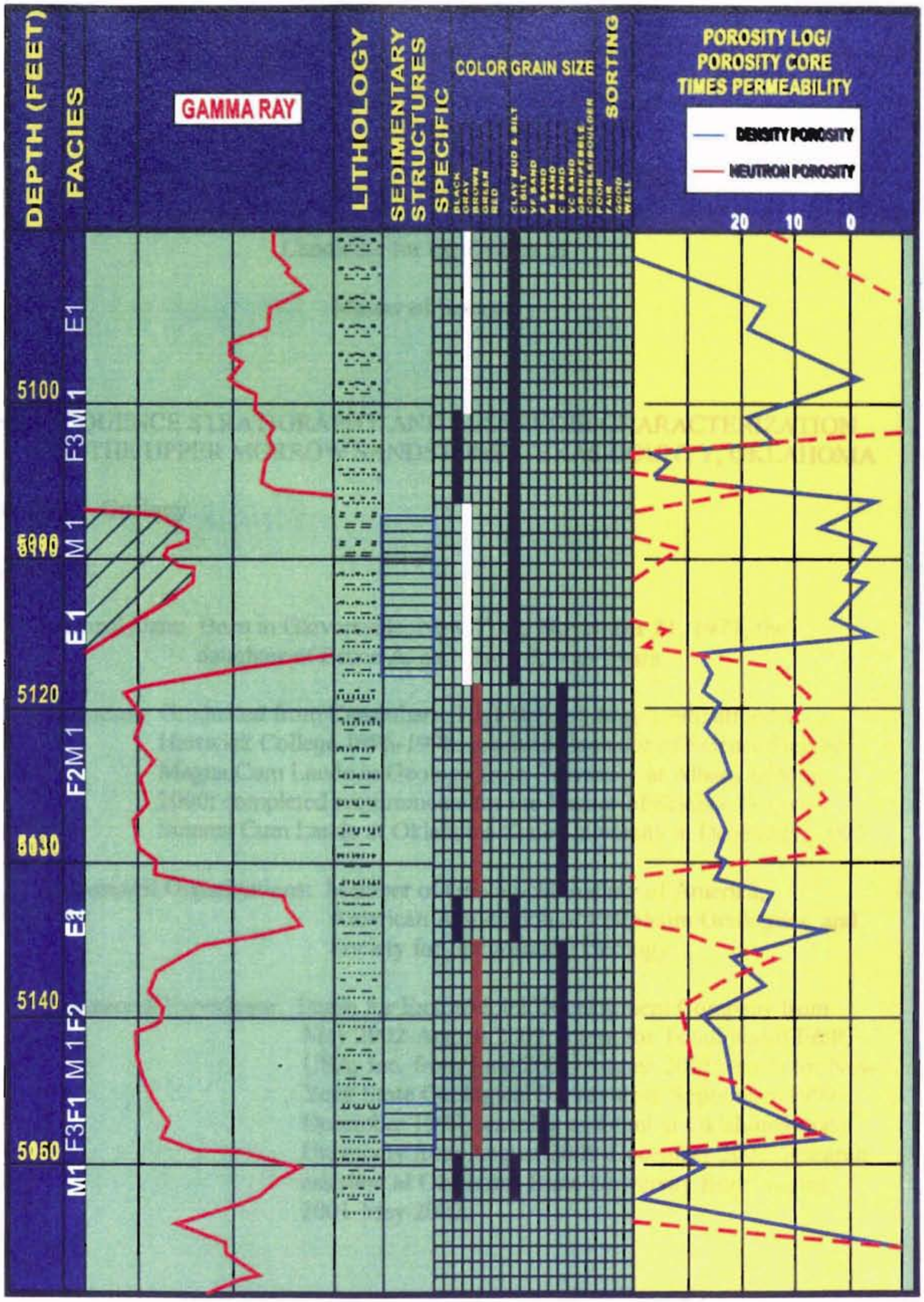
Petrolog of Hendrix #3 well from Carthage Field.
(Al-Shaieb and Puckette, 2001)



Petrolog from NE Hardesty #11-2 well from NE Hardesty Field.
(Al-Shaieb and Puckette, 2001)



Petrolog from RMU #6 well from SW Rice Field.



Petrolog from RMU #13 well from SW Rice Field.

VITA

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Erin E. Van Evera

Candidate for the Degree of

Master of Science

Thesis: SEQUENCE STRATIGRAPHY AND RESERVOIR CHARACTERIZATION OF THE UPPER MORROW SANDSTONE, TEXAS COUNTY, OKLAHOMA

Major Field: Geology

Biographical:

Personal Data: Born in Gloversville, New York, November 21, 1977, the daughter of Bruce A. and Carol P. Van Evera.

Education: Graduated from Canajoharie High School, May 1996; attended Hartwick College 1996-1998; received Bachelor of Science Degree Magna Cum Laude in Geology from University at Albany in May, 2000; completed requirements for the Master of Science Degree Summa Cum Laude at Oklahoma State University in December, 2002.

Professional Organizations: Member of Geological Society of America, American Association of Petroleum Geologists, and Society for Sedimentary Geology.

Professional Experience: Intern for ExxonMobil Development Company from May 2002-August 2002; intern for TotalFinaElf E&P, USA, Inc. from June 2001-August 2001; intern for New York State Geological Survey from September 1999-December 1999; teaching assistant at Oklahoma State University from August 2000-December 2002; research assistant at Oklahoma State University from August 2001-May 2002.