PETROLEUM GEOLOGY OF THE CROSS CUT AND MORAN SANDSTONES (LOWER MISSOURIAN), CALLAHAN AND EASTLAND COUNTIES, TEXAS

By

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CHAPTER I

ABSTRACT

In the study area in Callahan and Eastland Counties, Texas, the interval between the base of the Palo Pinto Limestone and the top of the Morris limestone (Pennsylvanian System, Lower Missourian Series, Upper Strawn Group) can be subdivided into three genetic units. They are, in ascending order (1) Lower Moran, (2) Upper Moran and (3) Cross Cut. These sandstones were deposited from east-southeast to west-northwest in a high constructive, elongate cratonic deltaic environment. Of the approximately five million barrels of oil produced from the Cross Cut and Moran in the study area, most came from the Upper Moran and to a lesser extent, the Cross Cut, whereas only a small number of wells produced from the Lower Moran. Depths of Cross Cut and Moran production range from 2100 feet to 2500 feet. Available cumulative production data indicate a rather consistent average of 30,000 barrels of oil per well.

The sandstones are very fine- to fine-grained sublitharenites. Much secondary porosity is developed where abundant sand-sized clay grains and to a minor extent

feldspar grains have been partially or totally dissolved through diagenesis. Numerous tiny patches of ankerite cement are scattered throughout the sandstone section in the cores. Pore-filling vermiform kaolinite is the only authigenic clay present in significant amounts. These sandstones, because of their well developed open pore systems with relatively little detrital matrix, authigenic clay or epitaxial cement, provide excellent petroleum reservoirs.

Sandstone geometry, log signature, outcrop and core sedimentology and thin section petrology indicate three facies; (1) distributary channel, (2) distributary mouth bar and (3) delta front. Strand zone development inferred from "hingelines" detected on structure, sandstone isolith, and total interval isochore maps provide further evidence for the delineation of the various facies and their relationships to one another. Production is obtained from all three facies. The Cross Cut and Moran fields in the study area are trapped by (1) stratigraphic termination of delta front sandstone lentils encased in shale, (2) up-dip pinch out of distributary channel complex sandstone or distributary channel sandstone against regional dip, or (3) compactional drape and/or up-dip pinch out of distributary channel sandstone related to underlying structure.

CHAPTER II

INTRODUCTION

Preface and Purpose

The Cross Cut and Moran sandstones are prolific hydrocarbon producers in western Stephens County, southeastern Shackleford County, Callahan County and the northern parts of Coleman and Runnels Counties of north-central Texas (Jones, 1983).

A northeast-southwest trend of production was established largely during the 1920's, 1950's and early 1960's. However, increased drilling activity during the early 1980's yielded discoveries of significant Cross Cut and Moran fields in northeastern Callahan County (Plate 17). Thus, the area to the east of the "fairway" of production appears to be prospective.

Only two short field studies comprise the entirety of pertinent published Cross Cut and Moran research and the efforts of most industry workers have been limited to isolated mapping over fields and prospects. Exploration efforts are further hindered by the facts that multiple sandstone bodies occupy the interval and that there is a marked diversity of trapping mechanisms and producing sandstones among Cross Cut and Moran fields.

The purposes of this study are to gain an understanding of the depositional setting, facies relationships and hydrocarbon habitat of the existing Cross Cut and Moran fields in northeastern Callahan County, Texas and to illustrate facies models which are applicable to Cross Cut and Moran petroleum exploration.

Study Area and Interval

The study area is located in north-central Texas and covers approximately 160 square miles in northeastern Callahan County and northwestern Eastland County (Figure 1). It extends from the Shackleford-Stephens/Callahan-Eastland County line south approximately 10 miles to the town of Putnam, Texas. From the Callahan/Eastland County line it extends west approximately 12 miles to Herr-King Field and east approximately 4 miles to the town of Rufus in Eastland County. Actually, the area corresponds to the "grid" system used by Perini Library in Abilene, Texas, specifically grids 5, 6, 7, 8, 9 and 10 in Callahan County and grids 1 and 9 in Eastland County (Plate 17). This area is located within the mature Bend Arch structural province which extends across a broad area of north-central Texas (Figure 2).

The interval studied is bounded at its top by the base of the Palo Pinto Formation and at its base by the top of the "Morris" limestone (Figure 3). Total interval thickness ranges from less than 140 feet to over 200 feet and

Figure 1. Location of the Study Area.

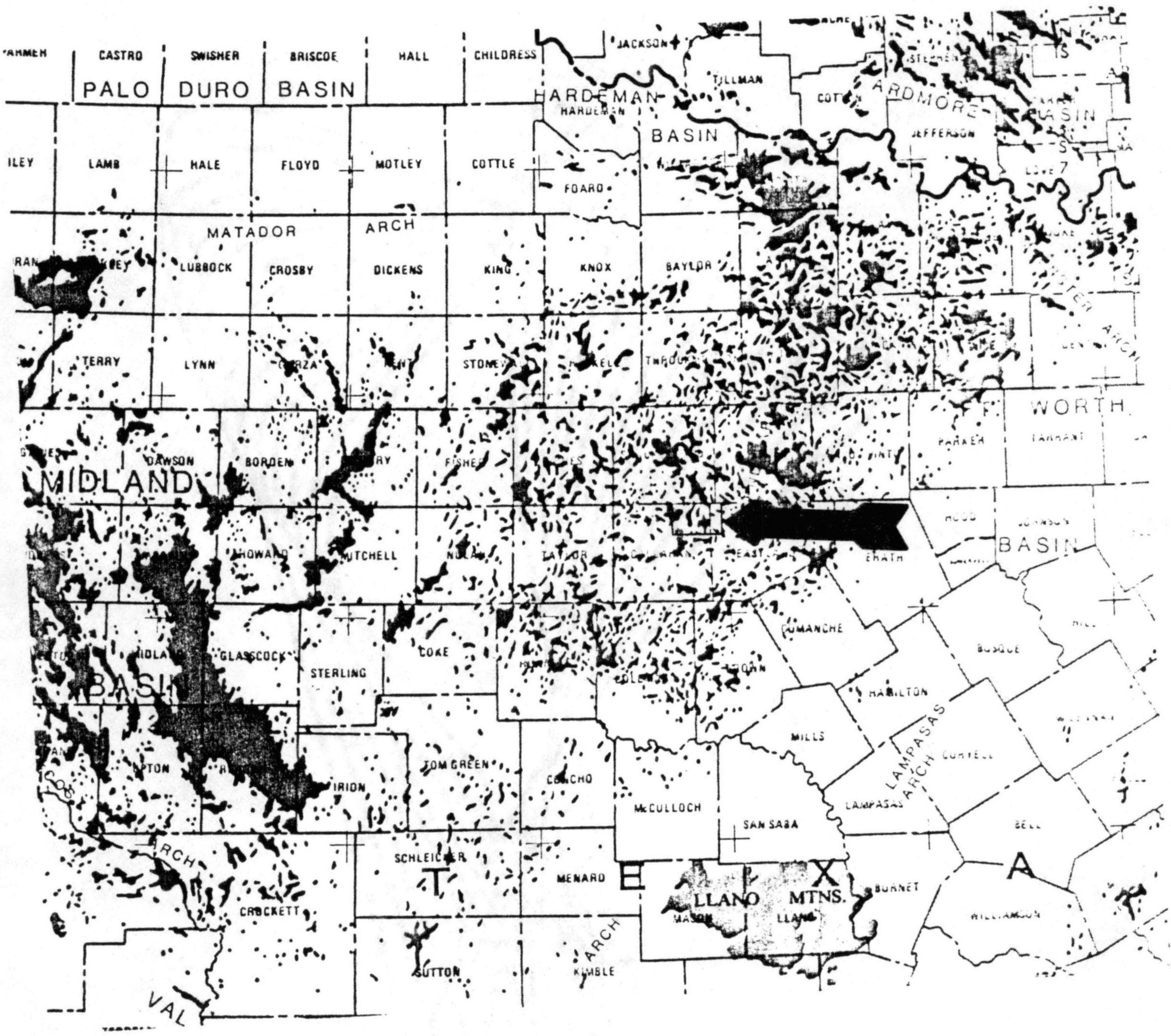

Figure 2. Location of the Study Area Within the North-Central Texas Producing Trend (modified from Terra Graphics, 1976).

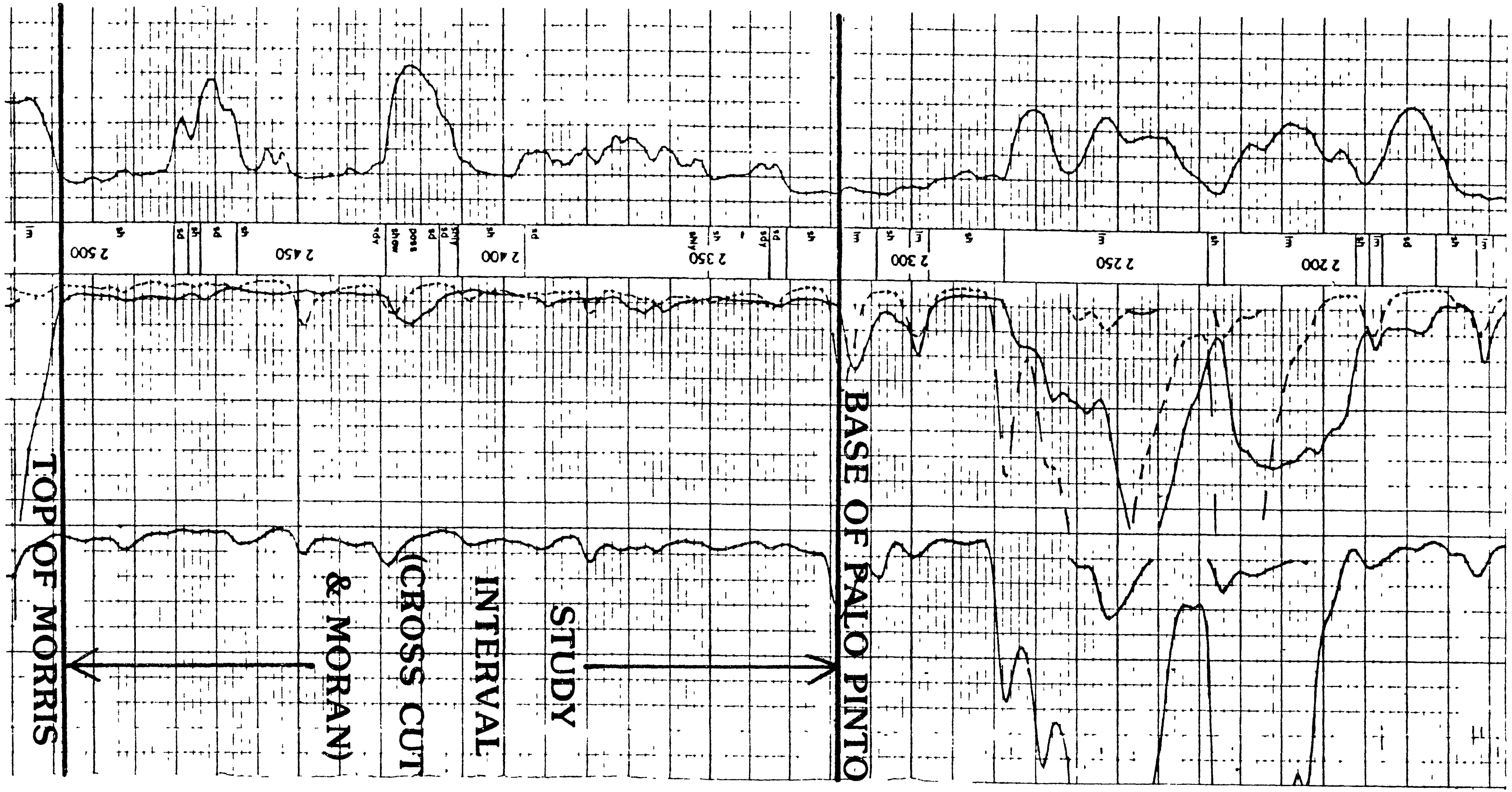

Figure 3. Type Log of the Study Interval. (S. C. Herring, Morris Snyder et al #3-C, 330' FSL & 990' FEL of Section 3, T&NO Survey, Callahan County, Texas, see Plates 1 and 3).

depths to the base of the interval range from approximately 1800 feet to 2700 feet.

Research Objectives and Methods

Four general objectives comprise the approach taken for this study. The first objective of the study was to correlate the section across the entire study area. Then the section was subdivided into genetic units for the purpose of separating the specific producing sandstone bodies. These were accomplished by means of electric log cross sections (Plates 1 through 5). Vertical sequences seen in the cores were also used in the genetic unit boundary determinations.

Second, analysis of available Cross Cut and Moran core and outcrop was performed on two scales. They were first examined macroscopically for sedimentological purposes. Gross vertical textural sequences and sedimentary structures served as depositional environment indicators, while hand specimen analyses (aided by 10x hand lens and binocular microscope) provided textural and compositional information (Plates 11 through 16). Then, thin sections were prepared from selected core samples. Detailed petrographic analysis (including staining for carbonate species determination) was performed using a high-powered polarizing microscope. The thin section study, aided by x-ray diffraction analysis, scanning electron microscopy and energy dispersive analysis, yielded information on texture, composition, diagenesis and porosity of the producing reservoir units.

Third, certain characteristics of the study interval and the important facies of the genetic units were mapped. A producing formations map (Plate 17) delineates the Cross Cut and Moran fields and provides discovery date and cumulative production data for each (Petroleum Information Inc., 1989). Structure at the top of the interval (base of Palo Pinto Limestone) was mapped (Plate 18) to depict present regional structure and to reveal any structural control on deposition or entrapment. A total interval isochore map (Plate 19) was prepared to show the direction of paleodip and to aid in sandstone trend interpretation. The trend, thickness and geometry of the producing sandstone body for each genetic unit are shown on the sandstone isolith maps (Plates 20, 21 and 22).

Fourth, each Cross Cut or Moran producing field was evaluated in terms of the facies of the productive unit and mode of hydrocarbon entrapment. Fields of each interval/type are depicted by means of specialized electric log cross sections (Plates 23 through 29) prepared in the light of the production, structure, isochore, isolith and core information.

Previous Works

Herr-King Field, the largest and most significant Cross Cut and Moran field in the study area, is the subject of two published works. Fraser (1956) provides information on the discovery and production history of the field. He includes several maps and cross sections which demonstrate the existence of a complex of several fields producing from the different sandstone units. The paper also contains brief discussions of the stratigraphy and reservoir geology of the field. Detailed cumulative production figures are given for each of the various fields, but the work was published only two years into the long life of Herr-King Field. Another synopsis of Herr-King Field production and completion data was done later in the life of the field and serves as a useful update and summary (Rainer, 1976).

Jones (1983) authored a study of the Callahan County Regular Field, a Moran field in the study area just north of the town of Putnam. This work provides detailed presentations of the field's discovery, completion practices, reservoir properties and cumulative production. He gives an interesting account of the origin of the Cross Cut and Moran play and the development of the terminology used throughout the several counties in which it produces. Also included are discussions on the use of seismic and dipmeter logging in the analysis of this Moran field.

These field studies provide useful historical, reservoir and production data for the specific fields, but contain only brief discussions of local geological settings of the Cross Cut and Moran. Although no other previous publications exist which deal specifically with the petroleum geology of the Cross Cut and Moran in the study area, there are numerous publications which mention the equivalent beds in their treatment of broader subjects. The surface exposures of the Cross Cut and Moran equivalents in Palo Pinto County, Texas have been discussed in numerous University of Texas publications.

Plummer and Moore (1921) named the Mineral Wells Formation which contains the surface equivalents of the Cross Cut and Moran. They applied the name Turkey Creek Sandstone to the specific sandstone beds within the Mineral Wells Formation which correlate to the Cross Cut and Moran. Bay (1932) described the cross-bedded conglomerate lentils in the upper part of the Mineral Wells Formation. Regional facies aspects of these beds are presented in Sellards, et al. (1932). In their 1935 University of Texas Bulletin, Plummer and Hornberger provide abundant paleontological information including an extensive list of good fossil localities. Hendricks (1957) gives the most complete accounting of the evolution of the stratigraphic nomenclature used for the Cross Cut and Moran surface equivalents.

Cheney applies information from both the surface and the subsurface to stratigraphic analysis of the study interval in his 1929 paper and again in his 1940 paper. Extensive geologic and tectonic histories of all of central and north-central Texas complete with regional isopach maps of all the geologic systems were presented by Cheney and Goss (1952). Cleaves (1982) and Sellards, et al. (1932)

also provide much good background information regarding regional tectonic and depositional histories.

Cleaves (1975) divided the upper half of the Strawn Group into eight genetic units and produced structure, isochore and isolith maps for each across a 23 county area of north-central Texas. The Turkey Creek Sandstone was the uppermost of these. His maps cover the entire extent of the depositional limits and therefore are extremely useful in determining paleodip direction, source direction, and general geometry of the overall depositional system. Detailed descriptions of Cross Cut (Turkey Creek) and Moran (ss2 or Devil's Hollow) outcrops were recorded by Cleaves (1975) and can be found using the location map in Cleaves' and Erxleben's 1982 guidebook.

CHAPTER III

TECTONIC AND STRUCTURAL SETTING

Introduction

The study area is located on the Eastern Shelf of the Midland Basin, also referred to as the Concho Platform (Figure 4). The Eastern Shelf is bounded on the west by the Midland Basin and on the east by the Bend Arch. The study area is situated on the upper western flank of the Bend Arch (Figure 5). The shelf is bounded on the north by the Red River Arch and on the south by the Llano Uplift. Aside from the farthest reaching deposits of the Cretaceous onlap, the sedimentary section present in the study area is entirely Paleozoic (Figure 6).

The Paleozoic Marathon-Ouachita Orogeny dominated the tectonic history of all of central Texas and thus, it was responsible for the stratigraphic and structural development of the study area. Sedimentation during the Paleozoic Era on a regional scale is marked by major changes in depositional setting (Figure 7). Local facies changes, changes in thickness due to subsidence or progressive uplift, and changes in source area and depositional slope were also numerous and important. Major regional unconformities which occur across the area record the loss of great thick

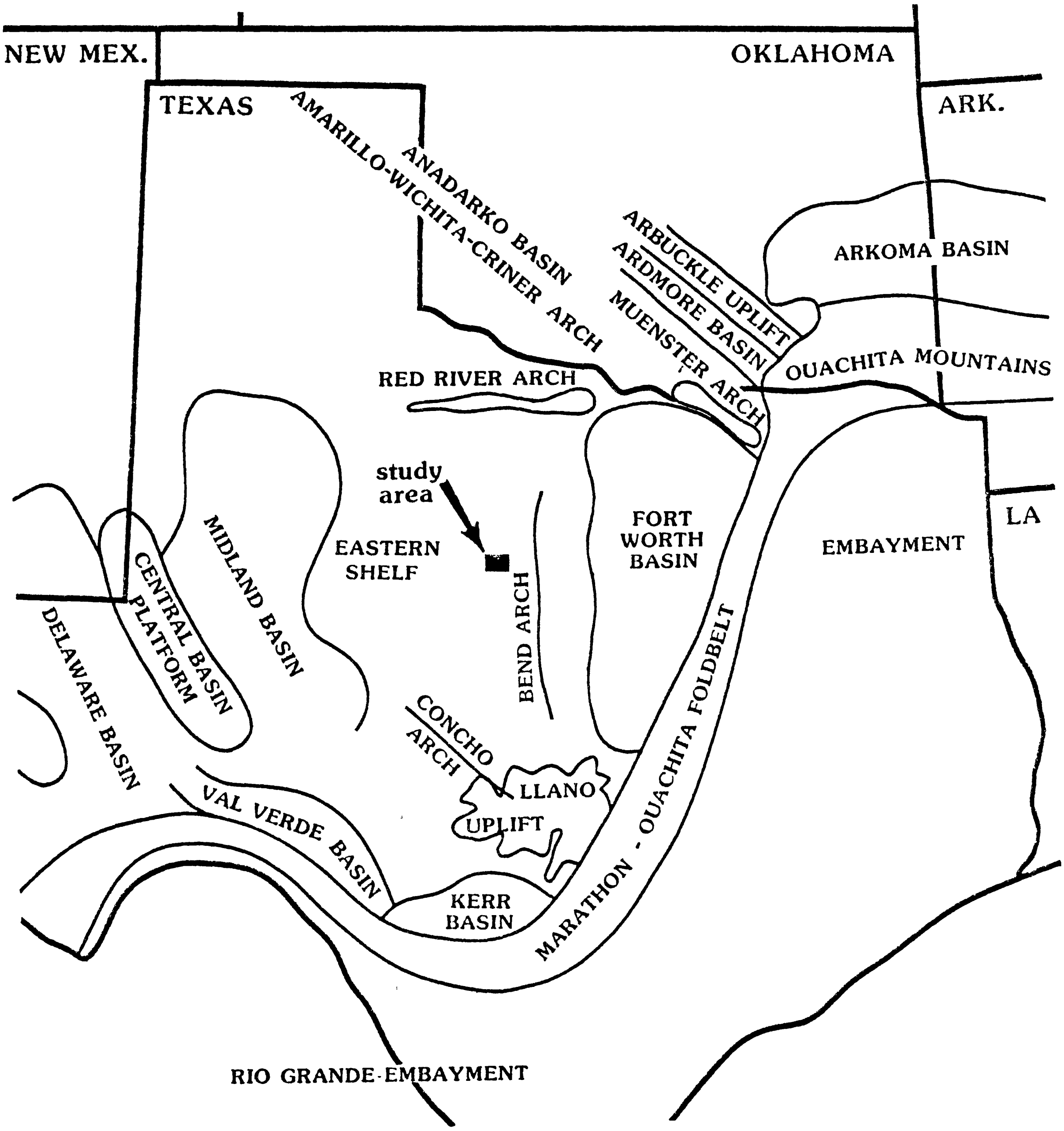

Figure 4. Location of the Study Area Within the Missourian Epoch Tectonic Framework (modified after Walper, 1982).

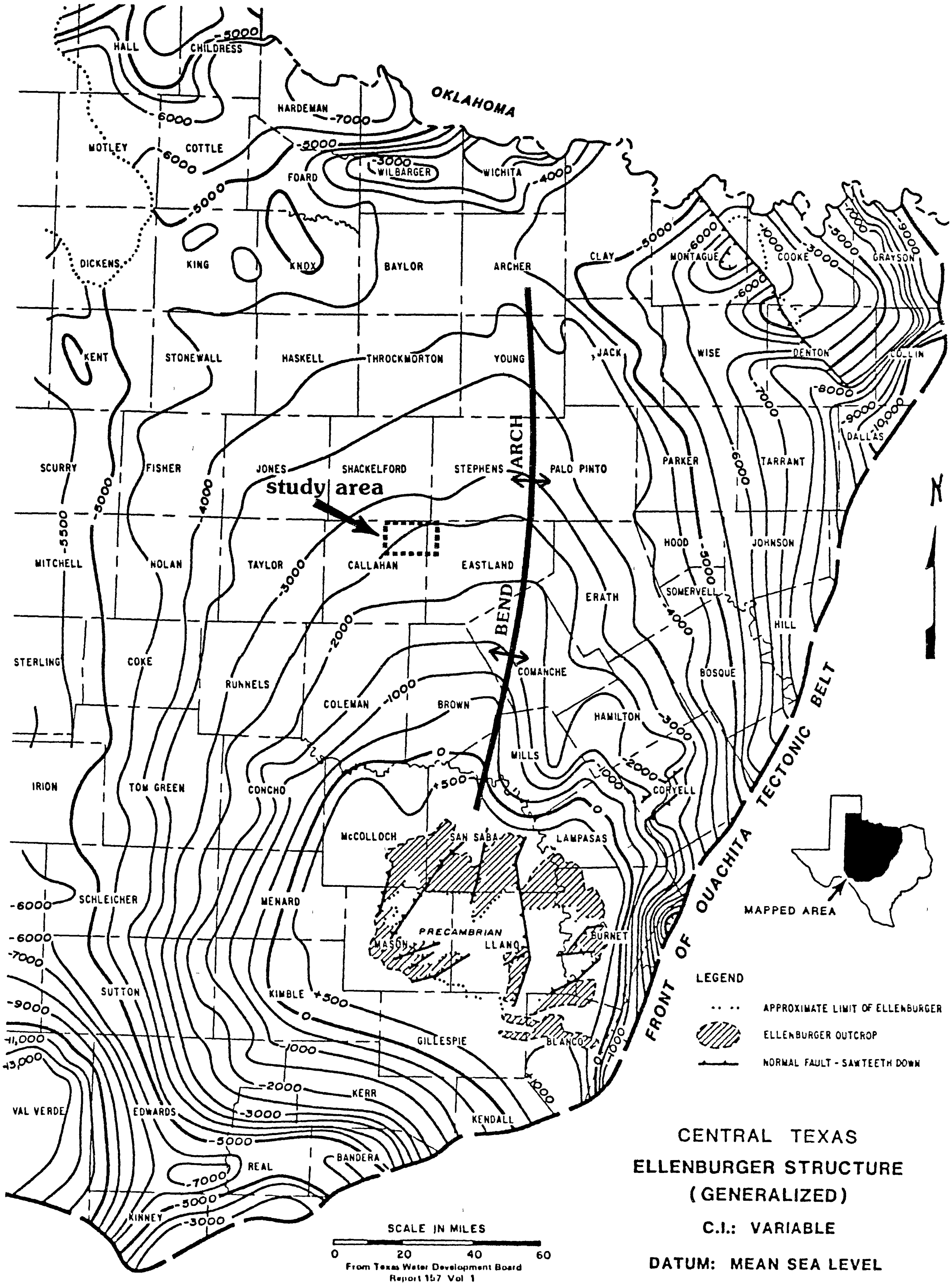

Figure 5. Location of the Study Area Relative to the Bend Arch (modified from Martin, 1982).

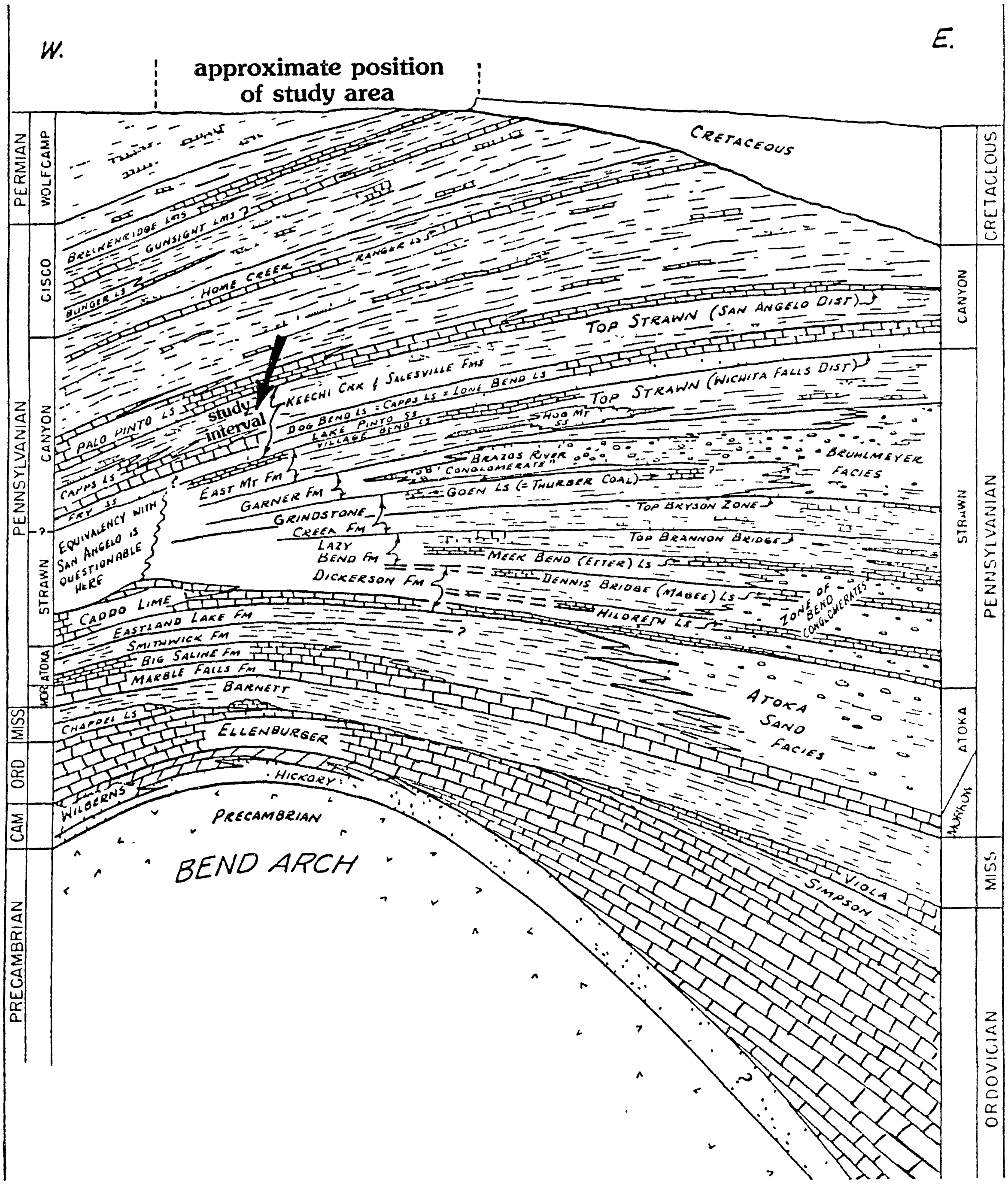

Figure 6. Composite Stratigraphic Basin, Bend Arch-Fort Worth Basin (modified from Gatewood, 1976).

TIME SCALE (Ma)	ASSOCIATED DEPOSITS IN STUDY AREA	TECTONIC HISTORY OF OUACHITA-MARATHON OROGEN
PENNSYLVANIAN (300)	molasse	final stages of cordilleran-type orogeny; subduction ceases
MISSISSIPPIAN	distal flysch	climax of orogeny; sediments derived from eroding "orogenic welt"
DEVONIAN (350–400)	non-deposition and/or erosion	continued development of subduction zone
SILURIAN		
ORDOVICIAN (450–500)	platform	development of Atlantic-type margin followed by initiation of subduction
CAMBRIAN		

Figure 7. Tectonic History of the Ouachita-Marathon Orogen and Associated Deposits in the Study Area (modified after Keller and Cebull, 1973).

nesses of section or extended periods of non-deposition.

Much new study, technology, and information has arisen in the decades since 1931 when W.A.J.M. van Waterschoot van der Gracht attributed the northward emplacement of the Ouachita rocks and the development of both the Ouachita and Wichita mountain systems to "general geotic creep (relatively) to the north." Now that plate tectonics concept is used to explain such orogenic activity, it is possible to explain regional and local events in terms of their global tectonic controls. What follows is a discussion, in chronological order, of any tectonic effects on the study area.

Regional Tectonic and Geologic History

Cambrian

There is no direct evidence in this area of the rifting which occurred in early Cambrian time. Any volcanics extruded into the rift may not have been very extensive and would probably have been destroyed during later subduction and/or collision or buried in the Gulf of Mexico (Keller and Cebull, 1973). Furthermore, the type of volcanism generally associated with rifting is not the type which produces great amounts of pyroclastic material that could have made its way far inland where it could have been preserved in the early Cambrian sedimentary section. Walper (1982) cited the nearby Reelfoot, Delaware, and Wichita aulacogens, as well as other aulacogens along the eastern margin of North America and evidence to attest to this rifting.

As the newly formed Iapetus Ocean opened, the trailing continental margin cooled and subsided. Cambrian sandstones, limestones and dolomites were deposited on the platform of a northeast trending seaway. This section thickens from 500 feet on the platform to 1500 feet (Cheney and Goss, 1952), in the direction of the incipient Marathon-Ouachita "geosyncline."

Ordovician

Thinning and eventual erosion of Upper Cambrian and Lower Ordovician beds over the Concho Arch indicate that the arch began undergoing uplift during the pre-Ordovician (Cheney, 1940). The Concho Arch is a very large structure which includes the Llano Uplift and a northwest trending arch axis which extends well up into north-central Texas. This uplift may be part of the cratonic unrest which Walper (1982) attributed to the initiation of subduction of the southern plate beneath North America. North-central Texas began broad uplift which caused the Ordovician System to be thinned and eventually exposed and eroded (Figure 5). The more concentrated uplift of the Concho Arch could have been in response to compressive stresses and/or intrusion related to subduction.

Silurian-Devonian

Widespread Mid-Paleozoic cratonic uplift resulted in non-deposition or thinning and eventual erosion of almost all of the Silurian and Devonian Systems (Walper, 1982). Mississippian and younger rocks rest unconformably on Ordovician rocks in most areas (Cheney, 1940) (Figure 5). Sellards, et al. (1932) reported that no Silurian beds are found in the Llano region, but speculated that the shallow sea which existed across southern Oklahoma at the time probably extended across Texas as well. Deposition of Devonian rocks was restricted to the incipient Marathon-Ouachita trough, but again, due to cratonic uplift and erosion there is no record of its landward extent (Sellards, et al., 1932). The recurrent, mild regional subsidence and uplift indicated by isolated outcrops of Devonian rocks (Cheney and Goss, 1952) was a phase of increasing cratonic unrest which began in Ordovician time with the initiation of subduction.

Mississippian

Tectonic activity on the craton and within the orogenic belt increased further during the final stages of closing of the Iapetus Ocean. The geosynclinal trough which first formed in Devonian time developed into the deeply subsiding Marathon-Ouachita basin across northeastern Texas (Burgess, 1976). At the same time an uplift, or orogenic welt (Keller and Cebull, 1973) formed and served as a source for the extensive Stanley and Jackfork deposits of southern Oklahoma. These rocks represent the first flysch deposition. The study area, being far removed from this trough, was the site of Chappel Limestone and Barnett Shale deposition. Subsidence associated with the development of this geosynclinal trough caused epeirogenic uplift on the Texas Craton (Cheney and Goss, 1952). The Red River and Wichita Uplifts also developed during this time. Basins adjacent to these uplifts received sediment, as is indicated by thickening of Mississippian beds on either side of the Red River Uplift and the Wichita Uplift (Cheney, 1940). Development of the Bend "flexure" began when Late Mississippian subsidence in the foreland Fort Worth Basin gave rise to an eastward-dipping monocline along the eastern margin of the Concho Platform (Cheney, 1940). However, an eastward loss of Chappel Limestone in this region indicates that this event was interrupted by another brief episode of westward tilting, probably caused by a pulse of uplift in the foldbelt.

Pennsylvanian

A period of local folding began in pre-Atokan time and persisted through Permian time. The east-west and northeast-southwest-trending folds which resulted were an important factor in the trapping of oil in the Pennsylvanian sandstones (Cheney, 1940). The Morrow Series in north-central Texas is generally thin across the Concho Platform, while extensive deposits of these rocks accumulated in the still rapidly subsiding Fort Worth Basin adjacent to the orogenic uplift. This thinning was due to regional uplift of the area, as well as to localized uplift of the Concho and Red River arches. These arches later experienced pre-Strawn uplift, which caused the Morrow to be absent over them. The elevation of the Red River Uplift prevented detritus from the Wichita Mountains from being deposited across the study area.

Denison, et al. (1969), noted large boulders deposited with the Atokan Haymond Formation in the Marathon Trough. They concluded that the maximum elevation of the orogenic uplift over the base of the trough occurred at this time. Keller and Cebull (1973) marked this point as the climax of the orogeny. Cheney and Goss (1952) cited these boulders as evidence for early movements of the Ouachita Mountain System. The orogenic uplift had reached sufficient prominence to deposit molasse across the platform. Throughout the remainder of Pennsylvanian time, alternating sequences of conglomerate, sandstone, shale and limestone were deposited across the study area (Cheney, 1929) (see Figure 6).

Two episodes of widespread submergence during Atokan time resulted in onlapping of beds (Cheney, 1940). Northeast-trending folding and faulting in Early Atokan time were associated with the foreland arching of the Upper Wichita Orogeny (van der Gracht, 1931). Local vertical movements in excess of 1000 feet that occurred during post-Smithwick, pre-Strawn time resulted in very discordant dips between these two Series. Cheney and Goss (1952), stated that the deposition of "Lampasas" (Atokan) beds occurred before thrusting in the Ouachitas. Arching and erosion of the pre-Strawn over the Bend Arch occurred, but diminishes north of Brown County, where the arch becomes a flexure (Cheney and Goss, 1952). Based upon facies distribution, Sellards, et al. (1932) concluded that the Strawn and Canyon depositional systems had north-south oriented shore-lines which migrated westward with time. This movement of the shoreline was due in part to simple progradation but was also contributed to by uplift in the east.

The most profound structural changes since pre-Cambrian time occurred between Atokan and Missourian time. The Concho Arch experienced its greatest amount of differential elevation then. It stood 10,000 feet above the base of the flanking basin. Active subsidence of the Fort Worth Basin ceased in Early Desmoinesian. Chert-rich Strawn molasse sediments were shed off of the uplifted Ouachita Foldbelt and prograded across the filled Fort Worth Basin. Because of the stable, featureless nature of the Concho Platform, the earliest deltas were thin and multilateral and prograded farthest westward. The Arbuckle and Wichita Uplifts were supplying arkosic detritus to northernmost-central Texas. Post-orogenic uplift of the Ouachita Fold-belt elevated the east flank of the Fort Worth Basin. The gradual westward tilting which resulted produced the west dipping limb of the Bend Flexure.

Cheney (1940) showed the overlap of Middle Canyon beds onto the Concho Arch. The absence of thinning for younger beds over this structure indicates that it stopped growing during Canyon time. Vertical accretion of a Palo Pinto-Winchell Carbonate Bank indicates that a distinct hingeline was developing between the Midland Basin and the Concho Platform. This accelerated subsidence completed the structural closure that defines the present Bend Arch (Cleaves, 1982).

The Arbuckle-Wichita-Amarillo Mountains grew and shed detritus during Virgilian time (Cisco Group). Marathon-Ouachita-Arbuckle orogenic uplift tilted late Missourian (Canyon) deposits westward. This is evidenced by westward thickening Cisco and Permian beds overlying eastward thickening Upper Canyon deposits. This elevation of the eastern platform to a level three miles above the base of the Permian Basin caused the removal of a wedge of Canyon and older beds (up to 5000 feet thick in the east) and the deposition of two miles of sediment in the Permian Basin. Erosion also occurred over the Llano Uplift (Cheney, 1940).

The Pennsylvanian System of north-central Texas was deposited under conditions which were rapidly changing in response to the increased tectonic activity during the final stages of the orogeny. Early Pennsylvanian crustal unrest was caused by increased subduction effects. These effects were in the form of the Wichita Orogeny and pronounced local and regional uplifts. Episodes of local folding and faulting and the initiation of flysch deposition into a geosynclinal trough resulted as well. Collision of the continents during Middle Pennsylvanian caused intense folding, thrusting, and uplift of the Ouachita Orogen and the initiation of molasse deposition across the study area. Late Pennsylvanian time was characterized by crustal relaxation. Foreland basin subsidence, orogenic uplift, flysch deposition, and pronounced crustal unrest largely diminished during this time. Crustal adjustment of the platform and adjacent basins modified continued molasse deposition, as did the effects of Wichita-Amarillo and Marathon-Ouachita-Arbuckle Orogenies (Burgess, 1976; Cheney, 1940; Cheney and Goss, 1952).

Permian

Progressive uplift of the Arbuckle Mountains during Virgilian time resulted in the removal of three miles of sedimentary cover and the dispersal of large amounts of granitic detritus during Wolfcampian deposition (Cheney, 1940). No Permian rocks were deposited over the crest of the Bend Arch. The Ouachita Mountains continued to rise, tilting the platform further to the west (Cheney and Goss, 1952).

Local Structure

The structure on the base of the Palo Pinto Formation is shown on Plate 18. This horizon represents the top of the study interval. Present regional dip is to the west-northwest (290 degrees azimuth) at a rate of 50 feet per mile. The direction of dip at the time of deposition (paleodip) can be inferred from the strike of the Palo Pinto Carbonate Bank and the orientation of the regional sandstone trend (Figure 8). The trend shown on the total interval isochore of the study interval (Plate 19) can also be used. It appears from these two maps that the direction of paleodip was to the north-northwest (320 degrees azimuth). Therefore it can be seen that a 30 degree component of western dip has been added to paleodip to give the resultant present structural dip. This westward tilting occurred as a result of continued uplift of the Ouachita-Arbuckle Orogen during late Pennsylvanian and early Permian time (Cheney, 1940).

Aside from some possible growth faulting, no major faulting of the study interval exists in the study area. The mapped surface is folded mildly but not systematically. There are, however, numerous small structural domes situated throughout the study area. These structures vary in size from about 100 acres to over a square mile and contain 20 to 40 feet of structural closure. Most are probably the result of compactional drape over Chappel (Mississippian) or Caddo (Strawn) pinnacle reefs or banks. Carbonate acre-

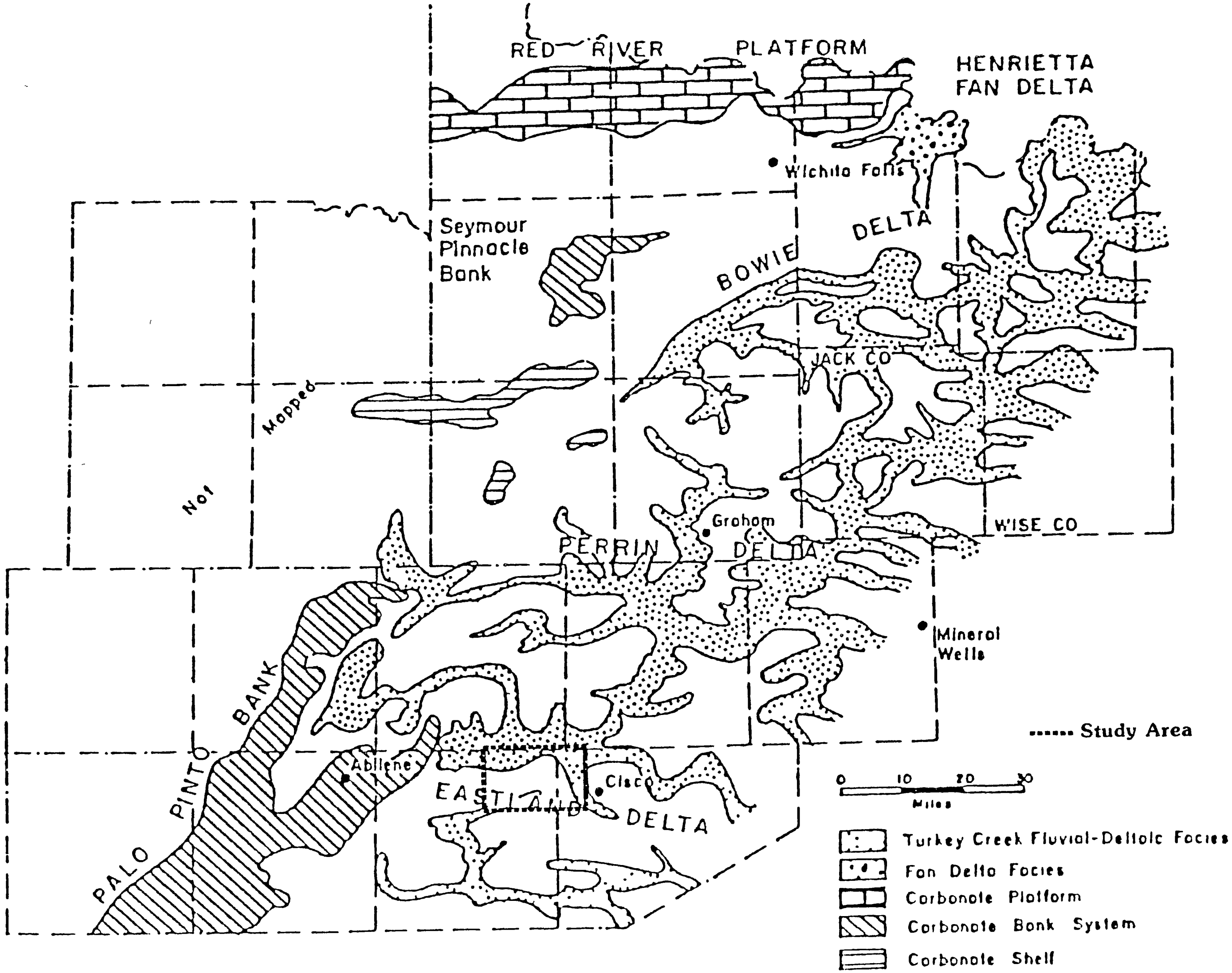

Figure 8. Regional Distribution of Cross Cut and Moran Depositional Systems (from Cleaves, 1975).

tion (reefing) in these units can result in the addition of over 100 feet of section within a lateral distance of a quarter mile (personal communication, Jones, 1989). Through differential compaction, subsequent beds are draped over these reefs. This situation may have caused or contributed to the entrapment of oil in a number of Moran oilfields in the southwest portion of the study area (see Plate 26). Compactional drape has also caused small structural closures over several of the thicker Cross Cut and Moran sand accumulations (see Plates 18, 20, 21 and 22).

Plates 23, 24 and 28 are structural cross sections across Herr-King Field, which is on the western edge of the study area. All of these demonstrate the sudden changes which occur between Herr-King Field and the adjacent eastern area. The total interval thickens significantly and there is a distinct change in the sand facies. Also, the lower boundary of the interval (the top of the Morris limestone) drops sharply, while the top of the interval (the base of the Palo Pinto Formation) remains relatively flat. This "hingeline" could be the result of growth faulting which commonly occurs at delta fronts.

CHAPTER IV

STRATIGRAPHY

Introduction

The surface equivalent rocks of the Cross Cut and Moran are exposed in several outcrops in central and northeastern Palo Pinto County (Figure 9). They have been classified as Pennsylvanian Strawn since the earliest studies of their fossil content by Dumble in 1890 (Hendricks, 1957). Cummins (1891) used the name Canyon for the overlying beds thereby placing the Strawn/Canyon boundary at the top of the study interval. The name Palo Pinto was applied by Plummer (1919) to this superadjacent limestone unit. Plummer and Moore (1921) named the sandstones in the interval Turkey Creek and shales above and below Keechi Creek and Salesville (respectively). A thin limestone bed below the Turkey Creek sands in the lower part of the Salesville shale was called Dog Bend by Sellards, et al. (1932). Another sandstone unit between the Turkey Creek and the Dog Bend is shown on Brown and Goodson's (1972) map and is listed simply as ss2. This is what Cleaves (1975) referred to as Devil's Hollow sandstone in his mapping and outcrop descriptions. Figure 10 illustrates the currently used formal surface stratigraphic nomenclature (Brown and

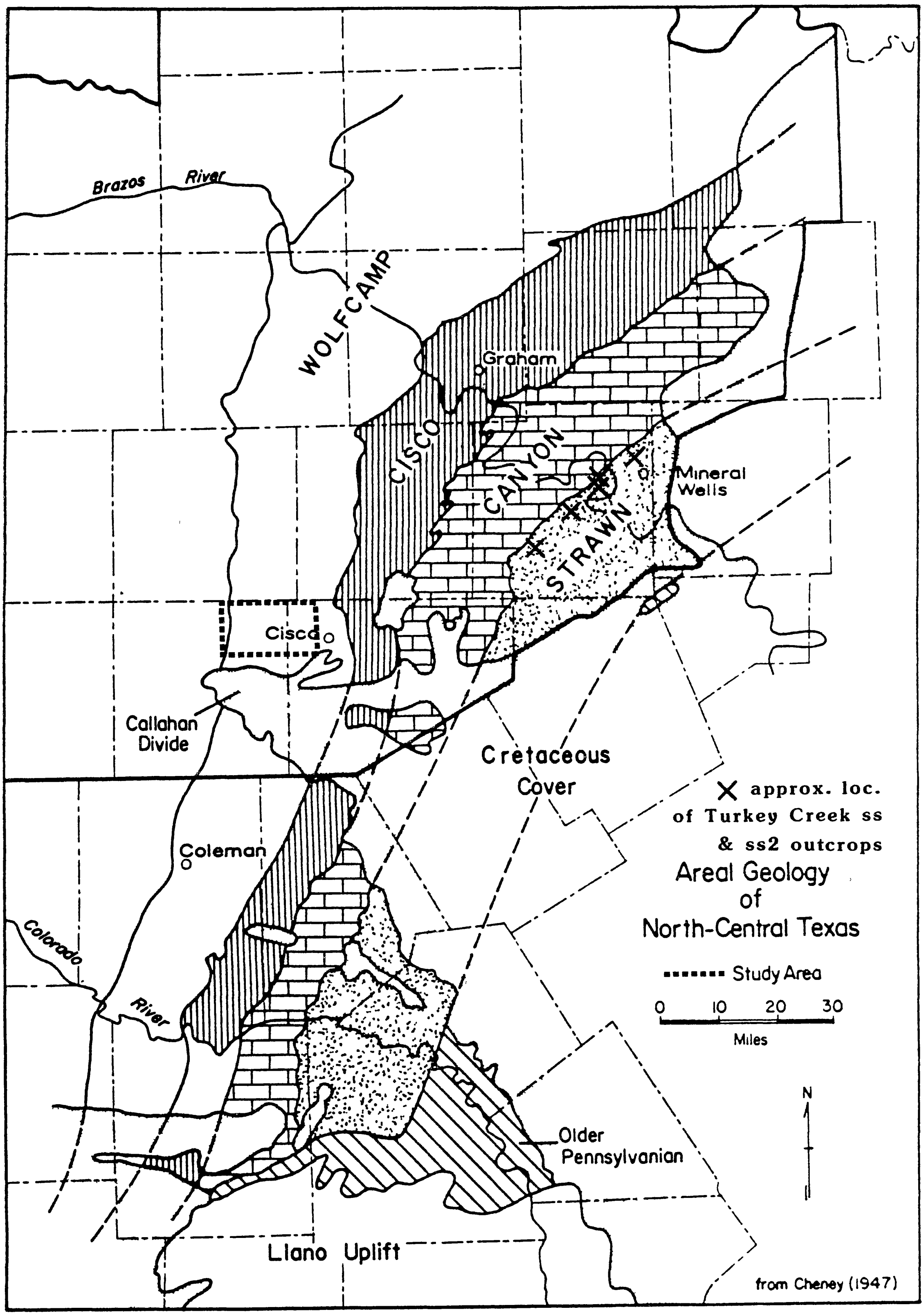

Figure 9. Areal Geologic Map of the Outcrop Zone of the Study Interval (modified from Cleaves, 1982).

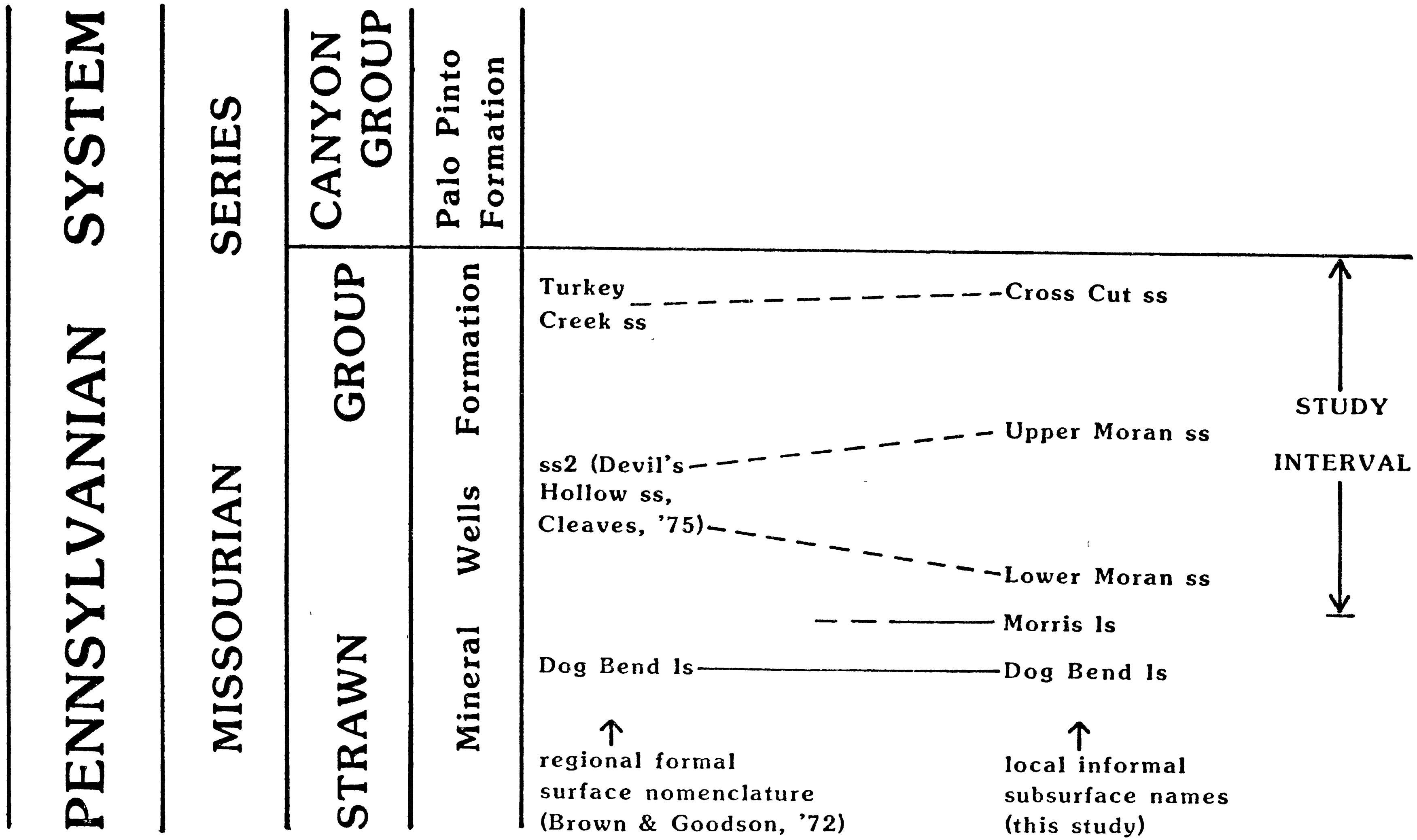

Figure 10. Stratigraphic Column Showing Equivalency of Cross Cut and Moran to Formal Surface Stratigraphic Units.

Goodson, 1972) and the equivalency of the Cross Cut and Moran to it.

The units which bound the study interval, namely the Palo Pinto Formation and the Dog Bend Limestone were correlated regionally, as a part of this study, from the outcrop through the study area (Figure 11). The base of the Palo Pinto Formation remains consistent enough to allow for accurate regional correlation. Within the study area the Morris limestone (informal parastratigraphic unit), a thin limestone bed approximately 70 feet above the Dog Bend Limestone, is more suitable for local mapping purposes. The interval between the Morris and the Dog Bend contains no sandstone and has no significant relationship to the study interval. Hence, it is best to not include it in the mapped intervals. Furthermore, the Morris limestone is the marker used by most industry workers and, because most Moran tests stopped drilling in the Morris, the Dog Bend is not penetrated in many of the wells in the study area. The Morris limestone is well developed throughout the study area, but has an eastward depositional limit in eastern Eastland County.

Because of the lack of regionally persistent limestone or other marker beds between the genetic units of the study interval, regional correlation of these units from outcrop to the study area would require detailed, well to well sandstone correlations which would be beyond the scope of this study. However, it can be seen from Figure 11 that it

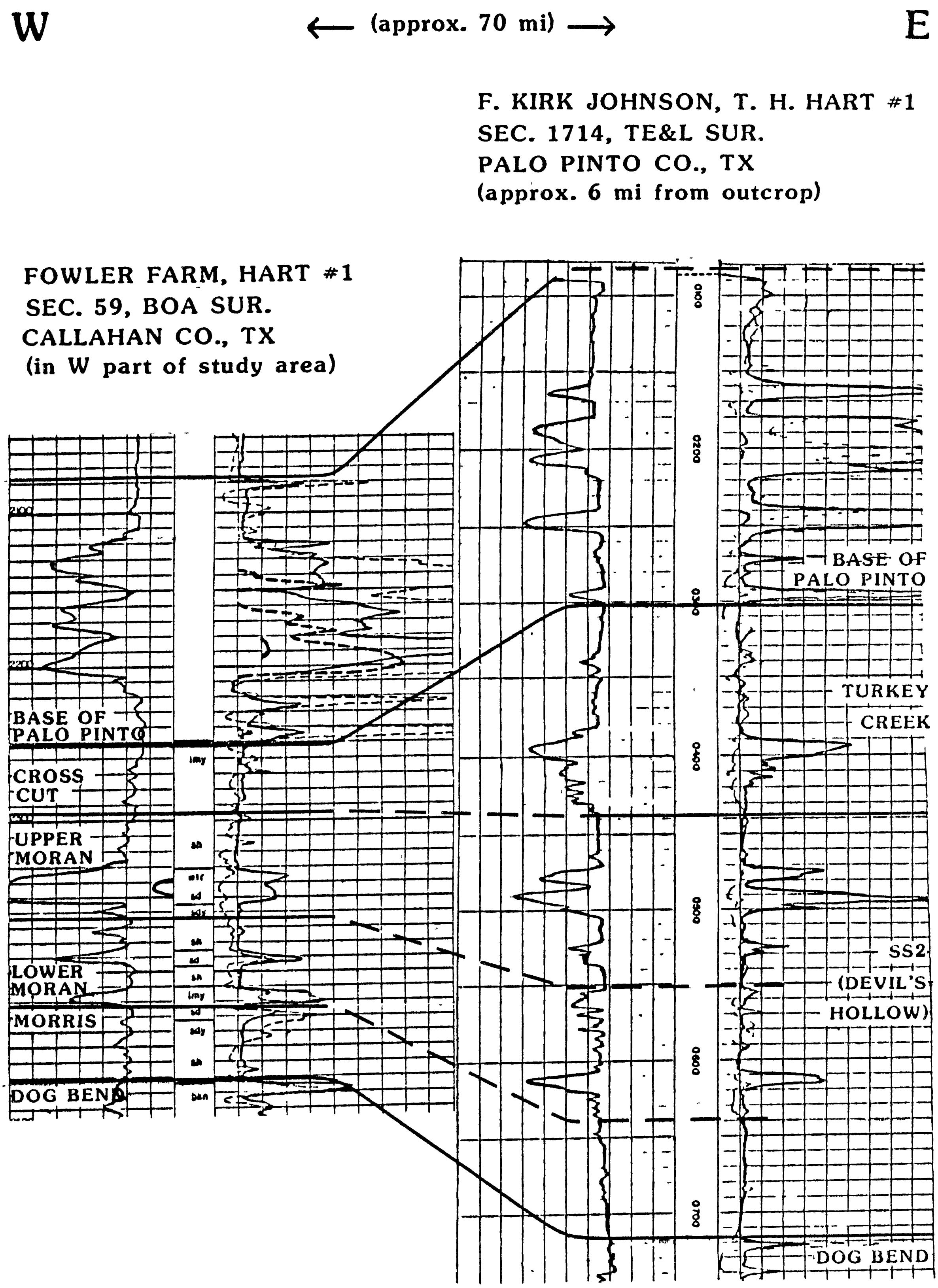

Figure 11. Correlation of the Study Interval from Outcrop to the Study Area.

is at least plausible to correlate Cross Cut to Turkey Creek and Moran to ss2 (Devil's Hollow).

There are two points of confusion in the stratigraphy of the Cross Cut and Moran. One arises as a result of the usage of the terms Strawn and Canyon as both group and series names. The usage of Strawn and Canyon as group names dates back to the earliest workers who placed the group boundary atop the study interval at the base of the Palo Pinto Limestone. This boundary was defined on the basis of field recognized lithologic units (Hendricks, 1957). The two groups are distinguished largely on the basis of the change from a predominantly clastic section in the Strawn Group to a more carbonate-rich section in the Canyon Group.

Cheney (1940) redefined the Strawn and Canyon as series on the basis of thorough and well documented fossil evidence. The stratigraphic position of this series boundary is below the study interval at the base of the Lake Pinto Sandstone. As a result, the Cross Cut and Moran (Turkey Creek and ss2, along with the Dog Bend and Lake Pinto) received the inexpedient distinction of precisely corresponding to that interval of overlap which belonged to both the Strawn Group and the Canyon Series. Both, the group and the series boundaries are correct and justifiable, but it is unfortunate that the same names were used for overlapping litho-stratigraphic and time-stratigraphic units. The current usage (see Figure 10) solves the problem by using Desmoinesian and Missourian for the series names and retaining Strawn and Canyon as group names.

Both the Moran sandstone and the Moran Formation are namesakes of the town of Moran, Texas in southeastern Shackleford County (2 miles north of the study area). Herein lies the second point of confusion surrounding the stratigraphy of the study interval. The local informal subsurface name used for the Moran sandstone in the study area originates from a huge 1920's oil discovery made in the study interval near the town of Moran (Jones, 1983). A formal surface unit, the Moran Formation is Permian (Wolfcampian) (Brown and Goodson, 1972) and derives its name from the same town of Moran, where it outcrops. As it happens, the Moran Formation is also the surface rock across much of the study area.

A typical deep test (near the center of the study area) would encounter the following (also refer to Figure 6):

surf.-1100'	L. Perm.-U. Penn. Cisco Gp ss & sh *
1100'-2000'	Penn. Canyon Gp ls & sh *
2000'-3300'	Penn. Strawn Gp ss & sh *
3300'-3700'	Penn. Strawn Gp (Caddo) ls, poss. reefing*
3700'-3900'	L. Penn. Atoka & Morrow Gps sh, ss & cgl*
3900'-4000'	Miss. (Barnett) ls & sh
4000'-4100'	Miss. (Chappel) ls, poss. reefing *
4100'-4800'	Ord. (Ellenburger) dol'ic ls *
4800'-5400'	Cambr. (Riley & Wilberns) dol'ic ls & ss
5400'	pre-Cambr. gran, ign, or meta

(Cheney and Goss, 1952; Herkommer and Denke, 1982). Productive intervals are indicated by an asterisk (*). With the multiplicity of productive sands in the Pennsylvanian section, the study area contains a dozen or more productive units at depths ranging from less than 500 feet to just over 4000 feet.

Local Cross Cut and Moran Stratigraphy

Figure 12 and Plates 1 through 6 demonstrate the correlation of the horizons which bound the study interval and those which subdivide it into genetic units. During preliminary correlations, approximately one wireline well log per square mile was selected which best represents the study interval in that small area. These logs were carefully correlated to create a completely correlated network of over 120 "type" logs. The logs shown on the cross sections were taken from this group. Besides demonstrating the interval and genetic unit correlations, these cross sections depict (as far as is practicable) all the various facies of each genetic unit throughout the study area. All Cross Cut and Moran producing fields in the study area are either represented in or correlated to the cross sections. Type logs representing Cross Cut or Moran fields which were not included in the cross sections are correlated in Plates 6 through 10. The wells used for these type logs are indicated on the maps (Plates 17 through 22) by small circles around their well symbols.

The stratigraphic datum for the cross sections (Plates 1 through 5) is the base of the Palo Pinto Formation. In addition to its stratigraphic significance (as a group boundary), this horizon is the most suitable stratigraphic

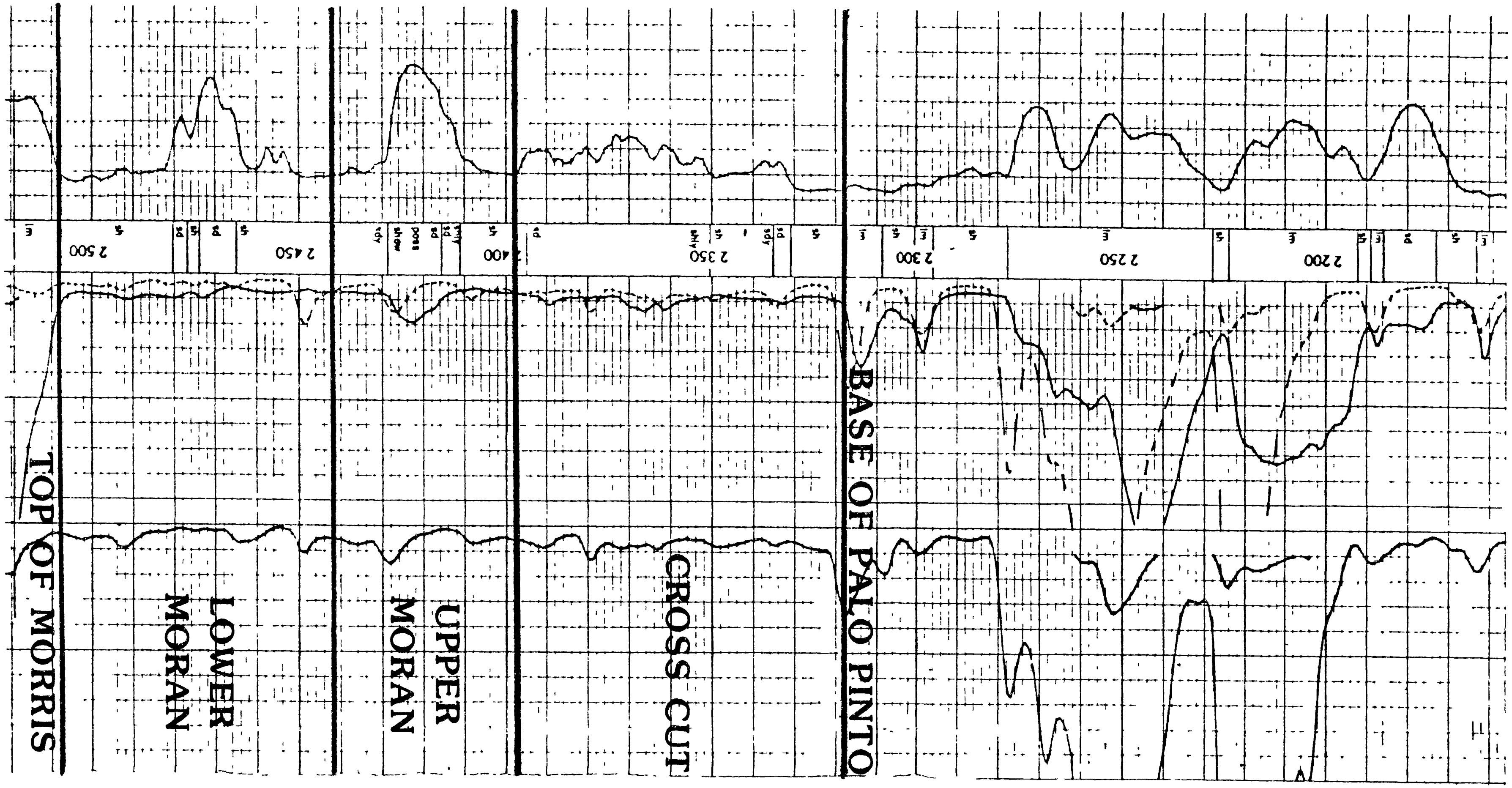

Figure 12. Type Log of the Cross Cut, Upper Moran and Lower Moran. (S. C. Herring, Morris Snyder et al #3-C, 330' FSL & 990' FEL of Section 3, T&NO Survey, Callahan County, Texas, see Plates 1 and 3).

cross section datum in the study interval. A more natural appearing fit of the genetic unit correlations is obtained with it as a datum than with the genetic unit tops, Morris limestone top or other markers.

The thickness of the total study interval is mapped in Plate 19. Figure 11 demonstrates that the study interval thins to the west. This is consistent with outcrop data (Bay, 1932), regional mapping (Cleaves, 1975), and regional paleogeologic setting, which all indicate that the Cross Cut and Moran were sourced from the east. However, Plate 19 does not contain a strong trend of thinning in any one particular direction. The paleostrike direction is rather clearly indicated and matches that shown by Cleaves' (1975) regional map (see Figure 8). The prominent isochore thicks and thins in the study area are closely related to both the geometry of the sandstone depositional tracts and predepositional and/or syndepositional paleotopography.

Among the most important objectives of this study is the subdivision of the study interval into genetic units. Proper delineation of these units is crucial to effective mapping and facies analysis. Intervening thin limestone beds are scarce but are scattered throughout the study area, especially in the eastern and southern portions. These markers were useful in identifying the tops of the genetic units and establishing a framework for genetic unit correlation (see Plate 4, log number 5). Ideally, each genetic unit consists of an interval of sandstone and/or shale with its lower boundary at the top of an underlying thin limestone bed and its upper boundary at the top of an overlying thin limestone bed. Generally there is sufficient character developed in the section to facilitate genetic unit boundary determination in the absence of bracketing limestone beds. Log signature pattern changes, resistivity and conductivity changes, and other marker beds all serve as reliable indicators of genetic unit boundaries (see Plates 1 through 11, 13, 23 through 29). Furthermore, the cores are invaluable as "hard data" in the establishment of genetic unit "ground truth." Fortunately, the genetic units are distinct and conformable (i.e. no downcutting or "pinching out"), with no drastic interval changes.

Figure 12 demonstrates the genetic unit correlations used in this study. There is no set nomenclature consistently applied by industry workers which accounts for the three different genetic units contained in the study interval. Examination of existing records and publications and discussion with current industry geologists reveal a loose working vernacular. Albiet, not without its misuses, overlap, and "lumping," the general consensus seems to be that the uppermost sandstone is referred to as "Cross Cut" and the lower two sandstones are called "Moran." Jones (1983) stated that the lowest sandstone has been referred to as "Morris" but it appears that this is only the case in other areas where the lowest sandstone is a more prominent producer.

Although there are three distinct mappable sandstone units in the study interval, it is proposed here to use the names Cross Cut for the uppermost sandstone and Moran for the two lower sandstones. This is in keeping not only with the common local usage but also with the application of only two names in the formal surface nomenclature (Turkey Creek Sandstone and ss2 or Devil's Hollow sandstone). It is further proposed in this study that the Moran be subdivided into Upper Moran and Lower Moran. The two are clearly separate and distinct sandstone bodies and are mappable as such (Plates 21 and 22). However, comparison of their sandstone isolith maps (Plates 21 and 22) reveals that the two units are very closely related depositionally. They have nearly identical types, distributions and geometries of facies. In contrast, the Cross Cut sandstone isolith map (Plate 20) illustrates the marked change which occurred after deposition of the Moran. The Cross Cut sandstone, while retaining similar type and geometry of facies, was deposited along a different depositional tract with little overlap or association with the underlying Moran sandstones. A cursory check of the study interval in surrounding areas indicates that this local stratigraphic scheme should be usable throughout the Cross Cut and Moran producing trend.

CHAPTER V

PETROLOGY AND DIAGENESIS

Methods of Investigation

The principal method of petrologic analysis of the rocks studied was thin section examination. Although only two cores of the study interval are available, they provide excellent samples of all three genetic units. One core taken from the Herr-King Field contained sandstones from each of the three genetic units (Plates 13 and 14) and the other core contained the Upper Moran sandstone reservoir from Jones Company's Callahan County Regular Field (Plates 11 and 12). After complete examination of the cores, representative reservoir sandstone samples were selected for thin section preparation. Each sample was completely impregnated with blue epoxy in order to preserve delicate structures and constituents and to highlight the pore spaces. Half of each thin section was stained with both Alizarin Red-S and potassium ferricyanide solutions to aid in carbonate species determination. X-ray diffraction analysis, scanning electron microscopy and energy dispersive analysis were also performed on one sample. The positions of the samples within the cores are indicated on the core petrologic logs (Plates 12, 14, 15 and 16).

Thin Section Petrology

Texture

There is little variation in the basic framework of the four sandstones cored, but there are some slight but important textural differences (Figure 13). The frameworks of all the samples consist predominantly of normal quartz grains. Grain sizes have a limited range of 0.07 mm (lower very fine sand) to 0.30 mm (lower medium sand). Average grain sizes for each of the individual sandstone units range from 0.12 mm (upper very fine sand) to 0.22 mm (upper fine sand). The overall average grain size for all the sandstones is 0.17 mm (fine sand). The grains are mostly subrounded to rounded and have moderate sphericity. Another framework element common to all the sandstones is clay grains. These, in general, have approximately the same grain size and rounding as their companion quartz grains.

The most important textural variation occurring among the samples is in the amount and type of the clay grains. Within each individual sandstone unit the amount of clay grains can range from less than 1% to over 6%. Two types of clay grains present are: (1) intraformational clay grains and (2) glauconite grains. The Jones core contains predominantly intraformational clay grains, whereas the clay grains in all three sandstones in the Sun core are mostly glauconite grains.

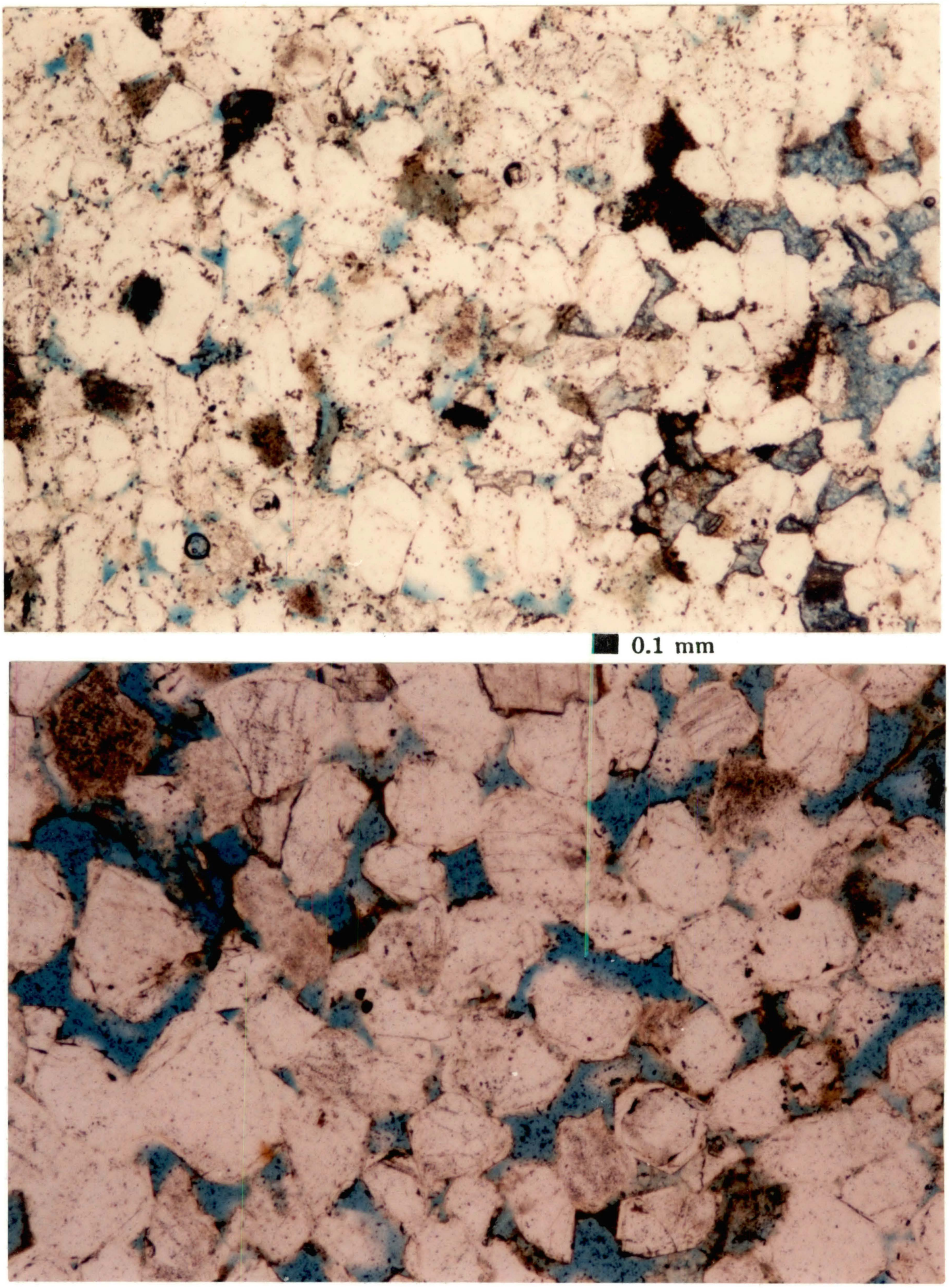

Figure 13. Textural Differences Between the Sun Core (Lower Moran, 2503', upper photo) and the Jones Core (Upper Moran, 2104', lower photo) (both photos are plane polarized, 40X).

The sandstones in the Sun core are somewhat finer grained, with a maximum average grain size of 0.15 mm (lower fine sand) versus a maximum average grain size of 0.22 mm (upper fine sand) in the Jones core. Other textural differences seen in the Sun core include increases in the amounts of silt sized carbonaceous material and detrital clay matrix, and the appearance of 1% to 20% micritic calcite matrix. There is an attendant slight decrease in sorting in the Sun core to moderately sorted from well sorted in the Jones core (Pettijohn et al., 1973). The sandstones in the study interval are all classified as sublitharenites (Folk, 1968) and are texturally and compositionally mature.

Quartz

Quartz is the dominant framework grain in all the samples. It comprises 85% to 95% of the framework and 60% to 75% of the total rock. Most of the quartz grains are normal with straight or slightly undulose extinction. Minor amounts (less than 1% each) of chert, strained quartz and polycrystalline quartz grains are present.

Feldspar

Only minor amounts of feldspar grains occur in the samples. Some of the few that are present are extensively corroded (Figure 14). The scarcity and extent of alteration of these grains makes it difficult to state the

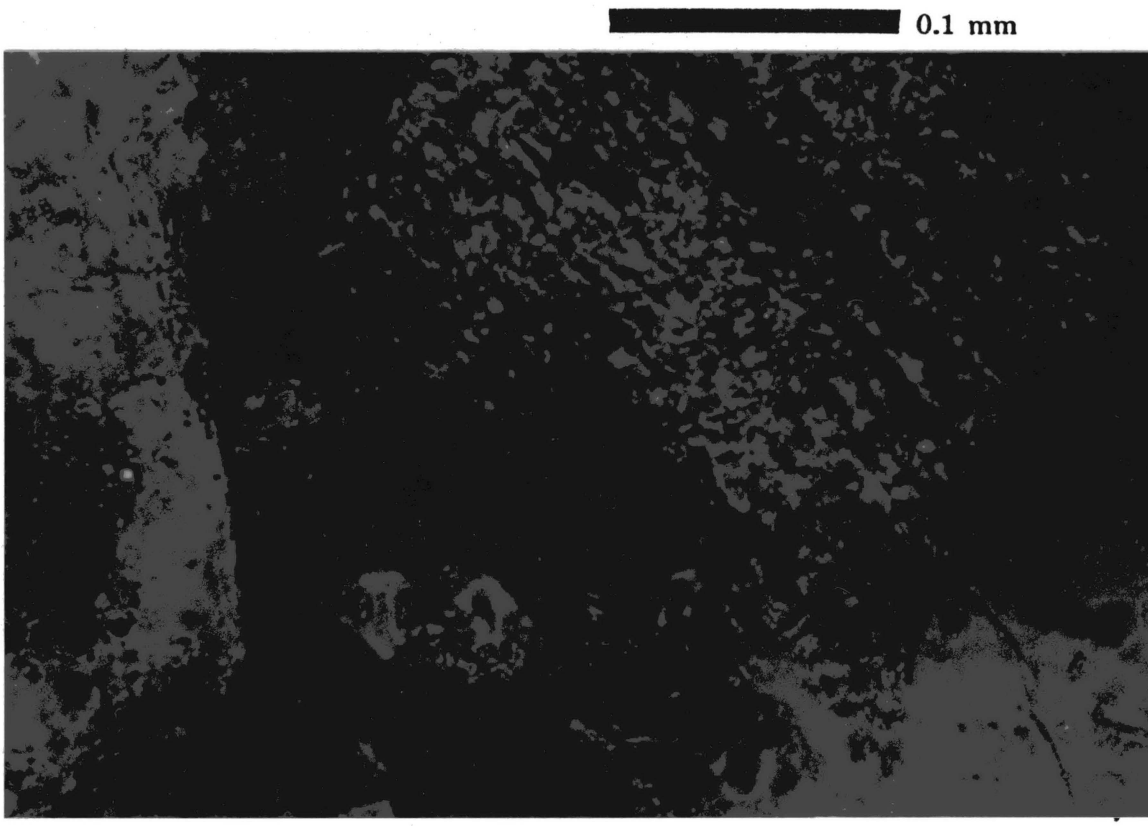

Figure 14. Extensively Corroded Feldspar Grain (Jones core, Upper Moran, 2100', plane polarized, 400X).

amounts of orthoclase and plagioclase feldspar. However, the conspicuously linear nature of the intraparticle pore seen in Figure 14 could be the result of the selective dissolution of a polysynthetic twin in a plagioclase grain

Rock Fragments

Aside from rare metamorphic rock fragments, the lithic component of the framework grains consists entirely of clay grains. The amount of clay grains ranges from 1% to 6%. They have a dark brown color and are non-silty (Figure 15). Some have been partially recrystallized. This authigenic illite is recognized by its bright golden interference color (Figure 16). Figure 15 also shows how ductile deformation of these grains can result in the formation of pseudomatrix. An example of the occurrence of clay grains in the sun core is shown in Figure 17.

Matrix

Matrix in these sandstones is mostly confined to scattered discrete zones where it occurs in abundance. This is the habit of all three types of matrix found in the samples. They are: (1) clayey, (2) silty, and (3) limy.

The clayey matrix, as in the case of the clay grains, is illitic in the Jones core and predominantly glauconitic in the Sun core. Black carbonaceous material and, to a lesser extent, quartz, make up the silty fraction of the detrital matrix. The wispy and maceral-like forms of the

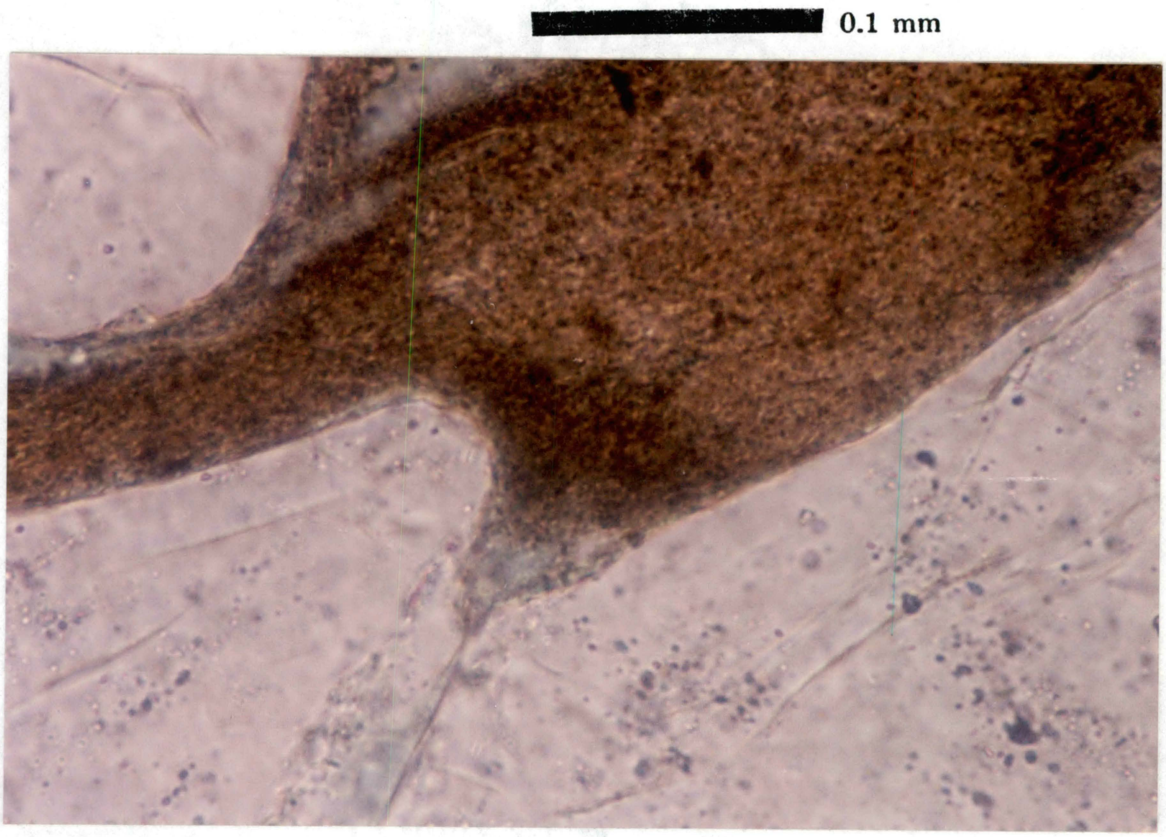

Figure 15. Illitic Intraformational Clast. (Jones core, Upper Moran, 2104', plane polarized, 400X).

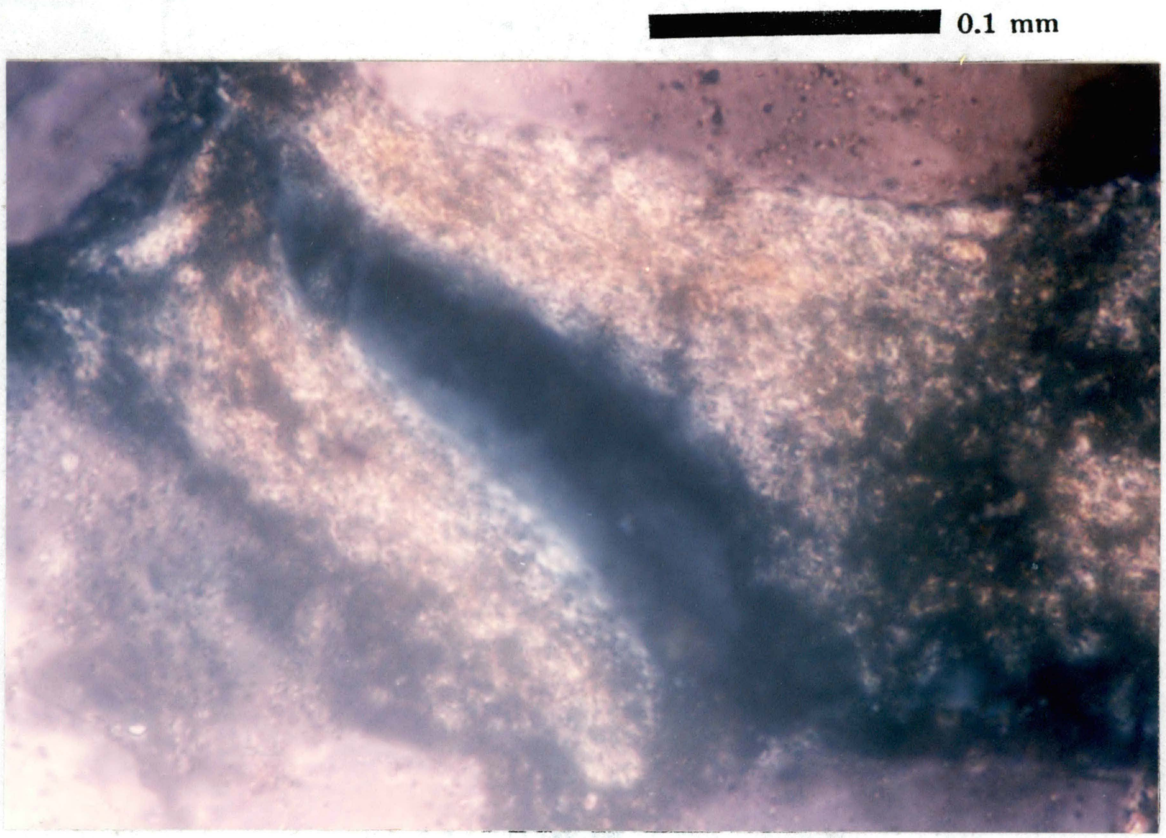

Figure 16. Recrystallization of an Illitic Intraformational Clast to Authigenic Illite (Jones core, Upper Moran, 2100', crossed polarizers, 400X).

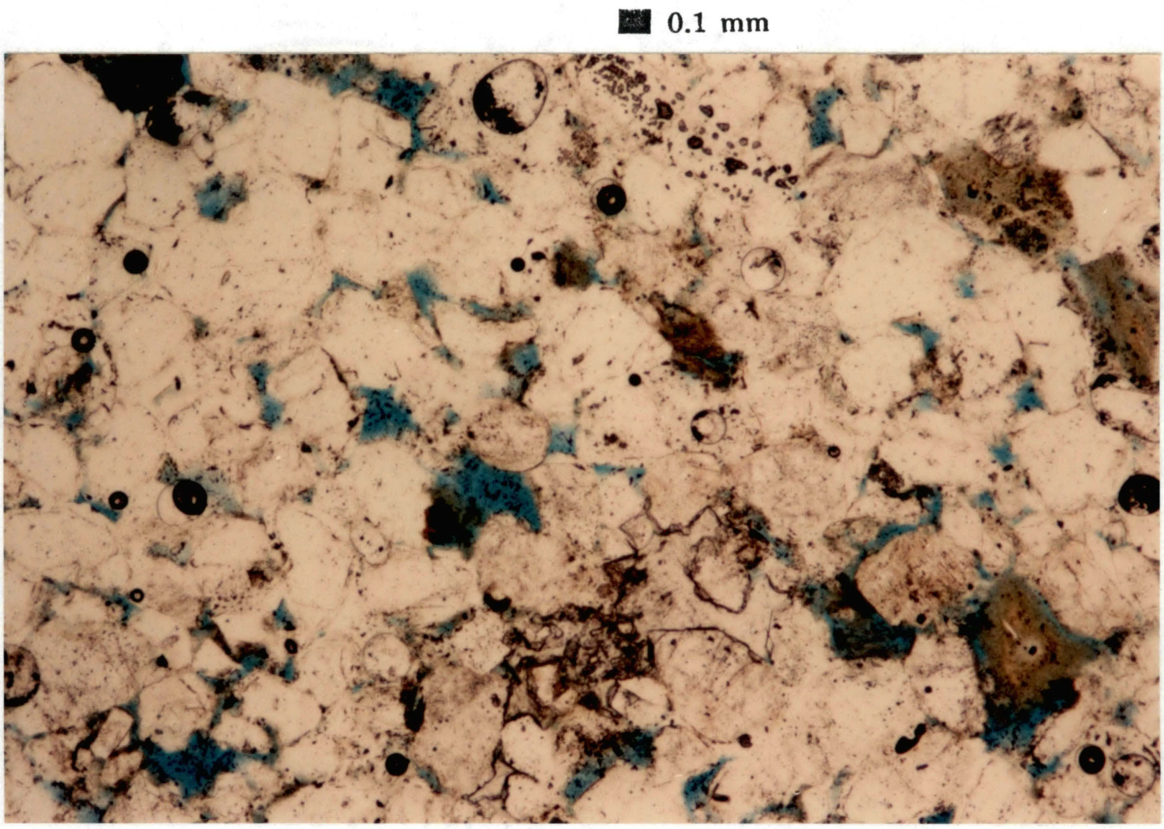

Figure 17. Sandstone Containing Clay Grains (Sun core, Upper Moran, 2456', plane polarized, 40X).

carbonaceous material indicate that it is plant debris (Figure 18). The clayey and the silty detrital matrices generally occur together and comprise up to 4% of the rock each in rare, thin zones within the sandstones (Figure 19).

The limy matrix consists of micrite. It occurs only in the Cross Cut sandstone in the Sun core. In these zones it is ubiquitous and is present in an amount of nearly 20%. While it occurs mostly as a thin grain coating (Figure 20), it also fills substantial interparticle space.

Provenance

The regional and local distribution of the Cross Cut and Moran Sandstones indicate that they had an eastern source. The paucity of feldspar grains and igneous and metamorphic rock fragments indicate that the source was most likely not granitic or other igneous or metamorphic terrain. The high degree of rounding, sphericity, sorting and compositional maturity of the framework grains suggests that they are recycled sediments. At the time of Cross Cut and Moran deposition, the Ouachita-Marathon Orogen had experienced maximum uplift and was the source of tremendous amounts of molasse sediment (Keller and Cebull, 1973). Also by this time, the Fort Worth Basin was filled and these sediments prograded across it and the Concho Platform into the study area (Cleaves, 1982). Although abundant chert clasts are present in these rocks in outcrop, it is evident that the vast majority of this unstable variety of

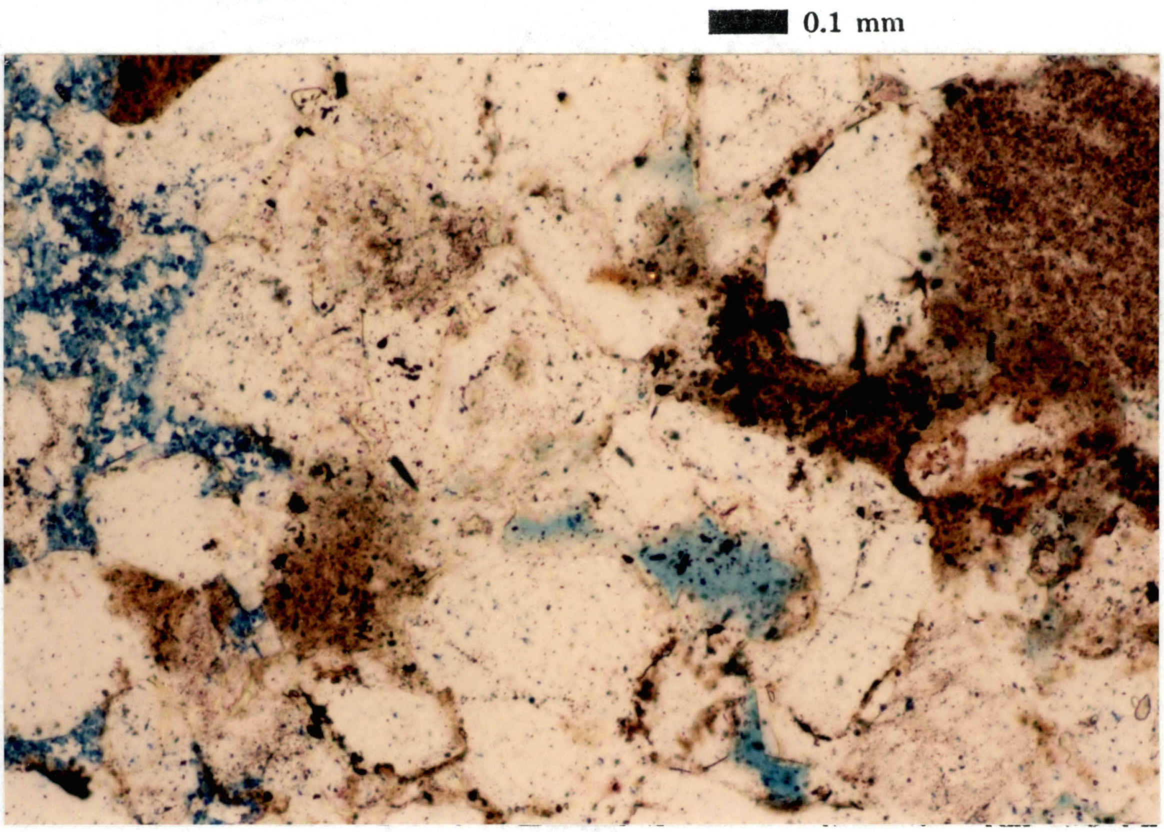

Figure 18. Silt-sized Detrital Carbonaceous Material (Sun core, Lower Moran, 2503',plane polarized, 100X).

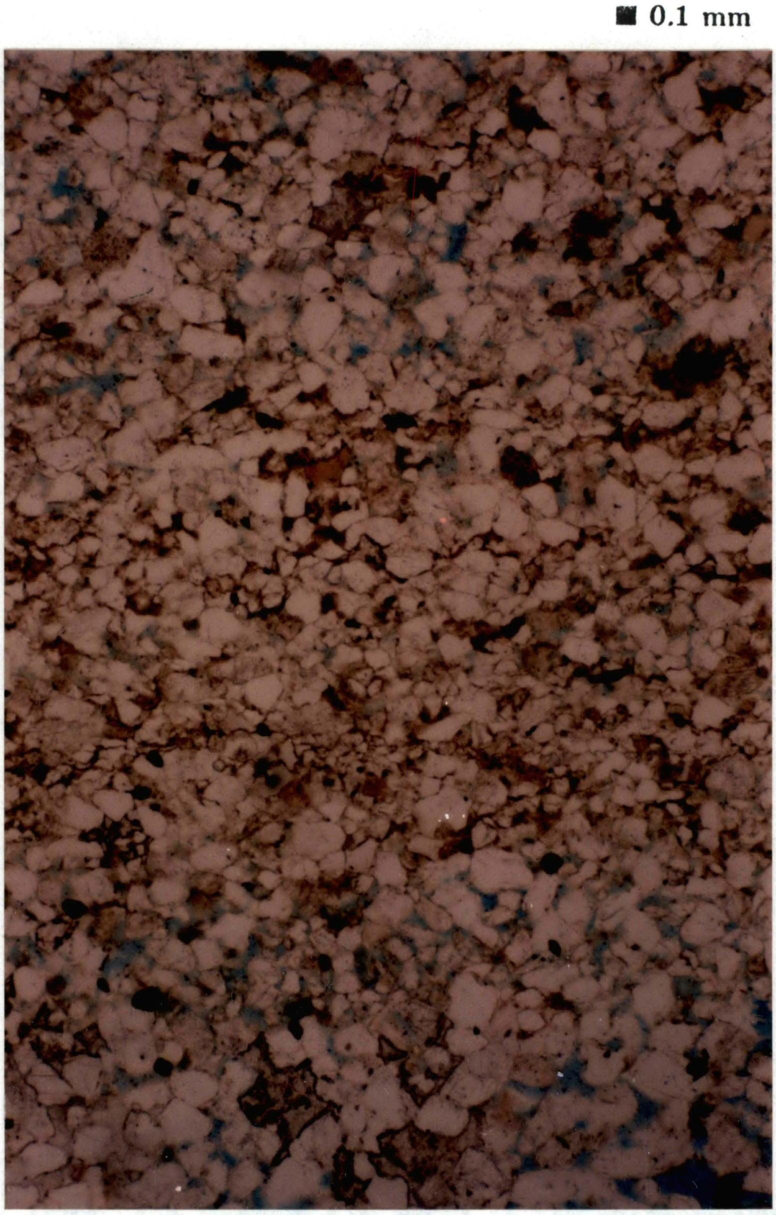

Figure 19. Thin, Discrete Zone Containing Abundant Detrital Matrix Consisting of Illitic Clayey Matrix and Carbonaceous and Quartz Silt (Jones core, Upper Moran, 2101', plane polarized, 20X).

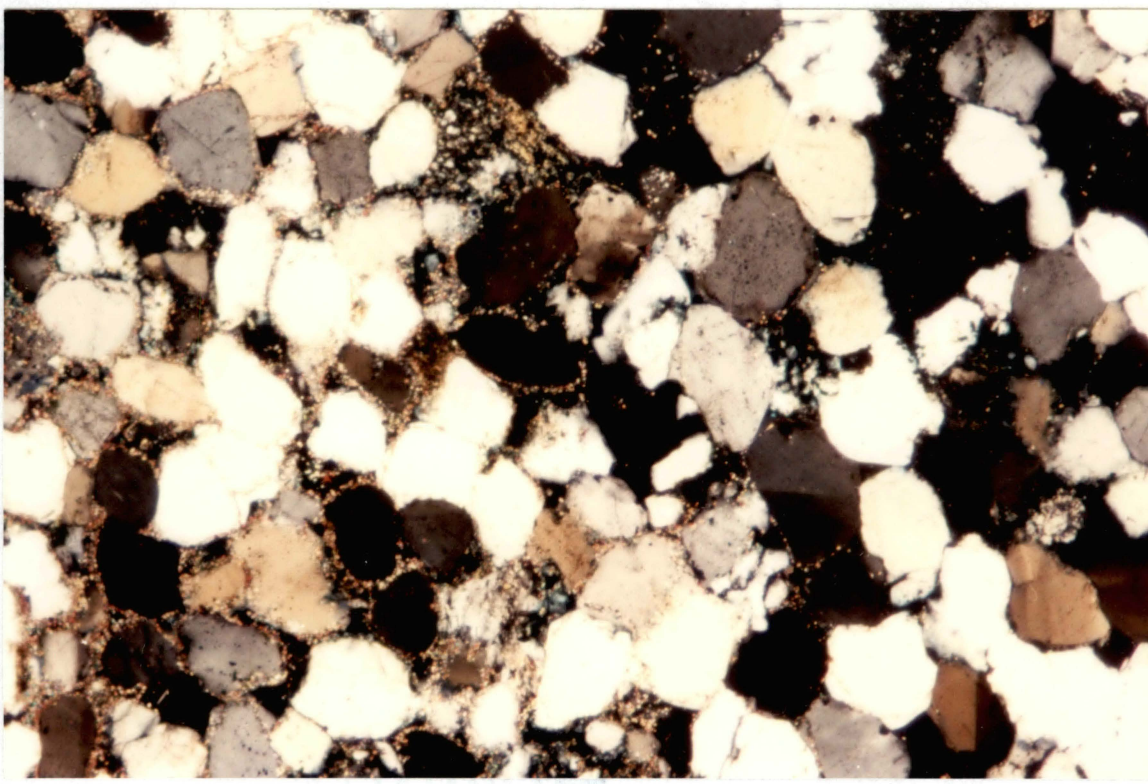

Figure 20. Sandstone With Sedimentary Micrite Matrix (Sun core, Cross Cut, 2404', crossed polarizers, 40X).

quartz did not survive the 80 mile trek to the study area. The abundant clay grains in the samples in the study area were locally derived intraformational clasts, some of which have since been diagenetically altered to glauconite. Regional and local distribution, petrology, and tectonic and basin histories of the Cross Cut and Moran sandstones indicate that these sediments were sourced by uplifted sedimentary rocks in the Ouachita-Marathon Orogen to the east and prograded some 120 miles west where they were deposited in the study area as mature sediments.

Diagenetic Constituents

Quartz Overgrowths

Syntaxial quartz overgrowths are present in all of the samples. They comprise 1% to 2% of total rock volume in the finer grained, less sorted, less porous sandstones to over 5% in the cleaner, more porous sandstones (see Figure 13).

Ankerite

Abundant tiny, distinct patches of pore-filling carbonate cement are scattered throughout all of the sandstones except the Cross Cut in the Sun core. Examples of this cementation in the Upper Moran reservoir sandstones in the Sun core and the Jones core are shown in Figures 21 and 22. When stained in a solution of both Alizarin Red-S and potassium ferricyanide the cement stained deep blue. By

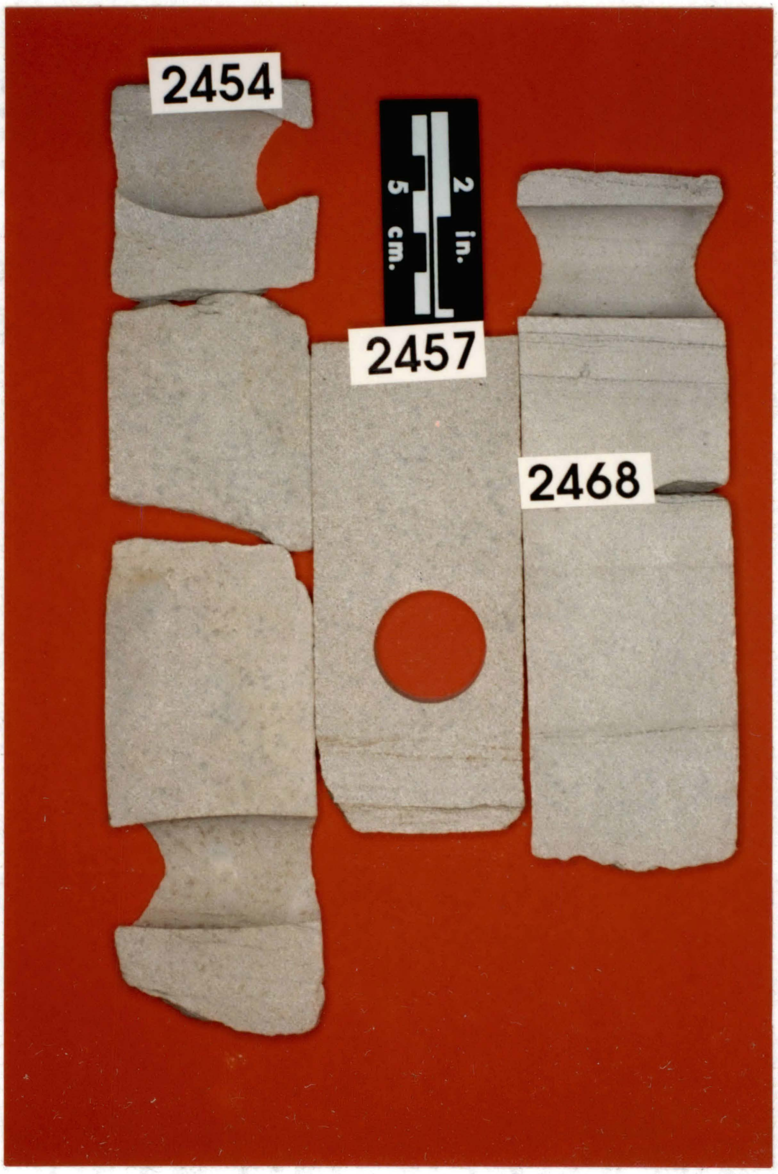

Figure 21. Patchy Ankerite Cement in the Upper Moran Reservoir Sandstone in the Sun Core.

Figure 22. Patchy Ankerite Cement in the Upper Moran Reservoir Sandstone in the Jones Core.

this process the carbonate species is identified as ankerite. The ankerite cement in all the samples displays a conspicuously patchy distribution, where small areas (1 to 3 mm) of sandstone, totally cemented, are surrounded by normal porous, cement-free sandstone (Figure 23). It is present in amounts ranging from 4% to 13%, averaging 9% of the total rock volume. However, within the cemented patches, it comprises nearly 50% of the rock. For example whole rock x-ray diffraction analysis indicated the presence of ankerite in the sample. However, when a small chip of uncemented rock from that same sample was examined with a scanning electron microscope and energy dispersive analysis, no carbonates were detected. In addition to being common throughout this study area, identical ankerite cementation was found to exist in neighboring areas in the Moran sandstone (Collier, 1984) and the "Gray" (Strawn) sandstone (Land and Dutton, 1978).

These patches of cement consist, with little exception, of large single dolomite crystals which envelope many sand grains (Figure 24) referred to as poikilotopic crystals (Tucker, 1981). Many of the ankerite crystals bear certain characteristic crystal forms such as curved crystals, sweeping extinction and knife-like ("scimitar") crystal terminations. Commonly referred to as "baroque" or "saddle" dolomite these curved crystals have incorporated iron and other impurities into their lattices. As a result they are less ordered and exhibit strongly sweeping extinc-

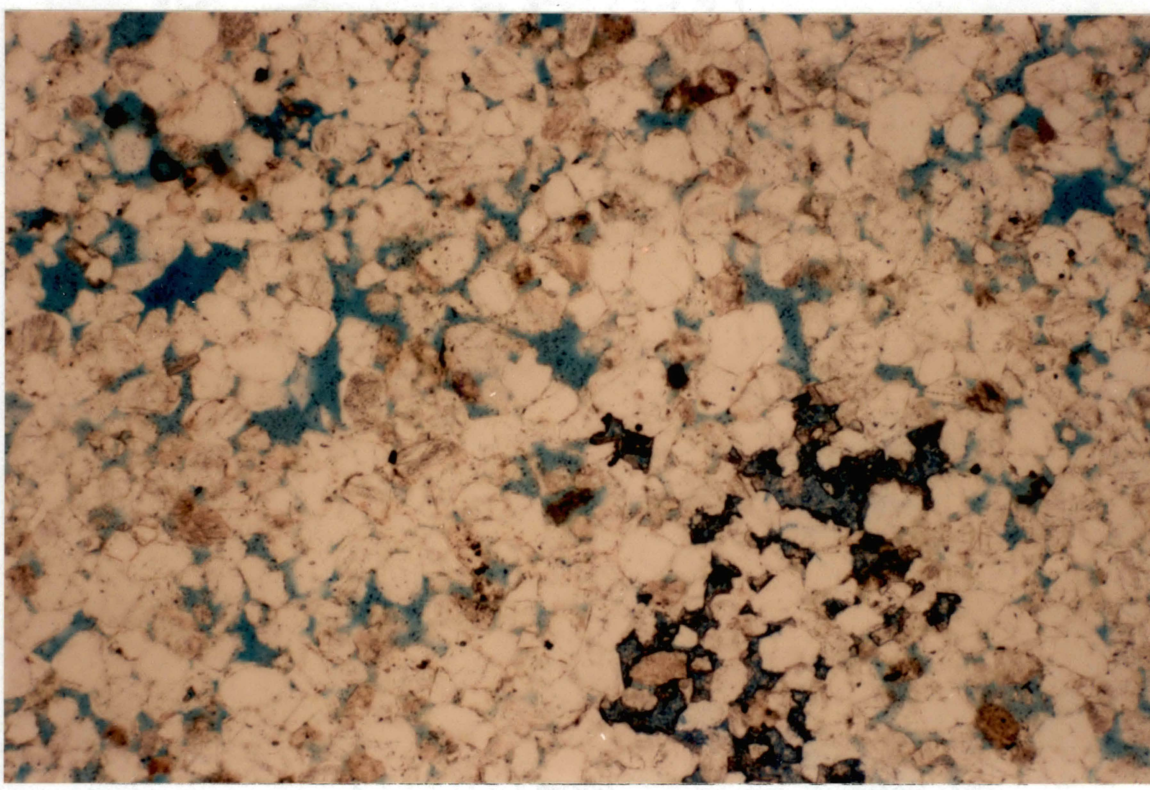

Figure 23. Patchy Distribution of Ankerite Cement (stained in Alizarin Red-S and potassium ferricyanide) (Jones core, Upper Moran, 2098.5', plane polarized, 20X).

0.1 mm

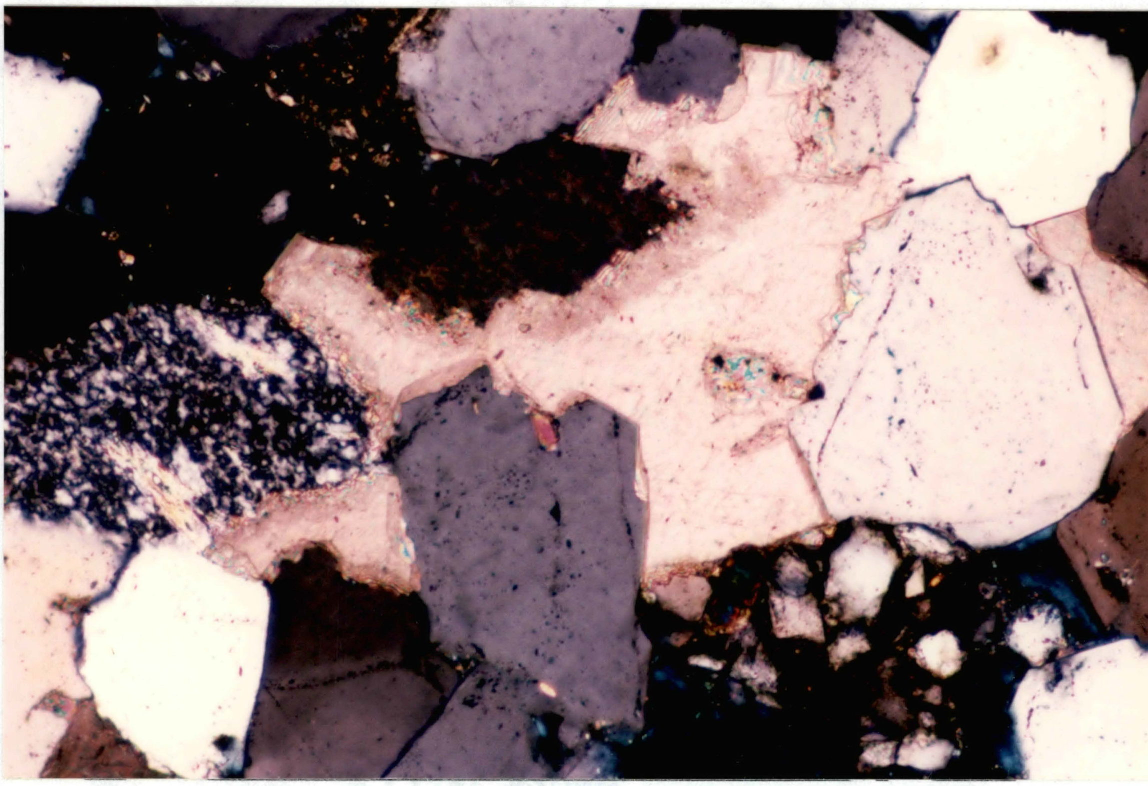

Figure 24. Poikilotopic Ankerite Cement (this part of this slide not stained) (Jones core, Upper Moran, 2101', crossed polarizers, 100X).

tion (Figure 25). Compositional zonation of the ankerite with dolomite is revealed by the staining in Figure 26. Although the great majority of the cement in all the samples is stained deep blue, indicating ankerite, notice the patch of stained cement in the lower left corner of Figure 27. It is stained a lighter shade of blue (turquoise), indicating ferroan dolomite. However, it also displays a speckled or "two-tone" appearance imparted by the presence of unstained cement, indicating dolomite. Therefore, it appears as if the cement is actually a solid solution dominated by ankerite, but also containing ferroan dolomite and dolomite.

The strongly replacive nature of the ankerite cement is evident in Figure 24, 25 and 26. Almost every grain in contact with the cement has highly irregular etched and corroded grain boundaries. Extremely large and oddly shaped intergranular areas filled with cement (Figure 27) were previously oversized pores, created by the dissolution of multiple framework grains.

Calcite

One sample (Sun core, Cross Cut sandstone, 2404 feet) contains abundant calcite coated grains (Figure 28). The coatings stained red in Alizarin Red-S and potassium ferricyanide. They are thin (0.01 to 0.02 mm) and incompletely developed and make up 10% of the sample. Roughly equal parts of the quartz framework grains are either fully

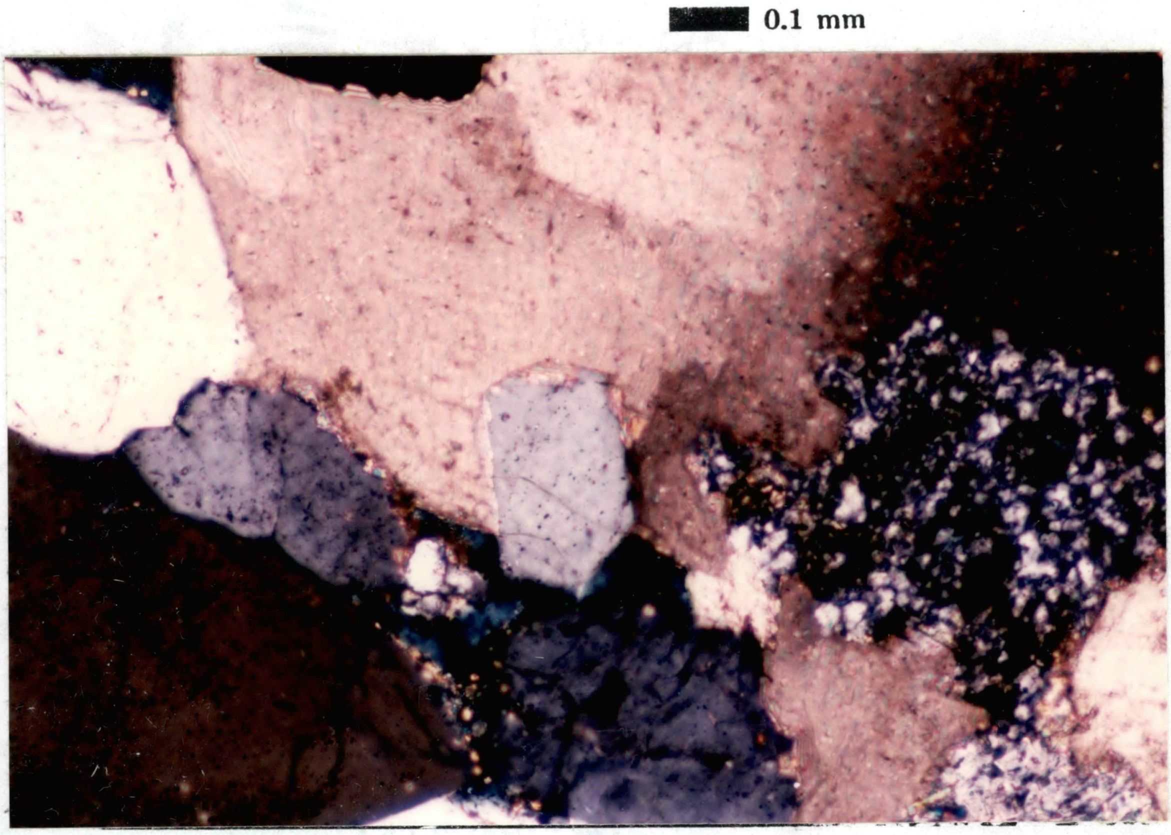

Figure 25. "Baroque" Ankerite Cement Exhibiting a Curved Crystal with Strongly Sweeping Extinction (note: the dark area seen in the upper right corner is the extinct portion of the same crystal) (this portion of this slide not stained) (Jones core, Upper Moran, 2104', crossed polarizers, 100X).

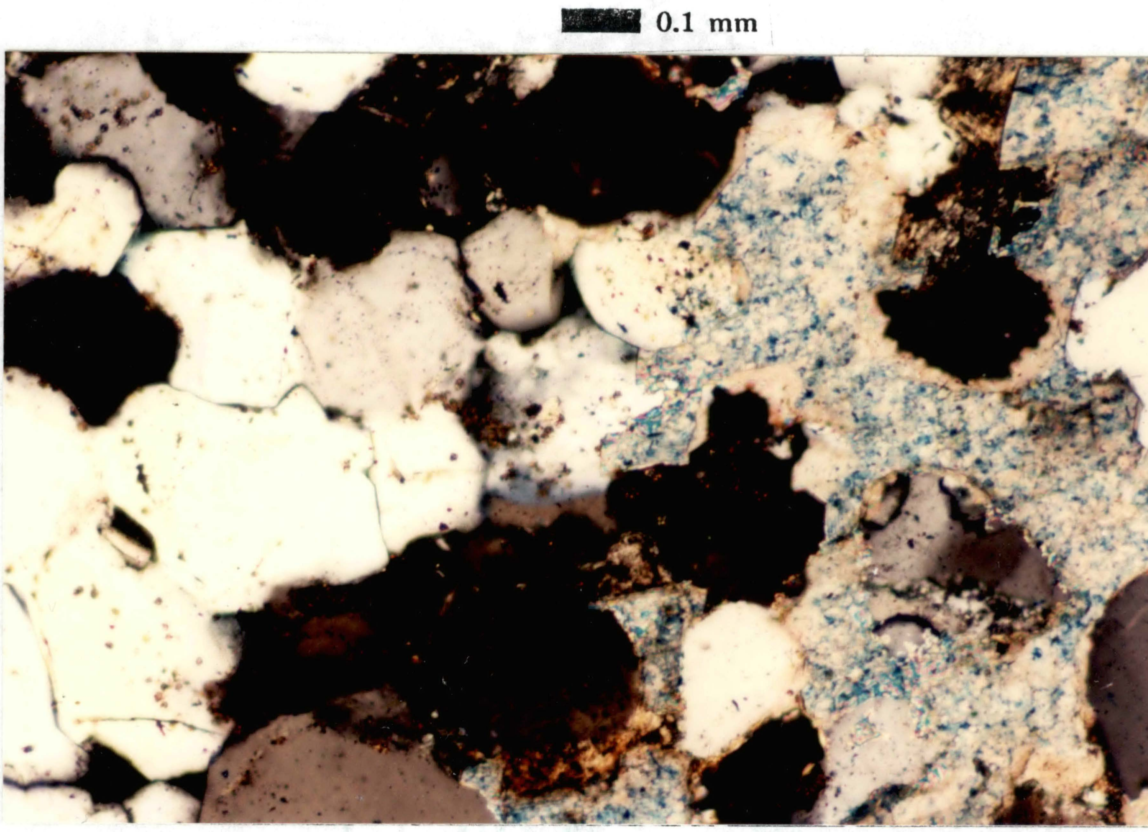

Figure 26. Compositional Zonation of the Ankerite with Dolomite Revealed by Staining (stained in Alizarin Red-S and potassium ferricyanide) (Sun core, Lower Moran, 2503', crossed polarizers, 100X).

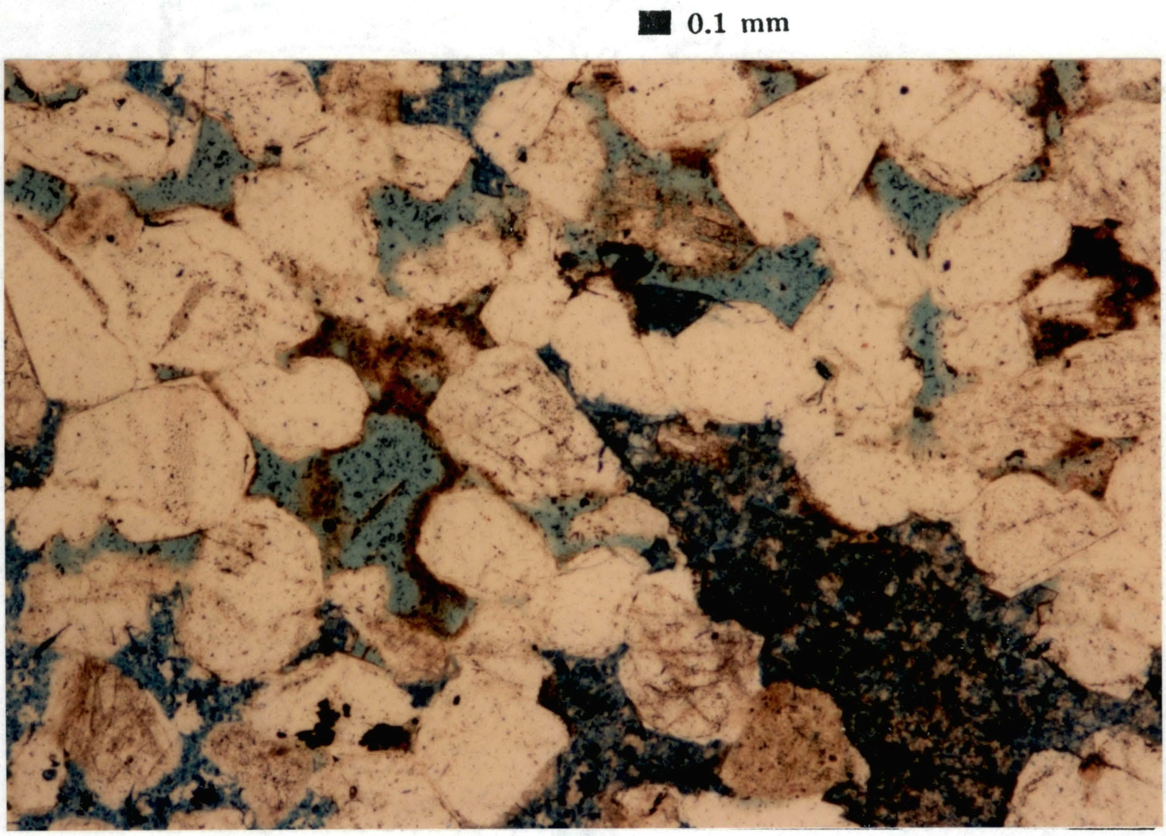

Figure 27. Large, Irregular Intergranular Space Filled with Ankerite Cement (stained in Alizarin Red-S and potassium ferricyanide) (Jones core, Upper Moran, 2104', plane polarized, 40X).

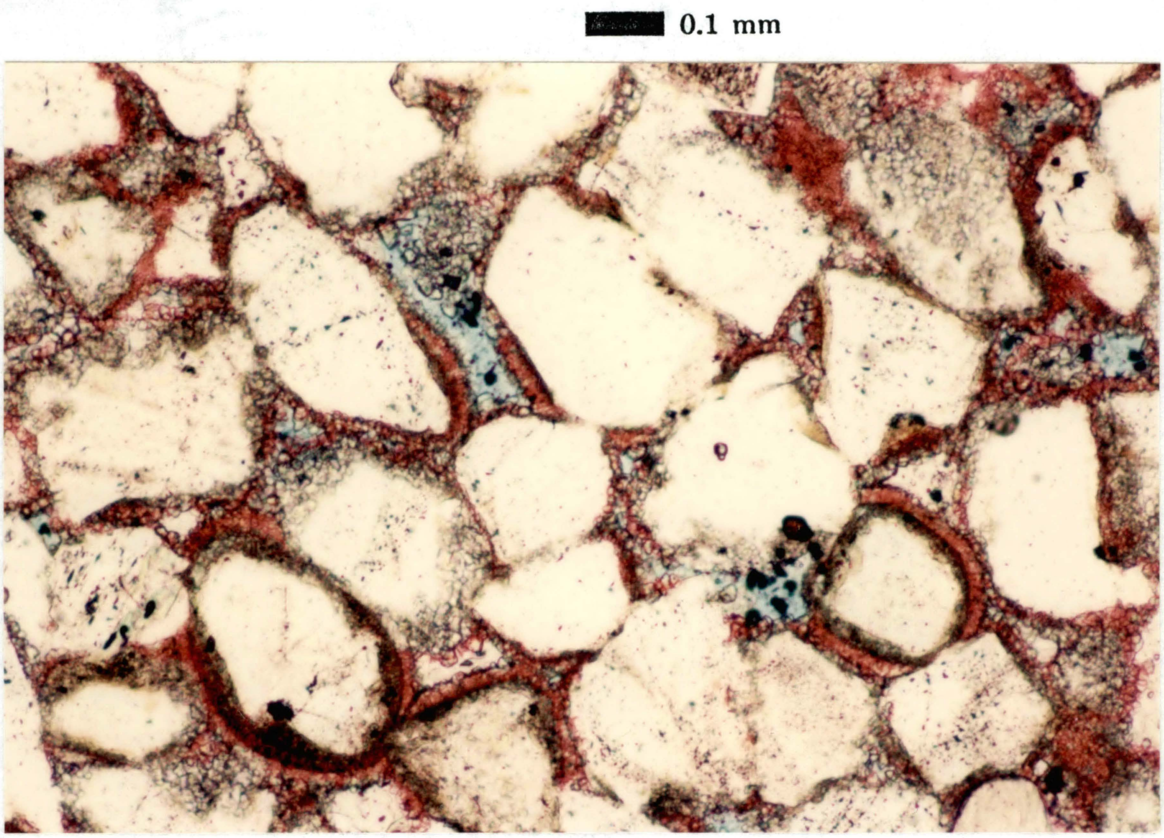

Figure 28. Calcite Coated Grains (stained in Alizarin Red-S and potassium ferricyanide) (Sun core, Cross Cut, 2404', plane polarized, 100X).

coated, partially coated or not coated at all. The coatings appear to possess a faint radial fabric.

Siderite

The sandy, clayey siltstone immediately above the reservoir sandstone in the Jones (Upper Moran) core is heavily cemented with siderite (Figure 29). Although the siderite is present throughout the sample, it is concentrated in concretionary masses 1 cm to 3 cm across. Total siderite content is 35%.

Authigenic Clays

Authigenic kaolinite, illite and chlorite occur in varying amounts throughout most of the samples. The most abundant is kaolinite, occurring in amounts ranging from less than 1% to 4%. The greatest concentrations of kaolinite are found in the most porous samples. One of the samples with the highest porosity is from 2105 feet in the Jones core (Figure 30, also see Plate 12). Figure 31 is a scanning electron microphotograph of that same sample. Both Figures 30 and 31 illustrate the high degree of crystallinity developed in this authigenic clay. The habit of all of the kaolinite is pore filling vermicular.

Illite is of secondary import as an authigenic clay in the samples. It occurs primarily as a product of recrystallization of detrital illitic clay clasts and matrix (Figure 16). To a lesser extent, it is present as pore

■ 0.1 mm

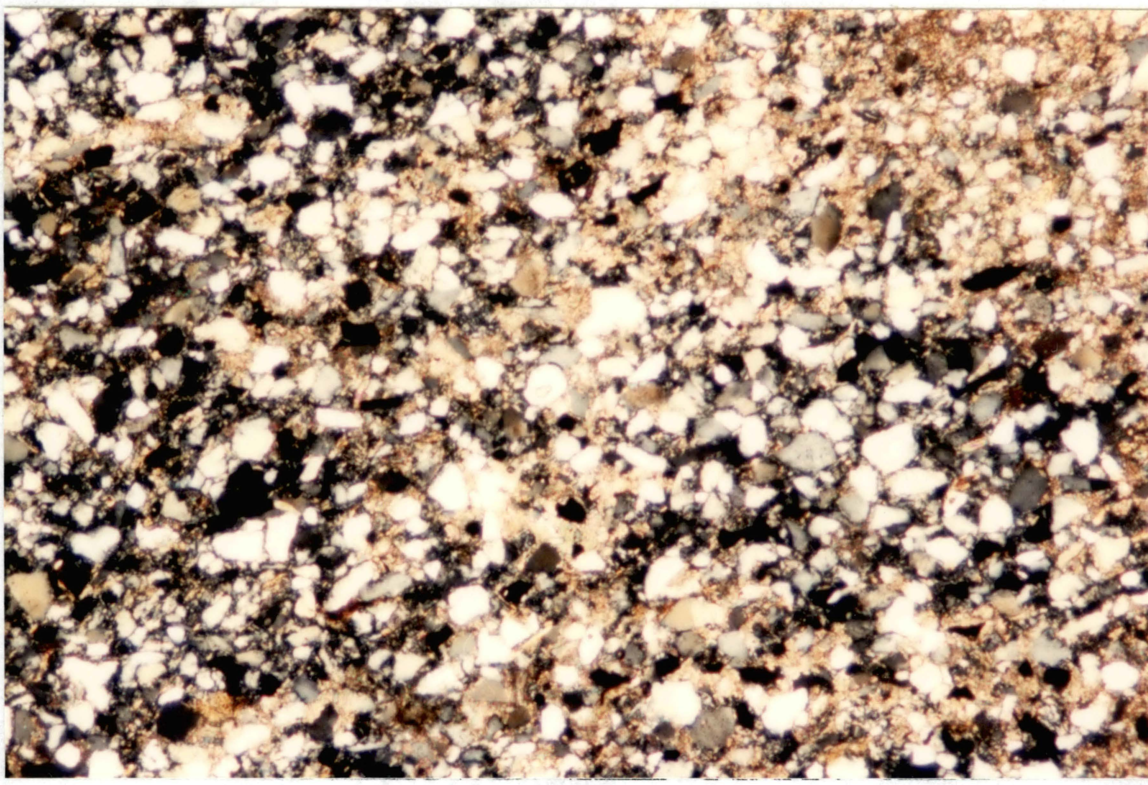

Figure 29. Concretionary Siderite Cementation in a Siltstone Above a Reservoir Sandstone (Jones core, Upper Moran, 2095', crossed polarizers, 20X).

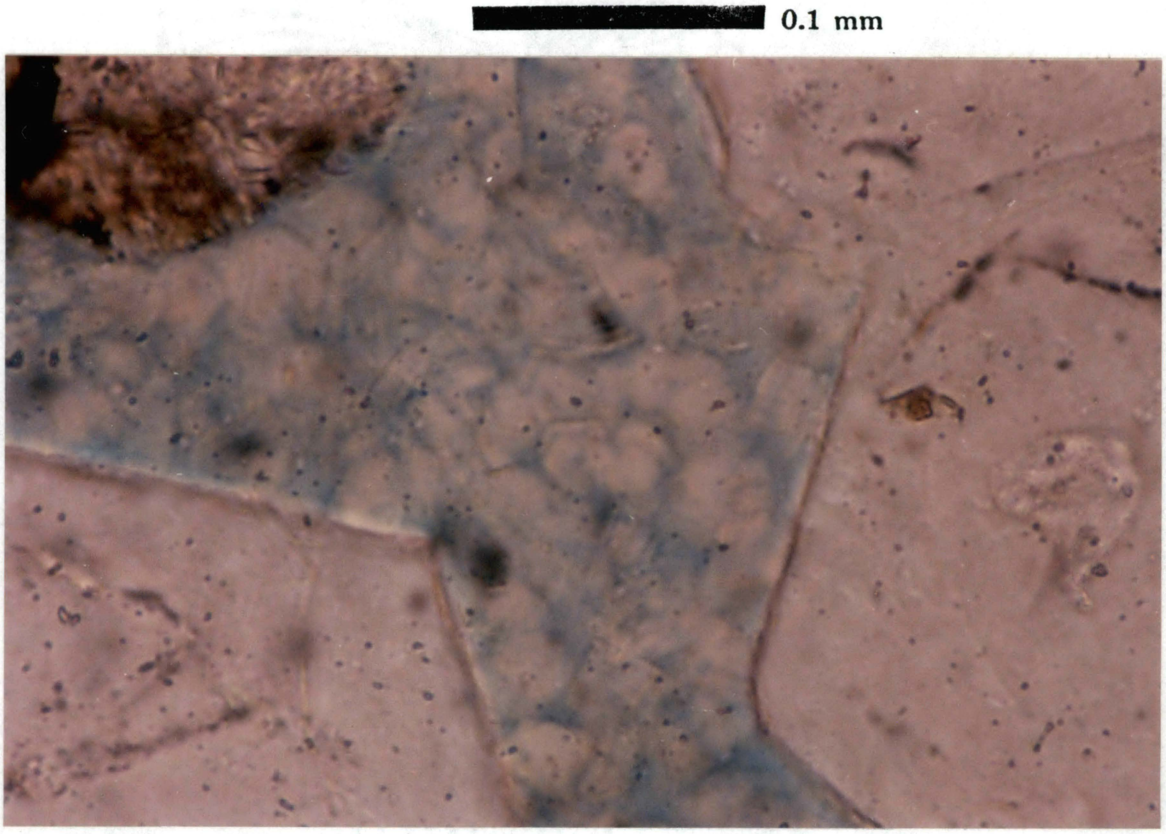

Figure 30. Pore Filling Vermicular Kaolinite (note the high percentage of intercrystalline porosity) (Jones core, Upper Moran, 2105', plane polarized, 400X).

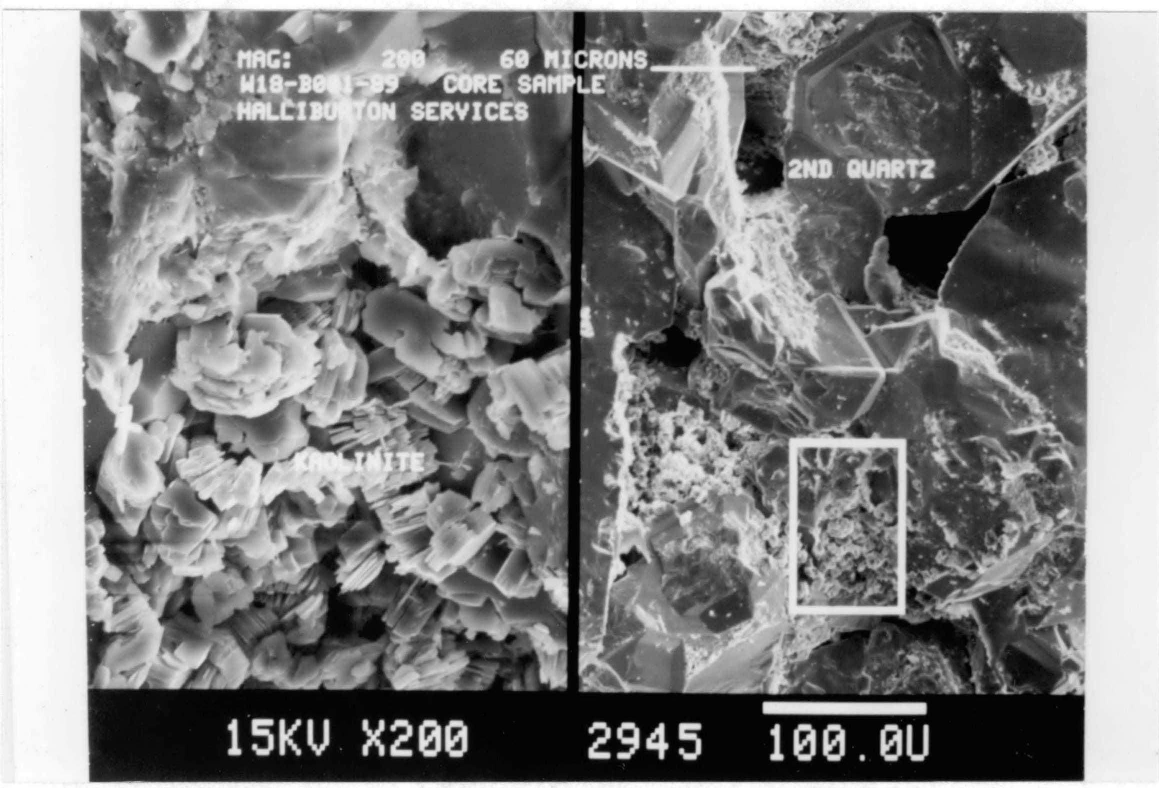

Figure 31. Pore Filling Vermicular Kaolinite, (Jones core, Upper Moran, 2105').

lining authigenic clay, but mostly not as a pore filling clay (Figure 32). A minor amount is seen as an alteration product of detrital feldspar grains (Figure 33). The scanning electron photomicrograph in Figure 34 (also see Figure 31) shows none of the characteristic fibrous, lath-like pore filling authigenic illite. The total amount of authigenic illite present in the thin sections is 1%.

Authigenic chlorite "dust rims" can be seen on many of the quartz framework grains. They are relatively poorly developed and do not appear to have had any great inhibiting effect on the growth of syntaxial quartz (see the two quartz grains in the upper right of Figure 24). The position of the chlorite beneath the quartz overgrowths indicates that it was formed earliest. This is common, due to early release of aluminosilicates and iron oxides from detrital clays (Blatt, 1979). None of the pore lining "edge-to-face" morphology, characteristic of chlorite is seen in the scanning electron microphotographs (see Figures 31 and 34).

Porosity

Introduction

The amount of porosity as a percentage of total rock volume varies among the samples from 4% to 18%. The porosities of the samples of the Sun core are systematically lower than those in the Jones core. The Cross Cut, Upper Moran and Lower Moran sandstones in the Sun core have

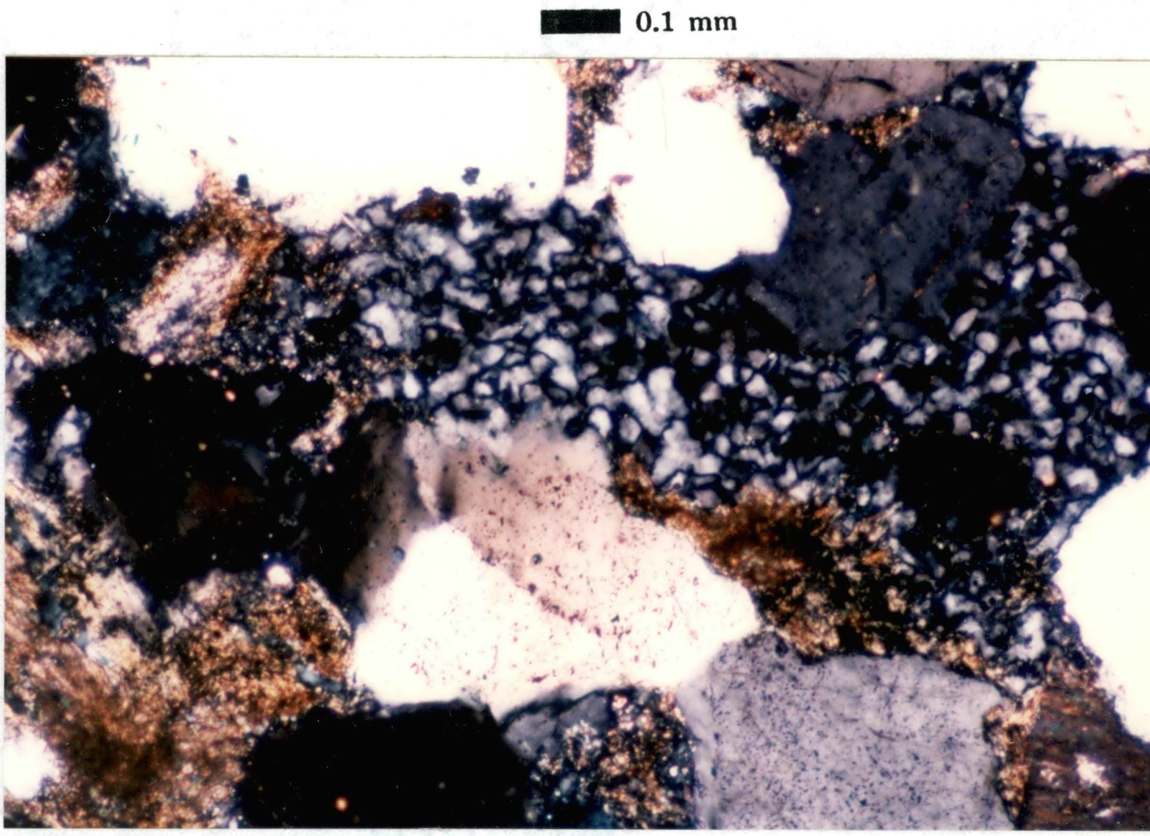

Figure 32. Pore Lining Authigenic Illite (Jones core, Upper Moran, 2104', crossed polarizers, 100X).

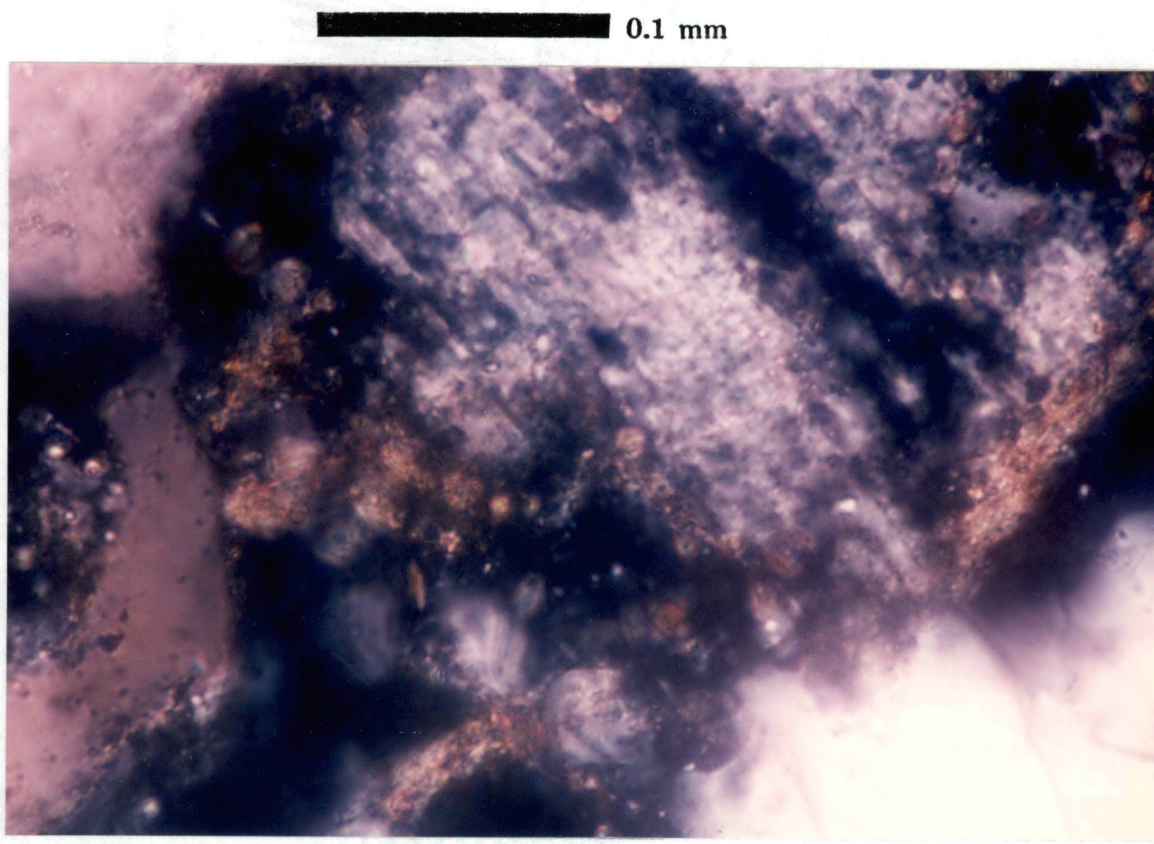

Figure 33. Authigenic Illite as an Alteration Product of a Detrital Feldspar Grain (Jones core, Upper Moran, 2100', crossed polarizers, 400X).

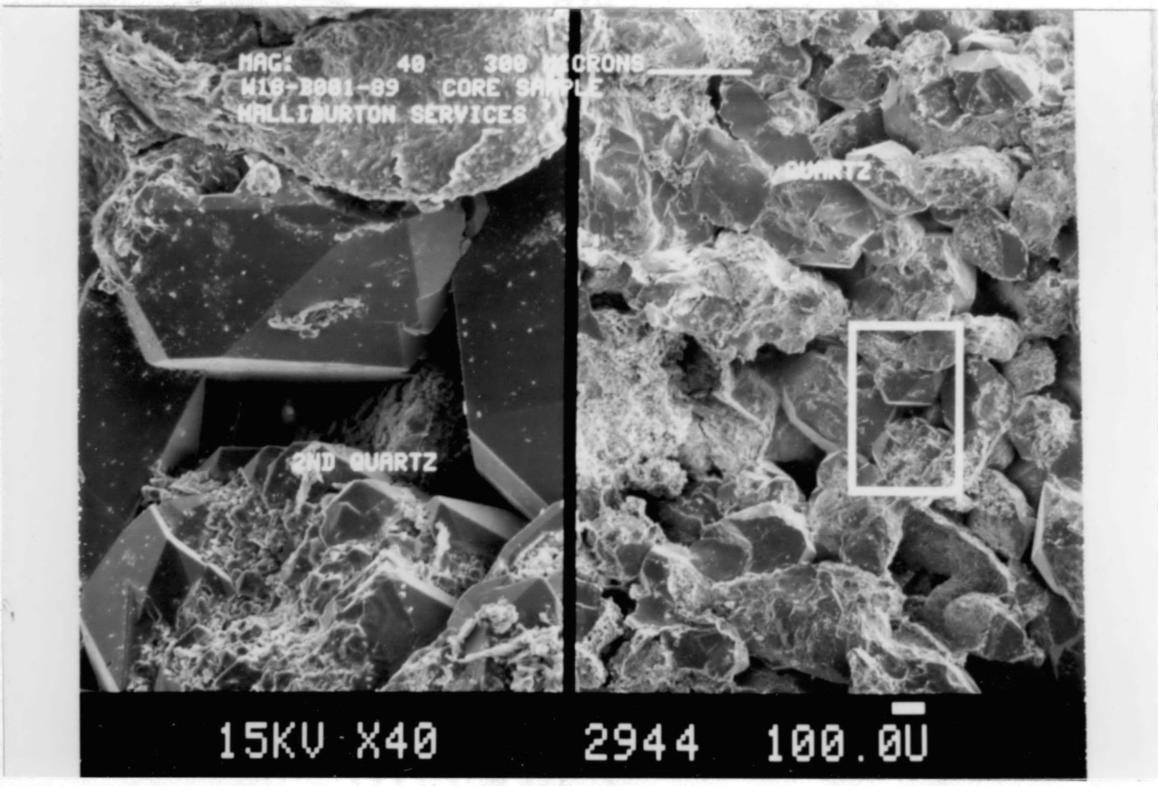

Figure 34. Well Developed, Open Pore System with Relatively Little Detrital Matrix, Authigenic Clay and Epitaxial Cement (Jones core, Upper Moran, 2105').

porosities of 4%, 7%, and 6% respectively. Porosities in the samples of Upper Moran sandstone in the Jones core range from 8% to 18%, averaging 14% of the reservoir sandstone interval as a whole. Practically identical individual and average porosity values are indicated by density log readings and thin section and conventional core plug analysis (Plates 11 and 12). This excellent correlation can be attributed to the relatively simple texture, mineralogy and pore system morphology of the sandstone. Measured permeabilities range from 54 md to 220 md, averaging 101 md.

There is only moderate variation in the amounts of porosity among the samples, and likewise the variations in pore type are few. Schmidt and McDonald (1979b) classified secondary pore types according to genesis and texture (preserved primary pore types can also be classified using this scheme). They recognized five significant genetic classes and five major groups of pore textures (Figure 35). With fifteen different textures and five genetic classes there are fifty three possible combinations of specific pore types. When the contributions of numerous constituents and genetic process mechanisms are factored in (e.g. feldspar grains and clay grains, ankerite cement and quartz cement, etc.) the number of possible pore types is even greater. The value in this method is that it provides a comprehensive, systematic and objective approach to dealing with the many variables inherent in complex pore sys-

Porosity Textures	Genetic Classes of Secondary Porosity				
	Result of Fracturing	Result of Shrinkage	Result of Dissolution of Sediment	Result of Dissolution of Cement	Result of Dissolution of Replacement
INTERGRANULAR TEXTURES					
Regular intergranular		X P	X P&C	X P&C	X P&C
Reduced intergranular		X P	X P&C	X P&C	X P&C
Enlarged intergranular		X P	X P&C	X P&C	X P&C
OVERSIZED TEXTURES					
Oversized fabric selective		X	X	X	X
Oversized crosscutting				X	X
MOLDIC TEXTURES					
Grain mold		X P©	X P&C©Ⓕ	X P&C	X P&C
Cement mold		X P		X P&C	X P&C
Replacement mold		X P		X P&C	X P&C
INTRA-CONSTITUENT TEXT					
Intragranular		X	X©Ⓕ	X	X
Intra-matrix		X	X	X	X
Intra-cement		X		X	X
Intra-replacement		X	X	X	X
FRACTURE TEXTURES					
Rock fractures	X		X P&C	X P&C	X P&C
Grain fractures	X©			X P&C	X P&C
Intergranular fractures	X			X P&C	X P&C

P&C indicates open void may extend over part of the textural precursor or over the complete textural precursor
P indicates open void may extend only over part of textural precursor

© indicates the involvement of clay grains in the developement of secondary porosity.
Ⓕ indicates the involvement of feldspar grains in the developement of secondary porosity.

Figure 35. Textural Spectrum of Secondary Sandstone Porosity (modified from Schmidt and McDonald, 1979b).

tems. It accommodates detail while allowing standardization and affording synthesis.

In applying this classification scheme to the samples of Cross Cut and Moran sandstones used in this study, six different specific pore types may be identified. Pores of three of the five genetic classes and two of the texture types, involving three different constituents (see Figure 35) all contribute materially to the pore system.

Fracturing and Shrinkage

Although no mechanical fracturing is present in any of the samples, shrinkage cracks in clay grains create many intragranular pores (Figure 36). Shrinkage of clay grains without cracking has resulted in the formation of partial grain mold pores (Figure 37). Clay grains make up an average of 4% of the samples, and many show signs of shrinkage with or without cracking. Up to 2% porosity is developed in pore spaces resulting from fracturing and shrinkage.

Dissolution of Sediment

Porosity created by the dissolution of sedimentary material results from the selective dissolution of soluble grains and matrix (Schmidt and McDonald, 1979b). Feldspar grain dissolution, which is quite common in other sandstones, is not the major contributor to secondary porosity in these samples. The provenance and maturity of these

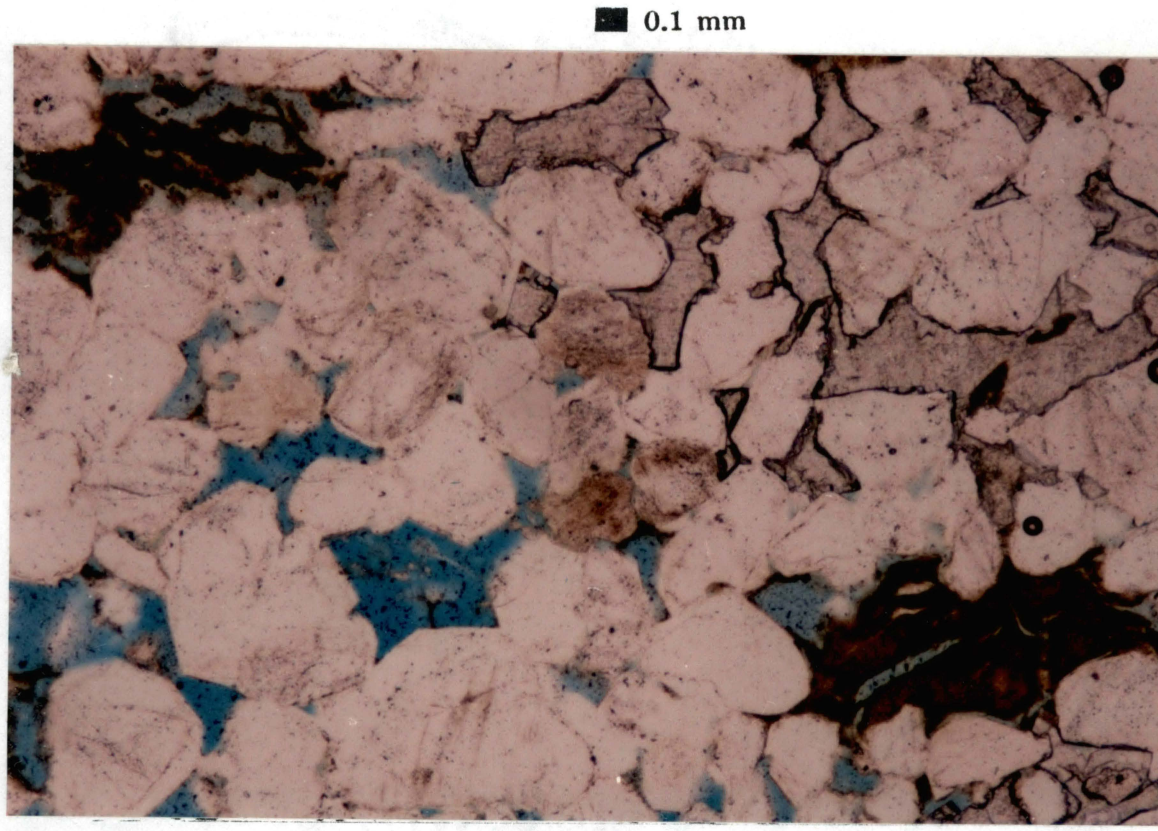

Figure 36. Intragranular Pores Created by Shrinkage Cracks in Clay Grains (Jones core, Upper Moran, 2105', plane polarized, 40X).

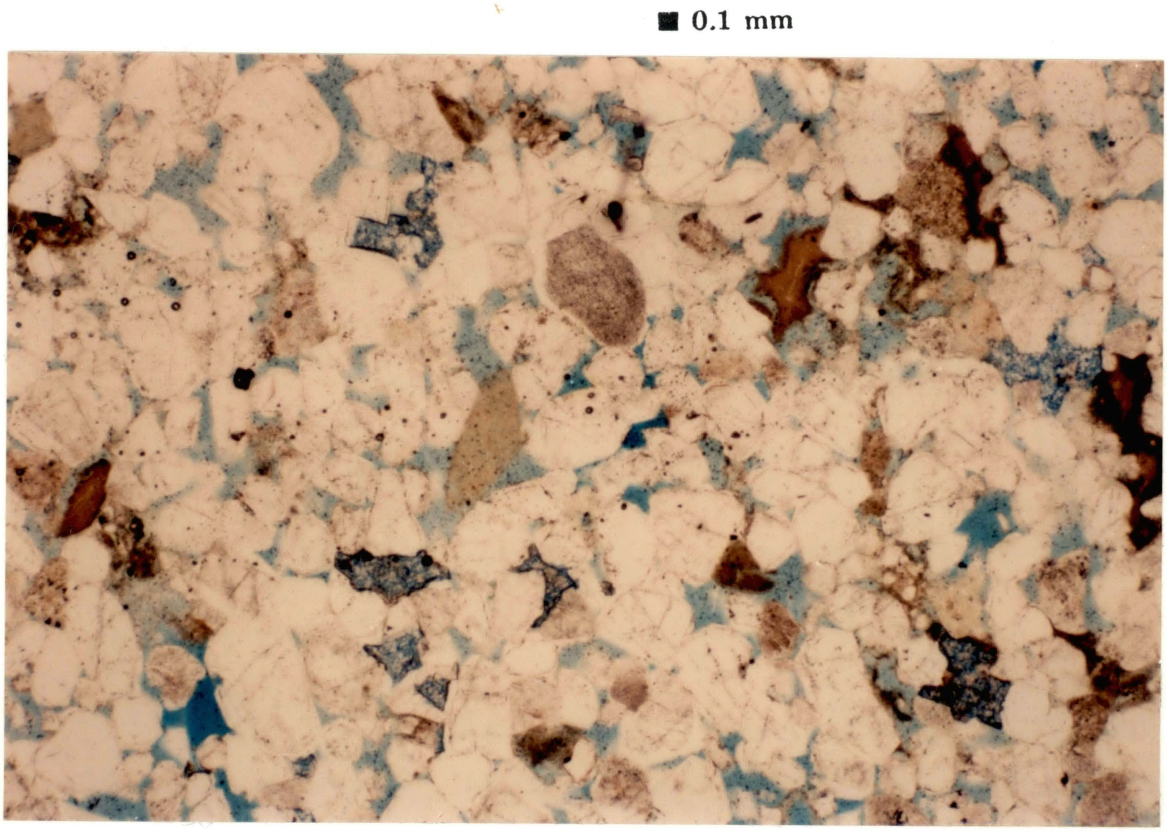

Figure 37. Partial Grain-Mold Pores Created by Shrinkage of Clay Grains (central upper right part of photograph) (Jones core, Upper Moran, 2105', plane polarized, 20X).

sandstones are such that these rocks contained very little feldspar to begin with. Clay grains however, are very abundant in these sandstones and it is their dissolution which created the overwhelming majority of the secondary porosity. Based on the ratio of the remains of partially dissolved feldspar grains to those of clay grains, it is estimated that 1% porosity may be attributed to the dissolution of feldspar grains and 13% to the dissolution of clay grains. Two textures of pores which are created as a result of the dissolution of feldspar grains and clay grains exist in the samples; (1) grain mold and (2) intragranular.

Grain mold pores are created selectively at the expense of grains and show outlines characteristic of the texture of their precursors (Schmidt and McDonald, 1979b). The pores in Figure 38 mimic clay grains in their size, shape and distribution. Figure 39 (also see Figure 14) shows how partial dissolution of sedimentary material can result in the formation of intragranular porosity. Both grain mold and intragranular pores are abundant, but since the grain mold pores are larger they are the principal contributor to porosity in the Cross Cut and Moran sandstones.

Dissolution of Cement and Replacement

Several forms of cement and replacement occur in the samples. Syntaxial quartz overgrowths, calcite grain coats, poikilotopic ankerite, siderite and kaolinite are

0.1 mm

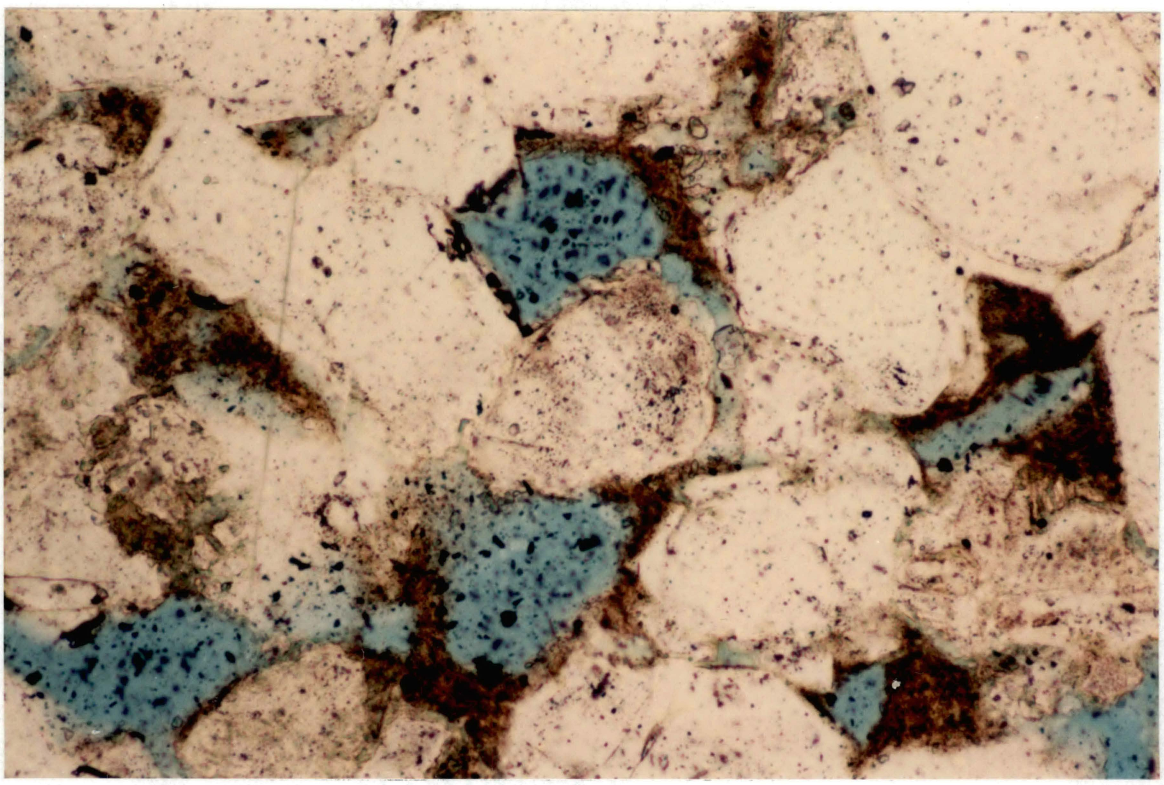

Figure 38. Grain Mold Pores Created by Dissolution of Sedimentary Clay Grains (Jones core, Upper Moran, 2104', plane polarized, 100X).

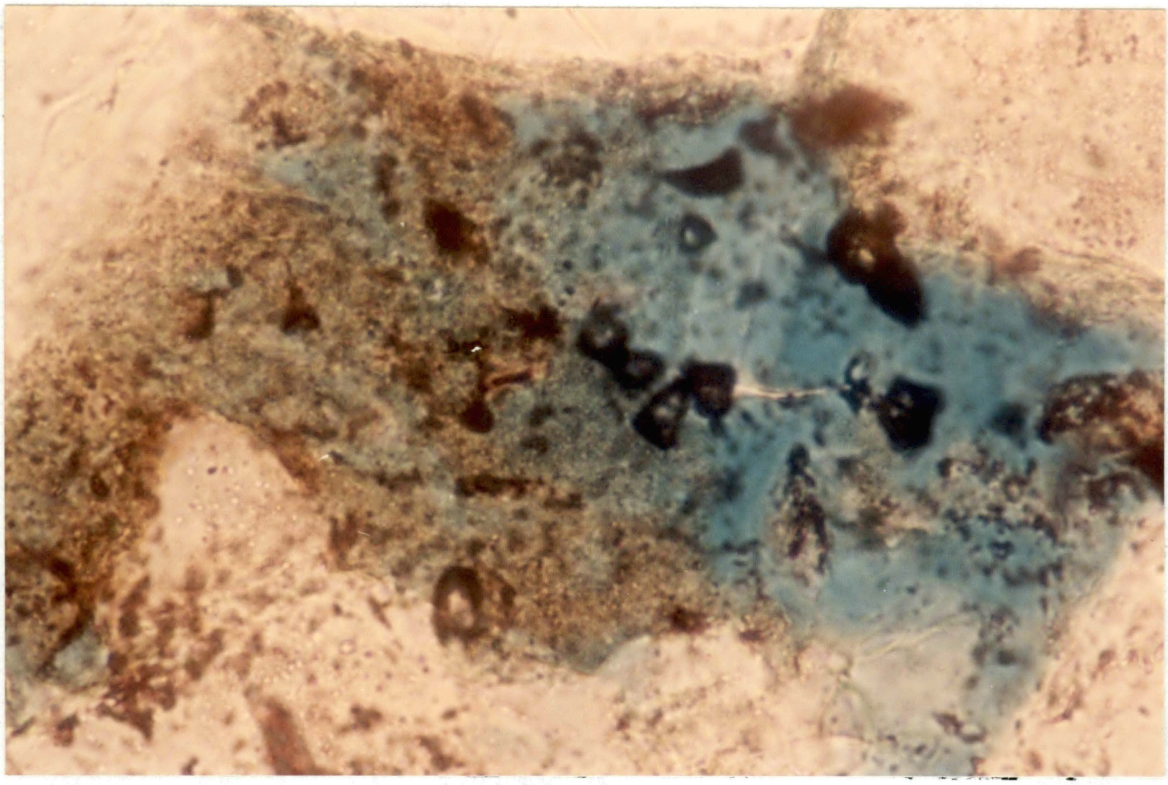

Figure 39. Intragranular Pore Created by Partial Dissolution of a Sedimentary Clay Grain (Sun core, Upper Moran, 2456', plane polarized, 400X).

present as cements; the ankerite may also be partially replacive. None of these, however, exhibit any appreciable dissolution. Therefore dissolution of cement and replacement do not contribute substantially to porosity in the samples.

Diagenetic Processes

The most important diagenetic processes relevant to the formation of secondary porosity in the samples are those which relate to the dissolution of the clay grains. Three separate processes are responsible for the predilection, development and preservation of these pores. They are (respectively): (1) shrinkage of the clay grains, (2) dissolution of the clay grains and (3) inhibition of consequential kaolinite precipitation.

Clay Grain Shrinkage

Shrinkage, with or without cracking, is common among the clay grains (see Figures 36 and 37). Although the porosity resulting from the shrinkage and cracks per se is only about 2%, these early spaces served to enhance the later development of dissolution porosity. By creating substantial space in and around most of the clay grains, these shrinkage features greatly increased initial permeability. Thus, the clay grains were exposed and subjected to increased contact with solvent formation waters. This mechanism of shrinkage is called syneresis and is due to spontaneous water loss of these clasts in response to changes in formation water chemistry (Donovan and Foster, 1972). The salinity change could have occurred shortly after deposition if these clay grains, which were formed in fresh water, became saturated with marine formation water. However, since the grains had undergone extensive ductile deformation prior to shrinkage and the shrinkage pores and cracks are preserved, it appears as if shrinkage occurred after mechanical compaction. Water expelled during early shale diagenesis is rich in ionic species (Hower, 1976). The shrinkage, due to sudden water loss, was the response of the heretofore fresh water clay grains to reach equilibrium with this new saline formation water.

Clay Grain Dissolution

Dissolution of the clay grains is the principal cause of secondary porosity in all of the samples. The process responsible for the dissolution is related to hydrocarbon maturation. Production of carbon dioxide and decarboxylation of organic matter are early processes of hydrocarbon maturation (McBride, 1977). Water, rich in carbonic and carboxylic acids, is expelled from shales into adjacent sandstones where it causes intense dissolution. Hydrolysis in the presence of these acids can result in the direct dissolution of both clay grains and feldspar grains (Al-Shaieb and Shelton, 1981). In this way, clay clasts and feldspar grains are removed without having been previously replaced by carbonate. It should be noted that no traces of replacive calcite or signs of replacement by calcite (e.g. corroded quartz overgrowths in contact with pores, etc.) are found in any of the samples.

Inhibition of Kaolinitization

Inhibition of kaolinite precipitation has occurred in these sandstones, thereby preserving much of the secondary porosity. Kaolinite commonly forms as an alteration product during the dissolution of clay grains and feldspars (Al-Shaieb and Shelton, 1981). However, it is clearly seen in the thin sections, that relatively few of these secondary pores contain kaolinite. The presence of organic anions of carboxylic acids (produced during hydrocarbon maturation) can result in the complexing of the aluminum released during feldspar and clay grains dissolution (Surdam, et al., 1984). Chelating is the specific means by which this complexing of aluminum is accomplished (personal communication, Al-Shaieb, 1984). By substituting for hydrogen in the carboxyl group, the metal cation (aluminum in this case) reacts with the organic anion (Krauskopf, 1979). As a result of this mobility of aluminum, there is sufficient mass transfer to create and preserve secondary porosity (Surdam, et al., 1984). Again, it can be seen how the development of secondary porosity is related to the maturation of hydrocarbon.

Quartz Cementation

Another important diagenetic process is the clay diagenesis which occurs in the shales within and below the study interval. Upon sufficient burial, the smectite in the shales will alter to illite, releasing silica in the process (Hower, 1976). The amount of this silica can be quite large, and when it is expelled into adjacent sandstones it can cause syntaxial quartz cementation. The depth and temperature required for this process would have necessitated its occurrence at or near maximum burial of the study interval. In a study of the "Gray" (Strawn) sandstone, a unit approximately 600 feet below the Cross Cut and Moran, in an area approximately thirty miles southwest of the study area, Land and Dutton (1978) performed extensive analytical geochemistry including isotope analysis. Oxygen isotope values for quartz cement indicated that it formed at a high temperature. They concluded, therefore, that most of the quartz overgrowths formed at maximum burial.

Ankerite and Kaolinite Cementation

The processes of ankerite and kaolinite cementation were also studied in Land and Dutton's (1978) study of the nearby "Gray" (Strawn) sandstone. Oxygen isotope analysis of these two components indicated that they were related to one another but not to the quartz cement (Land and Dutton, 1978). The "baroque", poikilotopic texture of the ankerite cement (see Figures 25 and 27) indicates that it formed at high temperature (personal communication, Al-Shaieb, 1984). Because there is no significant difference between the packing of the sand grains within and outside of the cement (see Figure 23) it is evident that the ankerite cementation occurred after mechanical and chemical compaction had ceased. The ankerite cement would not have survived the period of intense dissolution which followed decarboxylation of organic matter, so it must have formed after the development of secondary porosity. This is evidenced by the fact that it completely fills large secondary pores (see Figure 27). Likewise, the kaolinite is present as a secondary pore filling cement in a position subordinate to quartz overgrowths and partially dissolved clay clasts (see Figure 30).

The large amount of reduced iron which was mobilized in the formation of the ankerite, and the depleted carbon isotope values of the ankerite support its involvement with an organic system (Land and Dutton, 1978). Hydrocarbon generation was, most likely, the source of these organics. With the carboxylic acids and aluminum chelating agents spent, ankerite and kaolinite precipitated freely in the newly formed secondary pores. The decrease in carbonate solubility necessary for the ankerite precipitation was probably in response to the decreases in pressure and carbon dioxide solubility attendant with sedimentary unloading during uplift and erosion (Al-Shaieb and Shelton, 1981).

Ungerer, and others, (1990) proposed a theoretical scheme of primary oil migration at three successive stages. In their stage 1 (immature), oil saturation in the source rock is 0% and only water is expelled. By stage 2 (beginning of oil formation) oil saturation is 5% and hydrocarbons start to invade the microporosity in the source rock, but still no oil phase is expelled. In stage 3 (mature stage), oil saturation in the source rock has reached greater than 20% and oil expulsion occurs.

The various diagenetic processes inferred in this study can be linked to this scheme. The silica and ion rich waters responsible for quartz cementation and clay grain shrinkage in the sandstones would be those waters expelled from the source rock during stage 1. The waters containing organic acids and carbon dioxide which dissolved the clay grains and feldspars would have been expelled during stage 2. And, of course, the oil which ultimately filled the sandstone reservoirs would have been expelled from the source rock during stage 3.

Diagenetic Scenario

Introduction

The burial and diagenetic histories of the Cross Cut and Moran sandstones in the study area are presented schematically in Figure 40. The study interval is presently buried at an average depth of 2200 feet, overlain by the Cisco Group (at the surface) and the Canyon Group. The

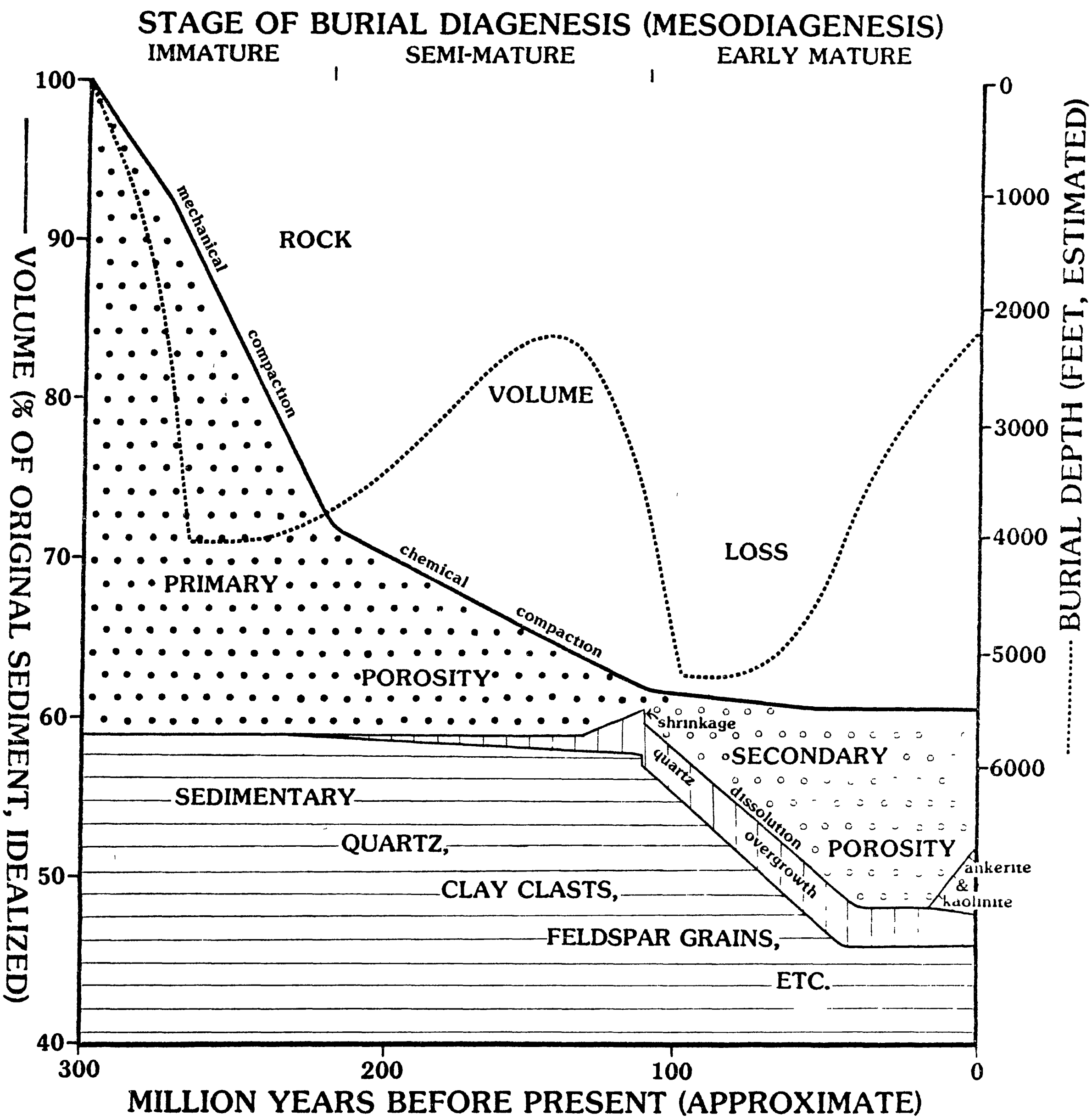

Figure 40. Schematic Burial and Diagenetic Histories of the Cross Cut and Moran Sandstones in the Study Area (adapted from Land and Dutton, 1978 and Schmidt and McDonald, 1979a).

area was once covered by the remainder of the Permian System. The maximum combined thickness of the Wichita-Albany Group and the Clear Fork Group (Permian) has been estimated at 1800 feet (Brown and Goodson, 1972). Therefore, the study interval could have been buried at a depth of up to 4000 feet at the end of Permian time. However, eastward tilting and uplift of the platform caused the removal of most of the Permian System over the study area. The thickness of the post-Clear Fork rocks was approximately 3000 feet (Land and Dutton, 1978). Based on these estimates, the rocks of the study interval attained a maximum depth of burial of approximately 5200 feet in early Cretaceous time.

Diagenetic history (of rocks in general) has been subdivided on the basis of burial position by Choquette and Pray (1970). Eodiagenesis is defined as the regime (eogenetic) at or near the surface of sedimentation, where the chemistry of the interstitial water is mainly controlled by the surface environment prior to effective burial. Mesodiagenesis is the subsurface regime (mesogenetic) during effective burial. Telodiagenesis represents the regime (telogenetic) at or near the surface after effective burial. Mesodiagenesis can be subdivided on the basis of the diagenetic alteration of primary and secondary porosity in response to progressive burial. Schmidt and McDonald (1979a) proposed four textural stages of mesodiagenesis. These are in order of progressive burial: (1) immature; (2) semi-mature; (3) mature and, (4) super-mature (Figure 41). They further subdivided the mature stage into two stages; "A" and "B." Mature stage "A" or early mature stage is the phase of maximum development of secondary porosity and mature stage "B" or late mature stage is characterized by the gradual destruction of secondary porosity mainly by chemical compaction (Schmidt and McDonald, 1979a). The Cross Cut and Moran sandstones in the study area have not been uplifted to the near surface, nor have they suffered significant destruction of their secondary porosity. Therefore, they have progressed no further than the early mature stage of mesodiagenesis (mature "A").

Diagenetic Scenario

The paragenetic sequence of the major diagenetic processes and products affecting the reservoir sandstones of the Cross Cut and Moran in the study area are as follows (see Figure 40).

Following Clear Fork deposition (Lower Permian) the rocks of the study interval were buried to a depth of approximately 4000 feet. Immature stage mechanical compaction was extensive due to ductile deformation of abundant clay grains and the lack of sedimentary or eogenetic carbonate cement. This was followed by semi-mature stage chemical compaction in the form of minor quartz cementation, sourced by pressure solution.

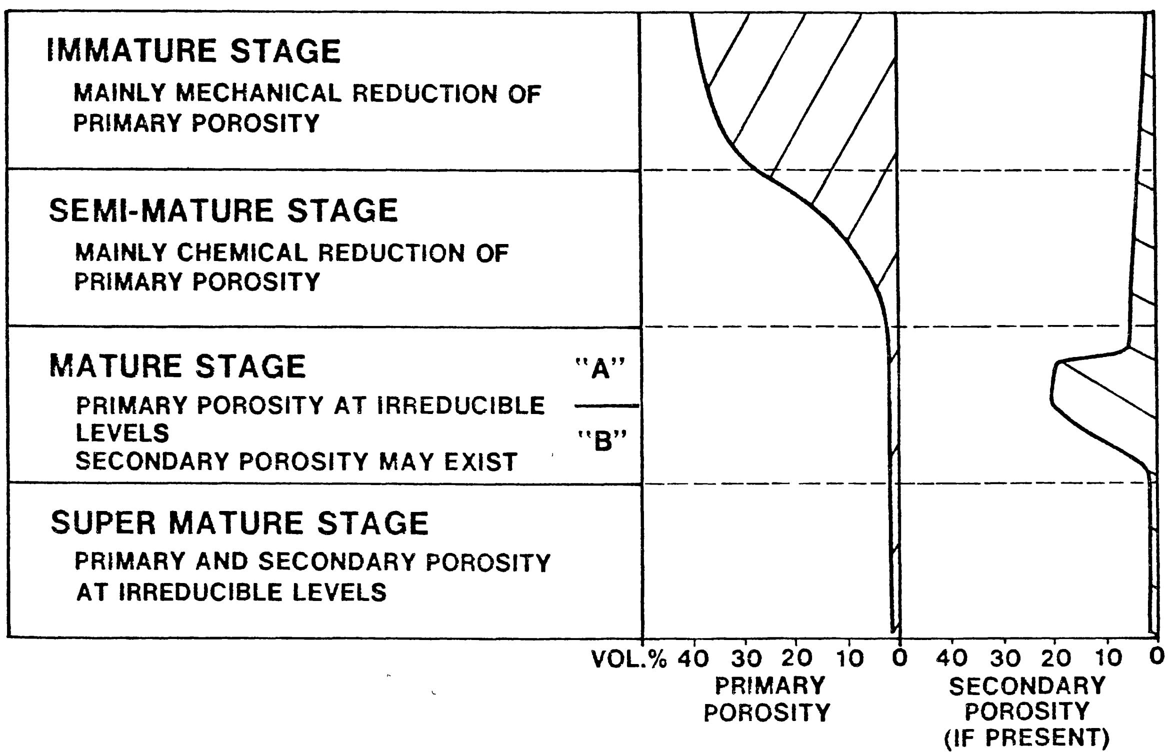

Figure 41. Textural Stages of Mesodiagenesis of Sandstone Porosity (Schmidt and McDonald, 1979a).

Meanwhile, the section was exhumed, and then later, was buried beneath an additional 3000 feet of rock during early Cretaceous time. At this point the Cross Cut and Moran sandstones reached their maximum burial depth of approximately 5200 feet. Chemical compaction was complete for the most part and the study interval had entered the early mature ("A") stage of mesodiagenesis.

Shale diagenesis began here and the attendant release of silica resulted in the formation of most of the quartz overgrowths at this time. The introduction of new ion-rich expelled shale water into the sandstones resulted in the shrinkage of clay grains. Only a small amount of secondary porosity resulted, but the added permeability would enhance the subsequent development of secondary porosity by permitting increased solvent fluid flow. Shale diagenesis progressed to the point of carbon dioxide generation and decarboxylation of organic matter. Waters rich in carbonic and carboxylic acids were expelled into the sandstones and the phase of maximum development of secondary porosity ensued. Extensive dissolution of clay grains and feldspar grains created up to 20% secondary grain mold and intragranular porosity. Meanwhile, the chelation of aluminum by carboxylic acid ions prevented the precipitation of kaolinite, thereby preserving the newly formed secondary porosity. When the carboxylic acids were spent, dissolution ceased.

In the absence of acids and aluminum chelating agents and in the presence of organics from hydrocarbon generation, moderate amounts of ankerite (and to a lesser extent, ferroan dolomite and dolomite) and kaolinite precipitated as pore filling cements.

Hydrocarbons (primarily oil) have since migrated into the sandstones. Where entrapment has occurred, these sandstones, with their well developed, open pore systems with relatively little detrital matrix, authigenic clay or epitaxial cement, provide excellent petroleum reservoirs (see Figures 13 and 34).

CHAPTER VI

ENVIRONMENT OF DEPOSITION

Deltaic Depositional Model

Introduction

Depositional systems are made up of assemblages of genetically related sedimentary facies. Ancient depositional systems can be identified by the nature and three-dimensional distribution of constituent facies. Surface and subsurface analysis of modern depositional systems allows three-dimensional characterization of their component facies. Models of modern depositional systems, based on such analysis, form the basis for facies classification. Criteria which are used to characterize facies include (1) vertical and lateral changes in the sediment texture and composition, (2) vertical and lateral changes in the types and dimensions of sedimentary structures, (3) the trend and geometry of the individual sand bodies, and (4) the spacial arrangement of the sand bodies relative to one another. For ancient deposits, these characteristic criteria are seen in outcrop, cores, thin sections, sandstone isolith map patterns and electric log signatures.

High Constructive Delta Model

Cleaves (1975) determined that the Strawn Group of north-central Texas was deposited by several fluvial-deltaic systems. Fisher (1969) and Galloway (1975) classified marine deltas on the basis of the relative effects of constructive fluvial and destructive marine reworking processes on delta morphology. Deltas dominated by fluvial progradational and aggradational processes are classified as high-constructive, whereas those whose morphologies controlled by marine reworking processes (tides and waves) are called high-destructive. Only high-constructive deltas are found in the Strawn Group of north-central Texas (Cleaves, 1975). Because these deltas are thin (100 feet to 300 feet) and were deposited across a stable, slowly subsiding shelf, they also fit into Brown's (1973) cratonic delta classification. Fisher (1969) further subdivided high-constructive deltas into "elongate" and "lobate" on the basis of the external geometry of the prograded delta-front sand body.

Characterization of Facies

Introduction

The principal sandstone facies found in the Cross Cut and Moran in the study area are: (1) delta front, (2) distributary mouth bar, and (3) distributary channel. They were identified as such by comparing evidence from outcrop, cores, thin sections, electric log signatures and sandstone isolith map patterns against models of modern facies and depositional systems. Five outcrops were studied. Their locations are given with their respective photographs in Figures 42, 49, 50, 51, and 52 (also see Figure 9 for their approximate map positions). All available cores of Cross Cut and Moran sandstone in the study area were examined. Electric and petrologic logs for each are shown in Plates 11 through 16 (a legend of symbols used and written descriptions are located in the appendix). The locations of the cored wells are indicated by small arrows on the sandstone isolith maps (Plates 20, 21, and 22). Electric logs from over 650 wells in the study area were utilized for sandstone thickness and facies log signature determination. The log signatures depicted on the sandstone isolith maps are tracings of actual SP curves which were selected to represent the various facies. Of course, the cross sections may also be referred to for numerous examples of log signatures.

The recognition of the differences in the log signatures and the identification of each to its associated facies was of great import in this study. During preliminary mapping, a notation indicating the log signature type was made along with each thickness value on the sandstone isolith maps. This practice facilitated interpretive contouring of the isolith values, which made allowances for facies changes. The resultant maps provide a "quantum leap" in information and interpretive value over isolith maps which contour sandstone thickness only. Gamma ray, microresistivity and porosity logs were available on less than 10 percent of the wells in the study area. Because of this, the SP and resistivity logs were used in determination of sandstone isolith values. These values were checked against those from wells where gamma ray, microresistivity, and porosity logs and/or cores were available. In most cases, the "cut-off" used was -40 mv from the "shale baseline" on the SP curve. Wherever SP curves are shown in any of the plates, this "cut-off" lines is depicted by a bold vertical line.

Delta Front Facies

This facies grades upward from a thin (30 feet or less), gray, unfossiliferous prodelta mudstone section. The delta front section contains thin beds and lenses of coarse siltstone and very fine sandstone interbedded with mudstone. Through progradation, the overall section gradually coarsens upward by a decrease in the mudstone and siltstone. This may result in the deposition of one or more massive or thin-bedded fine-grained sandstone beds near the top of the section. The delta front facies section is up to 40 feet thick. An outcrop of delta front facies rocks is shown in Figure 42. All three sandstone units (Cross Cut, Upper and Lower Moran) in the Sun core in

Figure 42. Prodelta and Delta Front Facies (Turkey Creek, Section 1, Cleaves, 1975, Farm to Market Route 4, 3.6 miles southeast of Palo Pinto).

Herr-King Field are delta front sandstones (Figures 43, 44, and 45 and Plates 14, 15, and 16).

The most prominent sedimentary structures in the delta front sandstones are graded beds and deformed bedding (Figure 46). Horizontal laminations are also common, with some thin, discrete zones having concentrated clay rip-up cobbles or macerated plant material (Figure 47). All of these sedimentary structures indicate frequent flood surges. Bioturbation may be found at the top of the delta front section if this part of the sequence is preserved (Figure 48). This part of the section may also contain zones of sedimentary calcite cement (see Figures 28 and 48). The presence of fully coated, partially coated, and non-coated grains together in the same rock (see Figure 28) may be the result of recycling of a beachrock-cemented distributary mouth bar sandstone. These coated grains and the abundant glauconitic clay clasts (see Figure 17) both indicate marine water influence in the environment of deposition of these particular sandstones.

The log signature of the overall section of the delta front, because of its progradational nature, is upward coarsening. However repeated flood surges produce a serrate log signature in which the individual thin sandstone beds show coarsening upward profiles, or fining upward profiles in the case of graded beds. As a result, a distinctive log signature is produced which is very different from those of the distributary mouth bar and distributary chan-

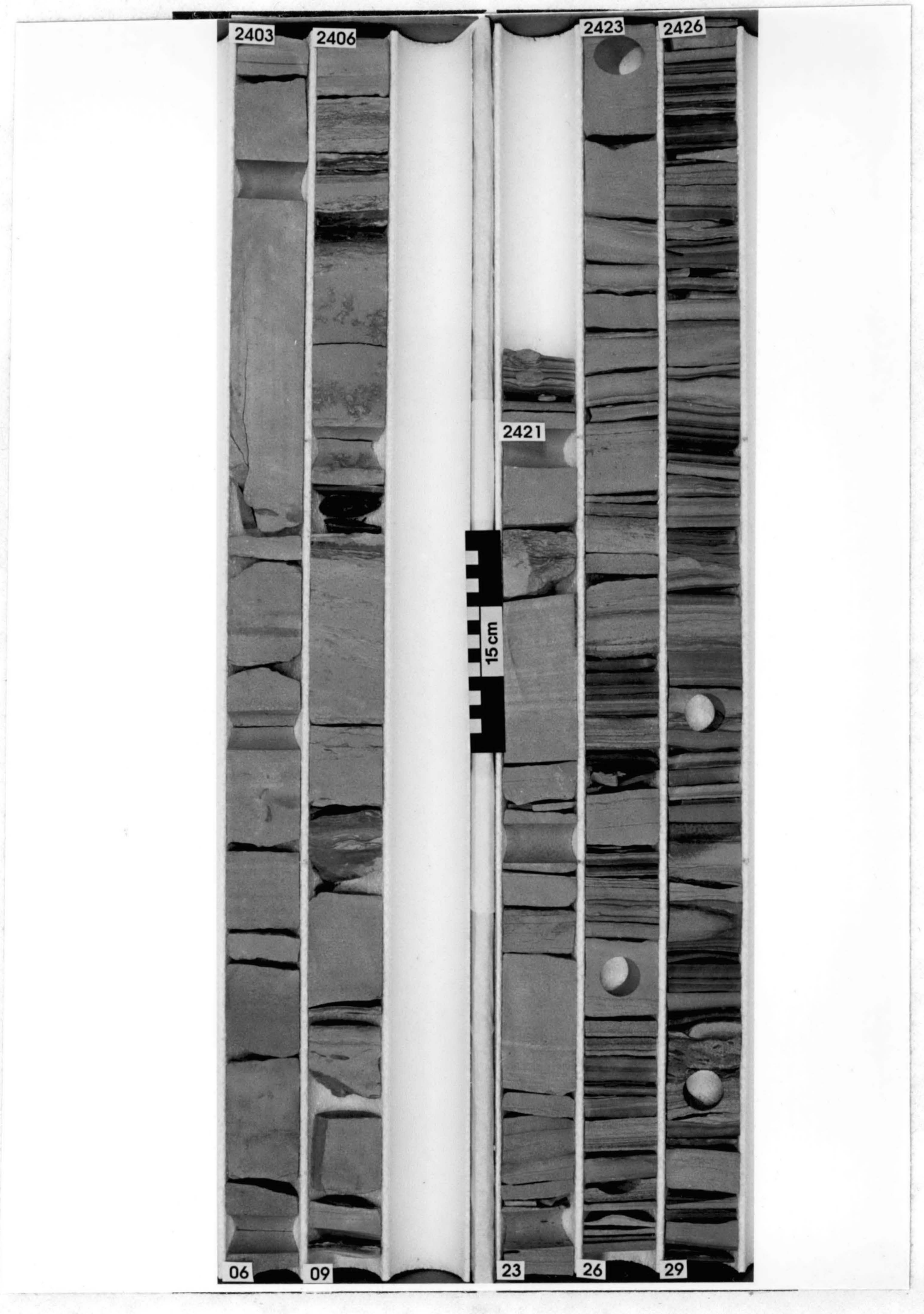

Figure 43. Delta Front Facies in the Cross Cut in the Sun Core.

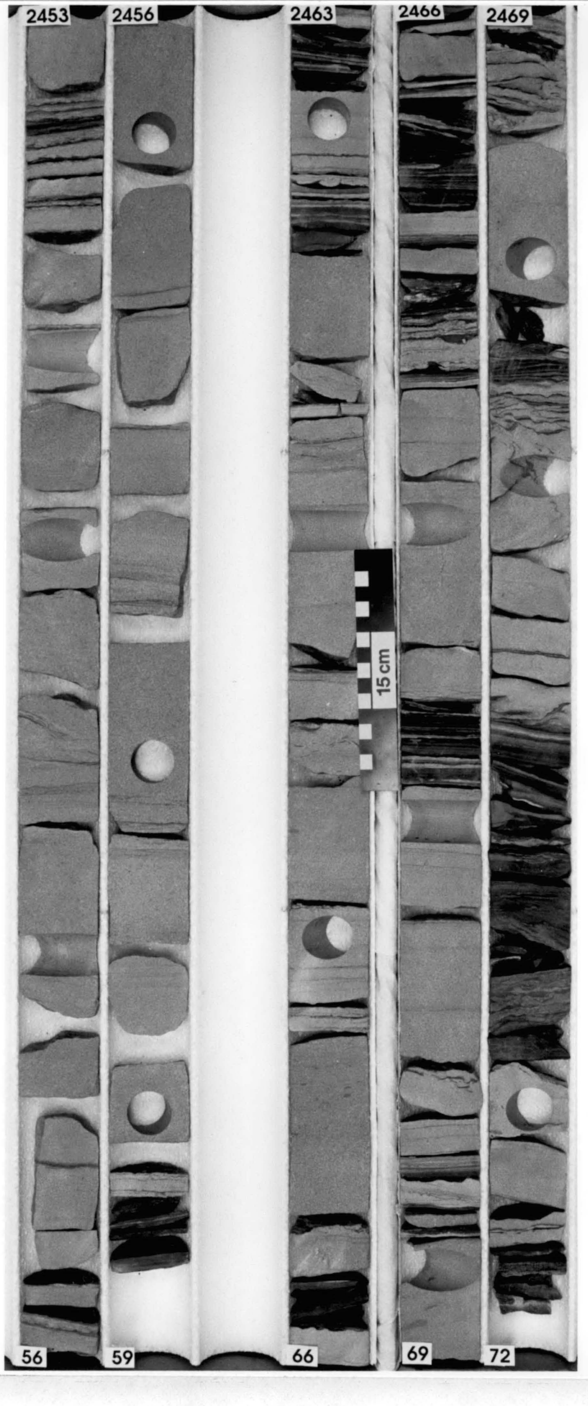

Figure 44. Delta Front Facies in the Upper Moran in the Sun Core.

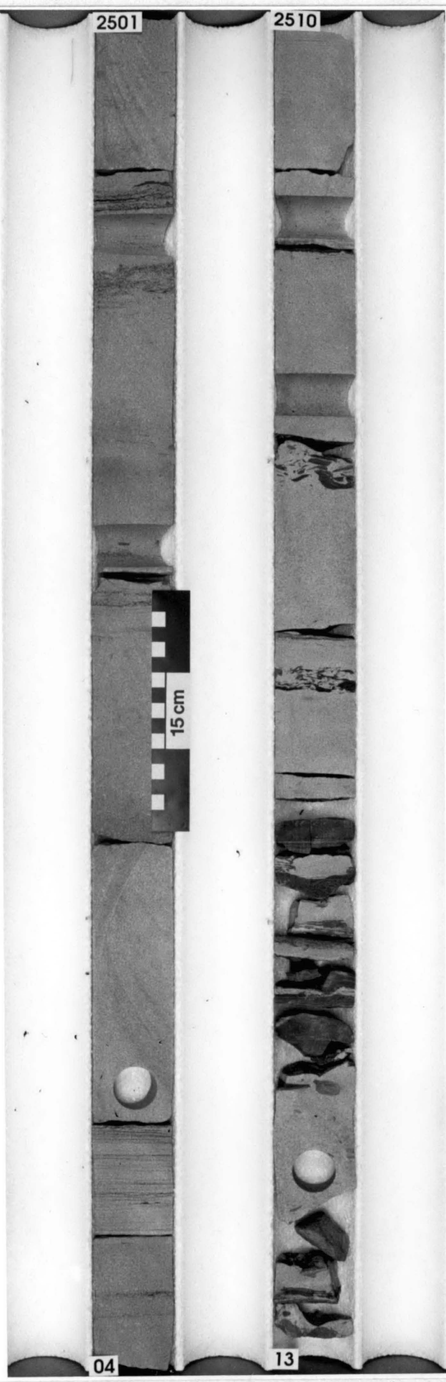

Figure 45. Delta Front Facies
in the Lower Moran in
the Sun Core.

Figure 46. Deformed Bedding in the Delta Front Facies (Sun core, Upper Moran).

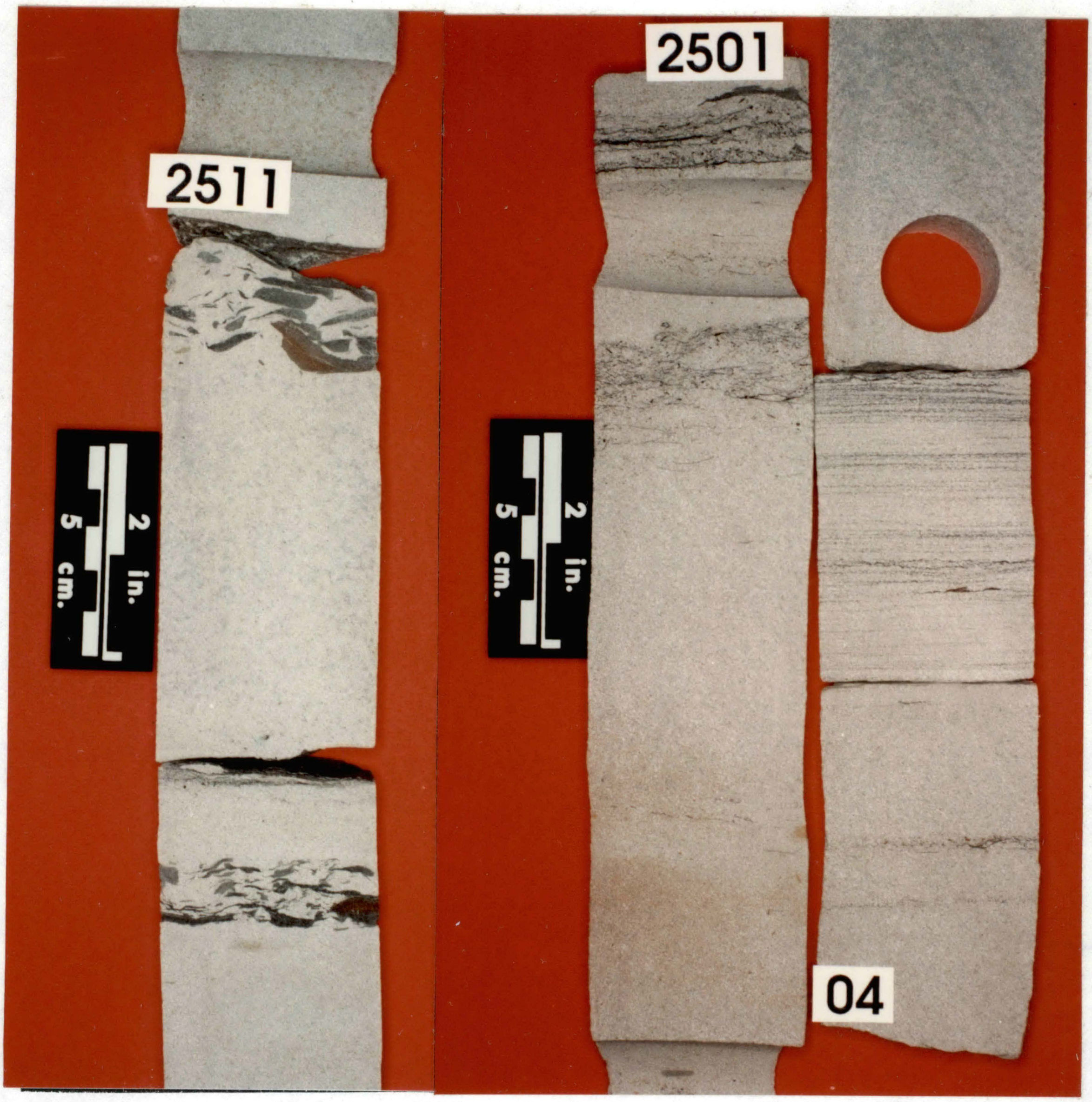

Figure 47. Horizontally Laminated Thin, Discrete Zones With Concentrated Clay Rip-Up Cobbles and Macerated Plant Material (Sun core, Lower Moran).

Figure 48. Zones of Bioturbation and Sedimentary Calcite Cementation at the Top of the Delta Front Sequence (Sun core, Cross Cut).

nel deposits. Where it is not abruptly abandoned or scoured by overlying distributary mouth bar or channel facies, the delta front facies has a gradational upper contact.

The sandstone of the delta front facies of the Cross Cut and Moran in the study area is distributed as numerous small, thin lentils associated with the distributary mouth bars. These sand bodies are less than one half mile wide and one mile long. They get up to nearly 40 feet thick but their average thickness is less than 20 feet. They trend roughly parallel to depositional strike and perpendicular to the axes of the distributary mouth bars. In all cases they are separated from the distributary mouth bars by areas with no sandstone. The importance of mapping each genetic unit separately was illustrated here. In a map of aggregate Cross Cut and Moran sandstone (not shown) the delta front and distributary mouth bar sand bodies all overlapped, masking the true spacial relationships of the facies and the trapping mechanisms of a number of oilfields in these sandstone bodies. Within each genetic unit, the delta front sandstone lenses appear to be in alignment, perhaps as a manifestation of a poorly developed ribbon or narrow sheet of delta front sand. Structural cross sections (Plates 23, 24, and 28) show that the delta front sandstones were deposited across a relatively steeply dipping seaward slope.

Distributary Mouth Bar Facies

The distributary mouth bar facies sandstone bodies are deposited at high sedimentation rates. This prevents marine reworking and results in the preservation of a relatively thick, mostly massive single sandstone unit (up to 40 feet). They may contain plane beds and low-angle large-scale trough cross beds. Most are fine grained with abundant plant material ranging from silt-sized macerals to tree trunks. Because it is the product of rapid deposition this facies lacks fossils and often displays a contorted basal contact. The basal contact is relatively flat and does not downcut significantly into underlying section. The distributary mouth bar facies is commonly found in sharp basal contact with prodelta or delta front rocks (Figure 49). Since its downcutting is minimal, the distributary mouth bar sandstone body is often placed well above the base of the genetic interval. The progradational nature of these deposits imparts a coarsening-upward profile to them. A smooth, blocky log signature results from the massive bedding, uniform fine-grained sandstone texture, and sharp upper and lower contacts.

Growth faults commonly occur in distributary mouth bars in response to sediment loading at the bar crest (Cleaves, 1975). No growth faults were seen in the Turkey Creek or Devil's Hollow outcrops, but the flexure seen along the eastern edge of Herr-King Field could be due to growth faulting, mud diapirism or both, in response to sed-

Figure 49. Distributary Mouth Bar Sandstone in Sharp Basal Contact with Delta Front Facies (Turkey Creek, Section 13, Cleaves, 1975, Farm to Market Road 919. 7.0 miles north of Gordon).

iment loading of the distributary mouth bar. By comparing the Herr-King Field structural cross sections (Plates 23, 24, and 28) with the structure map on the base of the Palo Pinto (Plate 18), it can be seen that the apparent structural drop is caused by the use of anomalously high wells for the up-dip ends of the cross sections. These isolated highs may have been caused by mud diapirism. However, the cross sections and the total interval isochore map (Plate 19) do show pronounced thickening at Herr-King Field, possibly due to growth faulting. Therefore, both the highs and the thicks could be related to sediment loading of the distributary mouth bar.

The sandstone isolith pattern of the distributary mouth bar facies is characterized by prominent, thick protrusions of the ends of distributary channel in the direction of the delta front (see Plates 20, 21, and 22). The bars are mostly dip-oriented, less than one half mile wide and one mile long, and are up to 40 feet thick. Deposition of the distributary channel over the distributary mouth bar amalgamates the two facies together on the maps, making it difficult to precisely delineate one from the other on the basis of sandstone isolith pattern alone.

Distributary Channel Facies

Distributary channel facies deposits record the change in the deltaic sequence from progradational to aggradational. The distributary channel sandstone bodies are over

40 feet thick in places, but their average thickness is about 30 feet. They are generally fine- to very-fine grained, but may have some medium-grained sand near their bases and may be silty towards their tops. Their basal contacts are sharp, erosional, and symmetrically convex downward. The extent to which Cross Cut and Moran distributary channel sandstones downcut into underlying rocks is small. In places distributary channels are found cutting into underlying delta front or distributary mouth bar facies (Figure 50). Figure 50 shows all three principal sandstone facies. Thick, massive distributary mouth bar sandstone has prograded over horizontally bedded delta front sandstone flags, while it has been downcut by overlying festoon cross bedded distributary channel sandstone.

Bedding in the lower portion of the distributary channel sandstones is poorly developed medium- to large-scale festoon cross bedding. Higher in the section there may be more well developed small-scale trough cross beds (Figures 51 and 52). In outcrop, the Turkey Creek and Devil's Hollow distributary channel sandstones contain abundant sand- to pebble-sized chert clasts, but only traces of chert are contained in the (Jones) core of an Upper Moran distributary channel sandstone in the study area. Abundant sand- to pebble-sized clay clasts are scattered throughout the channel section, and are often concentrated in linings of large-scale trough cross beds (Figure 53); likewise for

Figure 50. Distributary Mouth Bar Sandstone Prograded Over Delta Front Facies and Downcut by Overlying Distributary Channel (Devil's Hollow, Section 11, Cleaves, 1975, U.S. Route 180, 1.1 miles west of the Brazos River bridge).

Figure 51. Distributary Channel Sandstone (Turkey Creek, Section O, this study, U.S. Route 281, 5.3 miles north of U.S. Route 180).

Figure 52. Distributary Channel Sandstone (Devil's Hollow, Section 12, Cleaves, 1975, U.S. Route 180, 3.3 miles east of Palo Pinto).

Figure 53. Slump Deposit and Clay Pebbles in Distributary Channel Sandstone (Jones core, Upper Moran).

woody plant fragments. Rare slump deposits are also present (Figure 53).

The upper contact of the distributary channel facies is gradational but abrupt, due to rapid channel abandonment. After abandonment, up to 30 feet of delta plain or abandon channel fill facies clayey siltstones and mudstones may be deposited over the channel facies (see Figure 51). This contact can be seen in the Jones core at a depth of about 2098.1 feet (Figure 54). Sedimentary structures and features of the abandoned channel fill facies include extensive bioturbation of plant material-rich siltstone, root traces, and abundant very coarse sand-sized shell fragments set in calcite concretions (Figure 55). Siderite concretions, which commonly form in environments of mixing of fresh and marine waters (Jackson, 1970, Al-Shaieb, 1984, personal communication) are also present here (see Figures 29 and 55).

The log signatures of the distributary channel facies are somewhat variable but are nonetheless distinctive. Because these channels for the most part, do not migrate laterally, they lack a distinct fining-upward sequence. As a result, the log signature may show fining-upward sections, coarsening-upward sections, both, or neither. The sharp basal contact and abruptly gradational upper contact of the distributary channel sandstone facies produces a rather blocky overall profile. Variability in bedding and textural trends within the distributary channel may produce

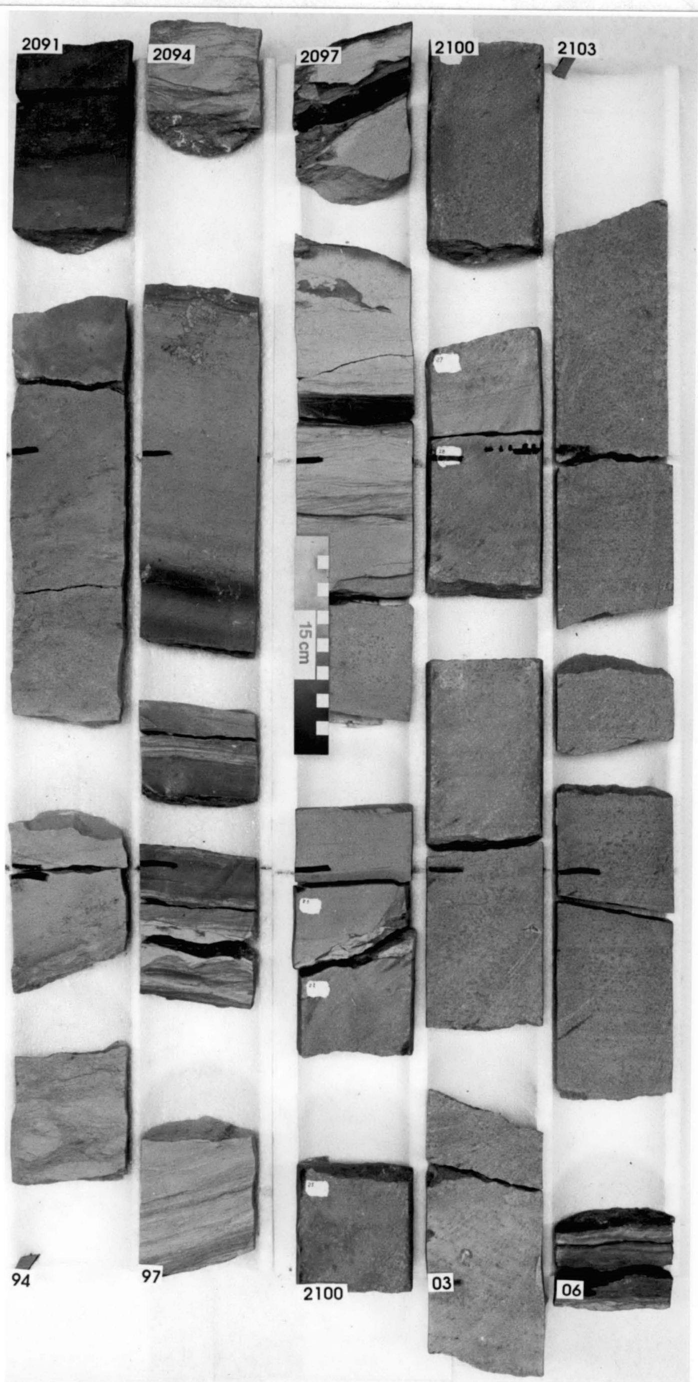

Figure 54. Distributary Channel Facies Overlain by
Abandoned Channel Fill Facies (Jones core,
Upper Moran).

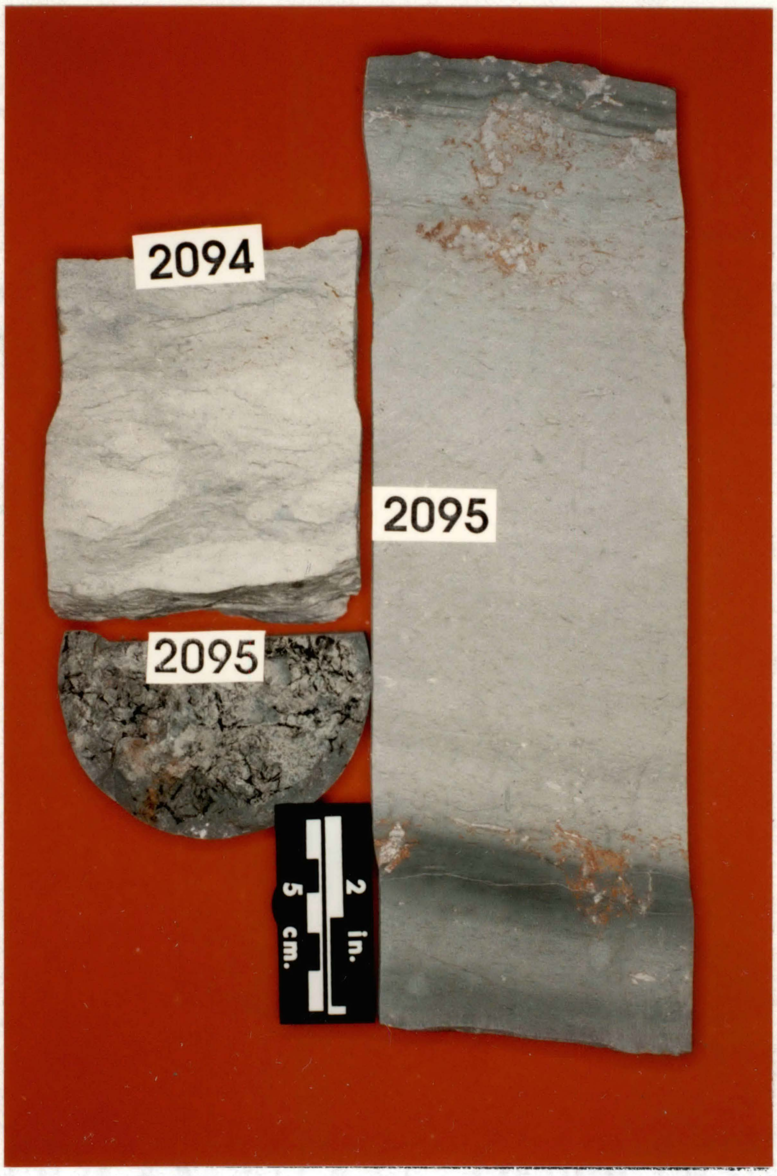

Figure 55. Abandoned Channel Fill Facies (Jones core, Upper Moran).

a serrate profile, but the sandstone body is rarely separated into more than one unit. Because of its erosional base, the sandstone bodies are deposited at or near the base of their genetic interval. The clayey siltstone of the abandoned channel fill facies produces a distinctive low SP (shale "baseline" minus approximately 15 mv), low amplitude serrate zone at the top of the sequence. Figure 56 presents typical examples of the characteristic SP log signatures of the various Cross Cut and Moran facies. It is useful for the comparing and contrasting of the distinctive features of each facies' log signature.

The geometry of the distributary channel sandstone facies is narrow (less than 1 mile wide), continuous and low to moderately sinuous. The sandstone body is dip oriented and has a distinct channel-like outline. As the channels approach the delta front, they widen and trend somewhat more along strike.

Depositional Interpretation

Introduction

The Cross Cut and Moran of the study area were deposited in the distal portion of a high-constructive delta system. Based on the morphology of the delta front, these deltas would be classified as elongate (Fisher, 1969). The delta fronts are not conspicuously lobate or arcuate, nor do they possess any sheet-like delta front sandstone body or any other significant marine-reworked

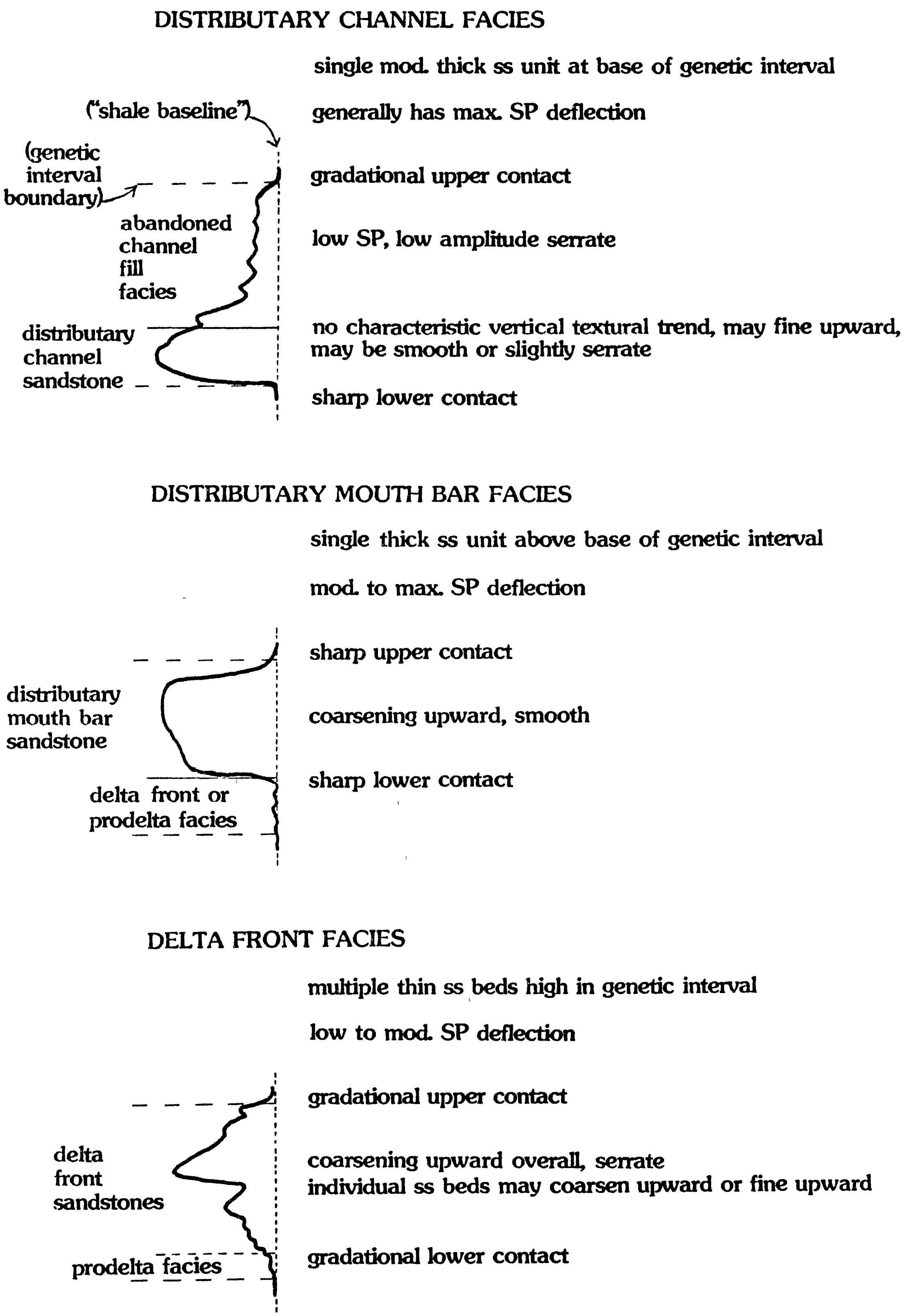

Figure 56. Typical Examples of the Characteristic SP Log Signatures of the Various Cross Cut and Moran Facies.

unit. However, because of the relatively poorly developed state of the individual delta sequences (less than 70 feet each) and their distal position within the depositional system, extensive progradation of the distributary channel and distributary mouth bars did not occur, and the underlying prodelta muds were relatively thin (less than 40 feet). Hence, prominent narrow and elongate bar-fingers (Fisk, 1961) of extensively prograded distributary channels and distributary mouth bars preserved in thick prodelta mud were not developed.

The deltaic sub-environments, associated facies, and related depositional processes of the Cross Cut and Moran sandstones in the study area are schematically portrayed in Figure 57. The deltaic depositional system in the study area can be subdivided into (1) upper delta plain, (2) lower delta plain, and (3) delta front. The demarcation of these is based upon changes in sandstone facies, trend, and geometry. The approximate positions of these inferred boundaries are indicated on the sandstone isolith maps by dashed wavy lines (Plates 20, 21, and 22). These changes indicate the development of a strand zone (Busch, 1974) at this point on the shelf over which the deltas were deposited. "Hingelines" or slope breaks which coincide with the changes seen on the sandstone isolith maps can be inferred from subtle changes in the spacing of the contour lines on the structure map (Plate 18) and to a lesser extent, on the total interval isochore map (Plate 19).

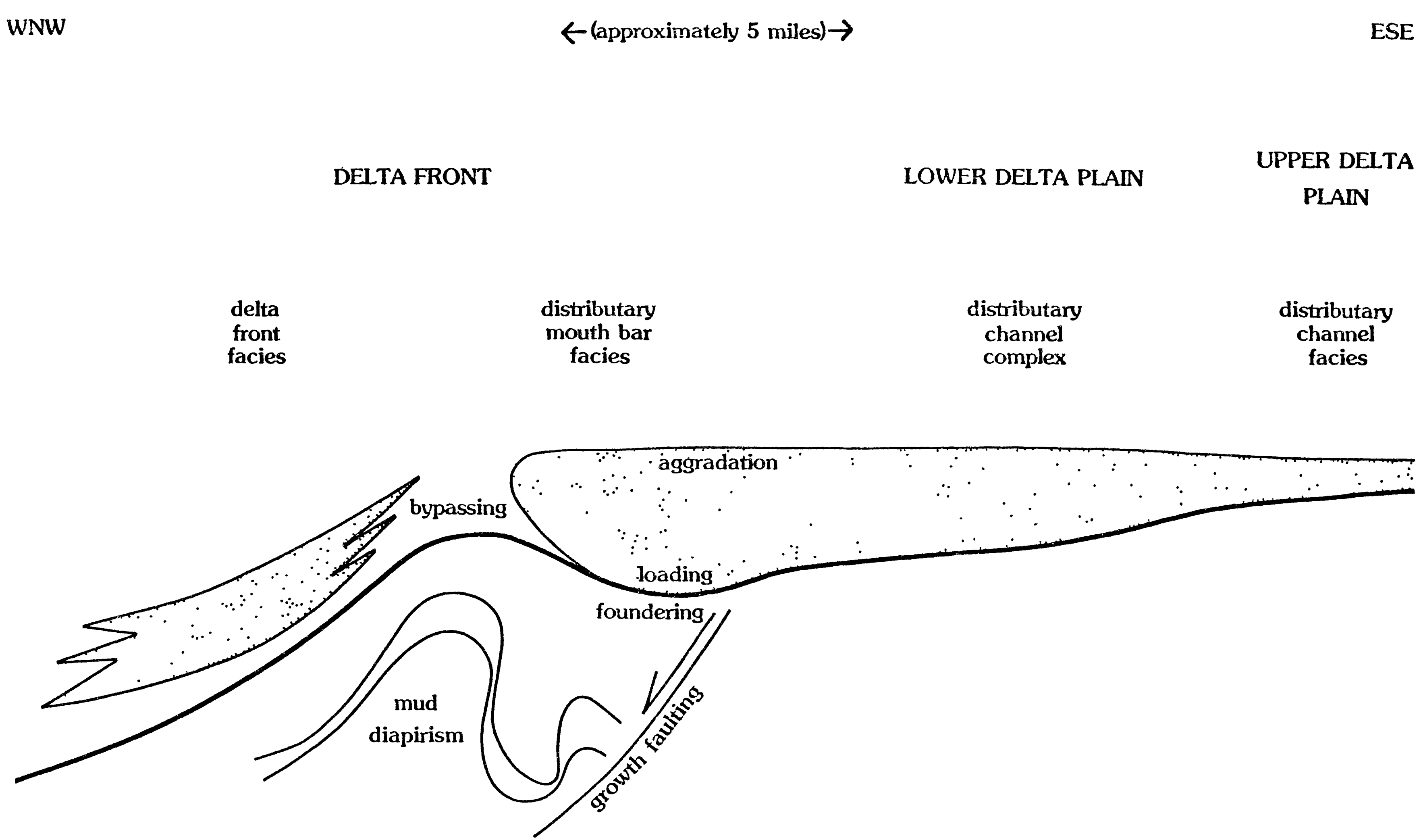

Figure 57. Deltaic Sub-Environments, Associated Facies and Related Depositional Processes of the Cross Cut and Moran in the Study Area.

It could be argued that the channels referred to here as distributary channels may be incised channels deposited at lowstand and that the delta front and distributary mouth bar deposits are highstand deposits. Accordingly, the area referred to here as upper delta plain would represent the lowstand marine shelf incised by the channel. Furthermore, in such a scenario, the incised channel would cut through and continue beyond the highstand delta front deposits. To prove this hypothesis, it would be necessary to work out the sequence stratigraphic relationships of the formation as a whole and of each genetic unit in detail. This would require the identification and mapping of regional transgressive limestones or black shales. Because of the limited area of this study and the unavailability of sufficient core and gamma ray log control, such sequence stratigraphic analysis was not undertaken.

Upper Delta Plain

Upper delta plain sandstone deposits occurs as distributary channels. The channel sandstones are relatively thin, have low sinuosities, and, overall, are poorly developed. These features attest to the conditions of low gradient and low rate of bedload sedimentation and to the general low level of progradational influence which must have existed. At the time of deposition, the study area comprised distal portions of small, stable, cratonic deltas. Lateral accretion in response to channel meander migration resulted in the formation of a few small point bars within the distributary channels.

Several small highs shown on the structure map (Plate 18), especially in the southwestern portion of the study area, are most likely the result of structural drape over deeper structures, probably pinnacle reefs. It appears that these may have affected the distribution of Cross Cut and Moran distributary channel sandstone deposits. Comparison of the sandstone isolith maps (Plates 20, 21, and 22) and total isochore map (Plate 19) with the structure map (Plate 18) in these areas suggests that slight thinning of the sandstone and the total interval, and changes in sandstone trend may have occurred over the paleotopographic highs. Another factor which appears to have had an effect upon sandstone distribution (in the Upper Moran and Cross Cut) is the presence of thick sandstone accumulations in the underlying interval. Comparison of the sandstone isolith maps (Plates 20, 21, and 22) with one another shows that thick sandstone accumulations in adjacent intervals may be locally related. However, upon closer scrutiny, it can be seen that these thick sandstone deposits do not directly overlie earlier thicks, but rather are slightly offset laterally. This situation, in places, produces a somewhat "shingled" spacial relationship between sandstone deposits of (vertically) adjacent genetic intervals.

The direct relationship which generally exists between sandstone thickness and total interval thickness is particularly striking in the case of the upper delta plain of the Cross Cut and Moran in the study area. Comparison of the sandstone isolith maps (Plates 20, 21, and 22) with the total interval isochore map (Plate 19) clearly shows the existence of well defined total interval thicks corresponding to the distributary channel deposits, while the interdistributary areas with no sand show markedly thin total interval values. What is remarkable is the close correlation between the outline of the thinnest areas (the 140 foot contour line) on the total interval isochore map and the zero sandstone isolith contour. The match is especially close where the southeastern edge of the Cross Cut delta meets the northwestern edge of the broad central thin and also where three re-entrant thins are intertwined with the Moran distributary channel sandstones in the south-central part of the map. The eastern end of cross section J-J′ (Plate 27, also see Plate 21) shows how the total interval thins drastically outside the channel. It shows not only the thin delta plain shale, but also a thin, locally developed, shelf limestone. These delta plain deposits are thin because adequate continuous subsidence was precluded due to the high structural stability of the shelf (Cleaves, 1973).

Although the Lower and Upper Moran are two separate and distinct genetic intervals, comparison of their sandstone isolith maps (Plates 21 and 22) clearly indicates that they were deposited along the same depositional tract.

Moreover, while the comparison of these with the Cross Cut sandstone isolith map (Plate 20) shows that the Cross Cut was deposited, for the most part, along a new depositional tract, it still partially occupied the former Moran channel. This abandonment and subsequent re-occupation of earlier depositional tracts are characteristic of cratonic deltas (Brown, 1979).

Lower Delta Plain

Distributary channel sandstones continue across the lower delta plains. The log signatures seen in these areas are similar to those found on the upper delta plain. However, the sand body ceases to exist as a narrow, sinuous, symmetrical channel. It takes on a wider, more lobate form as it approaches the delta front. Also, there is an overall increase in the amount and thickness of the sandstone, and its trend turns toward the direction of strike. These areas are characterized by relative flatness on the structure map (Plate 18) and the total interval isochore map (Plate 19). Again, it appears that these changes in sandstone geometry, trend and thickness are related to the development of a strand zone (see Figure 57). A decrease in gradient, accompanied by an increase in water depth, caused increased aggradation and coalescence of the distributary channel deposit. This resulted in the formation of a distributary channel complex in the areas of the incipient distributary mouth bars.

Delta Front

The delta front environment of the Cross Cut and Moran in the study area is characterized by two sandstone facies. They are (1) distributary mouth bar sandstone and (2) delta front sandstone. The development of distributary mouth bars is indicated by changes in log signature and sandstone thickness, trend and geometry (see Plates 20, 21, and 22). As in the case of the distributary channel complex, the change in trend and geometry and the increase in thickness of the distributary mouth bar sandstone appear to be in response to an even further increase in the influence of aggradation on sandstone deposition and preservation. Furthermore, comparisons of the sandstone isolith maps (Plates 20, 21, and 22) reveal evidence which suggests that progradation was impeded. Observe the area near the western edge of the study area, just east of Herr-King Field. Thick distributary mouth bar sandstone deposits from all three genetic intervals have accumulated in this general vicinity. Each delta (Lower Moran, Upper Moran, and Cross Cut) ceased progradation at this same point, and the thickest distributary mouth bar sandstones were deposited here. In this same area, there are four small structural highs (see Plate 19). With the exception of the one in the east half of BOA Sec. 62, these highs are not caused by underlying thick sandstone deposits. The remaining three highs were probably positive topographic features during Cross Cut and Moran deposition and as such, may have affected the sandstone distribution at the delta fronts (see Figure 57). These paleotopographic features probably resulted from mud diapirism or possibly were earlier structures. Because they formed something similar to a discontinuous strike-trending ridge at the time of deposition, they may have stopped progradation of the deltas and caused ponding of sediment behind them (see Figure 57). This is what may be responsible for the increased aggradation of the distributary mouth bars. Sedimentary loading, foundering, growth faulting and mud diapirism are all processes which contributed to this situation.

Separate and distinct delta front sandstone bodies developed seaward of the distributary mouth bars (see Figure 57 and Plates 20, 21, and 22). They are located in front of the aforementioned structural highs. An inflection on the total interval isochore map (Plate 19) roughly coincides with this structural trend. This "hingeline" delineates the drop from a flat area to the east to a low area to the west at Herr-King Field. Similar structural and total interval isochore anomalies also exist on the east side of the Moran deltas and at front of the Cross Cut delta (see Plates 18 through 22). Deposition of delta front sandstone in these areas occurred as the distributary mouth bar sandstones, which had aggraded to the point of instability, spilled sediments over the fronts of the deltas, into the lows.

The delta front sandstone bodies are separated from the distributary mouth bars by areas containing no sandstone (see Plates 20, 21, and 22). This discontinuity exists because the discharge of sediment from the distributary mouth bars to the delta front sandstone bodies occurred via several very localized sites of effluence. Comparison of the structure and isolith maps (Plates 18, 20, 21, and 22) shows that, at Herr-King Field, the distributary mouths developed between the structural highs. The distributary mouth bars of the successive genetic intervals are offset slightly, but all three deltas utilized these same spots as points of discharge. Consequently, the delta front sandstone bodies of the three genetic intervals also all occupy approximately the same position on the sandstone isolith maps (see Plates 20, 21, and 22). At the points of discharge, high flow conditions existed, and therefore no sand was deposited there. This sedimentary bypassing is what caused the segmentation of the delta front sandstone bodies and their separation from the distributary mouth bar sandstone bodies (see Plates 20, 21, and 22 and Figure 57).

CHAPTER VII

FIELD STUDIES

Herr-King Field

Location: Bayland Orphan Asylum Survey, Section 62; BBB & C RR Survey, Sections 141 and 142; C & M RR Survey, Section 1; J. Poitevent Survey, Sections 1 and 2; T & NO RR survey, Sections 1, 2, and 3 (western edge of study area).

Refer to plates: 13 through 24, and 28.

Productive intervals: Lower Moran, Upper Moran, and Cross Cut.

Facies of reservoir units: delta front sandstone.

Mode of hydrocarbon entrapment: stratigraphic termination of delta front sandstone.

Average cumulative production: 33.3 KBO/well.

Discussion: The western half of Herr-King Field is outside the study area (see Plate 17). Maps of the entire field are published in Fraser, 1956. The field has been waterflooded for secondary recovery purposes. The trapping mechanism is largely stratigraphic. With the exception of a few down-dip (southwestern) edge wells, all wells that penetrated sandstone were productive. The Herr-King Field is actually a complex of several separate but overlapping lenticular delta front sandstone bodies encased in shale (see Plates 20, 21, and 22).

The sandstone isolith maps (Plates 20, 21, and 22). indicate that these delta front sandstone bodies are developed directly in front of the most prominent distributary mouth bars. Furthermore, a slope down from the lower delta plain is indicated by a flexure on the structure map (Plate 18) and a thick on the total interval isochore map (Plate 19). These relationships are also evident in the structural cross sections (Plates 23, 24, and 28). The delta front sandstones are distinguishable from the distributary mouth bar sandstones on the basis of log signature and sandstone trend, thickness and geometry.

Exploration considerations: The strategy used to explore for these types of traps would involve (1) delineation of the limits of the lower delta plain and distributary mouth bars, and (2) identification of sites of probable delta front sandstone deposition within areas of thick total interval in front of well developed distributary mouth bars.

Because delta front sandstones are finer-grained, less well sorted, thin-bedded, and interbedded with shale, they have considerably lower porosities and permeabilities than other facies (see Plates 13 through 16). Hence, wells completed in delta front sandstone reservoirs may respond favorably to fracture treatment. These reservoirs are essentially oil filled lenses of sandstone completely encased in shale. As such, they have only a weak solution gas drive with little or no water drive. Therefore, early pressure maintenance by gas injection and later waterflooding may be prudent.

Fields which produce from distributary mouth bars are depicted on the east ends of Plates 24 and 28. However, cumulative production figures (Plate 17) indicate that production from these fields is marginal (less than 10 KBO per well, average). These reservoirs are, for the most part, open ended in the up-dip direction (see Plates 19, 20, and 21). But by sheer thickness of reservoir (over 40 feet), the tops of these overdeveloped sandstone bodies gained a slight structural advantage over the thinner sandstone to the east. Their structural position is probably aided by mud diapirism as well. Hence, only the very top portions of these sandstone bodies are trapped, and their underlying water columns are open in the up-dip direction. Growth faulting, which is common at the crests of distributary mouth bars (Cleaves, 1975), would be an excellent means by which these sandstone bodies could be trapped.

Callahan County Regular Field
(Lunatic Asylum, Upper Moran)

Location: Lunatic Asylum Survey, Sections 54 and 57 (northwestern part of study area).

Refer to plates: 17, 18, 19, 21, and 25.

Productive interval: Upper Moran.

Facies of reservoir unit: distributary channel complex sandstone.

Mode of hydrocarbon entrapment: up-dip pinch out of distributary channel complex sandstone.

Average cumulative production: 39.1 KBO/well.

Discussion: This field is trapped by simple up-dip pinch out of the distributary channel complex sandstone (see Plates 21 and 25). A large area of relatively thick total interval around this field indicates that a depression existed there at the time of deposition (Plate 19). The presence of several delta front sandstone bodies in this area also suggests a localized eastward facing delta front (Plate 21). This permitted an eastward protrusion of the distributary channel complex. A westward re-entrant of the zero sandstone isolith contour defines the trap of this field on its northern edge. Regional westward tilting of the basin subsequent to Moran deposition gives these sandstones the appearance of trending up-dip.

Exploration considerations: The strike-orientation of the up-dip edge of the distributary channel complex sandstone body necessitates westward re-entrance of the zero sandstone isolith contour in order for it to be trapped along strike. Conditions that would favor such an eastward protrusion of this facies include (1) a depression to the east, indicated by a total-interval thick, and/or (2) a localized, eastward facing delta front, indicated by the presence of delta front sandstones to the east. Fields of this type will probably have a strong water drive, owing to their position at the up-dip edge of an extensive porous sandstone body.

Callahan County Regular Field
(Lunatic Asylum, Cross Cut)

Location: Lunatic Asylum Survey, Sections 57 and 58 (northwestern part of study area).

Refer to plates: 17, 18, 19, 20, and 29.

Productive interval: Cross Cut.

Facies of reservoir unit: delta front sandstone.

Mode of hydrocarbon entrapment: stratigraphic termination of delta front sandstone.

Average cumulative production: 23.2 KBO/well.

Discussion: The trapping mechanism in this field is encasement of a lenticular delta front sandstone body in shale (see Plate 20). The conditions surrounding the occurrence of this delta front sandstone body are similar to those described for Herr-King Field. It occurs within the strand zone, as indicated by "hingelines" on the structure and total interval isochore map. Also, it is within an area of thick total interval, in front of well developed distributary mouth bars.

Exploration considerations: The significance of this field is its occurrence within a trend of several other Cross Cut delta front sandstone fields. The area of probable delta front sandstone development is already delineated. With existing well control, there is room to explore for more of these fields in this vicinity. For example, the Cross Cut delta front sandstone producer in University Lands Survey, Section 120 (see Plates 17 and 20) is one of the more recent discoveries in the study area. It is also one of the most prolific, producing nearly 53 KBO from one well in less than five years (Petroleum Information, Inc., 1989). So, it can be seen that "close in" exploration for these small, discrete delta front sandstone bodies within relatively densely drilled established producing trends should not be overlooked as a viable exploration strategy.

Strand zones comprise the delta fronts and lower delta plains which developed in the study area. Sandstone deposits of the delta front, distributary mouth bar, and distributary channel complex all developed within the strand zones. It has been shown in this study that strand zones can be demarcated by (1) recognizing changes in sandstone trend, geometry and facies as indicative of the development of the delta front and lower delta plain, and

(2) recognizing flexures or "hingelines" on structure and total interval isochore maps as indicative of changes in depositional slope that accompanied the development of the delta front and lower delta plain. The majority of the Cross Cut and Moran production comes from reservoirs deposited within the strand zone. Therefore the recognition and demarcation of strand zones should be a primary concern in Cross Cut and Moran hydrocarbon exploration.

Finley Field

Location: Deaf & Dumb Asylum Survey, Section 10 (southwestern part of study area).

Refer to plates: 17, 18, 19, 21, and 26.

Productive interval: Upper Moran.

Facies of reservoir unit: distributary channel sandstone.

Mode of hydrocarbon entrapment: thinning, pinch out, and/or compactional drape of distributary channel sandstone over deeper structure.

Average cumulative production: 42.8 KBO/well.

Discussion: This field is trapped by a combination of compactional drape and stratigraphic thinning and up-dip termination of distributary channel sandstone over a deep structure. A trend of small domal structural closures extends across this area (see Plate 18). Finley Field overlies one such structure. These structures are most likely the result of compactional drape over underlying pinnacle reefs, which are common in this area. Structural cross section I-I′ (Plate 26) demonstrates the compactional drape and related pinch out of the distributary channel sandstone. Comparison of the structure map (Plate 18) to the total interval isochore map (Plate 19) and the Upper Moran sandstone isolith map (Plate 20) indicates that the axis of the channel skirted the structure. The sandstone and the total interval thin slightly over the structure. Furthermore, the re-entrant of the zero sandstone isolith contour suggests that the pinch out of the sandstone is related to the structure.

Exploration considerations: Since distributary channel sandstones are dip-oriented, up-dip pinch outs of them are rare. But since they are also quite narrow, these small structures can produce localized re-entrants of the channel outline by which hydrocarbon entrapment can occur. Two key elements exist in fields of this type: (1) a pronounced local structure, and (2) a related thinning and/or pinch out of an overlying distributary channel sandstone. Small domal structures of this type are generally detectable by a localized anomalous spreading of structural contours. The "fairways" of distributary channel sandstone development are rather clearly indicated by dip-oriented trough-like thicks on the total interval isochore map

(Plate 19). Where there is sufficient well control, the relationship between the structure and sandstone thickness and trend should be examined in order to identify an area of probable sandstone pinch out. Exploration for these types of fields could also be undertaken by detailed sandstone mapping over and around existing pinnacle reef fields.

Callahan County Regular Field

(Texas Emigration & Land Survey, Upper Moran)

Location: Texas Emigration & Land Survey, Sections 2295, 2976, and 2977 (south-central part of study area).

Refer to plates: 11, 12, 17, 18, 19, 21, and 27.

Productive interval: Upper Moran.

Facies of reservoir unit: distributary channel point bar sandstone.

Mode of hydrocarbon entrapment: pinch out of distributary channel point bar sandstone against regional dip.

Average cumulative production: 41.6 KBO/well.

Discussion: This field has been waterflooded for secondary recovery purposes. It produces from one of the few point bar deposits which were developed in the study area. The asymmetrical geometry of the channel indicates that it had migrated laterally (Plate 21). The abrupt change from a thick channel fill section to a thin delta plain and shelf limestone section indicates the existence of a well developed cutbank along the eastern edge of the channel (Plate 27). Slump deposits, caved from the cutbank are in the core of the channel sand (see Figure 53). This abrupt sandstone pinch out forms the up-dip trapping mechanism. The field is trapped along strike on its northern end by a combination of sandstone pinch out and a permeability barrier. A re-entrant of the zero sandstone isolith contour, resulting from the lateral migration of the channel forms the sandstone pinch out here (Plate 21). However the middle well on cross section J-J' (Plate 27, Ray Green #6-A) contains seven feet of slightly porous sand. This sand is structurally above most of the field but produced only saltwater when completed (Jones, 1983).

This zone correlates to the abandoned channel fill facies zone found in the Jones core (Plates 11 and 12). Although this zone has some poor porosity and SP deflection, it is water saturated and has low permeability (Figure 58). A sharp contact between the oil saturated distributary channel sandstone reservoir and the abandoned channel fill is at the depth of 2098 feet (see Plates 11 and 12 and Figures 54 and 58). In the core, this contact is detected by an upward change from: (1) brown oil stained rock to unstained rock, (2) very fine sandstone to rippled sandy, clayey siltstone, and (3) an oily taste to a salty taste (Figure 59). The abrupt but subtle nature of

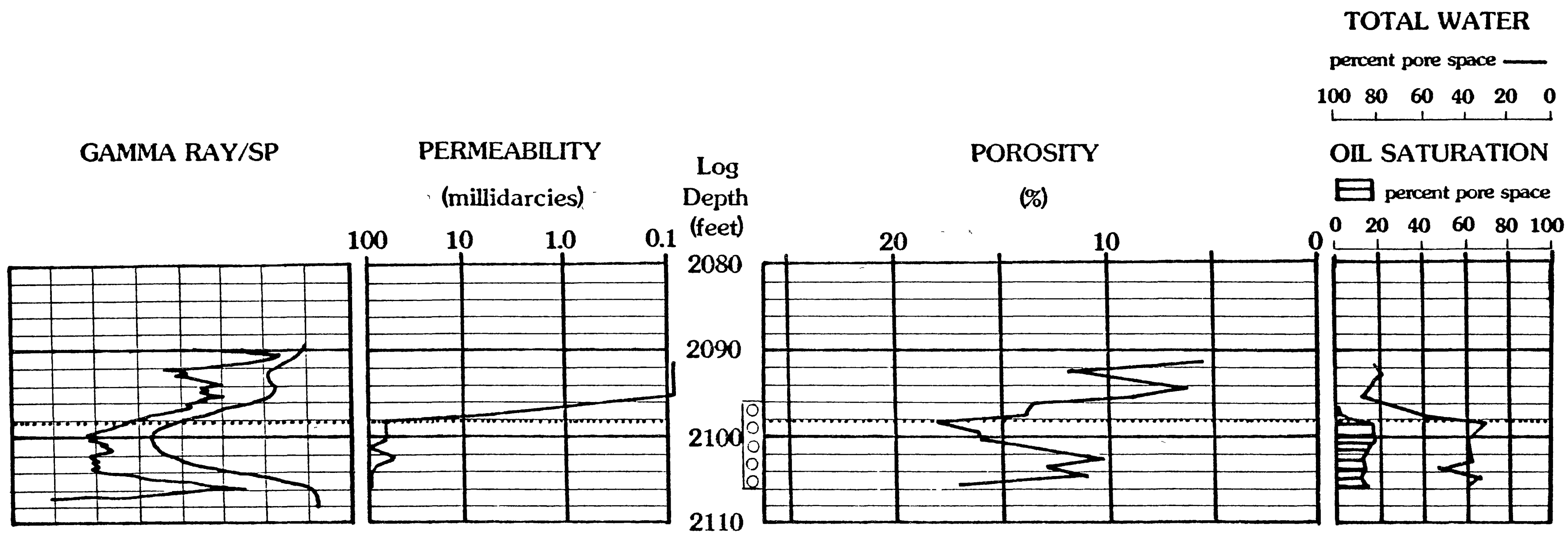

Figure 58. Results of Analysis of the Jones Core (Upper Moran) (modified from Core Laboratories, Inc., 1981).

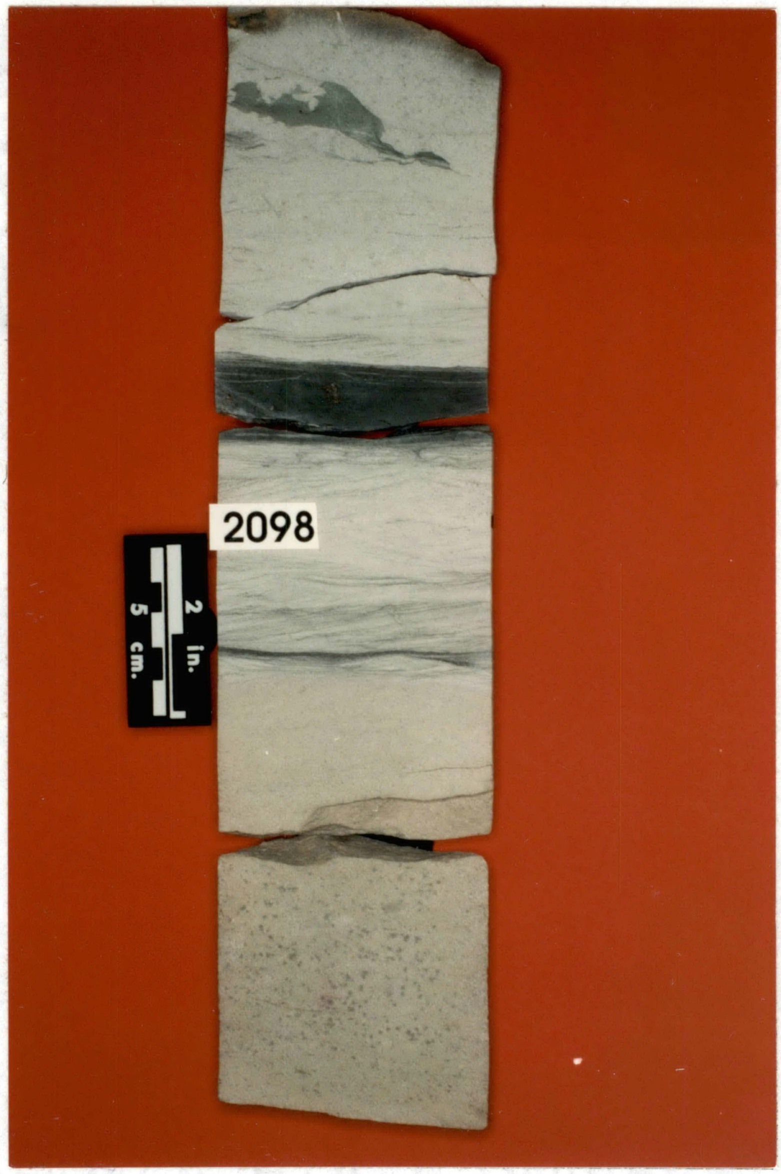

Figure 59. Contact Between Abandoned Channel Fill and Oil Saturated Distributary Channel Sandstone (Jones core, Upper Moran).

this contact is shown in Figure 60. This thin section was taken at the contact between the abandoned channel fill and the porous distributary channel sandstone. This horizon, the result of rapid channel abandonment, separates a high porosity, high permeability, oil saturated distributary channel sandstone reservoir from low porosity, low permeability, saltwater-saturated, sandy, clayey siltstone of the abandoned channel fill facies. Hence, the trapping mechanism along the northeastern edge is a pinch out of porosity and permeability due to a subtle textural change associated with a change in facies.

Exploration considerations: In this field, meandering and lateral migration of the channel are responsible for the conditions of hydrocarbon entrapment. Those conditions are: (1) the turning of the channel to a strike-orientation which allows pinch out against regional dip, and (2) the emplacement of the point bar away from the axis of the channel resulting in pinch out of the point bar sandstone along strike. Traps such as this are likely to develop at any point along the established distributary channel trend where sandstone isolith and total interval isochore maps indicate a sharp turn of the channel against regional dip.

Dipmeter analysis can be very useful in determining the orientation of a sandstone body. The strike of the cross beds which form in distributary channels and points bars are parallel to the axis of the channel or bar. The dipmeter reads the dips of these cross beds, thereby indi-

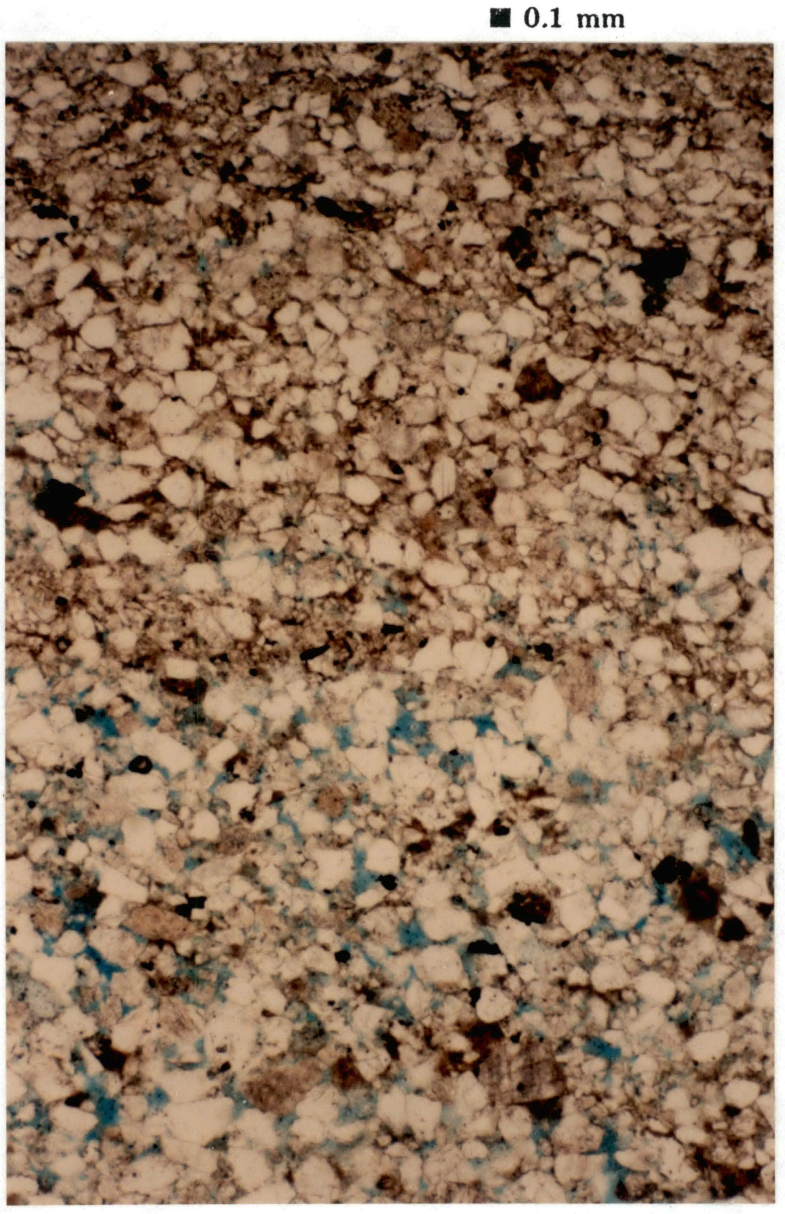

Figure 60. Contact Between Abandoned Channel Fill and Porous Distributary Channel Sandstone (Jones core, Upper Moran, 2098', plane polarized, 20X).

cating the direction normal to the axis of the channel or point bar. Hence, the trend of the axis of the deposit may be inferred from the dipmeter log as being perpendicular to the dips recorded within the sandstone body.

A dipmeter log was recorded in the well from which the Jones core was taken. A comparison of the dipmeter to the core reveals remarkable correlation between the two (see Plates 11 and 12). The massive bedding and poorly developed festoon and multimodal large-scale trough cross bedding which exist in the lower part of the point bar are indicated on the dipmeter log by low quality ("open tadpoles") chaotic dip readings. In the upper part of the point bar, well developed tabular and small scale trough cross beds are present and are indicated on the dipmeter log by a "blue pattern." This is the old Schlumberger terminology for a pattern of decreasing dip with depth. The dips here are to the northwest. These readings would indicate that the point bar is oriented northeast-southwest, which is in agreement with the well control. At the top of the sandstone the abundant ripple cross beds are indicated on the dipmeter log by numerous high quality, chaotic, low angle dip readings. The drape of the beds over the point bar shows up as a "red pattern" (increasing dip with depth).

CHAPTER VIII

SUMMARY OF CONCLUSIONS

The principal conclusions derived from this research are as follows:

1. Present structural dip is to the west-northwest (290 degrees azimuth) at a rate of 50 feet per mile.

2. The discordance between present dip and paleodip is the result of westward tilting of the study area during uplift of the Ouachita-Arbuckle orogen to the east and subsidence of the Midland Basin to the west.

3. Most of the small structural closures on the base of the Palo Pinto are the result of compactional drape over underlying pinnacle reefs or thick Cross Cut or Moran sand accumulations.

4. The Cross Cut and Moran are stratigraphically equivalent to the Turkey Creek Sandstone, Keechi Creek Shale, ss2, and Salesville shale of the Mineral Wells Formation, all of which outcrop in Palo Pinto County, Texas.

5. The Morris limestone is absent eastward of eastern Eastland County, Texas.

6. The Morris limestone is more suitable than the Dog Bend Limestone as the lower boundary for purposes of subsurface mapping of the study interval in the study area

because: (a) the interval below the Morris and above the Dog Bend contains no sand and has no significant relationship to the study interval so it is best to not include it in the mapped intervals, (b) it is the marker used by most industry workers, and (c) most Moran tests stopped drilling in the Morris so the Dog Bend is not penetrated in many of the wells in the study area.

7. The base of the Palo Pinto Formation and the top of the Dog Bend Limestone are regionally persistent and consistent enough to be correlated from outcrop, through the study area.

8. No regionally persistent limestone or other beds exist within the study interval to facilitate the regional mapping of the genetic units by means other than detailed, well to well sandstone correlation.

9. The base of the Palo Pinto Formation is the most suitable stratigraphic datum for cross sections of the Cross Cut and Moran interval because of its stratigraphic significance as a group boundary and because its use affords the best fit of the genetic interval correlations.

10. Intervening thin limestone beds are scarce, but are scattered throughout the study area and are useful in identifying the tops of the genetic units.

11. The genetic units are wholly conformable within the study area with no "pinching out" of entire genetic units or downcutting of one genetic unit into a lower genetic unit.

12. It is proposed in this study to use the names Cross Cut for the uppermost sandstone and Moran for the two lower sandstones in the study interval because (a) this is in keeping with the local usage and also with the application of only two names in the formal surface nomenclature, (b) the two lower sandstones (Moran) are very closely related depositionally to one another and (c) the Cross Cut sandstone was deposited along a different depositional tract with little overlap or association with the underlying Moran sandstones.

13. It is proposed in this study that the Moran be subdivided into Upper Moran and Lower Moran because the two are clearly separate and distinct sandstone bodies and are mappable as such.

14. The Cross Cut and Moran sandstones in the study area are very fine- to fine-grained sandstone sublitharenites. The framework grains are predominantly normal quartz grains with lesser amounts of sand sized clay grains and minor amounts of feldspar grains. The grains are mostly subrounded to rounded and have moderate sphericity. The sandstones are moderately sorted to well sorted and are texturally and compositionally mature.

15. Regional and local distribution, petrology and tectonic and basin histories of the Cross Cut and Moran sandstones indicate that they were sourced by uplifted sedimentary rocks in the Ouachita-Marathon Orogen to the east

and prograded some 120 miles west where they were deposited in the study area as mature sediments.

16. Abundant, tiny, distinct patches of poikilotopic, "baroque" ankerite cement are common throughout the sandstones of the study interval. The crystals display a minor amount of zonation with ferroan dolomite and dolomite. The ankerite comprises up to 13% of some samples.

17. The principal authigenic clay in the Cross Cut and Moran sandstones in the study area is pore filling vermicular kaolinite. It is most abundant in the more porous sandstones where it comprises up to 4% of total rock volume. Authigenic illite and chlorite are present only in minor amounts.

18. A typical Cross Cut and Moran reservoir sandstone may have approximately 14% average porosity (up to 18%) and an average of 100 md of permeability (up to 200 md).

19. Porosity figures indicated by density logs agree quite closely with those obtained from core and thin section analysis. This can be attributed to the relatively simple texture, mineralogy and pore system morphology of the sandstones.

20. The majority of the porosity in the Cross Cut and Moran sandstones in the study area is secondary grain mold and intragranular, created at the expense of clay grains and, to a minor extent, feldspar grains.

21. The abundant shrinkage features seen in the clay grains are the result of syneresis in response to a change

in formation water chemistry. This change occurred at near maximum burial when saline waters expelled during early shale diagenesis migrated into the sandstones. The early secondary porosity created by this shrinkage was small (less than 2%) but the permeability that resulted significantly enhanced later development of secondary dissolution porosity.

22. The creation of secondary porosity at the expense of clay grains and feldspar grains was accomplished through their direct dissolution by means of hydrolysis in the presence of organic acids.

23. The precipitation of kaolinite as an alteration product (which commonly accompanies hydrolysis of framework grains) was prevented in the case of these samples due to mobility of aluminum via its chelation by carboxylic acid anions.

24. The Cross Cut and Moran sandstones in the study area attained a maximum burial depth of approximately 5200 feet during early Cretaceous time. At present they have progressed through the early stage ("A") of mature mesodiagenesis, i.e. secondary porosity is at its maximum.

25. Precipitation of pore filling ankerite and vermicular kaolinite followed the development of the secondary dissolution porosity.

26. The sandstone samples studied have well developed open pore spaces with relatively little detrital matrix,

authigenic clay or epitaxial cement and, as such, provide excellent petroleum reservoirs.

27. The Cross Cut and Moran were deposited in the distal portion of a high-constructive elongate cratonic deltaic depositional system.

28. The principal sandstone facies found in the Cross Cut and Moran in the study area are: (1) delta front, (2) distributary mouth bar, and (3) distributary channel. Production is obtained from all three facies.

29. It is important to map the sandstones of each genetic interval separately in order to delineate facies changes and sandstone body separations which would be masked by overlap in a map of aggregate sandstone thickness.

30. The delta front facies section contains thin, very fine-grained sandstone layers interbedded with siltstone and mudstone in its lower part and may contain thick bedded fine sandstone beds near its top. It is generally 40 feet thick, overlying 30 feet or less of prodelta mud. Sedimentary structures in the delta front sandstones include massive bedding, graded beds, deformed bedding, flood surge deposits, horizontal laminations, and bioturbation. The sandstones may contain marine calcite cementation, glauconite, and abundant macerated plant material. The delta front SP log signature is upward coarsening and serrate with gradational upper and lower contacts. Multiple thin sandstone beds with low to moderate SP deflection

are concentrated in the upper half of the section. The delta front sandstones occur as numerous lentils, generally less than 20 feet thick, one half mile wide, and one mile long. They trend roughly parallel to depositional strike and are found near to, but separated from the fronts of distributary mouth bars. The Cross Cut, Upper and Lower Moran sandstones in Herr-King Field are all of the delta front facies.

31. The distributary mouth bar facies occurs as a single massive fine-grained sandstone up to 40 feet thick overlying delta front or prodelta rocks. Massive bedding and basal contortion are common; plane beds and low-angle large-scale trough cross beds may be present in the upper part. The SP log signature of the distributary mouth bar facies is characterized by a single, thick, upward coarsening sandstone located high in the genetic interval. The sandstone has sharp upper and lower contacts and a smooth blocky SP profile. Growth faulting and/or mud diapirism in response to sedimentary loading at the distributary mouth bars may have caused the apparent structural flexure seen at the delta front in the vicinity of Herr-King Field. The distributary mouth bar sandstone deposits appear on the sandstone isolith maps as thick, prominent, dip-oriented protrusions of the distributary channels toward the delta front. They are generally less than one half mile wide and one mile long.

32. The distributary channel facies consists of 20 to 40 feet of very fine- to medium-grained distributary channel sandstone overlain by up to 30 feet of abandoned channel fill or delta plain clayey siltstone and mudstone. The distributary channel sandstones have poorly developed medium- to large-scale festoon cross beds in the lower part and more well developed small-scale trough cross beds toward the top. They have sharp erosional basal contacts but generally have not downcut extensively into underlying section. The channel sandstones contain abundant sand- to pebble-sized clay clasts and woody plant fragments. The distributary channel facies SP log signature shows a single, moderately thick sandstone at the base of the genetic interval with a sharp basal contact and abrupt gradational upper contact. The smoothness and vertical textural trend of the profile is variable. The upper part of the section generally shows a slight, low-amplitude, serrate SP deflection. The distributary channel sandstone bodies are continuous, narrow, distinct, low to moderately sinuous and dip-oriented. The channels are generally symmetrical in cross section, but minor lateral accretion in places has resulted in the development of point bars. The distributary channels broaden, and turn somewhat along strike as they approach the delta front.

33. The demarcation of the different deltaic facies and sub-environments in the study area can be inferred from changes in (1) texture, composition, and sedimentary struc-

tures of the sandstones, (2) log signature, (3) sandstone trend, geometry and isolith map pattern, and (4) depositional slope, as inferred by "hingelines" detected on structure, total interval isochore and sandstone isolith maps and cross sections.

34. Paleotopographic highs, probably over deeper pinnacle reefs, existed at the time of Cross Cut and Moran deposition and caused thinning, trend changes, and structural drape in the Cross Cut and Moran sandstone deposits.

35. The presence of a thick accumulation of sandstone in the underlying genetic interval caused slight lateral offset or "shingling" of vertically adjacent sandstone deposits in the Upper Moran and Cross Cut.

36. There is quite precise correlation between total interval thickness and sandstone distribution. Areas of no sandstone development are delineated by thins on the total interval isochore map and areas of thick total interval generally contain thick sandstones.

37. The Lower Moran sandstone and the Upper Moran sandstone are two separate and distinct genetic intervals but were deposited along nearly the same depositional tract. The Cross Cut sandstone was deposited, for the most part along a different depositional tract but still partially occupied the former Moran depositional tract.

38. The morphologies of the Cross Cut and Moran delta fronts in the study area may have been controlled by mud

diapirism, growth faulting, and/or the existence of previous structures.

39. The recognition of ancient strand zones is an important factor in exploration for the types of deltaic sandstone traps found in the Cross Cut and Moran in the study area. Strand zones may be inferred from changes in depositional slope indicated by structure and total interval isochore maps, and by changes in sandstone facies, trend and geometry indicated by sandstone isolith maps.

40. The Herr-King Field comprises a complex of several separate, but overlapping lenticular delta front sandstones encased in shale.

41. The Cross Cut and Moran fields in the study area are trapped by (1) stratigraphic termination of delta front sandstone lentils encased in shale, (2) up-dip pinch out of distributary channel complex sandstone or distributary channel sandstone against regional dip, or (3) compactional drape and/or up-dip pinch out of distributary channel sandstone related to deeper structure.

42. The cumulative production for all Cross Cut and Moran wells in the study area averages 29.9 KBO/well and is as high as 52.9 KBO/well. Five fields, which comprise 77% of the Cross Cut and Moran wells in the study area and have produced 90% of the oil, average 34.7 KBO/well.

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APPENDIX

WRITTEN CORE DESCRIPTIONS

Jones Co., Williams 2976 #7 (See Plates 11, 12 and 21)
330' FS & EL's of Sec. 2976, TE & L Sur. Callahan County, Texas

Cored interval: Upper Moran sandstone 2100'-2117'
Core depth = log depth + 10'
Core diameter 3½"
Note: numerous small intervals (up to 3") throughout the core are completely missing, possibly due to sampling by a previous worker.

Log depth (feet) - Core description

2090-91 - (Only the lower few inches of this interval were recovered intact).
Shale. Gray. Moderately fissile, moderately soft, waxy, slightly carbonaceous. 1" bed of shale, black, very fissile, very soft, very carbonaceous.

2091-91½ - Shale, silty to sandy. Flaser/wavy bedded with siltstone to very fine grained sandstone, bioturbated. Dark gray to black, fissile, hard, slightly carbonaceous, abundant very coarse grained to granule sized brachiopod fragments, calcareous. Grades abruptly from silty sand. At base: abundant very fine grained coaly material, fossil fragments, lime and siderite concretions appear abruptly.

2091½-93½ - Sandstone, silty. Massive. Very light gray. Coarse silt to very fine grained. Rounded, moderately well sorted, hard. Fair porosity, salty taste. Quartz, abundant very fine grained coaly material, few large plant fragments, abundant recrystallized coarse grained fossil fragments set in calcite concretions, siderite concretions at base.

2093½-94½ - Sandstone, silty. Flaser/wavy bedded with shale and shaley sandstone, vertical burrows, load structures. Variegated very light gray and gray. Very fine grained, rounded, moderately well sorted, hard. Poor porosity. Quartz, abundant very fine grained coaly material, very coarse grained plant fragments, recrystallized very coarse grained fossil fragments set in calcite concretions, siderite concretions (especially at base), rare pyrite.

2094½-95½ - Sandstone. Massive. Gray. Very fine grained. Rounded, moderately well sorted, hard. Poor porosity, salty taste. Quartz, clay clasts, very fine grained coaly material, carbonaceous wisps, few very coarse grained fossil fragments.

2095½-98 - Sandstone, silty. Flaser/wavy bedded with shale and sandy shale, abundant vertical burrows at top, root traces, ripple cross-beds, load structures, inclined beds. Variegated very light gray and gray. Coarse silt to very fine grained. Rounded, moderately well sorted, hard. Moderate porosity, salty taste. Quartz, very fine grained coaly material, carbonaceous wisps, few coarse grained fossil fragments set in calcite concretions, abundant siderite in burrows. At base: Sandstone, silty, slightly shaley. Well developed ripple cross-beds. Salty taste. In abrupt contact with oil saturated sandstone below.

2098-2106 - Sandstone. Mostly massive, large ripple cross-beds and horizontal beds at top, poorly developed trough cross-beds scattered throughout lower part (extensive carbonate cementation may have masked some sedimentary structures). Buff to light brown. Fine grained at base grading to very fine grained at top, few intraformational clay cobbles and molds thereof near base. Rounded, well sorted, moderately friable. Good porosity, good live oil stain, odor and taste, bright yellow fluorescence (when cut in naphtha and/or HCl), no salty taste. Quartz, trace to 1% altered clay clasts scattered throughout, up to 6% in more porous zones, rare very fine grained coaly material increasing in abundance toward top, abundant (up to 30% of rock) small (1-3mm) patches of carbonate cement throughout impart a mottled appearance to rock, few occurring in layers, cement reacts very slowly in HCl. Basal contact of sandstone with underlying shale was missing from core.

2106-07 - Shale. Flaser/wavy bedded with shaley silt, bioturbated. Dark gray. Moderately fissile, moderately soft. Carbonaceous wisps, few coarse grained fossil fragments set in siderite and calcite concretions.

Sun Oil Co., R. D. Williams #1 (See Plates 13, 14 and 20) 2190′ FSL & 330′ FWL of Sec. 62, BOAL Sur., Callahan County, Texas

Cored interval: Cross Cut sandstone 2403′-2409′, 2421′-2429′
Core depth = log depth
Core diameter: 2"

Log depth (feet) - Core description

2403-09 - Sandstone. Mostly massive, few thin shale, shaley, or silty laminae or flasers throughout, few ripple cross-beds at top, few trough cross-beds, minor loading and bioturbation in shaley beds, few calcite and siderite concretions. Buff, very light gray where carbonate cemented, gray where shaley. Coarse silt to lower very fine grained at base, grading to upper very fine to lower fine grained at top, rare clay cobbles. Rounded, moderately good sorting, hard. Poor to fair porosity, very slight oil stain and scattered fluorescence (dull fluorescence produced after cutting with naphtha and/or HCl, turning to bright yellow after about 1 minute in more porous zones), no salty taste. Quartz, very fine to fine grained clay clasts scattered throughout, up to 3% in porous zones (glauconite in thin section), rare layers containing minor amounts of very fine grained coaly material, rare brachiopod shell fragments, rare calcite cemented layers (1 cm), cement reacts readily in HCl, slightly calcareous throughout, rare vertical fractures. Shale laminae are up to 2 cm thick, gray, fissile, moderately hard, non-silty, non-fossiliferous.

2421-29 - Sandstone, horizontally bedded, thin (1 cm) shale laminae abundant at base gradually decreasing to rare at top, shale flasers, minor loading and bioturbation in shaley beds. Buff, very light gray where carbonate cemented, reddish brown where sideritized, shale is gray. Lower very fine grained at base grading to fine grained at top, rare clay granules and cobbles. Rounded, fair sorting, hard, poor porosity, scattered very slight dull fluorescence (after cutting with naphtha) in top 1½′, slightly salty taste 2422-24. Quartz, shale clasts (trace throughout lower part up to 3% in more porous zones), minor amounts of very fine grained coaly material in top 3′, calcite cemented zones in top 5′ (cement reacts readily in HCl), patchy distribution of cement imparts a mottled appearance to some zones. Shale laminae are 1 cm thick, some wavy bedded, gray, hard, moderately fissile, non-silty, non-fossiliferous.

Sun Oil Co., R. D. Williams #1 (See Plates 13, 15 and 21)
2190′ FSL & 330′ FWL of Sec. 62, BOAL Sur., Callahan County, Texas

Cored interval: Upper Moran sandstone 2453′-2459′, 2463′-2472′
Core depth = log depth
Core diameter: 2"

Log depth (feet) - Core description

2453-58 - Sandstone. Mostly massive, few flasers/laminae of gray shale. Buff to light brown. Lower fine grained at base grading to upper very fine grained at top. Rounded, fair sorting, hard. Fair porosity, fair to poor live oil stain throughout, fair fluorescence scattered throughout (dull fluorescence produced after cutting with naphtha, turning to bright yellow after about 1 minute). Quartz, trace to 1% altered clay clasts throughout, up to 5% in porous zones (glauconite in thin section), minor amounts of very fine to fine grained coaly material scattered throughout, few zones with abundant (up to 20% of rock) small (1-2mm) patches of carbonate cement impart a mottled appearance to rock, cement reacts very slowly in HCl, rare sideritized shale laminae at top, rare vertical fractures. Abrupt basal contact.

2458-59 - (Only the top 2" of this interval were recovered). Shale, non-silty, dark gray to black, moderately fissile, moderately soft, non-fossiliferous, non-limy.

2463-66 - Sandstone, few shale flasers/laminae and associated thin (1 in.) shaley very fine grained sandstone laminae. Mostly massive. Buff to light brown. Fine grained, rare cobbles. Rounded, fair sorting, hard. Fair porosity, poor to fair live oil stain, fair fluorescence (dull after cutting with naphtha, bright yellow after 1 min.) no salty taste. Quartz, trace to 2% clay clasts, rare very fine grained coaly material, scattered carbonate cement reacts slowly in HCl, some siderite in shale.

2466-72 - Sandstone with abundant shale flasers/laminae with load structures (in zones up to 8" thick). Mostly massive, few ripple cross-laminae. Buff. Very fine grained. Rounded, poor to fair sorting, hard. Poor porosity, scattered slightly salty taste. Quartz, trace clay clasts, scattered carbonate cement reacts slowly in HCl. Shale is dark gray, fissile, moderately hard, non-silty, non-fossiliferous, non-limy.

Sun Oil Co., R. D. Williams #1 (See Plates 13, 16 and 22)
2190' FSL & 330' FWL of Sec. 62, BOAL Sur. Callahan County, Texas

Cored interval: Lower Moran sandstone - 2501'-2504', 2510'-2513'
Core depth = log depth
Core diameter = 2"

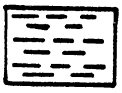
Log depth (feet) - Core description

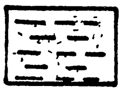
2501-04 - Sandstone. Mostly massive, some horizontally bedded. Buff. Lower very fine grained at base grading to fine grained at top, few clay cobbles. Rounded, fair sorting, hard. Poor to fair porosity, poor to fair live oil stain, fair fluorescence (dull after cutting with naphtha, turning bright yellow after 1 min.), no salty taste. Quartz, trace clay clasts (glauconite in thin section) scattered throughout, up to 2% in oil stained zone, several zones (2 in thick) containing abundant carbonaceous wisps, carbonate cement scattered throughout, reacts very slowly in HCl, abundant (up to 20% of rock) small (1-2 mm) patches of carbonate cement in some zones impart a mottled appearance to rock.

2510-13 - Sandstone. Massive, rare load structures associated with shale laminae and conglomerate layers. Buff. Very fine grained, several clay cobble horizons. Rounded, fair to good sorting, hard. Poor porosity, very slight salty taste scattered throughout. Quartz, scattered clay clasts and coaly material, trace of carbonate cement throughout, few zones of patchy carbonate cement impart a mottled appearance to rock, cement reacts very slowly in HCl. Shale laminae are dark gray, moderately fissile, moderately hard, non-silty, non-fossiliferous, non-limy.

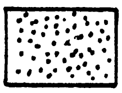
LEGEND OF SYMBOLS USED IN PETROLOGIC LOGS

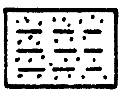
LITHOLOGY

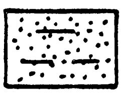
 mudstone

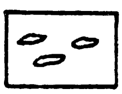
 silty mudstone

 siltstone

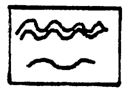
 sandstone

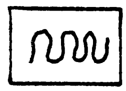
 interbedded sandstone/mudstone

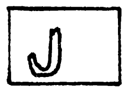
 muddy sandstone

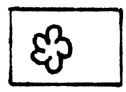
 conglomerate

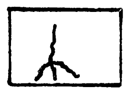
STRUCTURES

 ripple laminae
(D) ripple (F) flaser

 deformation
(F) flowage (L) load

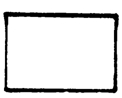
 burrow
trace fossil

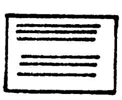
 bioturbated

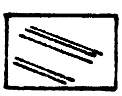
 root traces

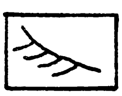
 concretions
(C) calcite (S) siderite

BEDDING (B)
LAMINAE (L)

 massive

 horizontal

 initial slope/dip

 cross bedding
(T) trough (P) planar

 thin section

 SEM

SL sublitharenite

VITA

Jason Forrest Hamilton

Candidate for the Degree of

Master of Science

Thesis: PETROLEUM GEOLOGY OF THE CROSS CUT AND MORAN SANDSTONES (LOWER MISSOURIAN), CALLAHAN AND EASTLAND COUNTIES, TEXAS

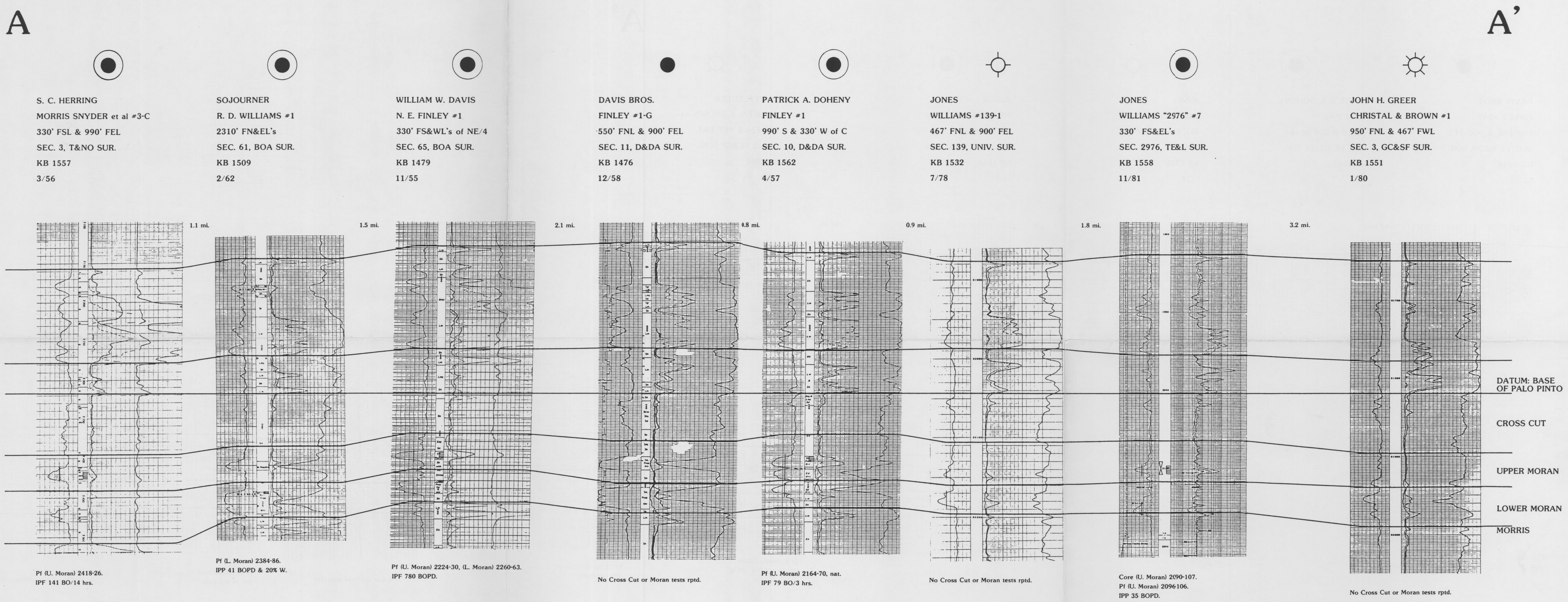
Major Field: Geology

Biographical:

Personal Data: Born in Kenosha, Wisconsin, November 1, 1960, the son of Robert Forrest and Mary Louise Hamilton.

Education: Graduated from Putnam City High School, Oklahoma City, Oklahoma, in May, 1978; received Bachelor of Science degree in Geology from Oklahoma State University, in May, 1984; completed requirements for Master of Science degree at Oklahoma State University in July, 1990.

Professional Experience: Junior member of The American Association of Petroleum Geologists; member of the Oklahoma City Geology Society; member of the Oklahoma City Geological Society Discussion Group; Chairman of the Oklahoma City Geological Society Grants-In-Aid Committee; Oklahoma State University Student Chapter of the American Association of Petroleum Geologists Sponsor and Representative to the Oklahoma City Geological Society; member of the Christian Oilmen's Association; 1979-1982 Ditch digger, R&M Sprinkler; 1982 Geological technician, Grace Petroleum Corp.; 1983-1984 Geological technician, ENSTAR Petroleum, Inc.; 1984 Contract geologist, Union Texas Petroleum Corp.; 1985 Geological assistant, OKT Petroleum Co., Inc.; 1985 Summer geologist, Exxon Co., USA; 1986-present geologist, OKT Petroleum Co., Inc.



OKLAHOMA STATE UNIVERSITY

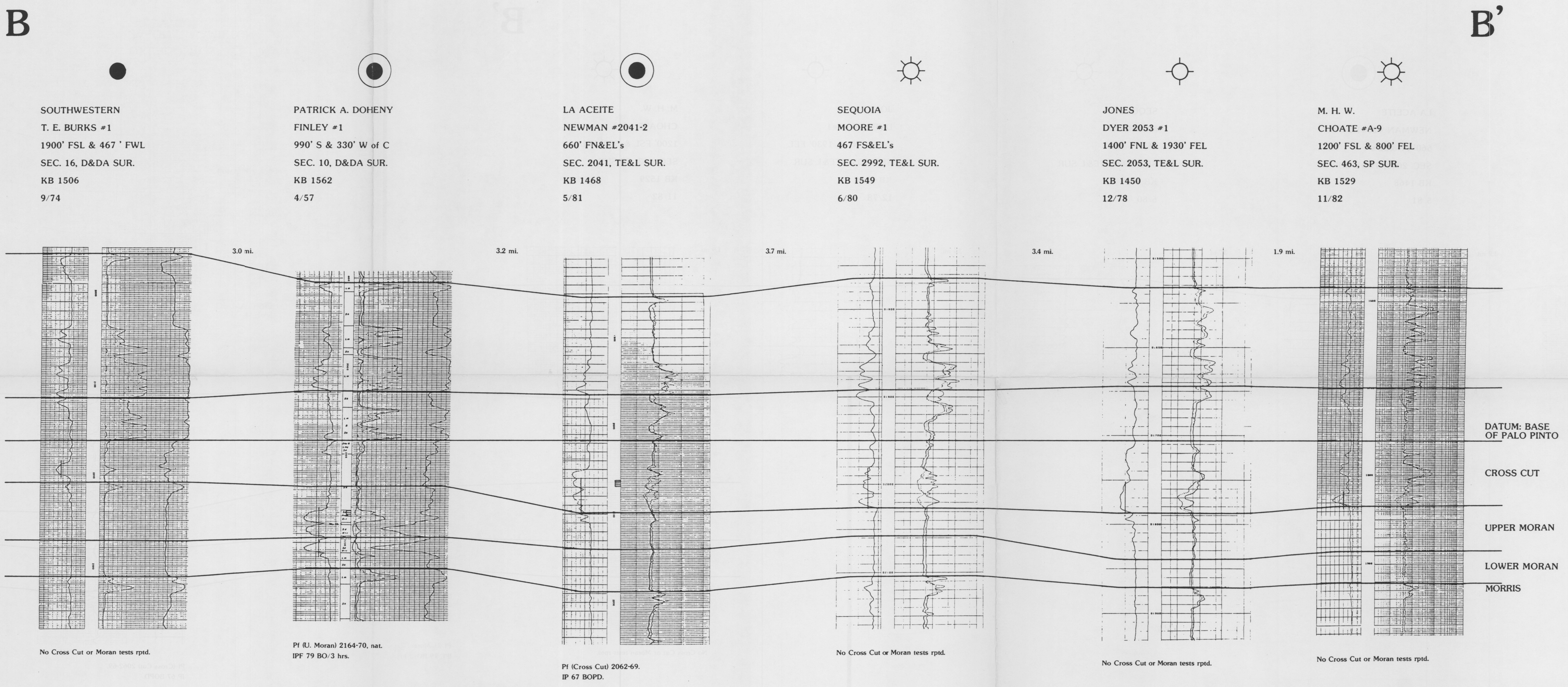
JASON F. HAMILTON - MS THESIS

Callahan & Eastland Counties, Texas

STRATIGRAPHIC CROSS SECTION A - A'

July, 1990

PLATE 1

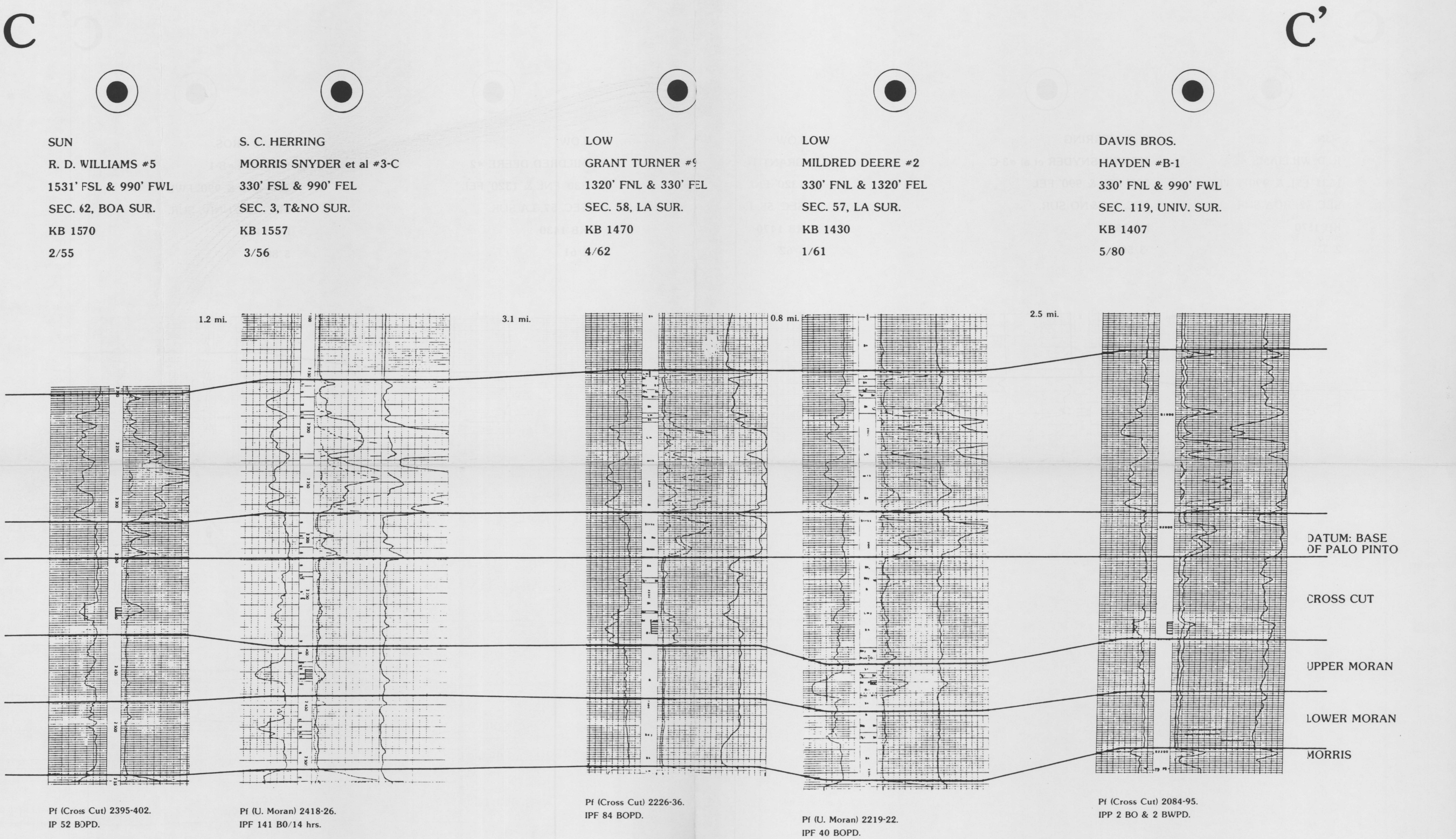


OKLAHOMA STATE UNIVERSITY
JASON F. HAMILTON - MS THESIS
Callahan & Eastland Counties, Texas

STRATIGRAPHIC CROSS SECTION B - B'

July, 1990

PLATE 2

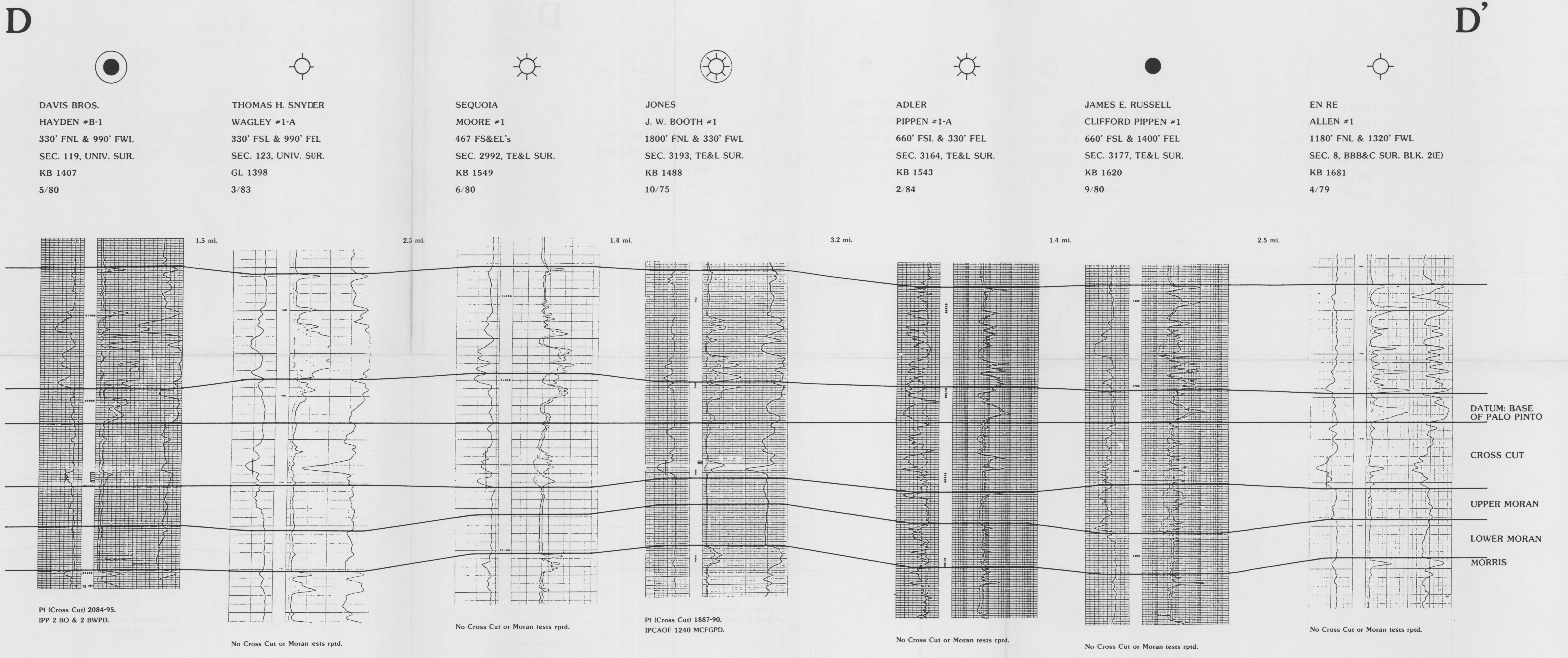


OKLAHOMA STATE UNIVERSITY
JASON F. HAMILTON - MS THESIS
Callahan & Eastland Counties, Texas

STRATIGRAPHIC CROSS SECTION C - C'

July, 1990

PLATE 3



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JASON F. HAMILTON - MS THESIS

Callahan & Eastland Counties, Texas

STRATIGRAPHIC CROSS SECTION D - D'

July, 1990

PLATE 4

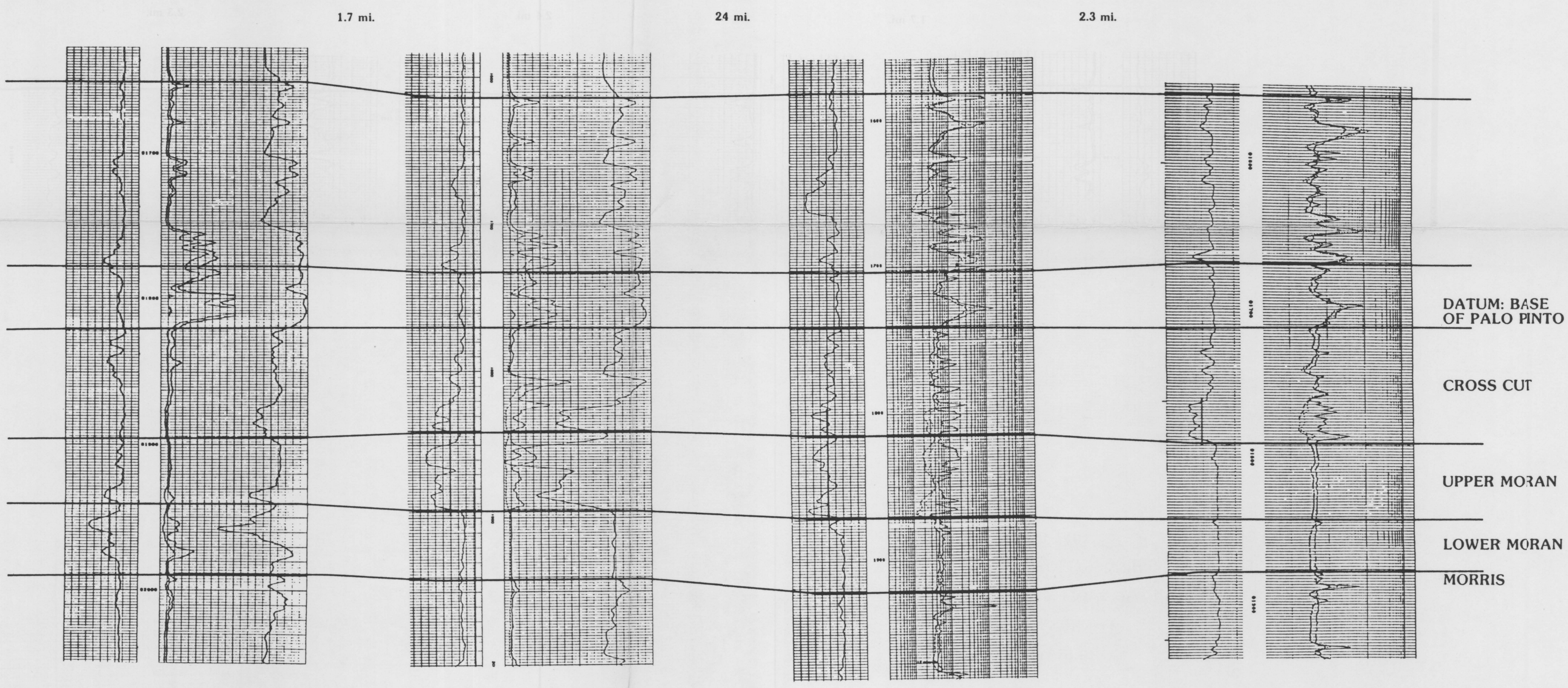
E — E'

JOHN H. GREER
CHRISTAL & BROWN #1
950' FNL & 467' FWL
SEC. 3, GC&SF SUR.
KB 1551
1/80

J. H. GREER
MARSTON SURLES #A-1
1470' FSL & 1320' FEL
SEC. 3157, TE&L SUR.
KB 1576
7/77

JAMES E. RUSSEL
CLIFFORD PIPPEN #1
660' FSL & 1400' FEL
SEC. 3177, TE&L SUR.
KB 1620
9/80

EN RE
ROY PIPPEN #9
2300' FSL & 2420' FEL
SEC. 502, SP SUR.
KB 1653
9/83



No Cross Cut or Moran tests rptd.

No tests.

No Cross Cut or Moran tests rptd.

No tests.

OKLAHOMA STATE UNIVERSITY
JASON F. HAMILTON - MS THESIS
Callahan & Eastland Counties, Texas

STRATIGRAPHIC CROSS SECTION E - E'

July, 1990

PLATE 5

TRUMPTER

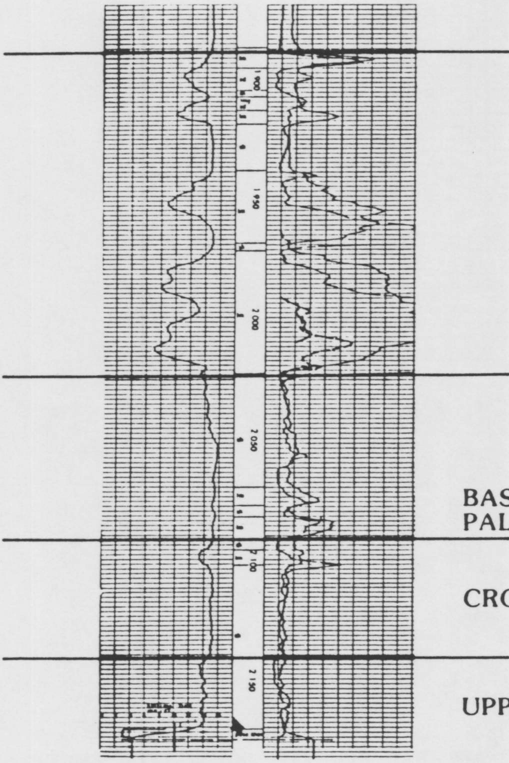
BETCHER #4

990' FSL & 330' FEL

SEC. 66, BOA SUR.

KB 1479

5/50



BASE OF PALO PINTO

CROSS CUT

UPPER MORAN

5 1/2" 2171 (U. Moran).

IPF 53 BO & 29 BWPD, 16/64"

chk., CP 150, TP 10, gty. 41.9.

B. F. PHILLIPS

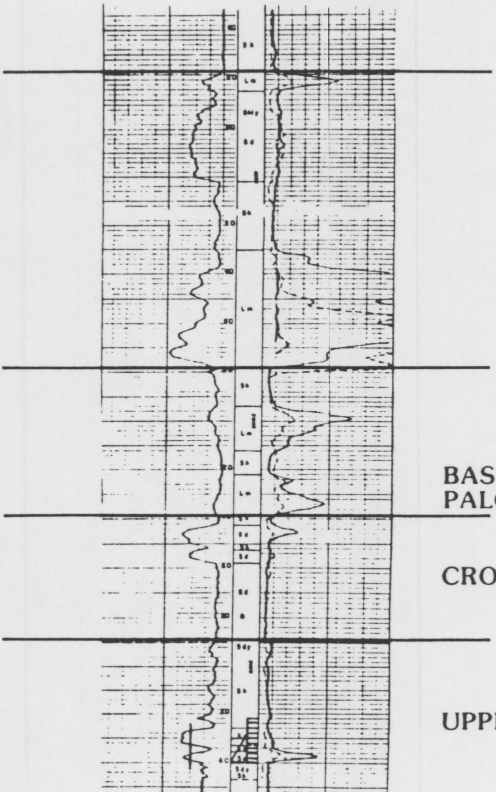
W. O. LAWSON #2

330' FS&WL's

SEC. 138, UNIV. SUR.

DB 1527

10/49



BASE OF PALO PINTO

CROSS CUT

UPPER MORAN

DST (U. Moran) 2132-40, op 1 hr.,
rec. 115' O & OCM, FP 0, SIP 600,
flwd by heads 31.2 BO/30 min.
Pf (U. Moran) 2122-40, shot 20 qts.
IPF 57 BOPD, 20/64" ch., gty. 41,
GOR 680:1, TP 50.

JONES

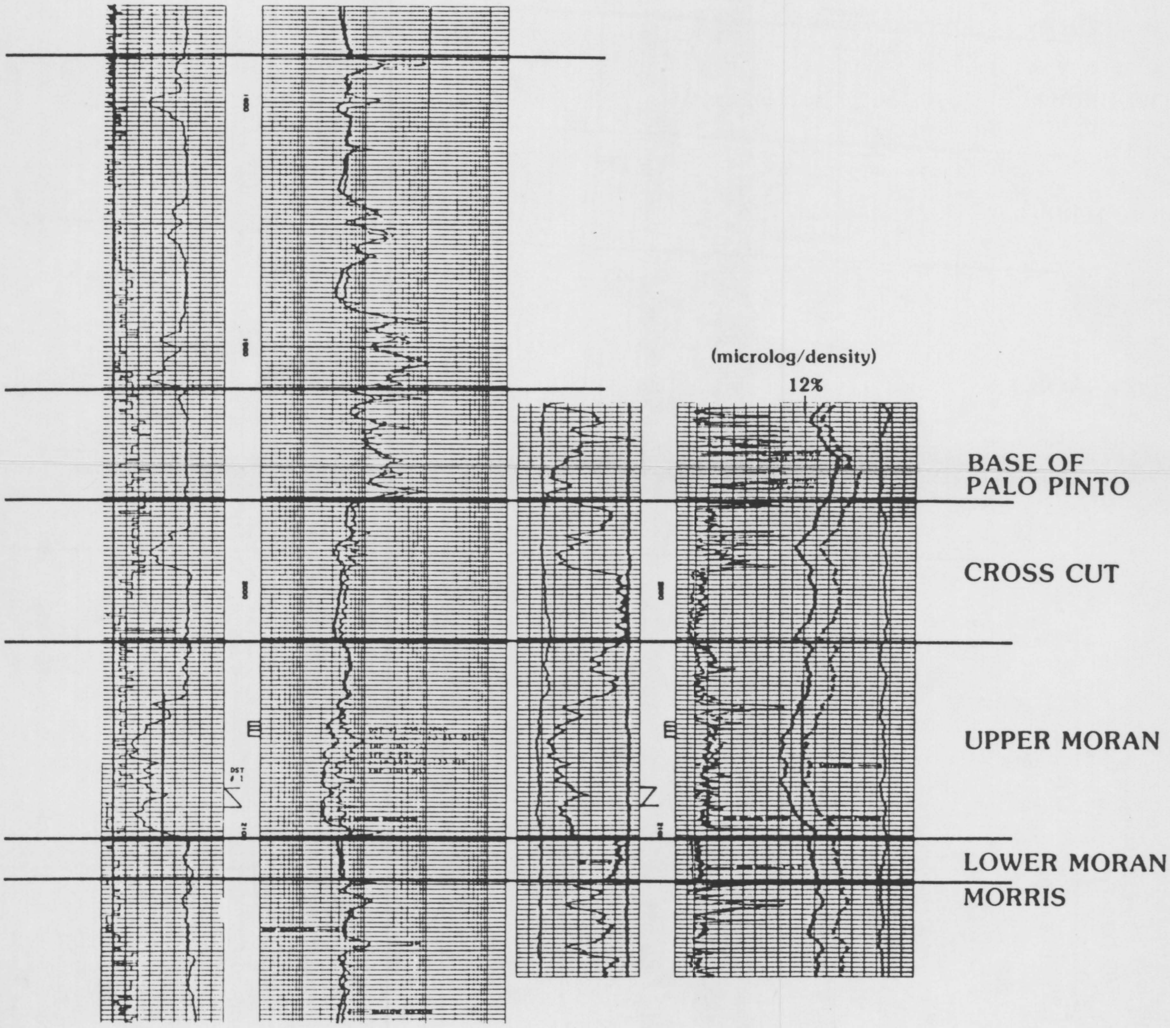
PRUETT "2277" #1

330' FNL & 400' FEL

SEC. 2277, TE&L SUR.

KB 1653

4/81



DST (U. Moran) 2082-90, 456' G, 1' FO, 85' O&GCM, IHP 1063, IFP 2, FSIP 697/120 min., FHP 1003.

Pf (U. Moran) 2055-61.

IPP 16 BO & 63 BWPD.

Plugged & abandoned.

WEST CENTRAL

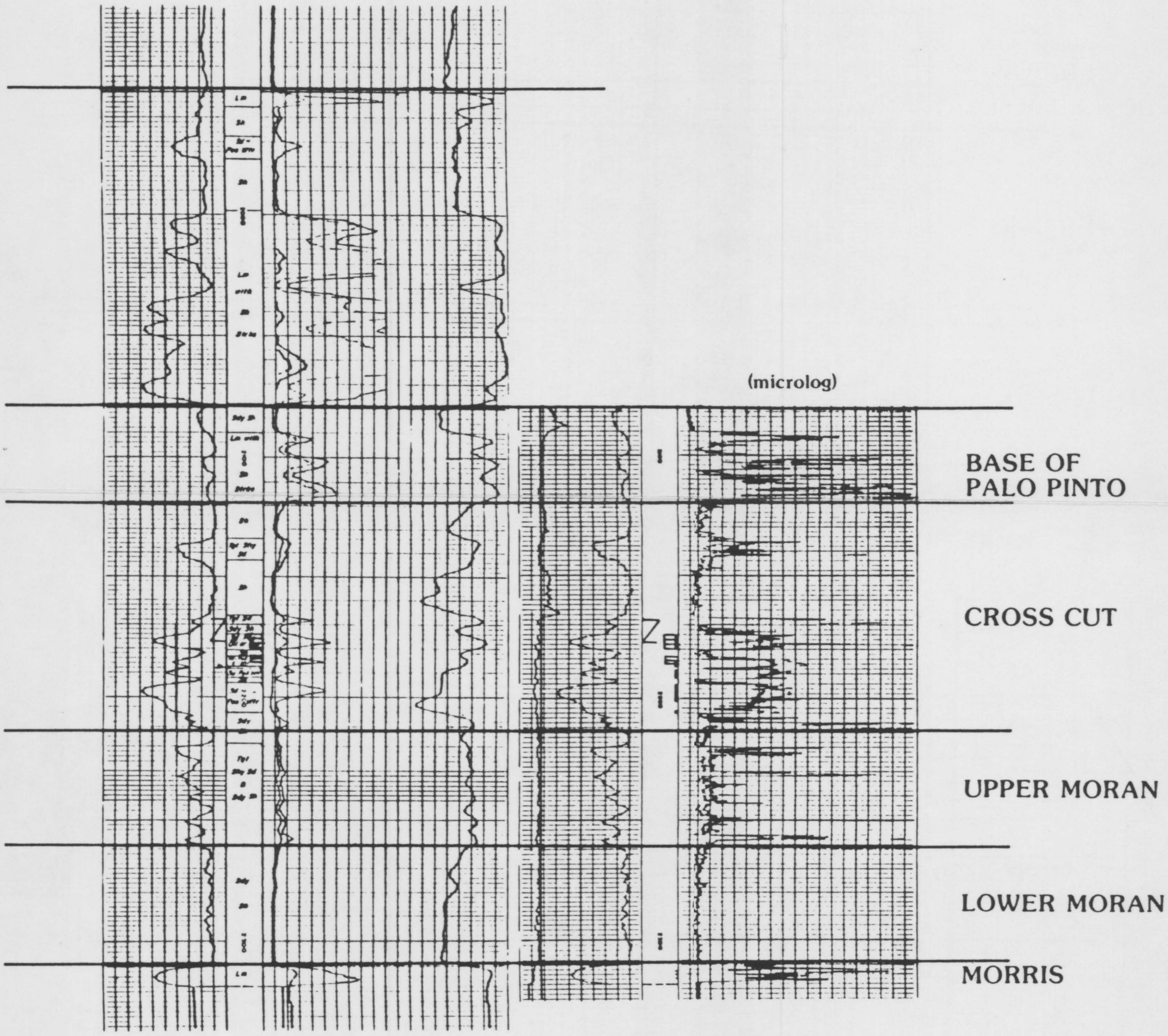
E. Y. ELLIOT #3

407' FSL & 1400' FEL

SEC. 57, LA SUR.

KB 1450

3/61



DST (Cross Cut) 2168-77/80 min., gd blo, G/2", 30 MCFPD, O/68", 230' O, 110' OCM, NW, FP 50-260, ISIP 1050/30 min., FSIP 1035/1 hr.

Pf (Cross Cut) 2174-80, 2183-86.

IPF 69 BOPD, 8/64" chk., GOR 452:1, gty 39, TP 200.

EN RE

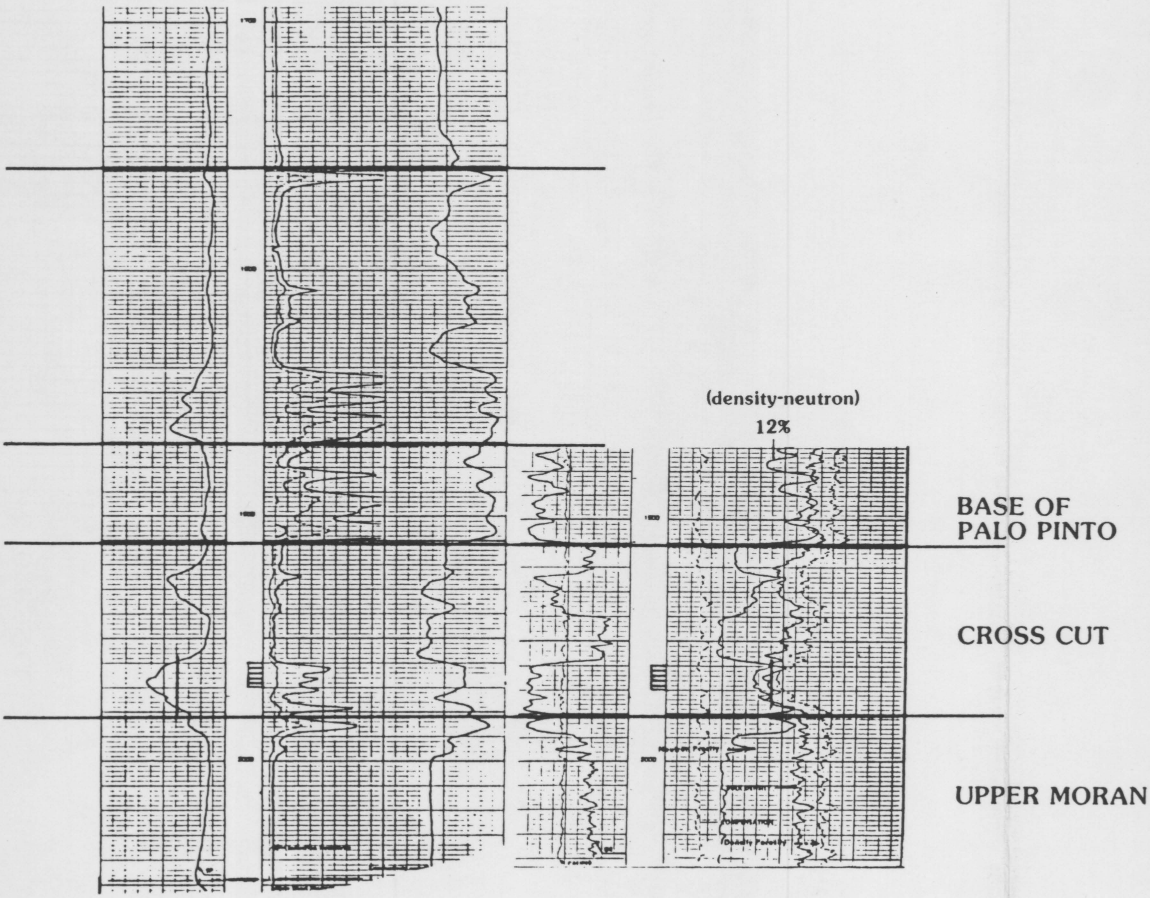
JOHN PRUETT #2

330' FSL & 780' FEL

SEC. 2287, TE&L SUR.

KB 1636

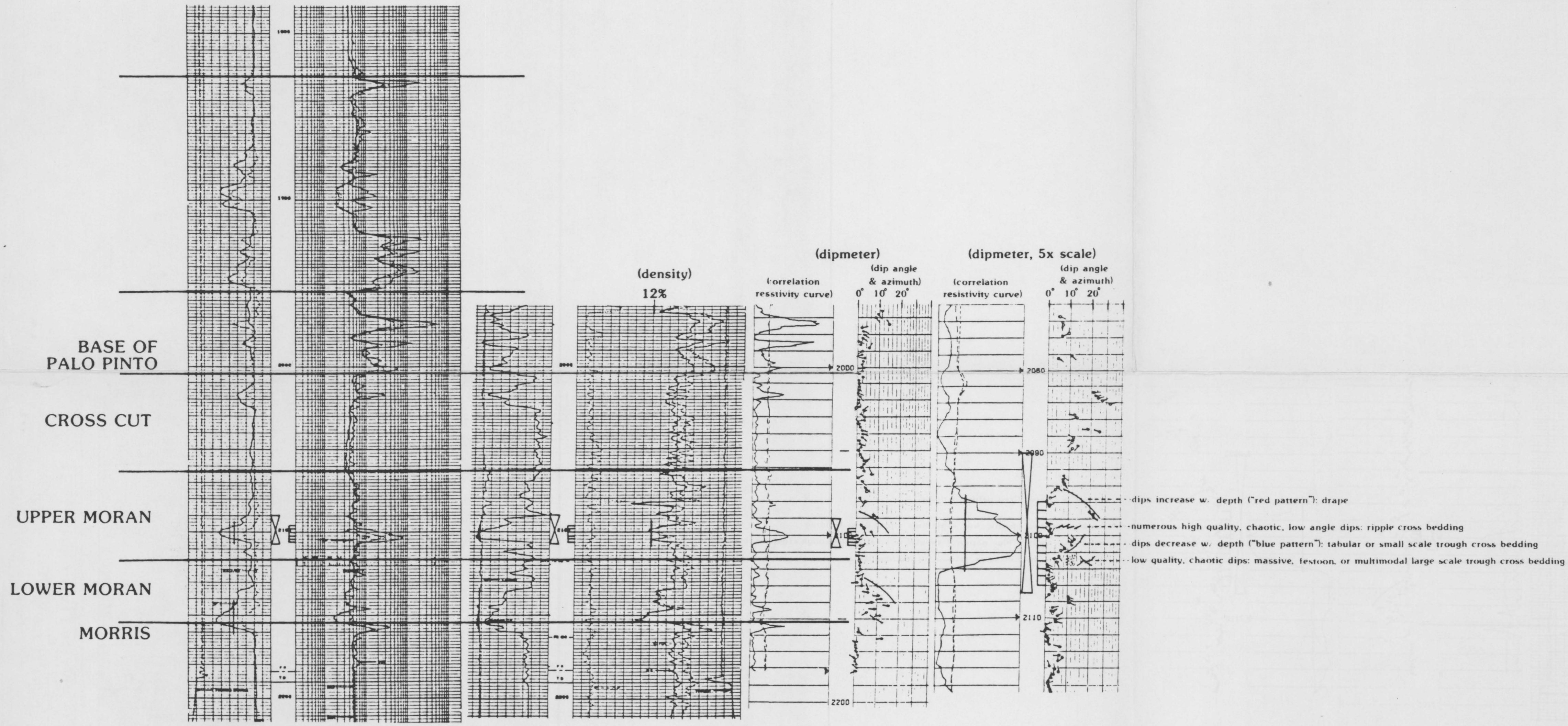
8/81



Pf (Cross Cut) 1960-70.

IPP 46 BOPD, 13/64" chk., gty 42, GOR 450, CP 450, TP 120.

JONES
WILLIAMS "2976" #7
330' FS&EL's
SEC. 2976, TE&L SUR.
KB 1558
11/81



C (U. Moran) 2090-107.
Pf (U. Moran) 2096-106.
IPP 35 BOPD, gty. 41, GOR TSTM.

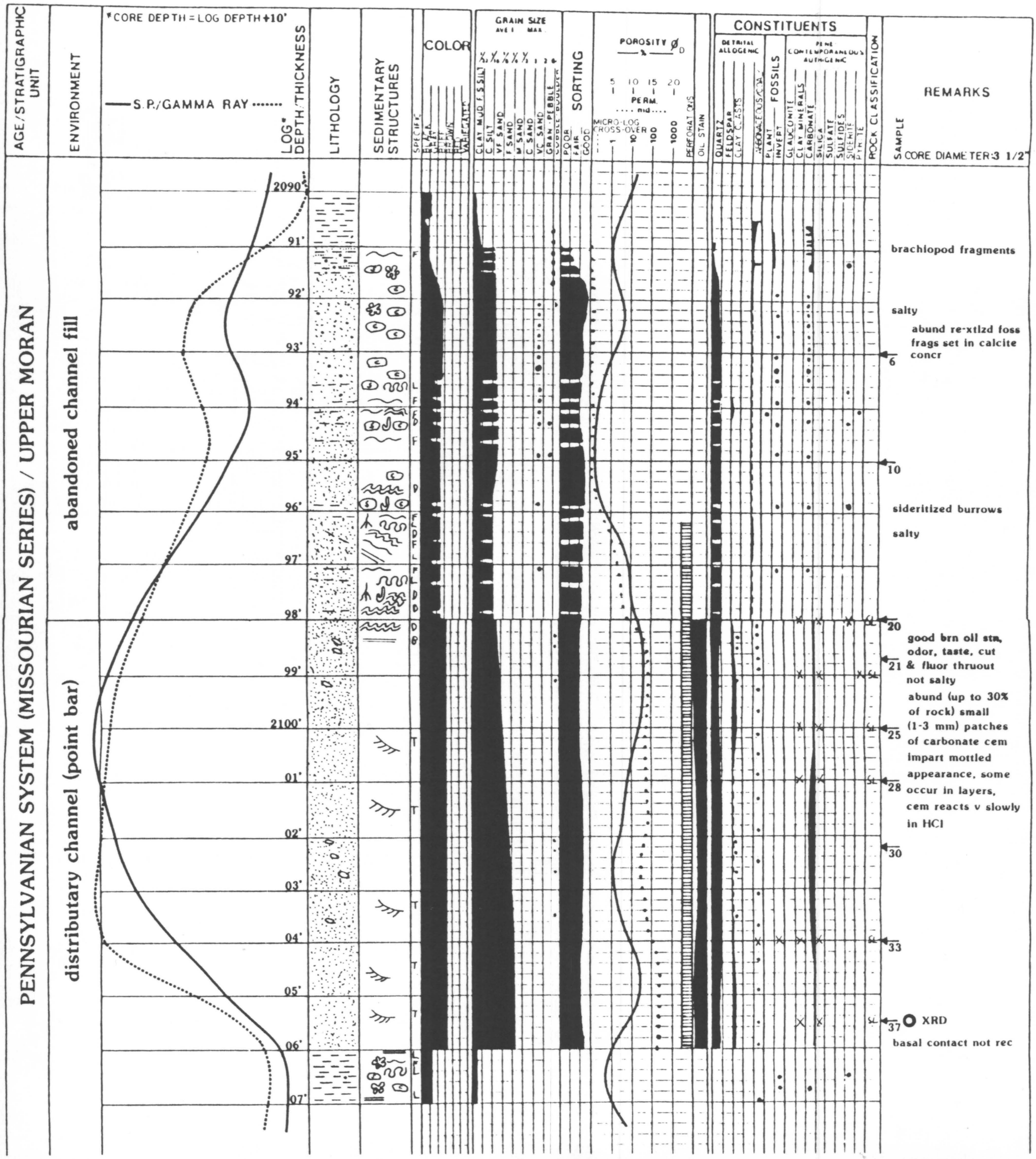
PLATE 12 OKLAHOMA STATE UNIVERSITY - JASON F. HAMILTON - MS THESIS July, 1990

Company **JONES CO. - WILLIAMS "2976" #7**

Well Location **330' FS&EL's of Sec. 2976**

TE&L SUR. - CALLAHAN CO., TEXAS

Petrologic Log



SUN

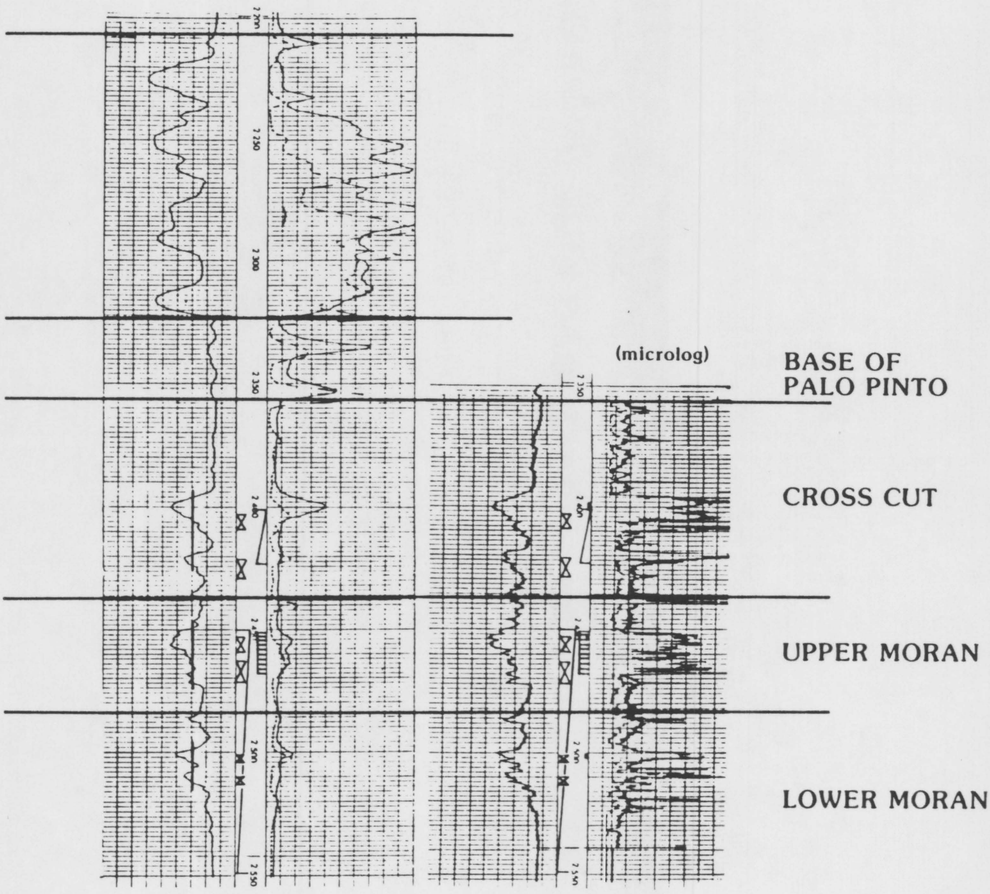
R. D. WILLIAMS #1

2190' FSL & 330' FWL

SEC. 62, BOA SUR.

KB 1578

1/55



C (Cross Cut) 2403-09, 2421-29.
DST (Cross Cut) 2401-23/2 hrs., G/26", 565' O, 50' HOCM, FP 130, BHP 1050.

C (U. Moran) 2453-59, 2463-72.
C (L. Moran) 2501-04, 2510-13.
DST (U. & L. Moran) 2450-2549/2 hrs., G/37", 1060 O&GCM, FP 330, BHP 1130.)
Pf (U. Moran) 2451-68.
IPF 175 BO/18 hrs., 18/64" chk., gty. 42.8, GOR 30(3, CP 460, TP 750.

PLATE 14 OKLAHOMA STATE UNIVERSITY - JASON F. HAMILTON - MS THESIS July, 1990

Company SUN OIL CO. - R. D. WILLIAMS #1

Well Location 2190' FSL & 330' FWL of Sec. 62

BOAL SUR. - CALLAHAN CO., TEXAS

Petrologic Log

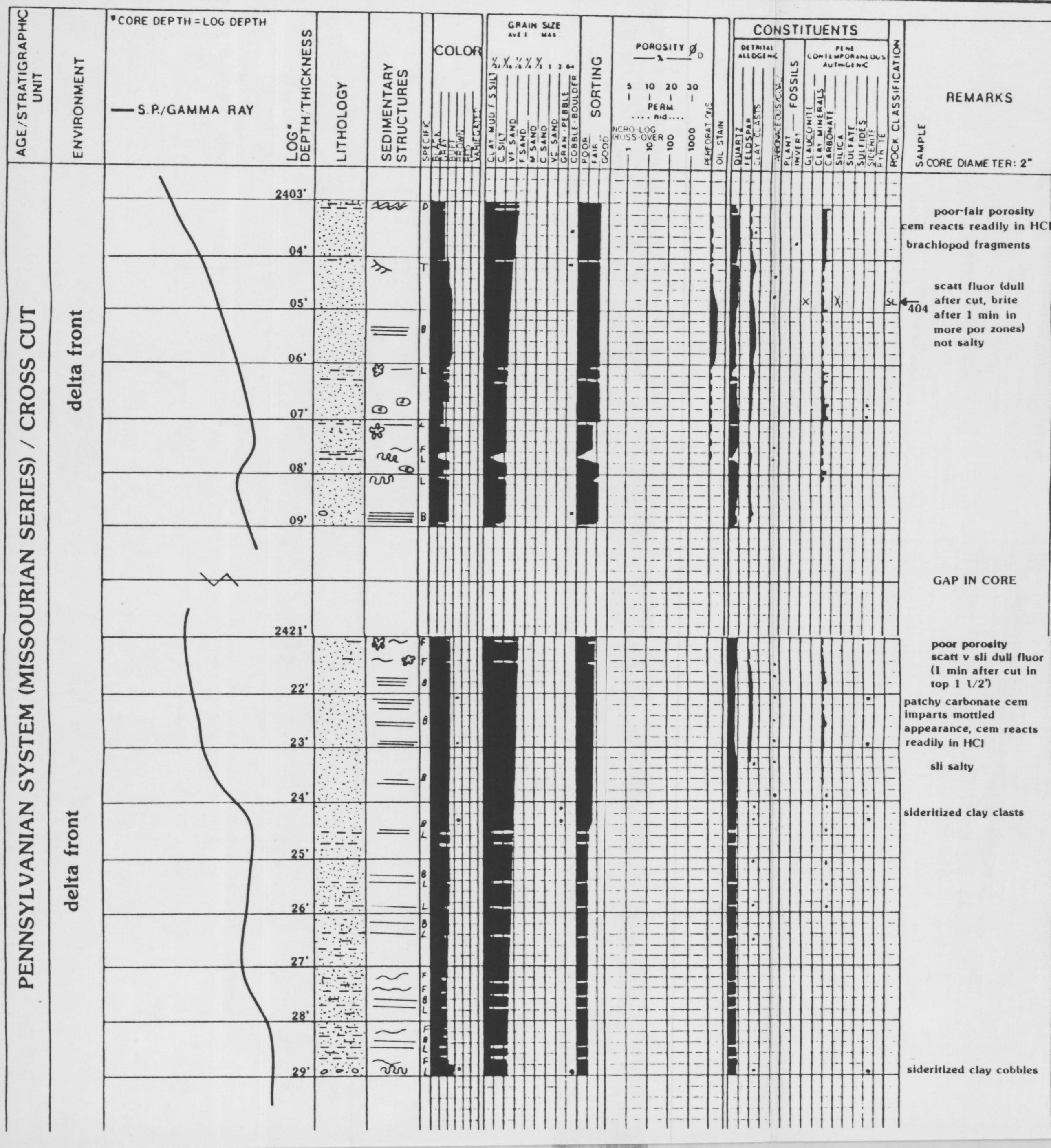


PLATE 15 OKLAHOMA STATE UNIVERSITY - JASON F. HAMILTON - MS THESIS July 1990

Petrologic Log

Company SUN OIL CO. - R. D. WILLIAMS #1

Well Location 2190' FSL & 330' FWL of Sec. 62

BOAL SUR. - CALLAHAN CO., TEXAS

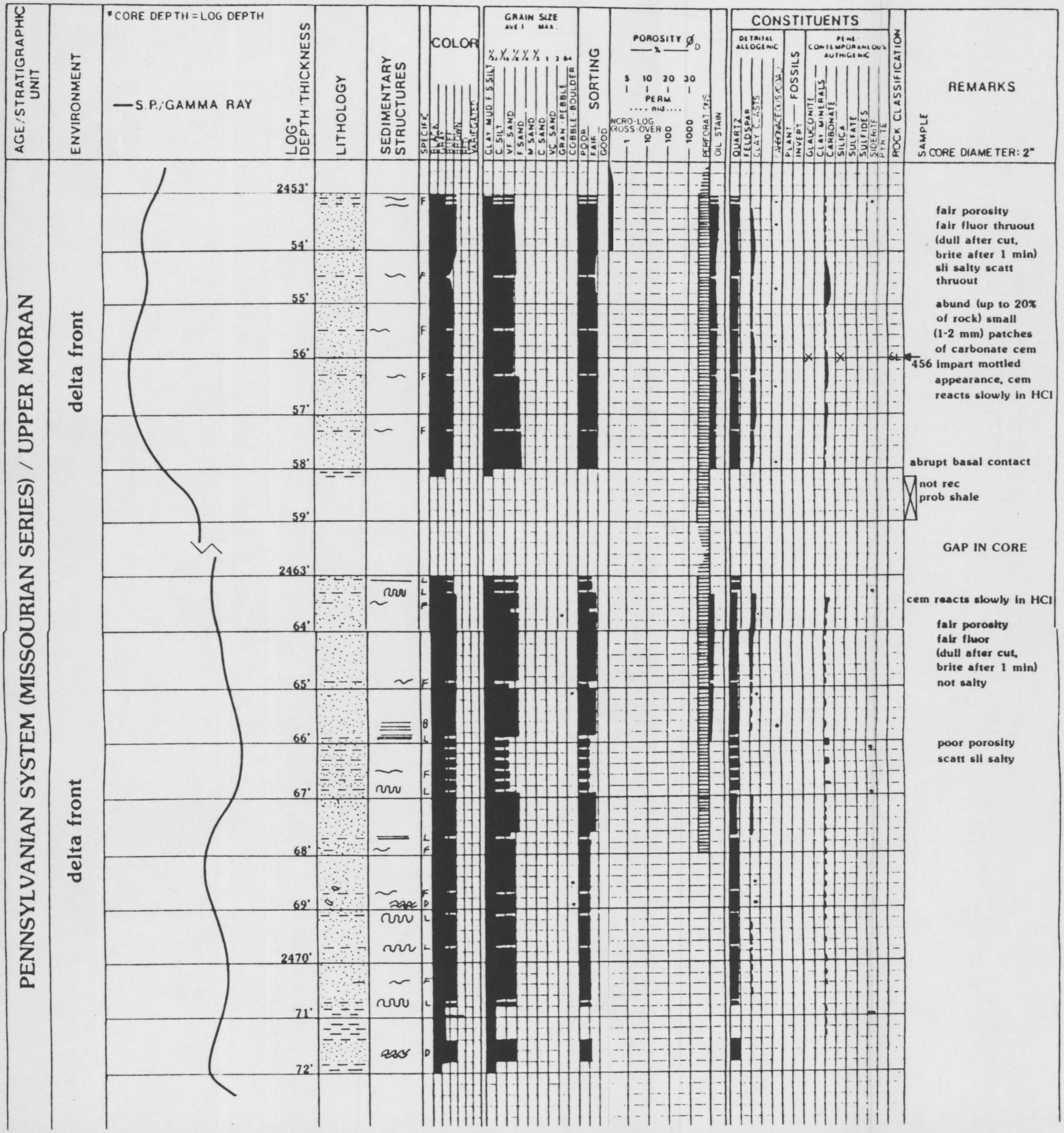


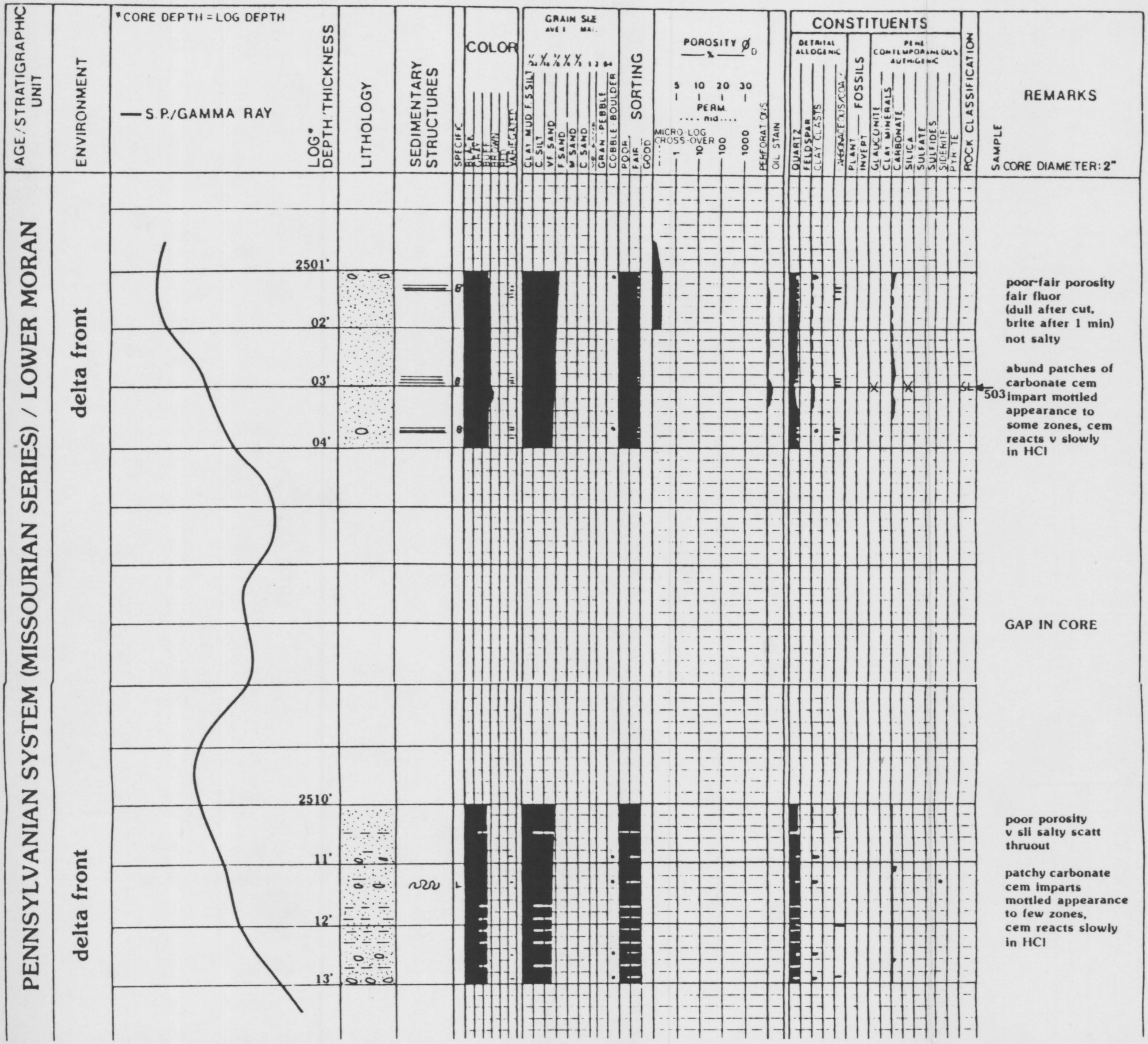
PLATE 16 OKLAHOMA STATE UNIVERSITY - JASON F. HAMILTON - MS THESIS July, 1990

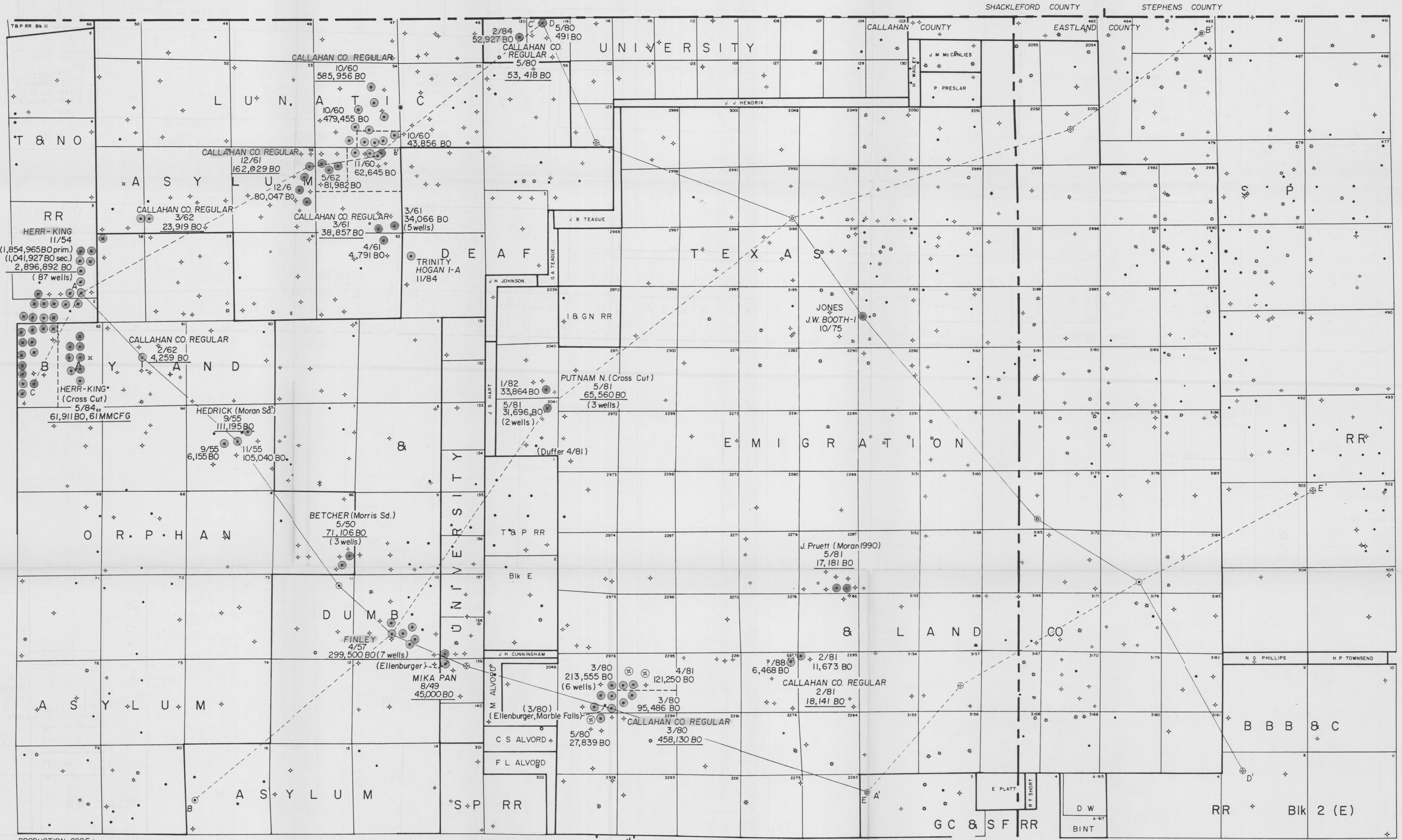
Petrologic Log

Company SUN OIL CO. - R. D. WILLIAMS #1

Well Location 2190' FSL & 330' FWL of Sec. 62

BOAL SUR. - CALLAHAN CO., TEXAS





PRODUCTION CODE:
- CROSS CUT
- UPPER MORAN
- LOWER MORAN

FIELD NAME
DISCOVERY DATE
CUM. PROD. (thru 12/88)

OKLAHOMA STATE UNIVERSITY

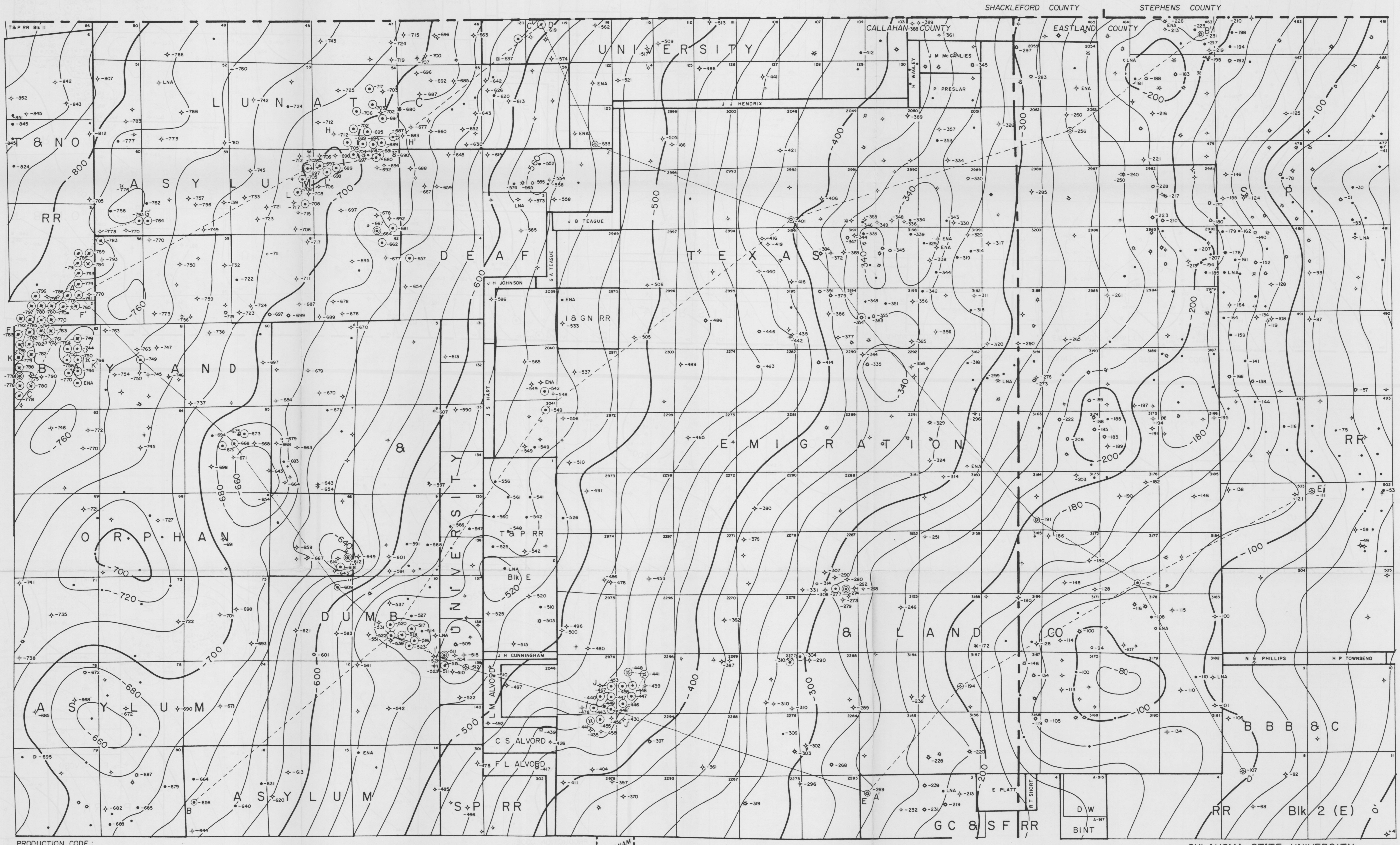
JASON F. HAMILTON - M. S. THESIS
Callahan & Eastland Counties, Texas

CROSS CUT & MORAN CUMULATIVE PRODUCTION

Note: Wells not penetrating base of Palo Pinto are omitted

July, 1990 — 1 mile

PLATE 17



PRODUCTION CODE:

- CROSS CUT
- UPPER MORAN
- LOWER MORAN

LNA - Log Not Available

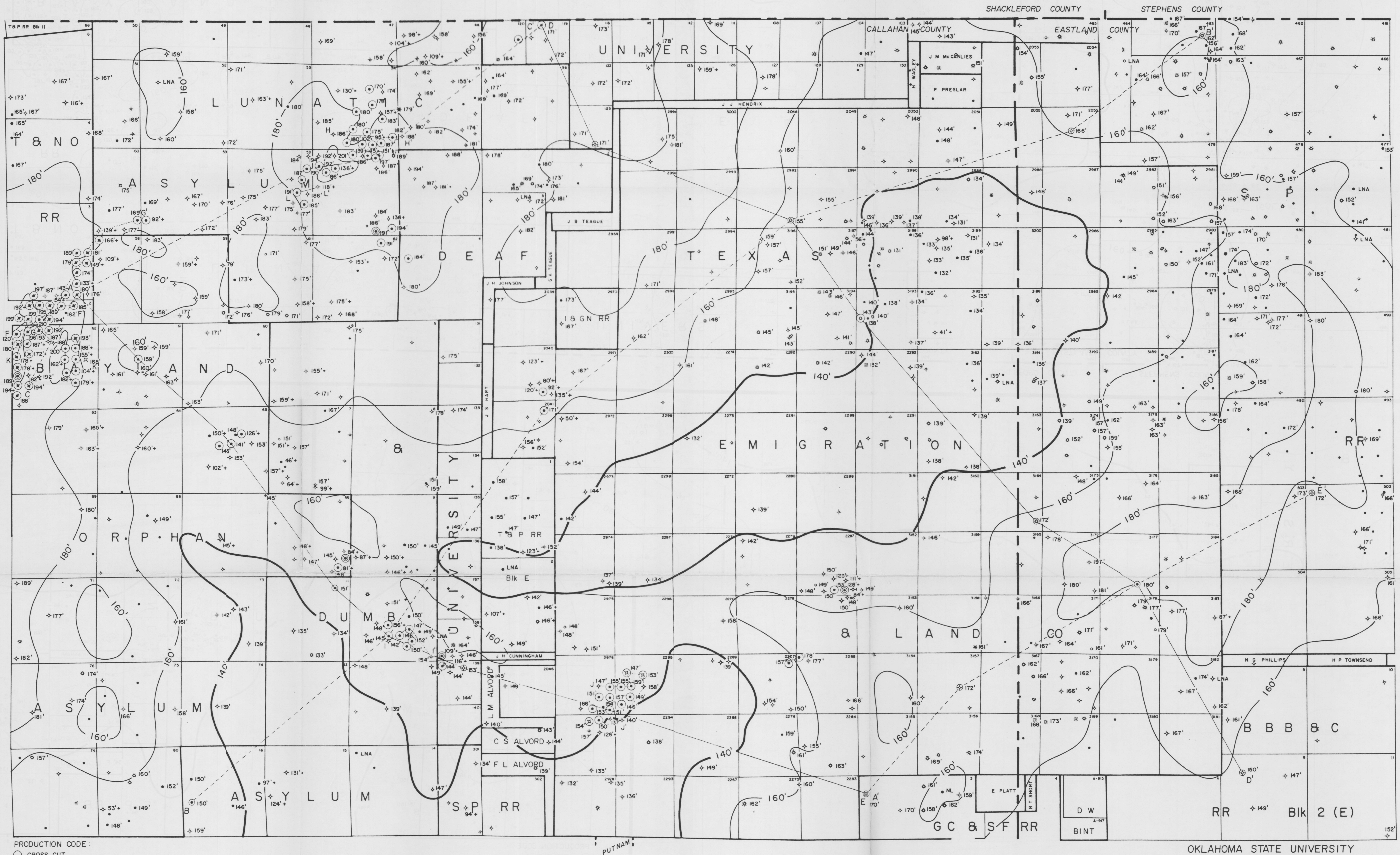
ENA - Elevation Not Available

OKLAHOMA STATE UNIVERSITY

JASON F. HAMILTON - M. S. THESIS

Callahan & Eastland Counties, Texas

STRUCTURE: BASE OF PALO PINTO



PRODUCTION CODE:
- CROSS CUT
- UPPER MORAN
- LOWER MORAN

LNA - Log Not Available

Note: Wells not penetrating base of Palo Pinto are omitted

OKLAHOMA STATE UNIVERSITY

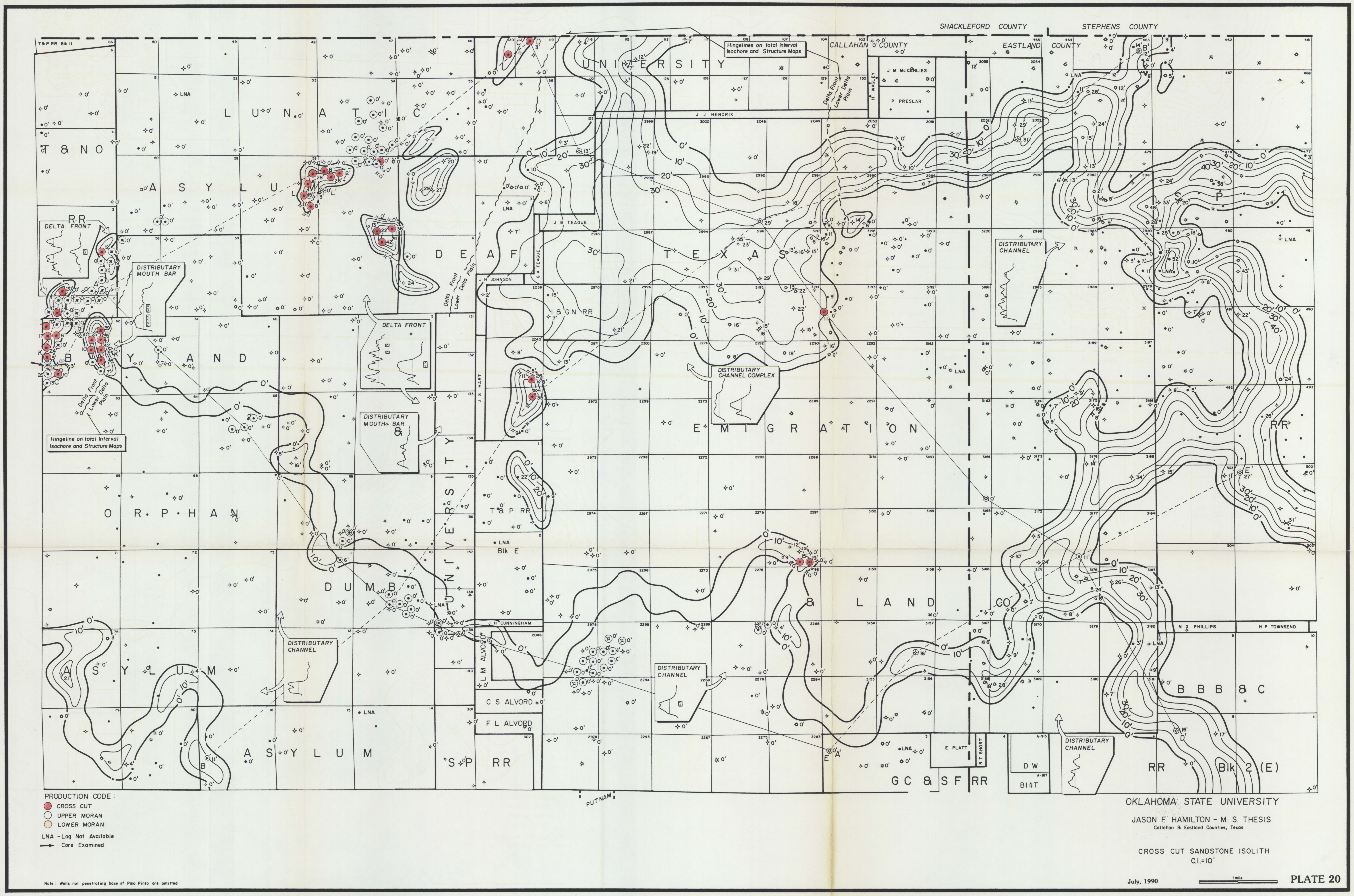
JASON F. HAMILTON - M. S. THESIS
Callahan & Eastland Counties, Texas

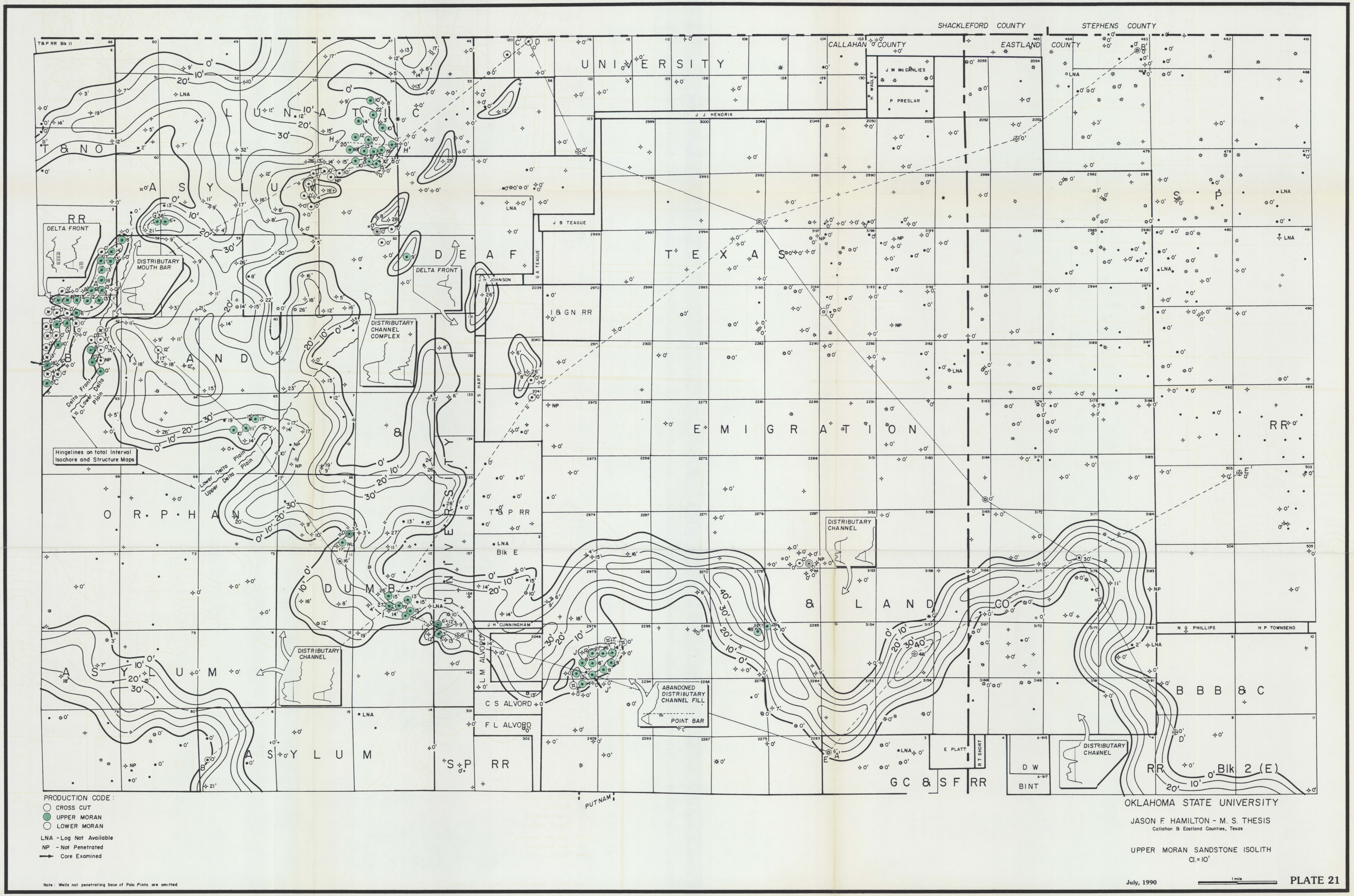
TOTAL INTERVAL ISOCHORE
BASE PALO PINTO
TO
TOP MORRIS
C.I.=20'

July, 1990

1 mile

PLATE 19


SHACKLEFORD COUNTY
STEPHENS COUNTY
CALLAHAN COUNTY
EASTLAND COUNTY
Hingelines on total interval Isochore and Structure Maps
Hingeline on total interval Isochore and Structure Maps
T&P RR Blk II
T & NO
LUNATIC
ASYLUM
DEAF
UNIVERSITY
TEXAS
EMIGRATION
ORPHAN
DUMB
& LAND
BLIND
BBB & C
RR Blk 2 (E)
GC & SF RR
S P RR
T&P RR
I & GN RR
Blk E
J J HENDRIX
J B TEAGUE
J H JOHNSON
J S HART
J H CUNNINGHAM
L M ALVORD
C S ALVORD
F L ALVORD
J M McCANLIES
P PRESLAR
N G PHILLIPS
H P TOWNSEND
E PLATT
R T SHORT
D W
BINT
PUTNAM
DELTA FRONT
DISTRIBUTARY MOUTH BAR
DISTRIBUTARY CHANNEL
DISTRIBUTARY CHANNEL COMPLEX
Delta Front
Lower Delta Plain
PRODUCTION CODE:
CROSS CUT
UPPER MORAN
LOWER MORAN
LNA - Log Not Available
Core Examined
Note: Wells not penetrating base of Palo Pinto are omitted
OKLAHOMA STATE UNIVERSITY
JASON F. HAMILTON - M. S. THESIS
Callahan & Eastland Counties, Texas
CROSS CUT SANDSTONE ISOLITH
C.I.=10'
July, 1990
1 mile
PLATE 20


SHACKLEFORD COUNTY
STEPHENS COUNTY
CALLAHAN COUNTY
EASTLAND COUNTY
UNIVERSITY
LUNATIC
ASYLUM
T & NO
RR
DEAF
TEXAS
EMIGRATION
& LAND
BLIND
ORPHAN
DUMB
UNIVERSITY
SP RR
GC & SF RR
BBB & C
RR Blk 2 (E)
J J HENDRIX
J M McCAULIES
P PRESLAR
J B TEAGUE
G A TEAGUE
J H JOHNSON
I & GN RR
J S HART
T & P RR
Blk E
J H CUNNINGHAM
L M ALVORD
C S ALVORD
F L ALVORD
E PLATT
R T SHORT
D W
BINT
N G PHILLIPS
H P TOWNSEND
PUTNAM
DELTA FRONT
DISTRIBUTARY MOUTH BAR
DISTRIBUTARY CHANNEL COMPLEX
DISTRIBUTARY CHANNEL
ABANDONED DISTRIBUTARY CHANNEL FILL
POINT BAR
Delta Front
Lower Delta Plain
Upper Delta Plain
Hingelines on total Interval Isochore and Structure Maps
PRODUCTION CODE:
CROSS CUT
UPPER MORAN
LOWER MORAN
LNA - Log Not Available
NP - Not Penetrated
Core Examined
Note: Wells not penetrating base of Palo Pinto are omitted
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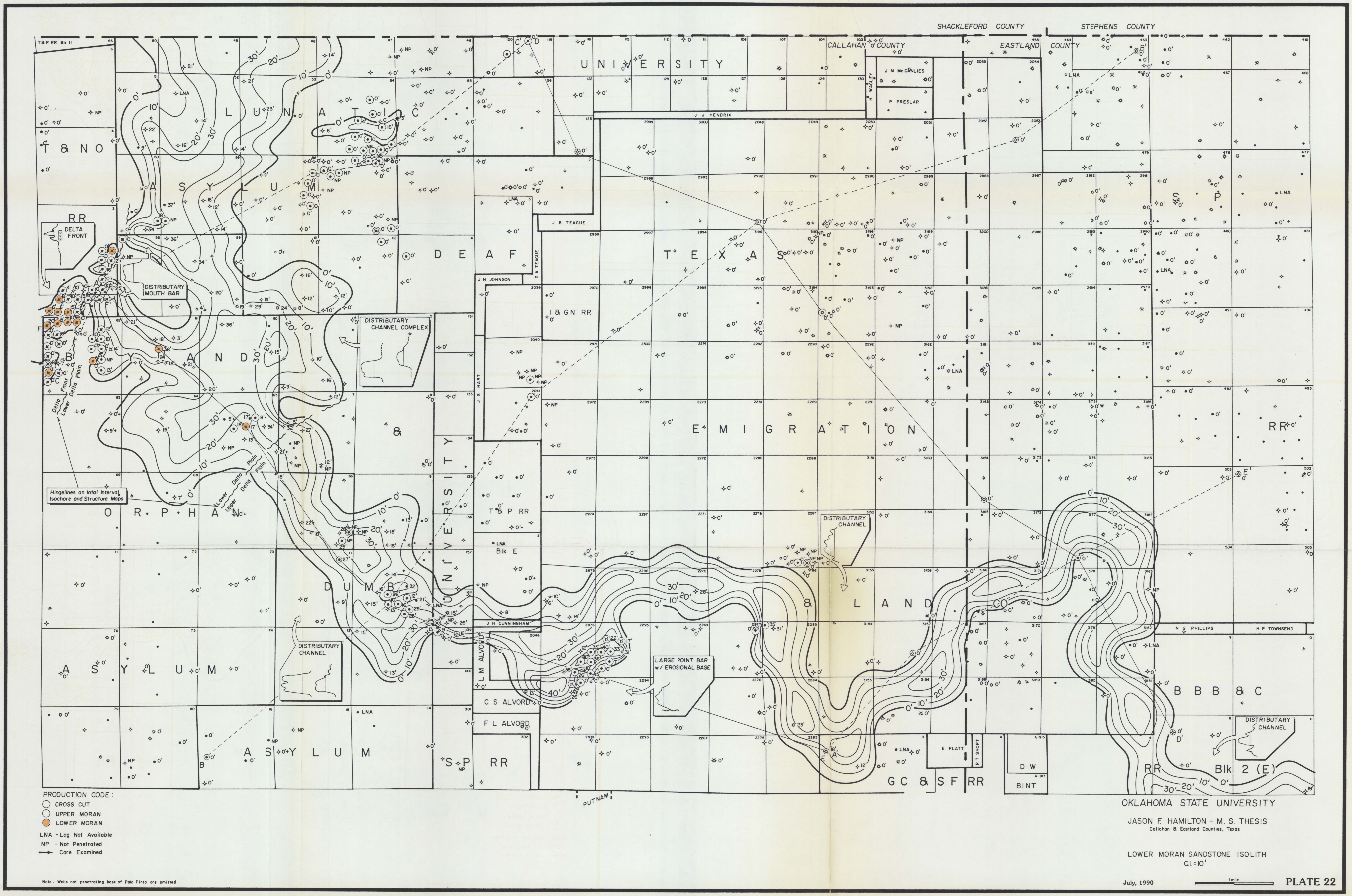
Callahan & Eastland Counties, Texas
UPPER MORAN SANDSTONE ISOLITH
C.I. = 10'
July, 1990
1 mile
PLATE 21



SHACKELFORD COUNTY
STEPHENS COUNTY
CALLAHAN COUNTY
EASTLAND COUNTY
UNIVERSITY
LUNATIC ASYLUM
DEAF & DUMB ASYLUM
BLIND ASYLUM
ORPHAN ASYLUM
T & NO RR
TEXAS EMIGRATION & LAND CO
S P RR
BBB & C RR
Blk 2 (E)
GC & SF RR
T & P RR Blk E
I & GN RR
J J HENDRIX
J M McCANLIES
P PRESLAR
J B TEAGUE
G A TEAGUE
J H JOHNSON
J S HART
J H CUNNINGHAM
L M ALVORD
C S ALVORD
F L ALVORD
N G PHILLIPS
H P TOWNSEND
E PLATT
R T SHORT
D W BINT
PUTNAM
DELTA FRONT
DISTRIBUTARY MOUTH BAR
DISTRIBUTARY CHANNEL COMPLEX
DISTRIBUTARY CHANNEL
LARGE POINT BAR w/ EROSIONAL BASE
Delta Front
Lower Delta Plain
Upper Delta Plain
Hingelines on total interval Isochore and Structure Maps
PRODUCTION CODE:
CROSS CUT
UPPER MORAN
LOWER MORAN
LNA - Log Not Available
NP - Not Penetrated
Core Examined
Note: Wells not penetrating base of Palo Pinto are omitted
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LOWER MORAN SANDSTONE ISOLITH
C.I. = 10'
July, 1990
1 mile
PLATE 22

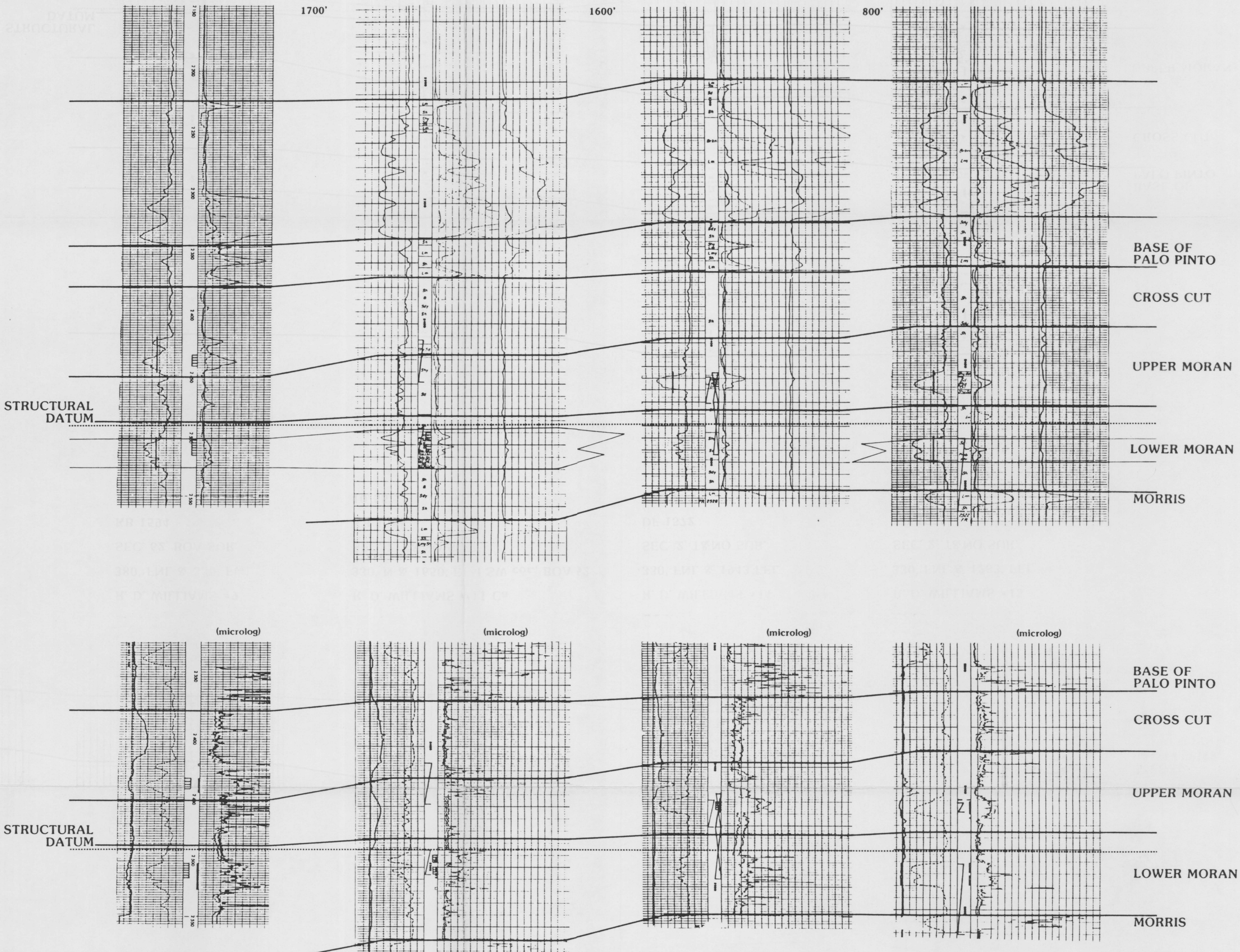
F F'

SUN
R. D. WILLIAMS #9
380' FNL & 330' FWL
SEC. 62, BOA SUR.
KB 1594
5/55

GULF
R. D. WILLIAMS #11 Ca
330' N & 1650' E of SW cor., BOA 62
SEC. 2, T&NO SUR.
KB 1588
10/55

GULF
R. D. WILLIAMS #14
330' FNL & 1943 FEL
SEC. 2, T&NO SUR.
DF 1572
11/55

GULF
R. D. WILLIAMS #15
330' FNL & 1283' FEL
SEC. 2, T&NO SUR.
KB 1555
12/55



Pf (L. Moran) 2502-14.
IPF 163 BOPD.

Pf (Cross Cut) 2432-41.
IPF 163 BOPD, 12/64" chk., TP 300, CP 175, GOR 300, gty. 41.4.

DST (Cross Cut & U. Moran) 2414-48/90", strong blo, 1000' G & 90' HO&GCM, FP 0, SIP 850/30", HP 1250.

DST (L. Moran) 2486-2506/64", G/4" TSTM, O/51", flwd to pits 12 min. at 10 BOPH, rev out approx. 25 BO to pits, rec 180' MCG&O below sub, 50% O, 40% G & 10% M, gty. 40.9, FP 130-350, SIP 1030-870/30 min", HP 1290.
Pf (L. Moran) 2490-96, 2500-06, swbd 44 BO/6 hrs., flwd 16 BO/14 hrs., thru 12/64" chk., TP 55, CP 310, A, frac w/ O & sd, flwd 88 BLO/2 hrs. thru 3/4" chk., TP 275-150, CP 2700.
IPF 290 BO/6 hrs., 1/2" chk., gty. 40.6, GOR 466, TP 380-240, CP 150.

DST (U. Moran) 2429-51/90", strong blo G/4 1/2", O/82", flwd to pits 8 min. at est. 10 BOPH, G vol. 144 MCFPD, rev out approx. 25 BO, rec. 145' HO&GCM, w/ rec. tool 30% O, 20% G, 30' O&GC salty M & 5' W, gty. 40.2, FP 0-250, SIP 820/30", HP 1230.
Pf (U. Moran) 2430-37, swbd 9 BLO/3 hrs., no W, flwd to tanks thru tbg. 20 BO/4 hrs., A, swbd 6 bbls A & 4 1/2 BO, frac w/ O & sd., started swab & well KO & flwd all LO & frac O/5 hrs. 45 min., 3/3/4" chk., flwd 49.84 BO/1 1/2 hrs., 1/2" chk., G vol. 329 MCFGPD, GOR 413, TP 200-220, CP 0.
IPF 204 BOPD, 1/2" chk., gty. 41.4, GOR 340, TP 400-200, CP 180-140.
C (U. Moran) 2423-51, 12' sd SO, & 16' sh.

C (L. Moran) 2451-94, 2 1/2' sd SO, 1 1/2' shly sd SO, 1 1/2' shly sd SO, & 38' sdy sh.

DST (U. Moran) 2412-19/35", strong blo G/4" at est. 15 BOPH, G vol. 196 MCFPD, gty. 40.4, rev out approx. 20 BO above rev tool, NW, FP 190-400, SIP 790/30", HP 1180.

DST (L. Moran) 2462-2522/105", gd-v. wk blo air, 20' salty M, 60' muddy SW & 1890' SW NS, FP 470-920, SIP 970/30", HP 1240.

Set pkr. (U. Moran) at 2409, KO & flwd 24.58 BO/3 hrs., 3/4" chk., NW, G vol. 119.4 MCFPD, gty. 42.8, TP 60-70.
IPF 264 BOPD, 1/2" chk., gty. 41.5, GOR 419, TP 60, CP 360-200.

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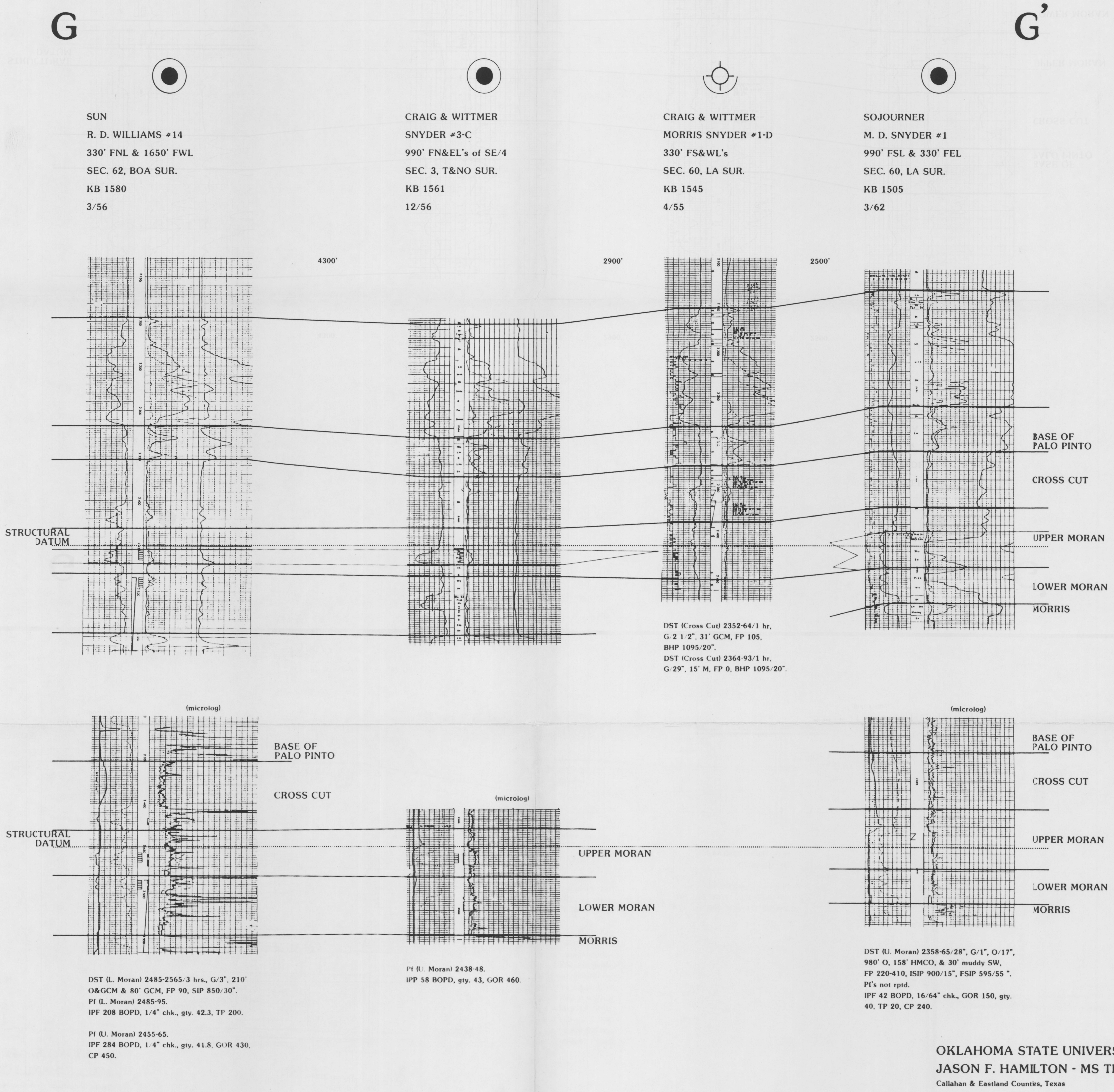
STRUCTURAL CROSS SECTION F - F'

July, 1990

PLATE 23



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STRUCTURAL CROSS SECTION G - G'

July, 1990

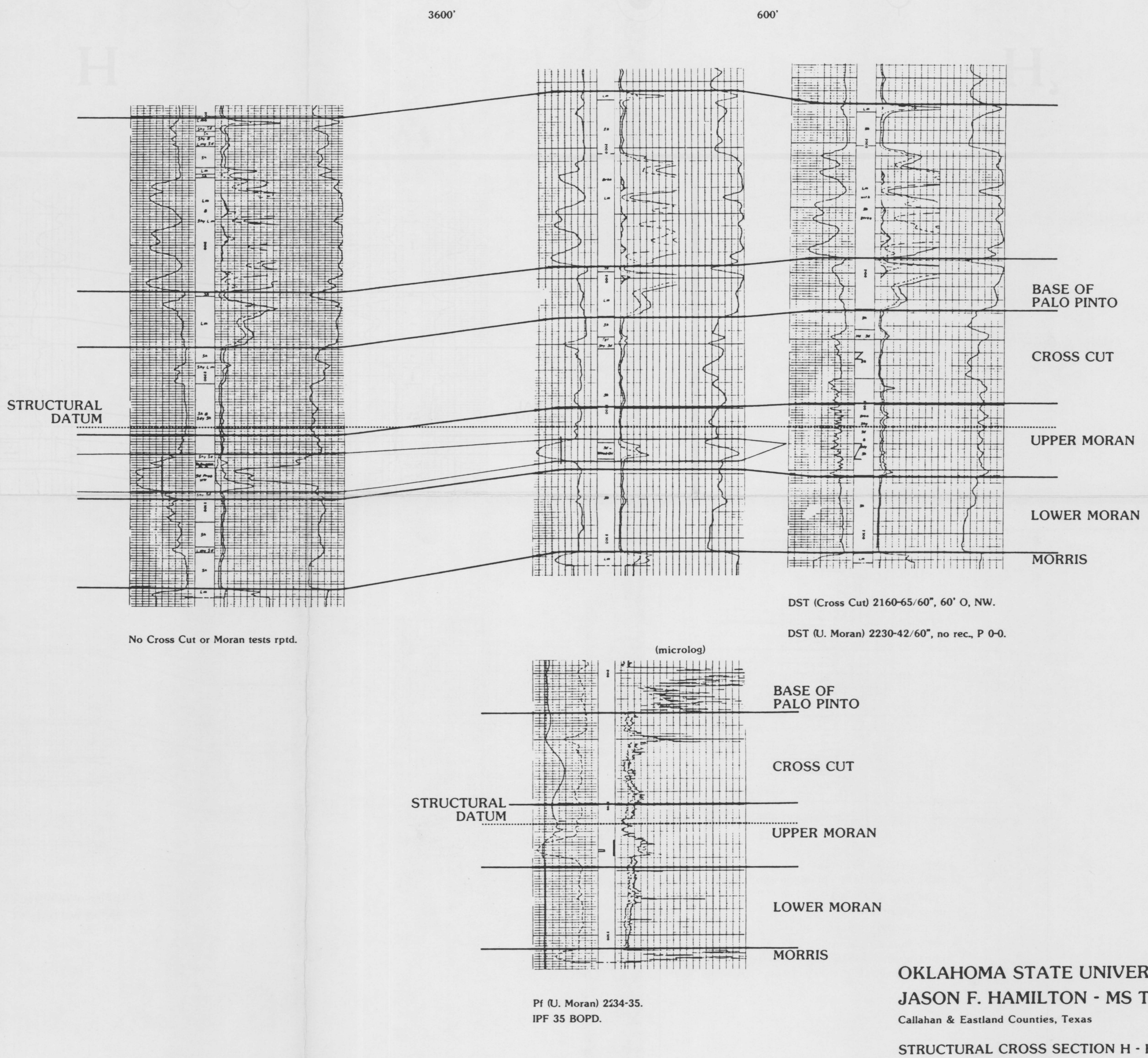
PLATE 24

H — H'

DAVIS BROS.
SAMUEL DILLER #14-B
1000' FSL & 1400' FWL
SEC. 54, LA SUR.
KB 1466
7/62

DAVIS BROS.
SAMUEL DILLER #10-B
990' FSL & 330' FEL
SEC. 54, LA SUR.
KB 1442
2/61

DAVIS BROS.
SAMUEL DILLER #11-B
990' FSL & 330' FWL
SEC. 55, LA SUR.
KB 1444
3/61



No Cross Cut or Moran tests rptd.

DST (Cross Cut) 2160-65/60", 60' O, NW.

DST (U. Moran) 2230-42/60", no rec., P 0-0.

Pf (U. Moran) 2234-35.
IPF 35 BOPD.

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STRUCTURAL CROSS SECTION H - H'

July, 1990

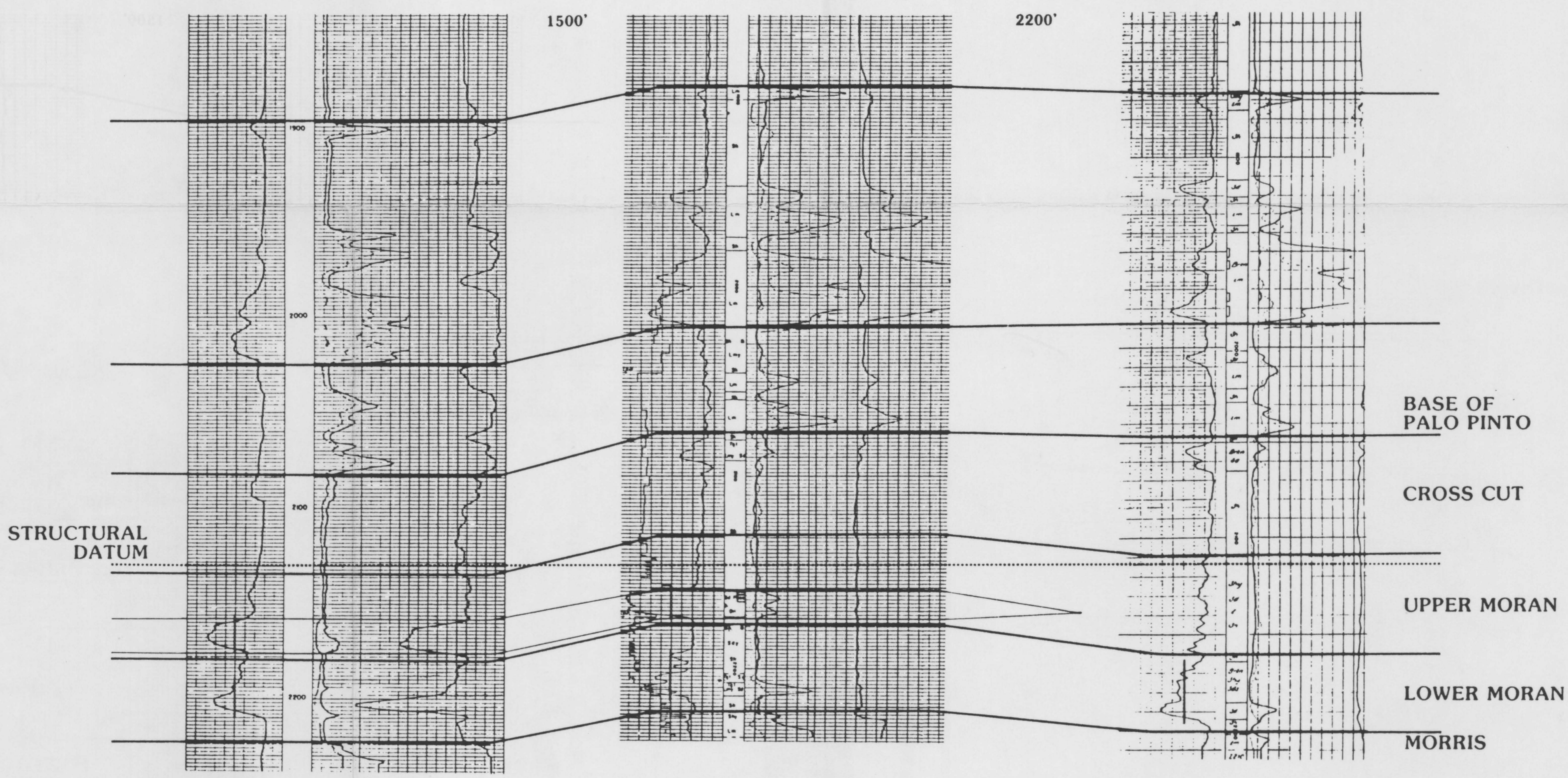
PLATE 25

I — I'

HLM
FINLEY #4
1320' FSL & 2320' FWL
SEC. 10, D&DA SUR.
GL 1543
8/80

DAVIS BROS.
N. L. FINLEY #3-C
660' FNL & 1750' FEL
SEC. 10, D&DA SUR.
KB 1559
4/58

B. F. PHILLIPS
FINLEY #2-B
330' FS&EL's
SEC. 10, D&DA SUR.
KB 1526
10/49



No tests.

Pf (U. Moran) 2160-65.
IPF 68 BOPD, 16/64" chl., gty. 42, TP 80, CP 200.

No Cross Cut or Moran tests rptd.

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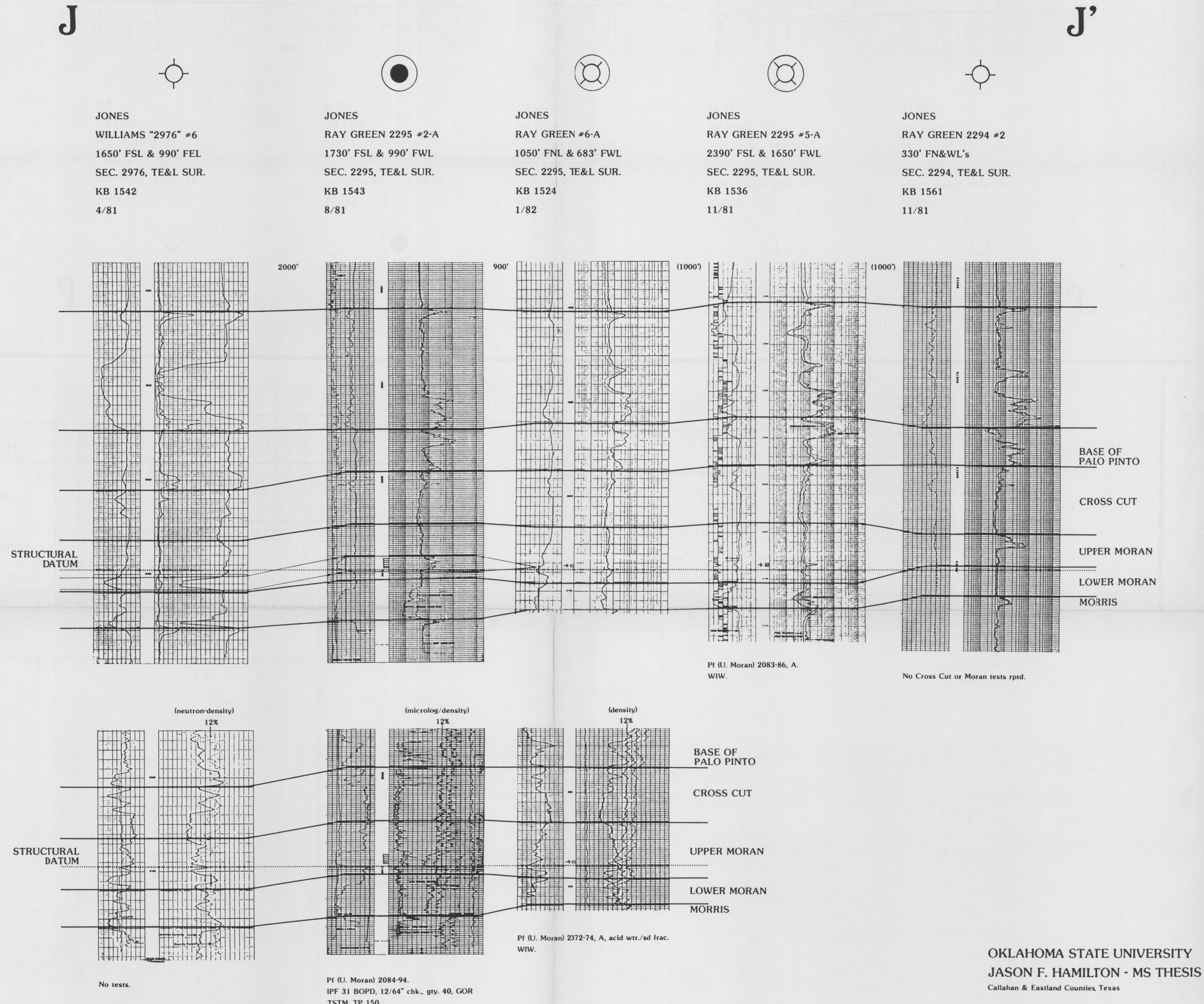
STRUCTURAL CROSS SECTION I - I'

July, 1990

PLATE 26



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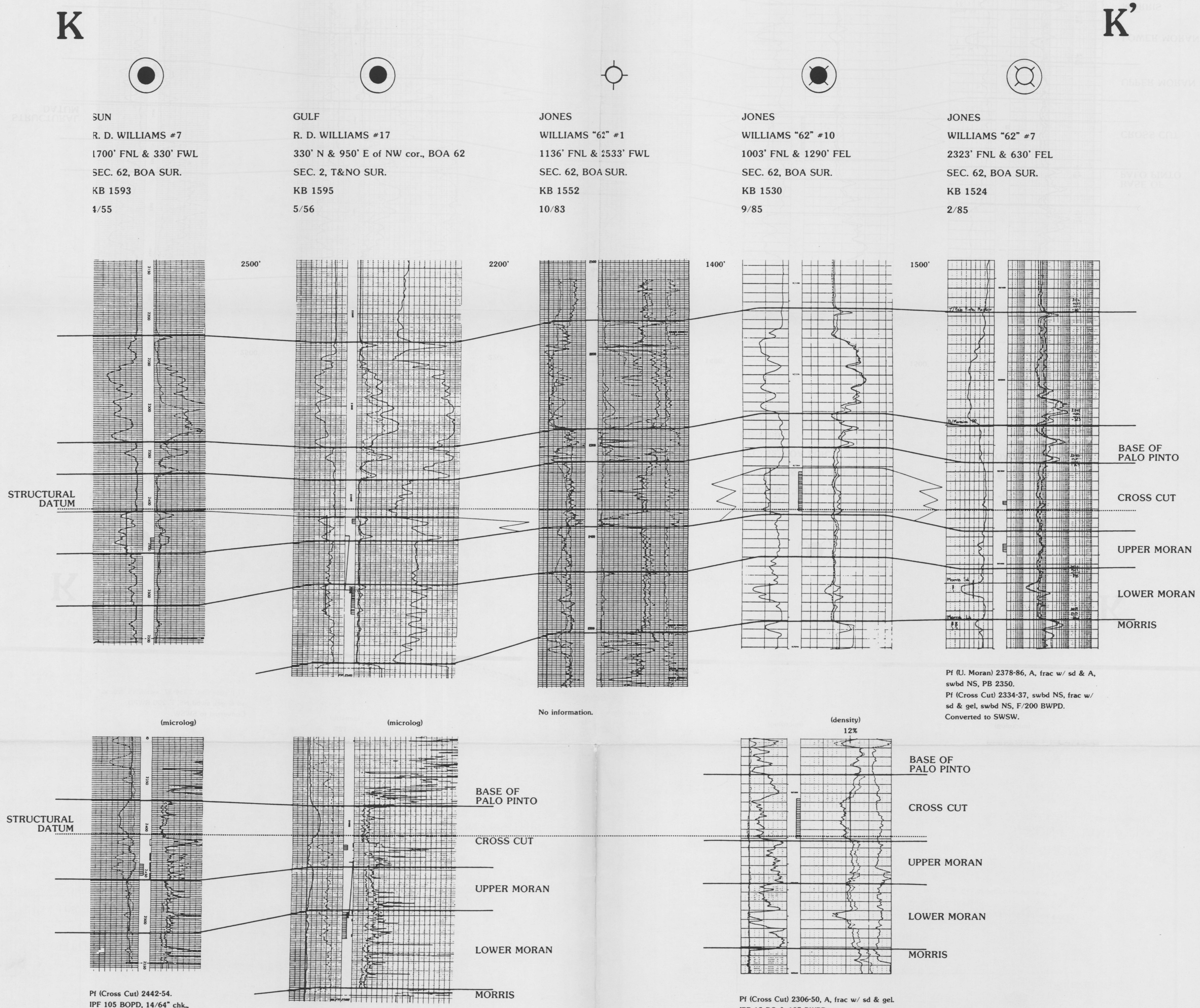
STRUCTURAL CROSS SECTION J - J'

July, 1990

PLATE 27



Pf (U. Moran) 2378-86, A, frac w/ sd & A, swbd NS, PB 2350.
Pf (Cross Cut) 2334-37, swbd NS, frac w/ sd & gel, swbd NS, F/200 BWPD.
Converted to SWSW.

Pf (Cross Cut) 2442-54.
IPF 105 BOPD, 14/64" chk., gty. 40.5, GOR 1613, TP 400, CP 900.

DST (Cross Cut) 2441-2500/2 hrs., G/13", 330' FO, 50' HO&GCM, FP 0-180, SIP 1000/30".
Pf (Cross Cut) 2423-28, swbd dry, frac w/ A & sd.
IPF 118 BO & 22 BSWPD, 1/4" chk., gty. 41, GOR 115, TP 200.

Pf (L. Moran) 2497-2526 (OA), swbd dry, A, frac w/ O & sd.
IPF 186 BO & 42 BSWPD, 1/4" chk., gty. 40.6, GOR 340, TP 400.

Pf (Cross Cut) 2306-50, A, frac w/ sd & gel.
IPP 15 BO & 127 BWPD.

2/88: converted to WIW.

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STRUCTURAL CROSS SECTION K - K'

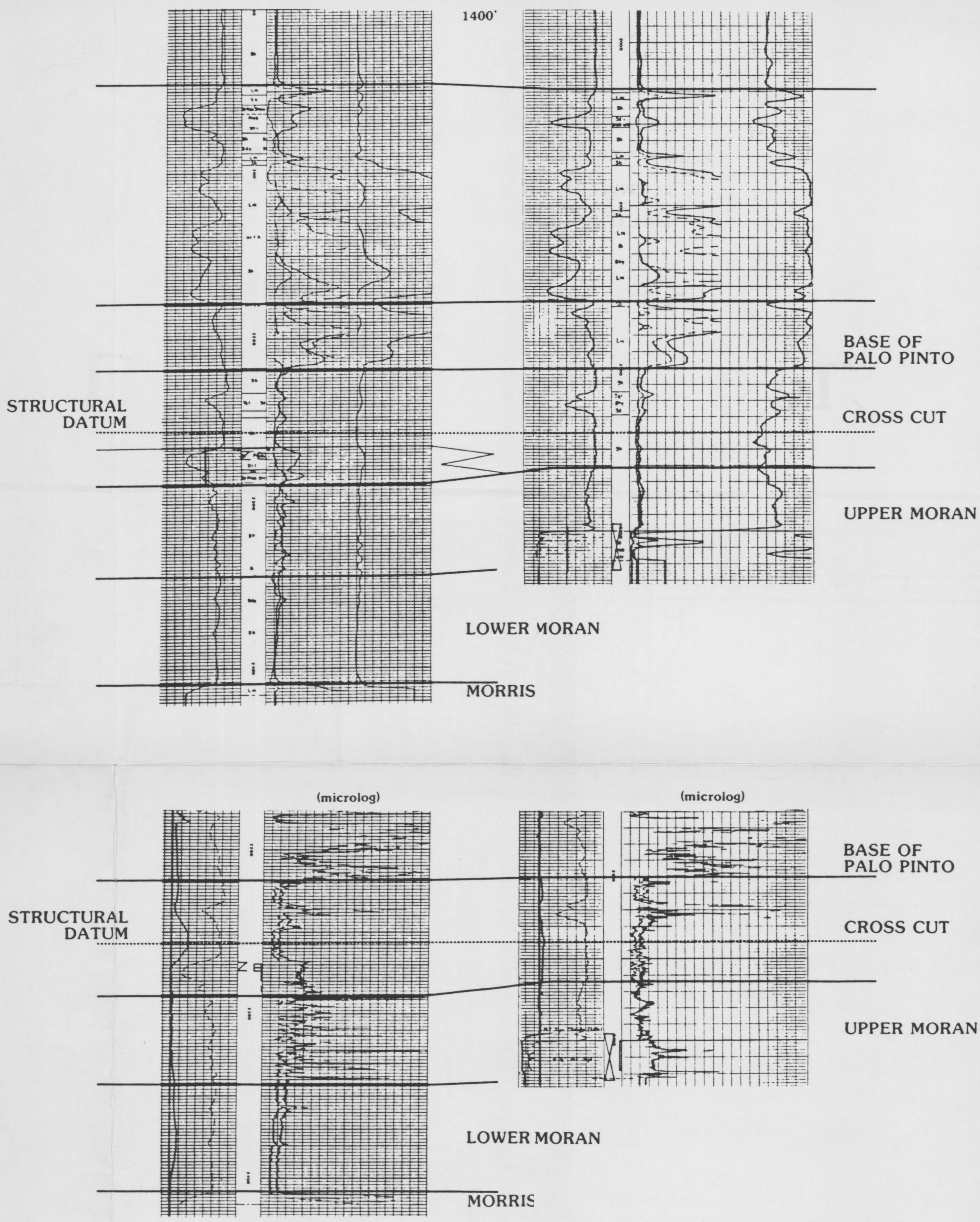
July, 1990

PLATE 28

L | L'

LOW
GRANT TURNER #3
2640' FSL & 990' FEL
SEC. 58, LA SUR.
KB 1510
12/61

RAY McGLOTHLIN et al
N. I. WILLIAMS #1
330' FS&WL's of NW/4
SEC. 57, LA SUR.
KB 1494
12/58



DST (Cross Cut) 2269-74/30", G/3",
1690' O & 70' OCM, FP 0-220, SIP
1160-1020/30".
Pf (Cross Cut) 2270-74.
IPF 157 BOPD, 16/64" chk., GOR 600,
gty. 42, TP 120, CP 640.

C (U. Moran) 2296-2324, 2' sh, 20 1/2'sd
NSO, 5 1/2' sh.
No Cross Cut or Moran tests rptd.

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STRUCTURAL CROSS SECTION L - L'

July, 1990

PLATE 29