FACIES ARCHITECTURE OF THE UPPER CALVERT BLUFF FORMATION EXPOSED IN THE HIGHWALL OF BIG BROWN MINE, FAIRFIELD, TEXAS

A Thesis

by

MICHAEL DALE STURDY

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

August 2006

Major Subject: Geology

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Approved by:

Chair of Committee,	Brian J. Willis
Committee Members,	Thomas E. Yancey
	Walter Ayers
Head of Department,	Richard Carlson

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ABSTRACT

Facies Architecture of the Upper Calvert Bluff Formation Exposed in the Highwall of Big Brown Mine, Fairfield, Texas. (August 2006)

Michael Dale Sturdy, B.S. University of South Alabama

Chair of Advisory Committee: Dr. Brian Willis

The facies architecture and geometry of stratigraphic surfaces within a lignite bearing interval of the Paleocene upper Calvert Bluff Formation is mapped on a photomosaic of the 150 ft (50 m) high and 12,000 ft (4km) long "C" area highwall of Big Brown Mine, near Fairfield, Texas. Observed bedding and facies architecture are interpreted in terms of temporal changes, depositional environments and sequence stratigraphic setting. A three dimensional grid of 89 subsurface logs is correlated to this photomosaic to characterize log response patterns of facies. Six facies are observed: 1) lignite, 2) interdistributary bay mud, 3) prograding delta, 4) delta top mud, 5) distributary channels, and 6) incised valley fill. The six facies were defined by a combination of mapped photomosaic observations and subsurface log correlations. The lignite deposit formed in a low depositional energy, low sediment input, high-organic productivity interchannel basin. Overlying mud records overbank flooding followed by avulsion and progradation of delta deposits. Tidal-flat deposits overlying prograding delta deposits record fluctuating energy conditions on the emerging delta top. Channel deposits cutting into the delta top record lateral channel migration across delta top

floodplains. These regressive delta deposits are capped by a local incised sequence boundary overlain by fluvial channel deposits inferred to have allowed sediment to bypass further basinward during lowstand. A sheet of channel deposits capping this highwall exposure records more recent erosion, followed by development of modern soil horizons.

The Big Brown Mine highwall exposes a relatively complete high-frequency Paleocene stratigraphic sequence developed in an area landward of the shoreline position during maximum transgression, that progresses upsection from: 1) highstand alluvial flood basin coals, 2) a thin condensed maximum flooding interdistributary shale, 3) a thick succession of regressive deltaic strata, and 4) a high-relief, sequence-bounding erosion surface overlain by a lowstand to transgressive fill of channel deposits. Correlations with regional Wilcox Group stratigraphic studies spanning coeval shoreline and shelf strata indicate that this high-frequency sequence is within the transgressive systems tract of a 3rd order stratigraphic sequence. It appears that high-frequency sequences of sub-regional extent control the complex distribution of coal seams within central Texas.

ACKNOWLEDGMENTS

I would like to thank my committee chair, Dr. Brian Willis, for his patience during the many life-changing events which continually occurred while conducting this study. I would also like to thank Dr. Thomas Yancey and Dr. Walter Ayers for their continued support during the course of this research. Thanks also to Steve Haney and TXU for providing data, access to the study area and geological insight to sediment at Big Brown Mine.

Thanks to Eric Robinson, Tara Kneeshaw and Brian Flynn who provided a place to stay during the final year of research. Finally, I would like to thank my friends and family for their support and encouragement throughout my lengthy saga to complete this study.

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INTRODUCTION

The Paleocene Calvert Bluff Formation of the Wilcox Group contains the largest reserves of lignite in the Gulf of Mexico basin. Surface strippable lignite in east-central Texas and associated potential deep basin methane reserves are important energy resources. Although sequence stratigraphic concepts have been widely applied to marine and shelf sediments of the Wilcox Group (Galloway, 1989b; Miller, 1989; Xue, 1997; Xue and Galloway, 1993, 1995), there has been less effort to extend this stratigraphy updip into paralic and fluvial deposits of the Gulf of Mexico basin. Lignite-bearing strata are abundant above the updip limit of recent regional studies of the Wilcox Group, and they provide a logical starting point for extending sequence stratigraphic correlations into nonmarine and paralic Wilcox Group deposits. Several investigators have suggested that the most extensive and economic coals occur along horizons formed during either regressive or transgressive maxima (Bohacs and Suter, 1997; Ryer, 1981, 1983); both are periods when shoreline deposits may stack vertically within the stratigraphic succession. Lignites of the Wilcox Group in the Hatchetigbee Formation in Alabama (Mancini and Tew, 1995) and at Bee Bluff in Zavala County, Texas (Breyer, 1997) have been interpreted to be components of highstand systems tracts overlain by type 1 sequence boundaries. Others suggest that coals of regional extent can be interpreted as

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This thesis follows the style of the *AAPG Bulletin.*

transgressive condensed sections within terrestrial deposits (Frazier, 1974; Galloway, 1989a; Hamilton and Tadros, 1994; Kosters and Suter, 1993; Bohacs and Suter, 1997).

Coals that cannot be correlated regionally may also have sequence stratigraphic significance, where they occur at specific horizons within a larger-scale hierarchy of stratal variations (Hamilton and Tadros, 1994; Bohacs and Suter, 1997). To determine the sequence stratigraphic setting, facies architecture and geometry in the sediment surrounding coal seams must be evaluated.

Early studies of coal bearing strata focused on the cyclical nature of transgressions and regressions. Studies in the mid-1950's increasingly focused on defining modern depositional analogs to improve interpretations of strata formed in ancient environments. Interpretations of coal-bearing strata with a cyclothem framework shifted to viewing these strata as deposits formed in a mosaic of environments (McCabe, 1987). Studies during this early period of coal deposition research began to relate compositional properties of coals to the depositional setting of peat. The energy crisis of the 1970's fueled numerous studies regarding deposition of coal-bearing strata. Although coals were interpreted to have formed in a wide range of depositional settings, most studies related these accumulations to meandering river, deltaic and back shore depositional environments. The widely cited Appalachian model of Horne et al. (1978) differentiated coal-bearing strata formed in fluvial, shoreline and deltaic environments and proposed models relating coal thickness, areal extent and quality within each of these depositional environments. Kaiser (1978) developed an exploration model using subsurface logs to show a relationship between sand-body geometry and the occurrence of lignite in the

Calvert Bluff Formation of east-central Texas. His work suggested that most economic coals in this region formed near transitions between the fluvial and upper delta plain environments.

Studies of coal-bearing deposits have generally been conducted primarily to develop exploration models to improve the economics of coal extraction. Coal seams were analyzed for thickness, lateral extent, quality and composition of encompassing sediments. Active surface mines provide unique opportunities to conduct three dimensional sedimentological studies. For example, Fielding (1984a; 1984b; 1985; 1986a; 1986b) conducted a series of studies of the Westphalian age Durham Coal Field in England that used migrating highwall exposures and adjacent closely spaced borehole data to document the three-dimensional lateral variability of fluvial-deltaic sediments and associated coal accumulations.

Coal deposits record accumulation of peat within swamps. Variables that affect peat formation are the elevation of the groundwater table, clastic sediment supply and peat production rate. Organic accumulation and conditions that favor plant growth are essential for peat formation (Bohacs and Suter, 1997). A groundwater table close to the surface prevents oxidation and allows preservation of accumulated organic material. Clastic sediment supply has adverse effects on the formation of coal. Where clastic input is high, peat formation is restricted and is commonly mixed with mud, producing carbonaceous shale rather than high-quality coal deposits. Thus, coal deposits reflect areas with rapid enough subsidence to allow thick accumulations of peat, which are also isolated from areas receiving high rates of clastic sediment. Understanding the depositional processes and features of clastic systems capable of initiating and preserving peat requires study of genetically related strata that record the broader depositional environments of the coal bearing strata (McCabe, 1984).

Objectives

Sequence stratigraphic research of the lignite-bearing Calvert Bluff Formation has focused primarily on deeper basin portions of this lithologic unit that are economic oil and gas zones (Xue and Galloway, 1997). Based on well log analysis, the Calvert Bluff Formation has been interpreted as highly-constructive delta deposits (Kaiser, 1978). Early studies of the up dip portions of this formation exposed in outcrop (including Big Brown Mine) generally suggest deposition on upper delta plains. These previous interpretations of depositional setting have been based either on broad regional stratigraphic studies (Kaiser, 1978) or on petrology of the lignite seams (English, 1988; Lentz, 1975). Studies undertaken in recent years have observed features associated with tidally-influenced deposition within these strata (Breyer, 1989; Klein, 2000; O'Keefe and others, 2005). Although depositional environments were assessed in previous studies of the Calvert Bluff Formation, documentation of facies variations and stratal architecture within large mine exposures have not been presented to support detailed paleoenvironmental interpretations.

This study refines previous interpretations of the upper Calvert Bluff Formation made by Lentz (1975), Kaiser (1978) and English (1988) by mapping important stratigraphic surfaces and facies elements to interpret facies architecture and depositional environments. Distinct facies types are defined and facies geometries are mapped on a photomosaic and correlated through a grid of adjacent subsurface logs to develop a model for deposition in the upper Calvert Bluff Formation at Big Brown Mine. The study interval is above the base of lignite seam 2 in the "C" area of Big Brown Mine near Fairfield, TX (Figure 1).

The goals are: 1) Define Big Brown Mine deposits within a regional depositional context based on a literature review; 2) Map facies and stratal geometries on photomosaics of the mine highwall; 3) Correlate facies variations observed in the highwall through an extensive collection of closely-spaced well logs collected to guide mining operations; 4) Integrate these data to define a facies model that can be used to improve depositional interpretations, well log correlation strategies, and prediction of lithic heterogeneities within less well documented analog subsurface deposits.

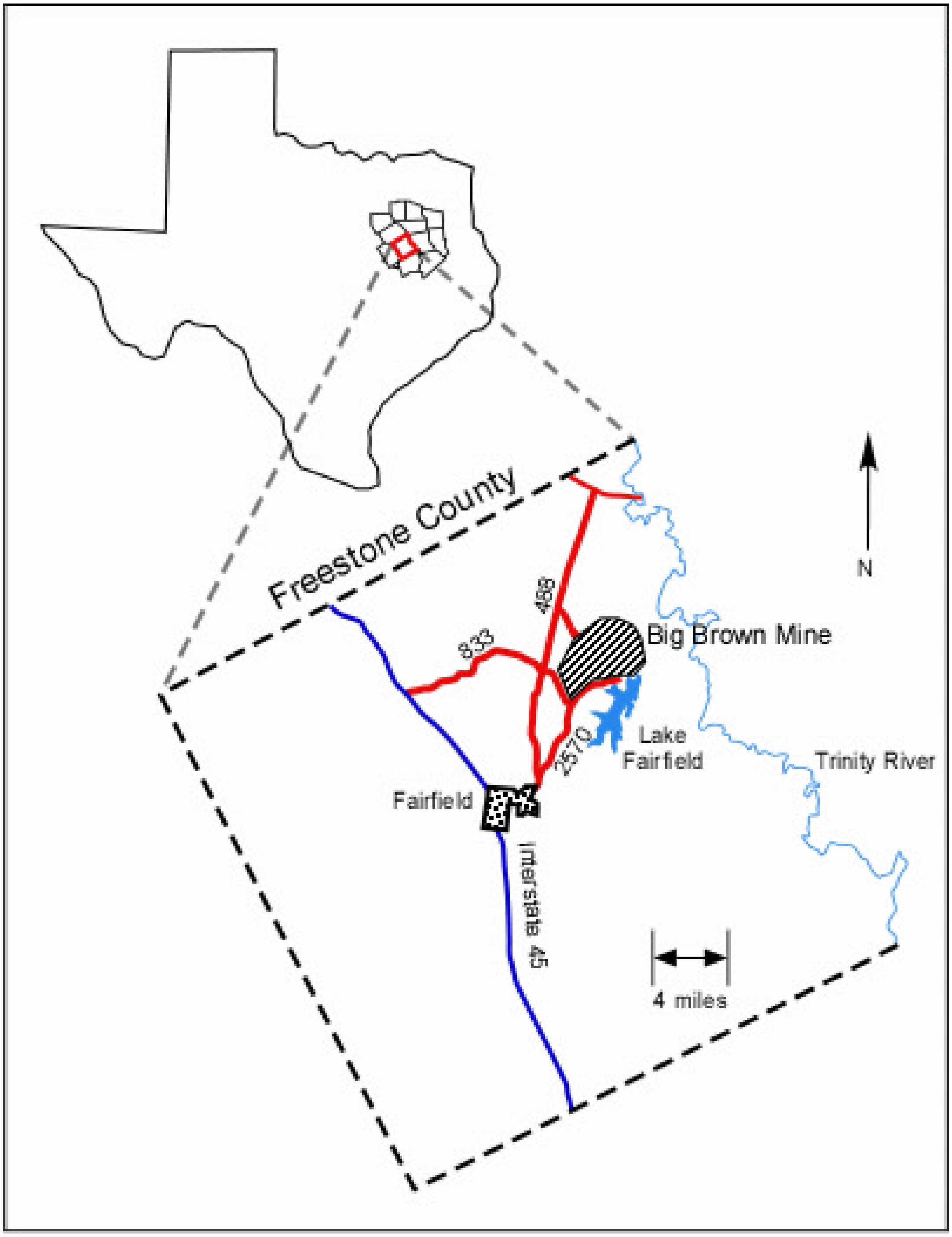

Figure 1- Location of Big Brown Mine. Map showing geographic location of Big Brown Mine in Freestone County, Texas.

CALVERT BLUFF FORMATION

The Paleocene-Eocene Wilcox Group is composed primarily of clastic sediments derived from the western United States Laramide Orogeny. The Wilcox Group outcrop belt extends from northeastern Mexico through Texas, around the Mississippi Embayment and into Alabama (Figure 2). In Texas, the Wilcox Group is divided into three regions: south, central and east. The south and east regions are generally not subdivided into formations. The central Wilcox Group region extends from the Colorado River in the south to the Trinity River to the northeast, and is divided into three formations: the Paleocene Hooper Formation, the Paleocene Simsboro Formation and Paleocene Calvert Bluff Formation. The Wilcox Group overlies the Paleocene Midway Group and is unconformably overlain by the Eocene Carrizo Sand (Figure 3). The Calvert Bluff Formation crops out from Red Rock at the southwest limit to the Neches River in northeastern Texas (Figure 4). The Paleocene Calvert Bluff Formation is named for exposures at Calvert Bluff on the Brazos River approximately 5.5 miles west of the town of Calvert, Texas (Barnes, 1970, 1974; Kaiser, 1978). This study focuses on the upper portion of the Calvert Bluff Formation that is exposed at Big Brown Mine.

Early research on the Wilcox Group focused on the lower portion of the Wilcox Group and subdivided this lithologic group into seven depositional systems (Fisher and McGowen, 1967). With the development of numerous mine mouth power plants in central Texas, researchers began to focus on the upper Wilcox Group due to the presence

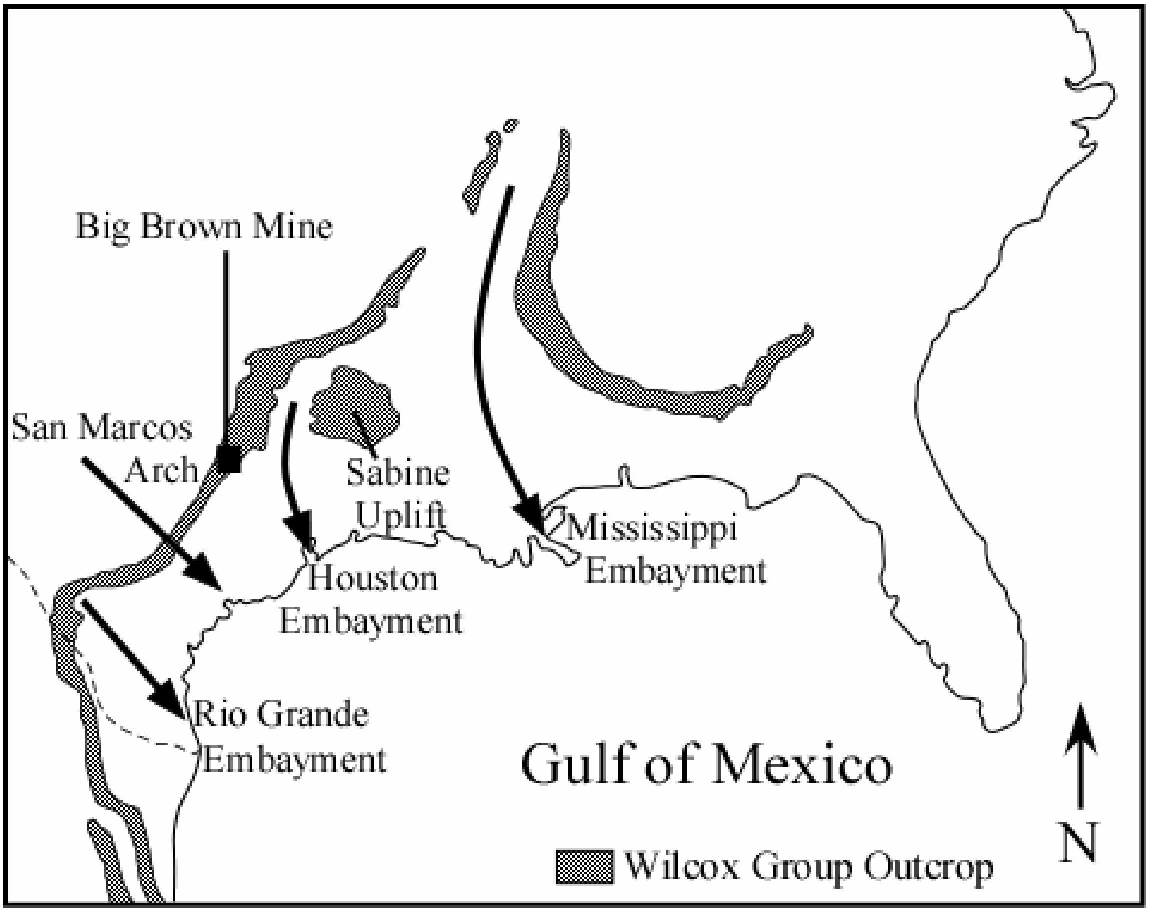

Figure 2- Wilcox Group outcrop trend. Map illustrating the trend of the Paleocene-Eocene Wilcox Group outcrop throughout the coastal plain regions of United States and Mexico in the northern Gulf of Mexico (from Nichols and Traverse, 1971).

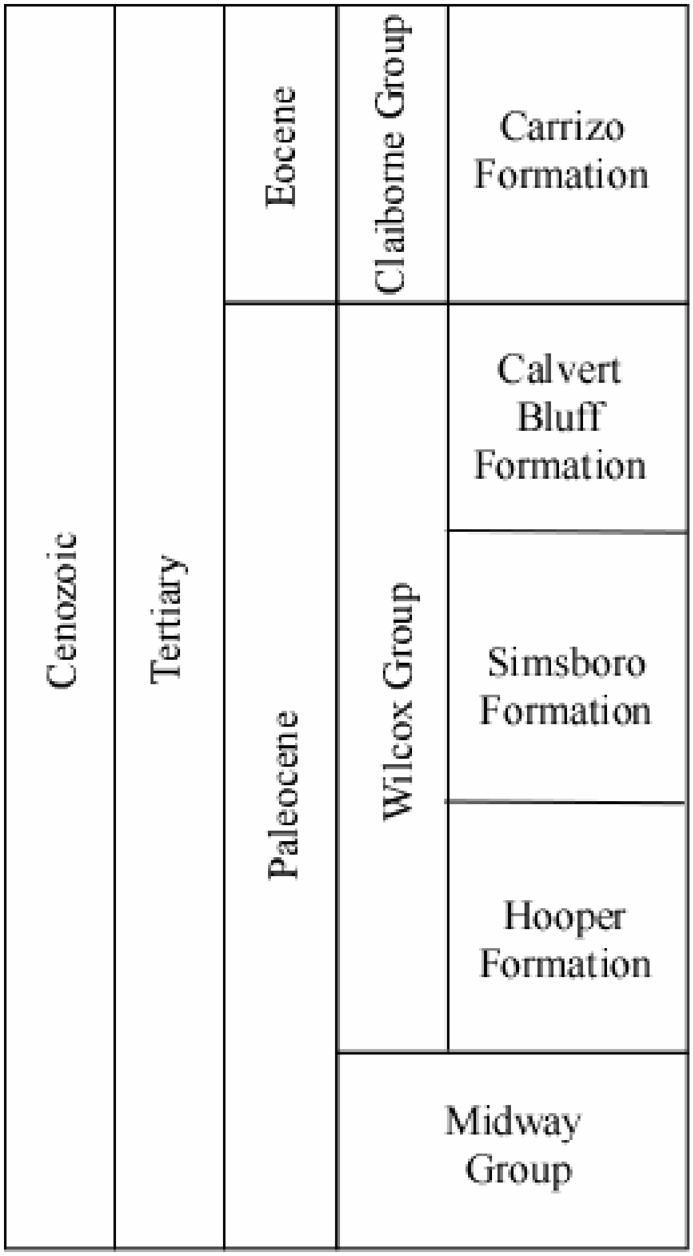

Figure 3- Stratigraphic column of the divided Wilcox Group in central Texas.

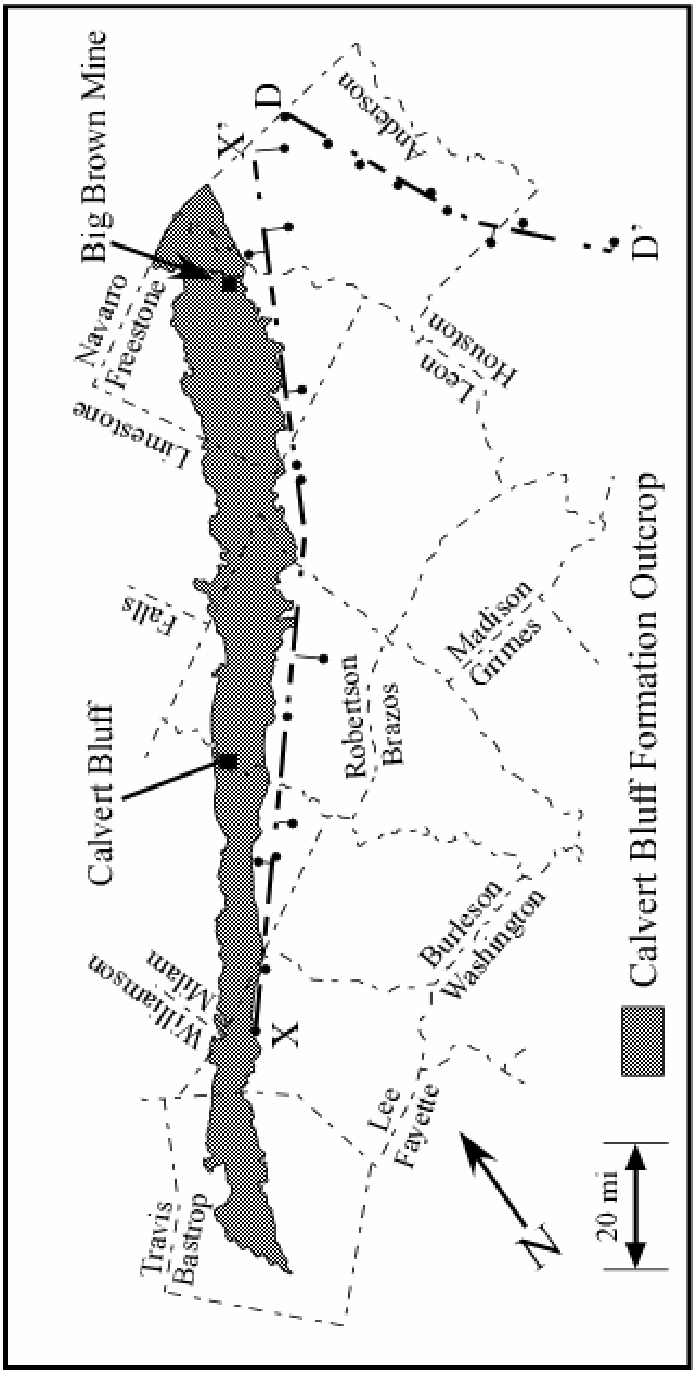

Figure 4- Outcrop trend of the Calvert Bluff Formation in central Texas. Lines X-X' and D-D' are regional cross section lines from Ayers and Lewis (1985). (*modified* from Kaiser, 1974)

of economic lignite deposits. These studies developed exploration models in order to exploit lignite deposits present in the lower portion of the Calvert Bluff Formation.

Early interpretations of the lower Calvert Bluff Formation relied on the use of geophysical logs to produce net sand percent maps. Initial interpretations of these maps placed lower Calvert Bluff Formation deposition on a fluvial-dominated delta complex and the underlying Simsboro Formation on associated delta plain environments (Kaiser, 1974). The upper Calvert Bluff Formation was interpreted to be deposited on the upper and lower delta plains as distributary channels and interdistributary basins (Kaiser, 1974). The sand percent map developed by Kaiser (1978) defines a channel system dipping 0.5 to 2 degrees southeast with fluvial systems generally flowing from northwest to southeast. Kaiser (1978) refined the delta plain interpretation of the lower Calvert Bluff Formation and placed deposition at the transition from lower alluvial plain dendritic channels to upper delta plain bifurcating channel systems.

Kaiser's (1974, 1978) interpretations of the highwall exposures within Big Brown Mine were further refined by Lentz (1975) and English (1988). Lentz (1975) and English (1988) recognized a cyclic style of deposition in these upper Calvert Bluff Formation deposits. Lentz (1975) termed the sequences "floodbasin cycles" and described an ideal sequence as being 50 feet (15 meters) thick, beginning with lignite, passing into clay and mud, then fine-grained sand and finally flat-bedded sand. Deposition of the lignite was interpreted to have occurred in poorly drained swamps in interlevee basins between sand channels. Peat formation was terminated by overbank flooding, which introduced fine-grained clastic sediments from adjacent channels into flood basin deposits. Overbank flooding was followed by channel avulsion which resulted in deposition of fine-grained crevasse splay sands with coarsening upward patterns. Flat-bedded sands, capping Lentz's (1975) flood-basin cycles, were interpreted to be lacustrine in origin. As lacustrine and crevasse splay deposition shifted laterally, swamps and marshes reestablish themselves and the cycle of deposition is repeated (Lentz, 1975; English, 1988).

The Atchafalaya Basin and Des Allemandes-Barataria Basin have been cited as modern analogues for lower Calvert Bluff Formation deposition. These analogues are based on similarities in sand channel and interlevee flood plain basin geometries depicted on sand percent maps derived from geophysical logs. Lentz (1975) first applied the Atchafalaya Basin of the Mississippi River as a modern analogue for Calvert Bluff Formation deposition. The Atchafalaya Basin was created by the formation of alluvial ridges which acted as natural levees to the Mississippi River. When the Atchafalaya River was subsequently introduced, the Atchafalaya Basin was filled with interfingering lacustrine deltas similar to the crevasse deposits seen in the Calvert Bluff Formation. Kosters and Suter (1993) found the Atchafalaya Basin to be inappropriate as an analogue for peat formation due to the presence of saline water, which inhibits the formation of thick high quality peats. The Barataria Basin may be a more appropriate analogue for the Calvert Bluff Formation paleoenvironment. The Barataria Basin occurs higher on the delta plain landward of the shoreline formed during maximum transgression. This is a zone of high groundwater discharge that protects peat formation from the destructive effects of saline water (Kosters and Suter, 1993; Bohacs and Suter, 1997). Although channel and interchannel geometries are similar in both basins, the presence of significant peat formation is critical in placing Calvert Bluff Formation deposition in the appropriate depositional environment. Palynology studies of the upper Calvert Bluff Formation peat deposits suggest a freshwater swamp environment for the lignite, which became more marine-influenced during deposition of sediment preserved higher in the section (O'Keefe and others, 2005). Therefore, peat development in the Calvert Bluff Formation must have occurred higher on the delta plain than Atchafalaya Basin deposition. The Barataria Basin is an appropriate analogue for deposits in Big Brown Mine that are contemporaneous with peat deposition due to similar channel and interchannel geometries, palynology data, and presence of significant peat deposits. However, tidally influenced deposits observed higher within the Big Brown Mine highwall suggests waters become more brackish than when peat accumulation terminated (O'Keefe and others, 2005).

Regional Framework

Several research groups have examined regional depositional characteristics of the Wilcox Group along the Texas Gulf Coast. A regional framework constructed by the Texas Bureau of Economic Geology focused primarily on the oil and gas rich lower portion of the Wilcox Group (Fisher and McGowen, 1967). The increased exploitation of lignite reserves in the upper Wilcox Group during the 1970s shifted the research focus to the middle and upper Wilcox Group. The Texas Bureau of Economic Geology published several reports that quantified lignite reserves and developed coal exploration models for the Texas Gulf Coastal plain (Kaiser, 1974; Kaiser, 1978; Kaiser and others, 1980; Ayers and Lewis, 1985). These reports define formations of the central Texas Wilcox Group on a number of well log cross sections and allow for relatively straightforward regional correlation to the sediments exposed in the highwall of Big Brown Mine.

The Wilcox Group is composed of three formational divisions in central Texas (Figure 3) and is generally held to represent a major progradational phase during the late Paleocene-early Eocene (Kaiser et. al., 1980; Middleton and Luppens, 1995). Sediments exposed in the Big Brown Mine highwall occur in the upper Calvert Bluff Formation and can be correlated to their equivalent down dip intervals in the regional cross sections of Ayers and Lewis (1985) (Figure 4). Calvert Bluff Formation deposition is cyclical in nature and composed of two distinct settings: nonframework, mud-rich interchannel floodbasins truncated by laterally equivalent framework multistory channel sands (Middleton and Luppens, 1995). Recent work by the United States Geological Survey (USGS) divided central Texas into the Northern Coal Zone (NCZ), Central Coal Zone (CCZ), and Southern Coal Zone (SCZ) and identified 18 coal zones within the central Texas Wilcox Group, nine of which are actively mined. Only the nine actively mined coal zones were correlated throughout the central Texas region. Big Brown Mine is located in the Northern Coal Zone and coal seams NCZ5, NCZ6, NCZ8 and NCZ9 are found within the boundaries of Big Brown Mine (Warwick and others, 2002).

METHODS

Facies Mapping in Big Brown Mine Highwall

Photomosaics of the Big Brown Mine highwall, constructed by stitching together many tens of photographs into one continuous image (Wizevich, 1991) were used as a base map for documenting spatial changes in facies and bedding architecture (Appendix A). Facies details in this exposure could only be observed in freshly mined areas due to rapid degradation of these relatively unconsolidated deposits by surface sheet wash and ground water piping. Beds defined by erosion or abrupt vertical changes in grain size and their internal facies were mapped on the photomosaic and a cross section depicting the sediment architecture was constructed. Lines of weighted thickness were used to distinguish different scales of bedding within a hierarchy of depositional units. Once the various depositional units were defined and mapped, facies associations and bedding types were interpreted in terms of depositional environment.

Recent advances in photo editing and graphic design software packages allow construction of high resolution photomosaics with minimal distortion. Photographs of the Big Brown Mine highwall were taken during 2004 and 2005 using a Kodak Easy Share DX6490 4.0 mega pixel digital camera. The digital .JPEG files were imported into Adobe Photoshop Elements 3.0 and warped to correct obvious perspective distortions caused by the angle between the film plane and the plane of the highwall as well as differing distances of basal and upper regions of the highwall from the camera lens. After perspective corrections were applied, pictures were cropped to eliminate excessive overlap between adjacent photos and saved as TIF files. The edited TIF files were loaded into a PanaVue ImageAssembler Standard Edition version 3.0.1 Mosaic Stitching Project, and stitched utilizing the Manual Stitch with Flags option. Completed segments of the mosaic were imported into Canvas 9.0.4 Build 820 and resized to a uniform scale. A lateral scale was determined from borehole log correlations and survey points obtained with assistance from the mine surveyor. Variations in lateral coverage of the initial parts of the photomosaic were corrected by stitching mosaics in PanaVue and transforming the images to a uniform size in Canvas 9.0.4. The result was a single photomosaic which spanned approximately 12, 400 ft (4 km) of exposed highwall from the southwestern toe of the pit northeast to the approximate midpoint of the highwall (Figure 5). Coordinates on the highwall photomosaic were cross referenced with subsurface log coordinates. Logs that are adjacent to the highwall were projected onto the photomosaic to establish an element of control for interpreting log response patterns throughout the mine.

Well Log Interpretation

TXU Mining Corporation made available its library of subsurface logs that record gamma ray, density and resistivity variations of deposits that have been excavated in Big Brown Mine over the past 30 years. Digital subsurface logs from the “C” area of Big Brown Mine were loaded into GeoFrame 4.0.3 Geology Office. Three subsurface log cross sections were created from 89 selected digital logs (Figure 5, Appendix B). The

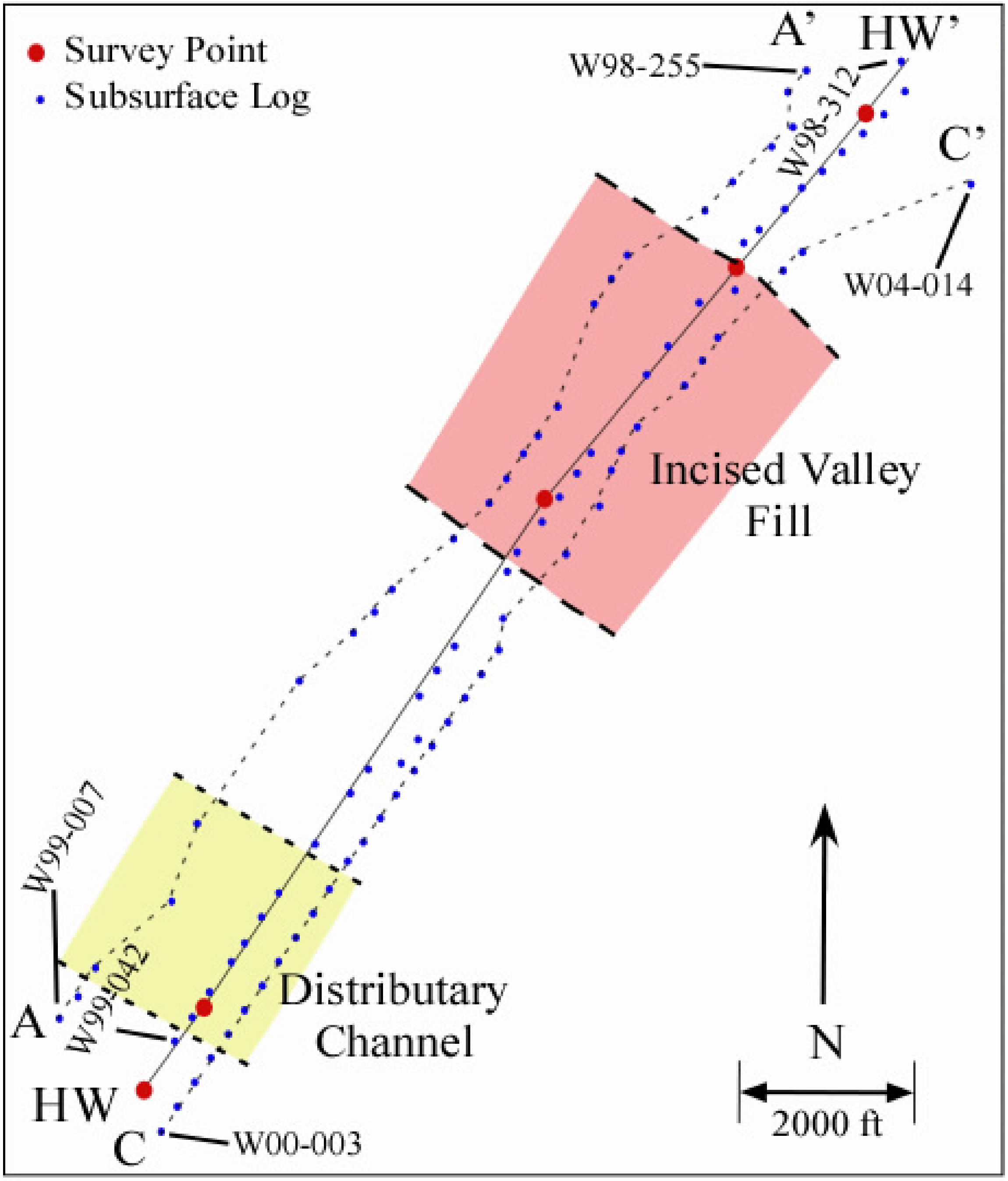

Figure 5- Subsurface Log Distribution. Basemap showing surface distribution of subsurface log boreholes. Line HW-HW' represents highwall at time of study. Subsurface logs at the end of cross sections have been labeled; for complete key to subsurface log distribution and cross section plates refer to Appendix B.

logs were correlated and different stratigraphic zones interpreted from log responses were identified. Line HW closely follows the path of the photomosaic, which provided an element of control for log interpretations. Lines A and C were used to add a third dimension to the interpretation. The interval of focus on the subsurface logs was the base of lignite seam 2 and the surface of Earth at the top of the log curves.

Subsurface logs are obtained by running a sonde equipped with various tools and sensors into a borehole. The logs utilized in this study were the gamma ray, density and resistivity logs. Gamma ray logs are a passive measurement of naturally occurring gamma rays from potassium, thorium, and uranium, which are typically less abundant in sands than in muds. The resulting curve functions are thus a proxy for shale percentage. Density log tools measure the bulk density of the surrounding sediment by emitting a gamma ray from a Cesium-137 source (Asquith, 1982). The gamma rays interact with the electrons in the surrounding formation via collisions called Compton Scattering. A detector on the sonde records the number of Compton Scattering collisions which are a direct function of the number of electrons in the surrounding formation. The recorded number of collisions can then be used as a proxy for density, which aids in lithologic identification. Induction resistivity logs measure electrical conductivity, which is the reciprocal of resistivity, by emitting alternating electrical currents. A magnetic field is created inducing secondary currents in the formation which are measured by the resistivity tool. Because rock is nonconductive, resistivity logs provide an indication of porosity and fluid content of the formation.

Previous Work

Other information utilized in this thesis is from previous studies conducted on the Big Brown Mine. Lentz (1975) compiled sulfur content data on the lignite seams. Sulfur occurs in the sedimentary environment in a number of minerals. The type of sulfur containing mineral in the sedimentary record can provide information regarding environment of deposition or diagenetic effects caused by groundwater movement through the subsurface. English (1988) conducted a petrographic study of the maceral composition of the lignite in Big Brown Mine. Maceral composition is related to flora present at the time of deposition of the peat. Therefore, maceral types identified by English (1988) provide useful data about the depositional environment of peats in Big Brown Mine. Klein (2000) provided data on palynology content and identified sediments which imply a possible coastal influence on portions of the sediment in Big Brown Mine. Palynology data consists of pollen content of plants present at time of deposition and in a manner similar to maceral composition provides information pertaining to paleoenvironment of the sediment.

FACIES

The Upper Calvert Bluff Formation in the highwall at Big Brown Mine can be separated into six distinct facies based on observations in the photomosaic and trends in gamma ray, density and resistivity log response. The six identified facies are: 1) lignite, 2) interdistributary bay mud, 3) prograding delta, 4) delta top mud, 5) distributary channels, and 6) incised valley fill. These facies and their internal geometry and subsurface log responses are described and interpreted in this section. In a later section, the stratal architecture is discussed.

Lignite

Description

The basal unit of the study area is a dark-brown to black lignite ranging from 0 to 8 feet (0 to 2.5 m) thick (Figure 6). No seam splitting of this lignite seam is observed within the confines of the study area. The lower bounding contact is abrupt and the upper bounding contact either grades vertically over a short distance from lignite to organic rich mud or is an abrupt contact with fine grained light gray sand. Klein (2000) observed reedy and ferny herbaceous material in this lignite as well as traces of lignified tree trunks in lower portions of the seam.

Subsurface log response of the lignite facies is characterized by very low gamma ray, very low density and high resistivity responses (Figure 7a). The gamma ray curve

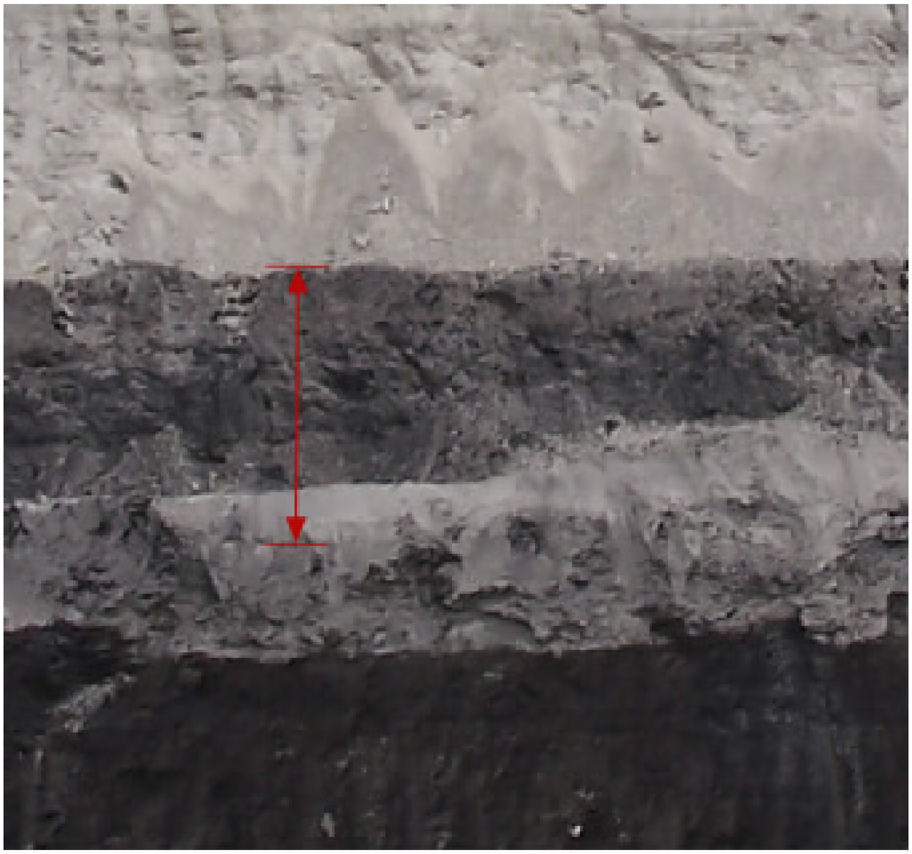

Figure 6- Lignite seam in Big Brown Mine. Lignite seam exposed in highwall at Big Brown Mine. Seam extends below gray sand which has fallen from highwall face and come to rest on small bench typically left at base of lignite seam by mine workers. Red arrow represents approximately 2 meters.

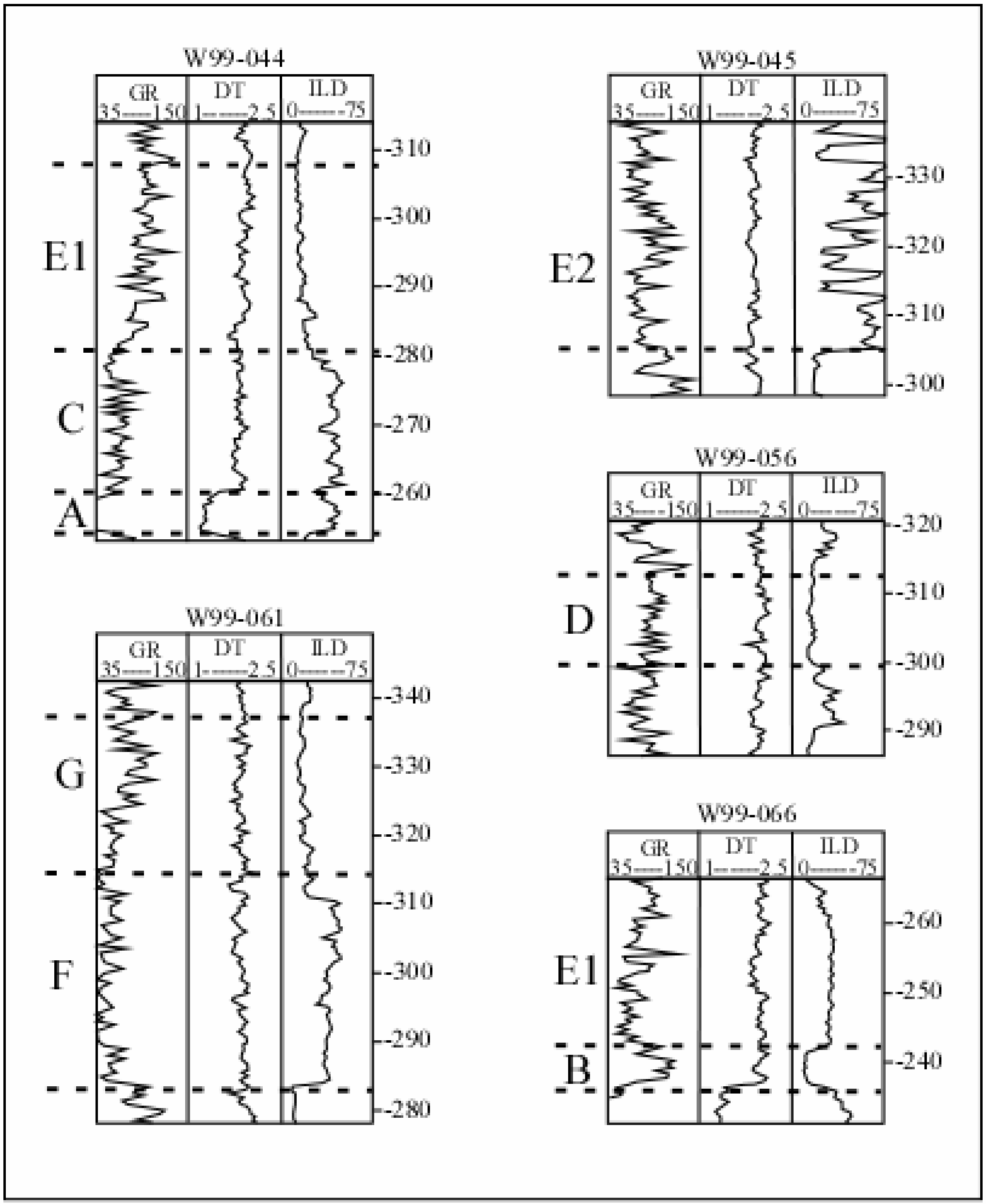

Figure 7- Subsurface Log Facies. Type log responses to facies identified in subsurface logs at Big Brown Mine. Facies recognized are as follows: A) lignite, B) distributary bay mud, C) prograding delta, D) delta top mud , E1) distributary channel, E2) post deltaic distributary channel, F) incised valley fill base, and G) upper incised valley fill.

deflects to the low value left side of the curve track due to the lack of radioactive materials in coaly rocks. Lignite is a low density material and this is expressed by an abrupt deflection of the log curve to the low value left side on the density log track. Coal is a nonconductive material and the resistivity log curve deflects to the far right of the log curve track, which indicates high resistivity.

Interpretation

Peat accumulates in reducing conditions when >75% of sedimentation is in the form of organic matter (Tye and Kosters, 1986). Environments conducive to these conditions have a high groundwater table, low clastic sediment input and high rate of organic activity. These conditions are common in upper delta plain interchannel regions. Such interchannel basins on upper delta plains tend to have a high rate of groundwater discharge because the water table is typically at or above the ground surface. This is especially true for deltas deposited during rising relative sea level. The rising sea level creates a saltwater wedge in the subsurface which causes the near-surface groundwater aquifer to rise above the ground surface as much as 27 miles (44 km) landward of the shoreline (Bohacs and Suter, 1997; Figure 8). Clastic sedimentation tends to be low on delta plain interchannel basins because the natural levees surrounding sand channels protect interchannel regions from clastic sediment invasion (Kosters and Suter, 1993). Coal seam splitting is generally inferred to indicate brief periods of clastic sediment input into the peat forming basin. The lack of seam splitting in this unit indicates the peat accumulated in an environment free of clastic contamination. Klein (2000) recognized

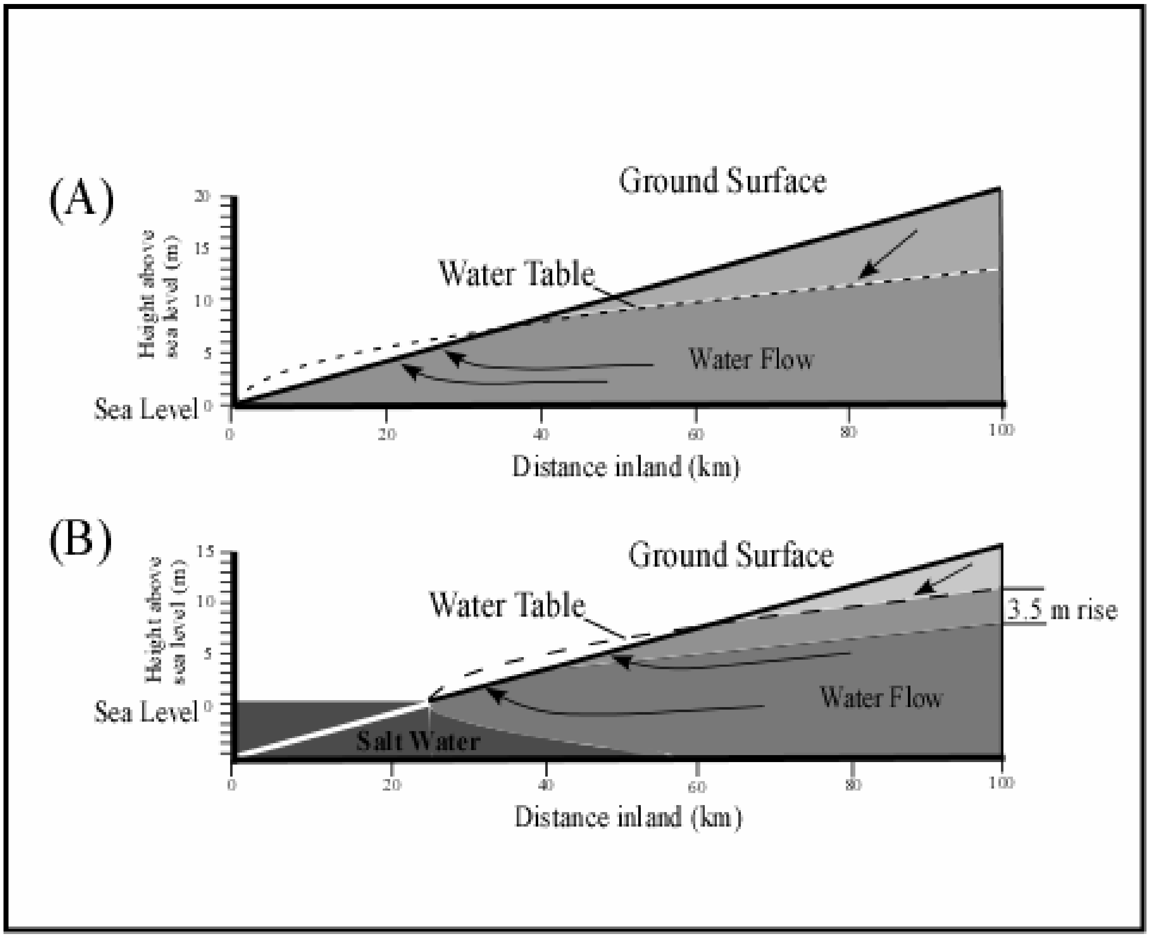

Figure 8- Effects of advancing salt water wedge. (A) Diagram of water table location without sea level rise or fall. (B) Effect of salt water advance on ground water table during 5 m rise in sea level. Salt water wedge causes the water table to rise 3.5 m. (modified from Bohacs and Suter, 1997)

palynological assemblages and English (1988) identified maceral composition indicative of subtropical paralic flora. Wet subtropical environments are known for their high organic production rates which accounts for the high rate of peat deposition present at the Big Brown Mine area during the Paleocene.

Interdistributary Bay Mud

Description

Beds of this dark brown mud are 0 to 10 feet (0-3 m) thick. When present this facies typically has an abrupt lower bounding contact with lignite. The upper bounding contact is a rapid gradation into the overlying prograding delta deposits. Interdistributary bay mud is not always observed in the photomosaic due to overlying sands dusting the face of the highwall. This facies is best observed in subsurface logs where weathering affects do not obscure the presence of the interdistributary bay mud.

Interdistributary bay mud is identified in subsurface log by high gamma ray response, right of middle density and low resistivity log responses (Figure 7b). The gamma ray curve of this facies deflects to the right of the log curve track and commonly exceeds 100 gamma ray API units. Fine-grained materials such as mud and clay typically sequester small amounts of radioactive potassium and thorium and therefore elicit the high gamma response. Density logs tend to increase to the right of center because fine grained sediments are more closely packed and have a lower porosity. The resistivity log curve strongly decreases abruptly at the start of this facies, which is to be expected as clays are known to be conductive.

Interpretation

Interdistributary bay mud is deposited in environments similar to peat, but has a lower organic content due to one of the three conditions for peat formation not being met (Bohacs and Suter, 1997). If the groundwater table rises too quickly because of rising relative sea level, channel waters may spill into interdistributary basins through avulsion or overbank flooding delivering fine-grain clastic sediment into the basin which dilutes and oxidizes organic matter. Rising relative sea level may also introduce saline water into the system, which inhibits organic activity and peat production, thus terminating peat accumulation (McCabe, 1984; Kosters and Suter, 1993; Bohacs and Suter, 1997). When higher energy currents occur within deepening bays, previously deposited distributary mud may be removed by scouring.

Prograding Delta

Description

These light-gray to gray fine-grained, cross stratified sands vary from 3-60 feet (1-18 m) thick with individual cross sets ranging from 2-12 inches (5-30 cm). The lower bounding contact either a rapid grades vertically over a short distance from interdistributary bay mud or is an abrupt contact with lignite. The upper bounding surface is either an erosional contact with distributary channels or an abrupt contact with delta top mud. Downward dipping cross-bed sets with possible mud drapes are abundant and sigmoidal cross-beds are occasionally observed (Figure 9). Trough cross-bedding with visible mud drapes are common in upper portions of the

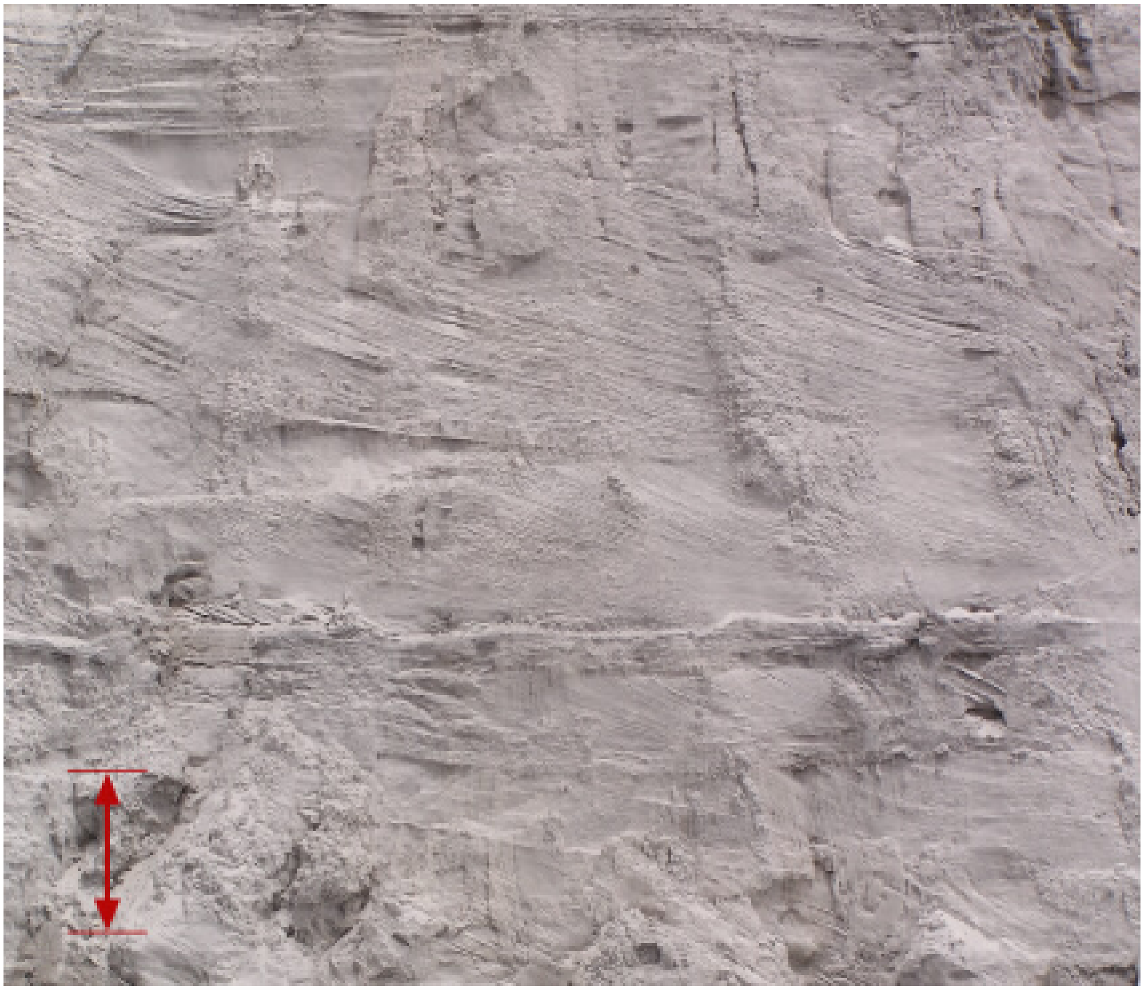

Figure 9- Downward Dipping Cross Bed Sets. Photograph of downward dipping cross bedding in lower portion of prograding delta. Scale bar represents approximately 30 centimenters.

prograding delta (Figure 10). Planar and sigmoidal cross-beds may be observed locally and occurrence of soft sediment deformation is rare (Figure 11).

Prograding delta facies are recognized in subsurface logs by their low value, serrated gamma ray curve, high to medium density curve, and middle to high resistivity curve values (Figure 7c). The gamma ray curve in this facies generally shows low levels of radioactivity, which indicates a coarse grain size interval. However, the gamma ray values often deflect locally to the right (high gamma ray response) which indicates fine-grained material is interspersed throughout the interval. The density curve remains in the center of the log track with little variation because the interval is relatively homogenous and larger grain size is not as closely packed as higher density fine-grained sediment. The high resistivity response is typical for a porous medium which is filled with a nonconductive fluid such as fresh groundwater.

Interpretation

Cross-bedding is typically deposited in the lower flow regime of fluvial and deltaic environments by dune migration. The height of individual dunes scale to 20% of the water depth and dune length scales to five times the depth of the water column (Allen, 1997). Dunes form in unidirectional flows and are often scoured by subsequent dunes as the sedimentary record is produced, so water depth is not always readily extrapolated. Trough cross-bedded dunes form in conjunction with a sinuous crest where scour pits are developed as the dune migrates downstream (Allen, 1997; Leeder, 1999). Planar cross strata are straight crested in plan view and are generally held to be deposited in a lower flow velocity environment than

Figure 10- Trough Cross Bedding with Mud Drapes. Photograph of trough cross bedding common in upper portions of prograding delta. Scale bar represents approximately 30 centimeters.

Figure 11- Cross bedding with mud drapes. Photograph of planar cross bedded sands with mud drapes in upper portion of prograding delta. Note soft sediment deformation just to right of scale bar. Scale bar is approximately 30 centimeters.

trough cross-bedded sand and typically in a lesser span of time which does not allow for dunes to develop a curved crest (Allen, 1997). Mud drapes deposited on the lee face of the dune scale cross-beds indicate a fluctuating energy environment commonly associated with tidal systems. Mud drapes are deposited on the lee face of dunes during the slackwater stage of the tidal cycle when flow velocity falls below the mud transport threshold (Allen, 1982; Visser, 1980). Unidirectional appearance of the dunes indicates a dominant flow direction which may be enhanced by fluvial currents. Sigmoidal bedding commonly occurs in tidally-influenced systems and basinward of the delta front where fluvial waters decrease in velocity (Willis, pers. comm.). The deceleration of the sediment laden flows over the dune crest allows for deposition of finer-grained sediment from suspension (Kreisa and Moiola, 1986).

Delta Top Mud

Description

Intervals of this facies are 0-35 feet (0-11 m) thick and consist of parallel laminated interbedded siltstone and sand packages separated by thin laterally continuous carbonaceous mud layers. Individual sand and mud interbeds are 2-9 inches (5-23 cm) thick and are probably composed of smaller laminations (Figure 12). The silt is gray on surfaces exposed to weathering but when recently exposed an iron oxide stain is observed. The sand laminations are light gray to gray. The lower bounding surface is abrupt contact with thin black carbonaceous mud and the upper bounding surface is an

Figure 12- Tidal Rhythmite. Tidal rhythmite bundles in delta top mud facies. Iron oxide stains are exposed when weathered face of highwall collapses. The horizontal black layer is the thin laterally extensive base of the delta top mud. Red arrow represents approximately 2 meters.

erosion surface. Observations are restricted to photography thus no small-scale sedimentary structures were able to be observed. Delta top mud is identified in subsurface logs by a high but serrated gamma ray response, a moderately serrated average density response, and a variable resistivity whose deflections correspond directly to the deflections observed in the gamma ray curve (Figure 7d). When the gamma curve deflects to the right, the resistivity is low and when the gamma curve deflects to the left, the resistivity is high. A serrated gamma ray curve indicates an alternating finer-grained and coarser-grained interval, the right deflections on the serrated curve indicate finer-grained materials such as clay and the left deflections represent relatively coarser-grained material such as fine-grained sand. The small variations in the density curve also reflect the alternating lithology; fine-grained clays are higher in density and correspond to the right deflections on the gamma ray and coarser-grained materials are lower in density and correspond to left deflections in the gamma ray curve. Resistivity is typically low, but significant high variations occur in association with intervals of low trends in the gamma ray values. Low resistivity occurs due to presence of conductive clay minerals and high resistivity occurs where sand rich intervals allow the flow of non-saline groundwater which is known to be nonconductive.

Interpretation

Parallel laminated sands and silts are referred to as rhythmites and may be deposited by either overbank depositional processes or in tidally influenced settings (Bridge, 1984; Tye and Kosters, 1986; Kosters, 1989; Tye and Coleman, 1989; Nio and Yang, 1991; Jorgensen and Fielding, 1996). Overbank rhythmites are deposited in basins with variations in sediment input and low energy conditions and tend to have highly irregular thickness variations associated with river flood events of varying magnitudes (Tye and Coleman, 1989). Overbank sedimentary structures are typically on the millimeter scale and ripple cross lamination and graded bedding are common (Tye and Kosters, 1986; Tye and Coleman, 1989; Jorgensen and Fielding, 1996). When rhythmites are deposited by overbank flooding, regular flood events prevent floral and faunal invasion (Tye and Kosters, 1986; Kosters, 1989; Jorgensen and Fielding, 1996). Overbank rhythmites are often in abrupt contact with underlying peat and carbonaceous mud (Tye and Coleman, 1989; Jorgensen and Fielding, 1996). Tidal rhythmites are deposited under fluctuating flow directions and energy conditions and tend to have more consistent and cyclic thickness variations (Nio and Yang, 1991). Rhythmites deposited on tidal flats have little to no organic accumulation or bioturbation, due to regular inundation by marine waters and tidal processes.

Distributary Channels

Description

Distributary channels are up to 45 feet (14 m) thick and have upward-concave basal erosion surfaces. For the post deltaic channel, individual beds vary from 3-9 feet (1-3 m) in thickness and consist of gray trough cross-bedding sands terminated by thin, dark brown mud layers. The mud layers dip 3-10 degrees to the southwest and generally terminate at the basal erosion surface (Figure 13). The lower bounding contact is an erosion surface and the upper bounding contact grades into a modern pedogenic surface.

Massive structureless sand occurs rarely, and when present disrupts adjacent stratification. Dark brown mud deposits interbedded with sand are present at the basal surface.

For distributary channels contemporaneous with deltaic deposition (Figure 13), individual sand beds are separated by discontinuous mud layers dipping southeastward at 3-5 degrees. Separation between mud layers varies from less than 1 ft (0.3 m) to 3 ft (1 m). Sedimentary structures observed in sandy intervals consist of trough cross-bedding. Near the cutbank, mud layers appear to be more numerous, thicker, and more closely spaced.

Subsurface log response is characterized by a low but serrated gamma curve, a variable density curve, and a generally high but variable resistivity curve (Figure 7e). Overall low gamma ray values punctuated by deflections to the right indicate an environment which is dominated by coarse-grain sediment but contains interbedded fine-grain sediment. Density curve variability is explained by variations in sediment grain size. Where the gamma ray curve is high, density is high and porosity is low; where the gamma ray curve is low, density is low and porosity is high. Variable resistivity also correlates to serrated gamma ray values. High gamma ray curve corresponds to low resistivity, fine-grained sediment which may occur at lateral accretion surfaces or sometimes interspersed in the fluvial sands. Low gamma ray curve response corresponds to a high resistivity curve which is indicative of non-conductive groundwater present between sand grains.

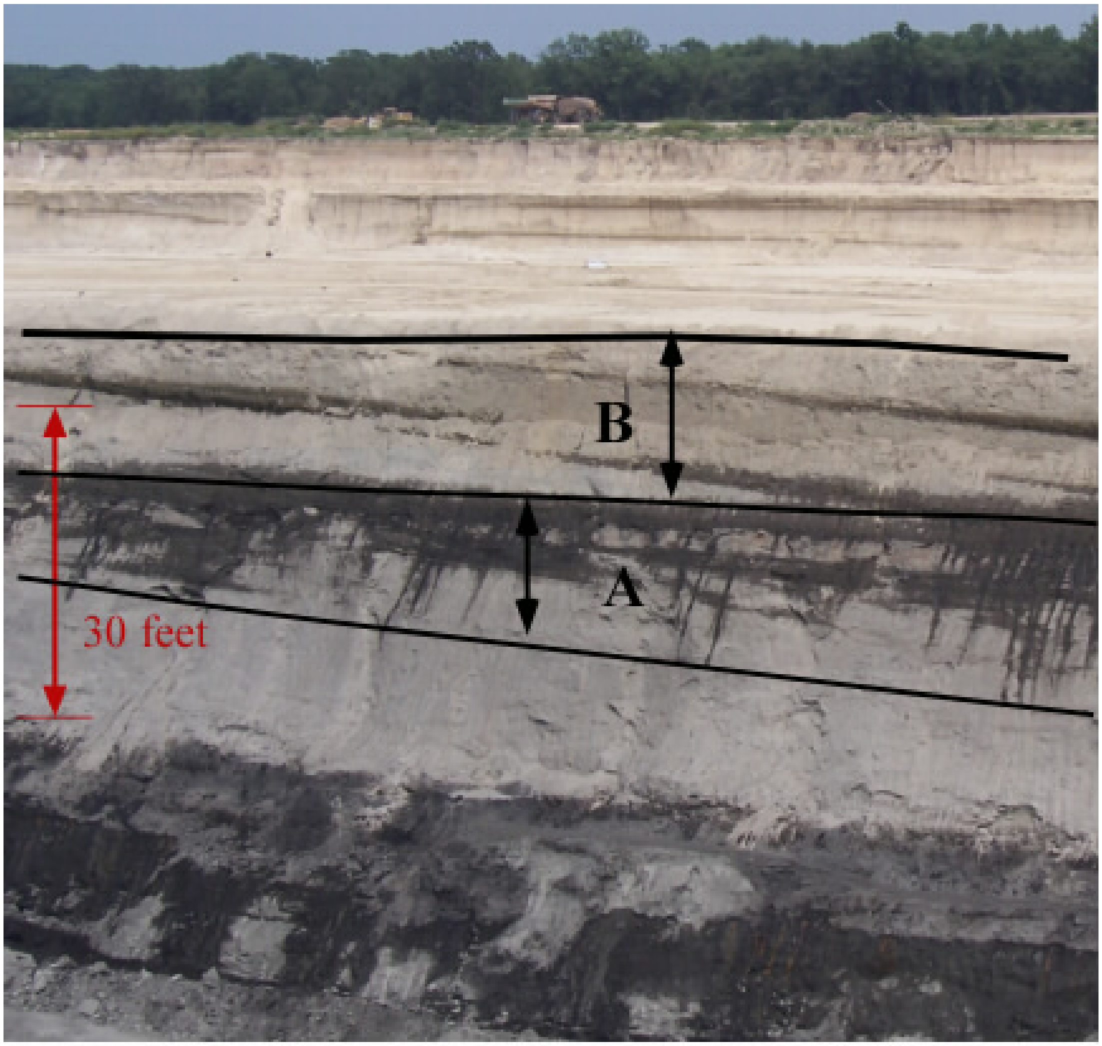

Figure 13- Lateral Accretion Surfaces. Photo of lateral accretion surfaces in the distributary channel facies. The dark layers dipping to the right in the photo are lateral accretion surfaces. (A) is the southwest distributary channel which incises into the prograding delta. Lateral accretion surfaces in this interval are discontinuous. (B) The post deltaic distributary channel which incises into the delta top mud. The lateral accretion surfaces terminate into the resistive organic rich mud at the base of the delta top mud.

Interpretation

This facies was deposited on a migrating point bar in a river or distributary channel. Trough cross-bedding records migration of dunes across channel bars during major floods. Inclined mud beds are lateral accretion deposits which record a pause in flow following river flood events. Migrating channels are dominated by coarse-grain sediments, which are often separated by fine-grain lateral accretion surfaces. Paleoflow in lateral accretion deposits is normal to the dip of the lateral accretion surface; therefore, paleoflow in these channels was to the southeast. Massive, structureless sands record emplacement of sand plugs by collapse or liquefaction of adjacent sandy banks (Turner and Munro, 1987; Reading, 1996).

Incised Valley Fill

Description

These brown to gray fine-grained cross stratified sands vary from zero to over 70 feet (21.3 m) thick. The lower bounding contact is an erosion surface, and the upper bounding surface is a gradation into modern paleosols. The lower portion of the incised valley fill is trough cross-bedded sand with little to no mud drapes (Figure 14). Upper portions of the incised valley fill are trough cross-bedded sand with the trough scours occupied by clay abandonment plugs (Figure 15).

The incised valley fill is characterized by two combinations of subsurface log responses: basal incised valley fill and upper incised valley fill. The basal incised valley

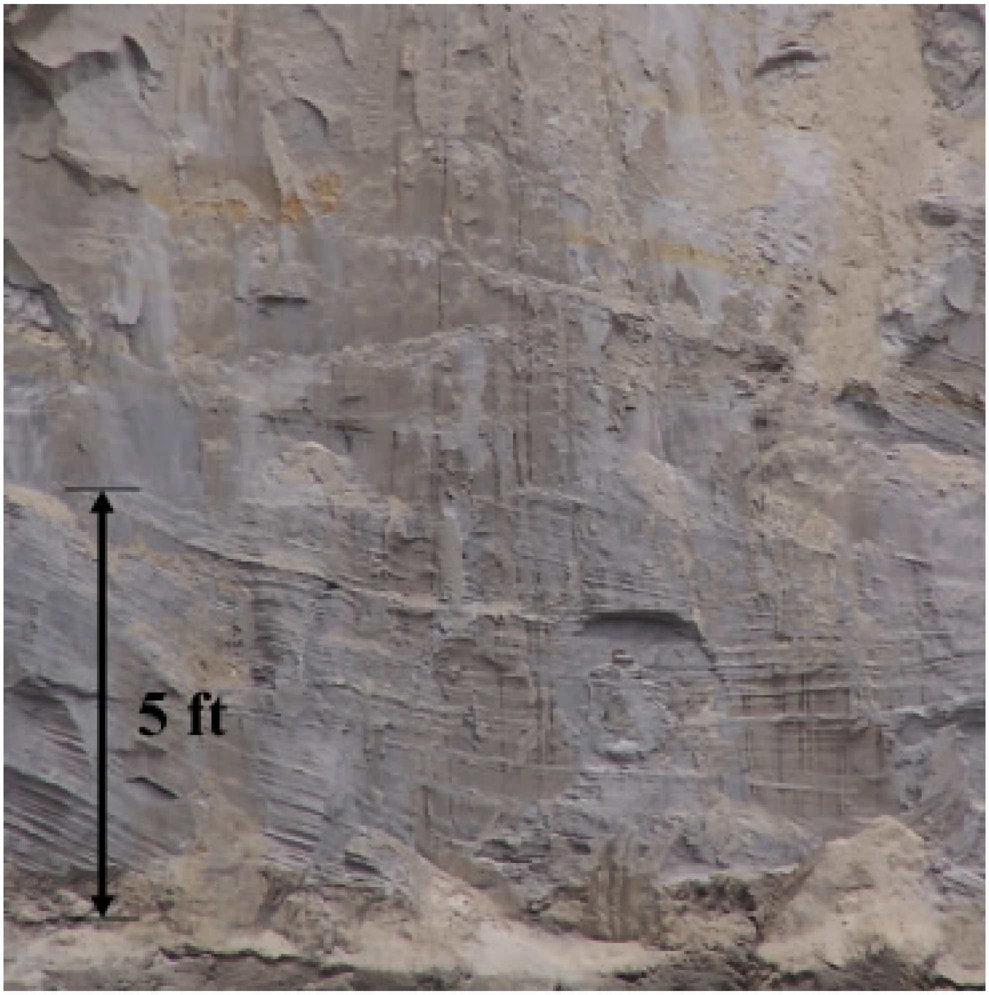

Figure 14- Base of incised valley fill. Homolithic trough cross bedded sand in base of incised valley fill.

Figure 15- Upper portion of incised valley fill. Heterolithic trough cross bedded sand in upper portion of incised valley fill. Dashed line highlights base of clay abandonment plug in trough scour. The upper portion of the incised valley fill heavily weathered from pedogenetic effects.

fill is recognized by a low gamma ray value, moderately low density value and a high resistivity value (Figure 7f). Low gamma ray values indicate very little fine-grained sediment, and are typical of high energy fluvial channel sands. Low density indicates high porosity and relatively homogenous sediments composed of a coarse grain size. The resistivity curve gives a high reading, which, like the distributary channel deposits is typical for a porous medium filled with non-conductive fresh groundwater

The upper subsurface log responses are characterized by a serrated gamma ray curve, variable density curve and variable resistivity curve (Figure 7g). Serrated gamma curve responses indicate vertical variations in grain size. As the incised valley filled vertically, lateral migration and abandonment of small channels occur. Leftward deflections of the serrated gamma curve correspond to the high energy coarse grains deposited by moving water, the rightward deflectins of the serrated gamma curve correspond to abandonment of minor channels and deposition of clay abandonment plugs. The density curve and resistivity log curve responses correlate to the leftward and rightward deflections exhibited by the serrated gamma curve. High density responses correlate to the high gamma curve readings of fine-grained sediment and low density responses correspond to the low gamma curve readings of coarser-grained sediment. High resistivity readings correspond to the non-conductive groundwater found in porous intervals (low density) of the coarse grain vertical intervals (low gamma ray).

Interpretation

Incised valleys are created by erosion into underlying sediment during periods of sea level fall or lowstand. Sediment bypasses the adjacent terrain and is deposited further into the basin. When sea level rises, incised valleys are filled by fluvial processes, which deposit cross-bedded sediments. Cross-bedding is typically deposited in the lower flow regime of fluvial environments by dune migration. Trough cross-bedded dunes form in conjunction with a sinuous crest where scour pits are developed as the dune migrates downstream (Allen, 1997; Leeder, 1999). Planar cross-beds are straight crested in plan view and are generally held to be deposited in a lower flow velocity environment than trough cross-bedded sand and typically in a lesser span of time which does not allow for dunes to develop a curved crest (Allen, 1997).

STRATAL ARCHITECTURE

The architecture of the Calvert Bluff Formation exposed in the highwall at Big Brown Mine is defined by vertical and lateral variations in facies and allostratigraphic surfaces. Based on facies composition, geometry, and bounding surfaces, deposits of Big Brown Mine can be divided into six depositional units: 1) lignite; 2) interdistributary bay mud; 3) prograding delta; 4) delta top mud; 5) distributary channels; and 6) incised valley fill. The architecture of these depositional units are first described and then interpreted. Refer to figure 16 for the cross section and bedding diagram of sediments exposed in the highwall of Big Brown Mine. Refer to Figure 17 for a paleo-geographic reconstruction of depositional environments. In a later section, sequence stratigraphic implications and significance are discussed.

Description

Lignite

The basal unit of the documented interval at Big Brown Mine is composed of a sheet like, laterally extensive, and undulatory lignite. It has a relatively constant thickness of approximately 6 feet (2 meters) and dips 2.5-3.0 degrees to the northeast. The unit extends to the southwest beyond the limits of the study. To the northeast the lignite pinches out against a channel levee flank. The lower bounding surface is abrupt with underlying mud and the upper bounding surface either grades vertically over a short

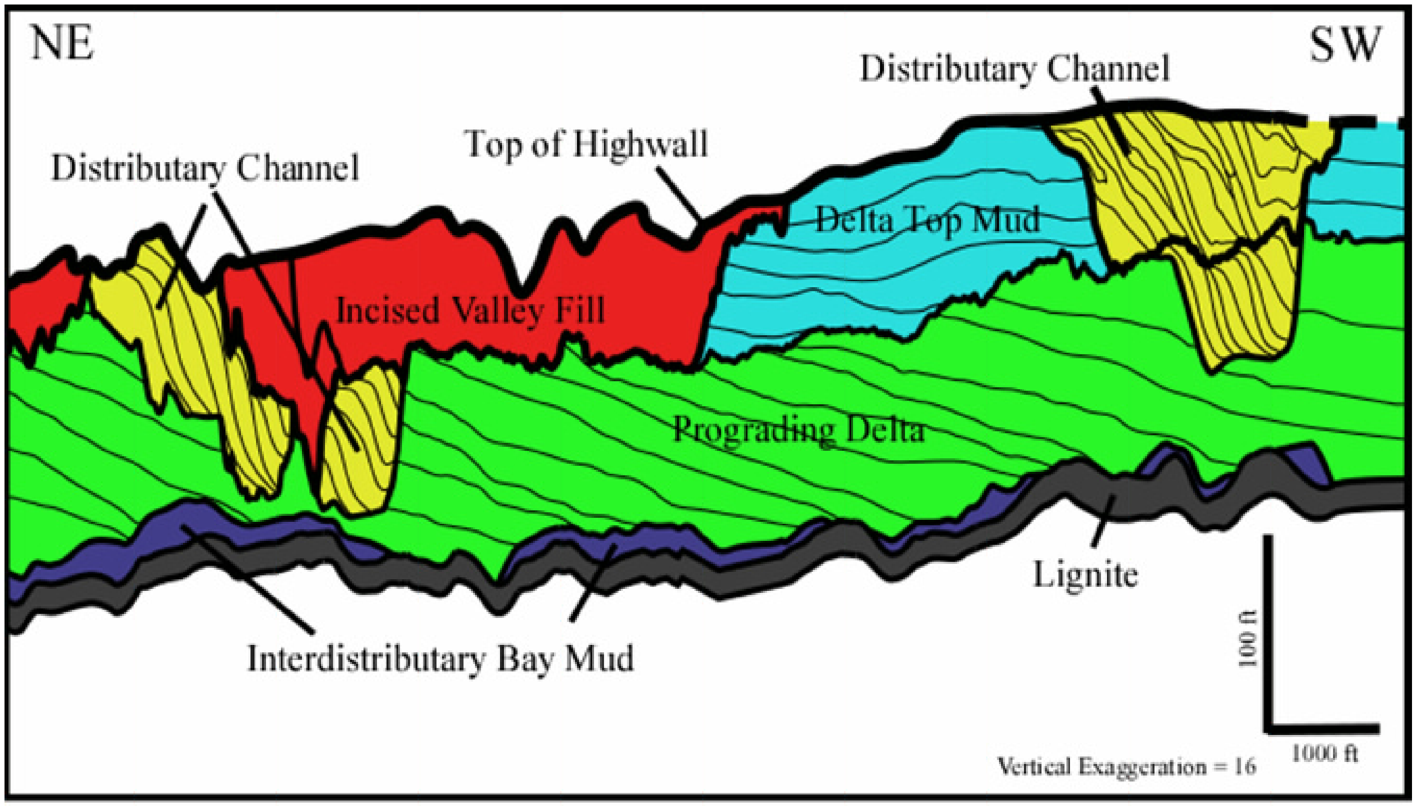

Figure 16- Compressed cross section of Big Brown Mine highwall. Illustration of stratal architecture of the southwest half of the exposed highwall at Big Brown Mine. Bold lines show bounding surface of facies associations, lighter lines show internal geometry mapped on the photomosaic.

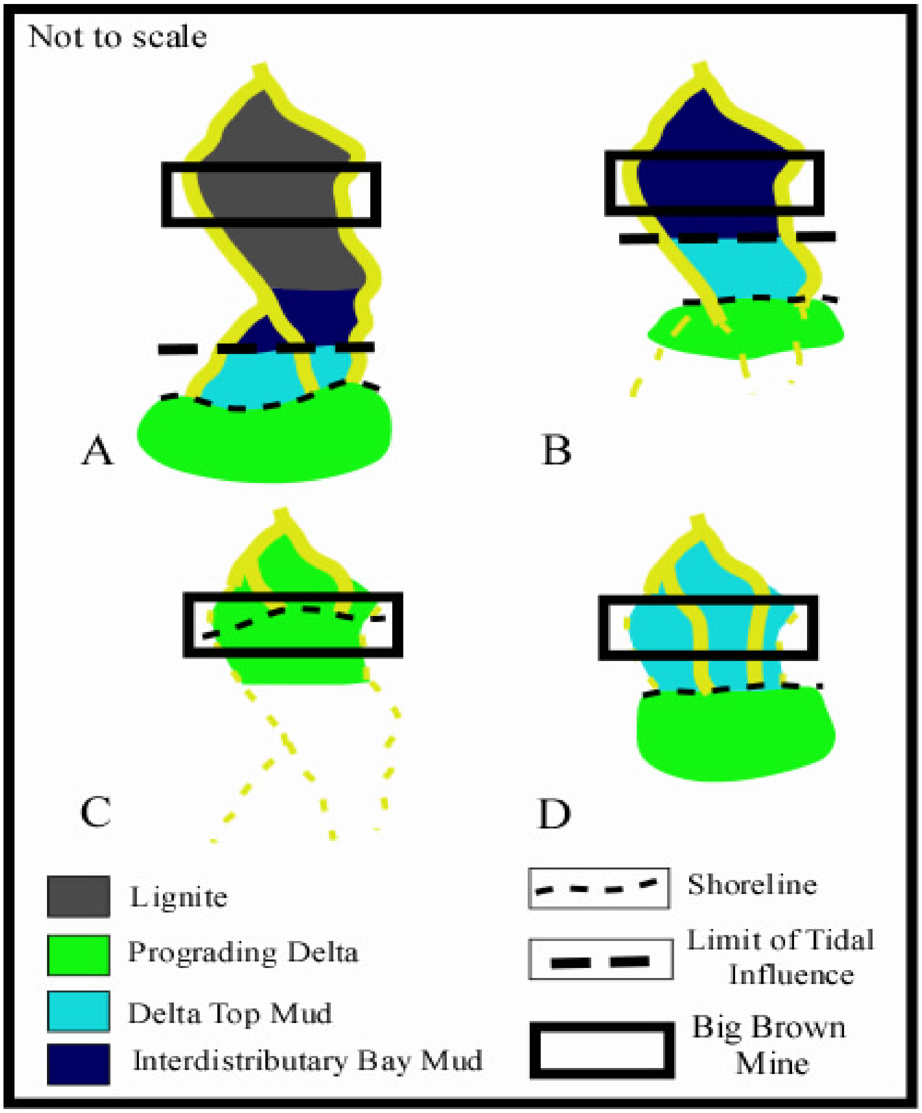

Figure 17- Paleo-geographic reconstruction. Location of Big Brown Mine relative to the position of the paleoshoreline and the limit of tidal influence during sediment deposition (A) Peat formation.
(B) Interdistributary Bay Mud. (C) Prograding Delta. (D) Delta Top Mud.

distance to interdistributary bay mud or is abrupt with prograding delta deposits. Lignite is easily identified and correlated in subsurface logs throughout the study area.

Interdistributary Bay Mud

Interdistributary bay mud is composed of brown, fine-grained sand and mud and is deposited above lignite when present. The unit was probably laterally extensive following original deposition. Topographic variations most likely created regions of preferential scouring by high energy prograding delta deposits during initial stages of delta progradation. Lower bounding contacts are characterized by vertical gradation over a short distance from lignite to interdistributary bay mud. Upper bounding contacts are a vertical gradation over short distances to prograding delta deposits as initial pulses of delta progradation mixed with interdistributary bay mud. To the northeast the interdistributary bay mud pinches out against a channel levee flank, and to the southwest, the unit extends beyond the study area. Subsurface log correlation is the preferred method of identifying lateral continuity of interdistributary bay mud. When not scoured by overlying prograding delta deposits, interdistributary bay mud is identified throughout the study by high gamma ray response and low resistivity response directly above lignite.

Prograding Delta

The prograding delta is a thick unit of cross-stratified sand with mud drapes. The lower bounding surface of the prograding delta rests on the interdistributary bay mud and in some instances it rests on the lignite. The lower surface is abrupt when the prograding delta is in direct contact with the lignite and it is a vertical gradation over short distances when in contact with the interdistributary bay mud. The upper bounding surface of the prograding delta is either a flat, laterally extensive, abrupt contact with overlying delta top mud and incised valley deposits or a local concave up erosion surface with two distributary channels. Laterally, the prograding delta extends beyond the limits of the study in both the northeast and southwest directions. The prograding delta is divided internally by a series of clinoforms dipping 2.5-3 degrees to the southwest that vary from 5-15 feet (1.5-4.5 m) in thickness. Clinoforms can be traced from upper contacts downward to where they downlap onto either interdistributary bay mud or lignite. The prograding delta is laterally expansive and can be readily identified in subsurface log throughout the study area.

Delta Top Mud

Delta top mud deposits in Big Brown Mine can be identified by tidal rhythmite packages separated by thin laterally expansive mud layers. The lower bounding surface of the delta top mud is a relatively flat, laterally expansive, thin, resistive organic-rich mud which has an abrupt contact with prograding delta deposits. The lateral and upper bounding surfaces of the delta top deposits are truncated by two erosion surfaces. An incised valley to the northwest and a distributary channel to the southeast both erosively truncate the delta top sediment creating a convex upward geometry. Internally the delta top mud deposits are flat parallel interbeds of silty clays and fine grained sands with mud drapes. The interbedded packages are divided by thin, flat, laterally expansive mud layers. Close well spacing coupled with facies identification in subsurface log allows for interwell correlation of delta top mud.

Distributary Channels

Three distributary channel deposits are observed in the area. Two channels occur prior to deposition of the delta top mud and one channel incises post deposition of the delta top mud. The two pre delta mud depositional distributary channels are identified by geographic location: a northeast channel and a southwest channel. The northeast channel is 775 ft (236 m) wide in photomosaic and has a concave upward erosion surface with abundant closely spaced internal lateral accretion surfaces dipping 3-5 degrees to the southwest. The base contact is a clear concave up erosion surface. The southwest channel (Figure 13) is 1,100 ft (335 m) wide in photomosaic and is identified by lateral accretion surfaces dipping to the southwest at a greater angle than the dip of the clinoform surfaces. The concave up erosional base of the southwest channel is inferred by abrupt changes in dip angles between prograding delta sands and steeper lateral accretion surfaces of the distributary channel sands. The upper bounding contact of both channels is defined by a flat, abrupt contact with overlying delta top mud. Subsurface log response for these two channels closely resembles that of the prograding delta. By close observation it has been determined that gamma ray responses in the channel regions is typically higher than that of adjacent prograding delta deposits. The other limiting factor affecting correlation in these intervals is well spacing. Having few wells that penetrate this interval makes it difficult to correlate these deposits throughout the mine. Without the photomosaic providing the basemap for subsurface log correlations, log response of the smaller distributary channels may be overlooked.

The post-delta top distributary channel is 2,350 ft (720 m) wide in photomosaic and incises into delta top mud. The lower and lateral contacts define a concave up erosion surface with delta top mud. The base of this distributary channel is flat and is an abrupt contact with the resistive organic rich basal unit of the delta top mud. The upper surface extends beyond the documented area but is probably cut by the incised valley to the northwest and extends into surface paleosols in the center and southwest. Lateral accretion surfaces dipping to the southwest at 2.5-3 degrees occur in the northwest portion of the distributary channel and terminate at the erosive base of the unit. Lateral accretion surface can be identified in subsurface log by a high gamma ray spike and a corresponding low resistivity spike, but due to well spacing constraints these surfaces cannot be traced between wells. Two isolated occurrences of massive structureless sand disrupt lateral accretion surfaces in the northwest section of this channel. The southwest portion of this distributary channel has concave up fine grain channel fill deposits infilling the thalweg of the channel. Subsurface log response in the upper more laterally extensive distributary channel is much more straightforward than for its smaller counterparts. Well penetration in this distributary channel occurs through fine grain channel fill deposits in the thalweg and through lateral accretion surfaces of migrating point bar deposits. Although lateral accretion surfaces cannot be correlated between logs, the surfaces can be recognized in individual logs due to their high gamma ray spike vertically juxtaposed to coarser grain low gamma response cross-beds.

Incised Valley Fill

Incised valley fill deposits are 5,500 ft (1,680 m) wide in photomosaic and are recognized by brown cross-bedded sands erosively cutting into gray to dark gray sediments. The lower bounding surface is flat and laterally extends unconformably on the thin resistive organic rich basal delta top deposit for 3,350 ft (1,020 m). Laterally the lower bounding surface is concave up and is an erosion surface to the southwest with delta top deposits and upsection is an erosion surface with the upper distributary channel deposit before grading into surface paleosols. To the northeast the erosive lower bounding contact extends upsection through distributary channel deposits and grades vertically to surface paleosols. The upper surface of the incised valley fill is the present day soil horizon. Internal variation occurs vertically through the incised valley fill as the deposit becomes more heterolithic upsection. The lower 30 ft (9 m) of the incised valley is a relatively coarse-grain, homogenous trough cross-bedded sand. As the valley widens vertically up section, the incised valley fill becomes dominated by trough cross-bedded sand with clay abandonment plugs occupying the trough scours. In the northwest portion of the valley fill, a previous incised channel occurs that is eroded by a second channel occupying most of the incised valley. Two subsurface log combinations differentiate between the homogenous basal portion of the fill and the heterolithic upsection portion of the fill. Low gamma ray responses and high resistivity responses are diagnostic of the basal portion of the valley fill, whereas high gamma responses and low resistivity responses are diagnostic of the upper heterolithic portions.

Interpretation

Sediment observed in the "C" area highwall at Big Brown Mine records the filling of an interdistributary basin. Elements of the floodbasin cyclic deposition model of Lentz (1975) and English (1988) are recognized in the stratal architecture. Lignite deposits record a low sediment input, high water table environment rich in organic productivity. Preservation of organic matter that comprise the lignite indicates a reducing environment which was not exposed to the destructive effects of oxidation. Accumulation of organic material was terminated by a sea level rise and the associated advance of a salt water wedge into fresh water coal swamps. Rise of the ground water table during sea level rise (Figure 8), ultimately forces channel waters to breach the levee tops and inundate the interlevee basins with sediment charged water. The introduction clastic sediment by overbank flooding deposited interdistributary bay mud above the lignite. The influx of interdistributary bay mud and increasingly brackish waters inhibited organic accumulation, causing peat formation to founder.

Continuing sea level rise caused upstream channel avulsion to this area which introduced higher energy, coarser-grained clastic sediment into the interdistributary basin. Although interdistributary bay mud generally overlies lignite in Big Brown Mine, prograding delta deposits are in contact with the lignite. These regions were probably topographically lower and became higher energy as the prograding delta filled in the bay. The areas were scoured of interdistributary bay mud, leaving prograding delta deposits directly overlying lignite. As river waters continued to flow into the distributary basin, a prograding delta was formed. Low-angle clinoforms traced throughout this prograding deposit indicate delta front progradation. In the upper 10-15 ft (3-4.5 m) of this prograding deposit, fine-grain sediments become commonplace as high energy sediment was bypasses basinward into areas with accommodation space at the prograding delta front. The fine-grained deposits probably indicate the presence of a lower energy fluvial-influenced tidal flat, which developed adjacent to incising distributary channels. The increase in mud drapes in the upper section of the prograding delta indicates increasing influence of tidal processes.

The channels incising into the prograding delta are distributary channels which probably fed delta front progradation basinward. Overlying the prograding delta are deposits of delta top mud. A thin, resistive organic-rich condensed mud forms the base of the delta top mud facies association which was deposited when clastic input was virtually terminated in the area. Further basinward progradation depleted the area of fluvial dominated deposits and tidal rhythmites were deposited on a tidal flat which developed on the thin, resistive organic-rich condensed mud.

Deposition of tidal rhythmites was terminated by a fluvial channel migrating across and incising into the tidal flat as the shoreline prograded basinward. Lateral accretion surfaces within this upper distributary channel record southwestward migration of a point bar. The lateral accretion surfaces terminate into the thin, resistive organic-rich condensed mud at the base of the delta top mud. Organic rich peats resist erosion by fluvial systems and abrupt contacts are common (McCabe, 1984). Channel migration ceases to the southwest as lateral accretion surfaces grade into fine-grain channel fill deposits caused by channel abandonment and subsequent infilling by low energy fluvial activity and occasional flood pulses. Two massive structureless sands occur in the migrating distributary channel probably caused by a slope failure in the cut bank.

The incised valley and fill formed by fluvial incision during a drop in relative sea level. Subsequent infilling indicates a rise in base level during relative sea level rise (Willis, 1998). The cross-bedded, coarse-grain sands deposited at the base of the incised valley record a high energy system with little variation in energy level. As the valley filled vertically, the fluvial system began migrating back and forth across the alluvial valley leaving behind trough cross-bedded heterolithic sediment. The scours of the troughs are filled with clay plugs deposited when individual troughs were abandoned and energy levels dropped.

Valley Fill Deposits

Two types of channel deposits are observed to cap the highwall in Big Brown Mine. The first type is documented in this thesis and is composed of homogenous sand at the base and vertically grades into heterolithic trough cross-bedded sand in the upper incised valley. Lentz (1975) and English (1988) recognized similar channel deposits in their work and interpreted them to be Wilcox Group in origin. The second type of deposit can be observed in the far northwest portion of the highwall and consists of poorly sorted gravel and coarse-grain sand. This second channel deposit was deposited much later than the incised valley fill documented in this study and is interpreted to be quaternary deposits associated with the ancestral Trinity River. These two deposits are very different and were deposited at vastly different times in the geological record.

DISCUSSION

A Sequence stratigraphic framework of the marine and shelf sediments of the Texas Wilcox Group is well documented (Xue and Galloway, 1995; Haq et al., 1988; Crabaugh and Elsik, 2000; Breyer, 1997; and many others). Applying sequence stratigraphy to shoreline succession is relatively easy, because there are generally obvious indicators for changes in shoreline position (regression verses transgression) and changing water depth that define system tract stacking patterns. Sequence stratigraphic concepts have proven more difficult to apply to fluvial and paralic deposits formed behind shorelines, because facies patterns can be more complex and do not necessarily change systematically with changes in accommodation development and aggradation rate. A sequence stratigraphic framework of updip portions of Wilcox Group sediments depends on correlating paralic and nonmarine depositional variations to marine and shelf coeval strata down dip. Defining a regional sequence stratigraphic framework of the Calvert Bluff Formation allows for accurate local paleoenvironmental and sequence stratigraphic interpretations of the sediments documented in Big Brown Mine.

Calvert Bluff Formation Sequence Stratigraphic Framework

The Calvert Bluff Formation is defined by two regional shale markers. The base is defined by the Butler Clay Member of the Calvert Bluff Formation and the top is defined by the contact with the Sabinetown Formation. The Sabinetown Formation is cut out unconformably in some locations by an erosion surface at the base of the overlying

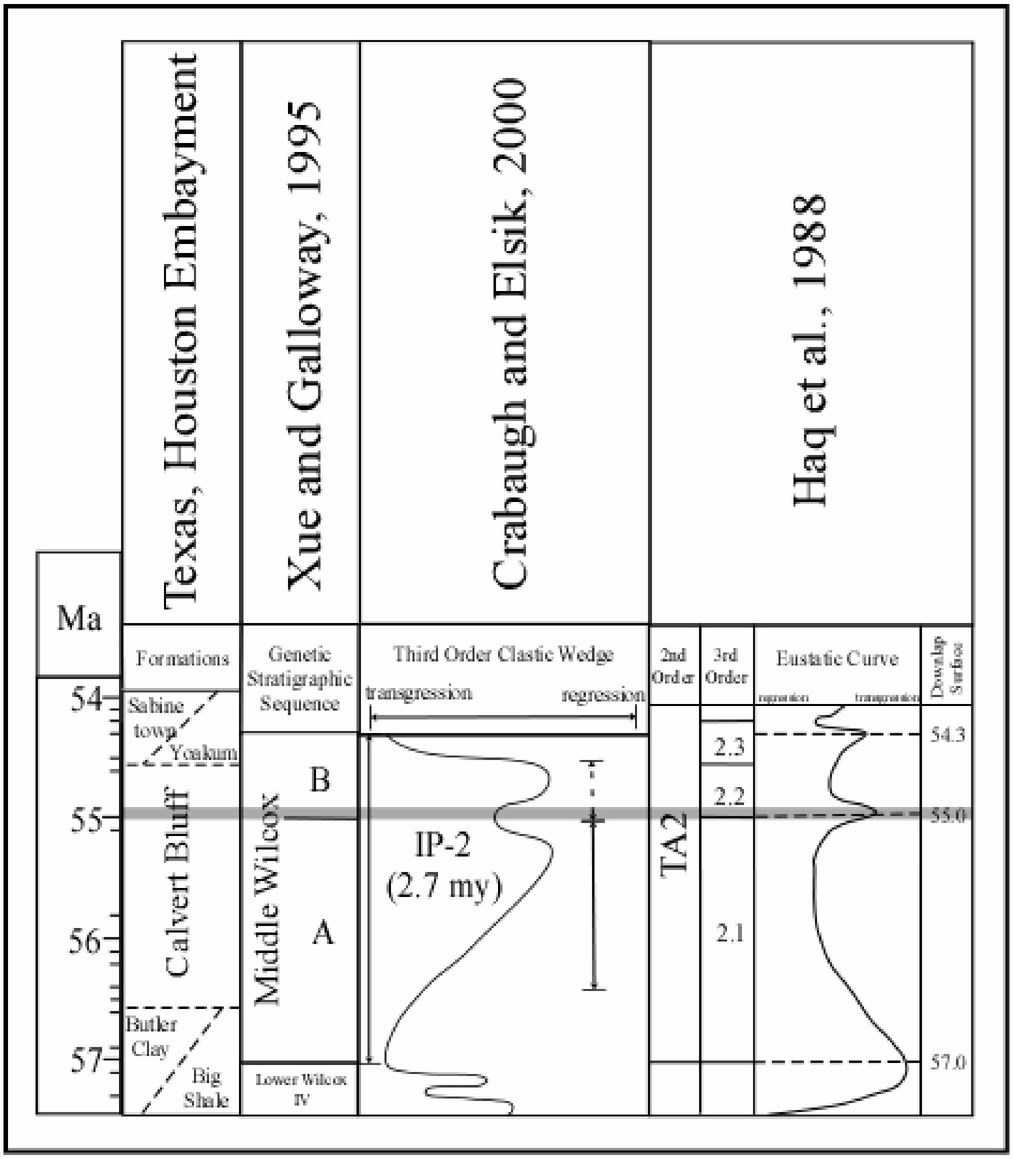

Figure 18- Big Brown Mine sequence stratigraphic framework. Shaded region is location of Big Brown Mine in relation to regional sequence stratigraphic studies by the Texas Bureau og Economic Geology (Texas, Houston Embayment), Xue and Galloway (1995), Crabaugh and Elsik (2000), and Haq et al. (1988). (modified from Crabaugh and Elsik (2000), Xue and Galloway (1995) and Haq et al. (1988)).

Carrizo Sand. Brewton (1992) correlated outcrops of the Butler Clay Member and the Sabinetown Formation to their down dip equivalents: the Big Shale and the Yoakum Shale, respectively (Figure 18). Xue and Galloway(1995) used the Big Shale and the Yoakum Shale to define the base and top of their middle Wilcox Group genetic stratigraphic sequence. They sub-divided the middle Wilcox Group into sequences A and B, defined by three transgressive surfaces. The base of sequence A is the Big Shale, which extends upsection to an unnamed transgressive surface. Sequence B extends upsection from the unnamed transgressive surface to the Yoakum Shale (Figure 18).

Xue and Galloway (1995) further correlated their regional transgressive surfaces to third order sequence stratigraphic surfaces of Haq et al. (1988). The base of sequence A (Big Shale) corresponds to the 57 Ma third order sequence boundary of Haq et al. (1988) and the top of sequence B (Yoakum Shale) is equivalent to the 54.3 Ma sequence boundary of Haq et al. (1988). The transgressive surface dividing Xue and Galloway's (1995) sequence A and B is probably the minor condensed section occurring at the 55 Ma of Haq et al. (1988). Deposition of the Calvert Bluff Formation thus is inferred to have occurred over 2.7 m.y.

Crabaugh and Elsik (2000) also suggested that the Calvert Bluff Formation was divided by a transgressive surface within their progradational IP-2 third order clastic wedge (Figure 18). The Big Shale was similarly interpreted to record a transgressive episode that defines the base of the Calvert Bluff Formation. A second transgressive episode defined within the Calvert Bluff Formation is equivalent to the minor marine flooding surface dividing the middle Wilcox Group genetic stratigraphic sequence of

Xue and Galloway (1995). These second transgressive deposits occur in the upper portion of the Calvert Bluff Formation. Episodes of transgression correspond to two zones of economic coal deposition in the Calvert Bluff Formation (Ayers and Lewis, 1985). The first occurrence of coal deposition is at the base of the Calvert Bluff Formation and is time equivalent to Crabaugh and Elsik's (2000) onset of transgression and Xue and Galloway's (1995) Big Shale marine flooding surface. The second major occurrence of coal is in the upper portion of the Calvert Bluff Formation and is time equivalent to Crabaugh and Elsik's (2000) minor onset of transgression in their IP-2 third order clastic wedge and the minor transgression dividing sequences A and B of Xue and Galloway's (1995) middle Wilcox Group genetic stratigraphic sequence and the 55 Ma minor condensed section of Haq et al. (1988). Economic peat deposition in the Calvert Bluff Formation appears to correspond to two periods of relative sea level rise (Figure 18).

Big Brown Mine Sequence Stratigraphic Framework

Coal deposition at Big Brown Mine probably occurred during a regional period of rising relative sea level. Conditions for coal deposition at Big Brown Mine were enhanced by transgressing seas. Transgression creates a landward advancing salt water wedge that raises the groundwater table during shoreline retreat (Bohacs and Suter, 1997; Figure 8). This rise in the water table creates accommodation within interdistributary basins and associated fluvial floodplains, and commonly creates ideal conditions for peat deposition. Peat accumulation is enhanced where interdistributary basins are filled with fresh waters. The coal at the base of the section exposed in Big Brown Mine likely records accumulation under fresh ground water conditions. Evidence for termination of peat accumulation, as water depths increased before progradation of the overlying deltaic succession, suggests that water subsequently became more brackish. Evidence for tidal influence recorded in some of these prograding delta and delta top facies also suggests some interaction with marine waters.

Galloway (1989a) recognized the significance of coal seams in defining genetic stratigraphic sequences of regional extent. Although the lignite seam at Big Brown Mine is not of regional extent, it has been shown by Warwick and others (2002) to occur in a broader interval with abundant coal seams that can be correlated regionally with transgressive surfaces recognized both along strike and down dip. The coal seam documented in this study is the highest lignite seam in this section and probably represents the upper surface of the coal zone observed in the upper portion of the Calvert Bluff Formation.

As the rate of relative sea level rise slowed, interdistributary bays began to fill with overbank crevasse splays, tidal flats, or thin bayhead deltas. These bays probably had highly variable connection to the open ocean, and thus may have varied significantly from fresh, to brackish, to fully marine waters at different stages of filling. Tides are generally inferred to have greater influence within bays that are relatively deep and have well connected outlets to the sea at least locally. Tides are less likely to occur within more restricted bays filled entirely with fresh ground waters. Wave influence is expected to be weak in most interdistributary bays, because wave power would rapidly attenuate within shallow bays. As interdistributary bays fill, crevassing across breached distributary levees and restriction of bay circulation may lead to fresher waters and more river-dominated, unidirectional currents. The deposits are expected to coarsen upward as waters shoal, and then become cut by distributary channels that bypass sediment to bay areas that are as yet unfilled.

The high relief erosion surface cut into the regressive deltaic succession exposed in Big Brown Mine suggests that this a high-frequency sequence, rather than simply a progradational parasequence capped by an abandonment flooding surface. Parasequences formed within larger-scale transgressive units are expected to be entirely aggradational, formed by locally prograding delta lobes and are first abandoned following river avulsion and then flooded during continued subsidence. In this case the high relief erosion surface cutting into the delta deposits suggests a fall in sea level (rather than a simple abandonment). Unlike simple parasequences, high frequency sequences indicate sediment bypass further basinward to shorelines that continue to regress. Although the base of the concave upward channels that caps the highwall exposure is also an erosion surface that defines sediment bypass basinward, the sequence stratigraphic significance is unclear because the character of the deposits basinward are unknown.

CONCLUSIONS

The documented deposits in the highwall at Big Brown Mine can be divided into six depositional units: 1) lignite, 2) interdistributary bay mud 3) prograding delta, 4) distributary channels, 5) delta top mud, and 6) incised valley fill. The lignite facies was deposited under low clastic sediment input, high water table, high organic productivity reducing environment shoreward of marine influence in an interdistributary basin. Rising relative sea level caused distributary channel waters to back up on the delta plain and breach the channel levees depositing interdistributary bay mud. Upstream channel switching caused by rising sea level led to the infilling of the basin by a prograding delta composed of clinoforming tidally-influenced cross-bedded sand. Infilling of accommodation space forced distributary channels to incise into the prograding delta and deposit sediment further into the basin. Channel switching sent the clastic sediment elsewhere and thin, resistive organic rich condensed mud was deposited on the delta top. Tidal rhythmites were deposited on the delta top tidal flat. Migration of a distributary channel across the floodplain incised the tidal flat and is recognized by lateral accretion surfaces and convex upward fine grain channel fill. The final depositional event was the incision of a fluvial valley into the migrating channel and delta top mud and subsequent filling of that channel with a fining upward sequence.

Sediment at Big Brown Mine can be divided into two sequence stratigraphic units separated by a high frequency sequence boundary. The lignite and interdistributary bay mud occur during transgression. The prograding delta, two lower distributary channels, and delta top mud were deposited during progradation and regression. The migrating distributary channel incising into the delta top mud indicates sediment bypass to regressing shorelines and occurs in the late highstand. The concave up erosional base of the incised valley fill occurs much later than other deposits at Big Brown Mine and represents lowstand fluvial bypass.

Two zones of economic lignite occurrence are recognized in the Calvert Bluff Formation. The most prolific zone occurs at the base of the Calvert Bluff Formation and is probably the landward equivalents of the Big Shale. The second interval occurs in the upper Calvert Bluff Formation and includes lignite extracted from Big Brown Mine. The coal zone in which Big Brown lignite was deposited corresponds to the following regional surfaces: 1) the marine flooding surface initiating sequence B of Xue and Galloway's (1995) middle Wilcox Group genetic stratigraphic sequence, 2) the minor transgression in the latter half of Crabaugh and Elsik's (2000) IP-2 third order clastic wedge, and 3) the 55 Ma minor condensed section of Haq et al. (1988).

Lignite in the Big Brown Mine is not regionally extensive, however the lignite deposits are in a zone of coal deposition in the upper Calvert Bluff Formation. Coals in the upper Calvert Bluff Formation were deposited in the upper delta plain of the Calvert Delta system. Deposition of the lignite, interdistributary bay mud, prograding delta, distributary channels, and delta top mud occurred during a minor regional transgression and later onset of regression.

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APPENDIX A

Appendix A contains the photomosaic constructed in this study. Plate 1 is a basemap showing locations of Plates 2-17. Plates 2-17 depict the photomosaic in order from the northeast to the southwest limit of the documented highwall. The bold dashed line at the top of the photomosaic represents the top of the lower bench along the highwall and does not correspond to any stratal architectural surfaces. Solid bold lines represent boundaries between stratal architectural units and correspond to the stratal divisions on Figure 16. The stratal architectural units have been labeled on the photomosaic. The thin, solid lines represent internal bedding geometries within the stratal architectural units. Vertical red lines represent the locations of survey points used to tie the highwall into the subsurface log framework. Blue subsurface log curves are gamma ray curves superimposed upon the photomosaic. The log curve also shows the vertical scale on the photomosaic. The blue line below the photomosaic is the distance scale. There is no vertical exaggeration on the photomosaic. Plates 1-17 can be viewed on attached pdf file.

APPENDIX B

Appendix B contains the three subsurface log cross section lines correlated in this study. Plate 18 is a basemap showing the geographic layout of the subsurface logs. Plate 19 is subsurface log cross section A-A'. Plate 20 is subsurface log cross section HW-HW'. Plate 21 is subsurface log cross section C-C'. Stratal architectural units correlated to the log cross section are labeled and separated by bold, black lines. The colors on the subsurface log curves correspond to quantitative values of the log responses. From low values to high values the colors range from red-brown-yellow-green-blue. Plates 18-21 can be viewed on attached pdf file.

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