

A MODERN RESERVOIR ANALOG FOR A POORLY DRAINED
“HIGH ACCOMMODATION” FLUVIAL SYSTEM: SEDIMENTARY
PROCESSES, ARCHITECTURE, AND RESERVOIR
CONNECTIVITY OF THE GRIJALVA SYSTEM, TABASCO STATE,
MEXICO

by

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Acknowledgements

I have had a fascination with rivers since childhood. I can always remember wondering why a river meandered and eroded some banks while depositing material on others. It was an interest that stayed with me through my youth and was reawakened while I served in the United States Army. As a young soldier serving in the 75th Ranger Regiment I was afforded the opportunity to travel the world and I spent a lot of time operating in deserts, jungles, mountains and forest encountering and crossing all types of streams and rivers. Years later as an undergrad my focus was in geomorphology. At the University of Texas at Arlington I knew I wanted to focus on fluvial geomorphology. John Holbrook not only accepted me as one of his students, but he even accepted my idea for my research. Due to logistic issues and funding needs I ended up taking on one of John Holbrook's projects that was fully funded, but no one wanted to work on because it was in Mexico. So, with some satellite photographs of the Grijalva Delta, Dr. Holbrook was able to focus my interest in Tie Channels and the morphology of wet, poorly drained basins. As my advisor, he has been an outstanding source of information, guidance, support and friendship. The same can be said about my other committee members, Merlynd Nestell, Andrew Hunt, John Wickham and Majie Fan who have selflessly given of their time and guidance during my studies and research.

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Most importantly I want to thank my wife and daughters for allowing me to pursue my interest and understanding all the hours I spent either studying or away conducting field work, either my own or helping a fellow grad student. My wife has been very supportive and understanding throughout these past 5 years; she especially understood when I had to perform my field work during December to January 2012, missing not only Christmas and New Year's, but also our wedding anniversary and my youngest daughter's birthday. Thank you for your love and support; I owe this all to you.

August 19, 2016

Abstract

A MODERN RESERVOIR ANALOG FOR POORLY DRAINED “HIGH ACCOMMODATION” FLUVIAL SYSTEM: SEDIMENTARY PROCESSES, ARCHITECTURE, AND RESERVOIR CONNECTIVITY OF THE GRIJALVA SYSTEM, TABASCO STATE, MEXICO

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High-accommodation fluvial systems are subject to much modeling and substantial rock drilling and imagination, but limited modern field observation. The Grijalva River system of Tabasco State, Mexico offers the opportunity to study these systems. In this area, subsidence rates of up to 9 mm/year result in high-accommodation conditions for the river as it approaches the Gulf Coast in southern Mexico. Lakes and small propagating channels, similar to what are commonly called “tie” channels, dominate the flood basin between major channel belts. Understanding of the co-evolution of lakes and tie channels is key to understanding the overall high-accommodation system.

Tie channels connect the floodplain lakes to the main river channel, and allow for the exchange of water and sediment into and out of the lakes. Tie channels also are instrumental in the filling/death of the lake. Tie channels propagate across lakes as deltas. The process of tie-channel propagation is still poorly understood. Nonetheless, once the tie channel reaches the other side of the lake, the lake is now bisected by the narrow alluvial ridge emplaced by tie-channel propagation, and the lake is bisected with respect to water and sediment, except during the rainy season. Asymmetry in sediment input now leads to the fill of compartments within the lake formed by tie-channel bisection, rather than overall aggradation of the lake as a whole.

This phenomenon is best exemplified in the area of study by the Pantanos de Centla. At this location, a tie channel propagated across the floodbasin lake in an orientation parallel to the main Grijalva River approximately 20 years ago. After the lake was compartmentalized by the tie channel, splay sediments from the adjacent Grijalva River could only reach the new northern compartment. This northern compartment is now filled and has evolved into a vegetated glade, while the southern compartment remains as a lake. Filling of the northern compartment now permits bypass of sediment from the Grijalva River into the southern compartment which has begun filling with splay delta sediment. Close examination of high-accommodation flood basin systems in the Grijalva River reveal that deposition in flood basins is characterized by local rapid aggradation

of sites and compartments rather than a uniform aggradation across the floodbasin. The co-evolution of tie channels and flood basin lakes are key elements of this aggradational process.

Table of Contents

Acknowledgements	iii
Abstract	vi
List of Illustrations	xii
List of Tables	xviii
Chapter 1 Overview of previous fluvial delta research	19
Accommodation Space	19
Well-Drained vs, Poorly Drained Flood Basins	22
.Tie Channel and Floodplain Lakes	27
Chapter 2	31
A modern reservoir analog for poorly drained “high-accommodation” fluvial systems: Sedimentary processes, architecture, and reservoir connectivity of the Grijalva River System, Tabasco State, Mexico	31
A modern reservoir analog for poorly drained “high-accommodation” fluvial systems: Sedimentary processes, architecture, and reservoir connectivity of the Grijalva River System, Tabasco State, Mexico	31
1.0 Introduction	31
2.0 The Grijalva/Usumacinta System	39
2.1 Regional Geology	44
2.2 Morphologic Features	47
Avulsion History	47
3.0 Methods	49
3.1 Air Photos	50
3.2 Site Selection	50
3.3 Radiocarbon Sampling	51

4.0 Results.....	54
4.1 General Physiography	54
Distributary vs. anastomosing system	55
4.2 Lithofacies	57
4.3 Floodplain Geomorphic Forms and Lithofacies.....	58
Levee	58
Crevasse Splay	59
Floodplain Sand Sheet.....	59
Mudflat	60
Floodplain Lake.....	60
Channel fills.....	61
Point bars	61
Swamp/glade	62
Tie-channel delta.....	62
4.4 Tie Channels and Tie-Channel deltas	67
4.5 Lithofacies Associations in Cross Sections of the Shallow	
Subsurface	67
4.6 Lake and Lake-fill Evolution	72
4.7 Accommodation and Aggradation rates	74
5.0 Processes and Rates for High-Accommodation Landform	
Evolution and Aggradation	80
5.1 The “Gun-Barrel” Hypothesis for Channel Propagation	80
5.1.2 Lakes and Lake-fill evolution	86
5.3 Accommodation rates.....	91
6.0 Reservoir implications	95

7.0 Conclusions	96
Chapter 3.....	99
3.0 Summary of Observations	99
3.1 Some summary observations of the tie channels.	99
3.2 Some summary observations of the lakes.	100
3.3 Future Work.....	100
3.3.1 Sediment Transport Rates	101
3.3.2 Bathymetry Survey.....	101
3.3.4 Modeling.....	101
Appendix A Addition Figures	103
Appendix B Boring Logs	110
References.....	112

List of Illustrations

Figure 1-1 Model for cyclic process at the belt scale amalgamation and sedimentation rate. (Bridge and Leeder, 1979).....	21
Figure 1-2 Model for floodplain paleosol variation in response to basin subsidence and sedimentation rate. (Kraus, 2002).....	22
Figure 1-3 Geometric model for prograding distributive fluvial systems. (Weissmann et al., 2013)	23
Figure 1-4 Examples of typical well-drained soil profiles. (Holbrook and Hull 2012)	24
Figure 1-5 A comparison of the architecture of interbelt areas of a well-drained floodbasin versus a poorly drained basin. (Holbrook and Hull, 2012)....	26
Figure 1-6 Models of channel belt dispersal in backswamp/floodplain strata. (Bridge and Tye, 2000)	27
Figure 1-7 Lake fill study area. The sediment filled western compartment and the current lake (eastern) compartment are visible. The old tie-channel dissecting the lake is identified as is a young tie-channel still propagating across the lake. The Grijalva River is located west of the lake and one of the splays coming from the river is visible.	29
Figure 2-1 Model of floodplain paleosol variations in response to basin subsidence and sedimentation rates. (Kraus, 2002)	34

Figure 2-2 Geometric model for prograding distributive fluvial systems. (Weissmann et al., 2013)	35
Figure 2-3 A comparison of the architecture of interbelt areas of a well- drained floodbasin versus a poorly drained flood basin. (Holbrook and Hull, 2012)	37
Figure 2-4 Models of channel belt dispersal in backswamp/floodplain strata. (Bridge and Tye, 2000)	38
Figure 2-5 Overview of the Grijalva wave-dominated delta and the high- accommodation fluvial system abruptly up depositional dip. Boring locations in the study area are outlined in the red rectangle.....	40
Figure 2-6 Propagating channel derived from splay channel off main river traversing floodplain lake and smaller propagating channels with lakes in the Grijalva delta, Tabasco State, Mexico. Propagating channels link larger channel belts and floodplain lakes.....	42
Figure 2-7 Stratigraphic column of the wet-basin high accommodation system of the Fort Union Formation. (Roberts and Stanton, 1994).....	43
Figure 2-8 Major Geological features of the Southern Gulf Coast study area in red box. Figure after von Nagy (1997).....	45
Figure 2-9 Late Holocene coastal features of the Tabasco Coastal Plain based on the analysis of aerial and Landsat imagery and West et al. (1969: Figure 21), study area in red box. Figure after von Nagy (1997).....	46

Figure 2-10 Map of the major distributary and paleo distributary systems of the Grijalva and Usumacinta deltas (study area in red box). A. Barí; B. Chicozapote; C. Guapacal; D. Blasillo; E. Peluzal; F. Pajonal; G. Encrucijada; H. Zapotal; I. Zanapa; J. Piedra; K. T Tular; L. Seco; M. Cuxcuxapa; N. Naranjo; O. Nacajuca; P. Samaría; Q. modern Usumacinta main distributary; R. San Pedro y San Pablo; S, T, U, V, W. Pom Systems; X. Palizada. Map data after Jiménez Salas (1990: Figure 1a), Instituto Nacional de Estadística (1980: Cartas geológicas, E15-4, E15-7, E15-5, E15-8, E15-6), Comisión del Grijalva (1968: Cartas topográficas, 16-19W, 23-26W, 29-32W, C), Subsecretaría de Infraestructura Hidráulica (1979: sheets 1, 2 and 3), Vera Herrera et al. (1988: Figure 3). Figure after von Nagy (1997)..... 47

Figure 2-11 Location of Avulsion on the Usumacinta River in the study area..... 49

Figure 2-12 Lake filled study area. The sediment filled western compartment and the current lake (eastern) compartment are visible. The old tie-channel dissecting the lake is identified as is a young tie-channel still propagating across the lake. The Grijalva River is located west of the lake and one of the splays coming from the river is labeled. 51

Figure 2-13 USDA Soil Texture Classification Triangle. Soil textural rock equivalents: Clay=Clayshale or claystone. Silty clay = Mudshale or mudstone, Silt loam = coarse mudstone to siltstone, loam=muddy sandstone to coarse

siltstone, sandy loam and loamy sand = muddy to poorly sorted sandstone, sand=mature sandstone).....	52
Figure 2-14 Rock equivalents to Soil Texture Classification Triangle.....	53
Figure 2-15 The location of the nine (9) peat samples submitting for radiocarbon dating.	53
Figure 2-16 Location of the four dams built up dip of the study area on the Grijalva River. (Peters, 2010)	56
Figure 2-17 Grijalva River cross-section 1.....	63
Figure 2-18 Grijalva River cross-section 2.....	63
Figure 2-19 Grijalva River cross-section 3.....	64
Figure 2-20 Grijalva River cross-section 4.....	64
Figure 2-21 Usumacinta River cross-section 1.....	65
Figure 2-22 Usumacinta River cross-section 2.....	65
Figure 2-23 Usumacinta River cross-section 3.....	66
Figure 2-24 Usumacinta River cross-section 4.....	66
Figure 2-25 Tie channel cross-section 1.	68
Figure 2-26 Tie channel cross-section 2.	69
Figure 2-27 Tie channel cross-section 3.	69
Figure 2-28 a) Tie-channel longitudinal profile down the levee on the Usumacinta River. b) Usumacinta tie channel longitudinal profile down the center of the tie channel.	70

Figure 2-29 Lake cross-section E-W, transecting an old tie channel, splays of the adjacent Grijalva system, and the delta front of the tie channel. The old tie-channel is matured, and filled and visible on the left side of the cross-section. The right side of this tie channel fill has been eroded away by wave actions from the lake.....	71
Figure 2-30 Lake cross-section N-S; growth of the old delta can be observed, as can the old channels.	71
Figure 2-31 a -d) The evolution of a Lago El Campo lake stage 1 through stage 4.	74
Figure 2-32 Accommodation vs. Time based on nine (9) peat samples submitted for radiocarbon dating.	76
Figure 2-33 Accommodation space based on surface of peat in the floodplain lake area centered on Lago El Campo.	78
Figure 2-34 Accommodation space fill based on sediment thickness above peat in the floodplain lake area centered on Lago El Campo.	79
Figure 2-35 Progradation: the generation of distributary channels by progradation (seaward aggradation) has the greatest potential for producing widespread alluvial deposits very significant in ancient alluvial sequences. (Slingerland and Smith, 2004)	88

Figure 2-36 Channel cross-section and a longitudinal profile in the Espina Lagoon west of the Grijalva River. Sand sheets are visible in the longitudinal profile.....	91
Figure 2-37 Conceptual model of tie channel evolution in a closed oxbow lake. a) Formation	94
Figure 3-1 Working in the glade of the propagating channel in the southern portion of Lago El Campo.....	99

List of Tables

Table 2-1 Lithofacies were grouped into five (5) categories defined by texture and organic content. These lithofacies represent lumping of categories from the USDA soil texture triangle (Figures 2-13 and 2-14) with apportion added for organic content.	57
Table 2-2 Subsidence/Accommodation Rates from Radiocarbon dates in Area 2.....	75
Table 2-3 Sediment Accumulation Rates in Floodplains Lake that had peat in the boring. All measurements are in meters.	77
Table 3-1 Channel Dimensions and Spacing	100

Chapter 1

Overview of previous fluvial delta research

Accommodation Space

High accommodation and low accommodation systems tracts are a mainstay of the sequence-stratigraphic paradigm where applied to fluvial strata (Catuneanu et al., 2009). Amalgamated channel belts record low-accommodation deposits, whereas non-connected channel-belt deposits with a high proportion of preserved flood basin strata are generally mapped as high accommodation fluvial strata deposits. Both types are common components of the geologic record (Catuneanu et al., 2006). High-accommodation strata record the condition where aggradation between channel avulsion return periods exceeds a channel-belt thickness, and as a result, channel belts do not vertically amalgamate (Allen, 1978; Bridge and Leeder, 1979; Straub et al., 2009). Initially, the transition from low-accommodation to high-accommodation was assumed to reflect a shift from a slow to more rapid base-level rise (e.g., Bridge and Leeder, 1979; Shanley and McCabe, 1994; Currie, 1997). This idea was modified to presume that a shift to high-accommodation conditions is generated by base-level rise at a rate much higher than sediment input, with the recognition that avulsion rates are not constant, but are directly proportional to the rate at which sediment is introduced (Bryant et al. 1995; Mohrig et al, 2000; and Straub et al., 2009). Recent works have recognized that additional complex variables control high-accommodation settings (Hajek et al., 2010; Strong et al., 2005; Hartley et al., 2010; and Weissman et al., 2013) and still others have questioned if the rate at which high-accommodation space is created is indeed the driving control on the generation of a “high-accommodation” systems tract (Miall, 2014; Gibling et al., 2011; Columbara et al., 2015). Columbara et al. (2015) in fact shows quantitatively that calculated accommodation rates do not correlate well to high vs. low-accommodation deposits in numerous rock record examples.

The stratigraphic record does record high vs. low-accommodation deposits (Catuneanu, 2006) and remain a valid and valuable mapping convention. Many of the early assumptions regarding the origin of these deposits are increasingly recognized as over simplifications and much remains to be learned about these deposits if accurately meaningful interpretations are to be applied. Understanding of these deposits derives

mostly from numerical models (Colombera et al., 2015) and studies of recent (e.g., Berendson and Stouthammer 2000, 2001) and ancient accumulations (Bridge and Leeder, 1979; Posamentier and Vail, 1988; Muto and Steel, 2000; and Muto and Swenson, 2005). Studies of modern and active high-accommodation processes are much more rare (e.g., Hartley et al., 2010; and Weissman et al., 2013), particularly for the wetter end of the high-accommodation spectrum (e.g., Detrick et al., 1999). Better constraints on rates and processes for high-accommodation, and better understanding of their interpretive meaning in the rock record, hinges upon gaining a much better understanding of their construction in modern field settings (Hull and Holbrook, 2016).

This study examines a modern high-accommodation setting in an effort to better constrain the processes and dynamics which govern high-accommodation deposition, particularly “wet” high-accommodation deposits. High-accommodation fluvial systems are subdivided into well-drained and poorly drained systems, whereby the water table is dominantly below vs. at or above the land surface, respectively (Kraus and Hasiotis, 2006). Well-drained systems have received more attention and are better understood than poorly drained systems (Kraus and Hasiotis, 2006). Poorly drained, or wet, deposits in high-accommodation settings result from a complicated mosaic of floodplain systems with internal processes that are poorly understood. This study will define common processes and lithofacies in the poorly drained Grijalva River system in Tabasco State, Mexico, in order to develop a modern analog of a wet high-accommodation system. The Grijalva system sits in a subsiding coastal plain with a large complex network of channels, glades, and floodplain lakes of various ages, and is located within a nature preserve, which helps minimize the impact of humans on surficial processes. The Grijalva system has floodplain features such as channel blowout and ribbon splays that are atypical of well-drained conditions. This research project will examine these processes, evaluate how lakes in high accommodation systems fill, quantify potential reservoir geometries and volumes, and assess the potential for reservoir connectivity. Splay deltas commonly default to linear ribbon instead of lobate forms in this setting, which appears to be a key characteristic and defining process of these wet systems. We offer a “gun barrel” hypothesis as a first round explanation of this phenomenon.

Cyclic Process at the Belt Scale

Accommodation : Sediment Supply vs. Amalgamation

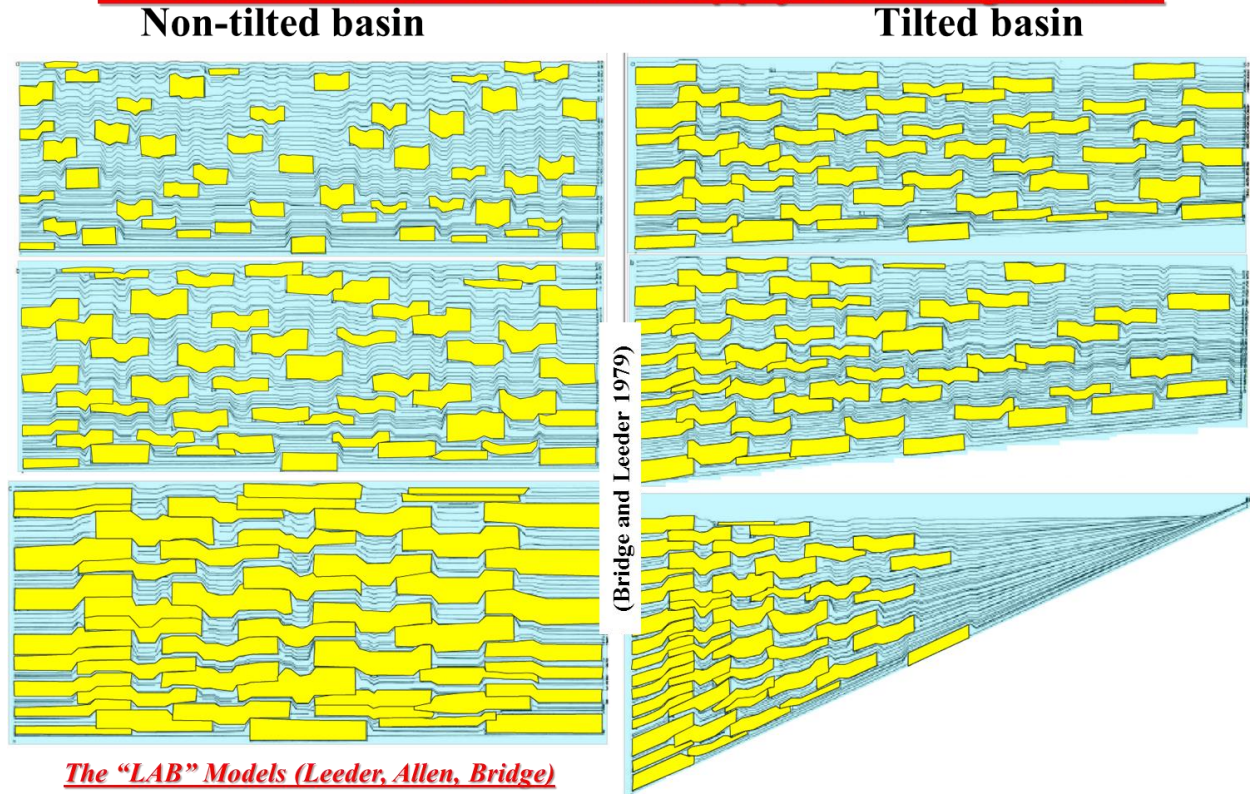


Figure 1-14 Model for cyclic process at the belt scale amalgamation and sedimentation rate. (Bridge and Leeder, 1979)

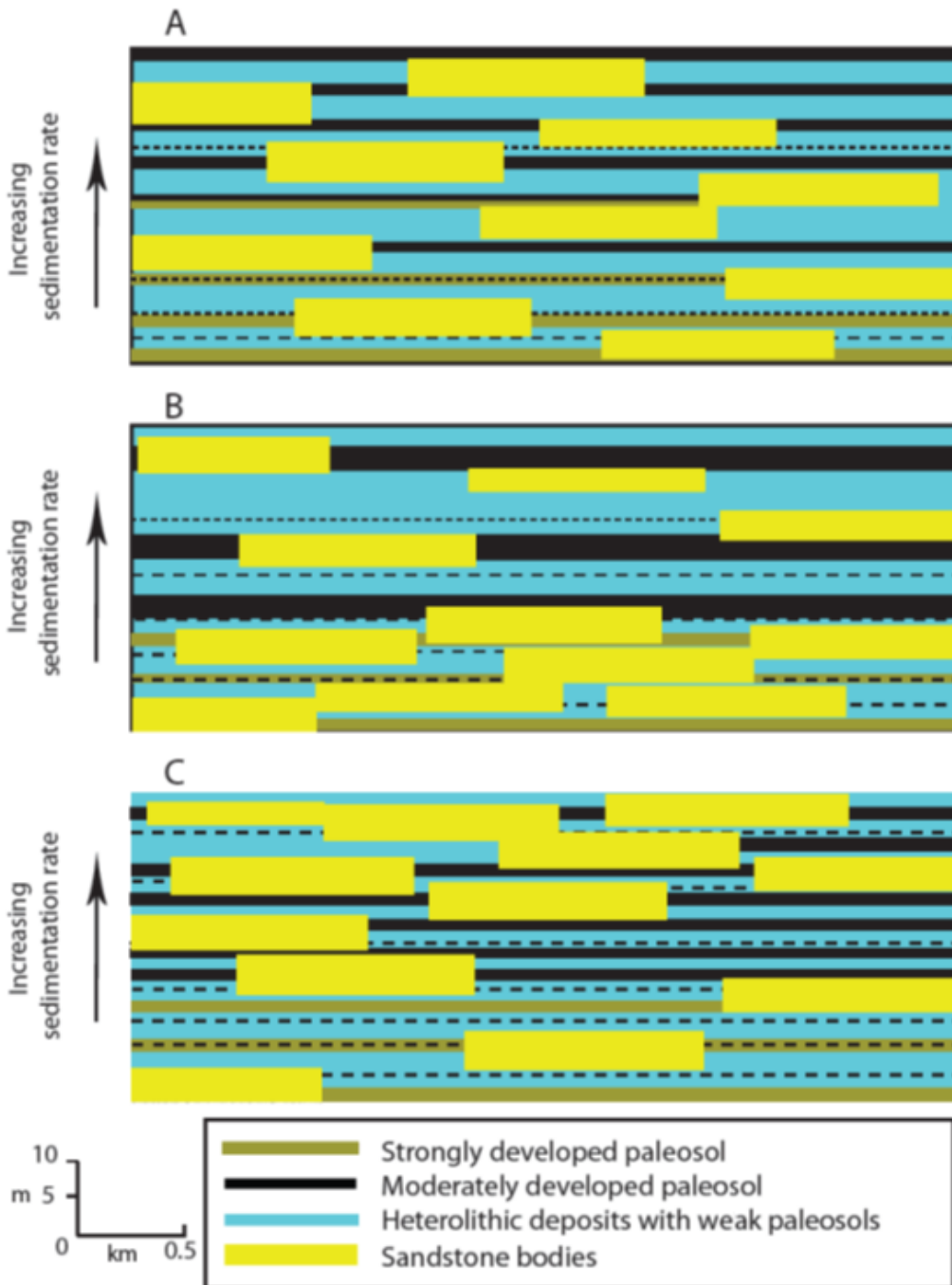


Figure 1-22 Model for floodplain paleosol variation in response to basin subsidence and sedimentation rate. (Kraus, 2002)

Well-Drained vs. Poorly Drained Flood Basins:

In well-drained flood basins, sedimentation rate exceeds water table rise (Wagoner et al., 1990; Posamentier and Allen, 1999). As a result, well-drained flood basins are mostly subaerially exposed with a dominance of low-stage-emergent mudflats and splays, which supports the development of better soil horizons in the flood basin (Wagoner et al., 1990; Posamentier and Allen, 1999; Weissmann et al., 2013). Well-drained

flood basin deposits are characterized by low organic content, rare coal development, and common bioturbation by rooting. Well-drained flood basins are common in proximal deposits of distributive fluvial systems (Hartley et al., 2010; Weissmann et al., 2013) where channel belts are progressively stacked and amalgamated and separated by soil-rich flood-basin mud (Figures 1-2 through 1-3).

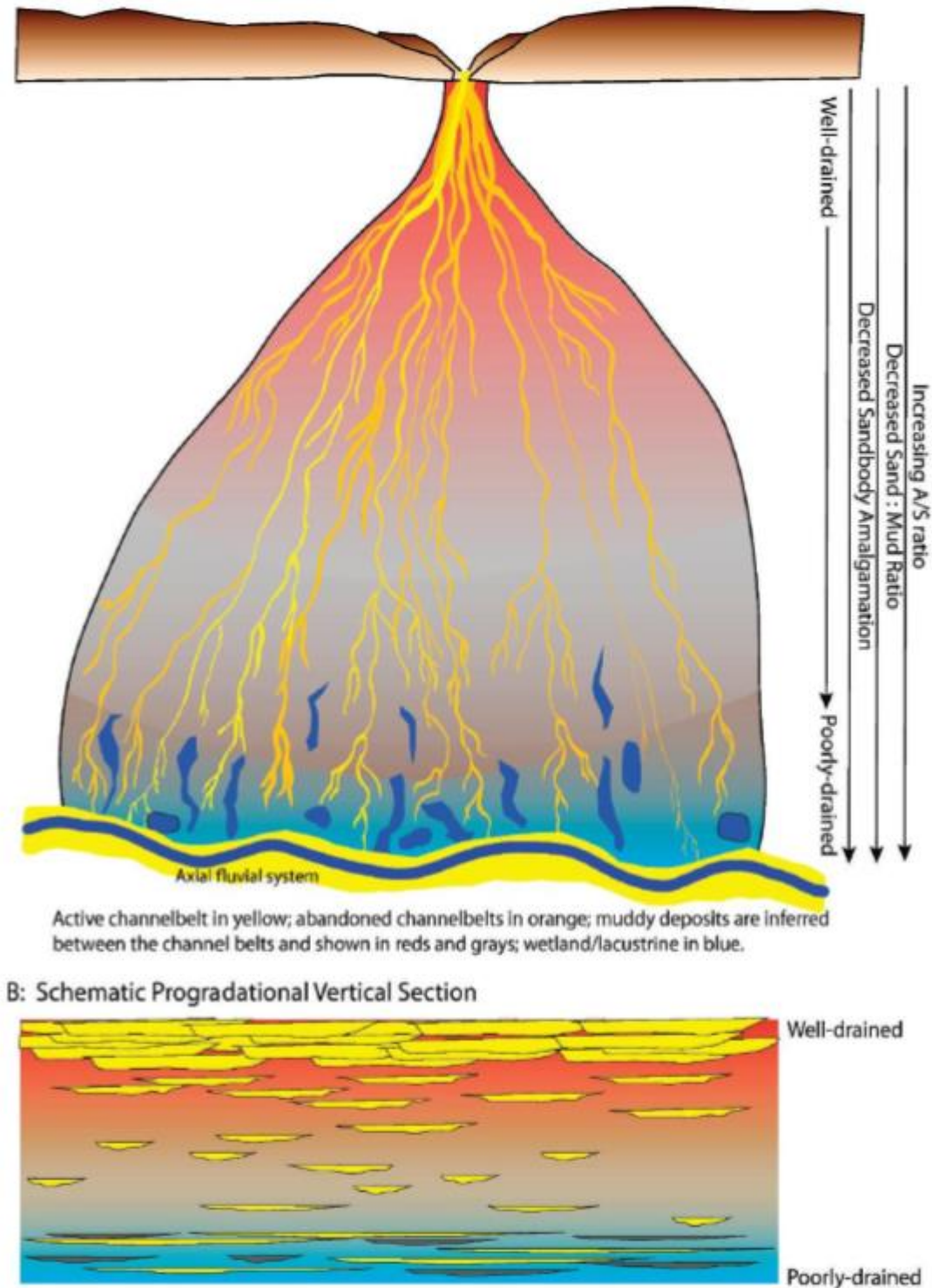


Figure 1-33 Geometric model for prograding distributive fluvial systems. (Weissmann et al., 2013)

Krause (2002) proposed a widely adopted and adapted architectural model for well-drained high-accommodation systems based on her study of the Willwood Formation in northern Wyoming. Her study showed variation in paleosol development within a floodplain reflecting local changes in sedimentation rates, largely recording a local depositional hiatus between avulsive events (Figure 1-2). The water table is below the aggrading flood basin surface in these instances, promoting a surficial zone of infiltration and development of well-drained soils. Channel belts develop from rivers that migrate within the confines of elevated flood basin deposits until local bedload deposition in the channel belt forces super elevation sufficient to trigger a protracted levee breach, leading eventually to avulsion of the channel to a new location (Smith, 1989; Bryant et al., 1995; Hellar and Paola, 1996; Kraus, 2002; Morhig et al., 2000; Jones and Hajek, 2004; Slingerland et al., 2004; and Jones and Schumm, 2009). Similar models are echoed by numerous subsequent works (e.g., Weissmann et al., 2013; Nay et al., 2015).

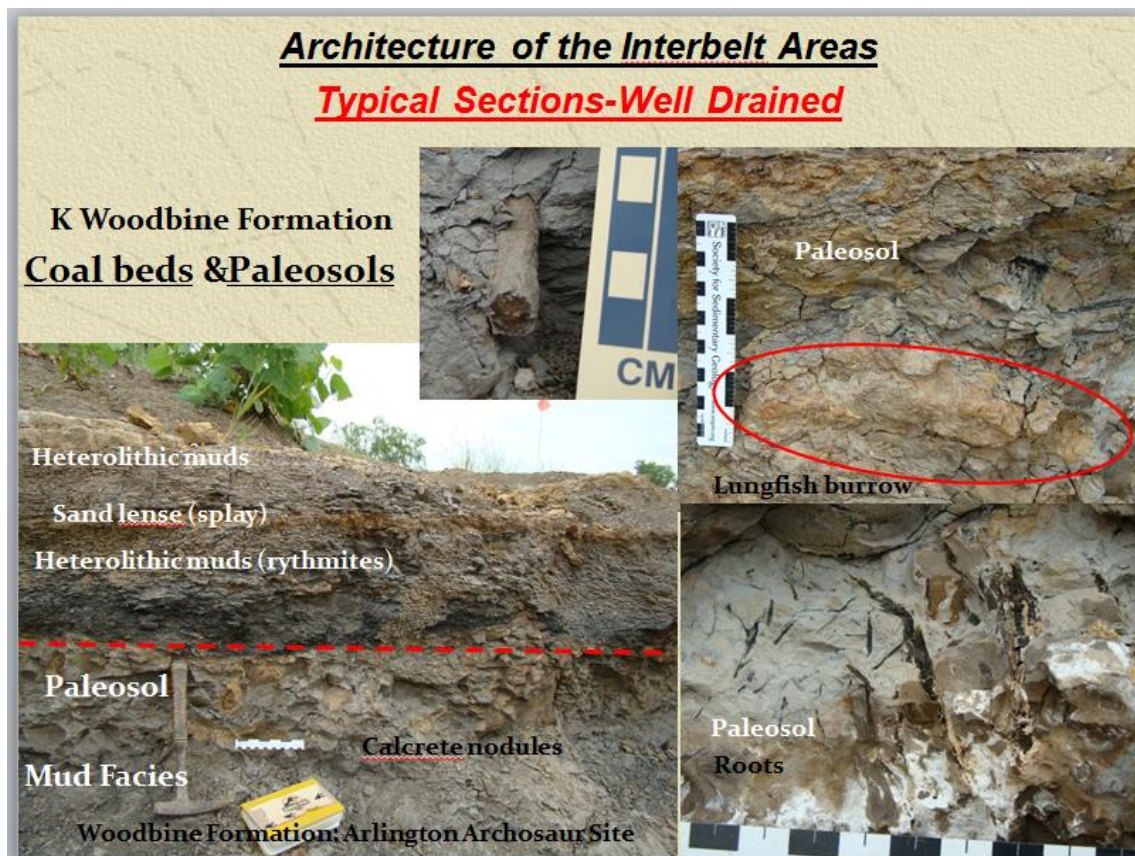


Figure 1-44 Examples of typical well-drained soil profiles. (Holbrook and Hull 2012)

Water table rise is equal to or higher than sedimentation rate in poorly-drained flood basins, and the flood basin land surface is either at or below the water table; forming abundant wet lands, swamps, and lakes in addition to the local low-stage emergent mudflats and splays typical of well-drained systems (Wagoner et al., 1990; Posamentier and Allen, 1999). Poorly-drained flood basin deposits are prone to peat-rich sediment in addition to mud. Wet high-accommodation systems are relatively common and are documented in the Joggins Formation within the Cumberland Basin, Nova Scotia, Canada (Davis et al., 2005; and Davis and Gibling 2003), the Willwood Formation in Wyoming (Abels et al., 2013; and Davis-Vollum and Wing, 1998), the Raton Formation near Trinidad, Colorado (Posamentier and Allen, 1993; and Hofmann et al., 2011), Upper part of the Breathitt Group and Conemaugh Formation, eastern Kentucky (Fischbein et al., 2009), as well as the Mungaroo Formation on the northwestern shelf of Australia, (Stoner and Holbrook, 2008). Poorly-drained flood basins are common in the distal zone of distributive fluvial systems geometric model where channel belts are isolated between finer flood basin sediments (Weissmann et al., 2013) (Figure 1-3).

Channels and channel belts range widely in geometry and size in poorly drained high-accommodation flood basins when compared to well-drained systems. This wide difference is largely because the high water tables and generally low slopes are conducive to channel bifurcation (Smith, 1986; Holbrook and Schumm, 1999; Schumm et al., 2000; Walling, 2008; Weissman et al., 2013), which promotes a wide dispersion of channel sizes. A distinctive channel common to poorly-drained high accommodation settings is the "tie channel". "Tie channels" were first proposed by Blake and Ollier (1971), and represent smaller and linear bidirectional-flow channels that propagate without bifurcating into a floodbasin from larger channels. Tie channels also tend to connect channels to two or more water bodies in high-accommodation flood basins systems as Rowland et al. (2005) documented in Fly River, New Guinea.

Architecture of the Interbelt Areas

Well-Drained Flood Basins



Architecture of the Interbelt Areas

Poorly Drained Flood Basins



Figure 1-55 A comparison of the architecture of interbelt areas of a well-drained floodbasin versus a poorly drained basin.

(Holbrook and Hull, 2012)

High-accommodation fluvial deposits are classically modeled as somewhat rectangular sandy channel belts disconnected and dispersed at low volume within muddy backswamp strata (e.g., Allen, 1978; Wright and Marriott, 1993; Shanley and McCabe, 1994, and others) (Figure 1-6). The reservoir sands in these sections are typically considered to be small, dispersed, and isolated within impermeable mudstone; therefore, these strata are usually assigned a low reservoir potential. Recent observation in modern systems, and in recent literature, suggest that this model is too simplistic for poorly-drained systems, particularly with regard to the assumed lack of sandy components within the backswamp deposits. Newer alternative models may be more realistic to high-accommodation settings that incorporate better potential for production from these generally low net-to-gross strata.

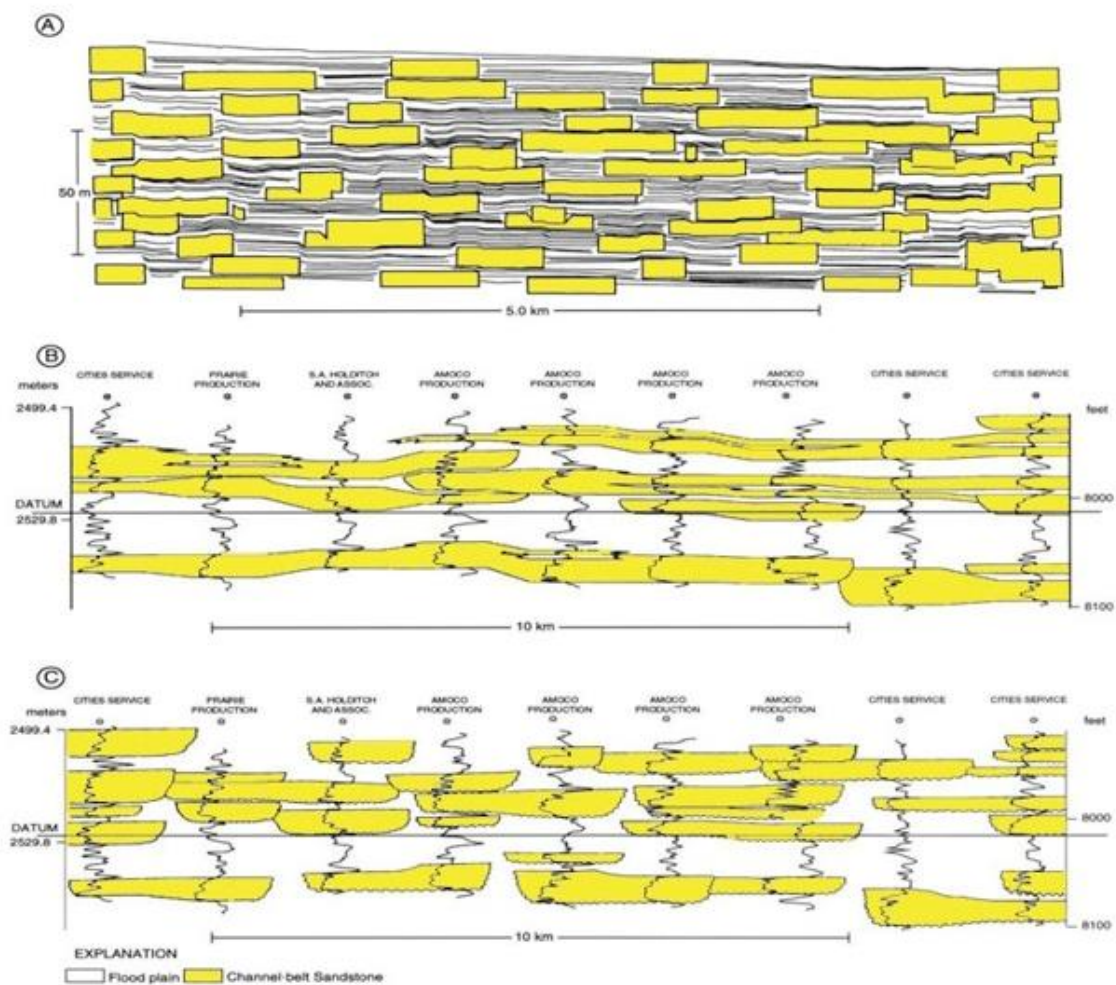
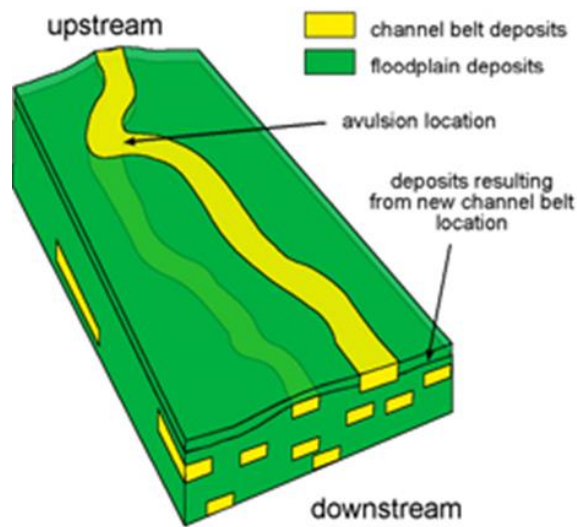


Figure 1-66 Models of channel belt dispersal in backswamp/floodplain strata. (Bridge and Tye, 2000)

.Tie Channel and Floodplain Lakes

The results of the present research assert that high-accommodation systems, like the Mungaroo, that are characterized by floodplain lakes, may have a built-in mechanism which fosters connectivity between channel belts through the backswamp deposits, and thus offers previously unrecognized production potential for high-accommodation strata. This mechanism is reflected in the tendency of splay deltas sourcing from one channel to propagate linearly until they encounter another channel. Splay deltas are traditionally modeled with lobate geometry within ancient rocks (Fielding, 1984; Guion, 1984; Glover and O’Beirne, 1994) based on analogy with marine delta lobes (e.g., Saucier, 1994) and some well-studied lobate deltas within freshwater lakes (e.g., Smith et al., 1989). More commonly, splays advancing into standing water within floodplain lakes form linear channels that propagate across the lake, forming a linear ribbon of splay delta deposits dissected by a central channel (Stoner and Holbrook, 2008). These “propagating channels” or “tie channels” appear to continue to propagate until they intersect another channel whereby they can rejoin the active river flow (Figure 1-7). This tendency for splay deltas to manifest as ribbon-form propagating channels rather than lobes has been suggested by a few authors working in the rock record (Jorgensen and Fielding, 1996; Avenell and Lang, 1998).

The tendency of splay deltas to form ribbons rather than lobes has important implications for production. First, splay deltas commonly encountered within cores of lake-prone high-accommodation sections should probably be modeled as ribbon rather than lobe geometry. Second, if these propagating channel systems generate sufficient sand, the resulting ribbons would tend to link more reservoir-quality channel belts. Rather than channel belts forming discrete reservoirs, they could be likened into veins joined by capillary propagating channels. This linkage between reservoirs would mean that production from one quality reservoir could potentially drain adjacent reservoirs through these capillary links, and result in recoverable gas volumes sufficient to warrant completion in high-accommodation intervals previously dismissed. In fluvial petroleum systems that are self-sourced, these capillaries could also prove integral to the charging history for larger sand bodies out of otherwise impermeable but organic-rich backswamp deposits.

For the benefits of this capillary theory to be practically applied there must be sufficient continuous sand preserved within these propagating channel ribbons to promote gas transmission. At present, these channel/splay ribbons are not well studied in modern depositional systems and this question cannot be easily answered. This project will examine how lakes in high accommodation systems fill and how modern propagating channel ribbon form to see if the lithologic and geometric characteristics of these channels are sufficient to connect larger belts. In addition, this study will examine and constrain the geometry and volume of the channel belts they connect. For this capillary theory to apply, the high-accommodation system must also be appropriate for generating propagating channels. A fundamental question remains as to which factors cause splay deltas to default to ribbon instead of lobate forms (e.g., hyperpycnal flow, fluctuation of water levels, vegetation, etc.). We offer a “gun barrel” hypothesis as a first round explanation of this phenomenon (Hull and Holbrook, 2012).

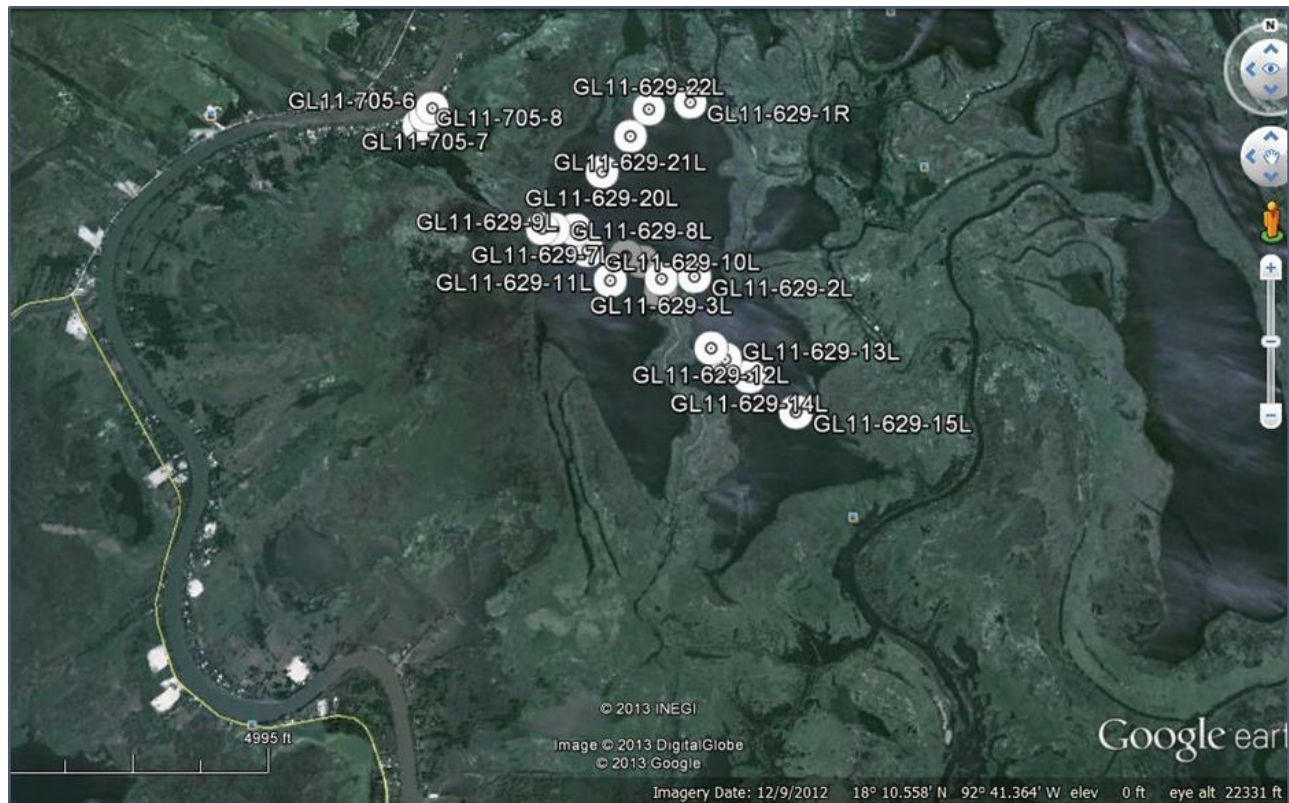


Figure 1-7 Lake fill study area. The sediment filled western compartment and the current lake (eastern) compartment are visible. The old tie-channel dissecting the lake is identified as is a young tie-channel still propagating across the lake. The Grijalva River is located west of the lake and one of the splays coming from the river is visible.

Chapter 2

A modern reservoir analog for poorly drained “high-accommodation” fluvial systems: Sedimentary processes, architecture, and reservoir connectivity of the Grijalva River System, Tabasco State, Mexico

Chapter Two of this dissertation has been prepared (title and authorship shown below) to submit September of 2016 as one manuscript to the American Association of Petroleum Geology (AAPG) to be published in the AAPG Bulletin. The objective of this paper is to provide a modern analogy for high-accommodation systems that form in a wet basin. An example of such a basin can be seen in the Triassic Mungaroo Formation present on the northwest shelf of Australia.

A modern reservoir analog for poorly drained “high-accommodation” fluvial systems: Sedimentary processes, architecture, and reservoir connectivity of the Grijalva River System, Tabasco State, Mexico

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1.0 Introduction

High accommodation and low accommodation systems tracts are a mainstay of the sequence-stratigraphic paradigm where applied to fluvial strata (Catuneanu et al., 2009). Low-accommodation deposits record amalgamated channel belts, whereas high accommodation fluvial strata are mapped as deposits with generally non-connected channel-belt deposits with a high proportion of preserved flood basin strata. Both types of systems are common sedimentary components of the geologic record (Catuneanu et al., 2006). High-accommodation strata record the condition where aggradation between channel avulsion return periods exceeds

a channel-belt thickness, and as a result, channel belts do not vertically amalgamate (Allen, 1978; Bridge and Leeder, 1979; Straub et al., 2009). Initially, the transition from low-accommodation to high-accommodation was assumed to reflect a shift from slow to more rapid base-level rise (e.g., Bridge and Leeder, 1979; Shanley and McCabe, 1994; Currie, 1997). This idea was modified to presume that the shift to high-accommodation conditions is generated by base-level rise at a rate much higher than sediment input, with the recognition that avulsion rates are not constant, but are directly proportional to the rate at which sediment is introduced (Bryant et al., 1995; Mohrig et al., 2000; and Straub et al., 2009). More recent works have addressed the many additional variables that control high-accommodation settings (Hajek et al., 2010; Strong et al., 2005; Hartley et al., 2010; and Weissman et al., 2013) and still others have questioned if a high-accommodation rate is indeed the driving control on the generation of a “high-accommodation” systems tract (Miall, 2014; Gibling et al., 2011; Columbara et al., 2015). Columbara et al. (2015) in fact show quantitatively that calculated accommodation rates do not correlate well to high vs. low-accommodation deposits in numerous rock record examples.

High-vs. low-accommodation deposits do exist in the stratigraphic record (Catuneanu, 2006) and remain a valid and valuable mapping convention. Many early assumptions regarding the origin of these deposits are increasingly appearing over simplified and much remains to be learned about these deposits to more accurately apply meaningful interpretations. Understanding of the formation of these types of deposits derives mostly from numerical models (Columbera et al., 2015), and studies of recent (e.g., Berendson and Stouthammer, 2000, 2001) and ancient accumulations (Bridge and Leeder, 1979; Posamentier and Vail, 1988; Muto and Steel, 2000; and Muto and Swenson, 2005). Studies of modern and active high-accommodation processes are much more rare (e.g., Hartley et al., 2010; and Weissman et al., 2013), particularly for the wetter end of the high-accommodation spectrum (e.g., Detrick et al., 1999). Better constraints on rates and processes for high-accommodation, and the general unraveling of their interpretive meaning in the rock record, hinges upon gaining a much better understanding of their construction in modern field settings.

This study examines a modern high-accommodation setting in an effort to better constrain the processes and dynamics which govern high-accommodation deposition, particularly for “wet” high-accommodation deposits. High-accommodation fluvial systems can be subdivided into well-drained and poorly drained systems, whereby the water table is dominantly below vs. at or above the land surface, respectively (Kraus and Hasiotis, 2006). Well-drained systems have received more attention and are better understood than poorly drained systems (Kraus and Hasiotis, 2006). Poorly drained, or wet, high-accommodation deposits result from a complicated mosaic of floodplain systems with internal processes that are not as well constrained. This study will examine and describe common processes and lithofacies in the poorly drained Grijalva River system in Tabasco State, Mexico, in order to develop a modern analog of a wet high-accommodation system. The Grijalva system sits in a subsiding coastal plain with a large complex network of channels, glades, and floodplain lakes of various ages, and is located within a nature preserve, which helps minimize the impact of humans on surficial processes. The Grijalva system has floodplain features such as channel blowout and ribbon splays that are atypical of well-drained conditions. This project will examine these processes, evaluate how lakes in high accommodation systems fill, quantify potential reservoir geometries and volumes, and assess the potential for reservoir connectivity. Splay deltas commonly default to ribbon instead of lobate forms in this setting, which appears to be a key characteristic and defining process of these wet systems. We offer a so-called “gun barrel” hypothesis as a first round explanation of this phenomenon.

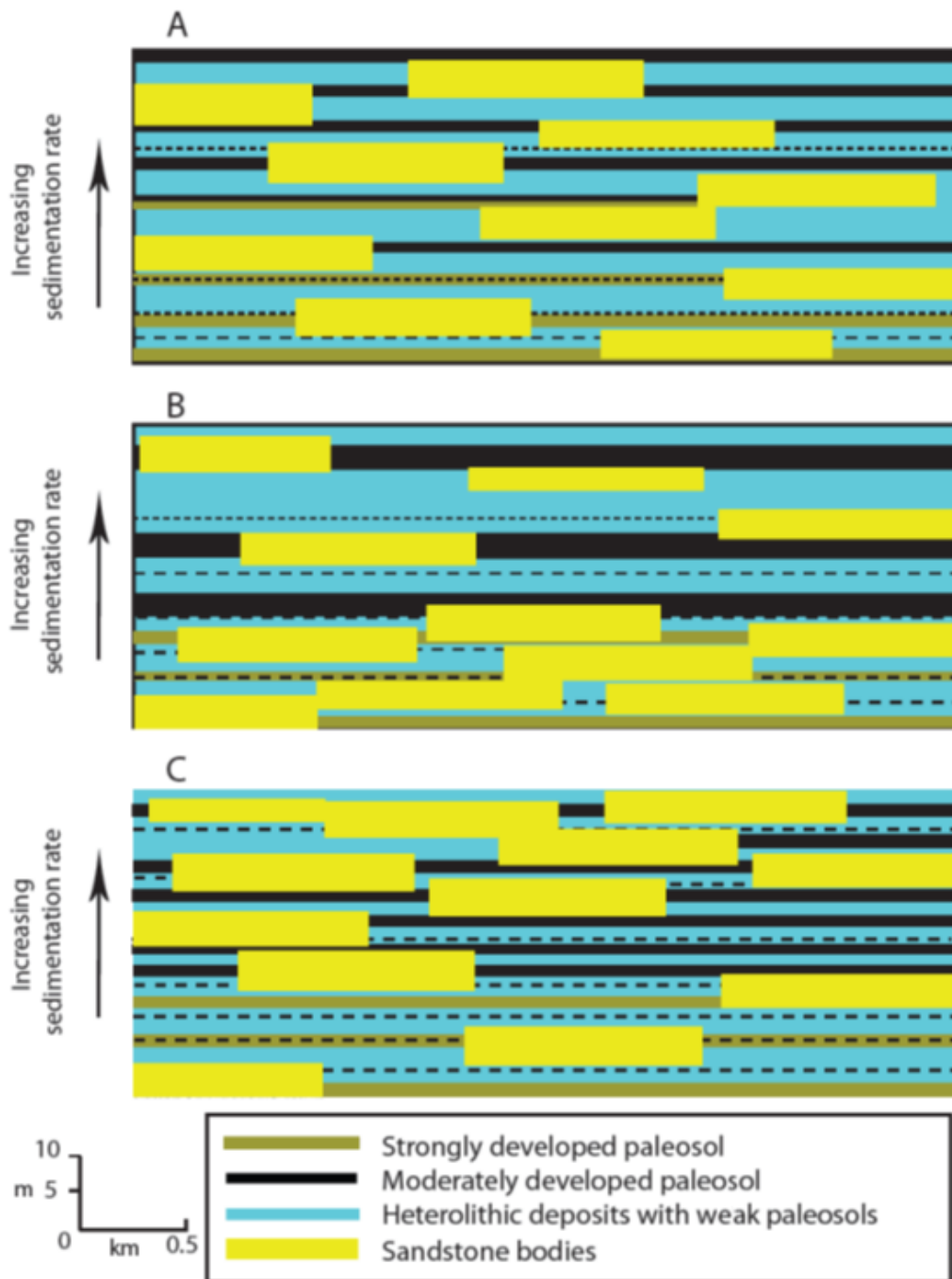


Figure 2-1 Model of floodplain paleosol variations in response to basin subsidence and sedimentation rates. (Kraus, 2002)

Well-Drained vs. Poorly Drained Flood Basins:

Sedimentation rate exceeds water table rise in well-drained flood basins (Wagoner et al., 1990; Posamentier and Allen, 1999). As a result, well-drained flood basins are mostly subaerially exposed with a dominance of low-stage-emergent mudflats and splays, which supports the development of better soil horizons in the flood basin (Wagoner et al., 1990; Posamentier and Allen, 1999; Weissmann et al., 2013). Well-drained

flood basin deposits are characterized by low organic content, rare coal development, and common bioturbation by rooting. Well-drained flood basins are common in proximal deposits of distributive fluvial systems (Hartley et al., 2010; Weissmann et al., 2013) where channel belts are progressively stacked, and amalgamated and separated by soil-rich flood-basin mud (Figure 2-2).

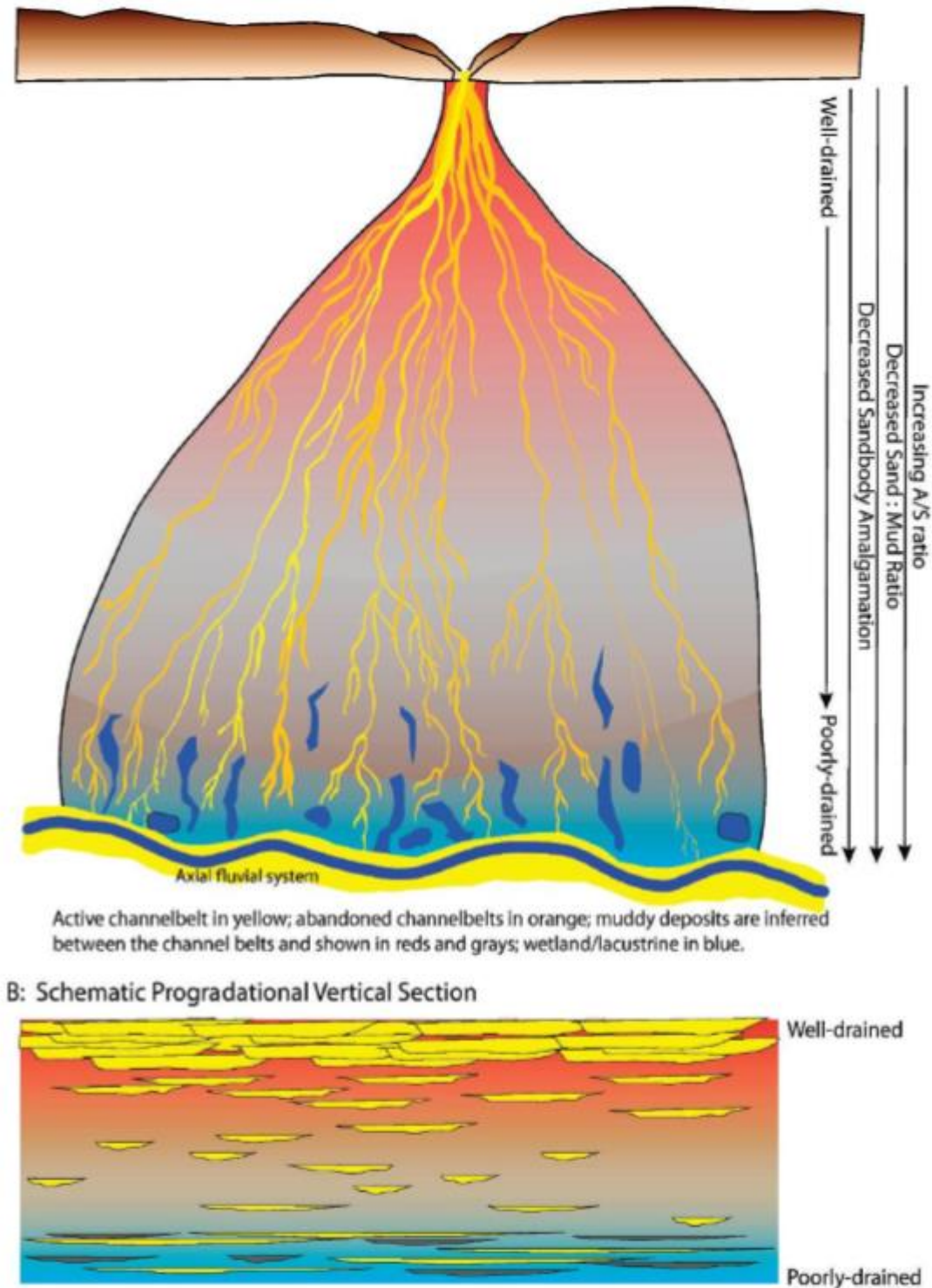


Figure 2-2 Geometric model for prograding distributive fluvial systems. (Weissmann et al., 2013)

Krause (2002) proposed a widely adopted and adapted architectural model for well-drained high-accommodation systems based on her study of the Willwood Formation in northern Wyoming. Her study showed variation in paleosol development within a floodplain reflecting local changes in sedimentation rates, largely recording a local depositional hiatus between avulsive events (Figure 2-1). The water table is below the aggrading flood basin surface in these instances, promoting a surficial zone of infiltration and development of well-drained soils. Channel belts develop from rivers that migrate within the confines of elevated flood basin deposits until local bedload deposition in the channel belt forces super elevation sufficient to trigger a protracted levee breach leading eventually to avulsion of the channel to a new location (Smith, 1989; Bryant et al., 1995; Hellar and Paola, 1996; Kraus, 2002; Morhig et al., 2000; Jones and Hajek, 2004; Slingerland et al., 2004; and Jones and Schumm 2009). Similar models are echoed by numerous subsequent works (e.g., Weissmann et al., 2013; Nay et al., 2015)

Water table rise is equal to or higher than sedimentation rate in poorly-drained flood basins, and the flood basin land surface is either at or below the water table, thus forming abundant wetlands, swamps, and lakes in addition to the local low-stage emergent mudflats and splays typical of well-drained systems (Wagoner et al., 1990; Posamentier and Allen, 1999). Poorly-drained flood basin deposits are prone to peat-rich sediment in addition to mud. Wet high-accommodation systems are relatively common and are documented in the Joggins Formation within the Cumberland Basin, Nova Scotia, Canada (Davis et al., 2005; and Davis and Gibling 2003), the Willwood Formation, in Wyoming (Abels et al., 2013; and Davis-Vollum and Wing, 1998), the Raton Formation, near Trinidad, Colorado (Posamentier and Allen, 1993; and Hofmann et al., 2011), the upper part of the Breathitt Group and the Conemaugh Formation, eastern Kentucky (Fischbein et al., 2009) as well as the Mungaroo Formation on the northwestern shelf of Australia, (Stoner and Holbrook, 2008). Poorly-drained flood basins are common in the distal zone of distributive fluvial systems (Weissmann et al., 2013) geometric model where channel belts are isolated between finer flood basin sediments (Figure 2-2).

Channels and channel belts range widely in geometry and size in poorly drained high-accommodation flood basins when compared to well-drained systems. This difference is largely because the high water tables

and generally low slopes are conducive to channel bifurcation (Smith, 1986; Holbrook and Schumm, 1999; Schumm et al., 2000; Walling, 2008; Weissman et al., 2013), which promotes wide dispersion of channel sizes. A distinctive channel common to poorly-drained high accommodation settings is the "tie channel". "Tie channels" were first proposed by Blake and Ollier (1971), and represents smaller and linear bidirectional-flow channels that propagate without bifurcating into the floodbasin from larger channels. Tie channels also tend to connect channels to two or more water bodies in high-accommodation flood basins systems as Rowland et al. (2005) documented in the Fly River, New Guinea.

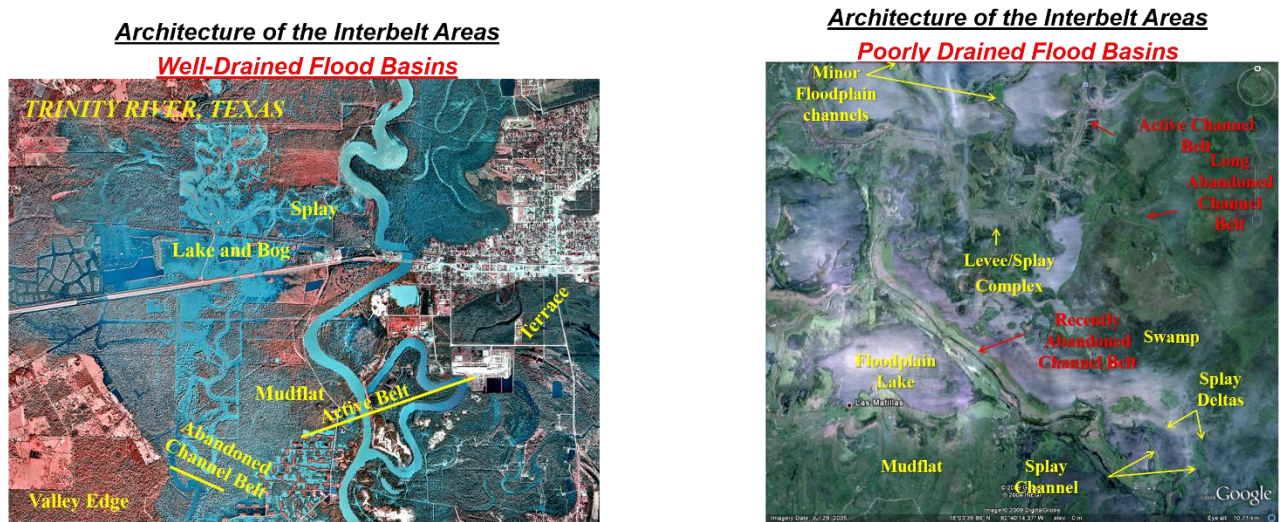


Figure 2-23 A comparison of the architecture of interbelt areas of a well-drained floodbasin versus a poorly drained flood basin. (Holbrook and Hull, 2012)

High-accommodation fluvial deposits are classically modeled as somewhat rectangular sandy channel belts disconnected and dispersed at low volume within muddy backswamp strata (e.g., Allen, 1978; Wright and Marriott, 1993; Shanley and McCabe, 1994, and others) (Figure 2-4). Because reservoir sands in these sections are considered to be small, dispersed, and isolated within impermeable mudstone, these strata are usually assigned a low reservoir potential. Recent observations, and recent literature citations, suggest that this model may be too simplistic for poorly-drained systems, particularly with regard to the assumed lack of sandy components within the backswamp deposits. Instead, alternative models may better apply to high-accommodation settings that incorporate better potential for production from these generally low net-to-gross strata.

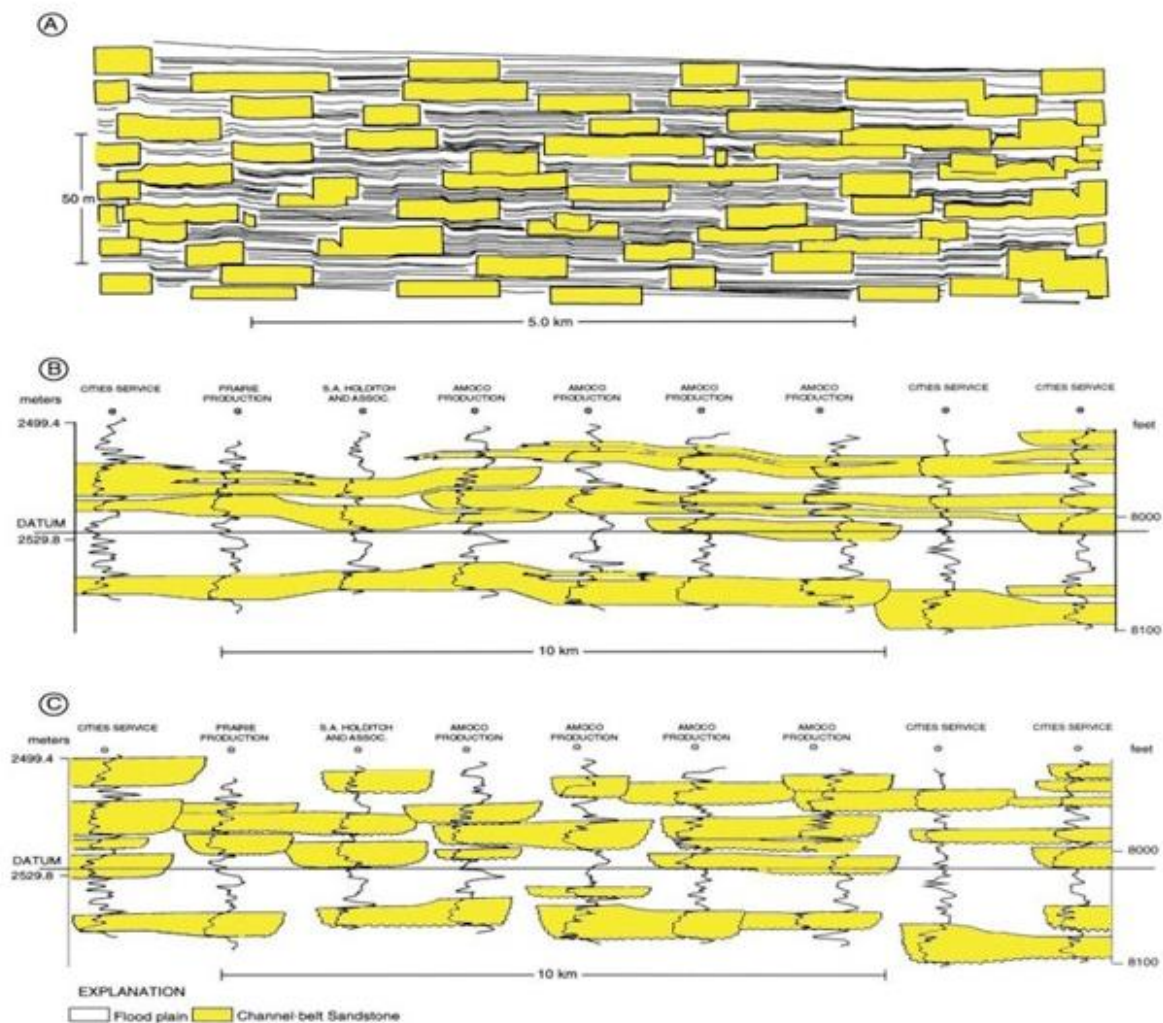
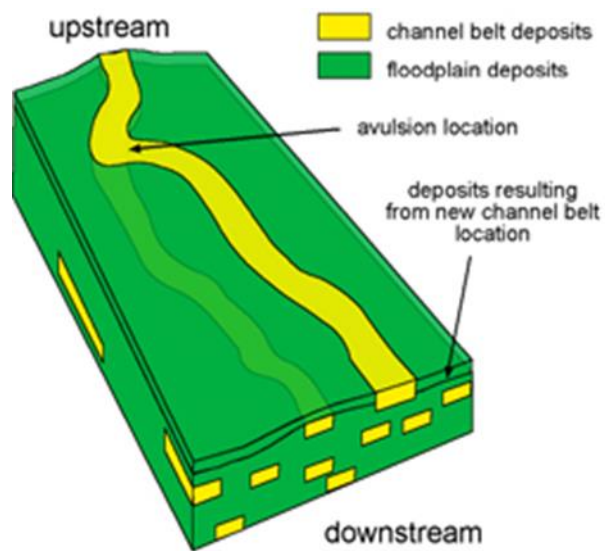


Figure 2-34 Models of channel belt dispersal in backswamp/floodplain strata. (Bridge and Tye, 2000)

2.0 The Grijalva/Usumacinta System

The Grijalva system is unusual in having a large high-accommodation alluvial plain approaching the coast above a distinct delta, with abundant floodplain lakes, well-developed ribbon splays at various stages of development, larger channel belts, and minimal human modification locally. The modern Tabasco Coastal Plain and more specifically the Grijalva Delta is composed of the coalesced deltas of two of Mexico's largest rivers, the Usumacinta and Grijalva, along with several other smaller rivers, into a complex and young landscape. The combined hydro geographic system of these rivers is the most important of North America after the Mississippi (von Nagy, 2003). Like all other coastal delta landscapes around the globe, the Grijalva Delta is the result of a complex hydrologic interplay between relative sea-level fluctuations and the geological dynamics of a river delta (Kraft and Chrzastowski, 1978, Wright, 1978). The coastal plain is a highly dynamic environment where multiple tectonic, eustatic, depositional, and erosional have formed and reworked the landscape, operating on various time scales from decades to millennia.

Most of the delta is in the Pantanos de Centla Biosphere Reserve located in the northeastern corner of the State of Tabasco. The reserve is located in the Grijalva-Usumacinta hydrological region. The major rivers in the reserve order of size are the Grijalva, with an annual discharge of 27,013 million cubic meters (953,960 cubic feet), and the Usumacinta, with 55,832 million cubic meters (1,971,700 cubic feet). No discharge data is available for the San Pedro River which joins the Grijalva and Usumacinta rivers at their confluence, called the Tres Brazos. Because of its discharge amounts, the Usumacinta - Grijalva Delta is considered one of the most important hydrological systems in Central and North America, and is the 7th most important worldwide based on its eco-hydrological system (Sánchez et al. 1988). The Usumacinta River is Mexico's largest river (INE, 2000). The Pantanos de Centla Biosphere Reserve is 302,706 hectare acres (748,003 acres) (Sánchez et al., 1988; INE, 2000) (Figure 2-5).

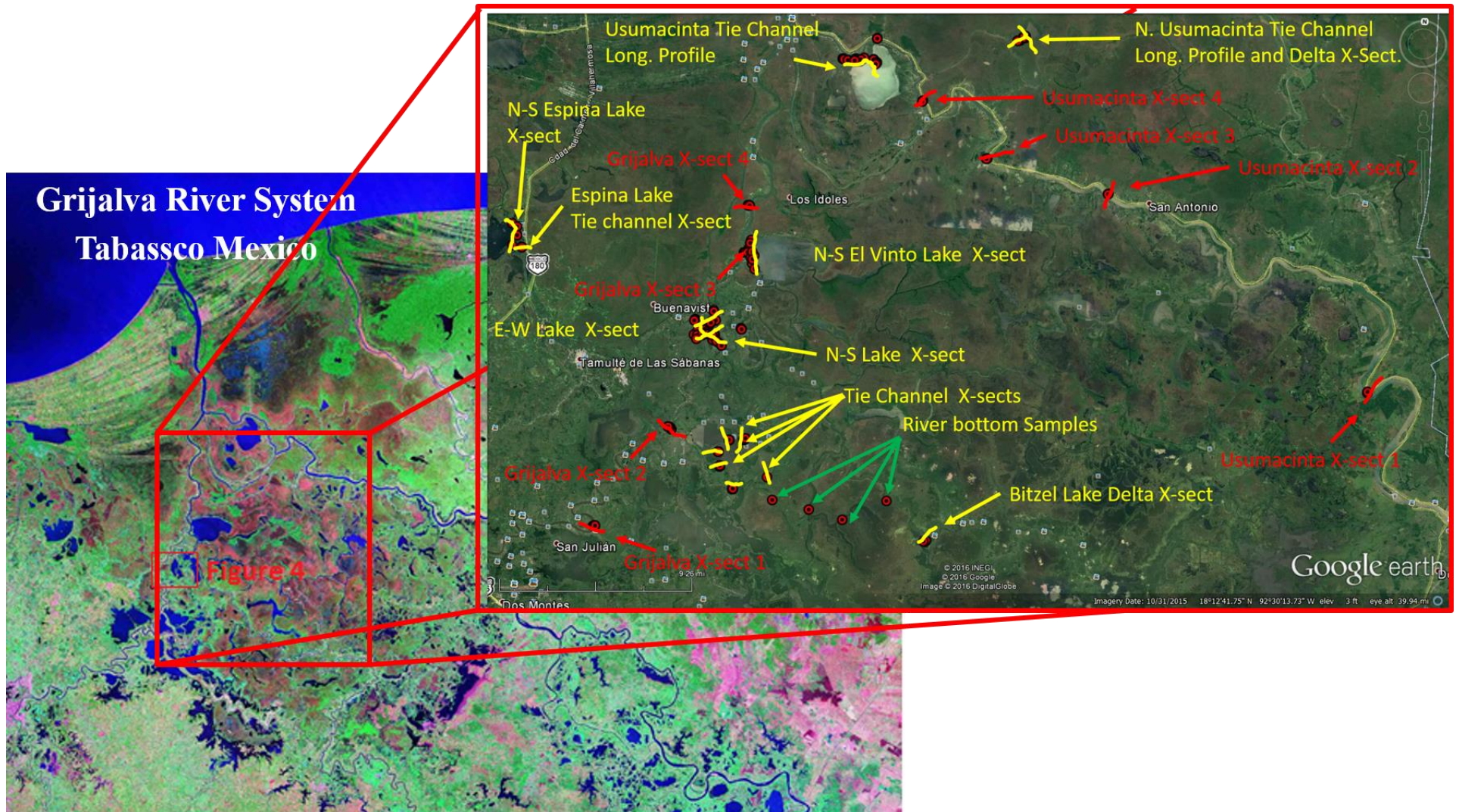


Figure 2-45 Overview of the Grijalva wave-dominated delta and the high-accommodation fluvial system abruptly up depositional dip. Boring locations in the study area are outlined in the red rectangle.

The climate in the Grijalva Delta is hot humid to sub humid, with high precipitation during the rainy season; average annual rainfall is exceptionally high, 1,591 mm (62.64 inches), with a maximum of 2,801 mm (110.28 inches) and a minimum of 916 mm (36.06 inches) There are two dry seasons, the first is during March and April, and the second during July and August. The average annual temperature is 25.9°C (78.62 °F). The topography is flat, varying from zero to seven meters above sea level (INE, 2000). Recent studies of Grijalva fluvial strata are minimal, and have focused primarily on geoarchaeological goals (Pohl, et al., 2007). The mix of splay, propagating channel, lake, swamp, channel belt, and emergent floodplain environments in the Grijalva system on air photos appears similar to the mosaic of environments interpreted in high-accommodation systems in productive formations like the Mungaroo in Australia (Stoner and Holbrook, 2008), and similar to the coal and lacustrine environments in units like the Ft. Union Formation, Wyoming and Montana (Roberts and Stanton, 1994), Straight Cliffs Formation, Utah (Hettinger, 1995), the Ziliujing and Qingshankous Formations in the Songliao Basin, China (Zou, 2012), Baxin Sag, Bohai Bay Basin, China (Zoe, 2012; Jiang et al., 2014) (Figure 2-7). The large Grijalva lake/marsh system (Figure 2-5) is bisected by numerous tie channels and is rich in organics, as noted in the heavy vegetation, regionally mapped peat layers, and organically rich lacustrine muds.

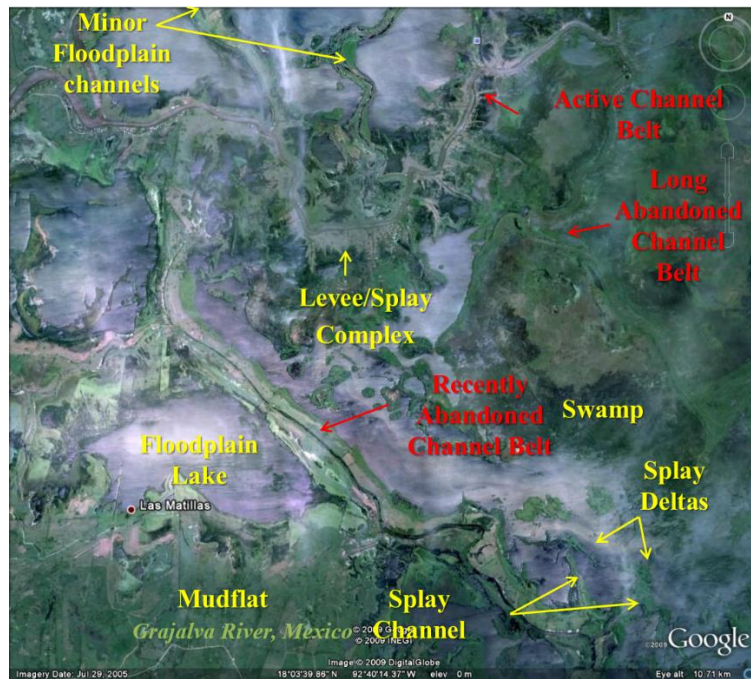
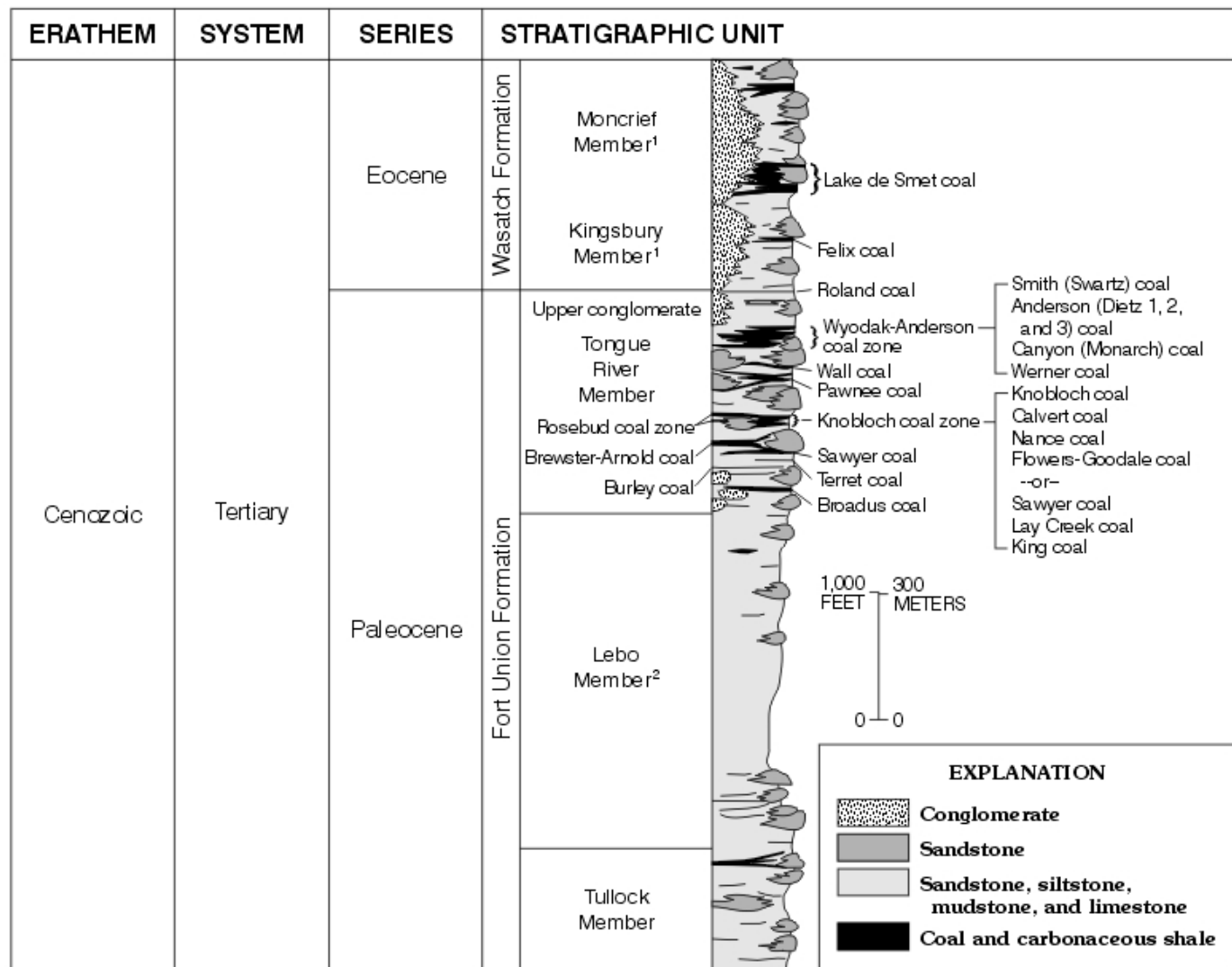


Figure 2-56 Propagating channel derived from splay channel off main river traversing floodplain lake and smaller propagating channels with lakes in the Grijalva delta, Tabasco State, Mexico. Propagating channels link larger channel belts and floodplain lakes.



¹ Wasatch Formation not subdivided into members in study area (eastern Powder River Basin).

² Defined as the Lebo Shale Member of the Fort Union Formation in Montana.

Figure 2-67 Stratigraphic column of the wet-basin high accommodation system of the Fort Union Formation. (Roberts and Stanton, 1994)

Wet coastal high accommodation systems are commonly reported in the geologic record (Posamentier and Allen, 1993; Davis-Vollum and Wing, 1998cx; and Hofmann et al., 2011), but are relatively uncommon in the modern depositional systems. The shortage of such coastal high-accommodation systems is mostly because modern eustatic sea level has remained relatively stable over the past 7 ka (Chemicuff and Whitney, 2006). Only rare deltas like the Grijalva pouring into coastal areas of highly active subsidence (Burkhart and Scotese, 1990; Ambrose, et al., 2003) have aggrading high-accommodation conditions today.

2.1 Regional Geology

Petroleum exploration drill log data indicate that Quaternary deltaic sediments of the Tabasco Coastal Plain are confined to a thin (10-50m) cap of unconsolidated sediments (Gutiérrez Estrada and Solis, 1983). The Plain is a subsection of the Isthmian Embayment and is the result of subsidence over a range of time-scales responsible for the creation of a gulfwards basin, which serves as a sink for sediments derived from upper Cenozoic igneous rocks, and Paleozoic to Cenozoic sedimentary and metamorphic rocks from the Sierra de los Chucumatenes and Sierra Madre de Chiapas ranges presently located to the south of the area (Ayala Castañares and Gutiérrez Estrada, 1990). The Isthmian Embayment is structurally divided into four components ultimately responsible for the variable surface geomorphology of the region (see Figure 2-8) (von Nagy, 2003). On the west, the Isthmian Embayment is dominated by the Isthmus Saline Basin with numerous salt diapirs in its northern section (lower panel of Figure 2-8) and broad salt massifs rising to within 60 m (196.85 ft.) of the surface in the southern section. To the east, salt domes, still numerous, are of less importance to landscape structure, with some notable exceptions; the modern town of La Venta and nearby Benito Juárez are situated on a salt diapir uplifted cap of older strata surrounded by more recent delta plain (von Nagy, 2003).

The Tabasco Coastal Plain is dominated by a fault-driven large-scale basin and uplift structures (upper panel of Figure 2-8). Much of the Grijalva River delta system correlates with the Comalcalco Basin, whereas the Usumacinta River follows the Macuspana Basin. In between these two basins is the Villahermosa Uplift. The northwest boundary of the Villahermosa Uplift roughly corresponds with the eastern edge of the arc of Grijalva distributaries. The eastern boundary roughly sections the area of the presumed oldest Middle to Late Holocene Usumacinta distributaries. Judging from some of the oldest beach-ridge systems visible in aerial photographs and Landsat imagery data along the eastern margin of the Grijalva delta (see Figure 2-8 for a map of these features), the southernmost Early-to-Middle Holocene marine transgression and much larger proto-Atasta-Pom lagoon system (Gutiérrez Estrada et al., 1982) roughly corresponds with the Macuspana Basin. Prominent fault lines visible in aerial and satellite imagery cross the Usumacinta delta along the eastern margin

of the Macuspana Basin (von Nagy, 2003). Fault lines visibly section older beach-ridges after passing through the Pom Lagoon indicating recent activity of subsidence.

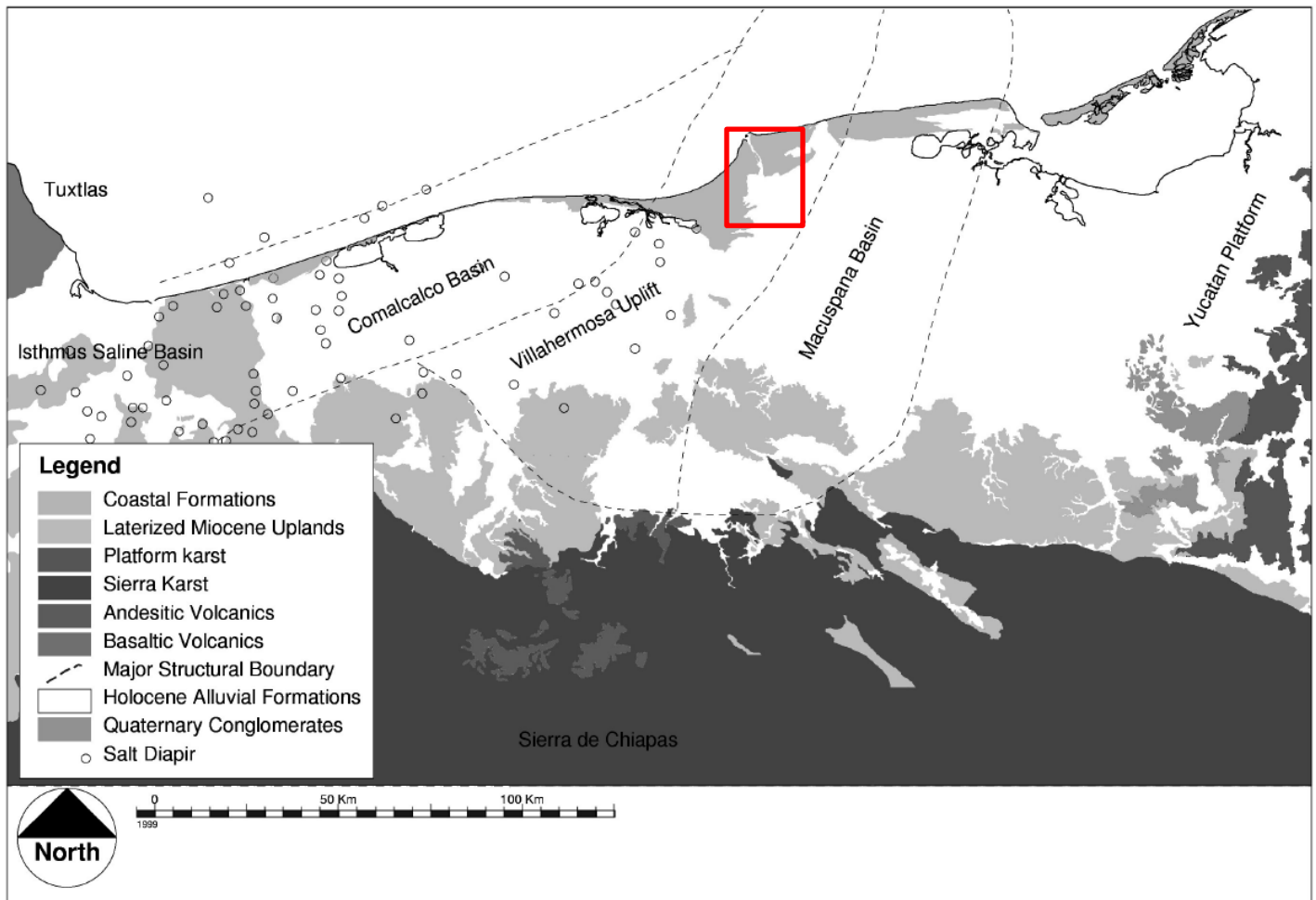


Figure 2-78 Major Geological features of the Southern Gulf Coast study area in red box. Figure after von Nagy (1997).

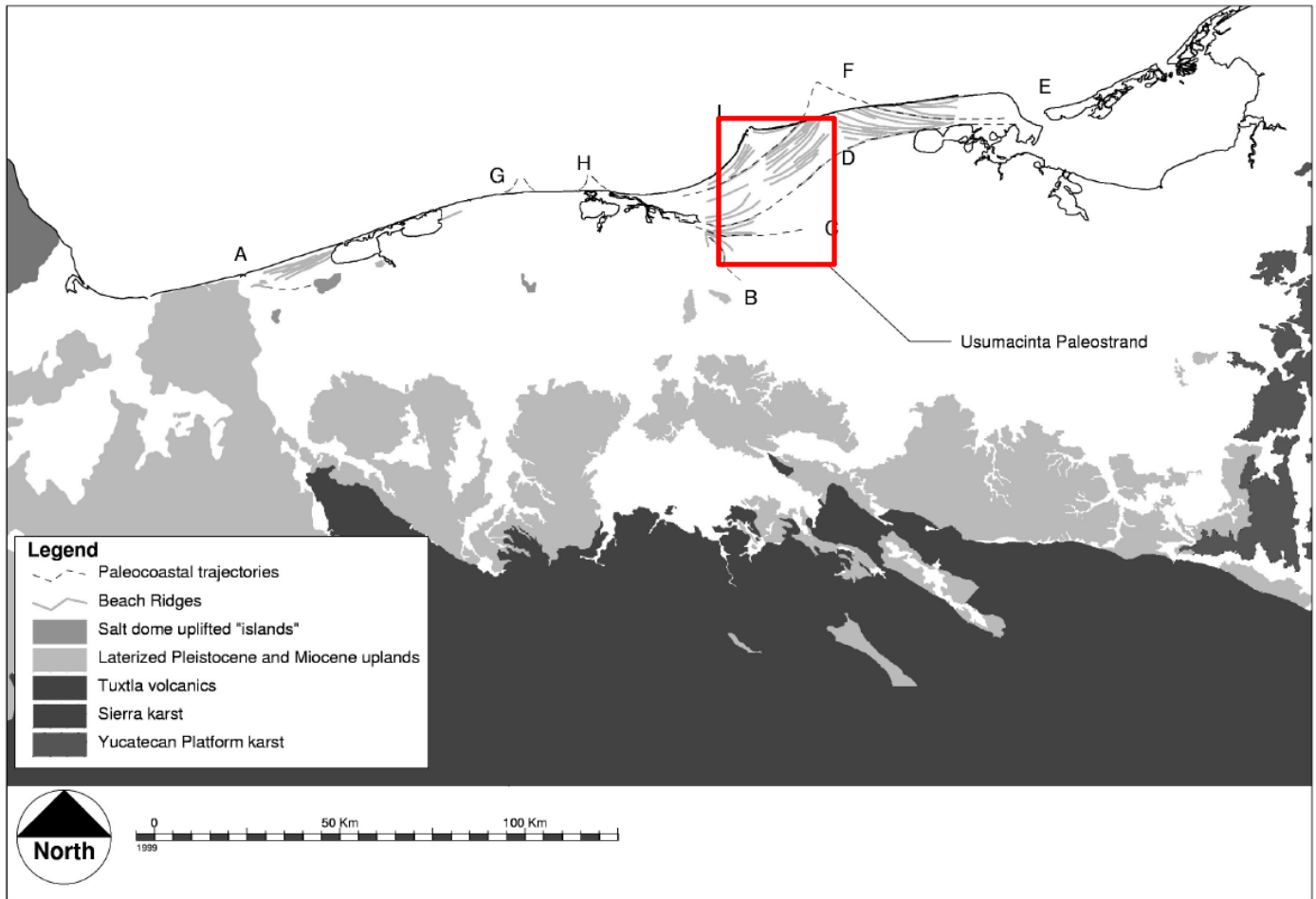


Figure 2-89 Late Holocene coastal features of the Tabasco Coastal Plain based on the analysis of aerial and Landsat imagery and West et al. (1969: Figure 21), study area in red box. Figure after von Nagy (1997)

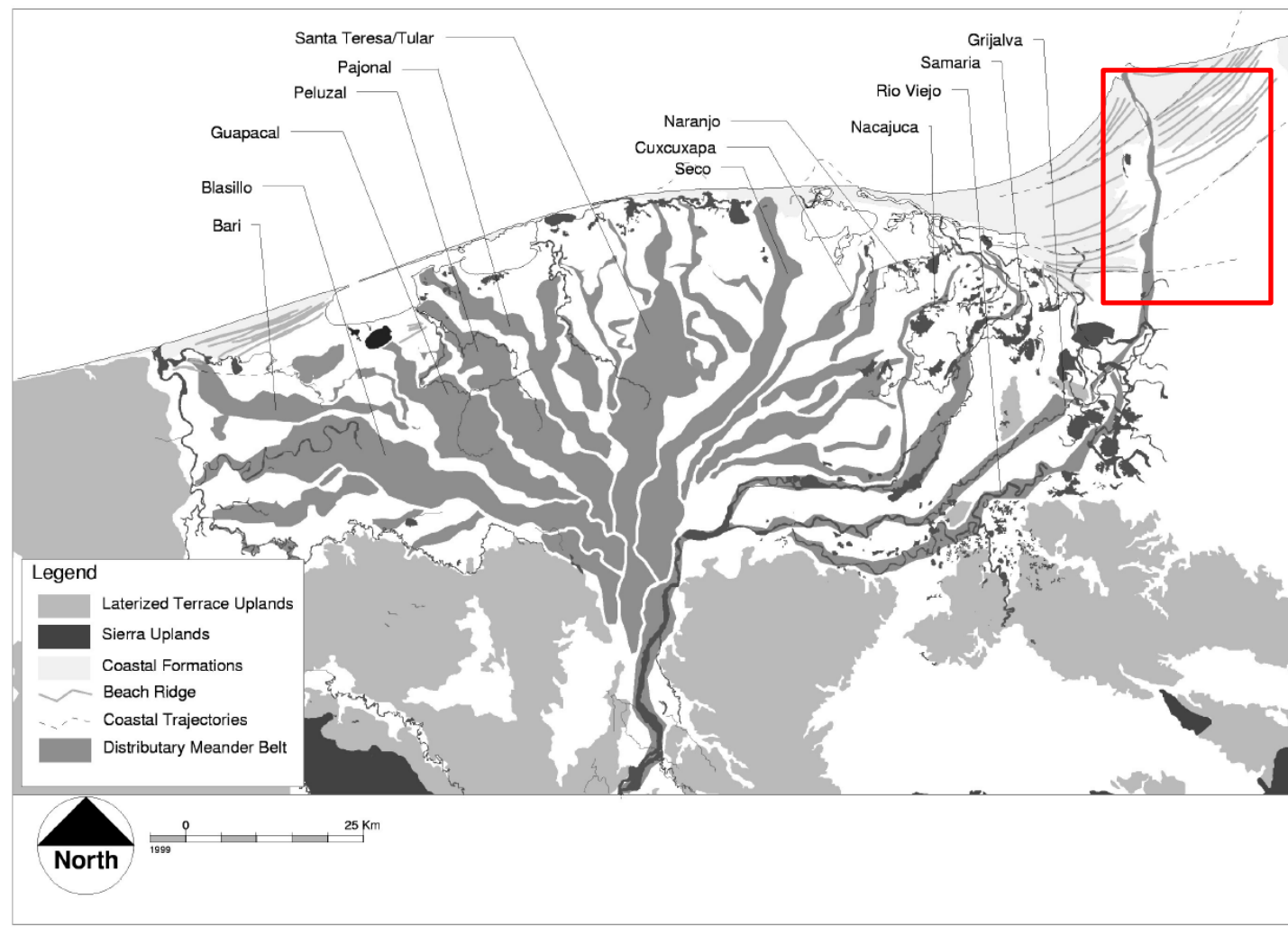


Figure 2-240 Map of the major distributary and paleo distributary systems of the Grijalva and Usumacinta deltas (study area in red box). A. Barí; B. Chicozapote; C. Guapacal; D. Blasillo; E. Peluzal; F. Pajonal; G. Encrucijada; H. Zapotal; I. Zanapa; J. Piedra; K. T Tular; L. Seco; M. Cuxcuxapa; N. Naranjo; O. Nacajuca; P. Samaría; Q. modern Usumacinta main distributary; R. San Pedro y San Pablo; S, T, U, V, W. Pom Systems; X. Palizada. Map data after Jiménez Salas (1990: Figure 1a), Instituto Nacional de Estadística (1980: Cartas geológicas, E15-4, E15-7, E15-5, E15-8, E15-6), Comisión del Grijalva (1968: Cartas topográficas, 16-19W, 23-26W, 29-32W, C), Subsecretaría de Infraestructura Hidráulica (1979: sheets 1, 2 and 3), Vera Herrera et al. (1988: Figure 3). Figure after von Nagy (1997).

2.2 Morphologic Features

Avulsion History

The channel network on the Grijalva delta which connects the main river trunks to the floodplain lakes is a network of multiple distributary channels which tend to occur at the margins in swampy, low lying areas otherwise characterized by bifurcating drainage networks. Although von Nagy (2003) counted approximately

26 major distributaries, the Grijalva delta developed approximately seven known main distributary mouths overlapping in time during the last 4500 years (Figure 2-10). The seven (7) major distributaries of the Grijalva Delta as identified by von Nagy (2003) are, in approximate order of occurrence from west to east, the Guapacal, Perusals, Pajonal, Mecoacán, Santa Teresa-Tular- Cocohital, Río Dos Bocas/Seco, and the modern Grijalva (Figure 2-10). Each of these distributary systems is related to major coastal distributary mouth features, including four now-truncated arcuate mouths, the Peluzal, Mecoacán, Tular, and Dos Bocas mouths (von Nagy, 2003). Highly truncated beach ridges converge roughly in front of the submerged levees of the Peluzal as they do on the gulfwards side of the Mecoacán Lagoon. The younger Tular and Dos Bocas, Río Seco mouths have undergone less reworking. The seven major mouth features imply a rough rate of delta avulsion of one every six hundred years (von Nagy, 2003). Avulsion rates in the Grijalva delta were not constant, but are the result of a complex interplay of climatically driven annual and seasonal rates of flow into the delta, fluctuations in relative (subsidence) sea level, with sea level the single most important factor.

The Usumacinta River has two avulsions within the study area. The first avulsion occurs just downstream from the Usumacinta cross-section 1 (see Figure 2-5). The Usumacinta River experienced a partial avulsion, where the avulsed channel diverged from the parent channel into its present day course. The parent channel along its ancient course is called San Pedro y San Pablo River. Further down dip between cross-sections three (3) and four (4) the Usumacinta has a local avulsion. The smaller avulsed channel is called the San Pedro River. The San Pedro rejoins the Usumacinta at the confluence with the Grijalva River. The confluence of the three rivers is called Tres Brazos and from this point down dip to the coast is the single channel of the Grijalva River (Figure 2-11).

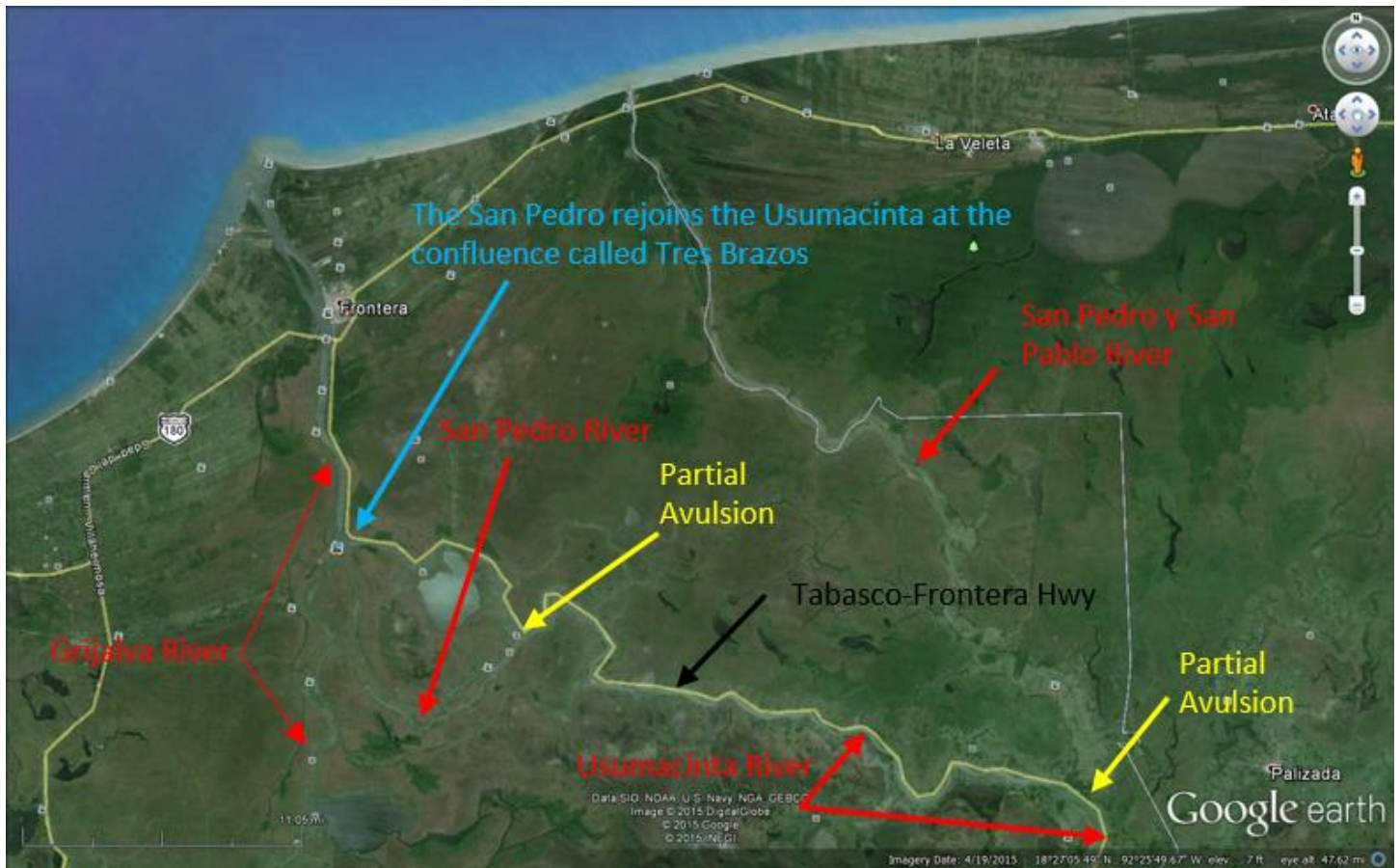


Figure 2-~~1044~~ Location of Avulsion on the Usumacinta River in the study area.

3.0 Methods

Channel belts and floodplain forms of the Grijalva and Usumacinta are examined using imagery and cores collected using the Dutch hand-coring system and hand-operated suction cores. Landforms such as lakes and channel belts are identified from aerial photography and examined through cross sections and longitudinal sections of closely spaced cores. These cores are used to compare modern environments with resultant core lithofacies to develop a database of analogs for deposits of various backswamp environments and to assess geometry of sand bodies, lateral interrelation of sandy and muddy lithofacies, and estimates of total net to gross of the broader fluvio-deltaic environment.

3.1 Aerial Photographs

A review of both limited historical aerial photographs from the 1970s to 1990s and satellite images from the 1970s to 2011 was performed to obtain a timeframe for not only the creation and growth of channels, but also the evolution of floodplain lakes and floodplain processes in general.

3.2 Site Selection

Field work was conducted during two field seasons, between June 21 and July 17, 2011 and between December 15, 2012 and January 14, 2013. Field reconnaissance was conducted using air photos and satellite images to select sites along the Grijalva River to install sediment borings to construct representative cross-sections for each major depositional setting. Additional field reconnaissance was conducted on the Usumacinta River and the coastline to augment data and evaluate possible future study sites.

Sites were selected based upon scientific value, access by either vehicle or boat, and permission from the landowner. Sediment borings were installed in both subaerial and subaqueous environments transecting key depositional environments at representative locations. Priority for drill sites included:

- meander bends on both the Grijalva and Usumacinta rivers to create cross-section maps of the channel belt width and depth as well as the floodplain geometry of both rivers;
- tie-channels within the lake systems both across belts and, where possible, at the constructing mouth of the channel;
- longitudinal profiles of selected tie channels to document the sand trends down channel and across the delta front;
- transects of borings within a selected lakes in a north-south and east-west direction (Figure 2-29); including the mouths of a propagating delta channel as part of the lake cross-section (Figure 2-30);
- large splays off the Grijalva River west of the lake/lagoon;
- coastal cheniers.

Boreholes were logged at 10cm (3.94 inches) intervals from full core sections. Samples were categorized for texture by relative percent category of clay, silt, and sand according to the United States

the approximate accommodation rate. Also, the measurement of sediment above the peat layer to the surface or lake bottom water interface allows for a local sedimentation/aggradation rate to be calculated.

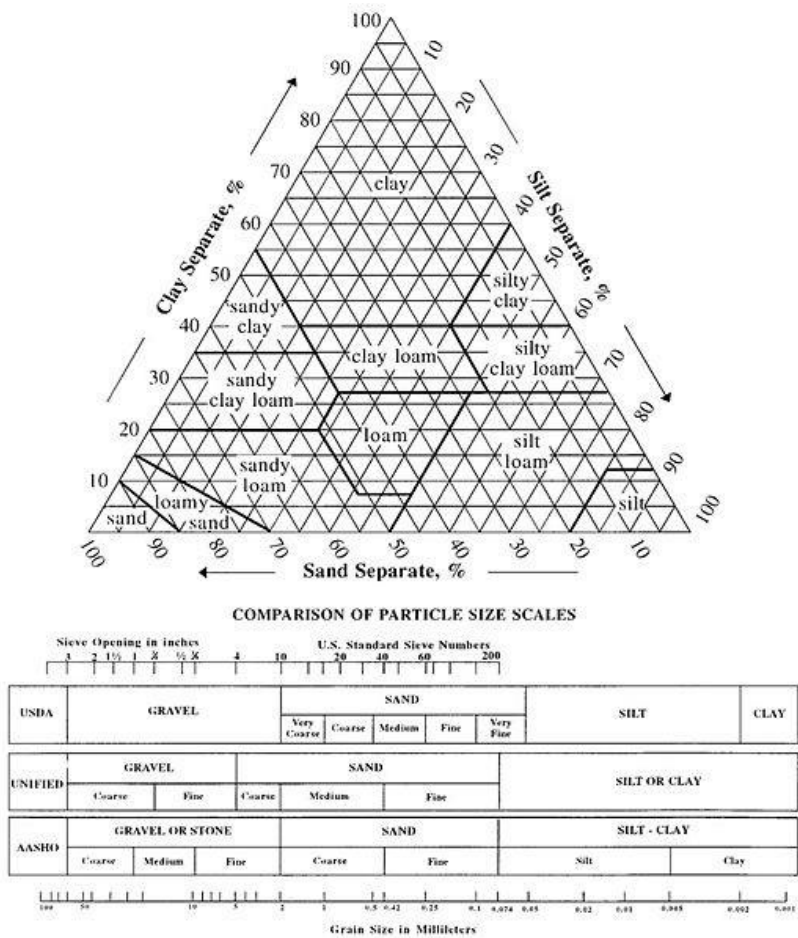


Figure 12-13 USDA Soil Texture Classification Triangle. Soil textural rock equivalents: Clay=Clayshale or claystone. Silty clay = Mudshale or mudstone, Silt loam = coarse mudstone to siltstone, loam=muddy sandstone to coarse siltstone, sandy loam and loamy sand = muddy to poorly sorted sandstone, sand=mature sandstone).

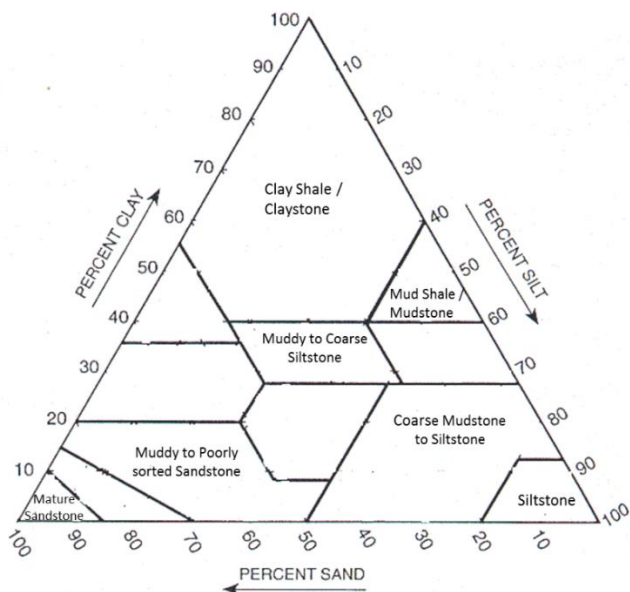


Figure 2-14 Rock equivalents to Soil Texture Classification Triangle.

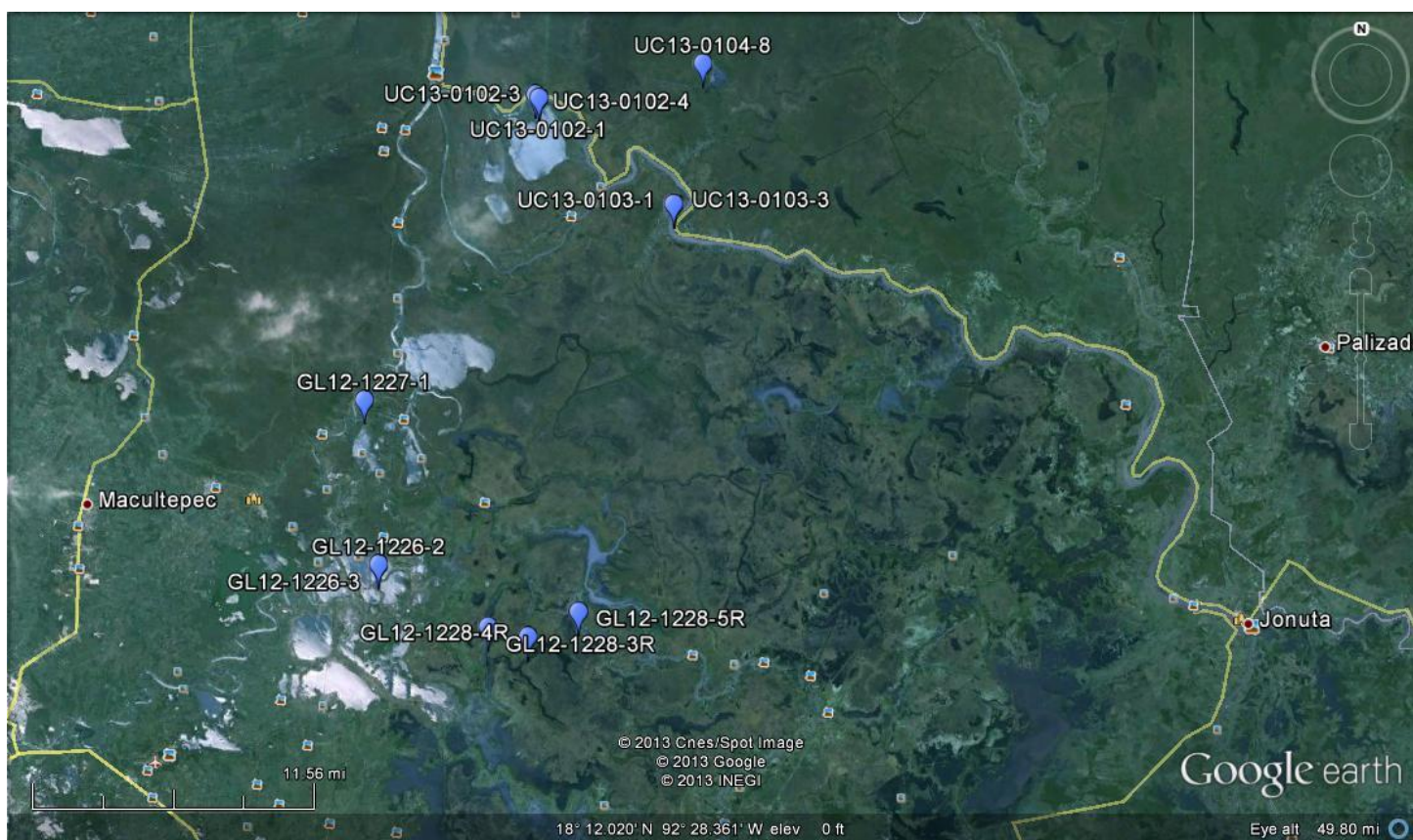


Figure 2-15 The location of the nine (9) peat samples submitting for radiocarbon dating.

4.0 Results

4.1 General Physiography

The main river channel is highly meandering and flows across a relatively flat coastal plain. Although accurate measurements for sediment load are not available, the unconsolidated sedimentary rocks of the drainage basin yield extremely large amounts of sediment as evidenced by the sediment plumes apparent in satellite images (Coleman and Huh, 2004). Satellite images of the delta and lower part of the alluvial valley (Figure 2-5) show a well-defined and highly meandering river channel, and enlargement of the image indicates numerous abandoned river channels. The construction of four dams in the mountains of the headwaters of the Grijalva River down to the lowlands (Figure 2-16) has drastically reduced not only flood flows, but also sediment transport of the Grijalva River, especially the bedload transport of gravel and sand (Peters, 2010).

The delta is disproportionately large for its feeding river system. The drainage basin for the combined Grijalva and Usumacinta River complex covers an area of 3,341 sq. km (1,289.97 sq. miles). The Magdalena delta in Columbia has a similar feeding river length compared to the Grijalva Delta, but is significantly smaller in size, 1,689 sq. km (652 sq. miles) (see Syvitski et al., 2012 for comparisons of deltas to river length). The surficially exposed delta records the Holocene deposition of both the Grijalva and Usumacinta rivers. The timing of the avulsion of the Grijalva River to its present course is unknown, but this process has since produced a series of seaward prograding beach ridges of a classic wave dominated delta, similar to the delta of the former course (Figure 2-5). A considerable amount of erosion and submergence characterizes the former delta in the form of truncated and flooded beach ridges. Coastal lagoons characterize the length of the delta and lie behind prominent barrier islands or prograded beach-ridge complexes. The large variation in river discharge during floods commonly top the river banks as defined by prominent crevasse splays and well-defined natural levee ridges (Figures 2-5 and 2-12). The tidal range is relatively low; high tide is 0.36 m (1.18 ft) and low tide is -0.05 m (-0.16 ft) and, although a few tidal channels are present, salt water does not penetrate deeply and most of the vegetation within the delta plain consists of fresh-water reed marshes. Saltwater can penetrate inland up

to 30 km (18 miles) during the dry season. Most of the small lakes seen in the image are the result of abandoned distributaries and meander cut-off lakes.

Distributary vs. anastomosing system

Distributive fluvial systems (DFS) characteristics are described previously in both modern and ancient settings, bearing names such as “alluvial fans,” “fluvial fans,” “humid alluvial fans,” and “mega fans” (e. g., Beatty, 1963; Gole and Chitale, 1966; Boothroyd and Ashley, 1975; Boothroyd and Nummedal, 1978; Heward, 1978; Kochel, 1990; Mohindra et al., 1992; Crews and Ethridge, 1993; Iriondo, 1993; Stanistreet and McCarthy, 1993; Stanistreet et al., 1993; Blair and McPherson, 1994; Gupta, 1997; DeCelles and Cavazza, 1999; Mack and Leeder, 1999; Horton and DeCelles, 2001; McCarthy et al., 2002; Harvey and Wells, 2003; Gumbrecht et al., 2004; Assine, 2005; Harvey, 2005; Leier et al., 2005; Sinha et al., 2005; Nichols and Fisher, 2007; Cain and Mountney, 2009, 2011; Chakraborty and Ghosh, 2010; Chakraborty et al., 2010; Hartley et al., 2010). On the Grijalva Delta, the channel system disperses by avulsion or bifurcation, or both as they enter areas of low gradient and or reduced valley confinement (Hartley et al., 2010.) Sediment load is dispersed in fan form from a central node as the channel enters the depositional plain. Coastal systems may display similar avulsive and distributive form as river systems approach the ocean (e. g., Berendsen and Stouthamer, 2001). In areas in which the DFS has significant accommodation (e. g., A/S ratios are high), wetland, lake, or playa depositional environments are likely to be present, depending on the climate. The wetland lithofacies will be represented by the distal DFS deposits, with significant but “lacustrine” or marsh deposits held between discrete channel belt deposits. (Weissmann et al., 2013) The Grijalva and Usumacinto rivers exhibit distributive fluvial system characteristics on the delta plain; however, some avulsed channels do reconnect with the main channel within a few kilometers of the avulsion (Figure 2-11).

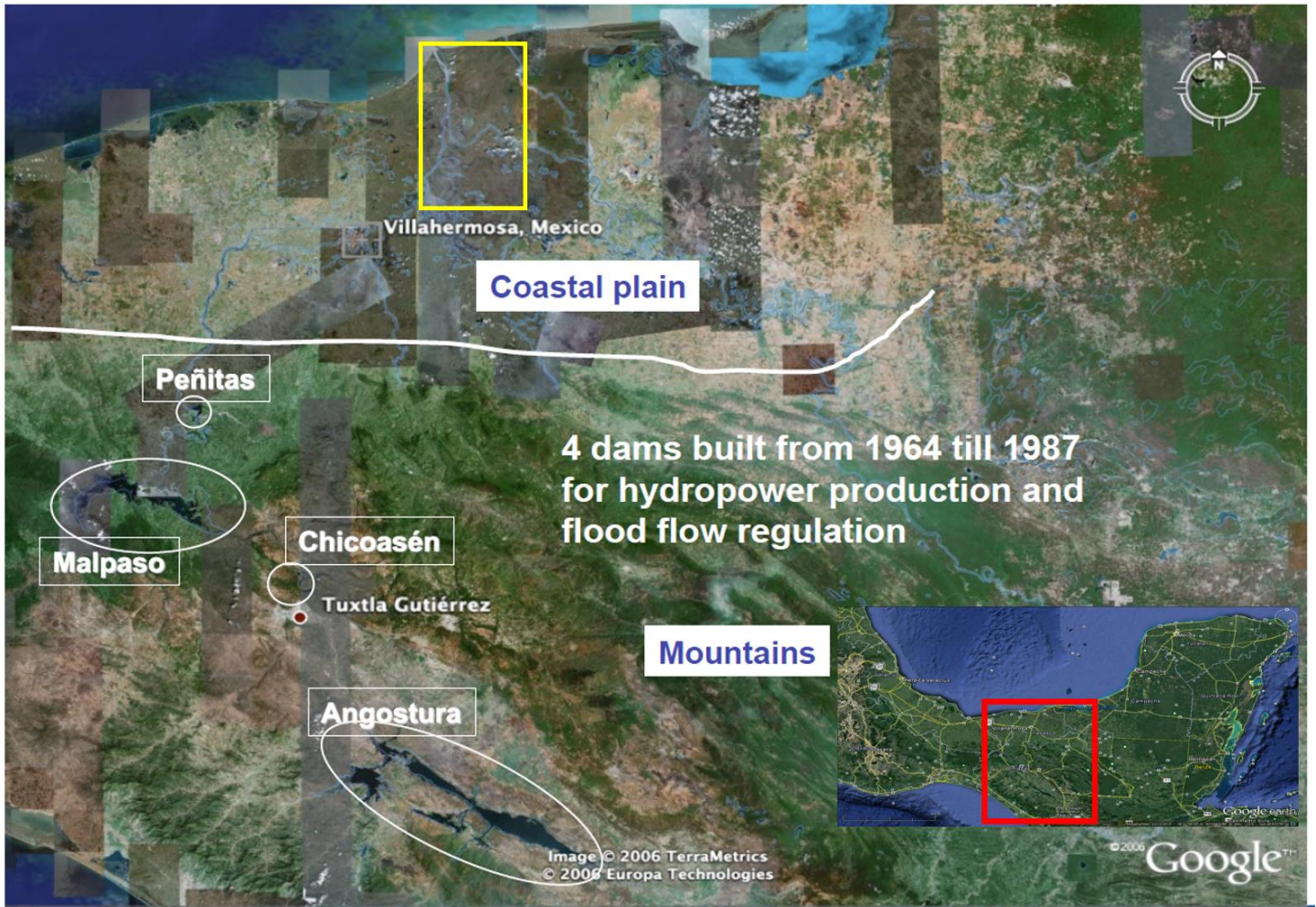


Figure 2-16 Location of the four dams built up dip of the study area on the Grijalva River. (Peters, 2010)

In a detailed study of Cenozoic channel-fill sandstone bodies in Spain and western Colorado, (Mohrig et al., 2000), inferred floodplain incision early in the avulsion process. The bodies display well-defined basal scour surfaces and occur as isolated, low-sinuosity ribbons, typically 10–30 m wide, set within thin-bedded to massive mudstone that comprises the majority of the stratigraphic successions (Slingerland and Smith, 2003). Wedge-shaped wings, interpreted as levee deposits, extend and thin basinward from the tops of many of the channel fills, grading into floodplain mudstone and abruptly overlying older mudstone.

If earlier deposits are not completely removed, however, evidence of reoccupation is commonly noted in the character of levee and channel-fill deposits (Kraus, 1996, Aslan and Blum, 1999; Stouthamer, 2000a; Mohrig et al., 2000; Makaske et al., 2002). Multistory and multilateral channel-sand bodies, particularly if separated by weathered horizons or mudstone layers, are likely indicators of abandonment and later

reactivation, as are stepped channel margins, suggesting successive episodes of reoccupation and widening (Mohrig et al., 2000). Multiple levels of levee deposits associated with the same channel fill, or a multistoried channel fill adjoining unusually thick levee deposits, are also indications of reoccupation (Stouthamer, 2000a, b).

4.2 Lithofacies

Table 2-1 Lithofacies were grouped into five (5) categories defined by texture and organic content. These lithofacies represent lumping of categories from the USDA soil texture triangle (Figures 2-13 and 2-14) with apportion added for organic content.

Lithofacies	Description
Sand	This facies comprises fine to medium sand moderately to well sorted with little to no organics or vegetation fragments.
Loam	This facies comprises sand, silt, and clay in relatively even proportions. The proportion of sand, silt, and clay varies, resulting respectively in sandy loam, silty loam, clay loam, sandy clay loam, silty clay loam, and loam where variation is nonsignificant.
Silty Clay	The clastic component of this facies is mostly clay with less than 50% and over 50% silt and sand. It is the most heterogeneous facies, ranging from thin interbeds of clay, silt and very fine sand to thicker beds of clayey or silty sand with up to 50% organics.
Clay	This facies is the finest of the clastics with less than 40% silt and less than 45% sand as clastic components and can contain from zero to 50% organics.
Peat	This facies consist of vegetation-rich materials ranging from pure peat to sediments composed of equally organic and inorganic detritus materials (Smith et al. 1989). Peat layers were commonly encountered and layers up to 1.5 m (4.92 ft) thick were logged. Some peat beds were not fully penetrated. Peats form in areas protected

Lithofacies	Description
	from fluvial deposition (Smith et al. 1989), and are currently forming today in large areas of the Grijalva lagoon/lacustrine delta system. Multiple peat layers were encountered at depth in several borings.

4.3 Floodplain Geomorphic Forms and Lithofacies

Levee

Raised elongated asymmetrical ridges border the channels. Levees scale in proportion to the adjacent channel ranging from a meter above adjacent floodplains on the young tie channels to 10 plus meters (32.8 plus feet) on the Grijalva and Usumacinta rivers. The levee crest on both main rivers raises one (1) to two (2) meters (3.28 to 6.56 feet) above the floodplain surface up dip of Tres Brazos and relatively shallower and more laterally extensive down dip of Tres Brazos.

The levee is composed almost entirely of fine-grained dominantly suspended-load sediments (dominantly silt-to-sandy loam) fining towards the backswamp (distal floodplain). The levees of the main rivers are heterogeneous with alternating layers silty loam to (fine) sandy, coarse silt loam fining upwards with thin interbedded clay layers. The levees along both the Grijalva and Usumacinta rivers are highly vegetated and hardened with vegetated debris with near vertical banks on straight sections of the river and cut banks. Levees along the tie channels are slightly elevated above the floodplain and heavily vegetated. The levees along the tie channels are also constructed of loam, but generally are composed of finer grained silts than the main river levees.

Levee form is influenced by, and in turn influences the channel-floodplain linkage, of biophysical processes (Brierley and Fryirs, 2005). Influencing the lateral transfer of water, sediment, and organic matter, levees are produced primarily from overbank suspended-load deposition at high flood stage. During overbank events, flow energy dissipates when the flow spreads out over the floodplain. Under these conditions, the flow has insufficient energy to carry its load. A marked reduction in velocity results in deposition of fine-grained

bedload and suspended load materials on proximal floodplains. Inter-bedded-flood cycle deposits, termed flood couplets, reflect rising-and falling-stage sedimentation (Brierley and Fryirs, 2005). Finer materials are carried into the distal parts of the floodplain. Highly developed levees along extensive fine-grained floodplains infer a laterally fixed channel zone, and well-defined segregation of water and sediment transfer between the channel and flood basin.

Crevasse Splay

Crevasse splays are common features along both the Grijalva and Usumacinta rivers. Typically, the crevasse splays have a lobate or fan-shaped planform thinning away and terminating in close proximity of the levee. The surface of the crevasse splay may have multiple distributary channels, producing hummocky topography. Rich in bedload material, predominantly fine-to-medium sand and coarse silt, the crevasse channel fills have a symmetrical, lenticular geometry and low width/depth ratio. Interdistributary splay deposits are dominated by loam.

Crevasse channels breach and erode the levee, taking bedload materials from the primary channel and conveying them onto the floodplain at high flood stage (O'Brien and Wells, 1986). Deposition reflects the rapid loss of competence beyond the channel zone. Flow velocity is able to carry relatively coarse material, which is spread outward onto a fan- shaped area of floodplain, which thins away from the levee. The angle of trajectory increases with the high levee back slopes and/or decreases with higher flow velocities. Crevasse channel fills represent bedload plugging of old crevasse channels, indicating an aggradational environment. Their formation, with the levees, is part of the process that builds an alluvial ridge and contributes to subaerial elevation of the channel belts above the water table.

Floodplain Sand Sheet

Floodplain sand sheets are flat tabular and laterally extensive in non-levee settings with massive, often poorly sorted sand lithofacies. These sheets show little lateral variation in thickness, mean grain size or internal structure. Surface expression generally conforms to the underlying floodplain. These deposits are differentiated from splays by their sheet geometry, extensive area, and muted distal thinning.

Sand sheets are associated with rapid sediment-charged bedload deposition on the floodplain during extreme flood events. This kind of deposition requires competent overbank flows for bedload materials to be deposited on the floodplain in sheet like forms that cover the entire surface. Sand sheets are common in sandy ephemeral streams and often form downstream of transitions from confined to unconfined flows and are associated with a break in slope. Sand sheets build the floodplain vertically.

Mudflat

Mudflat areas lie adjacent to or between active or abandoned channels and the valley margins. Mudflats are plains elongated parallel to active channels. They are topographically featureless, flat-topped to inclined forms, typically tilted away from the channel. Mudflats are subaerially exposed except during the rainy season.

Mudflats form when the reduction in energy gradient across the proximal floodplain to the distal floodplain only allows finer suspended-load materials to be transferred to the backswamp. This reduction in energy gradient results in slow rates of fine-grained (very fine sand to silt) vertical accretion in these low energy settings. A distinct gradation in energy with distance from the channel may result in pronounced textural segregation across the mudflat.

Floodplain Lake

The distal floodplain, at valley/basin margins, is typically the lowest area of the delta plain, and generally is submerged between flooding events. Floodplain lakes are major storage units of fine-grained, vertically accreted, suspended-load sediments. Morphology is typically flat with some depressions. Ponds, wetlands and swamps commonly are fed by lower order tributaries (tie channels) that drain directly onto the floodplain.

Floodplain lakes form when the reduction in the energy gradient from the proximal to distal floodplain only allows minimal fine suspended-load materials to be transferred to the backswamp, resulting in slow rates of fine-grained (fine silt to clay) vertical accretion in these environments. A distinct gradation in energy with distance from the channel may result in pronounced textural segregation across the floodplain. Backswamp wetlands, lakes, and pond features are common in this type of poorly drained (unchannelled), low-energy,

vertically accreting environment. Dense aquatic/swamp vegetation traps fine-grained suspended-load sediments, promoting accumulation of cohesive, organic-rich mud (Fryirs and Brierley, 2013). Lakes record locations where the accumulations of these fine-grained and organic materials are at insufficient rates to equal or surpass water table rise related to generation of accommodation.

Channel fills

As rivers move across the floodplain the active channel shifts or migrates laterally. The accumulation and preservation of a river only occurs if the river channel changes its position in some way, by either shifting laterally or changing its position in the floodplain by avulsion. When avulsions occur flow in the old channel is reduced; therefore the competency and capacity of the river is reduced. As the flow is reduced the bedload is deposited and the river flow can only transport suspended sediment. Over time, as the flow is reduced to non-existent, the suspended sediment is deposited in a fining upward pattern as the competency of the river is reduced. The final deposition is very fine clay accumulating from over bank flow deposits. Abandoned channels are also unlikely to remain empty. The abandoned channel will contain sluggish flow that will deposit its sediment load on the channel bottom. Over time sediment carried by over bank flows from active channels on the floodplain will be deposited and accumulate within the old channel.

Point bars

The accumulations of the finer bedload and suspended load, transported in a mixed load river that accumulates on the inside of a meander bend due to helicoidal flow in meandering rivers, are called point bars. Point bars are attached deposits of bed/suspended loads with bar surfaces and sedimentary structures inclined towards the center of the channel. Point bars show a fining-upward sedimentary sequence, with coarser bedload material at the bottom and a fining-upward succession of over bank deposits as well as fining-down-bar deposits. Point bars show the rivers lateral migration at meanders and are opposite of the cutbank, an erosional feature, of the meander bend.

Swamp/glade

A swamp can be a floodplain lake or pond and considered as a deep water wet lands environment (water depth >1 meter (~3 feet)) that has filled with sediment to a point where it transitions to a shallow water wet lands environment (water depth <1 meter (~3 feet)). A swamp is a low energy environment with dense aquatic vegetation that traps fine-grain suspended sediment permitting the accumulation/infilling of cohesive, organic rich mud. Over time these systems fill to only a few inches of depth. They can be completely dry during the dry season, with sedimentation and a transition in vegetation type that can survive during extended periods of time in flooded, anoxic and dry conditions.

Tie-channel delta

A tie-channel delta is actually a propagating splay delta because the tie channel has a low gradient which affects the channels competency and its capacity to transport bedload and suspended load. A tie channel's ability to transport its sediment load is further effected by the backwater effect cause by the velocity reduction of the flow entering the floodplain lake. This backwater effect propagates up dip, a process that results in the bedload (sand) being temporarily deposited upstream and the suspended loaded being carried out into the floodplain lake. Clays are transported out into the lake and form the prodelta and build up over time with the silt fraction settling out closer to the tie channel mouth. As the prodelta builds up and out across the lake the silty clay and clay form levees subaqueously and the cohesive nature of the clay allows the levees to harden as vegetation and debris become imbedded in the levees. The delta propagates as a ribbon as the sand is deposited up dip as a result of the backwater effect. This process results in no sand being deposited at the mouth of the tie channel; therefore, the channel mouth doesn't become clogged by a sand mouth bar that would cause it to bifurcate, resulting in the lobate delta style as is seen in coastal settings.

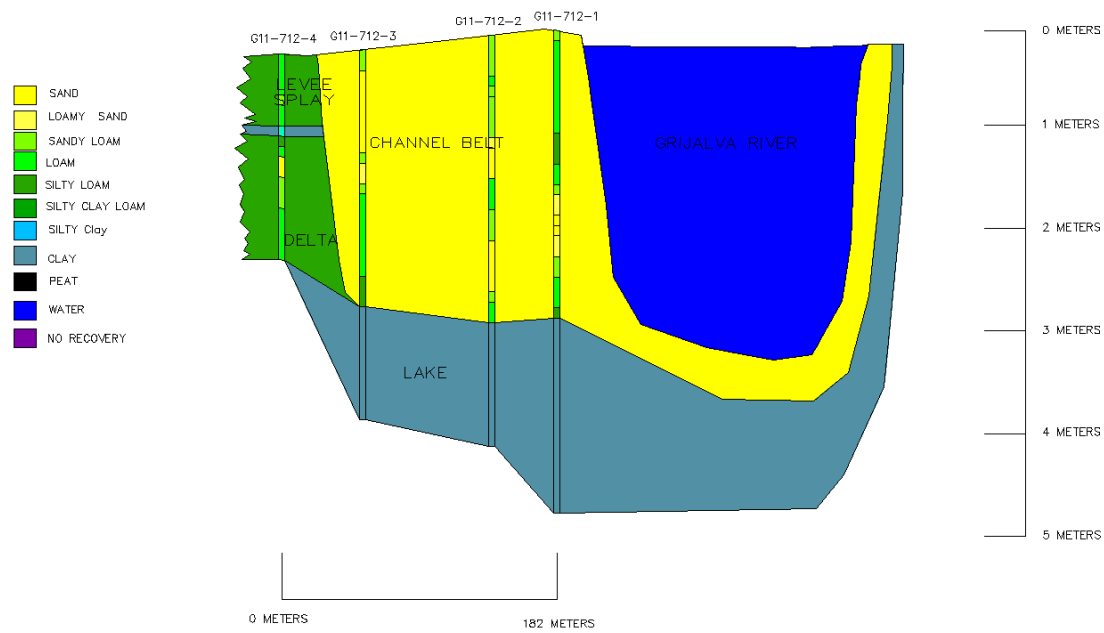


Figure 2-17 Grijalva River cross-section 1.

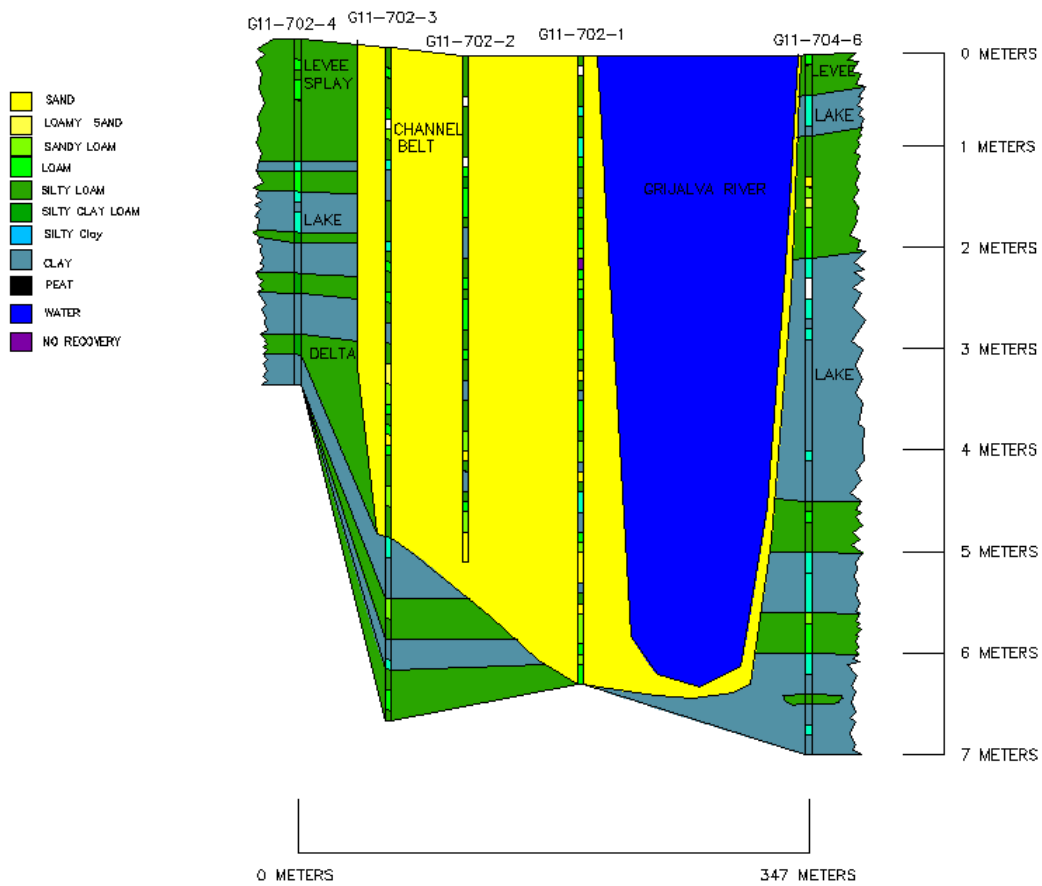


Figure 2-18 Grijalva River cross-section 2.

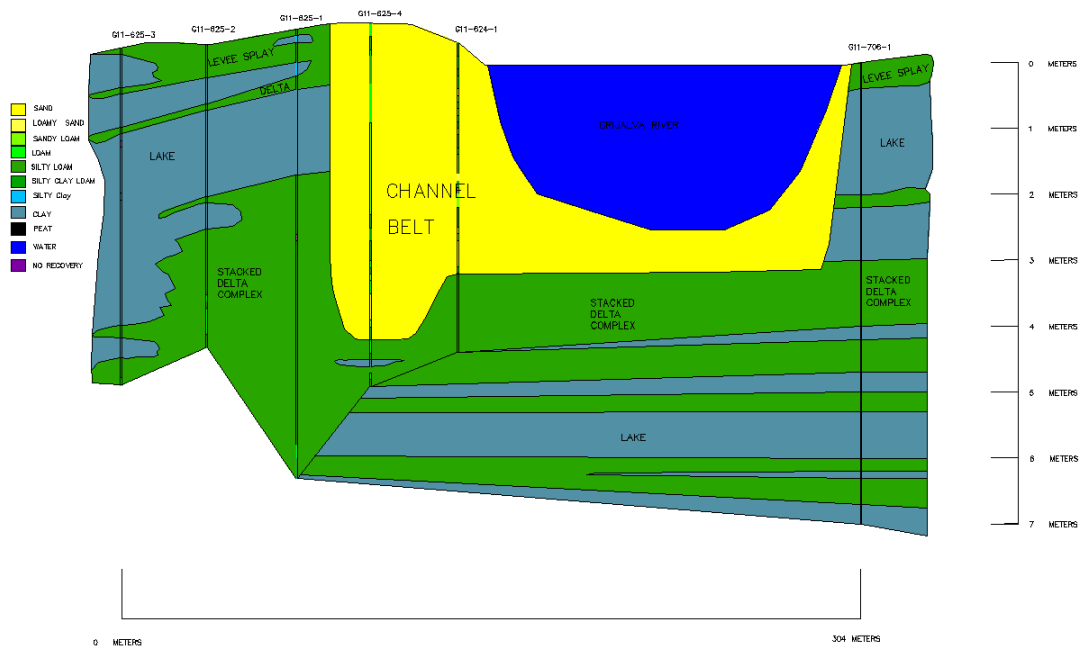


Figure 2-19 Grijalva River cross-section 3.

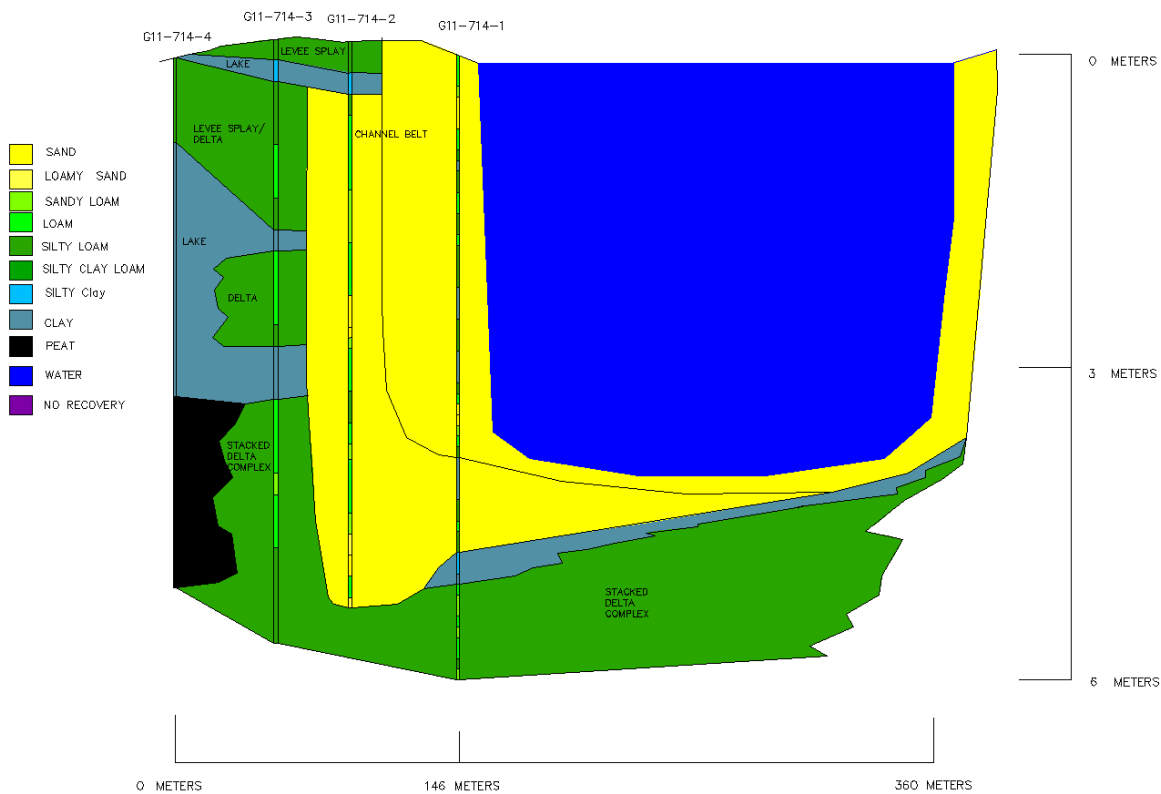


Figure 2-20 Grijalva River cross-section 4.

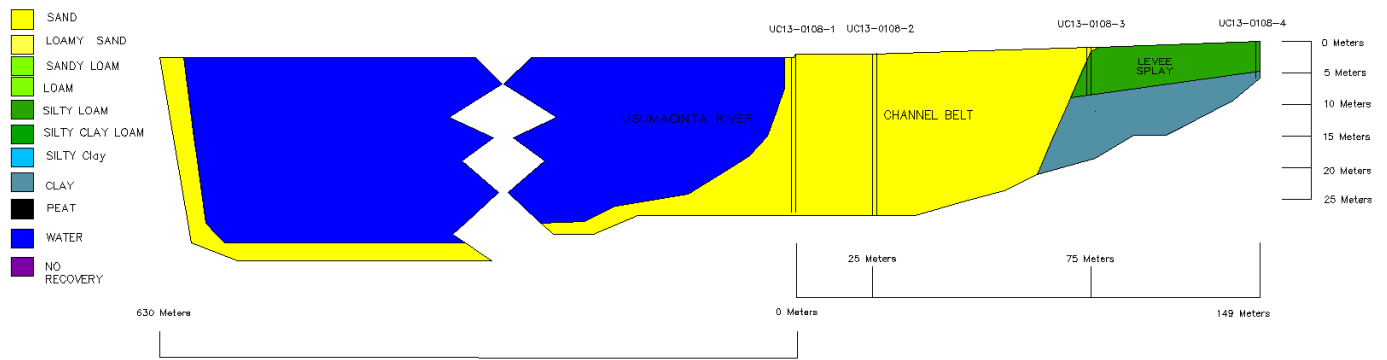


Figure 2-21 Usumacinta River cross-section 1.

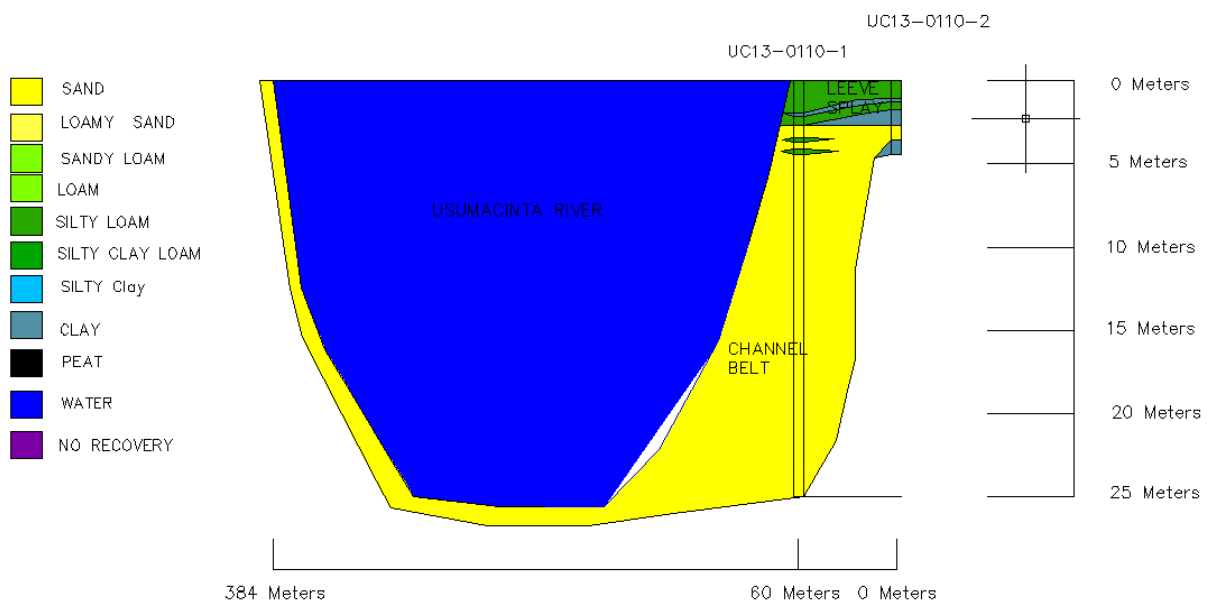


Figure 2-22 Usumacinta River cross-section 2.

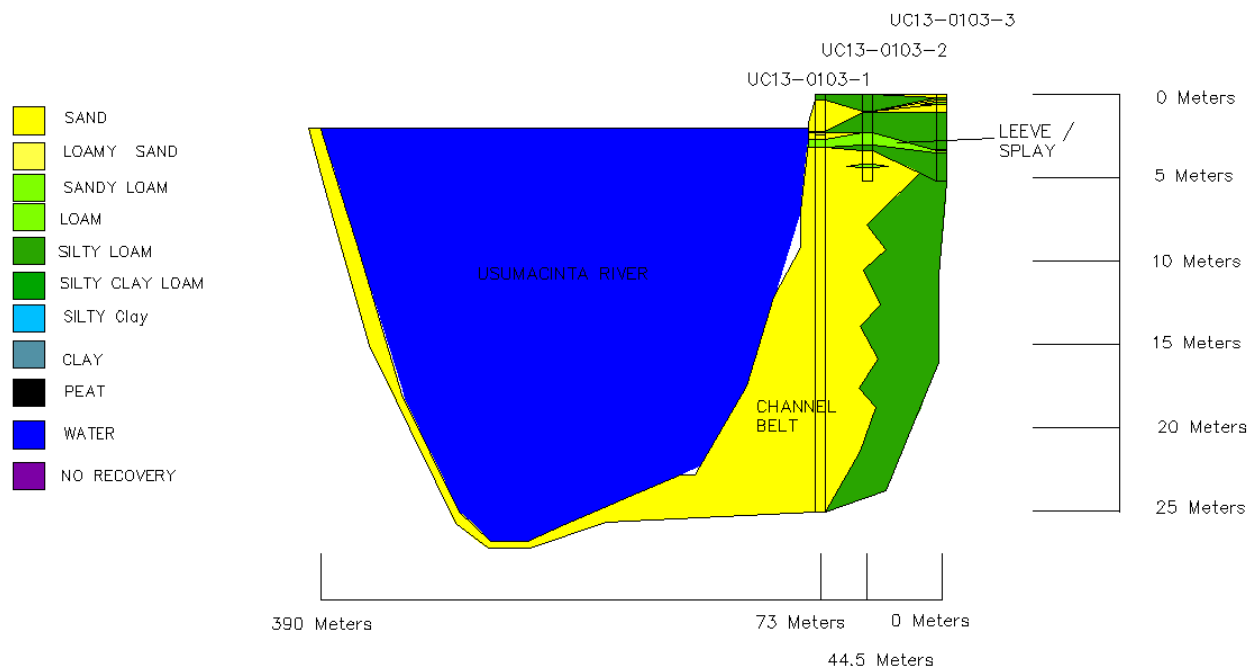


Figure 2-23 Usumacinta River cross-section 3.

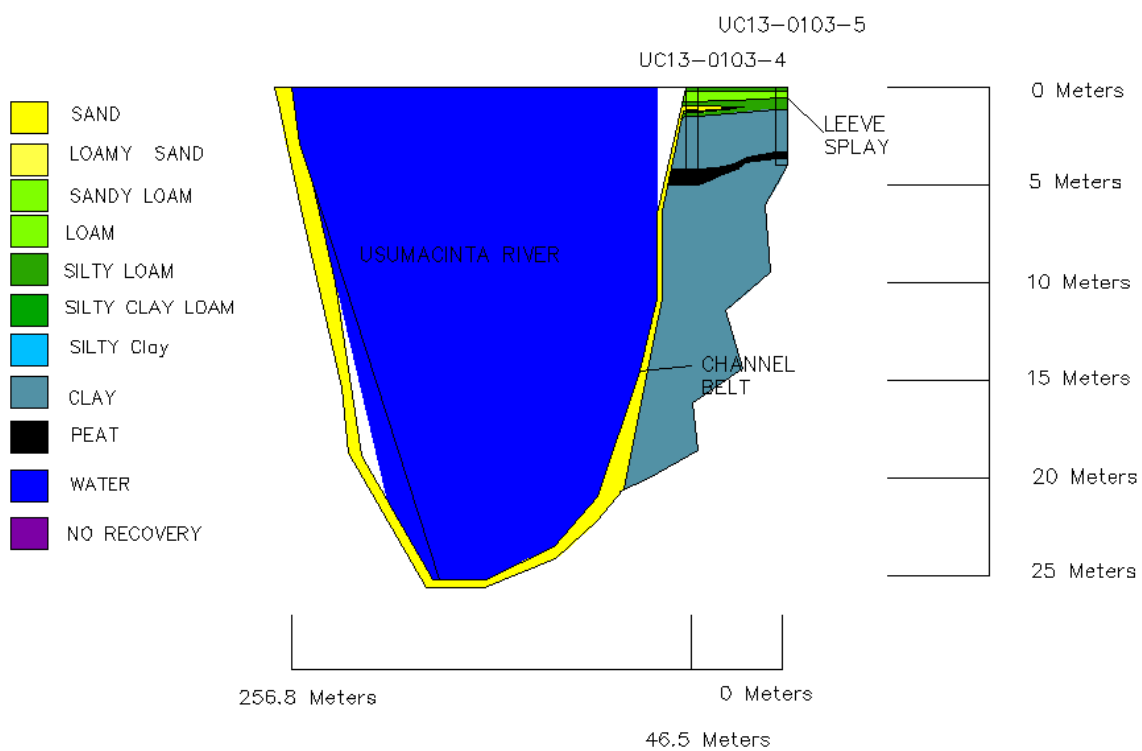


Figure 2-24 Usumacinta River cross-section 4.

4.4 Tie Channels and Tie-Channel deltas

The cross-sections at the terminal end of a tie-channel propagating across a lake in the Grijalva River basin (Figure 2-25), east-west lake cross-section (Figure 2-25) and the longitudinal Usumacinta tie channel profile (Figures 2-28a-b) show there is no sand at the mouth of these active tie channels. Channel fills cut through the surrounding delta lithofacies and into lacustrine lithofacies up dip of the delta mouth. The delta lithofacies are coarser than the lacustrine lithofacies, with silty loam as the dominate delta texture in contrast to lacustrine clay. The channel fills tend to be slightly coarser than the delta lithofacies and are characterized by loam strata with thin sand-to-sandy-loam beds. The total width and thickness of these delta and channel complexes can be ascertained from the cross section, but the surficial example suggests that the complex is scaled directly proportional with the size of the channel and the channel occupies less than 1/4th of the width of the complex. The splay/levee builds into the lacustrine and delta front deposits, and comprises similar silt loam lithofacies as the underlying delta bodies (Figure 2-25).

4.5 Lithofacies Associations in Cross Sections of the Shallow Subsurface

Cross-sections of lake strata of the Grijalva and Usumacinta delta plain depict (Figures 2-17 to 2-24) illustrate an interfingering of lithofacies characteristic of surficial deposits. Ribbons on loamy tie-channel delta front and levee deposits consisting commonly bisect clay lake and peaty swamp deposits (Figure 2-31). Silty delta ribbons reflect propagating delta front strata at the base and levee building at the top. Intermittent lacustrine lithofacies layers are in-between the delta and levee facies as a result of lake flooding between the bisecting delta propagation and levee initiation. Tie-channels cut through the center of propagating delta strata and into the lower delta facies. The channel lithofacies are coarser (loam, sandy loam and loamy sand) than the delta lithofacies that cuts and connect the minor sand deposits of these delta strata with the channel belt.

Borings taken in the major channel belts yield a dominance of sand and loamy sand that pierce lake complexes. Unlike tie channels, major through-going distributary channels commonly migrate and develop channel belts with defined point bars and channel fills. Whereas the channel belt and fill are marked as sand for clarity, both are in fact rather heterolithic (see borehole logs; Figure 2-17). Furthermore, the sand content of the

channel-belt deposit in down dip cross-sections is diminished relative to that present in up dip cross-sections. The Usumacinta River is a sandier system than the Grijalva River, and generally has larger and sandier channel belts. Both rivers, however, show the same narrowing of channel belts down dip. Correlation of fine strata in the top of the western three boreholes of Figure 2-20 argues that the sandy deposits record two stacked channel belts. At some point in time, the channel shifted east and cut down into the lower channel belt from a higher level. Over time, the active channel migrated east cutting into the outside bank while depositing a point bar on the opposite bank. See Table 3-1 for channel dimension and ratio data for channel belts.

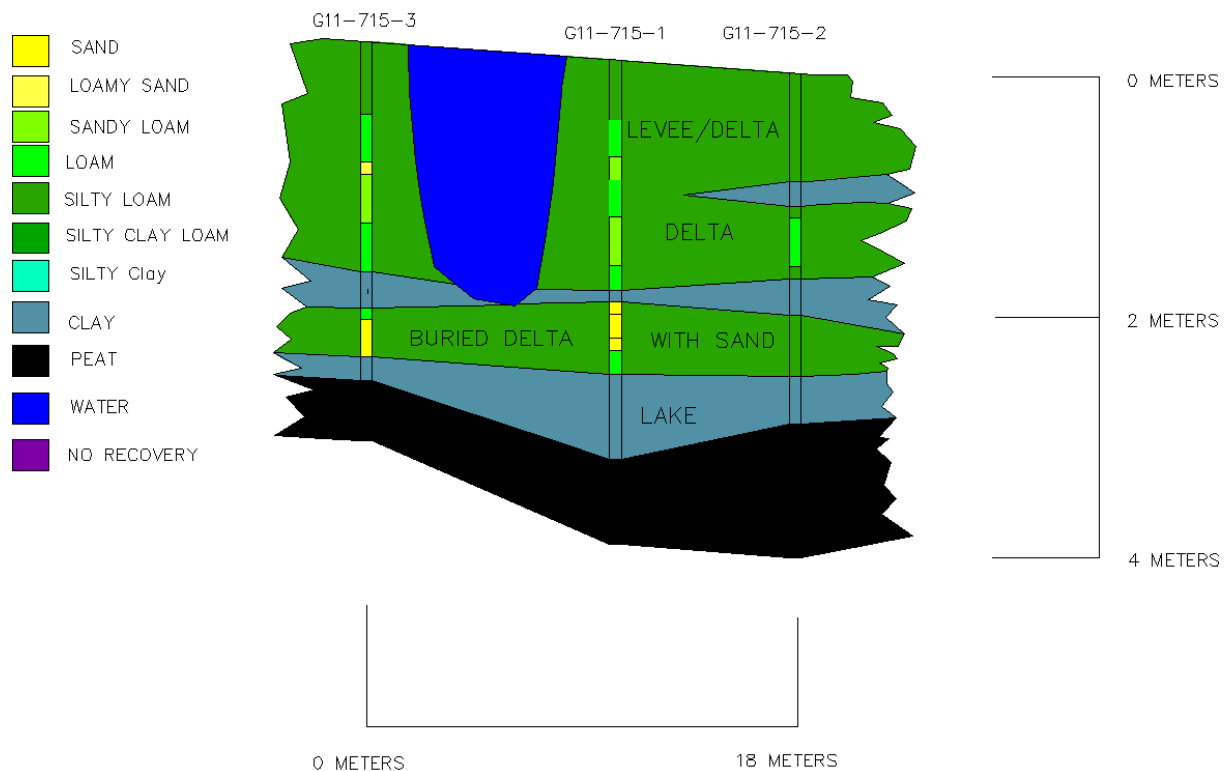


Figure 2-25 Tie channel cross-section 1.

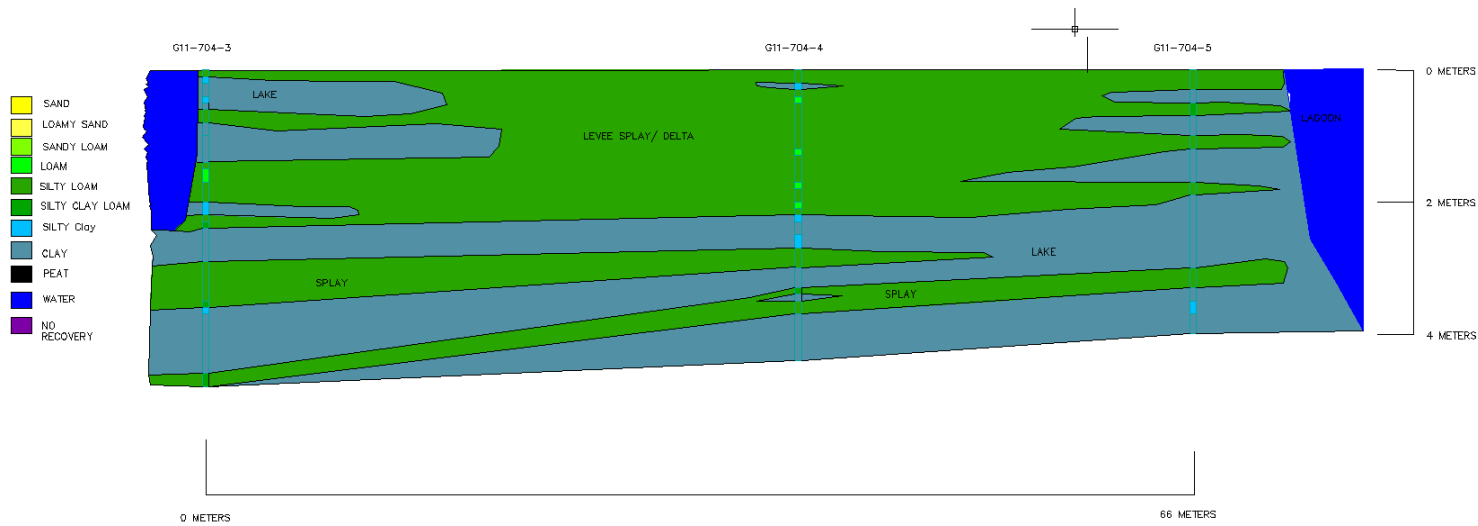


Figure 2-26 Tie channel cross-section 2.

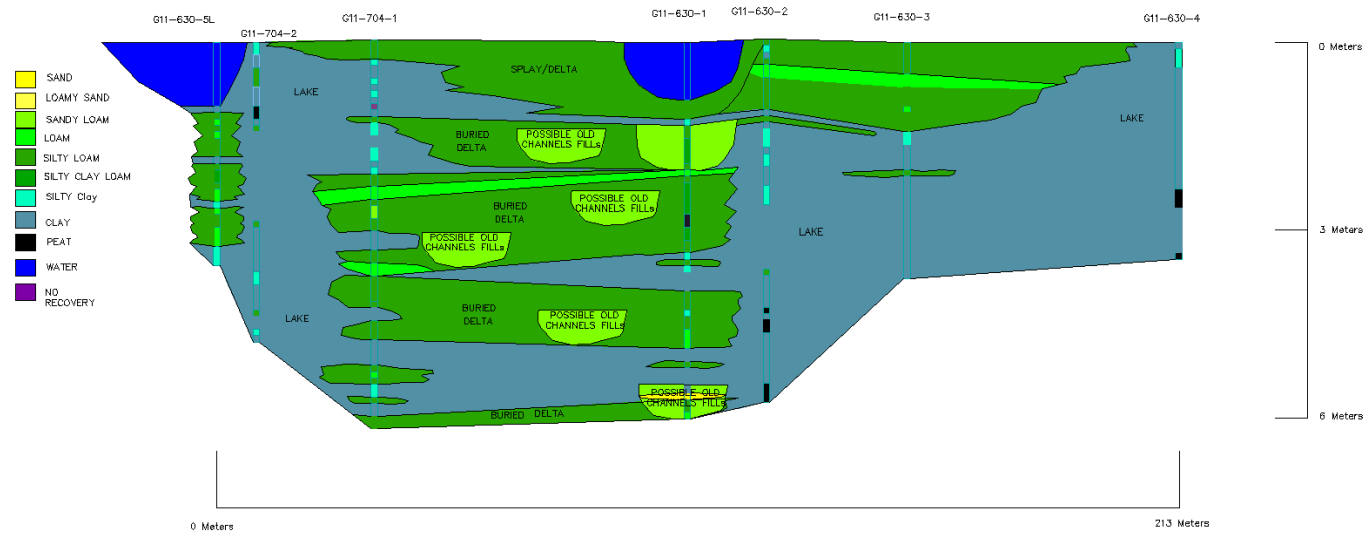
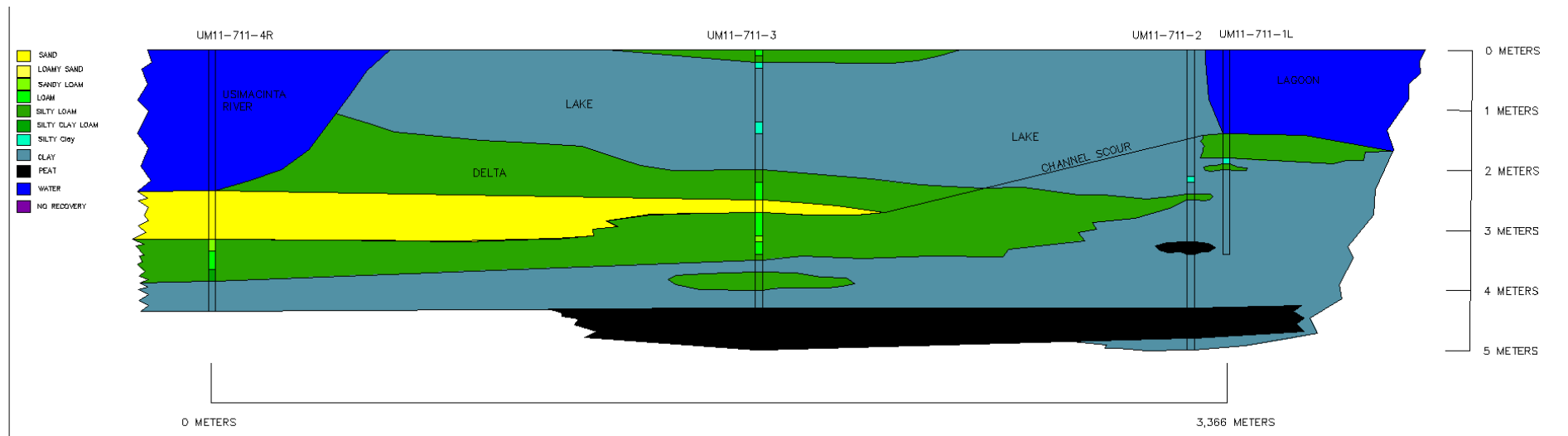
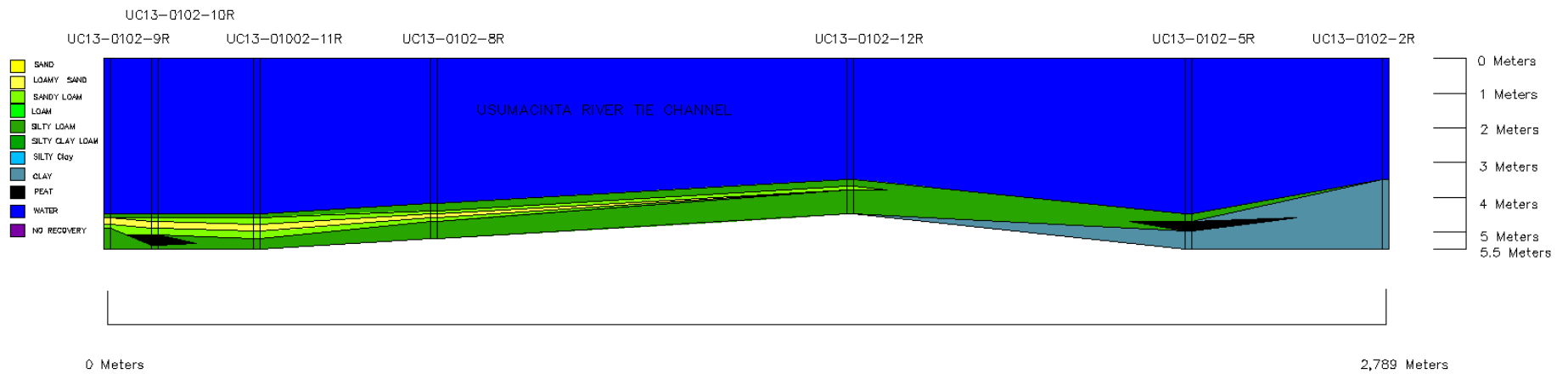


Figure 2-27 Tie channel cross-section 3.



a)



b)

Figure 2-28 a) Tie-channel longitudinal profile down the levee on the Usumacinta River. b) Usumacinta tie channel longitudinal profile down the center of the tie channel.

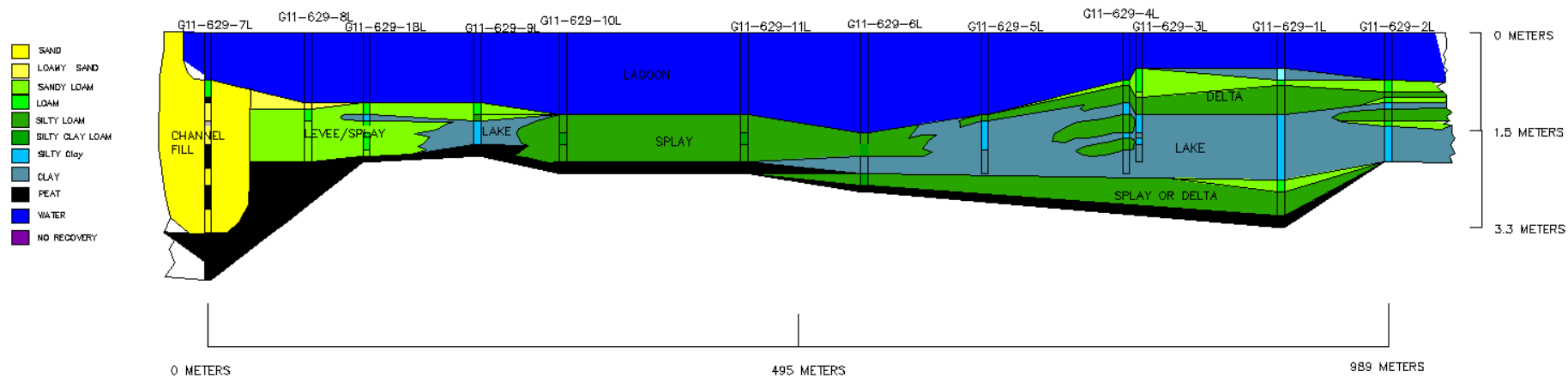


Figure 2-29 Lake cross-section E-W, transecting an old tie channel, splays of the adjacent Grijalva system, and the delta front of the tie channel. The old tie-channel is matured, and filled and visible on the left side of the cross-section. The right side of this tie channel fill has been eroded away by wave actions from the lake.

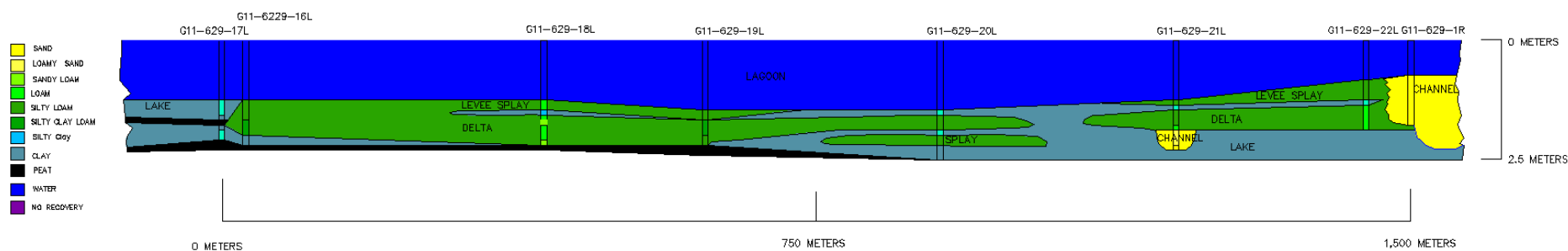
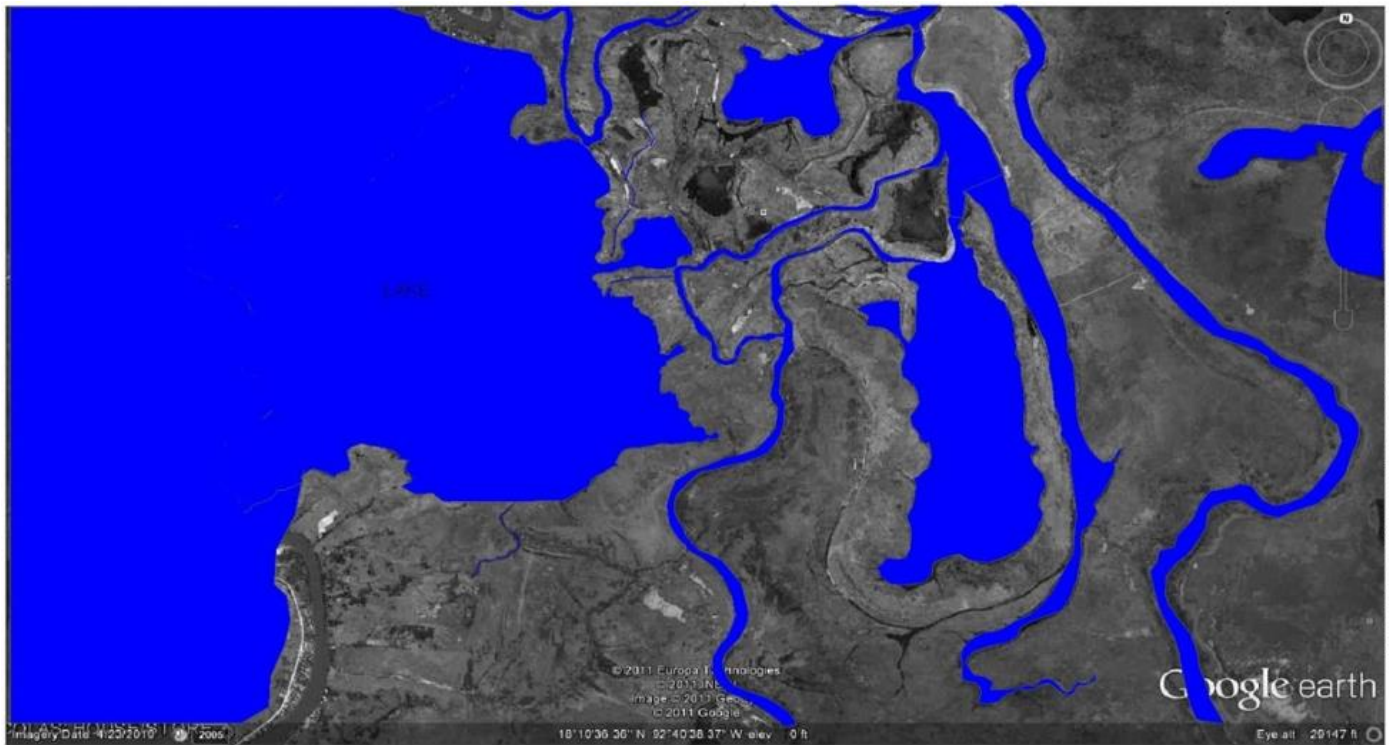
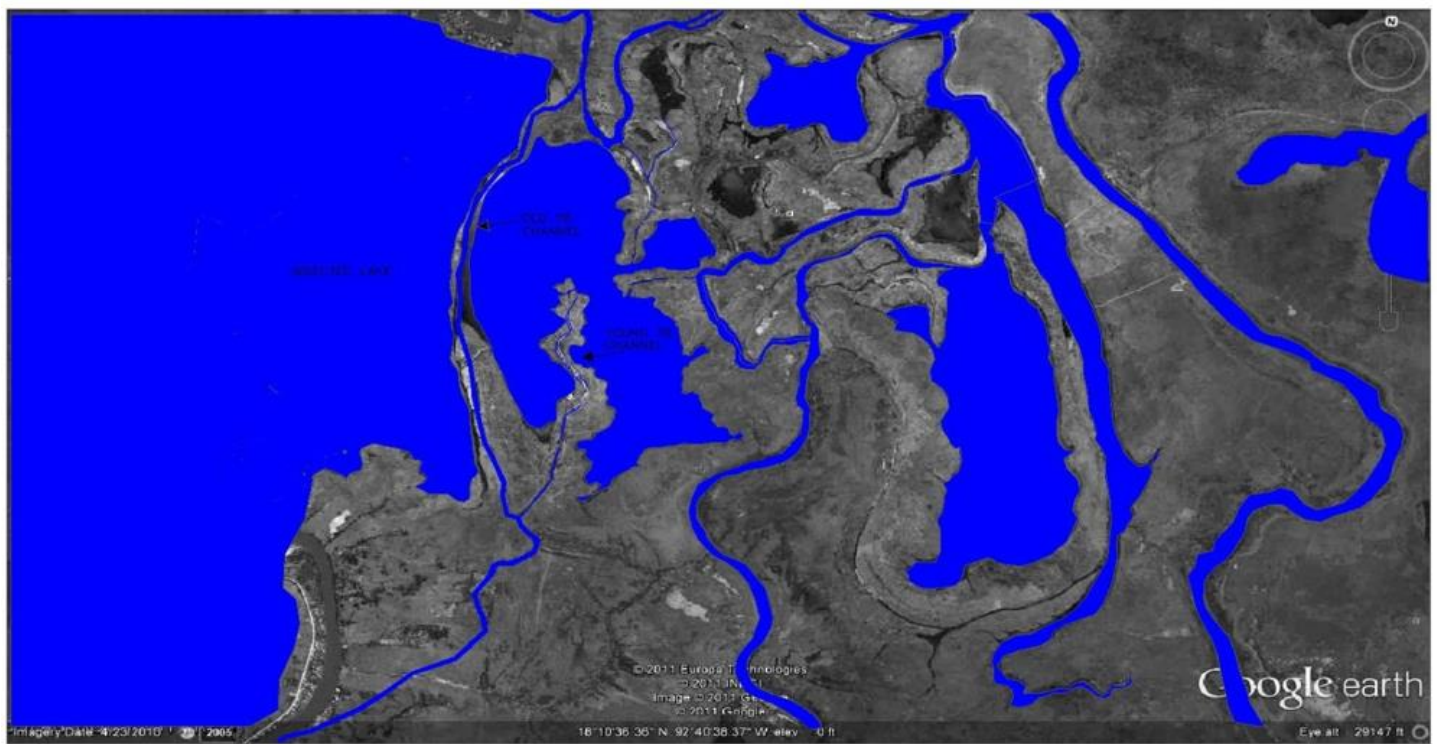


Figure 2-30 Lake cross-section N-S; growth of the old delta can be observed, as can the old channels.

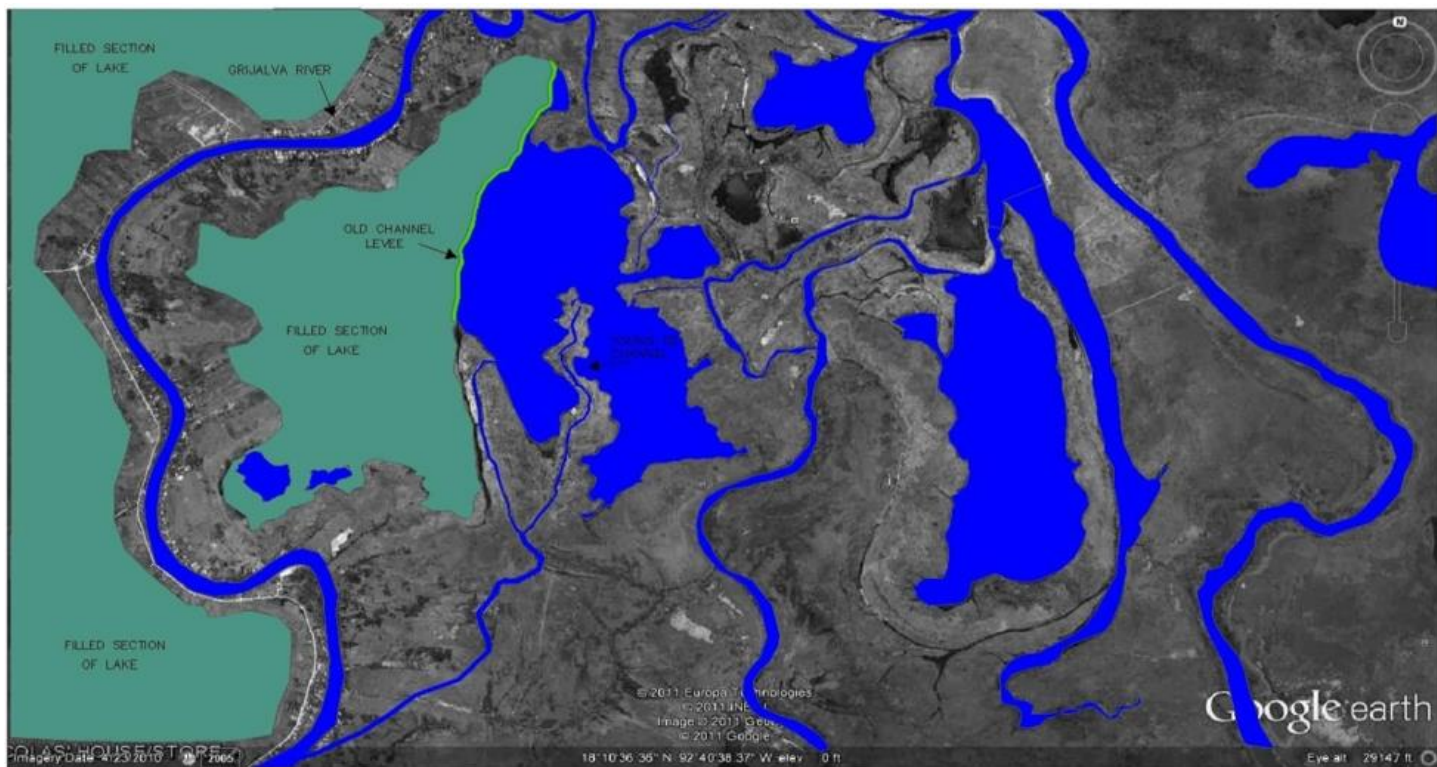
4.6 Lake and Lake-fill Evolution



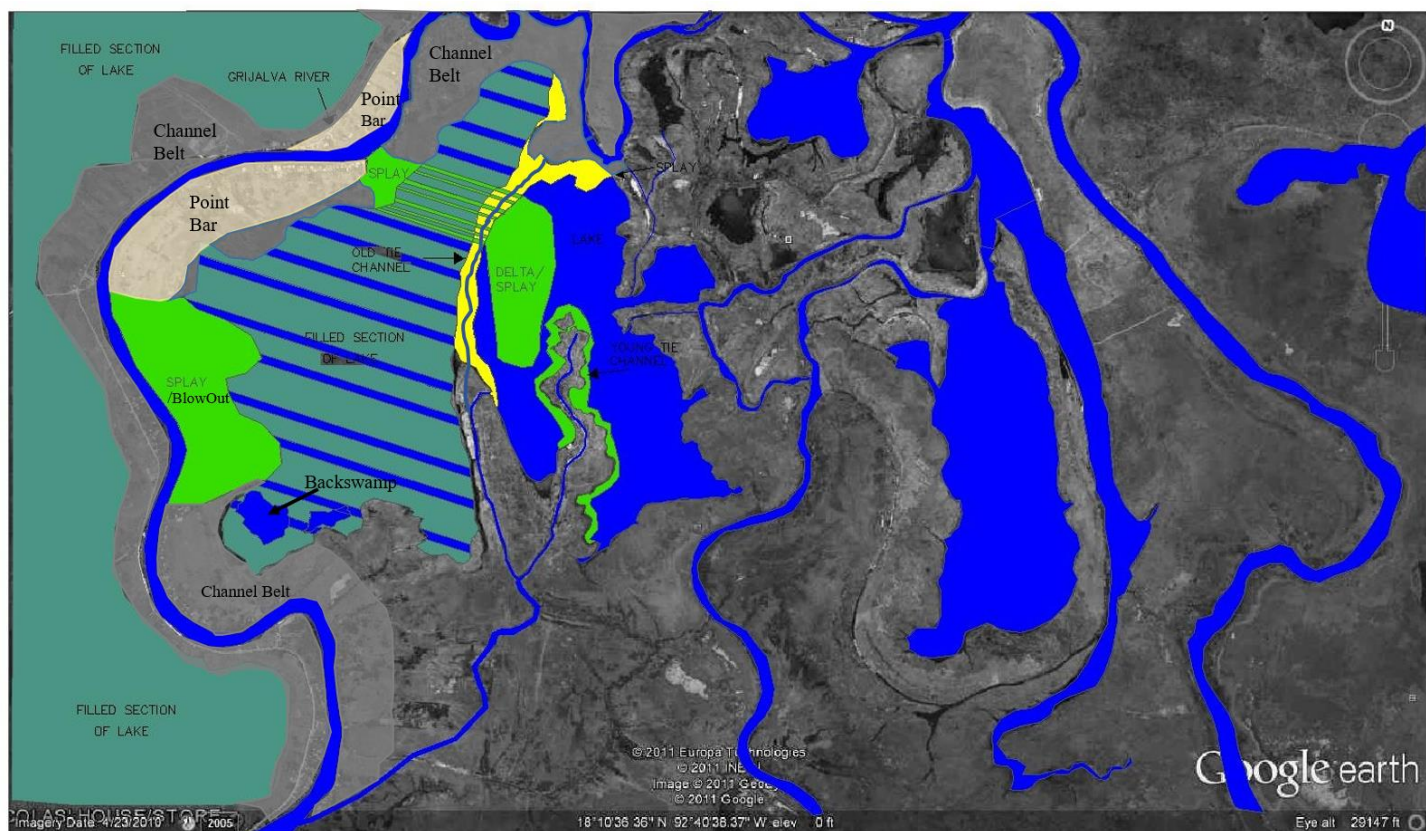
a)



b)



c)



d)

Figure 2-31 a -d) The evolution of a Lago El Campo lake stage 1 through stage 4.

4.7 Accommodation and Aggradation rates

Accommodation and aggradation history is locally revealed in the detailed stratigraphy of the Lago El Campo lake area (figures 2-29 and 2-30). Sediments of the upper part of the Holocene at this location record a dramatic change ca. 5000 year B.P. resulting from rapid to negligible sea level rise. This transition was followed by a deepening of the studied lake area as evidenced by the change from basal peat to lacustrine facies (Figure 2-31a). Early in the evolution of the lake, a muddy delta propagated across the lake that formed at the mouth of a tie-channel. The delta, consisting of loam and sandy loam delta-front deposits, grew across the lake until this tie-channel connected with another channel on the north side of the lake and sand then moved through the channel connecting the two separate channel belts (Figure 2-31b). Once the tie-channel extended across the lake, the lake became split by the tie-channel levee. This tie-channel ridge caused the compartmentalization of the lake. The part of the lake on the west side of the tie channel filled with overbank deposits from the adjacent Grijalva River, but the tie-channel levee protected the current lake (east side of the tie-channel) from filling by forming a topographical barrier to sediment influx. Splay overflow from the Grijalva River started dumping sediment laterally into the adjacent lake, but couldn't get over the old channel until it filled the adjacent lake compartment (Figure 2-31d). An earlier or roughly contemporary tie channel likely served as a forerunner of the channel course currently occupied by the Grijalva River.

Nine (9) peat samples were submitted to Beta Lab for analysis. Dates from laterally continuous peat layers were used to constrain local accommodation and accumulation rates within the targeted study area (Figure 2-16). Fifteen (15) of the fifty-four (54) borings contained peat at multiple depths, which would allow for a more detailed analysis of rates vs. time because it is possible to subtract different depths and dates to break out intervals of accommodation. However, unfortunately none of the nine (9) boring from which the peat samples were obtained and submitted for dating were from any of those fifteen borings containing multiple peat

layers, Therefore, only an average of the date vs. depth below sea level was obtainable as a means to get an average rate of accommodation and accumulation for the last 5k years.

There is some small variation locally within the Grijalva Delta with respect to accommodation. Its variation in accommodation space is one component of the complicated set of variables present within this delta system (different rates of compaction/subsidence, varying rates of sedimentation and sediment types). The variation in accommodation space is minimal and only accounts for a small error in the calculation for accommodation vs. time estimates. Accommodation rates were assessed by comparing dates and levels of peat layers to current sea level, and accumulation rates were assessed by comparing these same peat layers to a depth below the sediment surface. Accommodation is attributed to a combination of subsidence and modest sea-level rise ~ 6.0 mm/yr. (Balsillie and Donohue, 2004) within the past 5000 years. Boring UC13-0102-1 showed the greatest accommodation rate within the study area at 1.9 mm (0.07 in) per year (Table 2-3). Boring GL12-1228-5R showed the least accommodation rate at 0.4 mm (0.02 in) per year (Table 2-3). Average accommodation rate is 0.46 mm over the past 5000 years.

Table 2-2 **Subsidence/Accommodation Rates from Radiocarbon dates in Area 2.**

Sample ID	Sample Range	Top of Sample	Date BP	Correction Range
GL12-1227-1	4.0-4.4m	4m	3820	+/- 30 BP
GL12-1228-4R	1.7-2.0m	1.7m	2710	+/- 30 BP
GL12-1228-5R	0.8-1.1m	0.8m	2140	+/- 30 BP
UC13-0102-1	3.5-3.8m	3.5m	1840	+/- 30 BP
UC13-0102-3	2.4-2.6m	2.4m	3660	+/-BP 30
UC13-0102-4	3.5-4.0m	3.5m	4270	+/- 30 BP
UC13-0103-1	3.6-4.0m	3.6m	3630	+/- 30 BP
UC13-0103-3	4.7-5.0m	4.7m	4810	+/- 30 BP
UC13-0104-8	3.7-4.0m	3.7m	4690	+/- 30 BP

The assumption is that peat beds form at or near the contemporary sea level and that the peat was formed at the former surface as a glade, much like the current surface features (see Tornqvist et al., 2008, on their research on subsidence in the Mississippi delta area).

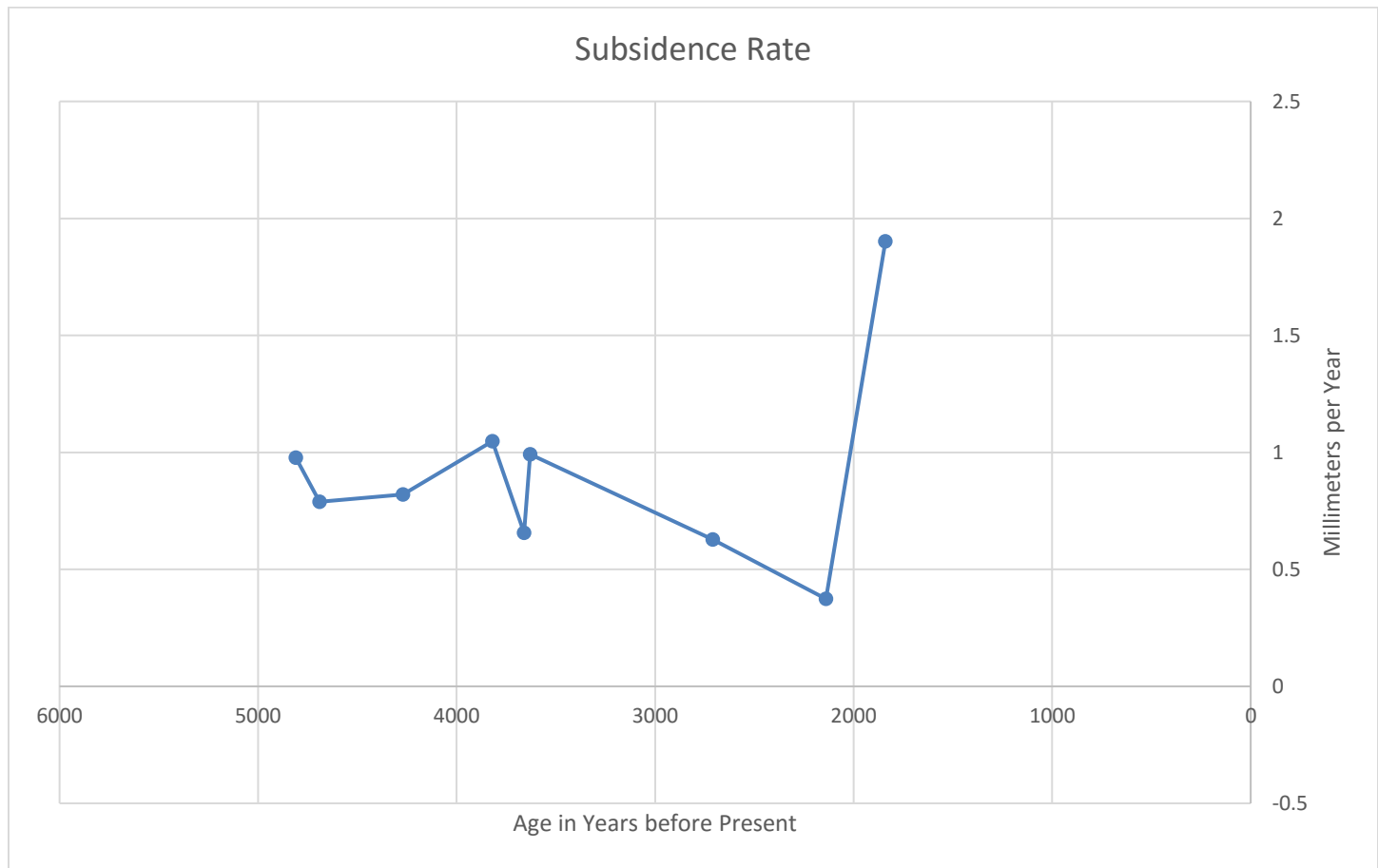


Figure 2-32 Accommodation vs. Time based on nine (9) peat samples submitted for radiocarbon dating.

Data that was obtained from the lab analysis of the nine (9) previously mentioned peat samples provided a date range for a single regional peat layer that was encountered across the delta (see figures 2-16 through 2-30 and Tables 2-2 and 2-3). These data allowed for a common surface to be used to correlate accumulation rates from within the floodplain lakes. Table 3 shows that sediment accumulation rates do not consistently match the accommodation rates, and space is commonly unfilled. This mismatch allows for the formation of the floodplain lakes that are commonly seen in wet-high accommodation system, such as those seen in the Grijalva Delta.

Table 2-3 Sediment Accumulation Rates in Floodplains Lake that had peat in the boring. All measurements are in meters.

Sample ID	Depth to Peat	Sediment Thickness	Depth of Water/Unfilled Space
GL11-629-10L	2.3	0.9	1.4
GL11-629-11L	2.5	1	1.5
GL11-629-16L	2	0.9	1.1
GL11-629-17L	1.6	0.5	1.1
GL11-629-18L	2.1	1	1.1
GL11-629-1L	3.1	2.5	0.6
GL11-629-6L	2.7	1	1.7
GL11-629-7L	1.2	0.4	0.8
GL11-629-9L	2.1	0.9	1.2
GL11-630-5L	3	1.1	1.9
GL11-706-3L	1.7	0.9	0.8
GL11-706-4L	2.4	1.5	0.9
GL11-706-5L	2.6	1.8	0.8
GL11-706-6L	2.4	1.2	1.2
GL11-706-7L	2.2	1.2	0.8
GL11-706-8L	2.5	1.4	1.1
GL11-706-9L	2.1	1.7	0.4

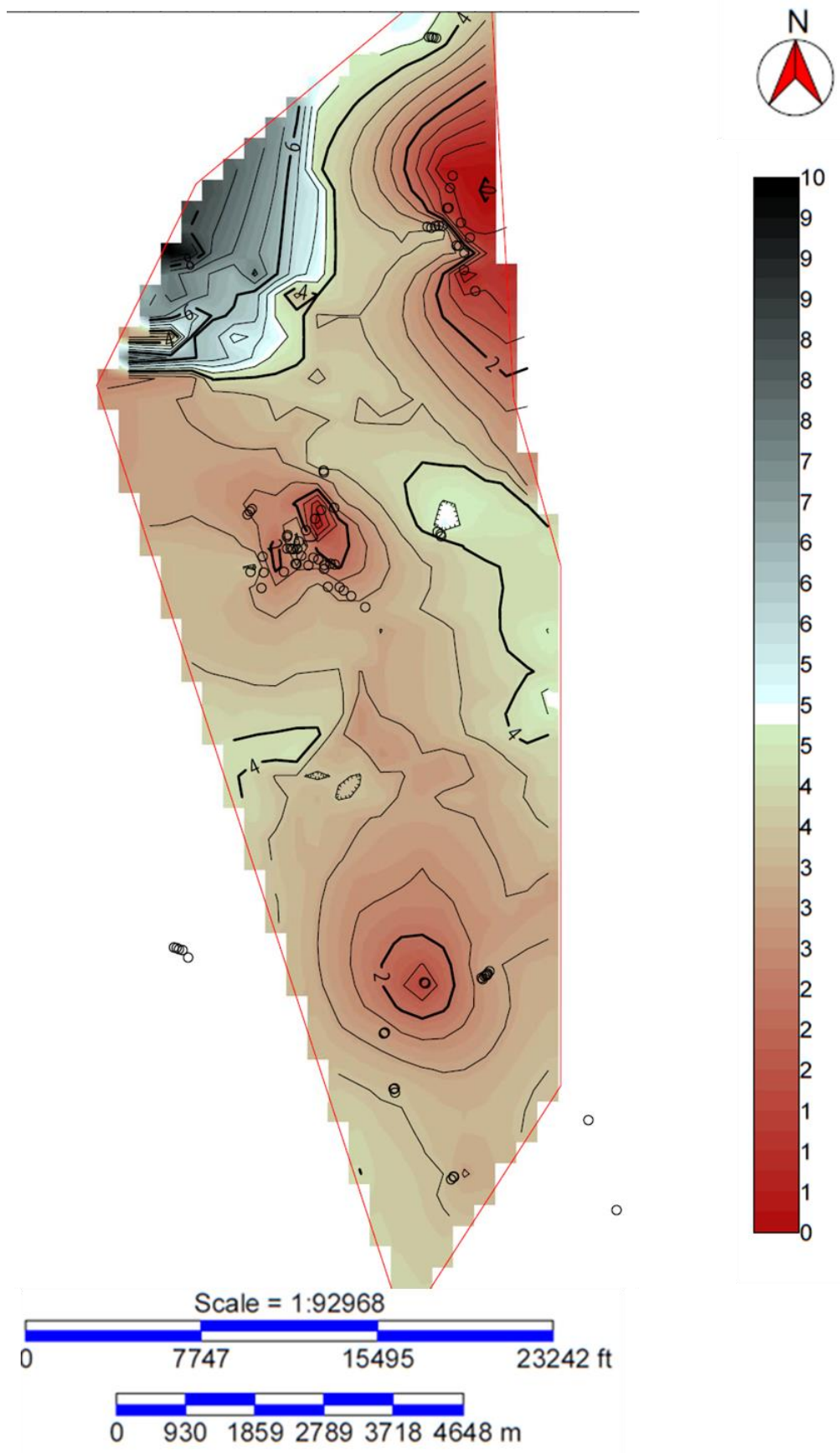


Figure 2-33 Accommodation space based on surface of peat in the floodplain lake area centered on Lago El Campo.

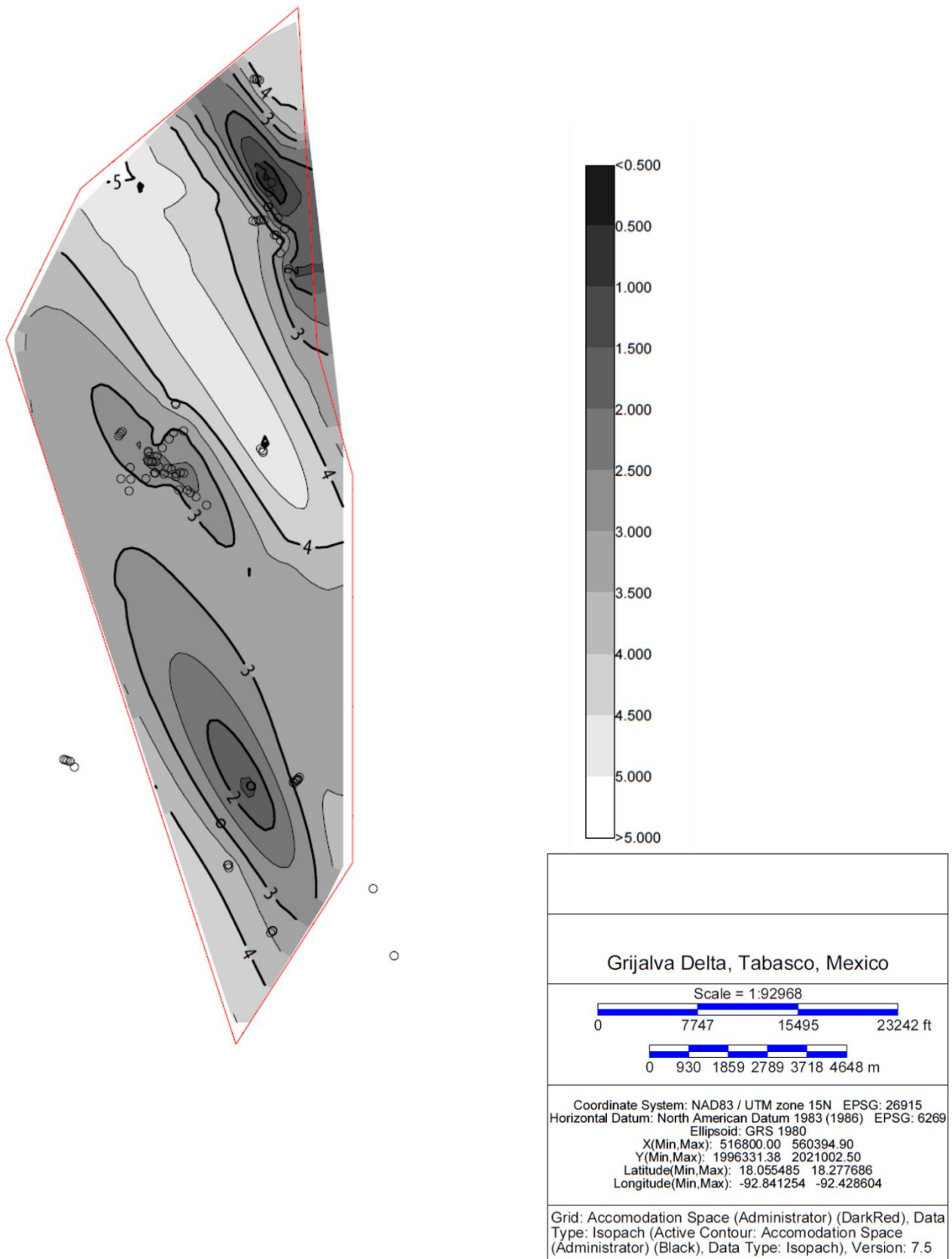


Figure 2-34 Accommodation space fill based on sediment thickness above peat in the floodplain lake area centered on Lago El Campo.

5.0 Processes and Rates for High-Accommodation Landform Evolution and Aggradation

The Grijalva system can be subdivided into channel belt and floodplain deposits, formed from lateral accretion (within channel) and vertical accretion (overbank) deposits, respectively (Brierley and Fryirs, 2005). Floodplains can be further divided into proximal (channel-marginal) and distal (valley-marginal) zones. Floodplain form reflects the arrangement of out of channel sediment build-up and sediment reworking at flood stage. Proximal-distal gradation in grain size is common, dependent on the nature of the channel-marginal units, and whether they allow deposition of coarse sediments beyond the channel zone.

5.1 The “Gun-Barrel” Hypothesis for Channel Propagation

The establishment and growth of new channels are a primary process in landform evolution and aggradation in wet high-accommodation systems. Day et al. (2008) showed that deposition by development and aggradation of channels accounted for over 40% of total deposition over a 340 year period over a similar wet high-accommodation Fly River system in New Guinea. Rowland et al. (2005), Day et al. (2008) and Constantine et al. (2010) have drawn attention to tie channels with bi-directional flow connecting the main river to oxbow's and other floodplain lakes. On the Fly River in Papua, New Guinea, these channels play a major role in transferring fine sediment from channel to flood basins, resulting in about 40% of the total river sediment load being deposited overbank and up to 10 km away from the main floodplain channel (Day et al., 2008). Avulsion and development of new channels across emergent floodplains by incisional (Mohrig, 2000; Slingerland and Smith, 2004) and reoccupation (Slingerland and Smith, 2004; Aslan et al., 2005) processes are well covered and apply here as well. Channels transecting mudflats and emergent areas appear to initiate from splays and levee breaches that evolve stepwise into permanent channels (incision: e.g. Smith, 1989), or locally follow older channel courses still emergent as low topography on floodplains (reoccupation: Figures 2-17 through 2-24 and 2-26). What distinguishes wet high-accommodation systems like the Grijalva, however, is the diminished area of the emergent floodplain. Large areas of standing water do not promote development and growth of new channels by incisional or reoccupation processes, and incision and reoccupation, though active, are subdominant processes for channel development. Instead, channel propagation (e.g., Edmonds and

Slingerland, 2010) across standing bodies of water is the primary means by which new channels grow. Tie channels that join lakes to the main channel lengthen across lakes and continue to grow until abandoned, or they link with another channel in the system. Tie channels that endure can gain sufficient flow and length to transfer discharge beyond the confines of the initial lake they tie, and thus eventually become primary distributaries. Because most of the main distributaries of the Grijalva system cross standing bodies of water, including the main Grijalva channel, they would likely have each been tie channels at some point in their history.

The growth and evolution of tie and distributaries channels drive aggradational processes and warrants particular consideration here. This section pulls together recent and emerging ideas on the propagation of channels across standing water bodies to develop a model for the growth of distributary channels in high-accommodation settings like the Grijalva system. This model is here referred to as the “gun-barrel” hypothesis.

Channel propagation works through the growth of subaqueous levees at the mouth of channels debouching into standing water bodies. One central component for the formation of the subaqueous levees is the jet theory established by Tollen in 1926 (Bates, 1953). Sedimentation at the margins of a jet has long been recognized as levee growth mechanism (Bate, 1953; Axelsson, 1967; Write, 1977; and Edmonds and Slingerland, 2010). When the suspended load transported by the channel enters the still water of a lake, the river jet mixes with the still lake water at the edge of the jet because of friction. This process results in deposition along the outer edge of the jet due to the reduction in velocity. Subaqueous levees are known to form at the mouth of these channels within the delta front. The levees form where the river water jet meets with the frictions of the basin water causing deposition of the suspended load and the piling of sediments into subaqueous levees (Rowland et al., 2010). The levees develop and grow subaqueously basinward.

Rowland has been able to replicate levees similar to the tie channel levees observed in Mexico, the Fly River, and the Denton Creek delta at Grapevine Lake in Texas (Tomanka, 2012) in flume studies. Rowland found that sediment particle size, therefore settling velocities, is a controlling factor in levee morphology; straighter levees are the results of higher settling velocities whereas slower settling velocities result in levees flared towards the toe (Rowland, 2012). The tie channel cross-sectional profiles seen in Figures 2-28 a and b

and Figures 2-30 and 2-6 are consistent with the levee morphologies of the experimental levees of Rowland and other workers. Tomanka (2012) found that the Denton Creek levees were also consistent with this cross-sectional profile.

The cross-section at the terminal end of a tie-channel propagating across a lake in the Grijalva River basin (Figure 2-26) shows a lack of sand at the mouth of the tie channel. In the center of the cross-section at the base is the first of a series of buried deltas, some with penetrations of a likely channel on the eastern margin that has cut through the surrounding delta lithofacies. The channel fill lithofacies consist of loam and sand, but the deltas from these types of deposits are consistently muddy, with loams generally as the coarsest material and sand layers rare. The cross-section shows a series of buried muddy deltas like the current surficial delta with offset channels that have propagated across the lake cutting down into the clay-rich lacustrine lithofacies. The delta lithofacies are coarser than the lacustrine lithofacies, with silty loam as the dominate delta texture. The channel fills are also muddy lithofacies, however, but tend to be slightly coarser than the delta front lithofacies and are characterized by loamy strata with thin sand-to-sandy-loam beds. The total width and thickness of these delta and channel complexes can be ascertained from the cross section, but the surficial example suggests that the channel fill occupies less than 1/4th of the width of the complex. The boreholes thus have less than a 1:4 chance of bisecting channel fills, and are inferred where not encountered based on the analog with the surface example. At the surface is the final splay/delta body that has built into the lacustrine lithofacies. The mouth of the active tie-channel is shown in the center of the splay/delta. The splay/delta body is made up of the same muddy lithofacies as the buried delta bodies.

Continued growth of mud rich subaqueous levee deposits eventually builds levees to emergence where dewatering and vegetation harden these levee strata. Levees along propagating tie channels are relatively straight and consist of silt rich strata with minor sand stringers deposited over cohesive prodelta silty clay cut into the lake clay deposits. These cohesive subaqueous levees built up over time and became embedded with vegetative debris allowing the levees to resist erosive forces of higher flows during the rainy season. Levees continue to build until they became emergent and, while subaerially exposed, the levees became highly

vegetated, thus hardening the levees even more. Tomanka (2012) documented the coarsening up sequence of levee construction, and observed that trees and woody debris became lodged on emergent subaqueous levees during flow events, and that over time, these deposits are buried, become part of the levee, and increase the stability of the levee (Tomanka, 2012). Archer (2005) suggests that humic acid and low pH could aid flocculation of clay and silt in the Rio Negro, and the same probably applies to drainages elsewhere. This process likely also aids in clay deposition and levee growth.

Suspended load outpaces bed load transport forcing the channel to propagate as a non-bifurcating mud delta (Figures 2-28a and 2-28b). Sand becomes trapped upstream in the channel because of low gradients, whereas the mud continues to be transported by discharge momentum. Lamb et al. (2008) discusses the linkage between slope gradient and critical shear stress for particle incipient motion and sediment transport. A slope-dependent critical Shields stress has broad implications as the assumption of constant τ^*_c is the basis of many models used to predict such things as bed load transport, debris flow entrainment, bedrock erosion, downstream fining, and bed particle size (Lamb et al., 2008). Mud deltas do not need to bifurcate because there is no sand bar creating a blockage at the channel's mouth. Edmonds and Slingerland (2009) modeled the formation of deltas formed by suspended load systems and found that, as the suspended load became finer and more cohesive, the deltas didn't experience bifurcation and resembled the bird's foot morphology similar to the channel networks seen in the Grijalva system. The propagating channels of the Grijalva system lack sand deposits near their mouth and behave like the modeled mud deltas, with the exception that they rarely bifurcate.

A longitudinal profile of a young tie-channel in a lake in the Usumacinta River lake system (Figure 2-28a) shows the suspended load outpacing the bedload (sand). The profile starts within the tie-channel just down from where it joins the feeding tributary channel of the Usumacinta River with the next two borings installed within channel fill about two feet from the open channel and a final boring installed in the lake at the mouth of the tie-channel adjacent to a small island within the lake. Lacustrine lithofacies build above the peat facies in the center of the cross-section. The peat is evidence of a shallow lake or swamp that over time became too deep for the formation of peat, thereby transitioning to an open lake condition. The lacustrine lithofacies

was subsequently built over by the delta of the tie-channel. There is a thick fine channel fill between the delta and basal sand fill in the second boring. The current delta front is visible below the active channel at the mouth of the channel in the last two borings. There is a large sand body that has moved about halfway down the tie-channel as bedload transported down the channel from the confluence of the tie-channel and floodplain tributary of the Usumacinta River. This sand does not make it out of the channel to be deposited in the delta front and lags delta propagation. Therefore, there are no sand bars in the mouth of the tie channels. This absence is the reason the tie channels do not bifurcate and form traditional lobate geometries, but propagate as ribbons. The lack of sand in the mouth of the tie channels on the delta front is consistent in all cross-section of all of the tie channels and is consistent with the finding of tie channels on the Fly River and Mississippi River (Rowland et al., 2005, 2010) and Denton Creek (Tomanka, 2012).

An additional longitudinal profile of the same young tie-channel in Figure 2-28a starts within the tie-channel just upstream from where it joins the feeding tributary channel of the Usumacinta River with the next seven (7) borings installed within channel fill about two feet from the open channel and a final boring installed in the river at cross-section prior to the mouth of the tie-channel (Figure 2-28b). Lacustrine lithofacies build above the peat facies at both ends of the profile. The lacustrine lithofacies were subsequently built over by the delta of the tie-channel. There is a large sand body that has moved about halfway down the tie-channel as bedload down channel from the confluence of the tie-channel and floodplain tributary of the Usumacinta River. This sand does not make it out of the channel to be deposited in the delta front and lags delta propagation.

Large flows mobilize sand, some of which will be transported to the end of channels, but by this time the levees are hardened into a “gun barrel” that is not easily breached, and the sand mobilization does not result in bifurcation, and typically does not even reach the channel mouth. Most of the sand that escapes the channel appears to form overbank sheets at high flow conditions. Coarser material will start to move through the system as the levee grows basinward. During storm events, the flow will top the levee and the coarser material will be deposited on and adjacent to the levee with the finer sediments being deposited out on the floodplain. At times, the coarser material will be temporarily deposited in the channel bottom. This deposition usually occurs at the

waning flows of storm events. If the channel bottom becomes higher than the adjacent floodplain, the levee can be breached by a splay or a blowout depositing sheets of coarser material such as the sand sheets seen in Espina Lagoon (Figure 30). The overtopping of the levees allows the levees to grow vertically and major floods that over top the levees and blowouts allow the levee to grow horizontally as well. It is the sheets of sand formed in the lake section by this horizontal growth that are called wings. Huling (2014) discusses the wings, sand sheets from the overtopping of the levees, in his work on the Jurassic Kayenta Formation in Utah. Tomanka (2012) also documented the deposition of wings from flows overtopping the levee in his work on the modern delta of Denton Creek, Texas. Huling (2014) documented wings extending as far as 25 meters (82 ft.) and Tomanka (2012) measured the width of sand wings up to 183 meters (600 ft.) in places.

Channels that propagate beyond the lake may eventually grow into a mature river system through-growing distributaries that acquire the energy to move sand as bedload. These channels make the sand stringers that locally bisect lake deposits. Figures 2-25, 2-28a, 2-28b and 2-30 show the tie channels that have grown to sufficient size to move some of the sand bedload across lakes, at least during a high flow event. This movement is evident by the presence of a sand stringer observed in the cores either at the mouth of the tie channels or in-channel up dip from the mouth of the tie channels. The propagation of channels through standing water bodies eventually results in bisection of lakes and is the process that generates the elaborate network of distributaries observed in the Grijalva system.

Lacustrine lithofacies top older peat facies at the bottom of the cross-section seen in Figure 2-27. The peat is evidence of a swamp. Over time the swamp got deeper and reached a point where the lake was too deep for the formation of peat resulting in the deposition of typical lacustrine lithofacies. This process was followed by a propagating delta that is shown as a buried delta in the center of the figure. This buried delta had some sandy wings that could be from a storm pulse. The buried delta was deposited preceding the propagation of the channel front, and the possibility is presented that these deposits record some hyperpycnal flow that carried sand well into the front of the channel. The buried delta was topped by lake-fill strata that were subsequently

topped by continued muddy delta deposits and then topped by a levee splay system. The delta and levee splay deposits are made up of coarser grain material than the lacustrine lithofacies. The channel is active and unfilled.

Figures 2-29 and 2-30 demonstrate how a large lake system was bisected by a tie channel that propagated across the lake as a mud front delta and connected with a larger channel belt on the north side of the lake. Once the channel connects downstream, sand begins to move through the system (Figure 2-30). The reason for this process is that once the tie channel connects with the larger channel, the tie channel is no longer flowing into a stagnant water body; therefore, the backwater effect no longer controls the system. This effect allows the bedload to continue being moved during normal flows. The evidence of this process is visible in the East-West lake cross-section where the mature tie channel belt on the western portion of the lake connects with a main channel belt, and then sand moves through the system creating the sandy ribbons. If the mature tie channel captures the flow of the main channel, the tie channel can grow and mature into a large river like the Grijalva River (see Figures 2-31a-2-31d).

5.1.2 Lakes and Lake-fill evolution

Channel propagation processes result in a dynamic and interactive evolution between channel and lake-fill processes. This type of propagation process is best exemplified in the Pantanos de Centla where a tie-channel propagated across this flood basin lake in an orientation parallel to the main Grijalva River (south to north). After the lake was compartmentalized by the tie-channel, splay sediments from the adjacent Grijalva River could only reach the new western compartment. This western compartment has filled over the past 20 plus years and has evolved into a vegetated glade while the eastern compartment remains as a lake. Filling of the western compartment now permits bypass of sediment from the Grijalva River into the eastern compartment which has begun filling with splay delta sediment from the Grijalva. Close examination of high-accommodation flood basin systems in the Grijalva River area reveal that deposition in flood basins is characterized by local rapid aggradation of sites and compartments rather than by a uniform aggradation across the flood basin. This model implies that facies in lakes may not correlate chronologically across tie-channels because lakes that are

lateral in the rock record may have filled at different times with partitions to sediment in between the different partitions.

The co-evolution of tie-channels and flood basin lakes are a key element of this aggradational process. The cross-sections (Figures 2-29 and 2-30) of a lake within the Grijalva River basin shows the peat located at the bottom of the cross-section is evidence that the lake was originally an extensive swamp that allowed the organic-rich clay sediments to form a peat (Figure 2-30). The tie-channel that cut through the delta and into the underlying peat filled with alternating layers of sand and peat, and is topped by a layer of sandy loam. It does appear to have sufficient sand to connect the Grijalva belt and the tie channel at the southern and northern terminus of the channel, respectively. In the center of the cross-section is a delta/splay body from the river over bank deposits (Figure 2-30d) extending out into the north side of the lake. A buried delta or splay is located on the eastern side of the cross-section. The buried delta or splay is topped by lacustrine lithofacies followed by another delta from the young tie-channel visible in Figure 2-30. The delta of the young tie-channel consists of silty loam to sandy loam lithofacies. The coarser facies were at the mouth of the tie-channel on the north end of the propagating delta.

The North-South cross-section of the same lake in Figure 2-29 shows the basal peat used as a marker in the south does not extend into the lake strata of the north at this horizon (Figure 2-30). The south end of the lake was either much shallower than the northern half, or the swamp that is evidenced by the peat facies in the south is from a later lake body than in the north. The peat in the south end of the lake is topped by a clay lacustrine lithofacies. The same delta and splay that was visible in the center of Figure 2-29, with inter-bedded lacustrine lithofacies, is apparent in the middle of this cross section. This cross section also shows this delta and splay to be 631m long and 325m wide, respectively (2,070 ft. long and 1,066 ft. wide). An old channel cutting into the lacustrine facies is visible on the north end of the lake below the delta and levee splay of the active channel flowing into the lake from the north. The buried channel is filled with loam to loamy sand lithofacies and the active channel is filled with one (1) meter of sand. The sand in the northern end of the lake records a

splay that poured from a breach in the tie channel that runs along the north perimeter of the lake. The lower delta deposits below this appear to be related to propagation of this northern tie channel.

Organic processes are also highly important in the lake depositional processes of the Grijalva system. The floodplain lakes of the Grijalva River delta are very similar to floodplain lakes studied in the Middle Parana floodplain where 5% of the surface is covered with free or rooted aquatic vegetation, although the coverage of aquatic vegetation ranges from 0 to 100% in lakes with areas less than 2 km² (Paira and Drago, 2006). Numerous tie channels, tributary channels and lakes in the Grijalva system are completely covered with these floating aquatic plants to such a degree that passage by boat is not possible during certain times of the year. This coverage is noticeable in aerial images used during this study. Lakes are therefore important carbon sinks and large portions of the thick organic matter on their surface can be remobilized and completely excavated during large floods (Drago et al., 2003).

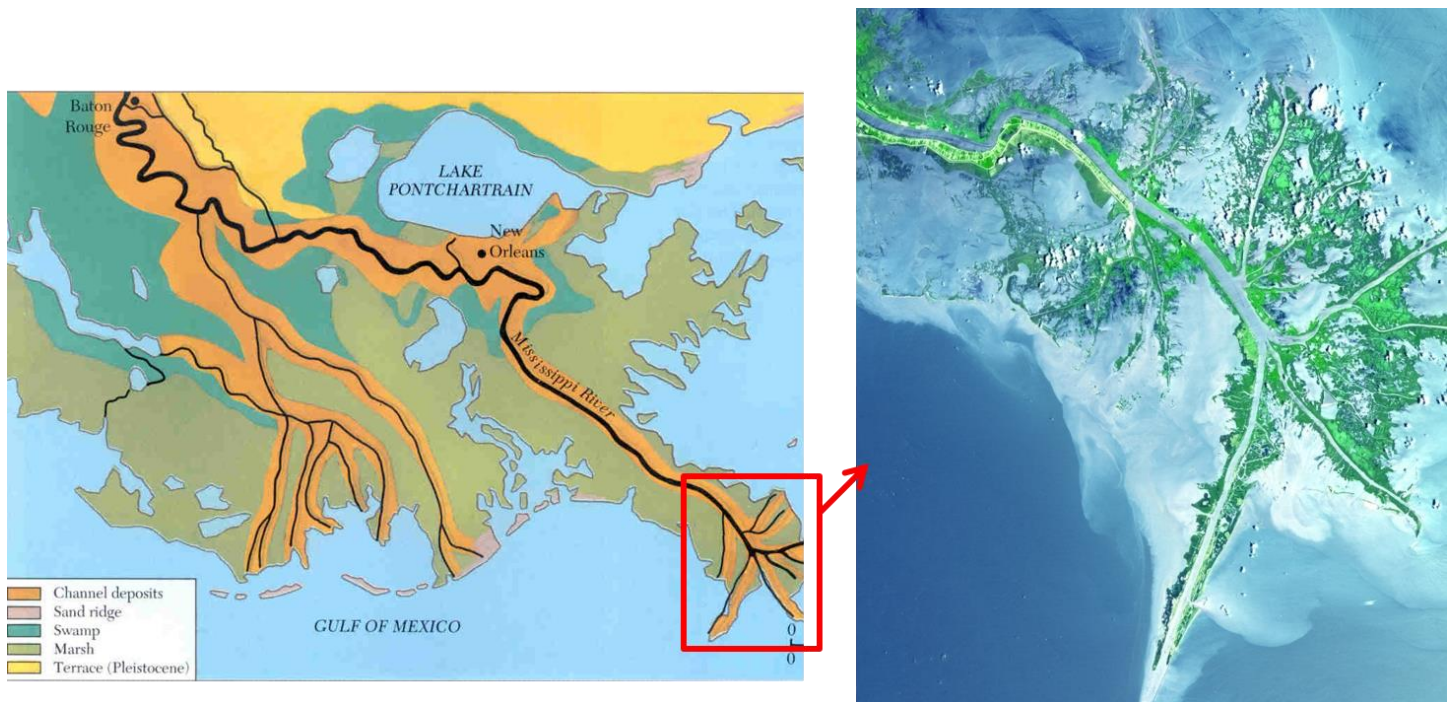


Figure 2-35 Progradation: the generation of distributary channels by progradation (seaward aggradation) has the greatest potential for producing widespread alluvial deposits very significant in ancient alluvial sequences. (Slingerland and Smith, 2004)

The high organic productivity in lakes promotes organic-rich clay (lacustrine lithofacies) and peat formed in these organic-rich, low-energy depositional settings. Persistent slack water conditions and high

organic matter availability promotes deposition of a relatively homogeneous succession of very soft fine-grained sediments with high organic content. The elevated organic matter concentrations are commonly found within stagnant or slow-flowing freshwater and are indicative of moist sheltered environments rich with vegetation, such as in a swampland developed at the margins of a lagoon that is occasionally flooded (Rossi et al., 2011).

Accommodation and accumulation are highly uneven in the Grijalva system (Figures 2-29 and 2-30). Syvitski et al. (2000), observed that flow diverges through multiple channels into lakes that point to these lakes being locations of significant sediment sequestration in multiple wet-high-accommodation settings. Satellite imagery shows depression lakes with bright reflectance as a result of high sediment concentrations as the seasonal flood wave pushes sediment-laden water across these zones of depression (Kettner et al., 2010). Some of these lakes persist over millennia suggesting the rate of subsidence at lake sites is commonly still greater than the rate of aggregation (Syvitski et al., 2000). The complex mosaic of accommodation evident in the lake systems of the Grijalva (Figures 2-29 and 2-30) supports this supposition. Elements of the floodplain system appear to persist as local lack-rich systems for long durations. Some of these lakes (e.g., Lake Viento) remain quite deep despite continued sediment input. Other areas (e.g., Pantanos de Centla) record enduring but complex lake and swamp deposition within the area.

Cores of deposits of these lakes argue that these systems do not consistently fill from a set depth with lacustrine clay, but instead have a complex history involving periodic transformation to swamp environments. The East-West cross-section of a lake within the Grijalva River basin (Figure 2-29) exemplifies this pattern seen throughout the field area. The base of the cross section shows a woody/fibrous peat located at the bottom of the cross-section as evidence that the lake was originally an extensive swamp (Figure 2-29). This peat layer was encountered all across both the Grijalva River Basin and the Usumacinta River Basin and appears to correlate with the approximate age and depth below sea level to the peat layer referenced in the research by von Nagy (2003), west of the study area. This peat dates to 4810 years before present and likely is a basal peat recording regional groundwater rise in association with initial marine transgression into the study area (Tornqvist et al.,

2008). This event was followed by a deepening of the lake as evident by the lacustrine clay lithofacies topping the peat (Figure 2-31a). Early in the evolution of the lake, a muddy delta propagated across the lake that formed at the mouth of a tie-channel. The delta, consisting of mainly loam to sandy loam, grew across the lake until this tie-channel connected with another channel on the north side of the lake, and sand then moved through the channel connecting the two separate channel belts (Figure 2-31b). This pattern is repeated in loamy lenses scattered throughout the lake fill recording numerous tie channels that intruded into the lake from multiple entry points over the last 4810 years and records aggradation to date at this site.

Lake deposits in cores show interbedding of lake strata and peat deposition. Layers of fibrous, woody/grassy, peat cutting through the lake's clay deposits (Figure 2-29) indicate that the lake periodically shallowed sufficiently to support rooted plants, but then returned to deeper lake conditions. Glades rich in emergent aquatic grasses and additional woody plants are abundant in the area and record conditions where lakes filled to a few decimeters of water at low flow, and support abundant plant growth and fibrous peat accumulation. This degree of filling likely occurred in this lake fill periodically and temporarily accounted for similar peat accumulation.

Lake-fill sequences of the Grijalva system thus do not reflect a static process of single-stage filling of a local depression, but instead record a complex interplay between aggradation and accommodation over a long history of shifting lake environments. Mixed peat and lake clay strata argue that the lake experienced periods of filling and peat growth followed by deepening and reestablishment of deeper-water lake deposition. This interchange of deposit type attests to the regeneration of accommodation in concert with lake filling. In addition, the lake's evolution revealed periodic intrusion and bisection by channels that altered patterns of sediment input, local lake filling rates, and altered the surficial geometry of the lake body. Therefore, these lakes cannot be regarded as static bodies with enduring geometries, but instead, must endure as lake complexes with a changing depth and facies mosaic that dynamically interacts with distributary channels.

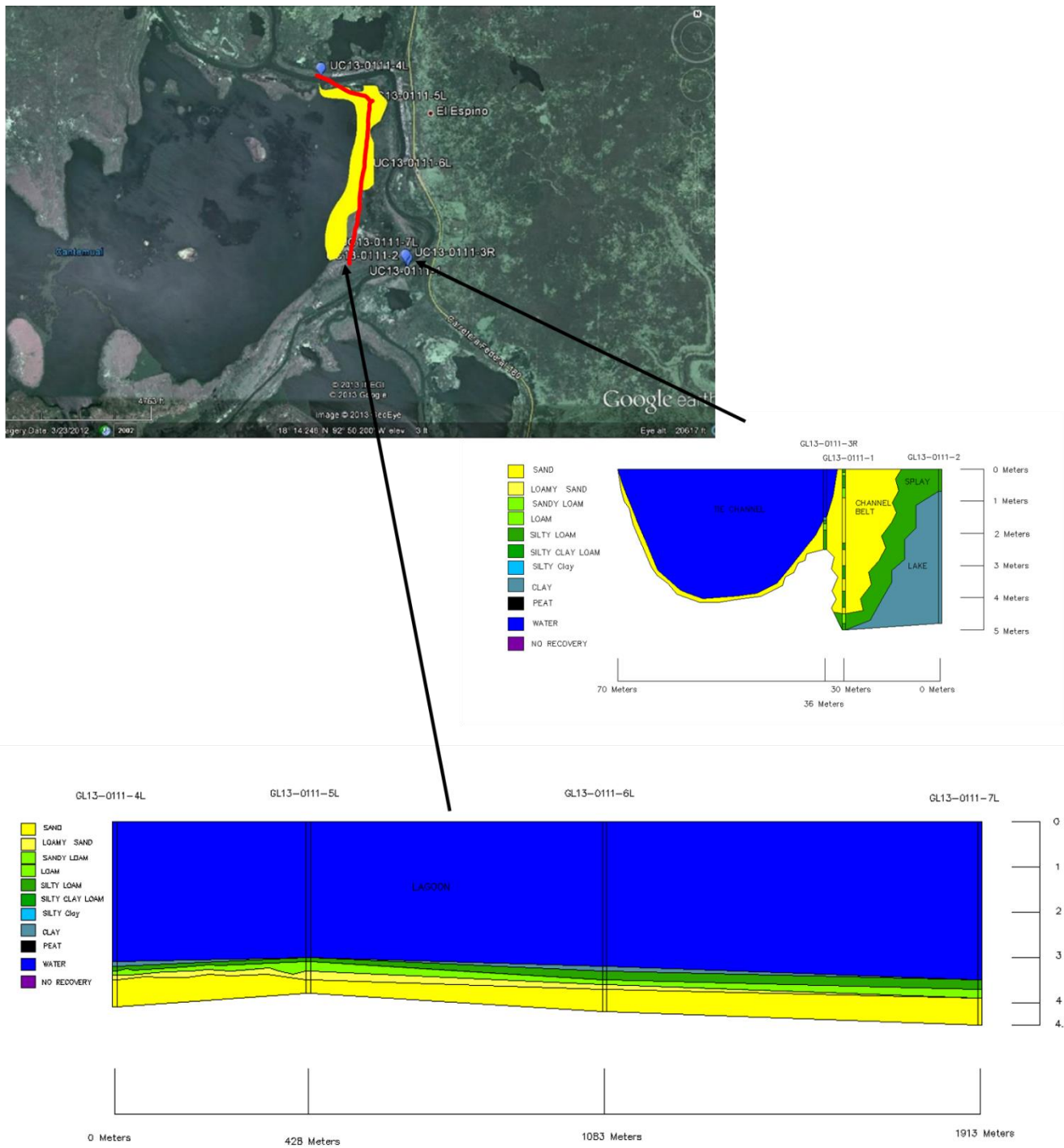


Figure 2-36 Channel cross-section and a longitudinal profile in the Espina Lagoon west of the Grijalva River. Sand sheets are visible in the longitudinal profile.

5.3 Accommodation rates

Colombero et al. (2015) studied 20 ancient fluvial systems and compared the evolution of different fluvial successions that record vertical changes in channel-deposit proportions concurrent with temporal

changes in overall aggradation rates. In this study, no significant relationships were observed between mean channel-complex thickness and mean aggradation rate (Pearson's $r = -0.130$, $p\text{-value} = 0.59$), or between mean channel-complex width and mean aggradation rate ($r = -0.054$, $p\text{-value} = 0.82$) (Colombere et al., 2015). Colombere stated that their results supported the finding of Gibling et al. (2011) that it is dangerous to infer accommodation conditions from the degree of channel-body amalgamation, and further support a recommendation that terms such as high- or low- accommodation systems tracts be avoided when their recognition is based solely on channel-body density.

Data from the study suggest that the evolution of fluvial systems does not routinely follow the pattern expected by common stratigraphic models: observations on channel-body density, geometry, and stacking pattern do not prove to be reliably diagnostic of rates of the creation of accommodation (Colombere et al., 2015).

This study in the Grijalva Delta examines accommodation verse accumulation in a modern system over a much smaller temporal scales than the study of Colombere et al. (2015). The setting is that of high accommodation at the time scale studied, but maybe in a much larger time scale of several hundred thousand years, the accommodation rate may be lower.

The locations of the borings where peat samples were collected are shown in Figure 2-17. These nine (9) peat samples were submitted to Beta Lab for analysis. Table 2 shows the calculated dates for the surface of the peat layers. Boring UC13-0102-1 showed the greatest subsidence rate within the study area at 1.9 mm (0.07 in) per year. This subsidence rate is much lower than the 9 mm (0.35 in) subsidence rate that is occurring just to the west of the study area north of Comalcalco towards the coast (per conversations with Marcos senior geologist Geo Sol).

Whereas the Grijalva Delta system is a high accommodation system, that property does not mean the system is filling at a fast rate. Actually, based on field data collected from the sediment above the peat and ^{14}C dates of the peat, the system is filling at a much slower rate than might be expected. The filling of accommodation space isn't uniform and accumulation happens in a very patchy way that defies the chrono

equivalence of units because most of the sedimentation accumulates on the levees (Figure 2-36 and Table 2-3). These findings are consistent with those studies of the Fly (Day et al., 2008), Mississippi (Tornqvist et al., 2008) and the Rhine (Middlekoop et al., 2010; Berendsen and Southhammer, 2000 and 2001). Accommodation space is filled very slowly, with the accommodation rate filling at different rates across the basin. It is easy to see from Figure 2-33 that even very big rivers can't fill subsidence very quickly in some cases.

The complexity of accommodation interplaying with the unevenness of filling likely contributes to the overall expression of high accommodation though the average rate of accommodation is relatively slow. Luca et al. (2015) found an average aggradation rate of 0.31 meters/1,000 years. Instead of forming a blanketing layer of sediment evenly across the area studied, sediment more often fills the accommodation in stripes (i.e., in propagating channels) and blotches (i.e., in compartmentalized lakes). Nonetheless, the Grijalva system is producing deposits considered high accommodation with respect to the mud/sand ratio and channel-belt connectivity. The interplay of accommodation and sedimentation, however, is complex and non-uniform. It is this non-linear filling behavior spatially that permits low accumulation in protected sediment zones, and this type of sedimentation is likely the key to the preservation of generally high accommodation (muddy) floodbasin deposits within systems that are not aggrading quickly with significant sediment input like the Grijalva system. Likewise, the impact of channel propagation as a pivotal process means that wet high accommodation systems do not generate the sandy wide belts typical of widely migrating channels, and this limited lateral migration likely also contributes to the minimal channel amalgamation.

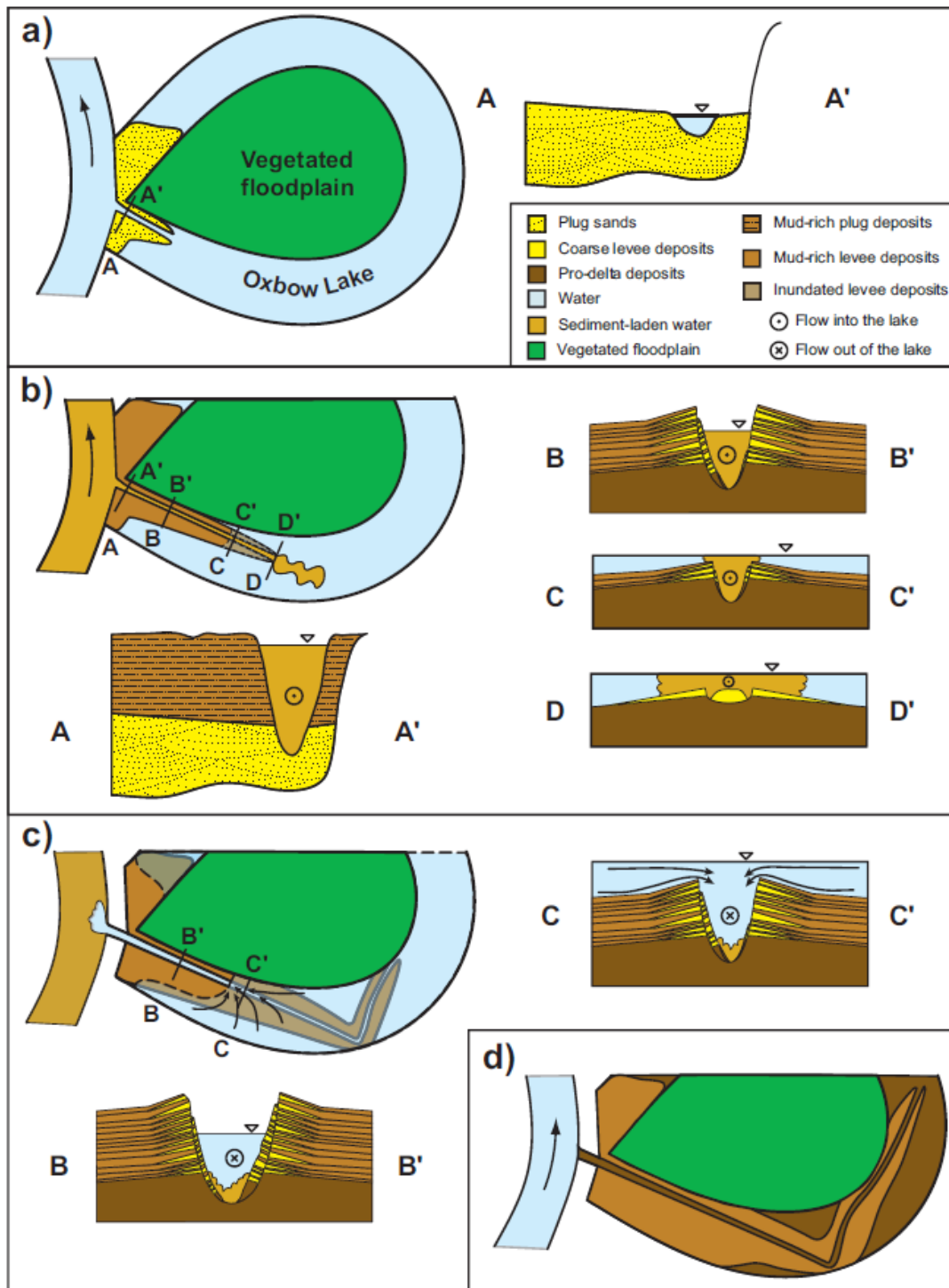


Figure 2-37 Conceptual model of tie channel evolution in a closed oxbow lake. a) Formation of the tie channel occurs coincident with the sealing of the cutoff meander bend and creation of an oxbow lake. b) Continued deposition at the river junction leads to the complete sealing of the oxbow lake from the river (A-A') and creation of a sediment laden jet of water. At the terminus (D-D') of the channel, subaqueous levees form where coarse sediment rapidly

settles out of suspension along the margins of the jet forming levees, and a small mouth bar forms along the channel centerline. c) During outflow from the lake, sediment-poor water spills into the channel over inundated levees (C-C'). In the channel, outflow scours the channel bed, removes sediment, undercuts the banks and triggers bank failures. d) Once the channel ceases to function, the lake slowly fills with mud and organic detritus delivered by floods and runoff from the surrounding floodplain. (Rowland et al., 2005)

6.0 Reservoir implications

This work clearly illustrates some important caveats in the models of Bridge and Leeder (1979) and Allen (1978) and subsequent efforts that equate architecture with accommodation state. First, sedimentation models commonly assume channel belts retain size as the accommodation state increases. This assumption is likely flawed for wet high-accommodation systems. Belts tend to become narrower and numerous, and the total sand content tends to decrease as rivers progress from high to low accommodation settings and within high-accommodation settings in the downstream direction. This decrease in sand down dip is captured in more recent models that assume high-accommodation deposits are more distributive (Kraus, 2002). Sand-sized particles move down stream as bedload, predominately during high flow events, which usually occur during the rainy season, and the sand is lost down dip from upstream building of sand bars and splays. Channel size in the Grijalva system is determined by tie channel maturity (young, mature, old), which is highly variable across the systems, and the amount of sand within the system is directly correlated to channel belt size. This interpretation differs from the more well-drained LAB models where channels are assumed to maintain approximate size with increasing aggradation. Tie channels also have a natural tendency to reconnect with other channels as they migrate across the lakes and will continue to propagate across until the channel reconnects to the main channel, or until channels overextend and are abandoned for a new channel.

Channel belts with a similar geometry to those of the Grijalva River system are commonly attributed to changes in the accommodation/sediment supply (A/S) ratio (e.g., Bryant et al., 1995; Gardner et al., 2004, Huerta et al., 2011). Huerta et al., (2011) expanded on this model, showing that channel belts and floodplains form under different A/S conditions. Under their scenarios, sand surrounded by significant floodplain deposits

indicates high accommodation and high sediment supply; amalgamated sand bodies indicate relatively low accommodation and high sediment supply, and the presence of lacustrine and wetland deposits indicate high accommodation and low sediment supply, and stacked channels authenticate low accommodation and low sediment supply. Comparison of accommodation and accumulation rates in the Grijalva system shows that sediment supply and trapping was indeed insufficient to fill available accommodation.

Blowout sand sheets and splay deltas of the main channel can be cut by tie and distributary channels by creating connections of small, medium and large channels and channel belts that bisect otherwise fine-grain organic rich floodbasin source rock (peat/coal/shales). Tie channels bisecting lakes result in compartmentalization of the lake, leading to differential sedimentation rates within the lake complex (Figure 2-30). The tie channel's levee provides protection to one side of the tie channel while the opposite side infills. Therefore, discrete lake fill units need not correlate across bisecting tie channels. Because the blowout wings originate from the tie channels, they have a higher potential of persisting across adjacent lake deposits in the same lake system.

7.0 Conclusions

The tendency of splay deltas to form ribbons rather than lobes has important implications for oil and gas production. First, splay deltas commonly encountered within cores of lake-prone high-accommodation sections should be modeled as ribbons rather than lobe geometry. Second, these mature propagating channel systems generate sufficient sand; the resulting ribbons tend to link more reservoir quality channel belts. Rather than channel belts forming discrete reservoirs, they can be linked into veins joined by capillary propagating channels. In fluvial petroleum systems that are self-sourced, these capillaries could also prove integral to the charging history for larger bodies of sands formed out of otherwise impermeable but organic-rich backswamp deposits. For the benefits of this capillary theory to be practically applied there must be sufficient continuous sand deposition preserved within these propagating channel ribbons to promote gas transmission.

As tie channels propagate across floodplain basin lakes, these channels propagate as mud front deltas. As the tie channels mature and propagate across the lake, linking one channel belt to another, channel belt sand

begins to move as bedload through the system due to the removal of the backwater effect. An old tie channel in the lake cross-section is an example of a mature tie channel. The longitudinal profile of the young tie channel in a lake in the Usumacinta River like system demonstrates the movement of sand bedload downdip towards the delta front until the bedload reaches the backwater affect zone. As the tie channel continues to propagate across the lake, the backwater affect zone moves further downdip allowing the sand bedload to also move downdip until it reaches the new backwater effect zone.

Fluvial deltas form as an elongated channel when there are no outside forces such as tides, currents and waves to destroy the subaqueous levee system. These channels are of elongated/ribbon form because the sand bedload is trapped updip from the river's mouth. This loss of energy due to the backwater affect allows the suspended load to out run the bedload and form the subaqueous levees of cohesive material. These cohesive subaqueous levees channelize the flow creating a jet flow at the channel mouth. Because the sand bedload is held updip by the backwater affect, the sand bedload doesn't reach the river's mouth; no sand mouth bars are formed in the river's mouth, and therefore there is no channel switching to cause the traditional lobate form associated with fluvial deltas in marine settings. Any sand that makes it down the channel by storm surges/pulses is shot out past the channel mouth by the jet flow and forms small sand stringers out on the delta front.

As mature tie channels bisect the floodplain lakes, the shallow lakes began to fill with sediment forming swamps containing high organic materials. Glades start to form as the swamps fill and consist of various forms of vegetation from scattered trees to saw grass. The accumulation of this organic matter eventually results in the formation of peat interbedded with highly organic clays. Peat mires form in humid, swampy conditions in areas where rainfall exceeds evaporation and organic growth is rapid (Guion et al., 1995). Low ash, ombrotrophic coals, such as the ones in the Cretaceous Neslen Formation of the Mesaverde Group in eastern Utah, formed in raised swamp environments in which there was low clastic input and low subsidence (McCabe, 1987; Guion et al., 1995). Coals present in the Cretaceous Blackhawk Formation at the top of the Mesaverde Group in Utah have been interpreted by previous authors as raised mire deposits (Davies et al., 2006; Jerrett et

al., 2011). Coals formed in paralic coastal or deltaic settings are subjected to the influence of a continuously rising mire water table relative to the sediment surface. The mire water table is controlled by a combination of the regional base-level precipitation and autocompaction of any peat present (Davies et al., 2006). The rate of generated accommodation space must match the rate at which peat is produced for sustained episodes of the accumulation and preservation of the sediment package (Davies et al., 2006); a similar environment is envisioned for the Grijalva system deposits.

These organic-rich clays and peats form in environments similar to those that formed the Joggins, Blackhawk, and Mungaroo Formations, to name a few. The organic rich-clay and peat mires form hydrocarbon source rocks of organic rich shale with thin bedded sandstone beds that connect different channel belts. These sandstone bodies are charged by the shale/coal source rocks around them. This inter-connectivity would allow for the placement of a well that could not only drain the individual sandstone reservoir, but the entire field.

3.0 Summary of Observations



Figure 3-1 Working in the glade of the propagating channel in the southern portion of Lago El Campo.

3.1 Some summary observations of the tie channels.

- Little sand comes out of the mouth of river tie channels, and tie-channel delta mouths are dominantly silt loam with stringers of loam to sand (Figure 2-29 and 2-30, boring 3L).
- Tie channels do not tend to make belts, but are generally single channels/channel flanked by wings formed of delta front and levee complexes

- Sand is lost passing down active tie channels.
- The average tie-channel width in the area studied is 12 meters and the tie channel delta/levee complex is 113 meters.

Table 3-1 Channel Dimensions and Spacing

Channel Type	Average Spacing	Average Width	Average Thickness
Major channel belts	6.25 km	313.35 m	5 m
Medium channel	414 m	40 m	3 m
Tie-channels	350 m	15.2 m	1 m
Splay Delta	410 m	208 m	2 m
Tie Delta	360 m	350 m	1 m

3.2 Some summary observations of the lakes.

- Lakes fill by compartmentalization because bisection from tie channels creates topographic barriers to sediment entering lake compartments. Compartmentalization means that strata of lake fill may not correlate across tie channels into adjacent compartments because these strata were not deposited coevally.
- Tie channels propagate across lakes and continue until reaching another belt, upon which they become conduits for sand; thus, they can form thin sandy channel fills that can connect channel-belt reservoirs.
- Sheets of silt and sand in lake fills likely result from true splay deltas as tie-channel deltas tend to form ribbons.

3.3 Future Work

The present study has focused on the dynamics of wet-high accommodation basins and reach scale dynamics of delta channel networks (tie channels) and their impacts on floodplain lakes. Future research on larger channel systems is necessary to better understand how these channel dynamics function. On a smaller scale, this study has suggested more investigation into some interesting directions; how subaqueous levees form

and how they propagate as linear deltas rather than as a lobate delta; how tie channels bisect a lake leading to compartmentalization and differential filling; and lastly, how tie channels can mature and capture enough flow to grow into a major river like the Grijalva River.

3.3.1 Sediment Transport Rates

A detailed field study into the sediment transport rates of the Grijalva River, Usumacinta River, some of the smaller channels within the Grijalva Delta as well as some of the tie channels should be conducted. Sediment sampling of both bedload and suspended sediments should be collected over a period of time to obtain seasonal average sediment transport rates of the main river channels as well as the tie channels propagating across the floodplain lake systems. This plan of work would allow for a better understanding of the lake filling rates and tie channel levee building rates. In addition, hydrology and hydraulic measurements would be collected in the field as well as obtained from gauging stations.

3.3.2 Bathymetry Survey

Bathymetric survey of the tie channels and floodplain lakes in conjunction with addition sediment core sampling would enhance our understanding of the lake evolution-filling history. A bathymetric survey would also allow us to see the lake floor in profile providing addition insight into pro-delta/delta/tie channel development in non-marine environment.

3.3.4 Modeling

The data collected in the field can be used to improve the existing theoretical models for delta evolution, delta propagation, in-channel processes such as subaqueous levee development and bifurcations. Models such as Delft3D have been successfully used by numerous researchers using theoretical data, which has resulted in a better understanding of some of the dynamics of delta formation, and tie channels (Edmonds and Slingerland, 2008; Edmonds et al., 2008; Edmonds et al., 2009). However, the Delft3D model used by Edmonds needs to be validated by field data to determine how well the model predictions match real world environments.

Appendix A
Addition Figures

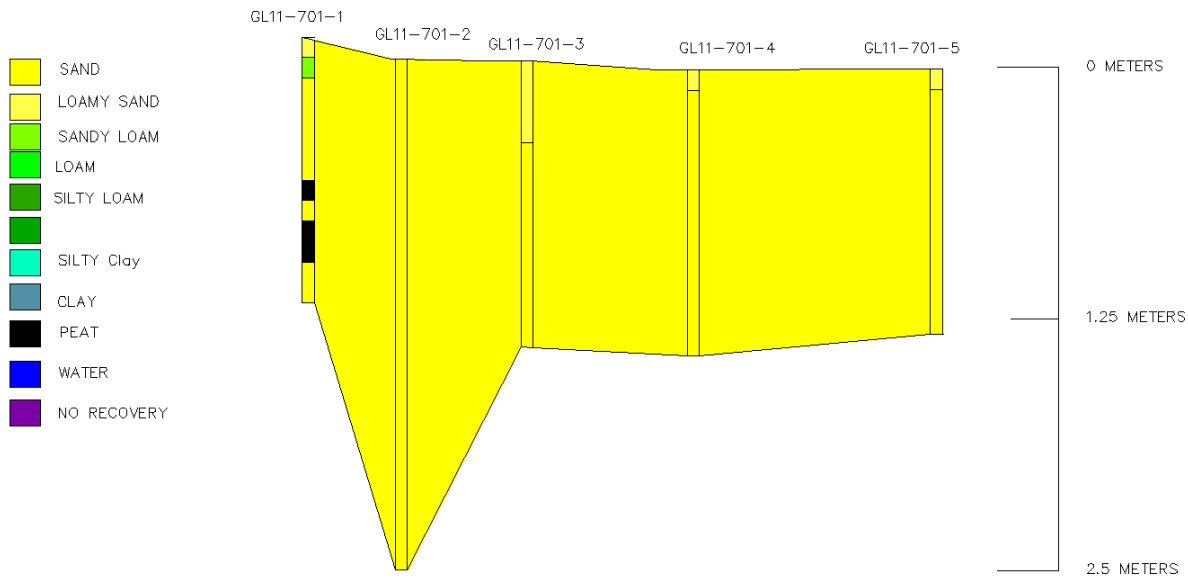


Figure Appendix A-1 Cross-section of the coastal beach chenier. As observed in the cross-section, the relic beach ridge consisted predominately of sand with two small organic/peat layers.

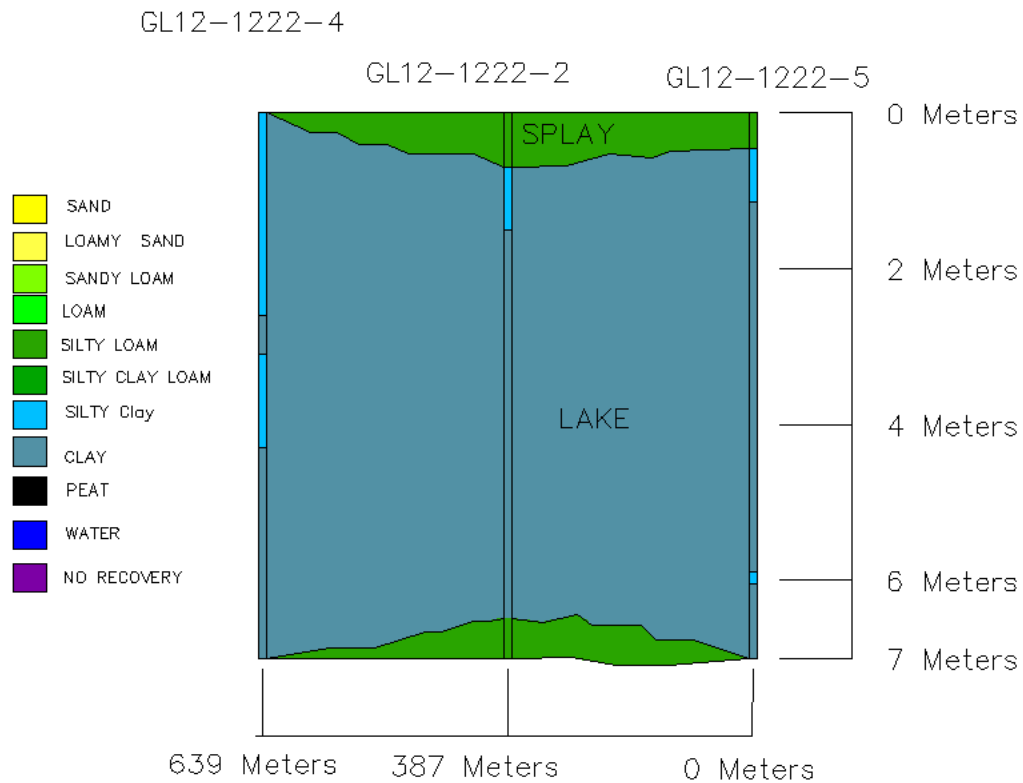


Figure Appendix A-2 E-W Cross-section of the glade west of Lago El Campo with sediments supplied as a splay along the east bank of the main channel of the Grijalva River. Typical clay lacustrine lithofacies top an older possible splay facies at the bottom of the cross-section. The silty loam is evidence of an old buried delta/levee splay. The silty loam lithofacies is slowly filling the available space in the glade and has filled in most of the western portion west of the old tie channel shown in figures 2-29 and 2-30.

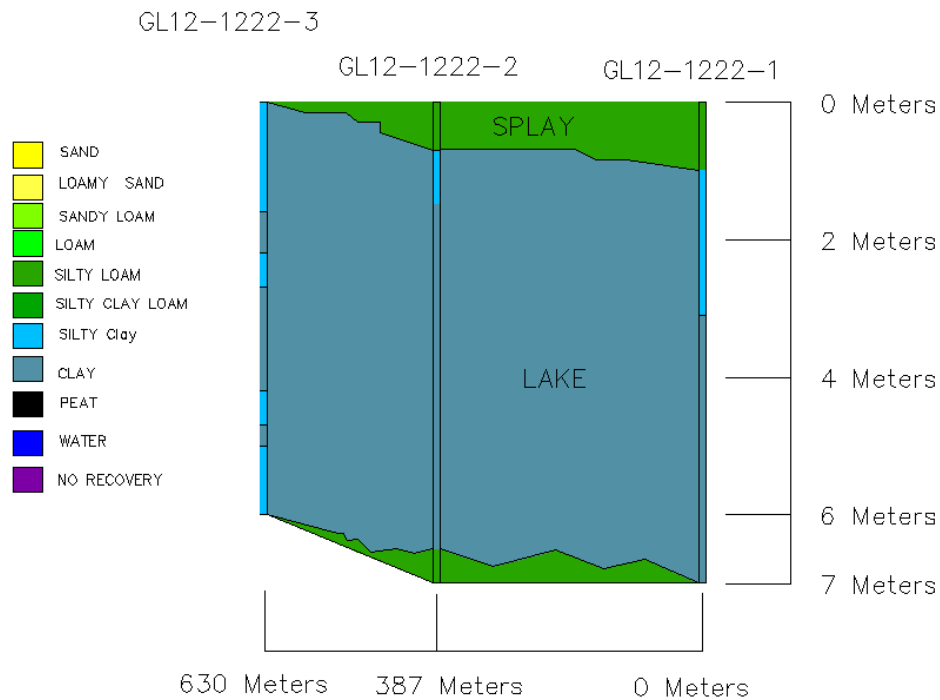


Figure Appendix A-3 E-W Cross-section of the glade west of Lago El Campo with coarse sediments from a splay located along east bank the main channel of the Grijalva River just west of this location. Typical clay lacustrine lithofacies top an older possible splay facies at the bottom of the cross-section. The silty loam is evidence of an old buried delta/levee splay. The silty loam lithofacies is slowly filling the available space in the glade and has filled in most of the western portion west of the old tie channel shown in figures 2-29 and 2-30.

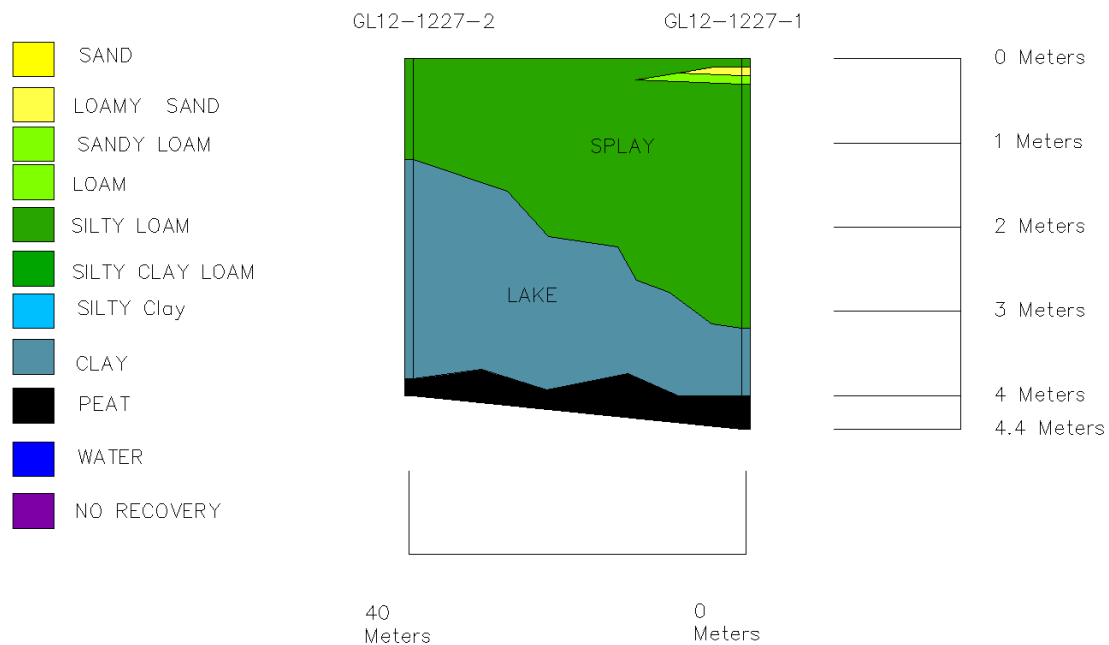


Figure Appendix A-4 Cross-section of a splay along one of the medium sized floodplain channels between Lago El Campo and the main channel of the Grijalva River. Clay lake lithofacies top an older peat facies at the bottom of the cross-section. The peat is evidence of a swamp. Once the lake became too deep to sustain the formation of peat, this deepening resulted in the typical clay lacustrine lithofacies observed above the peat. This deposition was followed by the buildup of propagating delta/levee splay. Sandy wings are evident near the surface of the cross-section. The coarsening up of sediment is indicative of the delta/levee splay. Silty loam to sand lithofacies make up the delta/levee splay facies, with loam to sandy loam making up the channel levee and delta wings.

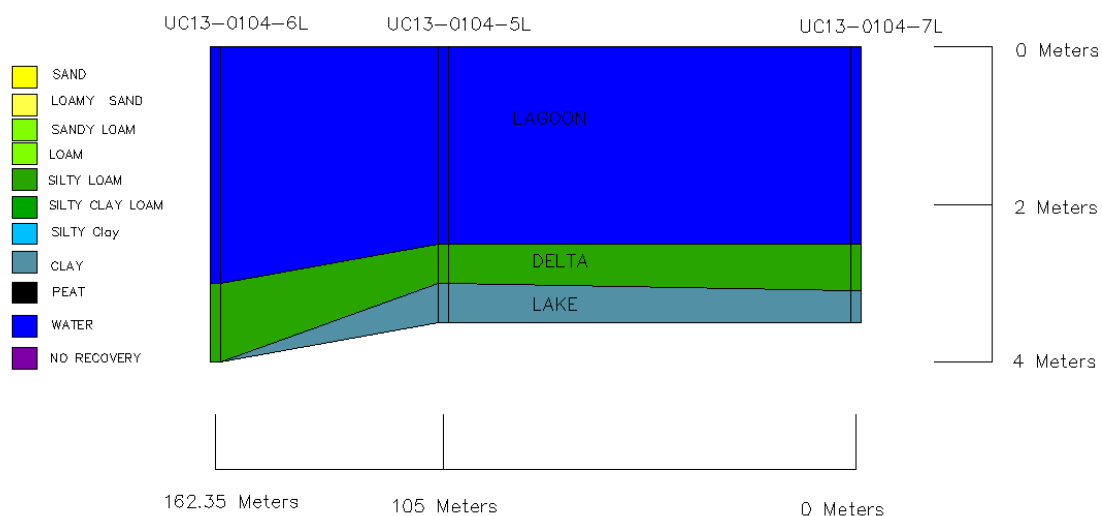


Figure Appendix A-5 Cross-section across the delta front at the mouth of a tie channel in a small lagoon north of the Usumacinta River (facing east towards the lagoon). The delta consists of silty loam and is thicker to the north.

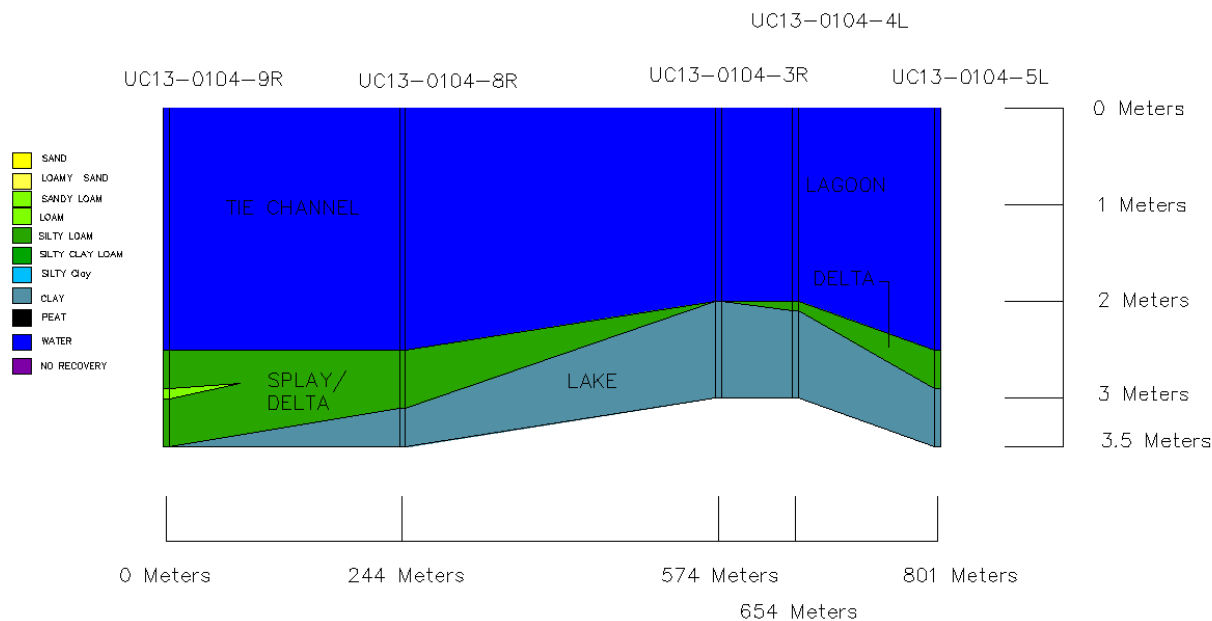


Figure Appendix A-6 Usumacinta tie channel longitudinal profile down the center of the tie channel. There is no sand at the mouth of the tie channel. The silt loam of the delta can be observed building upward on top of the lacustrine lithofacies in the lagoon.



Figure Appendix A-7

Location map depicted the sample locations for Figures Appendix A-5 and A-6.

Appendix B

Boring Logs

See Electronic Supplement for PDFs

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