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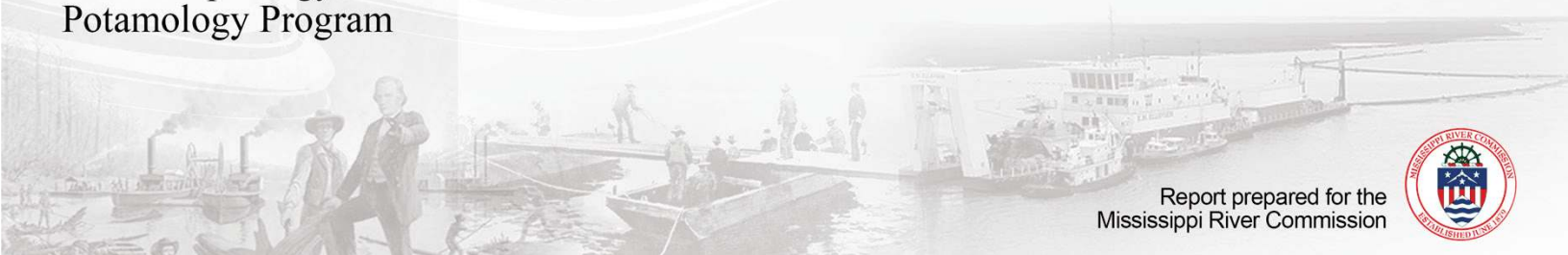
The Influence of Geology on the Morphologic Response of the Lower Mississippi River

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Mississippi River
Geomorphology &
Potamology Program



The Influence of Geology on the Morphologic Response of the Lower Mississippi River

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Final report

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Abstract

The Mississippi River is heavily influenced by structural and geologic controls involving regional uplifts, faults, clay plugs, outcrops of Tertiary clay, and Pleistocene gravel in its bed and tributaries. Degradation is continuing to migrate upstream on the Lower Mississippi River (LMR) and has presently moved as far upstream as the Hickman, KY, area. Left unchecked, this degradation could continue to advance on the LMR and ultimately migrate upstream into the Ohio and Middle Mississippi River systems. This degradation would not only adversely affect the stability and environmental features in the main stem of the river but also introduce headcutting into the many tributaries that enter the river in this degradational zone. Detailed studies of the exact role of these features, particularly with respect to retarding or halting long-term degradational processes along the river, have not received much attention. In this study, potential areas where geologic outcrops may influence river morphology are identified, and examples are provided that support the concept that geologic outcrops may be extremely important features that serve as temporary or permanent grade control along the river.

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Preface

The research documented in this report was conducted as part of the Mississippi River Geomorphology & Potamology (MRG&P) Program under project “Geomorphic Assessment.” The MRG&P Program is sponsored by Headquarters, U.S. Army Corps of Engineers (USACE), and is managed by the USACE Mississippi Valley Division (MVD) in Vicksburg, MS. The MRG&P Technical Director was Dr. Ty Wamsley.

The MVD Commander was MG Richard G Kaiser. The MVD Director of Programs was Mr. James Bodron.

The Mississippi River Commission provided Mississippi River engineering direction and policy advice. The Commission members were MG Richard G Kaiser, USACE; the Honorable Sam E. Angel; the Honorable R.D. James; the Honorable Norma Jean Mattei, PhD; RDML Shepard Smith, National Oceanic and Atmospheric Administration (NOAA); BG Mark Toy, USACE; and BG Paul Owen, USACE.

At the time of publication of this report, Dr. Jackie S. Pettway was Acting Deputy Director of the Coastal and Hydraulics Laboratory, and Mr. Jeffrey R. Eckstein was Acting Director.

COL Bryan S. Green was Commander of ERDC, and Dr. David W. Pittman was Director.

Unit Conversion Factors

Multiply	By	To Obtain
cubic feet	0.02831685	cubic meters
feet	0.3048	meters
miles (U.S. statute)	1,609.347	meters
mils	0.0254	millimeters

1 Introduction

Background

The Mississippi River and Tributaries (MR&T) Project is one of the most complex and comprehensive water resources projects in the world. The primary elements of the MR&T Project include: levees; channel improvement features such as cutoffs, bank stabilization, dikes, and dredging; floodways and diversion structures; and tributary basin improvements. Understanding the response of the river to these features, as well as natural factors such as floods and droughts, hurricanes, neotectonic activity, geologic controls, and climatic variability is critical to the long-term management of the system. To meet this challenge, the Mississippi River Geomorphology and Potamology (MRG&P) Program was developed. The MRG&P Program has adopted a program of study consisting of individual study elements that build upon each other to meet desired goals. Developing a better understanding of the influence of geologic controls on the morphology of the Lower Mississippi River (LMR) is one of these study elements.

Objective

The objectives of this study are to utilize existing geological and geomorphic data to highlight the morphological importance of geologic outcrops along the LMR, particularly along the degradational reaches of the river where outcrops of clay and resistant gravel could retard future degradation. This preliminary study uses examples from the LMR to illustrate the potential grade control functions of geologic outcrops and is intended to serve as a catalyst for more-detailed investigations as part of the MRG&P Program.

Approach

The approach used to illustrate the importance of geologic controls on the morphologic character of the LMR involved three interrelated elements: (1) historical geologic studies of the LMV were summarized to serve as a framework for understanding the geologic character of the system; (2) comparisons of thalweg and tertiary elevations were examined to provide insight into locations where potential geologic controls might exist along the LMR; and (3) detailed analyses were

conducted at two specific locations (Helena, AR, and Hickman, KY) to provide examples of locations where geologic controls may be a dominant factor affecting the river morphology.

Points of contact

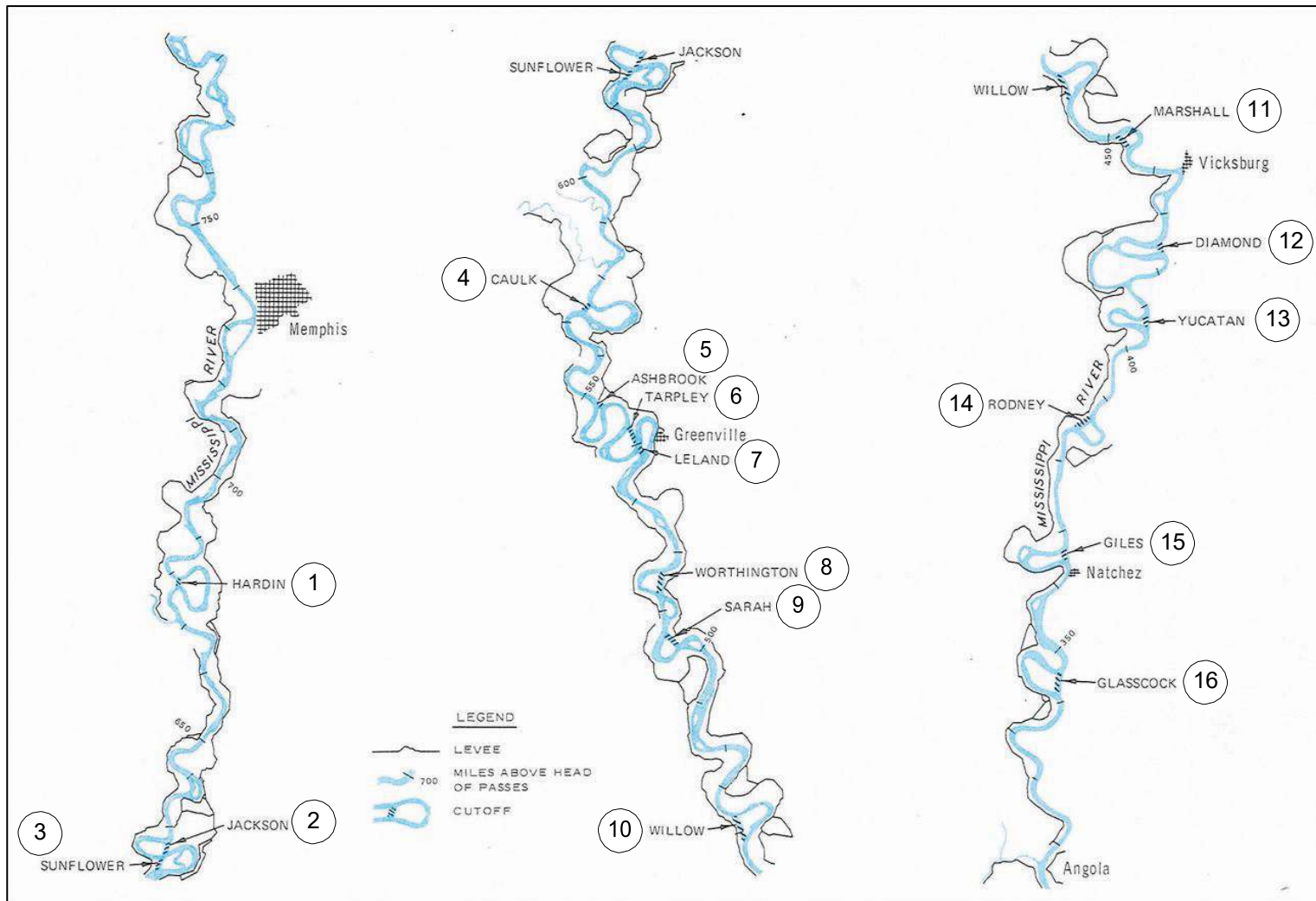
Points of contact for this report are found in Appendix B.

2 Historical Investigations on the Lower Mississippi River (LMR)

A brief history of studies involving the geology of the Lower Mississippi Valley (LMV) for purposes of assessing river morphology is described here for background information. The following review summarizes three principal types of geologic studies that were sponsored by the Mississippi River Commission (MRC). These types include (1) studies dealing with the surface geology and stratigraphy, (2) studies involving bank failure and relationship to alluvial depositional environments, and (3) those studies focusing on neotectonic activity in the LMV. Schumm and Spitz (1996) described the Mississippi River as being an example of a large river that has geologic control on its shape, pattern, and magnitude of change through time. Thus, this system is not completely controlled by hydrology and hydraulics alone but has reacted to structural and geologic control involving regional uplifts, faults, clay plugs, outcrops of Tertiary clay, and Pleistocene gravel in its bed and tributaries.

MRC studies of the geologic controls affecting the behavior of the Mississippi River in the LMV first began in 1941 because of bank-caving problems that were associated with the cutoff program and the need to control river migration (Moore 1972). Following the 1927 Flood, the MRC eliminated 151.9 miles of the Mississippi River in the LMV through a series of 16 oxbow cutoffs between 1929 and 1942 (Figure 1). The purpose for the cutoff program was to efficiently route floodwaters through the central part of the alluvial valley, thereby lowering flood stages. The effectiveness of the cutoff program in the central part of the LMV would eliminate the need for the proposed Eudora-Tensas floodway in the central part of the alluvial valley that was planned and would cross parts of eastern Arkansas and Louisiana (Camillo 2012).

Figure 1. River cutoffs between Memphis and Angola between 1929 and 1942 (Winkley 1977).



Geologic studies by the MRC were initially conducted full time by Dr. H. N. Fisk and his staff of geologists at Louisiana State University (LSU) between 1941 and 1947. Fisk and his team of geologists produced a comprehensive investigation on the alluvial geology of the LMV (Fisk 1943, 1944). This comprehensive study provided MRC and District engineers in the LMV with a geologic framework for effectively engineering the present-day MR&T system. This body of work provides detailed information about the geologic history of the alluvial valley, characteristics of coarse-grained meander-belt deposits, alluvial environments of deposition, and the nature of the bedrock geology into which the Mississippi River has incised.

Fisk's team conducted nearly 50 studies for the MRC in the short span of 7 years (see Appendix A for a list of selected MRC studies conducted by Fisk and his team between 1941 and 1947 that were formally published as Waterways Experiment Station [WES] technical reports). These different investigations involved channel erosion and bank stability, levee underseepage, the foundation geology beneath several lock and dam sites, a study into the effects of fine-grained alluvial deposits on Mississippi River activity, and a comprehensive study into the capture of the river's course by the Atchafalaya River.

Studies directed by Fisk incorporated the latest scientific methods for this time, involving the use of engineering borings, aerial photography, detailed topographic map data, and laboratory soil testing data. In addition to his internationally recognized geologic study of the LMV (Fisk 1944), Fisk (1947) conducted studies on the effects of fine-grained alluvial deposits on Mississippi River activity. This study showed that fine-grained backswamp deposits and clay-filled abandoned channels or *clay plugs* significantly restricted river migration, as compared to coarse-grained braided stream (or outwash plain) and point-bar deposits, which form distinct meander belts that contain abandoned channels and past courses of the Mississippi River. Studies of the river by Fisk (1943) divided the river system into reaches based on the underlying geologic control. More recently, Schumm and Spitz (1996) divided the river between Cairo, IL, and the Old River Control Structure (ORCS) into 24 reaches with types of reach pattern (straight and degree of sinuosity) and possible geologic controls (lithology, fault, uplift, and tributary junction) identified.

After 1948, Fisk would serve as a consultant to the MRC and direct two other comprehensive studies on Mississippi River activity. The first

involving the natural diversion of the Mississippi River to the Atchafalaya River, because of its shorter length and improved gradient advantage to the Gulf of Mexico (Fisk 1952). Consequently, the ORCS was built by the U. S. Army Corps of Engineers (USACE) to regulate flow from the Mississippi River into the Atchafalaya Basin and prevent the eventual river capture by this shorter river course.

The second study directed by Fisk as an MRC consultant involved the impact of the geology upon Mississippi River activity from Memphis, TN, to the mouth of the Arkansas River (Mabrey 1949). Mabrey (1949) concluded the presence of clay plugs constituted the major restrictive influence on river activity, until the use of revetments in modern times. They also concluded that the effect of shortening the course of the river by the cutoff program is the “acceleration in river activity caused by the increased velocity and local change in alignment.” The presence of revetment was also considered a likely destabilizing influence within non-reveted reaches from observations of bank recession rates between Memphis and the mouth of the Arkansas River.

The team of geologists that Fisk had assembled at LSU was moved to Vicksburg, MS, in 1948 to be closer to the MRC and were located at the WES as the newly formed Geology Branch in the Soils Laboratory. This group of geologists would be actively involved in detailed mapping of the alluvial geology of the LMV for the MRC for purposes of bank stability and levee underseepage research at mainly the 15-minute (1:62,500) map scale from the 1950s to the mid-1990s (Dunbar et al. 1994, 1995; Fleetwood 1969; Kolb 1949, 1962; Kolb and Van Lopik 1958; Kolb et al. 1968, 1975; Krinitzsky 1949, 1950, 1965; Krinitzsky and Smith 1969; Krinitzsky and Wire 1964; May et al. 1984; Saucier 1964, 1967, 1969, 1994; Schultz and Kolb 1950; Schultz and Krinitzsky 1950; Smith et al. 1986; Smith and Russ 1974; Smith and Saucier 1971).

This large body of published geologic maps from the LMV, as well as other focused geologic studies that were conducted by WES for the MRC, would be summarized by Saucier (1994), 50 years after the anniversary of Fisk's (1944) internationally recognized LMV publication (Saucier et al. 1996). Saucier's (1994) comprehensive report would be published as a two-volume set, with Volume 2 comprised of geologic maps of the alluvial valley at the 1:250,000 scale. Volume 1 presented the update and revision to the geologic history and chronology first described by Fisk (1944) of the

Mississippi River's alluvial valley, based on palynology studies, radiometric age dating, the oxygen-isotope record, archaeological data, and the benefit of more than 100,000 engineering borings from the LMV. Geologic map data and studies compiled for the MRC during this 50-year period are presented at the USACE LMV geologic web site (<http://lmvmapping.erdcd.usace.army.mil>).

In addition to the geologic mapping program described above, the MRC sponsored focused studies on river bank stability as part of the revetment program in the LMV. The MRC potamology program would produce approximately 80 reports of investigations, including studies by Winkley (1970, 1977) on the legacy effects of the cutoff program by General Ferguson (Ferguson [1939]) and its relationship to the alluvial geology, the floodplain history, and man's activities. The work by Winkley (1970, 1977) and Smith and Winkley (1996) is a review of the impacts of river engineering by the USACE upon a large fluvial geomorphic system that was changed to meet the requirements for flood control and navigation for purposes of public safety and commerce. A general history summarizing potamology research by the MRC is also presented by Smith and Winkley (1996) and Biedenharn et al. (2014).

Research by the MRC into the bank failure process involved developing new methods to perform undisturbed soil sampling of saturated sandy soils; developing state-of-the-art laboratory soil tests; performing studies of the river bank geology; developing empirical relationships about the geology, the soils, and engineering properties; and monitoring the performance of the revetment in all the different levee reaches. Bank stability research by the MRC was confined mainly to the upper part of the alluvial valley and would be eventually discontinued in 1977 because of the success of the revetment program in controlling river bank stability.

In terms of the floodplain geology and its control on river activity, two major classes of bank failures were identified. Bank failures were classified as being either (1) shear failures or (2) flow failures. Shear failure of the upper, fine-grained, cohesive topstratum occurred by arcuate shearing and slumping of the topstratum into the river, which was mainly due to the loss of the underlying foundation sands from river scour (Figure 2). Flow failures involved initially the lower sand or substratum deposits. Scouring by the river during flooding at the toe of the bank slope initiates a flow failure, as the loose sands forming the submerged bank are oversteepened,

causing sand to flow into the scour pool. Usually, flow failures trigger a shear failure of the upper bank, as the sands beneath the topstratum are removed and the cohesive topstratum cannot support its own weight over a prolonged time period. Krintizsky (1965) illustrated the relationship of the failure process to different floodplain depositional environments (Figure 2).

A review of the early potamology work conducted in the upper valley was reported by Hvorslev (1956), later summarized by Banks and Strohm (1965) and more recently by Smith and Winkley (1996). It was found that all the historic flow failures in the Memphis and Vicksburg Districts occurred in point-bar deposits. These deposits contained three basic soil zones: (1) a cohesive overburden, (2) underlying fine sands (upper Zone A sand series), and (3) deeper coarse sands and gravels (lower Zone B sand series), which is shown in Figure 3. It was determined that all of the major flow failures studied were progressive rather than instantaneous (i.e., liquefaction) in nature. An important empirical relationship that was developed from these early studies was the ratio between the overburden thickness to the Zone A sand thickness, known as the R-value (Torrey and Gann 1976). Stable banks were those with an R-value greater than 0.85 and less than 20-feet (ft) thick Zone A sands as shown by Figure 4 (Hvorslev 1956).

Study of flow failures in the Memphis and Vicksburg Districts was eventually discontinued in 1977 (Gann 1981). A total of 204 flow failures was identified with 90% occurring in the Vicksburg District and only 10% in the Memphis District. Criteria used to determine susceptibility were compared against more than 2,300 boring locations and annual hydrographic surveys, but only 36% of these locations ever experienced failure. The ability to predict severity of scouring was missing in these empirical studies. Additionally, the revetment programs would extend throughout both of these districts by the 1980s and stabilize the course of the river.

Figure 2. Environments of deposition and general mechanics of bank failure in the Lower Mississippi River Valley (Krinitzsky 1965).

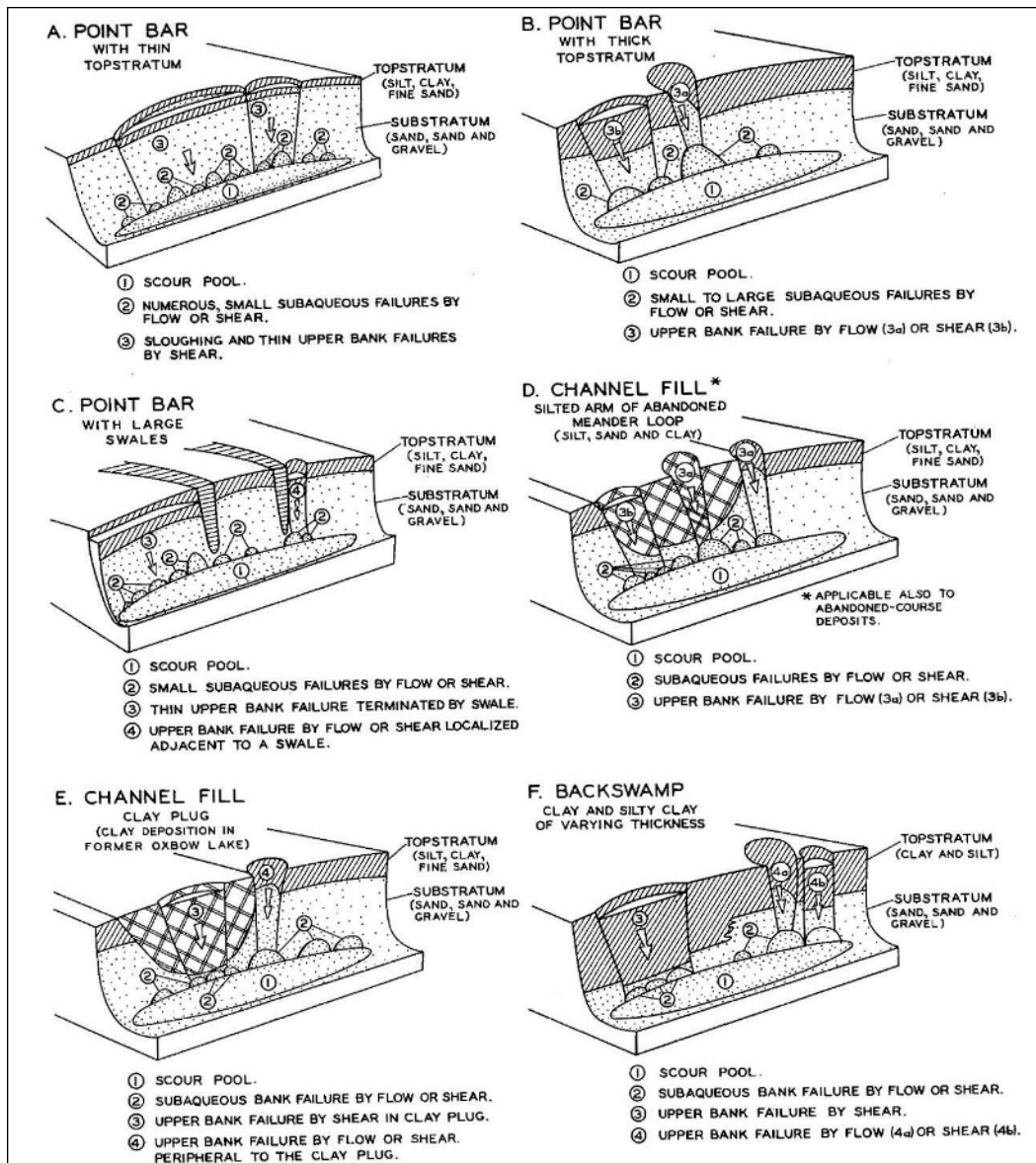


Figure 3. Soil profile for typical LMR point-bar deposits (Hvorslev 1956). U.S. sieve size openings are as follows: No. 40 = 0.425 millimeter (mm), No. 60 = 0.250 mm, and No. 200 = 0.075 mm. Note the fining-upward trend in grain size with the point-bar deposit, corresponding to lateral accretion for channel sands and vertical (overbank) accretion for overburden deposits.

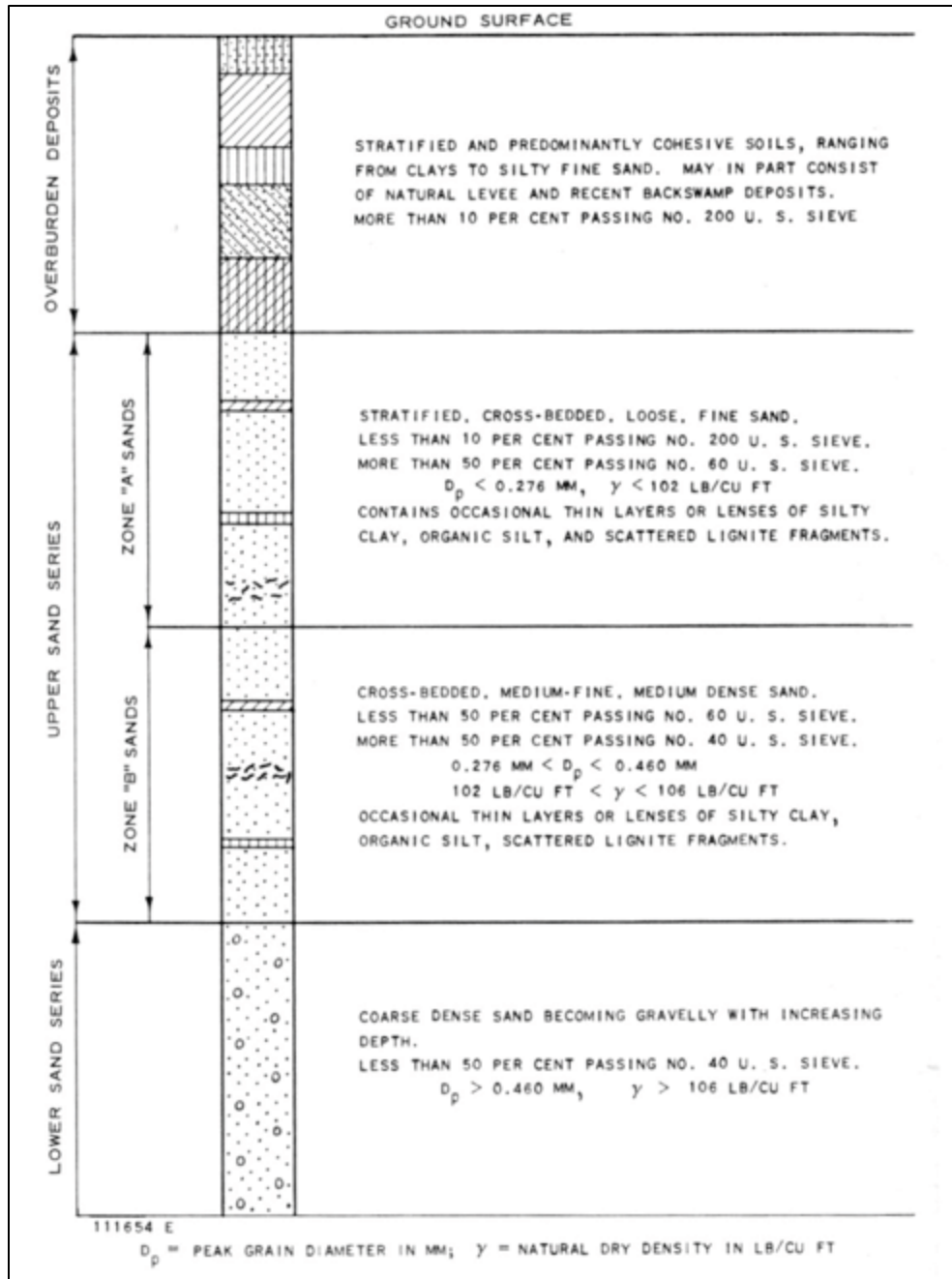
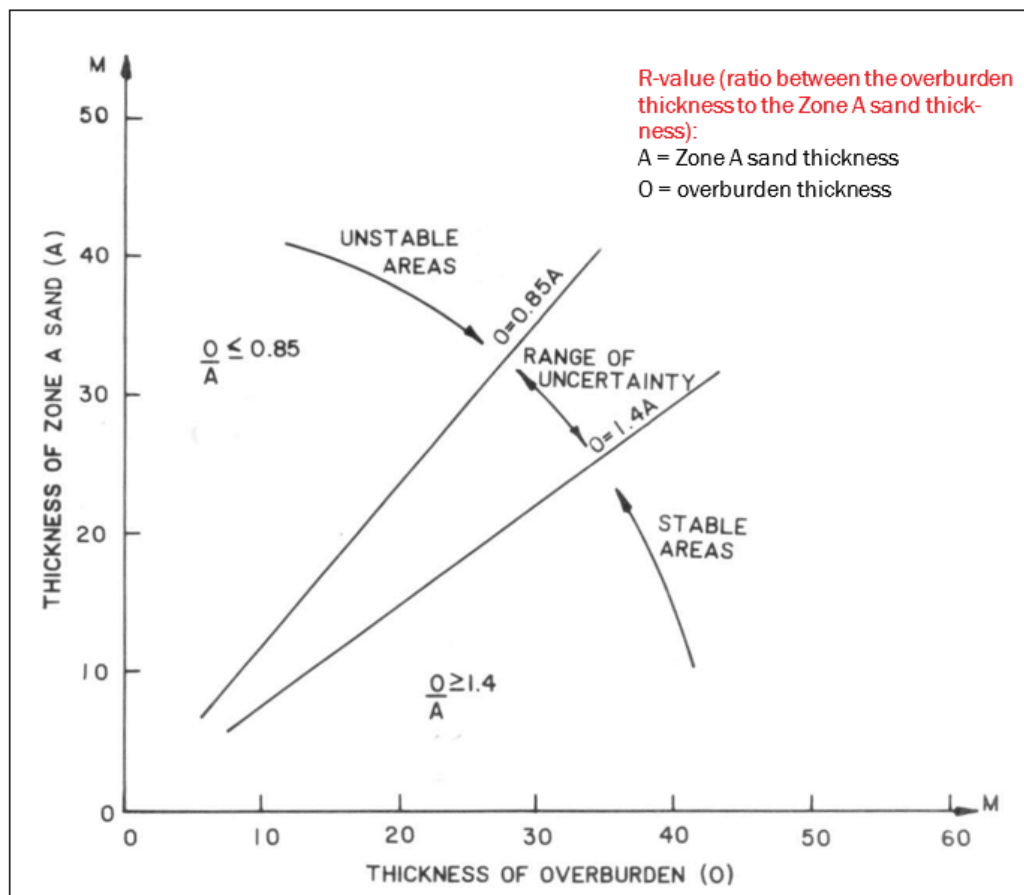


Figure 4. Empirical relationship between thickness of overburden (topstratum), thickness of Zone A sand (see Figure 3), and bank stability (Hvorslev 1956). Stable banks are those with $R = O/A > 0.85$ and generally less than 20 ft of Zone A sands.



MRC research into bank stability shifted to below Baton Rouge between 1970 and 1994. Focused studies of bank stability were conducted following the 1973 Flood as four large flow failures occurred at low water (Torrey 1988; Torrey et al. 1988). Study of these flow failures by Dr. Torrey revealed that the liquefaction-type failures originally hypothesized by the earlier MRC studies did not fit the field evidence at these locations (Torrey et al. 1988). Failures below Baton Rouge were generally progressive in nature, and the failures were confined entirely to the Zone A sands. Because of the field evidence obtained, a retrogressive failure mechanism was proposed by Torrey et al. (1988) to describe the rapid drawdown failures observed below Baton Rouge. This research developed methods to identify areas susceptible for bank failure. Annual hydrographic surveys and soil information derived from boring data from the river bank are used to determine the shape of the critical bank slope for the different survey range lines. Revetment control is

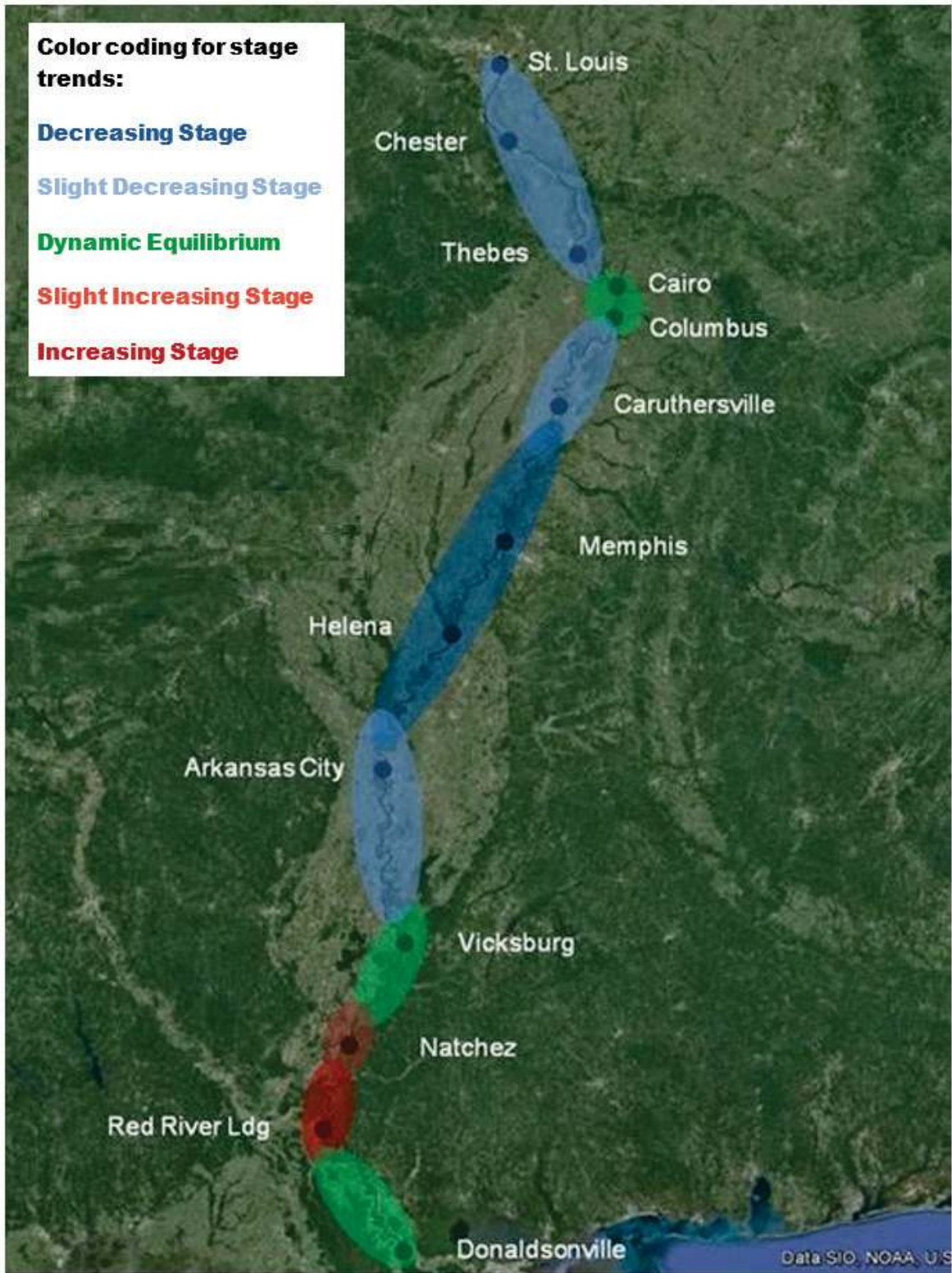
incorporated where channel scour has eroded below the idealized stability line along the different survey lines.

The last category of research sponsored by the MRC for purposes of predicting river behavior and morphology involved an examination of neotectonic activity in the LMV (Schumm et al. 1982; Schumm and Spitz 1996). The effects of crustal movements involving vertical uplifts and subsidence spanning decades to century time scales can potentially have long-term impacts to engineering and flood control structures and impact drainage patterns in the LMV watershed, channel aggradation and degradation, channel sinuosity, avulsion, and flooding where the subsidence is occurring. Three major structural features are identified in the LMV: (1) the Lake County Uplift (area of the New Madrid seismic zone), (2) the Monroe Uplift (northeast Louisiana and southeast Arkansas), and (3) the Wiggins Uplift (southern Louisiana). Fisk (1944) and Krinitzsky (1950) described faults and their characteristics in the LMV and their relationship to earthquake historic activity in the LMV. Schweig and Van Arsdale (1996) described geological and geophysical evidence of tectonic activity in the New Madrid seismic zone. The USACE has traditionally not considered earthquake activity in its levee design in the LMV as the probability of a maximum flood event coinciding with a large magnitude earthquake is considered an extremely rare event. However, earthquakes are considered in the design and safe operation of USACE flood control dams and water storage reservoirs, especially those that border the New Madrid seismic zone and would be impacted by an earthquake from this source area.

3 Current Investigations of Potential Impacts of Geologic Outcrops

In an MRG&P companion study by Biedenharn et al. (2017), stage trends along the LMR were evaluated using specific gage records. This study revealed that the LMR is still responding to the meander cutoffs between 1929 and 1942, with degradation (channel scour) migrating upstream and aggradation (channel filling) downstream. These trends are most distinct at low-water conditions, which generally are indicative of bed changes in the river. This study indicated that the most pronounced degradation is occurring in the reach from just south of Helena, AR, to near Osceola, TN, and in recent years, this degradation has begun to migrate farther upstream to just south of Cairo, IL. The extent of this degradation zone is shown on the plan map in Figure 5. This degradation is expected to continue to migrate upstream and if left unchecked, could advance into the Ohio and Middle Mississippi Rivers. Although the time scale for this degradation might be measured in multiples of decades, the impacts to navigation, bank stability, side channel habitat, and river structures could be severe. The long-term ultimate lowering is a function of many factors, one of which is the presence of geologic controls in the bed of river. The following discussion provides examples of locations where geologic controls may be a dominant factor affecting the river morphology.

Figure 5. Low-water stage trends along the Mississippi River (from Biedenharn et al. [2017]).



Contour maps of the top of Tertiary elevations along the LMR were acquired from the WES geologic maps of the Mississippi River (Kolb et al. 1975; Saucier 1964, 1969, 1994; Smith and Russ 1974; Smith and Saucier 1971). These maps are available at the USACE web site (<http://lmvmapping.usace.army.mil>). Using the Tertiary contour data contained on these maps, the approximate elevation of the top of the Tertiary was identified at every location where the contour crossed the river. Figure 6 is a plot of the top of the Tertiary elevation (feet, National Geodetic Vertical Datum) versus river miles [RMs]; Above Head of Passes [AHP]) for the Vicksburg and Memphis Districts. Also shown in Figure 6 is the lowest thalweg elevation taken from the 1962, 1975, and 1989 surveys. Comparison of the thalweg and Tertiary elevations provides insight into locations where the top of the Tertiary is in the proximity of the river bed. For most of the river, the Tertiary is well below the river bed, but there are numerous locations where they interact. Figure 7 is a plot of the locations (red circles) where the thalweg is within 5 ft of the top of the Tertiary. These locations are also shown on the plan map in Figure 8. These data provide a broad-scale view of locations where the Tertiary may be a factor in the river morphology. Of course, the precise manner in which the Tertiary may influence the river morphology is dependent upon the character of the Tertiary materials, which could range from erosion-resistant clays to highly erodible sands.

The goals of this study were not to conduct a detailed geologic investigation of all these sites but rather to highlight the potential importance of these features so that more in-depth investigations can be conducted as part of the MRG&P Program. Two examples are provided that identify locations where geologic controls may have played a significant role in limiting the upstream advancement of channel degradation.

Figure 6. Comparison of thalweg and Tertiary elevation along the LMR.

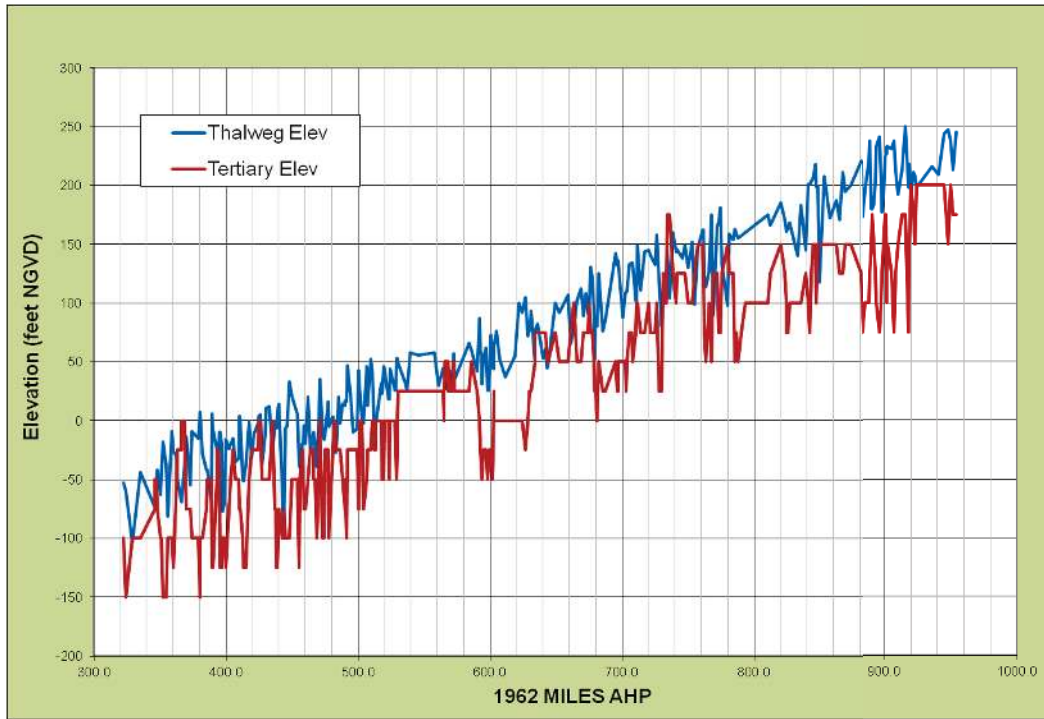


Figure 7. Thalweg elevation minus the top of Tertiary elevation. Red dots indicate locations where the Tertiary is within 5 ft of the thalweg.

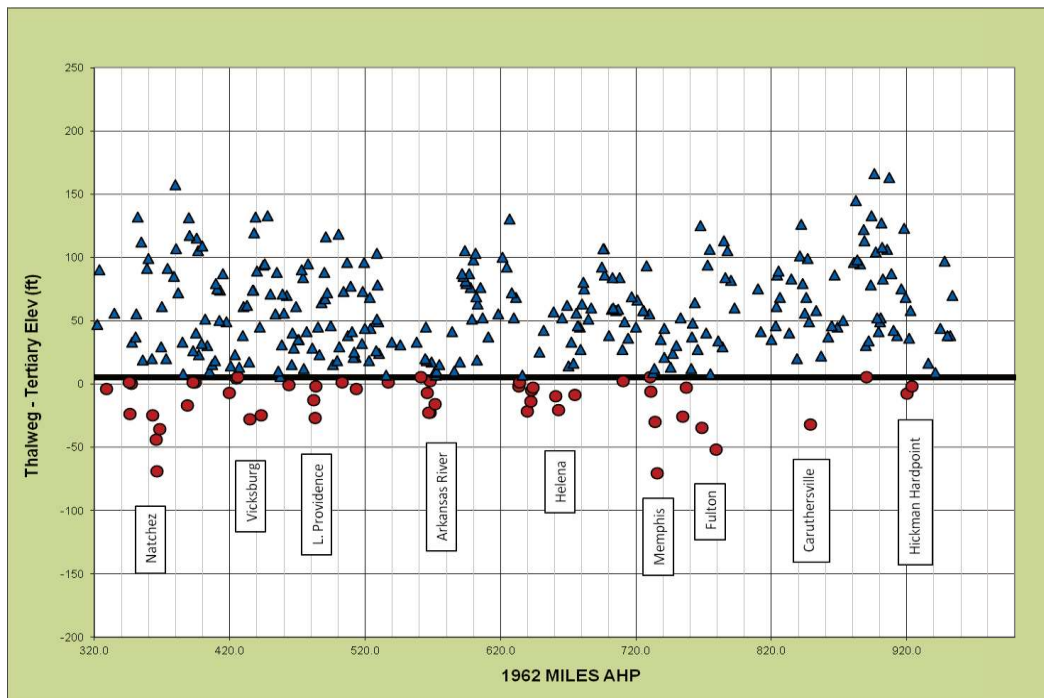
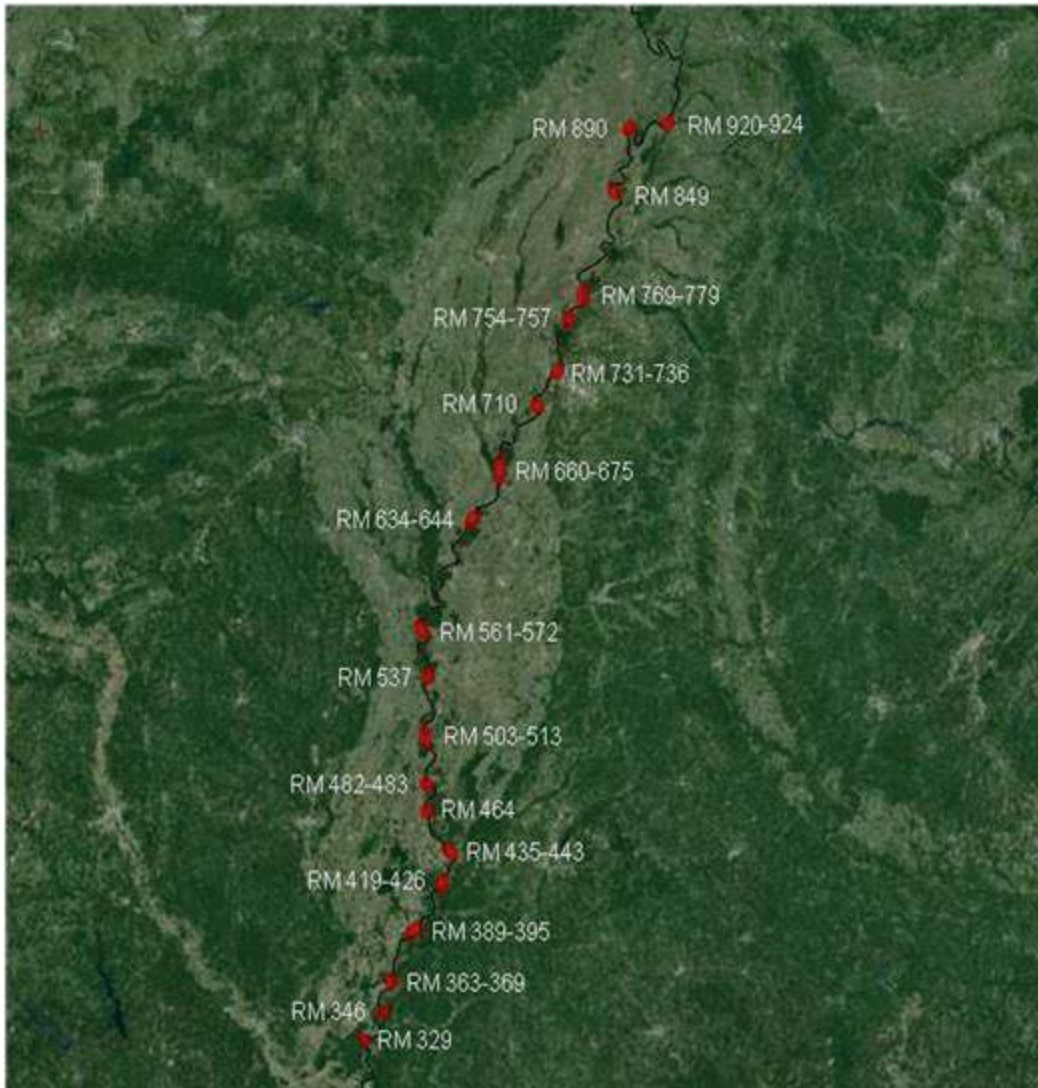


Figure 8. Locations (red shapes) of potential Tertiary outcrops along the Mississippi River.



Potential importance of geologic controls on Helena reach

Geologic outcrops appear to have played a dominant role in the morphologic character of the river in the vicinity of Helena, AR (approximate RM 663). In this subsection, the general geology of the Helena reach is presented, followed by a discussion of the morphologic adjustments in this reach.

Geology of the Helena reach

Geologic information on the Helena reach is presented to better understand the nature of the channel-bed deposits in this reach and their possible effects on the behavior of the river channel. A geologic map of the

Helena area is presented in Figure 9 that shows the Helena, AR, area as being located on the southern end of Crowley's Ridge. The ridge corresponds to Early Pleistocene Uplands or terrace deposits formed by the Mississippi River that extends nearly 215 miles in length. These uplands separate an older course of the river that once flowed in the Western Lowlands from the main valley of the present-day river that occupies the Eastern Lowlands portion of the LMV, which was initially formed by the ancestral Ohio River.

Crowley's Ridge represents a 5- to 10-mile-wide terrace remnant containing the elevated floodplain surface and associated alluvial sediments that were deposited when the river was flowing at a much higher elevation than the present day. Saucier (1994) estimates Crowley's Ridge to be between 800,000 to 1.3 million years in age, which he classified as being part of the Intermediate Upland Complex. Overlying the alluvial deposits along the length of Crowley's Ridge are multiple loess sheets (windblown silt deposits) that were formed during episodes of major continental-wide glacial melting, where vast quantities of outwash were released by the retreating glaciers to their respective drainage valleys. Glacial outwash in the northern part of the alluvial valley is widespread and corresponds to mapped braided stream deposits by Saucier (1964).

The west-to-east cross section in Figure 10 presents the distribution of alluvial sediments across Crowley's Ridge and the modern-day floodplain. Beneath the recent alluvium and older terrace deposits (Crowley's Ridge) are Tertiary (Eocene) deposits that are assigned to the Jackson Group (Yazoo Clay and Moody's Branch) and Claiborne Group (primarily Cockfield in this area). Subsurface data are based on the comprehensive WES geology mapping program in the LMV that was sponsored by the MRC (Saucier 1964, 1994) (see the USACE web site <http://lmvmapping.usace.army.mil>). Descriptions of these two Tertiary groups and the individual formations comprising these groups are listed in Table 1 (Saucier 1994).

Figure 9. Geologic map of the Helena, AR, area from the Latour 15-minute quadrangle (Saucier 1964). Cross section A-A' is presented in Figure 10. Upland area in the middle of the quadrangle is an Early Pleistocene terrace estimated to be 700,000 to 1.3 million years before the present day.

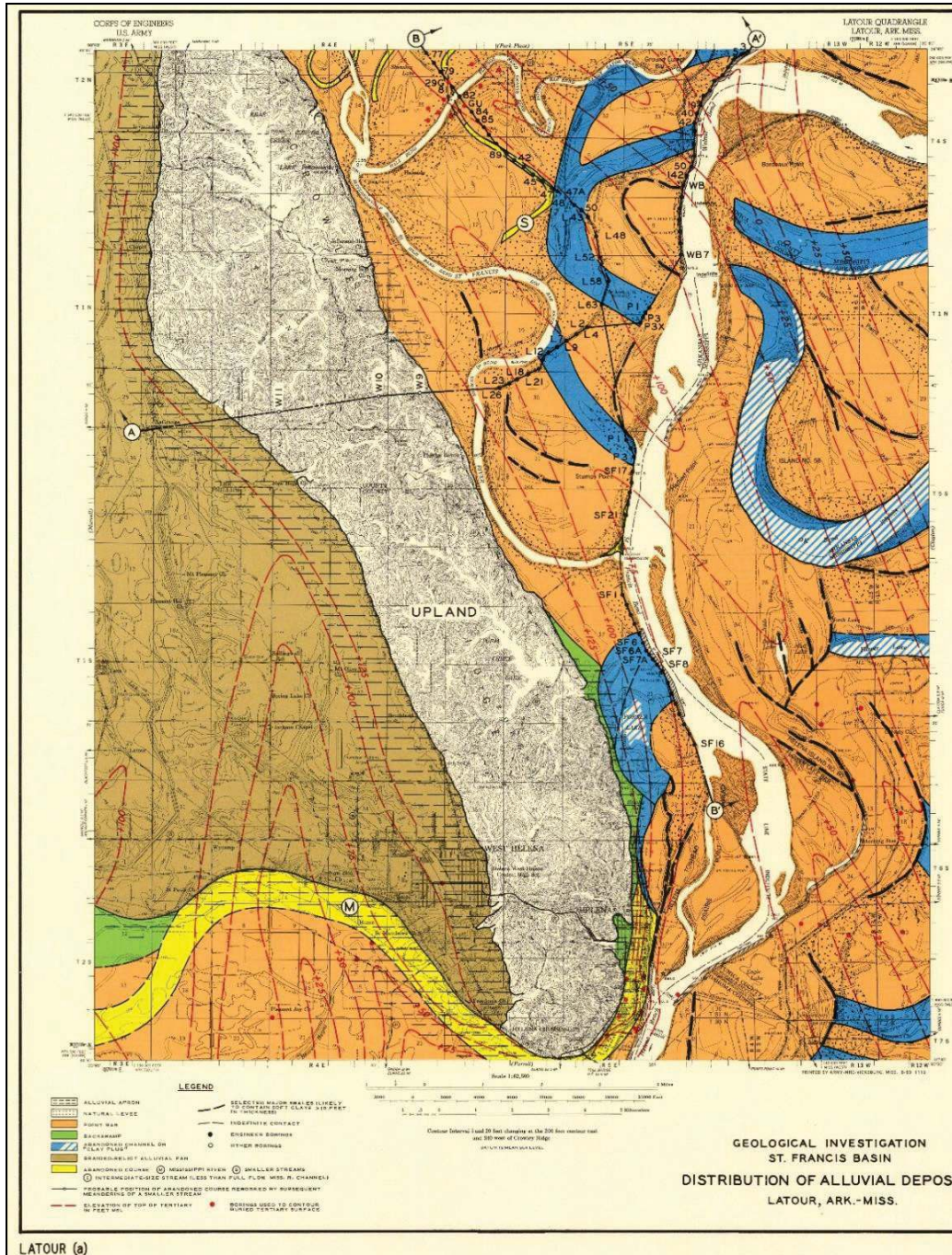


Figure 10. Cross section A-A' showing the distribution of alluvial sediments across Crowley's Ridge in the vicinity of Helena, AR. The ridge separates the Western and Eastern Lowland Valleys that were formed by ancestral Mississippi and Ohio River systems, respectively, during the Early Pleistocene. In this reach of the river, Tertiary stratigraphy transitions from fine-grained Jackson Group (Yazoo Clay) to the coarse-grained Claiborne Group (primarily Cockfield in this area).

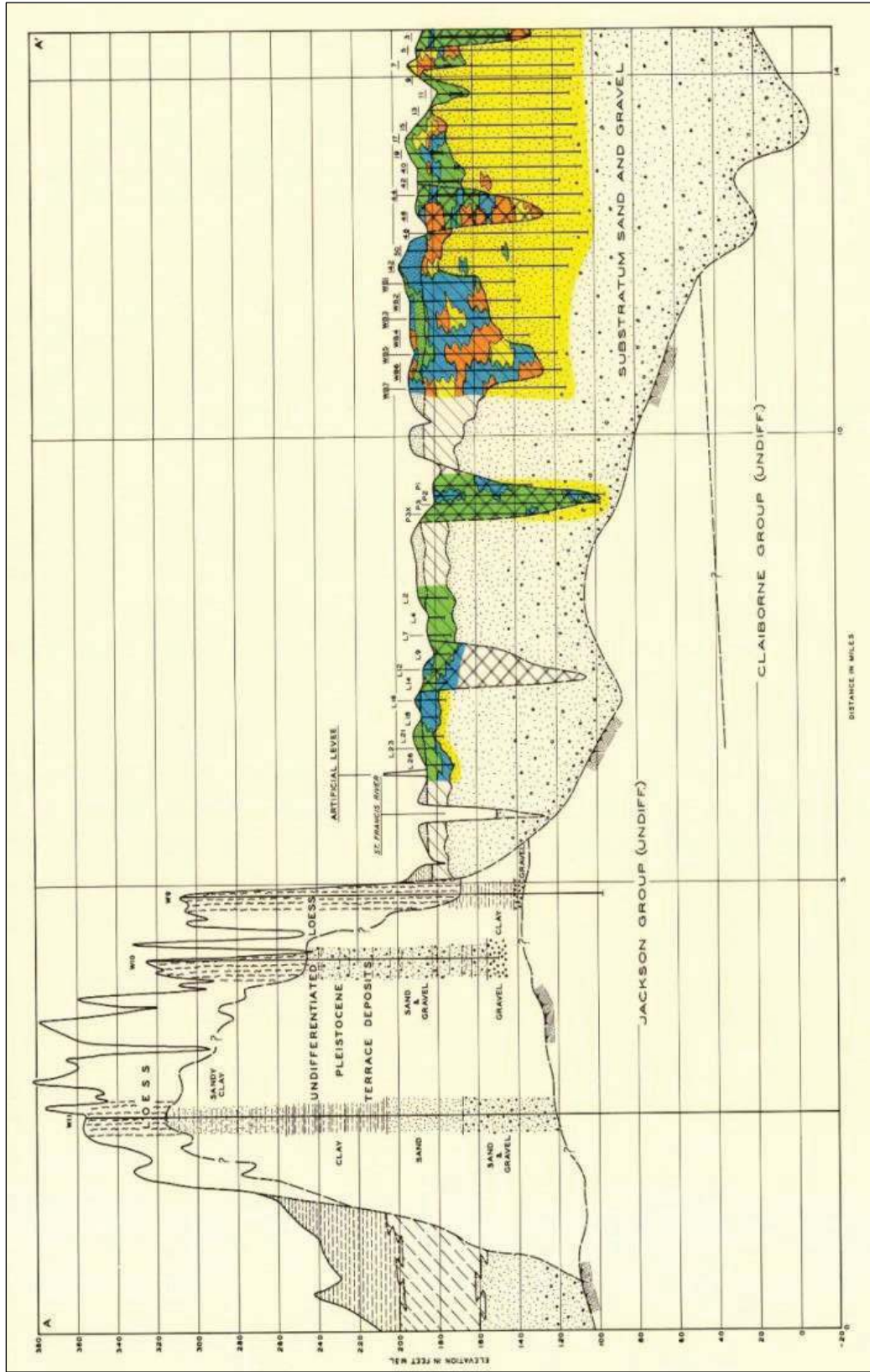


Table 1. Summary descriptions of the Tertiary groups and the individual formations comprising these groups for the LMV (adapted from Saucier [1994]).

Era	System	Series	Group	Formation or Unit	Thickness Range (feet)	Lithology	
Cenozoic	Quaternary	Holocene		Alluvium	0-400	Unconsolidated clays, silts, and sands deposited in fluvial, deltaic, lacustrine, and marine environments.	
		Pleistocene		Valley Trains	50-300	Two sequences (Early and Late Wisconsin) of braided-stream deposits consisting of massive sands and gravels.	
				Loess	0-75	Five sheets of tan to light brown, lightly calcareous, massive, eolian silts of Late to Middle Pleistocene age.	
				Deweyville Complex	40-80	Fluvial terrace with thin fine-grained topstratum and thick coarsegrained substratum.	
				Prairie Complex	60-200	Diverse time-transgressive depositional sequence representing fluvial to marine environments.	
				Intermediate Complex	50-150	Fluvial terrace deposits of well-oxidized clays, silts, sands, and gravels. Includes Montgomery terrace.	
		Tertiary	Miocene		Upland Complex	20-100	Well-dissected deposits of highly-oxidized, fluvial (braided-stream) sands and gravels. Includes Bentley and Williana terraces and Citronelle and Lafayette Formations.
					Pascagoula	0-200	Gray fluvial to estuarine clays and sandy clays with layers of sand and sandstone. Occasionally fossiliferous.
					Hattiesburg	0-450	Hard, gray clays with claystone and thin, greenish sandstone and cemented sand layers. Includes Fleming Formation of Louisiana.
			Oligocene	Vicksburg		Catahoula	0-350
					Bucatunna	30-40	Dark brown, lignitic clays of marine or estuarine origin. Few thin siltstone layers.
					Byram	40-50	Highly fossiliferous marine clays and sandy marls with zones of nodular or lenticular limestone.
					Glendon Limestone	30-40	Alternating thick layers of hard, sandy limestones and clayey, sandy marls.
					Mint Springs	20	Fossiliferous, sandy and clayey marls with occasional phosphatic and lignitic pebbles.
				Forest Hill	0-150	Clayey, lignitic silts irregularly interbedded with fine, cross-bedded sands and thin layers of clayey lignite.	
	Eocene		Jackson		Yazoo Clay	0-500	Dark gray, massive clays with widely scattered, irregular zones of silty clays. Occasionally fossiliferous.
				Moodys Branch	0-40	Fossiliferous, sandy and clayey marls with occasional layers and nodular zones.	
		Claiborne		Cockfield	200-400	Lenticular, alternating, thin strata of gray to gray-brown clays and light gray silts or silty sands. Scattered lignite fragments and layers.	
				Cook Mountain	130-160	Thick, brown, hard clays and reddish, clayey limonite alternating with thin beds of glauconitic sands.	
				Sparta Sand	400-500	Massive, light gray, fine to medium sands interbedded with thin layers of brown, lignitic sandy clays. Includes Memphis sand.	
			Cane River	0-200	Green and brown, calcareous, glauconitic, and fossiliferous clays, marls, and sands. Includes Kosciusko Formation.		
			Carrizo Sand	0-190	Light gray to brownish-gray, fine to coarse, micaceous sands.		
Wilcox			Undifferentiated	100-920	Fine to medium, lignitic, sands and sandy clays and lignite. Massive sands, some coarse and graveliferous, in upper and basal portions.		
Paleocene	Midway		Porters Creek Clay	200-670	Massive, gray, fissile shales, clay shales, and clays with sandy clay beds.		
			Clayton	0-60	Gray, calcareous, glauconitic, fossiliferous shales with scattered lenses of white limestone near base.		

The north-to-south cross section (B–B') identified in Figure 9 is presented as Figure 11 and shows the distribution of alluvial and Tertiary sediments from boring data that were used to construct the cross section. Included in Figure 11 is the legend for this section showing soil types and associated depositional environments mapped on the surface and extend into the subsurface. As depicted by the abandoned channels in the two cross sections, the river is capable of scouring to the underlying Tertiary deposits.

A longitudinal profile of the Tertiary stratigraphy is presented in Figure 12 between Cairo, IL, and Natchez, MS (Fisk 1943). This section displays the upvalley extent of the Jackson Group sediments beneath the Holocene alluvium to the vicinity of Cairo, IL. The section identifies reaches where the river has scoured through the Jackson Group into the underlying Claiborne Group. As shown by the cross sections in Figures 10 and 11, the Jackson Group beneath the alluvium transitions to the Claiborne stratigraphy in the vicinity of Helena, AR, and at Hickman, KY.

A profile of hydrographic survey data of the thalweg from 1962 and 2013 is presented in Figure 13 for a reach of river at Helena between RM 646 and RM 673. Two sets of thalweg elevations are shown in Figure 13. One is the minimum thalweg elevation from the surveys of 1962, 1975, and 1989, and the other is from the most recent survey in 2013. Also included on this profile is the top of Tertiary surface derived from the geologic mapping data from this area (Saucier 1964). The graph of thalweg and Tertiary elevation identifies large-scale changes in channel bathymetry that have occurred over the nearly 50-year period of record. The thalweg of the river has scoured into contact with the Tertiary surface at various points as shown in Figure 13.

Figure 11. North-to-south cross section B-B' in Figure 9 (Saucier 1964). Note the proximity of the abandoned channels scouring into the underlying Tertiary surface. The Helena reach is a transition point between Jackson and Claiborne Group deposits.

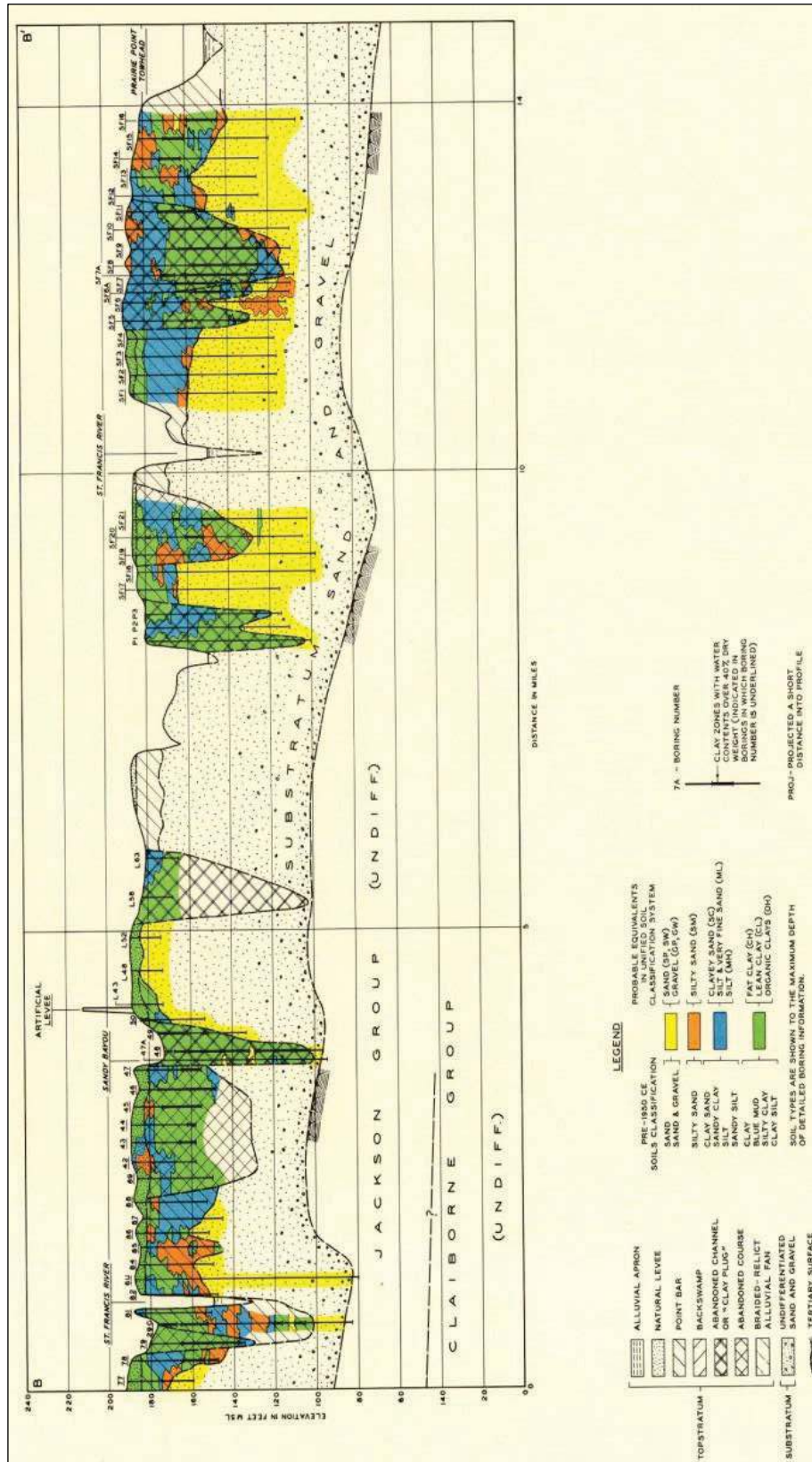


Figure 12. Part of the longitudinal profile between Cario, IL, and Natchez, MS, showing the distribution of Tertiary sediments beneath the Holocene alluvium (Fisk 1943). The Jackson Group of sediments (primarily Yazoo Clay) extends up the alluvial valley and contains reaches where the river has scoured into the underlying Claiborne Formation. Hickman and Helena are identified (on the top of this profile) and contain Jackson Group deposits as previously described. Vicksburg Group sediments correspond to marine limestones which extend upvalley to about the vicinity of Lake Providence, LA.

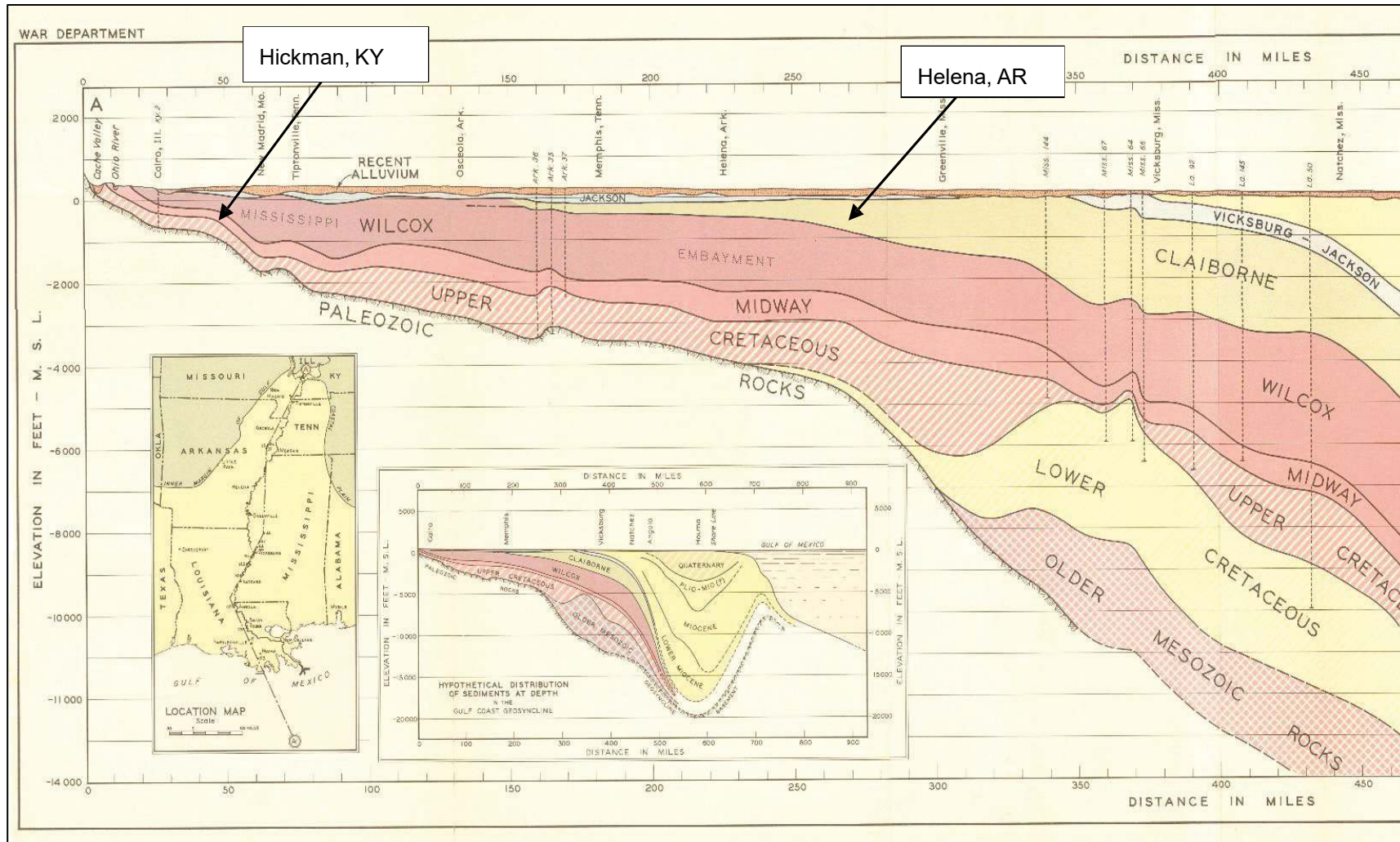
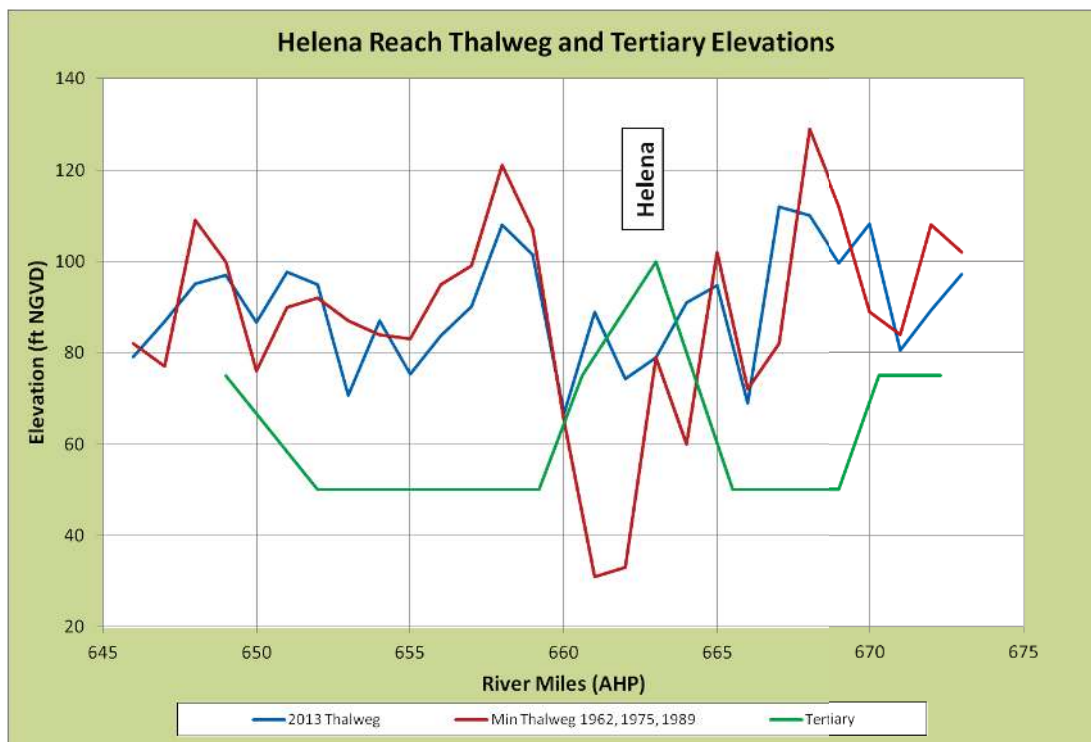


Figure 13. Thalweg and top of Tertiary profile for the Helena reach between RM 646 to RM 673. The survey data show the changes that have occurred during the past 50 years of record.



Morphologic adjustments in the Helena reach

The Helena gage, located at RM 663, is near the upstream limits of the meander cutoffs that were constructed between 1929 and 1942. Three cutoffs were constructed in the vicinity of Helena in 1941 and 1942. The Hardin cutoff was completed in 1942 and is upstream of Helena between RM 675 and RM 680. The Jackson and Sunflower cutoffs were completed in 1941 and 1942, respectively, and are between RM 625 and RM 630. Channel degradation resulting from the cutoffs was observed downstream of Helena at Arkansas City and Rosedale in the 1930s and early-1940s. However, with the exception of a very slight lowering in the early-1930s, the Helena gage was relatively stable from approximately 1940 to the early-1970s. This is illustrated in Figure 14, which shows the low-water (190,000 cubic feet per second [cfs]) specific gage record at Helena from the early-1930s to 2012. This lack of stage change in this period is remarkable, particularly when considering that the Jackson-Sunflower cutoffs were constructed between Rosedale and Helena in 1941 and 1942, respectively. These two cutoffs, located only approximately 30 miles downstream of Helena, shortened the river by approximately 19 miles. Thus, even though there was downstream degradation, and additional shortening with the Jackson-Sunflower cutoffs, the Helena stages were not affected during this time period.

Figure 14. Specific gage record for 190,000 cfs at Helena and low-water slope between Helena and Rosedale.

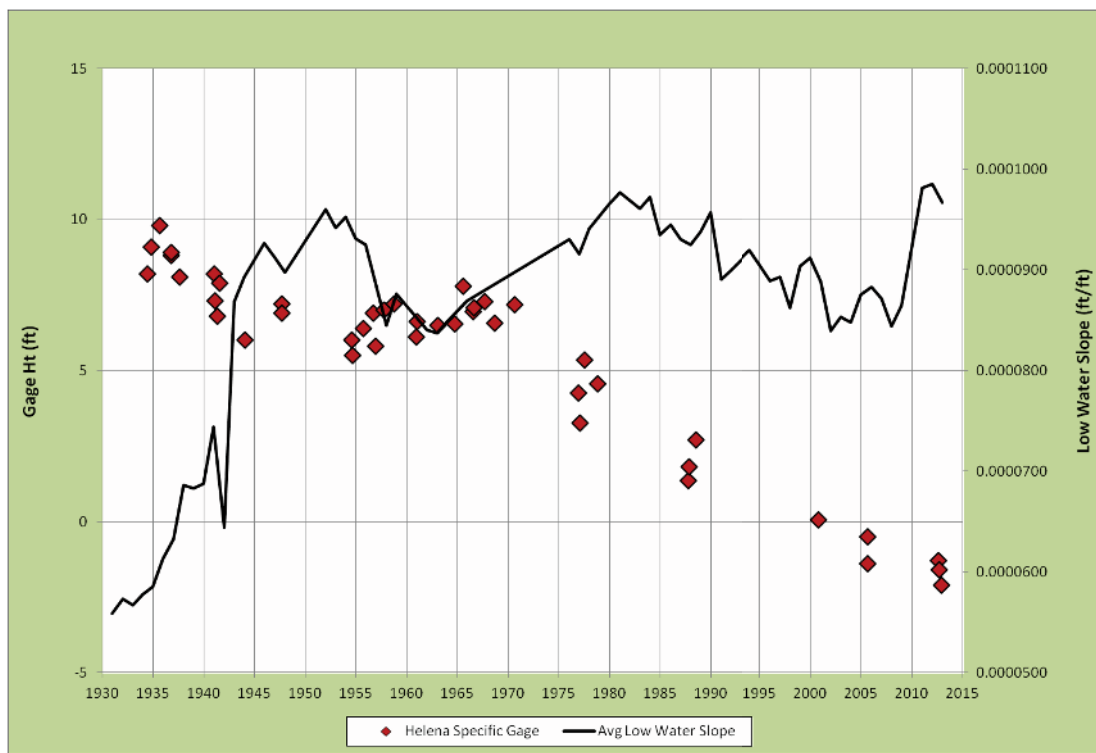


Figure 14 also includes the low-water slopes between Helena and Rosedale from the 1930s to 2013. These slopes were calculated from the daily stage data at these two stations at low-water conditions. These data clearly show the dramatic slope increase between these two stations in the late-1930s through the 1950s as Rosedale degraded and Helena remained relatively stable. As shown in Figure 14, the slopes increased from approximately 0.00006 in the 1930s to approximately 0.000095 by the 1950s. This increase in slope of over 50% would have significantly increased the sediment-transport capacity and erosion potential in this reach. This oversteepened slope zone may be somewhat analogous to the knickzones that are observed in small streams where headward advancing channel incision (headcutting) is checked by erosion-resistant outcrops in the bed (Schumm et al. 1984).

Based on the proximity of the thalweg and Tertiary materials in this reach (Figures 7 and 13), it is likely that these erosion-resistant materials may have served as grade control in this reach. Depending upon the erosion resistance of these outcrops, these features may provide long-term, practically permanent grade control or may persist for a temporary time period until they are finally eroded away, allowing the headcutting to

continue upstream. When the longer-term specific gage record at Helena (Figure 14) is examined, it appears that this may, in fact, have been what happened. As shown in Figure 14, there was essentially no change in the stages from the early-1940s to the early-1970s, indicating that the bed was relatively stable. However, beginning in the early-1970s (possibly triggered by the 1973 Flood), a degradational trend began that has persisted through the present-day. Thus, one possible explanation for this response is that the increased channel slopes discussed above combined with the high-water event of 1973 may have finally breached the thin erosion-resistant layers at Helena, thereby allowing channel degradation to begin in the reach. Obviously, more-detailed investigation will be required to confirm this.

Although the underlining geology does appear to have played a dominant role in the morphologic response in this reach, more-detailed investigations would be needed to establish the precise mechanism involved. Note that other factors may be involved here as well. For example, the degradation upstream of Helena may have resulted in accelerated sediment supply to the Helena reach, which may have contributed to the stability in this reach. More-detailed hydrologic and geotechnical investigation would be needed to establish the precise geomorphic processes responsible for the observed behavior in this reach.

Potential importance of geologic controls on Hickman (hardpoint) reach

As shown in Figure 7, there is a potential interaction between the Tertiary and the river bed near Hickman, KY. Memphis District personnel have documented the presence of an erosion-resistant outcrop between RM 920 and RM 921 (Figure 15), just downstream from the Hickman harbor. Numerous tow groundings have been reported at this site during periods of extreme low water, and consideration has been given to removing this layer to maintain the navigation channel. However, concerns have been expressed that this layer may be providing grade control for the upstream reaches and that removal of this outcrop might result in channel degradation migrating farther upstream into the Middle Mississippi River and up the Ohio River to Olmstead Lock and Dam. In response to these concerns, the Memphis District has initiated a geomorphic investigation as part of the MRG&P Program. Although this study is on-going and not yet complete, some preliminary results are provided to highlight the impacts of this geologic control.

Figure 15. Aerial view of the Hickman area. Scour pool is between RM 920 and RM 921.



Geologic setting of the Hickman area

Geomorphic and geologic data were evaluated from the Hickman, KY, area to better understand the influence of geologic controls on the bed and banks of the river for characterization of the deep scour hole. Geologic data from the Hickman area include WES-era 15-minute alluvial mapping by Saucier (1964) and mapping by the U. S. Geological Survey (Finch 1971 a,b) at the 7-1/2 minute scale. The geology of the Hickman area in the vicinity of the scour pool is shown on the geologic map and cross section in Figures 16 and 17, respectively. The surface geology consists primarily of Mississippi River alluvial deposits and Tertiary (65 to 2 million years) uplands. Alluvial deposits were formed by the Mississippi River, primarily during the Holocene (<10,000 years). These deposits are classified according to their mode of origin or according to depositional environments that create distinct surface landforms (Figure 16). Tertiary sediments in the surrounding uplands and underlying the Holocene alluvium in the Hickman area were deposited under marine conditions and by river systems draining the continental interior which flowed to the Mississippi Valley embayment.

Figure 16. Geologic map of the Hickman area showing alluvial environments of deposition and underlying contours on top of Tertiary deposits (Saucier 1964). The southern portion of cross section B-B is shown in Figure 17. The red arrow corresponds to the approximate location of the scour pool. Tertiary uplands correspond to the black-and-white area of the figure (in the southeast corner).

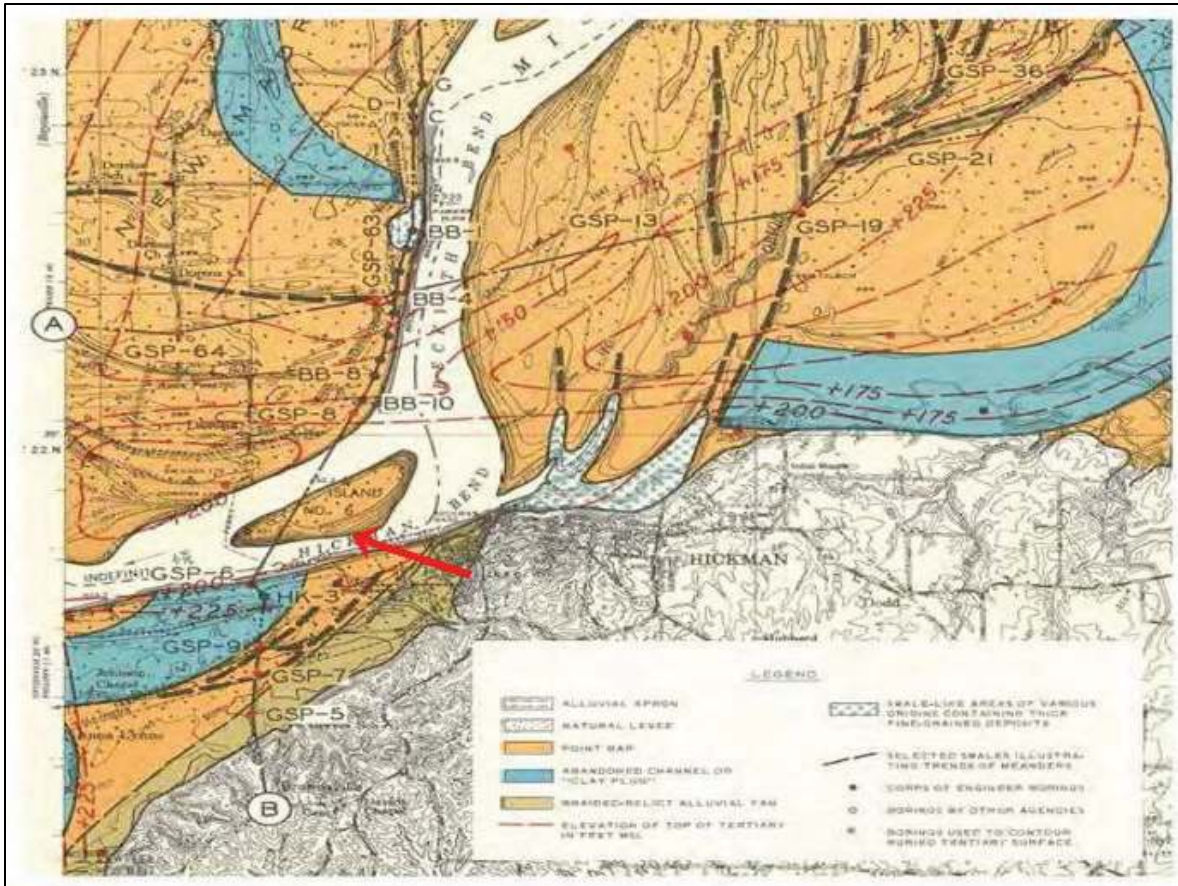
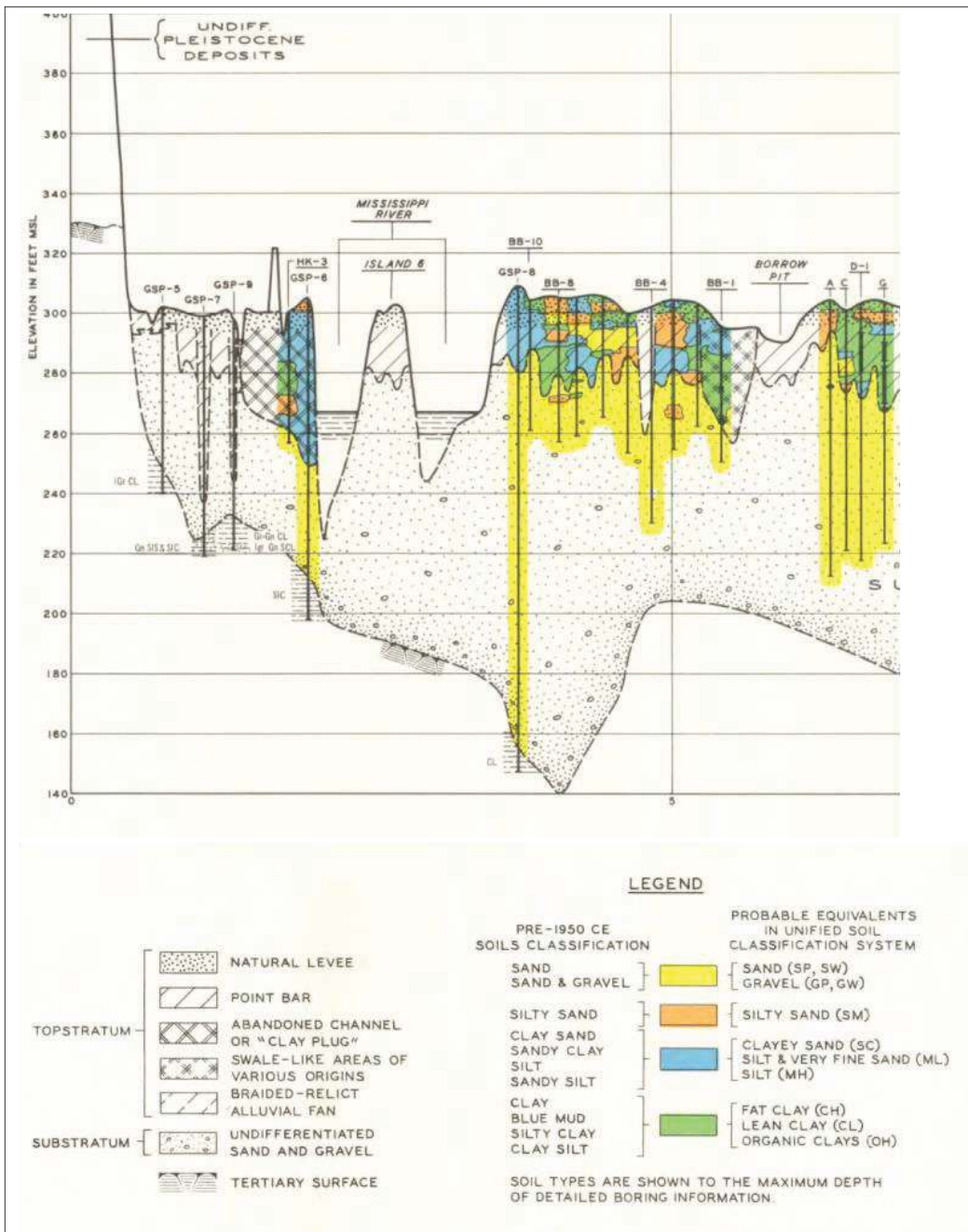


Figure 17. Portion of cross section B-B showing the environments of deposition in profile view at the Hickman scour pool location (Saucier 1964). The scour pool has eroded into the Tertiary deposits to elevation ~140 ft based on 2013 survey data.



Geologic mapping by Saucier (1964) and Finch (1971 a,b) identified the alluvium in the vicinity of the Hickman hardpoint reach to be 80 to 100 ft thick. The Holocene alluvium is comprised of Mississippi River floodplain deposits that are generally separated into a fine-grained topstratum and an underlying coarse-grained substratum (Figure 17). The fine-grained topstratum typically varies between 20 to 50 ft thick. Sand and gravel deposits

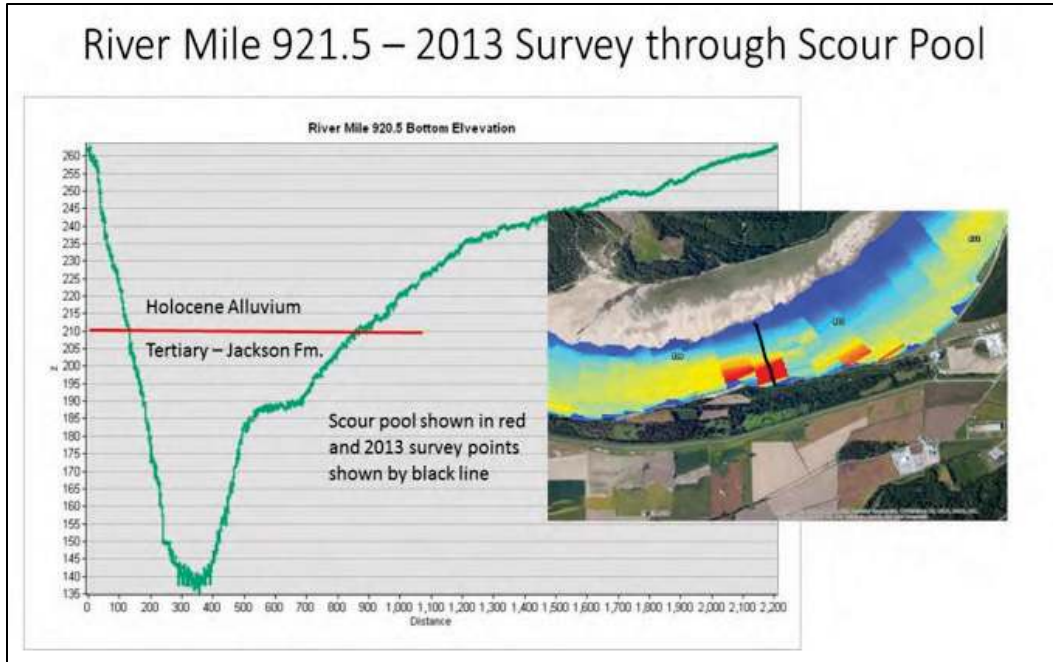
beneath the topstratum comprise an alluvial aquifer. The Tertiary surface beneath the alluvium at the south (left) bank of the river is between elevation 200 to 220 ft (Figure 17).

The fine-grained top stratum was formed by active river migration during the Holocene and consists primarily of abandoned channels or oxbows of the Mississippi River and point-bar deposits. Fisk (1947) described old oxbows as *clay plugs* because of the fine-grained fill contained in these abandoned channels. Filling of oxbows occurs by overbank deposition (vertical accretion) during the annual flooding cycle, when the river overtops its banks and transports fine-grained sediment to distal parts of its floodplain. Through time, oxbow lakes can become completely filled with sediment and can act as hardpoints in the river (Fisk 1947; Mabrey 1949). Gagliano and Howard (1984) described the evolution and filling stages for the typical oxbow lake from their study of abandoned channels in the LMR below Greenville.

Point-bar deposits in terms of their soil texture are a fining upward sequence, with coarse sands and gravel at their base and fine-grained silts near the surface (Figure 17). The fine-grained portion or topstratum forms by vertical accretion of fine-grained sediment during flooding. In contrast, coarse substratum deposits are formed by the lateral accretion process (channel migration) of point bars to the convex side of the river channel. Through time, extensive point-bar deposits develop across the floodplain and create distinctive meander belts involving multiple abandoned channels and river courses.

The river at the Hickman site is eroding older point-bar and abandoned channel deposits of the Mississippi River. The abandoned channel that is present in the south bank contains a variably thick (between 20 to 50 ft), fine-grained topstratum, underlain by 50 to 60 ft of substratum sands and gravels (Figure 16). Based on 2013 bathymetric survey data from the scour-pool reach, the river in the Hickman bend has scoured through these substratum sands and into the underlying Tertiary deposits to elevation 140 ft, as shown by Figure 18. Scouring into the Tertiary deposits is as much as 75 ft deep at the downstream extent of the upper arm of the abandoned channel.

Figure 18. Bathymetry data from the 2013 survey showing depth of the Hickman scour pool. Vertical erosion into the Tertiary Jackson Formation is coincident with the transition of the channel bottom to the convex side (point-bar side) of the abandoned channel (clay plug) identified in the surface geology map in Figure 16.

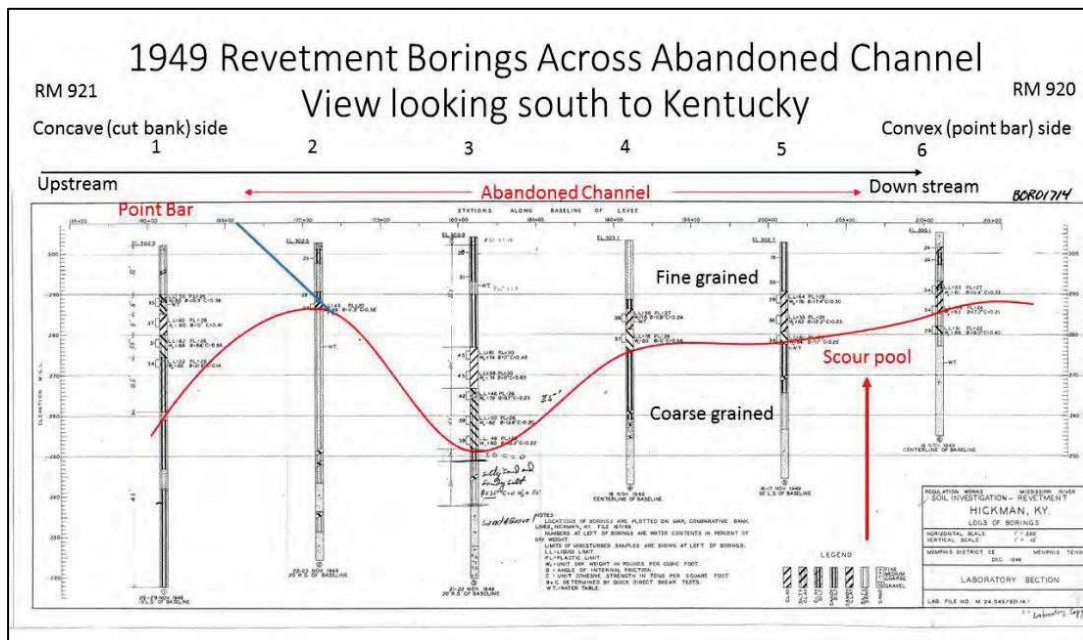


The Tertiary stratigraphy underlying the substratum sands at this location is primarily Eocene (34 to 56 million years) sands and silty sands of the Jackson Formation. This stratigraphy is confirmed by the deep rotosonic borings that were drilled by Memphis District in October 2013 (Figure 19). However, rotosonic boring No. 4 contains the presence of stiff Tertiary clay, which may denote a paleo-surface valley or unconformity as compared to boring Nos. 1 to 3. Deep vertical erosion into the Tertiary Jackson Formation in the scour pool is coincident with the transition in soil texture in the river channel bottom from fine-grained to coarse-grained, as the thalweg of the river meets the convex side (point-bar side) of the old abandoned channel that is present at the south bank, as shown by the surface geology map in Figure 16. Revetment borings drilled in the 1940s, in Figure 20, show the change in soil texture within the channel topstratum from upstream to downstream.

Figure 19. 2013 roto sonic borings at the Hickman scour pool area.



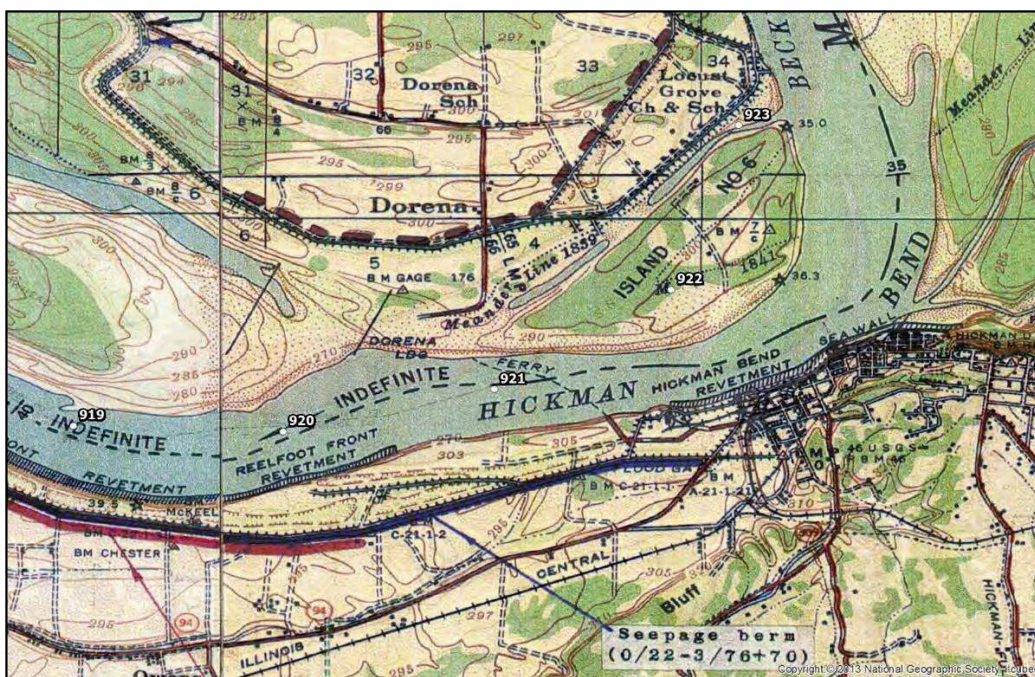
Figure 20. 1940s revetment borings across the abandoned channel in the Hickman reach showing the change in elevation of the fine-grained topstratum from upstream (left part of illustration) to downstream.



The thickness and distribution of the fine-grained abandoned channel deposits along the south bank in the Hickman reach are directly affecting channel scouring and ultimately bank stability at this location. MRC study of river migration during the 1940s showed how fine-grained sediments such as abandoned channels act as hardpoints and cause scouring in the channel (Fisk 1947; Mabrey 1949) and affect the bank failure process (Krinitzsky 1965). Revetment protection in the 1940s along the south bank was not present in the vicinity of the deep scour pool but was present both upstream and downstream (Figure 21). The absence of revetment protection along the upper arm of the abandoned channel is likely attributed to the fine-grained abandoned channel deposits being present here. However, presence of revetment upstream in the point-bar deposits was likely a contributing factor to deepening in this reach. The first addition of revetment protection in the scour reach was constructed in the 1950s. Bathymetry data from the 2013 survey show the extent of the vertical down cutting that has taken place at this location (refer to Figure 18).

In summary, the fine-grained nature of the abandoned channel deposits within the Hickman reach and their impact on river migration were first described by Fisk (1947) as being a hardpoint because of their stratigraphy. Krinitzsky (1965) further described the failure mechanism and its characteristics for fine-grained alluvial deposits. Thus, localized deepening due to the fine-grained nature of the abandoned channel, coupled with the upstream revetment protection in the point-bar deposits to prevent bank migration, has deepened this reach, which incised into the sandy Tertiary deposits. The scour pool is situated where the transition between the maximum channel fill and minimum channel fill occurs, or the present-day river channel scouring into the point-bar side of the old abandoned channel.

Figure 21. Topographic map from 1939 showing absence of revetment in the vicinity of the scour pool corresponds to the reach between RM 922.5 to RM 921.5.



Morphologic response of the Hickman reach

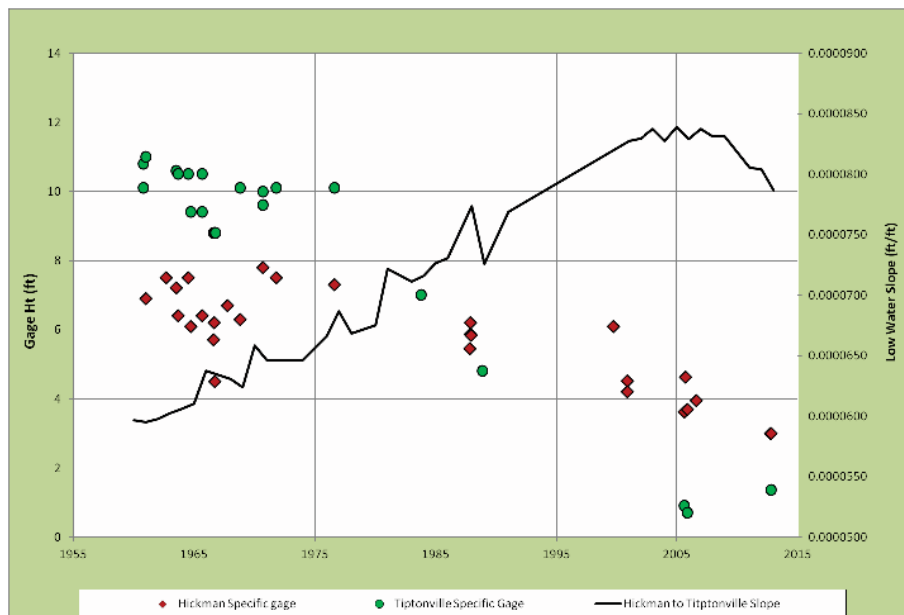
Detailed multi-beam surveys show a deep scour hole immediately downstream of the resistant layer (Figure 22), which has persisted for multiple decades as evidenced by historic hydrographic surveys. Specific gage records developed at Hickman (RM 922) and Tiptonville (RM 872.4) by Biedenharn et al. (2017), and low-water slope data, were used to determine if there is evidence that the resistant outcrop is proving any grade-control function. Figure 23 shows the low-water specific gage records at Hickman and Tiptonville for the 1960 to 2012 time period. As shown in Figure 23, the low-water stages at Hickman have fluctuated somewhat, but overall have been relatively stable from the 1960s through the late-1990s. However, between 2000 and 2012 there appears to have been a lowering trend of approximately 2 to 3 ft. In contrast, the stages at Tiptonville have exhibited a steady decreasing trend that has persisted to the present day, with an overall lowering during this period of approximately 8 to 10 ft. Figure 23 also includes the low-water slope between Hickman and Tiptonville for the 1960 to 2012 time period. This curve was developed from the daily stages at Hickman and Tiptonville for low-water stages. As shown in Figure 23, the slope between Hickman and Tiptonville has increased from approximately 0.00006 to 0.00084 between the early-1960s and the mid-2000s. This 40% increase in slope

reflects the relative stability of the Hickman site versus the downstream degradational site at Tiptonville. These data support the conclusion that the geologic outcrop at Hickman may be providing some grade-control function. Again, more-detailed investigation will be required to establish the exact mechanisms involved at this site.

Figure 22. Scour hole (dark blue) downstream of resistant layer (higher red shades) at Hickman.



Figure 23. Low-water specific gage records at Hickman and Tiptonville. Also shown are the low-water slopes between Hickman and Tiptonville.



4 Conclusions and Wider Applications of this Study

The general geology of the Mississippi River has been well-documented (Fisk 1944; Saucier 1994). River engineers have conducted geological investigations to address local scour, bank failure mechanisms, and the geomorphic response of river reaches. Geological investigations have also identified potential locations where resistant bed material outcrops occur. However, detailed studies of the exact role of these features, particularly with respect to retarding or halting degradational processes along the river, have not received much attention. The two examples provided in this preliminary study support the concept that geologic outcrops may be extremely important features that serve as temporary or permanent grade control along the river. Unfortunately, the existing knowledge of the location and erosion resistance of these features, as well as how they will impact the morphology of the river, is limited.

As the USACE strives to manage the river over the coming decades to hundreds of years, an understanding of how these geologic features may affect the long-term morphology of the river (particularly the degradational potential) will be critical to the following.

- Decisions to remove, leave in place, or reinforce geologic outcrops
- Planning local training works
- Projecting long-term geomorphic trends
- Calibration and interpretation of long-term numerical models

Developing this knowledge will require a dedicated program of study. These studies should focus on the following.

- Locating potential geologic control features. This would include not only the spatial limits of the features, but the elevation of the features as well.
- Characterizing these features, particularly with respect to erosion potential. This would require detailed geotechnical investigations to establish the material types, as well as the depth and lateral extent of the features.
- Analyzing how these features may, or may not impact channel morphology, particularly, long-term channel degradation. This will require detailed geomorphic analyses, as well as possible hydrodynamic and sediment-transport modeling.

References

- Banks, D. C., and W. E. Strohm. 1965. *Methods of Preventing Flow Slides*. Potamology Investigations Report 12-16. Vicksburg, MS: U. S. Army Engineer Waterways Experiment Station. <http://hdl.handle.net/11681/3134>.
- Biedenbarn, D. S., W. A. Stroupe, and J. H. Brooks. 2014. *A Review of the Lower Mississippi River Potamology Program*. MRG&P Report No. 1. Vicksburg, MS: U.S. Army Engineer Research and Development Center. <http://hdl.handle.net/11681/3192>.
- Biedenbarn, D. S., M. A. Allison, C. D. Little, Jr., C. R. Thorne, and C. C. Watson. 2017. *Large-Scale Geomorphic Change in the Mississippi River from St. Louis, MO, to Donaldsonville, LA, as Revealed by Specific Gage Records*. MRG&P Report No. 10. Vicksburg, MS: U. S. Army Corps of Engineers, Mississippi Valley Division. <http://dx.doi.org/10.21079/11681/22744>.
- Camillo, C. A. 2012. *Divine Providence: The 2011 Flood in the Mississippi River and Tributaries Project*. Paper 142. Vicksburg, MS: U.S. Army Corps of Engineers, Mississippi River Commission, Omaha District. <http://cdm16021.contentdm.oclc.org/cdm/compoundobject/collection/p16021coll4/id/181/rec/1>.
- Dunbar, J. B., M. R. Blaes, S. E. Dueitt, J. R. May, and K. W. Stroud. 1994. *Geological Investigation of the Mississippi River Deltaic Plain*. Technical Report GL-84-15. Report 2 of a series. Vicksburg, MS: U.S. Army Engineer Waterways Experiment Station.
- Dunbar, J. B., M. R. Blaes, S. E. Dueitt, and J. R. May. 1995. *Geological Investigation of the Mississippi River Deltaic Plain*. Technical Report GL-84-15. Report 3 of a series. Vicksburg, MS: U.S. Army Engineer Waterways Experiment Station.
- Ferguson, H. B.. 1939. *History of the Improvement of the Lower Mississippi River for Flood Control and Navigation, 1932-1939*. Vicksburg, MS: U. S. Army Corps of Engineers, Mississippi River Commission.
- Finch, W. I. 1971a. *Geologic map of part of the Hickman quadrangle, Fulton County, Kentucky, and Mississippi County, Missouri*. Map GQ-874, 1:24,000 scale, Geologic Quadrangle Maps of the U.S.; Reston, VA: U. S. Geological Survey. <https://pubs.er.usgs.gov/publication/gq874>.
- Finch, W. I. 1971b. *Geologic Map of Part of the Bondrant Quadrangle, Fulton County, Kentucky, and New Madrid and Mississippi Counties, Missouri*. Map GQ-944, 1:24,000 scale, Geologic Quadrangle Maps of the U.S. Reston, VA: U.S. Geological Survey. <https://pubs.er.usgs.gov/publication/gq944>.
- Fisk, H. N. 1943. *Summary of the Geology of the Lower Alluvial Valley of the Mississippi River*. Vicksburg, MS: U.S. Army Corps of Engineers, Mississippi River Commission.

- Fisk, H. N. 1944. *Geological Investigation of the Alluvial Valley of the Lower Mississippi River*. Vicksburg, MS: U.S. Department of the Army, Mississippi River Commission.
- Fisk, H. N. 1947. *Fine-Grained Alluvial Deposits and Their Effects on Mississippi River Activity*. MRC-WES-2000-2-48, two volumes: July (Volume One) and paperback (Volume Two). Vicksburg, MS: War Department, Corps of Engineers, Mississippi River Commission, Waterways Experiment Station.
- Fisk, H. N. 1952. *Geological Investigation of the Atchafalaya Basin and the Problem of Mississippi River Diversion*. Two volumes: April (Volume 1). Vicksburg, MS: U.S. Army, Corps of Engineers, Mississippi River Commission, Waterways Experiment Station.
- Fleetwood, A. R. 1969. *Geological Investigation of the Quachita River Area, Lower Mississippi Valley*. Technical Report No. S-69-2. Vicksburg, MS: U. S. Army Engineer Waterways Experiment Station.
- Gagliano, S. M., and P. C. Howard. 1984. *The Neck Cutoff Oxbow Lake Cycle along the Lower Mississippi River*. Edited by C. M. Elliot, 147–158. In *River Meandering, Proceedings of Rivers '83*, October 24–26, 1983, New Orleans, LA; New York, NY: American Society of Civil Engineers.
<http://cedb.asce.org.erdclibrary.idm.oclc.org/CEDBsearch/record.jsp?dockey=0040788>.
- Gann, A. R. 1981. *Verification of Empirical Method for Determining Riverbank Stability, Report 12-24: 1974 through 1977 Data*. Miscellaneous Paper S-78-5, Report 19. Vicksburg, MS: U. S. Army Engineer Waterways Experiment Station.
<http://hdl.handle.net/11681/20664>.
- Hvorslev, M. J. 1956. *A Review of the Soils Studies*. Potamology Investigations Report 12-5. Vicksburg, MS: U. S. Army Engineer Waterways Experiment Station.
<http://hdl.handle.net/11681/3147>.
- Kolb, C. R. 1949. *The Entrenched Valley of the Lower Red River*. Technical Memorandum No. 3-298. Vicksburg, MS: U. S. Army Engineer Waterways Experiment Station.
<http://cdm15141.contentdm.oclc.org/cdm/ref/collection/p266001coll1/id/1970>.
- Kolb, C. R., and J. R. Van Lopik. 1958. *Geology of the Mississippi River Deltaic Plain: Southeastern Louisiana*. Technical Report No. 3-483. Two volumes. Vicksburg, MS: U.S. Army Engineer Waterways Experiment Station.
- Kolb, C. R. 1962. *Distribution of Soils Bordering the Mississippi River from Donaldsonville to Head of Passes*. Technical Report No. 3-601. Vicksburg, MS: U.S. Army Engineer Waterways Experiment Station.
- Kolb, C. R., W. B. Steinriede, E. L. Krinitzsky, R. T. Saucier, P. R. Mabrey, F. L. Smith, and A. R. Fleetwood. 1968. *Geologic Investigation of the Yazoo Basin, Lower Mississippi Valley*. Technical Report No. 3-480. Vicksburg, MS: U.S. Army Engineer Waterways Experiment Station.
- Kolb, C. R., F. L. Smith, and R. C. Silva. 1975. *Pleistocene Sediments of the New Orleans - Lake Ponchartrain Area*. Technical Report No. S-75-6. Vicksburg, MS: U.S. Army Engineer Waterways Experiment Station.

- Krinitzsky, E. L. 1949. *Geological Investigation of Gravel Deposits in the Lower Mississippi Valley and Adjacent Uplands*. Technical Memorandum No. 3-273. Vicksburg, MS: U.S. Army Engineer Waterways Experiment Station. <http://hdl.handle.net/11681/21296>.
- Krinitzsky, E. L. 1950. *Geological Investigation of Faulting in the Lower Mississippi Valley*. Technical Memorandum No. 3-311. Vicksburg, MS: U.S. Army Engineer Waterways Experiment Station.
- Krinitzsky, E. L., and J. C. Wire. 1964. *Groundwater in Alluvium of the Lower Mississippi Valley (Upper and Central Areas)*. Technical Report No. 3-658. Two volumes. Vicksburg, MS: U.S. Army Engineer Waterways Experiment Station.
- Krinitzsky, E. L. 1965. *Geological Influences on Bank Erosion along Meanders of the Lower Mississippi River*. Potamology Investigations Report No. 12-15, 56 p., September; Vicksburg, MS: U. S. Army Engineer, Corps of Engineers, Waterways Experiment Station. <http://hdl.handle.net/11681/3125>.
- Krinitzsky, E. L., and F. L. Smith. 1969. *Geology of Backswamp Deposits in the Atchafalaya Basin, Louisiana*. Technical Report S-69-8. Vicksburg, MS: U.S. Army Engineer Waterways Experiment Station.
- Mabrey, P. R. 1949. *Geological Investigation of Mississippi River, Memphis, Tennessee, to Mouth of Arkansas River*. Technical Memorandum No. 3-288. Vicksburg, MS: U. S. Army Engineer Waterways Experiment Station. <http://hdl.handle.net/11681/21439>.
- May, J. H., L. D. Britsch, J. B. Dunbar, J. P. Rodriguez, and L. B. Wlosinski. 1984. *Geological Investigation of the Mississippi River Deltaic Plain*. Technical Report GL-84-15. Vicksburg, MS: U.S. Army Engineer Waterways Experiment Station.
- Moore, N. R. 1972. *Improvement of the Lower Mississippi River and Tributaries, 1931 – 1972*. Vicksburg, MS: Department of the Army, Corps of Engineers, U. S. Army, Mississippi River Commission. <http://cdm16021.contentdm.oclc.org/cdm/ref/collection/p16021coll4/id/76>.
- Saucier, R. T. 1964. *Geological Investigation of the St. Francis Basin*. Technical Report No. 3-659. Vicksburg, MS: U.S. Army Engineer Waterways Experiment Station.
- Saucier, R. T. 1967. *Geological Investigation of the Boeuf-Tensas Basin*. Technical Report No. 3-757. Vicksburg, MS: U. S. Army Engineer Waterways Experiment Station.
- Saucier, R. T. 1969. *Geological Investigation of the Mississippi River Area: Artonish to Donaldsonville, LA*. Technical Report No. S-69-4. Vicksburg, MS: U.S. Army Engineer Waterways Experiment Station.
- Saucier, R. T. 1994. *Geomorphology and Quaternary Geologic History of the Lower Mississippi Valley*. Two volumes. Vicksburg, MS: U.S. Army Engineer Waterways Experiment Station.
- Saucier, R. T., L. M. Smith, and W. J. Autin (Eds.). 1996. "Geology in the Lower Mississippi Valley." *Engineering Geology* 45(1-4). (Conference proceedings, special issue dedicated to H. N. Fisk). <https://www.sciencedirect.com/science/journal/00137952/45/1>.

- Schultz, J. R., and C. R. Kolb. 1950. *Geological Investigation of the New Orleans Harbor Area*. Technical Memorandum No. 3-391. Vicksburg, MS: U.S. Army Engineer Waterways Experiment Station.
- Schultz, J. R., and E. L. Krinitzsky. 1950. *Geology of the Lower Red River*. Technical Memorandum No. 3-319. Vicksburg, MS: U. S. Army Engineer, Waterways Experiment Station. <http://hdl.handle.net/11681/21210>.
- Schumm, S. A., C. C. Watson, and A. W. Burnett. 1982. *Investigation of Neotectonic Activity within the Lower Mississippi Valley Division*. Phase I, Potamology Program (P-1), Report 2. Vicksburg, MS: U. S. Army Engineer, Waterways Experiment Station. <http://hdl.handle.net/11681/3129>.
- Schumm, S. A., M. D. Harvey, and C. C. Watson. 1984. *Incised Channels: Morphology, Dynamics, and Control*. Littleton, CO: Water Resources Publications. <https://www.wrpllc.com/allbooks.html>.
- Schumm, S. A., and W. J. Spitz. 1996. "Geological Influences on the Lower Mississippi River and Its Alluvial Valley." *Engineering Geology* 45(1-4): 245-261. <https://www.sciencedirect.com/science/article/pii/S0013795296000166>.
- Schweig, E. S., and R. B. Van Arsdale. 1996. "Neotectonics of the upper Mississippi Embayment." *Engineering Geology* 45(1-4): 185-203. <https://www.sciencedirect.com/science/article/pii/S0013795296000130>.
- Smith, F. L., and R. T. Saucier. 1971. *Geological Investigation of the Western Lowlands Area, Lower Mississippi Valley*. Technical Report No. S-71-5. Vicksburg, MS: U.S. Army Engineer Waterways Experiment Station.
- Smith, F. L., and D. P. Russ. 1974. *Geological Investigation of the Lower Red River-Atchafalaya Basin Area*. Technical Report No. S-74-5. Vicksburg, MS: U.S. Army Engineer Waterways Experiment Station.
- Smith, L. M., J. B. Dunbar, and L. D. Britsch. 1986. *Geomorphological Investigation of the Atchafalaya Basin, Area West, Atchafalaya Delta, and Terrebonne Marsh*. Two volumes. Technical Report GL-86-3. Vicksburg, MS: U.S. Army Engineer Waterways Experiment Station.
- Smith, L. M., and B. R. Winkley. 1996. "The Response of the Lower Mississippi River to River Engineering." *Engineering Geology* 45(1-4): 433-455. <https://www.sciencedirect.com/science/article/pii/S0013795296000257>.
- Torrey, V. H., and A. R. Gann. 1976. *Verification of Empirical Method for Determining Riverbank Stability, 1970 and 1971 Data*. Report 17 of a series. Potamology Investigations Report 12-22. Vicksburg, MS: U.S. Army Engineer Waterways Experiment Station. <http://hdl.handle.net/11681/3124>.
- Torrey, V. H. 1988. *Retrogressive Failures in Sand Deposits of the Mississippi River, Report 2: Empirical Evidence in Support of the Hypothesized Failure Mechanism and Development of the Levee Safety Flow Slide Monitoring System*. Report 2 of a series. Technical Report GL-88-9. Vicksburg, MS: U.S. Army Engineer Waterways Experiment Station. <http://hdl.handle.net/11681/12688>.

- Torrey, V. H., J. B. Dunbar, and R. W. Peterson. 1988. *Retrogressive Failures in Sand Deposits of the Mississippi River, Report 1: Field Investigations, Laboratory Studies and Analysis of the Hypothesized Failure Mechanism*. Report 1 of a series. Technical Report GL-88-9. Vicksburg, MS: U.S. Army Engineer Waterways Experiment Station. <http://hdl.handle.net/11681/13068>.
- Winkley, B. R. 1970. *Influence of Geology on the Regimen of a River*. Meeting preprint 1078 in *Proceedings of the ASCE National Water Resources Conferences, January 23-26*, Memphis, TN, 1–35.
- Winkley, B. R. 1977. *Man-Made Cutoffs on the Lower Mississippi River, Conception, Construction, and River Response*. Potamology Investigations Report 300-2. Vicksburg, MS: U.S. Army Engineer Waterways Experiment Station. <http://hdl.handle.net/11681/3153>.

Appendix A: Selected Historic Geologic Reports by Dr. Fisk (and his staff of geologists) for the MRC

Table A1 contains a listing of selected geologic reports prepared for the MRC. These historic potamology reports and studies were authored by Dr. Fisk and his staff of geologists at LSU between 1941 and 1947

(<http://www.mvd.usace.army.mil/Missions/MississippiRiverScienceTechnology/MSRiverGeomorphologyPotamology/FieldData/HistoricStudies/Geological.aspx>).

This body of work provides detailed information about the geologic history of the alluvial valley, characteristics of coarse-grained meander-belt deposits, alluvial environments of deposition, and the nature of the bedrock geology into which the Mississippi River has incised.

Table A1. Selected geologic reports prepared for the MRC, authored by Fisk (and his staff of geologists).

1941	1.	"Reports on possible factors contributing to bank erosion near Baleshed Towhead," G. H. Matthes, MRC, 11 August 1941.
	2.	"Application of geological studies to underseepage problems in the Lower Mississippi Valley," MRC, 12 December 1941.
1942	3.	"Geological study of underseepage conditions at Elton Slough (La.)," MRC, 24 February 1942.
	4.	"Geological report on the Baton Rouge underseepage area," MRC, 7 July 1942.
	5.	"Geological report on the Wilson Point underseepage area (River Mile 492 AHP) La.," MRC, 9 September 1942.
	6.	"Geological report on the Commerce underseepage area (Miss.)," MRC, 10 September 1942.
	7.	"Geological report on the Trotters underseepage area (Miss.)," MRC, 12 September 1942.
	8.	"Preliminary investigation of the sediment forming the floor of the channel of the Mississippi River between Mile 270 and 281 B.C.," MRC, 12 May 1942.
	9.	"Geological history of the alluvial valley of the Mississippi River," MRC, 9 December 1942.
	10.	"Summary of observations on the occurrence of seepage made during the geological investigation of underseepage sites," MRC, November 1942.

1943	11.	"Geological report on the abandoned Carlisle Lake meander area near Homochitta, Miss. (River Mile 485 AHP)," MRC, 10 May 1943.
	12.	"Sediment report, Warfield Point and Greenville Bend (River Mile 528 AHP)," MRC, 12 June 1943.
	13.	"Geological report on clay plugs in the Vicksburg Engineer District," MRC, 15 June 1943.
	14.	"Geological study of sediments adjacent to the American cut-off revetment," MRC, 16 July 1943.
	15.	"Summary of the geology of the lower alluvial valley of the Mississippi River," MRC, 30 October 1943.
	16.	"Geological investigation of Faulting at Vacherie, La.," MRC, 17 May 1943.
1944	17.	"Geological investigation of the lower alluvial valley of the Mississippi River," (<i>Printed</i>), MRC, 1 December 1944.
1945	18.	"Geological aspects of increased Atchafalaya River flow," MRC, 9 July 1945.
1946	19.	"Geological investigation of the sediments in the Palmyra Lake area," MRC, 20 May 1946.
	20.	"Geological investigation of the sediments of the Wilson Point area (La.)," MRC, 30 May 1946.
	21.	"Preliminary report on borings in the alluvial valley," MRC, 2 October 1946.
1947	22.	"Fine-grained alluvial deposits and their effects on Mississippi River activity," MRC, 1 July 1947.
	23.	"Geological investigation, Reid Bedford bank caving area (Madison Parish, La.)," MRC, 25 July 1947.
	24.	"Geological investigation of underseepage sites in Memphis, Vicksburg, and New Orleans Engineer Districts," WES, December 1947.

Appendix B: Points of Contact

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14. ABSTRACT The Mississippi River is heavily influenced by structural and geologic controls involving regional uplifts, faults, clay plugs, outcrops of Tertiary clay, and Pleistocene gravel in its bed and tributaries. Degradation is continuing to migrate upstream on the Lower Mississippi River (LMR) and has presently moved as far upstream as the Hickman, KY, area. Left unchecked, this degradation could continue to advance on the LMR and ultimately migrate upstream into the Ohio and Middle Mississippi River systems. This degradation would not only adversely affect the stability and environmental features in the main stem of the river but also introduce headcutting into the many tributaries that enter the river in this degradational zone. Detailed studies of the exact role of these features, particularly with respect to retarding or halting long-term degradational processes along the river, have not received much attention. In this study, potential areas where geologic outcrops may influence river morphology are identified, and examples are provided that support the concept that geologic outcrops may be extremely important features that serve as temporary or permanent grade control along the river.					
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