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Geologic Controls of Sand Boil Formation at Buck Chute, Mississippi

Seth M. Martin, Joseph B. Dunbar, Maureen K. Corcoran,
and Darrel W. Schmitz

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Geologic Controls of Sand Boil Formation at Buck Chute, Mississippi

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Abstract

Sand boil formation due to underseepage is a potential failure mechanism for levees in the Lower Mississippi River Valley. Sand boils were identified in the Buck Chute study area in the 1990s during high-water events and during the 2009 Flood. The site is unique due to the presence of point bar and abandoned channel deposits. To understand the role of these alluvial deposits on sand boil formation at the site, a geologic investigation of the subsurface was conducted. Using shallow geophysics, cone penetrometer tests (CPT), borings, and a geographic information system (GIS), researchers concluded that the thin blanket associated with point bar deposits, abandoned channel deposits causing a blocked seepage path, and head differential changes caused by the Muddy Bayou Control Structure were the controls of sand boil formation at Buck Chute.

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Contents

Abstract	ii
Figures	iv
Preface	vi
Unit Conversion Factors	vii
1 Introduction.....	1
1.1 Hypothesis	1
1.2 Purpose of study	2
1.3 Approach	2
2 Description of Study Area.....	4
2.1 Location.....	4
2.2 Geology.....	4
2.3 Description of alluvial deposits.....	7
2.4 Levee development at Buck Chute.....	11
2.5 Muddy Bayou Control Structure	15
3 Literature Review	18
3.1 Geology of the Lower Mississippi River Valley.....	18
3.2 Underseepage studies	19
3.3 Buck Chute studies	20
4 Methods	21
4.1 Electrical resistivity tomography	21
4.2 Borings	22
4.3 Cone penetrometer test	24
4.4 Geographic information system.....	24
5 Results	26
5.1 Electrical resistivity tomography	26
5.2 Borings	29
5.3 Cone penetrometer test	29
5.4 Geographic information system.....	29
5.5 Summary cross sections	38
6 Discussion	42
7 Conclusions.....	46
References	48
Appendix A: Cone Penetrometer Test Reports	50
Report Documentation Page	

Figures

Figures

Figure 1. Distribution of alluvial deposits in the Buck Chute region (Modified from Kolb 1968).	3
Figure 2. Topographic map of the region surrounding the Buck Chute site (Modified from USGS 1:24000 topographic map downloaded from ESRI ArcMap 10.1 library).	5
Figure 3. Aerial imagery of the immediate vicinity of the Buck Chute site with the locations of sand boils (Modified from World Imagery base map downloaded from ESRI ArcMap 10.1 library).	6
Figure 4. Diagram of point bar deposits (USACE 1956).	8
Figure 5. Diagram of channel fill deposit (USACE 1956).	12
Figure 6. 1915 MRC hydrographic survey of Buck Chute (Modified from MRC 1975, sheet 48).	13
Figure 7. 1926 MRC hydrographic survey of Buck Chute (Modified from MRC 1975, sheet 48).	14
Figure 8. Diagram of the evolution of the Mississippi River levees (USACE 2011b).	15
Figure 9. 1949 engineering drawing for the Buck Chute Levee enlargement (USACE 1949).	16
Figure 10. Location of Muddy Bayou Control Structure relative to Buck Chute (Modified from USGS 1:24000 topographic maps downloaded from ESRI ArcMap 10.1 library).	17
Figure 11. AGI SuperSting 8 ERT survey equipment.	22
Figure 12. Location of regional boring cross section B-B' (Modified from World Imagery base map downloaded from ESRI ArcMap 10.1 library).	23
Figure 13. Distribution of CPTs at Buck Chute (Modified from World Imagery base map downloaded from ESRI ArcMap 10.1 library).	25
Figure 14. Location of ERT surveys relative to sand boil activity (Modified from World Imagery base map downloaded from ESRI ArcMap 10.1 library).	27
Figure 15. ERT results near the 2009 sand boils from January and February.	28
Figure 16. ERT results near 1990s sand boils from March 2014.	28
Figure 17. Location of borings at Buck Chute (Modified from World Imagery base map downloaded from ESRI ArcMap 10.1 library).	30
Figure 18. Boring cross section (Modified from Kolb 1968).	31
Figure 19. Location map of CPT cross sections (Modified from USGS 1:24000 topographic maps downloaded from ESRI ArcMap 10.1 library).	32
Figure 20. CPT cross section A-A'	33
Figure 21. CPT cross section B-B`	34
Figure 22. CPT cross section C-C`	35
Figure 23. CPT cross section D-D`	36
Figure 24. CPT cross section E-E`	37
Figure 25. 1990s sand boils elevation profile.	38
Figure 26. 2009 sand boils elevation profile.	38

Figure 27. Location of summary cross sections (Modified from World Imagery base map downloaded from ESRI ArcMap 10.1 library).	39
Figure 28. 1900s sand boils summary cross section.....	40
Figure 29. 2009 sand boils summary cross section.	41
Figure 30. Controls of the 1990s formation of sand boils.	44
Figure 31. Controls of the 2009 formation of sand boils.	45

Preface

This study was conducted for the U.S. Army Corps of Engineers (USACE) under the Flood and Coastal Storm Reduction USACE Civil Works Program (Work Unit J22621). The technical monitors were Dr. Cary A. Talbot, Coastal and Hydraulics Laboratory (CHL), and Dr. Maureen K. Corcoran, Geotechnical and Structures Laboratory (GSL).

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

Unit Conversion Factors

Multiply	By	To Obtain
feet	0.3048	meters
gallons (US liquid)	3.785412 E-03	cubic meters
miles (US statute)	1,609.347	meters
pounds (mass)	0.45359237	kilograms

1 Introduction

The Mississippi River and Tributaries (MR&T) project was formed as a result of the Flood Control Act of 1928, following the devastating Mississippi River Flood of 1927. The MR&T project includes 3,787 miles of levee embankments and flood walls, of which 2,216 are along the main line Mississippi River (Camillo and Percy 2004). MR&T levee design has developed through numerous iterations, which were driven by levee performance during high-water events. The earthen levees that now border the Lower Mississippi River (LMR) are engineered to prevent overtopping by a project maximum flood (PMF), to withstand the stresses of flood loading, and to be resistant to surface erosion. Internationally, levees are used as flood protection and share similar design features; however, the LMR levee system presents unique problems due to the expansive alluvial deposits of the Lower Mississippi River Valley (LMRV).

At the Buck Chute study location, as well as throughout the LMRV, a potential failure mechanism is internal erosion by underseepage. During a high-water event, hydrostatic pressure increases in the pervious substratum. If the upward hydrostatic pressure in the substratum is greater than the downward force of the impervious top stratum, or blanket, heave occurs. Heave of the blanket will permit groundwater to seep and/or flow through the blanket to the ground surface. Piping occurs when seeping water removes material from the subsurface and transports it to the surface, creating a sand boil on the landside of the levee. Piping may eventually remove enough material from the levee foundation to cause failure by subsidence.

1.1 Hypothesis

Sand boil formation at the Buck Chute site is the result of geology consisting of point bar and abandoned channel deposits with a thin blanket and pervious substratum. By conducting shallow geophysics, collecting cone penetrometer tests (CPT) and boring data, and compiling a geographic information system (GIS), researchers will confirm that the controls are a combination of point bar and abandoned channel deposits.

1.2 Purpose of study

The proposed study is a geologic evaluation of an area known as Buck Chute. The site has a history of sand boil development and is unique because of the proximity of both abandoned channel and point bar deposits. The purpose of the study is to identify the geologic controls of sand boil formation through both geological and geophysical investigations and through a review of the levee performance and construction history. By understanding the geology at Buck Chute and its influence on sand boil formation, researchers can identify other levee sections with similar geology and monitor them closely during future high-water events.

1.3 Approach

In order to determine the geologic controls of sand boil formation at the Buck Chute site, the research team conducted an extensive literature review, compiled existing subsurface data, constructed a GIS, and conducted field investigations. Though reports related specifically to Buck Chute are limited, previous underseepage studies (USACE 1941, 1949, 1956, and 2002) examined the geologic process of sand boil formation in river meander environments. Fisk (1944), Kolb (1968), and Saucier (1994) documented the formation of the geologic features found at Buck Chute. This literature provided the information and background necessary to complete the study. Subsurface investigations have occurred at the site, though no geologic interpretations have been drawn from the data (Figure 1). Boring and CPT data were compiled to produce cross sections that were used in the geologic interpretation. A GIS that was created for the study area allowed for efficient spatial data analysis and production of figures. Examples of the data brought into the database are LiDAR (Light Detection And Ranging) elevation data, historic USACE Mississippi River meander maps, U.S. Geological Survey (USGS) topographic maps, sand boil locations, CPT and boring locations, geophysical surveys, aerial imagery, and levee stationing. The field investigations were noninvasive geophysical surveys due to the sensitivity of the levee and permitting requirements. Before the geophysical investigations at Buck Chute were conducted, a permit request was submitted to the levee board for approval.

2 Description of Study Area

2.1 Location

Buck Chute is located in Warren County, MS, on the southern arm of a neck cutoff oxbow called Eagle Lake, which was formed in 1866 (Gagliano and Howard 1984; Bragg 1977). The reach of levee adjacent to Buck Chute falls under the jurisdiction of the Vicksburg District of the U.S. Army Corps of Engineers (USACE) and the Mississippi Levee Board. A topographic map of the region (Figure 2) identifies the Mississippi River, Buck Chute, and the main line levee system. Figure 3 is an aerial photograph displaying the locations of the 1990s and 2009 sand boils at Eagle Pass, Eagle Lake, and Buck Chute. A chute is a surface water flow path that typically allows floodwater to transverse a low section of land. Though no historic documentation specifically stating the origins of the name “Buck Chute” was found during this study, it is assumed that the chute in this case is the batture channel that connected Eagle Pass to Eagle Lake prior to the levee construction.

2.2 Geology

Buck Chute is located in the Yazoo Basin within the LMRV. Successive glaciations throughout the Quaternary period (2 million years ago) produced the present-day alluvial valley that contains floodplains formed from both braided and meandering alluvial deposits. Coarse Quaternary sands and gravels of early braided Mississippi River systems overlie marine Tertiary clays of the Zilpha formation of the Claiborne Group in the Eagle Lake area (USACE 2011a). The Late Wisconsin (20,000 years ago) was the last major low stand of sea level, after which the sea level rose to its present level (Saucier 1994). The last 10,000 years correspond to the Holocene and were marked by a low gradient, meandering Mississippi River system, characterized by point bar, abandoned channel, abandoned course, and back swamp deposits. The abandoned channel, Eagle Lake, was formed by the lateral migration of the Mississippi River. The lateral migration process creates an impervious blanket composed of point bar top stratum and backswamp deposits that overlie the pervious substratum of point bar and braided stream deposits.

Figure 2. Topographic map of the region surrounding the Buck Chute site (Modified from USGS 1:24000 topographic map downloaded from ESRI ArcMap 10.1 library).

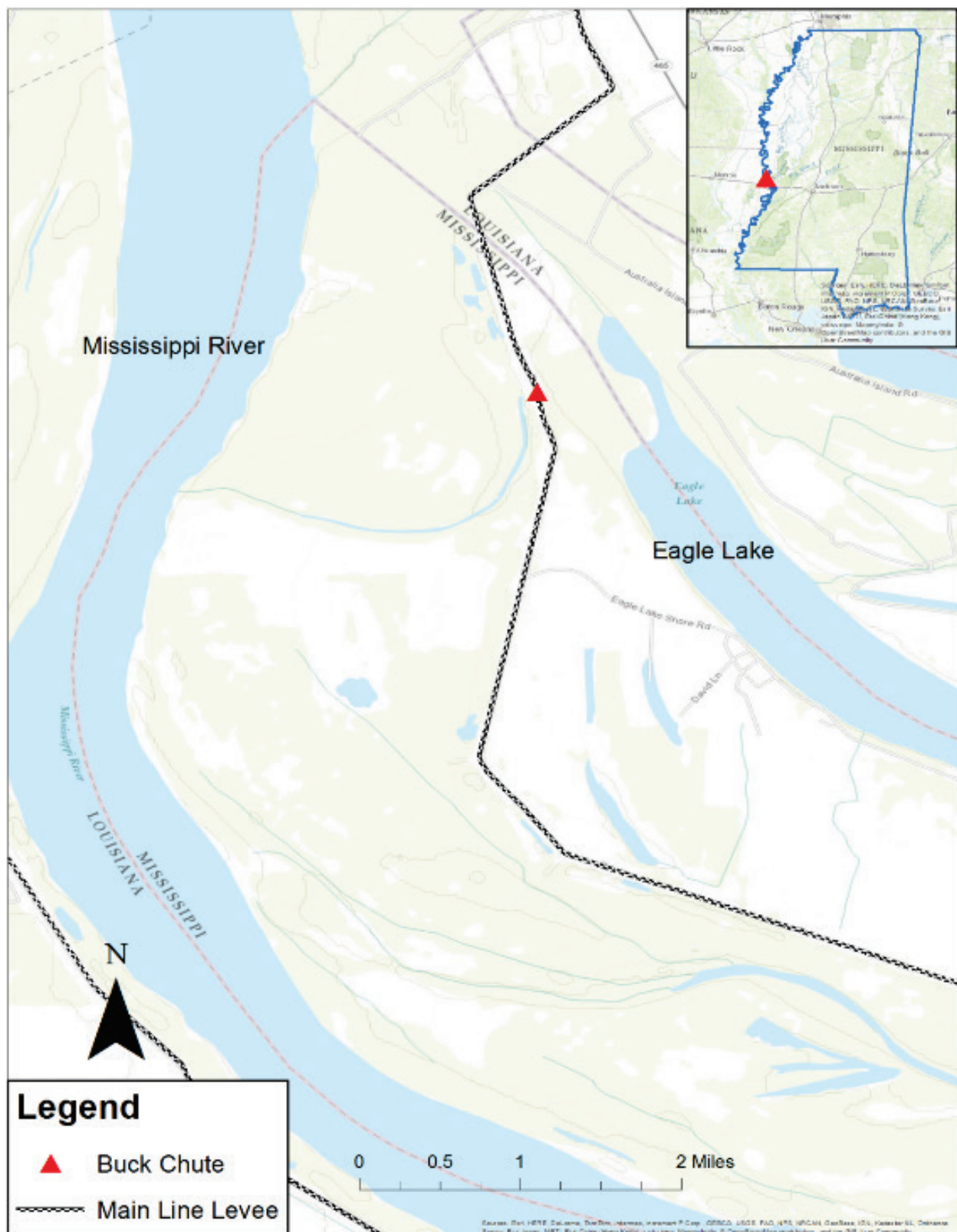


Figure 3. Aerial imagery of the immediate vicinity of the Buck Chute site with the locations of sand boils (Modified from World Imagery base map downloaded from ESRI ArcMap 10.1 library).



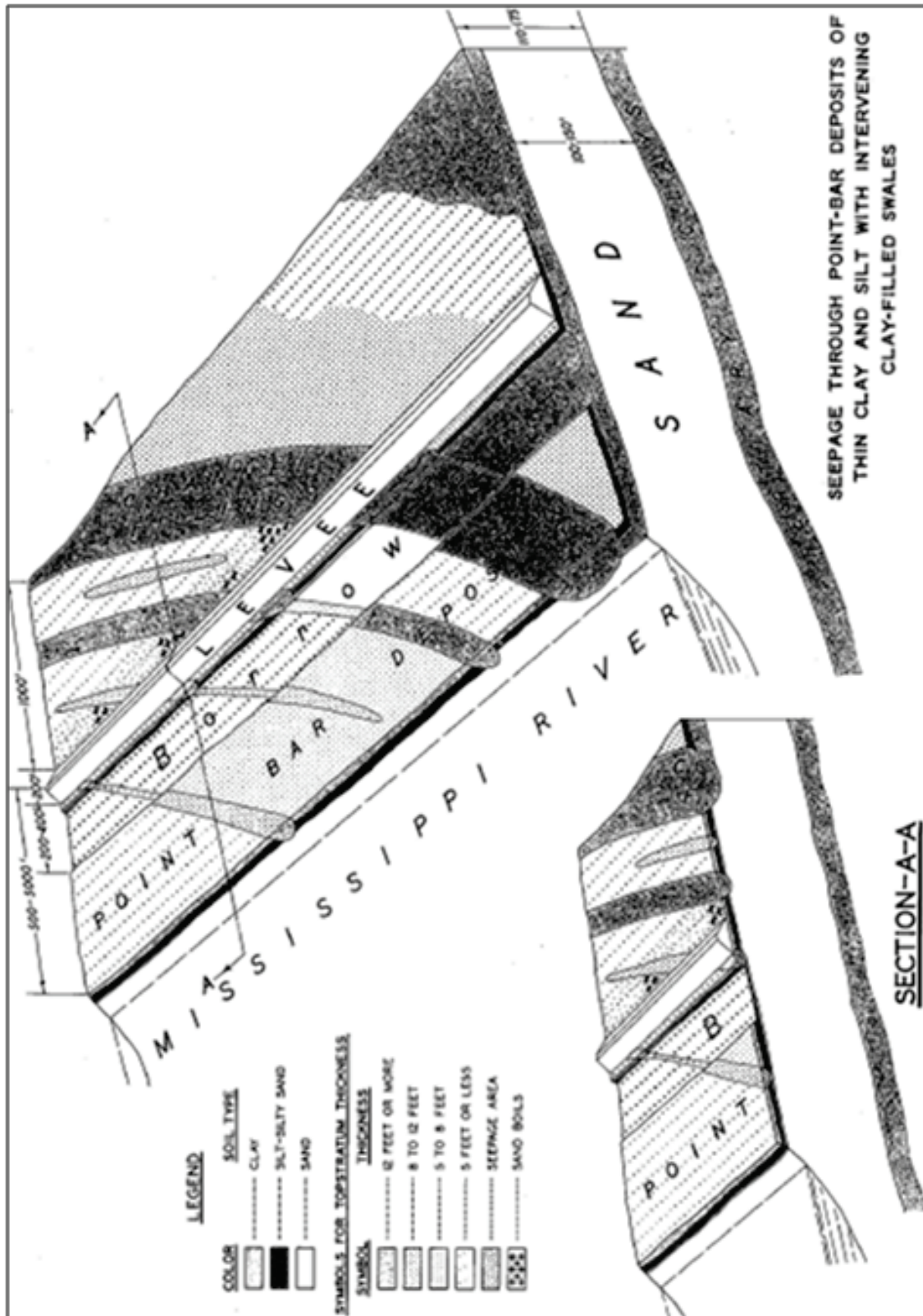
The alluvial deposits of the 1:24000 USGS Alsatia Quadrangle, in which Buck Chute is located, and the three adjacent quadrangles were mapped by Kolb (1968). Aerial photographs were used to delineate alluvial deposits, and borings were used to validate the delineations and to make corrections where necessary. Figure 1 is a map of the alluvial deposits of the region surrounding Eagle Lake and is a compilation of the Alsatia, Onward, Tallabena, and Vicksburg quadrangles.

2.3 Description of alluvial deposits

Point bar deposits are formed by channel processes and lateral accretion. While at a nonflood river stage, sand bars form in the low velocity zones on the inside of a meander bend. Low velocity bars are typically no higher than the water surface and consist of the maximum grain size able to be transported within the water column at that stage. More substantial sand bars form during high flow events when coarser sediments are transported within the water column. The sediment is deposited in low velocity zones within the flood stage channel, which often corresponds with the existing nonflood stage point bars. During these high flow events, scour occurs on the backside of the point bar, which becomes a backwater as the stage decreases. The backwater gradually fills with fine-grained sediment that drops out of suspension during subsequent changes in river stage.

Eventually the river migrates away from the backwater, creating a depression filled with clay-size sediment (Fisk 1947). The silt and sand deposited in elongated bars during the higher flow are referred to as “ridges,” while the silt and clay deposited in the depressions between the bars are referred to as “swales” (Figure 4). Most swales are 100 to 500 ft wide with some exceeding 1,000 ft and range in depth from less than 40 to 80 ft. The soil sequence of a ridge grades downward from sandy silt at the near surface to well sorted, coarse sands of the pervious substratum. Away from the active channel, vegetation traps fine-grained sediment, creating a thin cover of finer grained material over the ridge and swale topography. Top-stratum thicknesses generally range from 5 to 25 ft with the exception of larger swale deposits that can reach depths of 40 ft (Kolb 1968). The substratum is composed of coarser material with a higher hydraulic conductivity.

Figure 4. Diagram of point bar deposits (USACE 1956).



Point bars underlie 60 percent of the Mississippi River levees and have been historically attributed to the majority of sand boil formation instances (Kolb 1975). Sand boils most commonly occur adjacent to the swales, as these tend to restrict subsurface flow, thereby increasing the localized hydrostatic pressure. The orientation of the point bar deposits beneath the levee often dictates the location of sand boil formation. Clay bodies forming at an acute angle to the levee are the more common geometry for boil formation; however, boils also occur at an obtuse angle, but this is less common. Boils also occur when the orientation of the ridge and swale is at a right angle to the levee; however, the locations are random and not really controlled by the impervious swales (Kolb 1975).

Natural levees are overbank deposits that consist of coarse material deposited as a stream exceeds the bank's full height. The water velocity within the channel is higher than that of the overbank flow, resulting in coarse sediment coming out of suspension and being deposited on the floodplain adjacent to the channel. Natural levees are broad features that decrease in height with distance from the channel. The deposits become finer with increasing distance, which reflects decreased carrying capacity with decreased velocity. Levees are often marked by small scour channels that occur at right angles progressing away from the parent channel. If large and pronounced, these channels are considered crevasses. When crevasses are filled with sediment, the material tends to be much coarser than the material that forms the levee itself. Typical levee deposits consist of silts, silty clays, and sands. Due to rapid drainage, water content is low, and organics are not present other than roots (Kolb 1968).

Because natural levees consist of semipervious material, they can provide a pathway for seepage. An example is a natural levee that overlies an impervious deposit; the levee will act as a conduit for water to migrate where it would not have otherwise been able. Another instance is when a crevasse scours completely through a natural levee deposit by ancient floods and is backfilled with clays; sand boils can occur but will be restricted to the crevasse channel (Kolb 1975).

Backswamp deposits consist of clays that are deposited after a river has exceeded the bank-full stage, and sediment-rich water spreads out over the floodplain. The decreased velocity of the water allows sediment to fall out of suspension and be distributed into low lying areas. Backswamp deposits have large lateral extent, have low topographic relief, and are marked by

dendritic drainage patterns. Consisting predominately of dark gray clays to silty clays and organics, such as peat layers and woody material, the Yazoo Basin backswamp deposits can vary from 30 to 50 ft thick (Kolb 1968).

Because of the lateral extent, thickness, and impervious nature, backswamp deposits are the least likely to cause sand boil formation. Unless pierced by a borrow pit or creating an impervious floor on top of which are pervious deposits such as a natural levee, there is not substantial data to indicate these deposits are a cause of sand boil formation (Kolb 1975).

In a meandering river system, the main channel of the river is in a state of constant migration and, as a consequence, will often abandon portions of the channel in favor of shorter segments. Channel fill deposits, both abandoned channels and abandoned courses, are the thickest and most impervious of the alluvial deposits. “Abandoned channel” refers to an oxbow that has been cut off and over time has become filled with sediment. An abandoned course is similar to an abandoned channel, but consists of more than one oxbow or a longer segment of the river (Kolb 1975). In the Yazoo Basin, abandoned channels are numerous, usually 5 to 10 miles long, several thousand feet wide, and 70 to 90 ft deep (USACE 1968). Abandoned courses are less frequent because lengthy segments are often modified or destroyed by the river migration process but display the same depth and width as abandoned channels (Kolb 1968).

As described by Galiano and Howard (1984), cutoff, lacustrine, and terrestrial stages define the evolution of channel fill deposits that once separated from the parent channel. The cutoff stage is the abandonment of the river channel segment; the subsequent filling of the segment is controlled by the orientation and proximity to the river. Sedimentation begins immediately with sands and silts forming bars in the abandoned portion close to the still active river. As the abandoned course or channel becomes more hydraulically disconnected, the sediment load transported in the water column becomes finer. Once the bars block significant inflow from the river, the lacustrine phase begins. This stage is marked by the formation of the batture, which is the fine-grained sediment near the end of the detached segment. Batture channels allow connection to the river, thereby maintaining both the lake level relative to the river and the sediment influx that forms the batture. The final stage is the terrestrial stage, when the segment becomes completely filled with sediment and vegetation that is tolerant of poorly drained soils covering the former river channel (Fisk 1947).

The effect of channel fill deposits on sand boil formation is similar to that of swales. The sediment composition is silty sands to thick blue muds and clays; however, the fill deposits are much greater in width, depth, and extent than swales (Fisk 1947). Water migrating through the pervious substratum will encounter an impervious “clay plug” of a channel fill deposit forcing increases in the hydrostatic pressure that result in heave. Sand boils are most frequently observed when a levee crosses a channel fill deposit at an acute angle. The lateral extent of the fill deposit can cause sand boils over a much larger area than an individual swale (Figure 5).

Though not a depositional feature, borrow pits have an effect on the formation of sand boils. Borrow pits are the result of excavated soil that was used to construct a levee. Early levee construction practices used the material close at hand, which was often at the base of the levee. If the pit punctures the blanket, the result is an entry point into the pervious substratum at or near the toe of the levee. Subsurface hydrostatic pressure is then directly affected by high-water events (Kolb 1975). USACE (1956) concluded that removal of the blanket, except where several feet of clay were left in place, was the source of seepage.

2.4 Levee development at Buck Chute

Understanding the development of the levee system at Buck Chute is important in order to understand the historic levee performance issues. Mississippi River Commission (MRC) hydrographic surveys indicate that the levee at Buck Chute was constructed between 1915 and 1926 (Figures 6 and 7). The levee was constructed to the 1914 levee standard, which maintained a grade 3 ft above the 1912 Flood high-water line, had slopes of 1: 3 on both the riverside and the landside, and had a banquette 5 to 8 ft below the levee crown with a width of 20 to 40 ft that deepened the levee height (USACE 1972). Figure 8 displays the historical development of the MR&T levee standards. At the time of construction, 90 percent of the levees constructed were considered “B” sections, a classification due to the loam composition of the levee material (USACE 1972). The 1949 USACE engineering drawings chronicle the enlargement to the 1947 Levee Code, 1:4 slope riverside and 1:5.5 landside, and mark the addition of both the riverside and landside berms as well (Figure 9). No records of Buck Chute construction activities from 1949 until the U.S. Army Corps of Engineers, Vicksburg District, constructed the berm in 2011 were located during this study. USACE (2011a) noted that the reach of levee that contains Buck Chute was not analyzed or constructed until the 1973 Project Flood Flowline.

Figure 5. Diagram of channel fill deposit (USACE 1956).

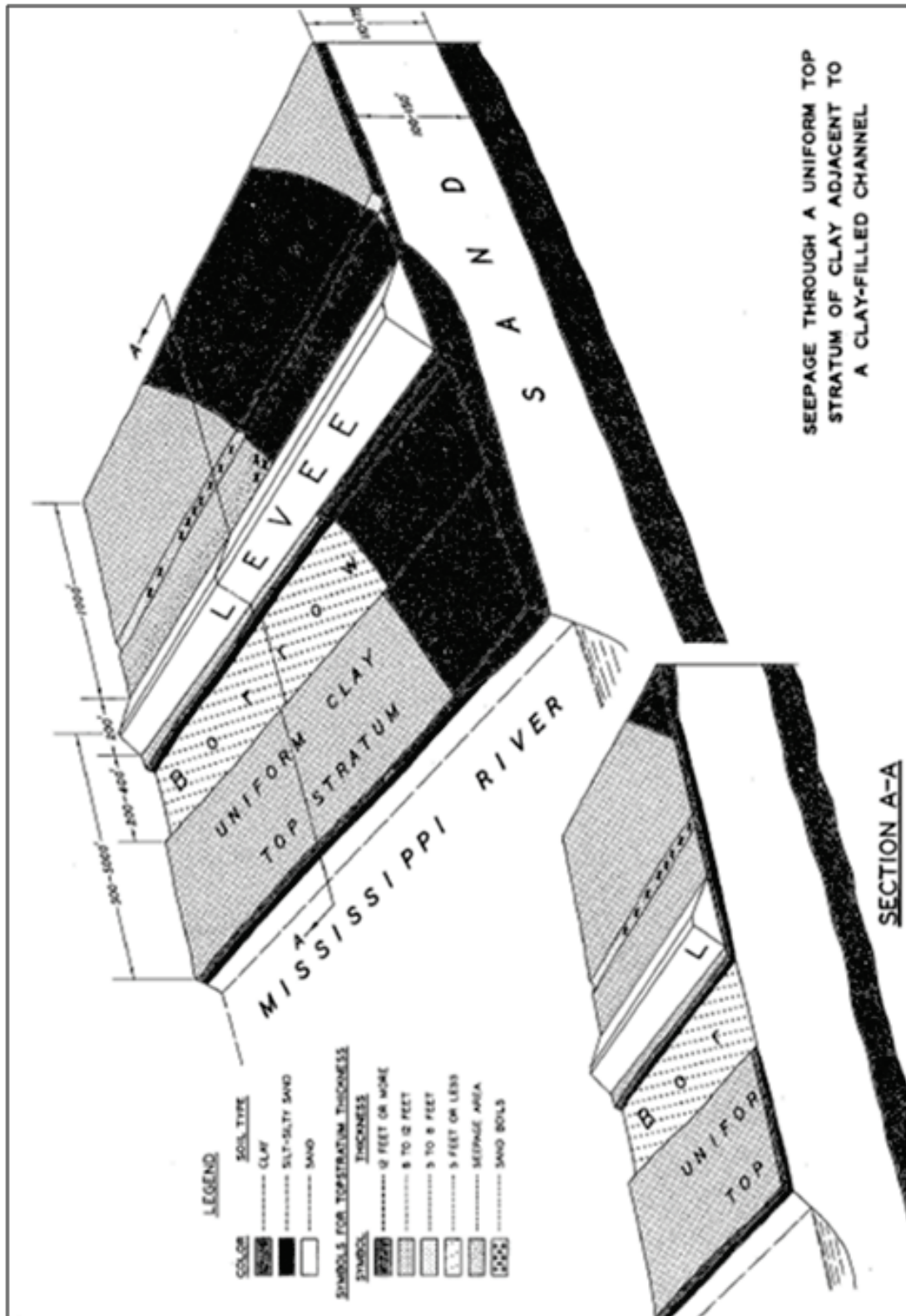


Figure 7. 1926 MRC hydrographic survey of Buck Chute (Modified from MRC 1975, sheet 48).

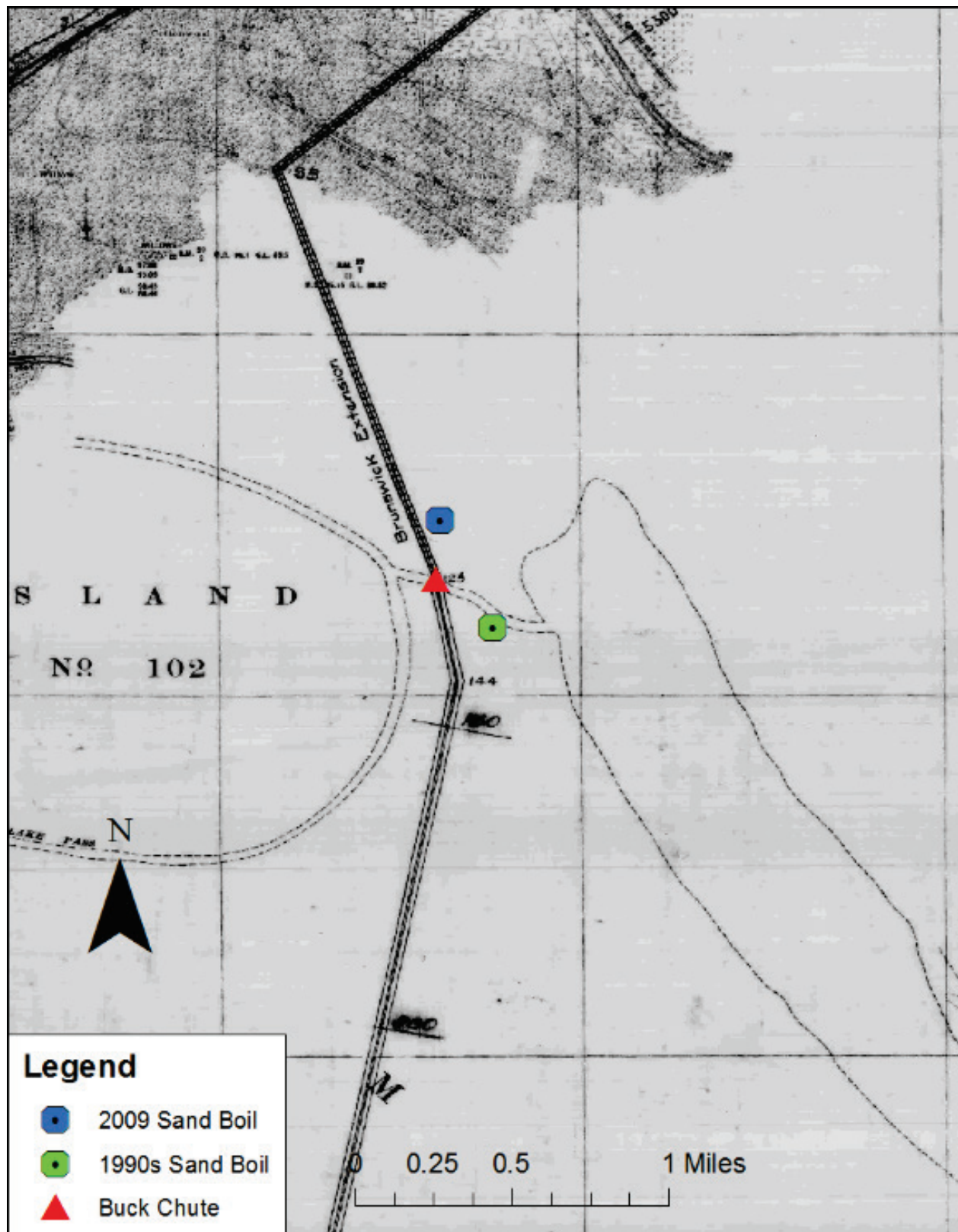
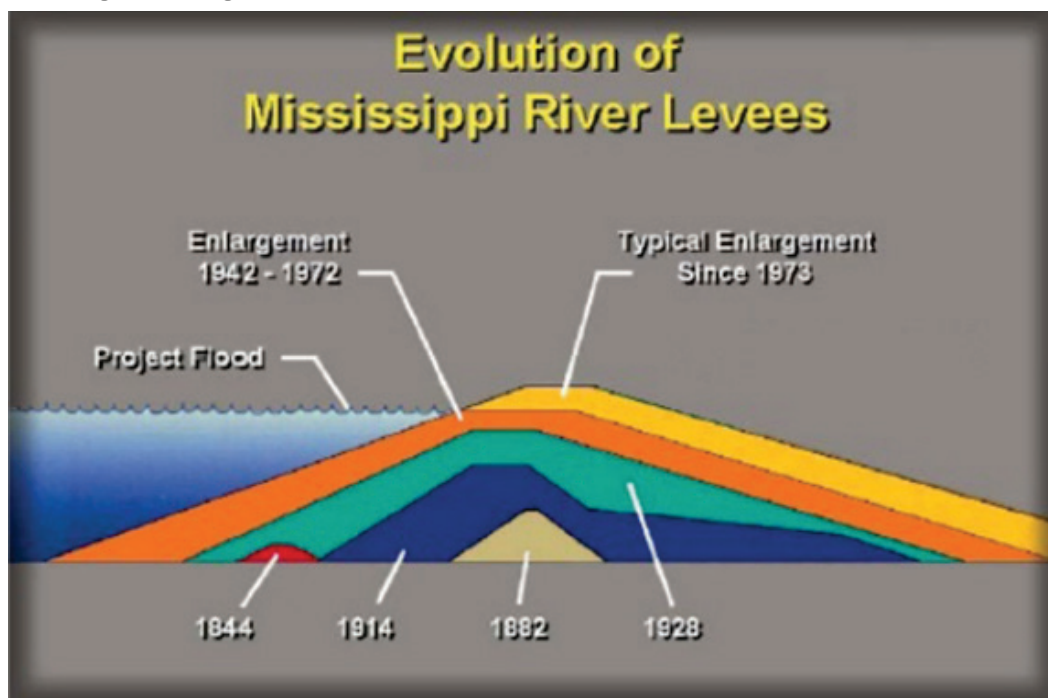


Figure 8. Diagram of the evolution of the Mississippi River levees (USACE 2011b).

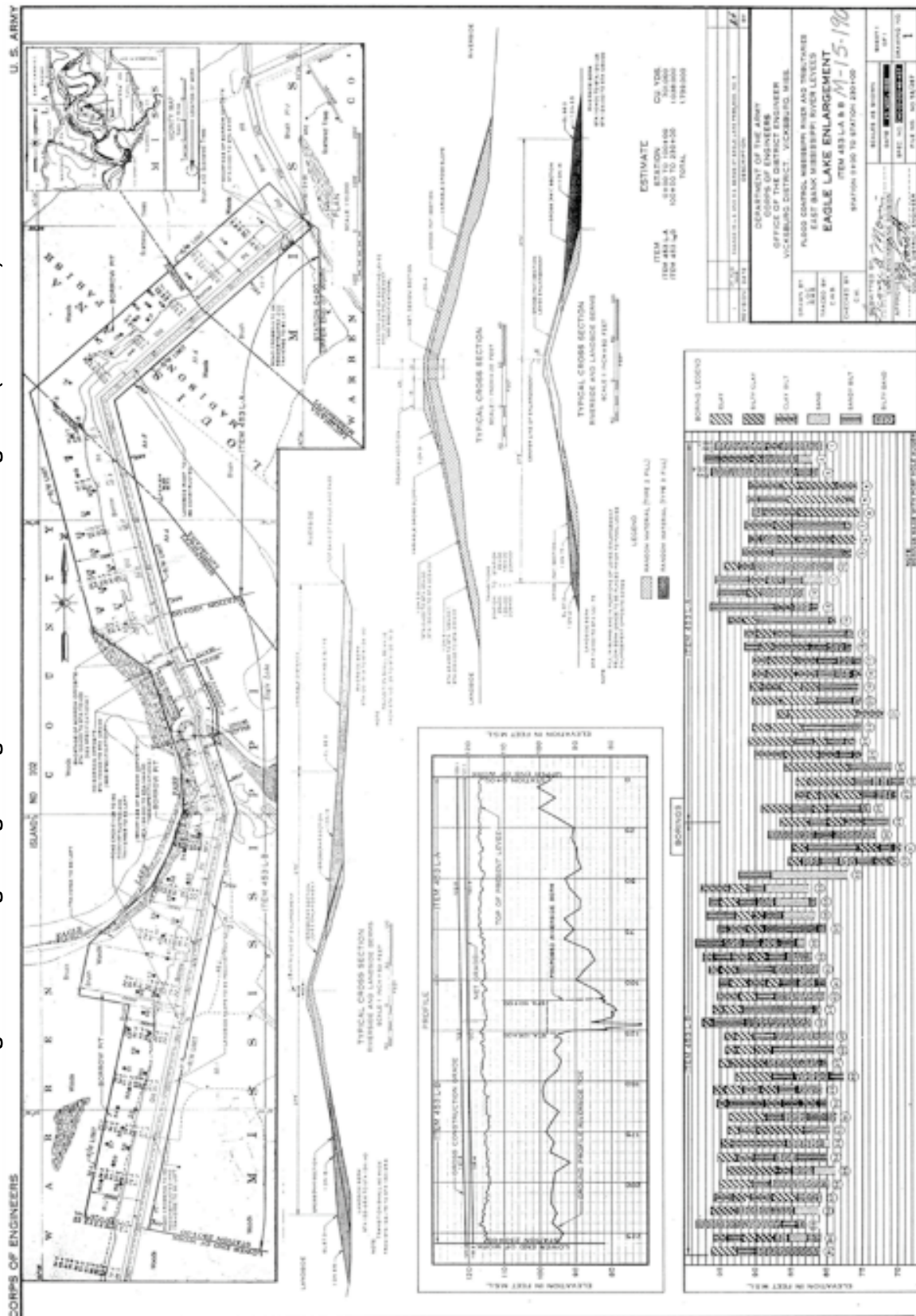


2.5 Muddy Bayou Control Structure

The Muddy Bayou Control Structure has two functions: to maintain a constant Eagle Lake level for recreation and to prevent the agricultural runoff from entering the lake. Muddy Bayou controls water influx from the Yazoo Basin into the northeast of Eagle Lake (Figure 10). The USACE 1973 Flood Report contains the flood inspection for the Buck Chute area; backwater was observed up on the toe of the levee with no boils noted.

During the 1973 Flood, the Muddy Bayou Control Structure and Yazoo Backwater Basin Levee had not been built. As a consequence, Eagle Lake rose until it inundated the levee toe. In the 1979 Flood Report, sand boils were documented along the “chute” that is the batture channel on the landside of the levee. The record high water for the control structure occurred on 22 May 1979, verifying its presence during the 1979 event. Prior to construction of the control structure, floodwaters either reduced the head due to tailwater and prevented sand boils from forming, or the boils were simply under water so that no boils were observed prior to 1973. In 2011 with the flood crest approaching, USACE increased the level of Eagle Lake from its normal of 75 to 90 ft. It was not determined what effect this had on sand boil formation during the high-water event; however, no boil activity was recorded.

Figure 9. 1949 engineering drawing for the Buck Chute Levee enlargement (USACE 1949).



3 Literature Review

3.1 Geology of the Lower Mississippi River Valley

Two authoritative geologic investigations of the LMRV were published by Fisk (1944) and Saucier (1994). Fisk mapped the geology of the LMRV, in a manner that was not previously possible because of lack of data, by using topographic maps produced by the Mississippi River Commission (MRC), aerial photography, and borings from both engineering and water supply projects. He was able, for the first time, to determine the chronology of the valley's evolution from the spatial distribution of alluvial deposits and their topographic position. Though many of the concepts Fisk initially proposed have stood the test of time, new concepts and geologic tools emerged during the 50 years following the publication of his report. Saucier (1994) used advances in geologic dating techniques, archeological investigations, geophysics, increased amount of boring data, and localized geologic investigations to update the chronology of the alluvial valley.

Fisk (1947) examined the effect of the fine-grained sediment on the Mississippi River migration. The study concluded that the combination of the fine-grained bed and bank material and the low gradient cause the slow meander of the Mississippi River within its alluvial valley. Because both the bank and bed material are cohesive, the sediments act as a unit rather than as individual grains, which is harder to erode in a cutbank. A portion of the study was the detailed discussion of the composition of the depositional environments. The grain-size distribution and spatial distribution of the alluvial deposits are the controlling factors of subsurface flow and, therefore, are critical to sand boil formation.

While Fisk (1944) and Saucier (1994) discussed the larger scale LMRV geology, Kolb (1968) focused on of the Yazoo Basin. The report detailed the thickness, frequency of occurrence, and grain-size distribution of the alluvial deposits and the Tertiary formations below the alluvial aquifer. The discussion of the depositional environment, top stratum, and substratum was critical in interpreting the geologic features of the Buck Chute site.

Gagliano and Howard (1984) described the meander cutoff process and the formation of oxbow lakes in the LMRV. Their study described the

formation of the batture and the sedimentation process for oxbow lakes. The filling process of the batture is dictated by the orientation of the oxbow arms to flow direction, which in turn controls the rate of sedimentation and grain size of the deposited sediment. Understanding the progression of sedimentation in Eagle Lake was necessary to draw conclusions about the geologic process of sand boil formation.

3.2 Underseepage studies

The MR&T levee system experienced underseepage and numerous sand boils during the 1937 Flood. As a result, MRC initiated a general study of underseepage (USACE 1941). The study laid the foundation for all USACE underseepage studies to come in later years. At several sites, a detailed study of the geology, soil properties, and head elevations using piezometers in the substratum occurred. The principle findings of this report were the relationship of the pervious substratum to the impervious top stratum in point bar deposits and the recommended use of relief wells and berms to control sand boil formation at the levee toe.

The underseepage study by USACE (1956) expanded on the number of field sites in the LMR and included additional field sites in the Middle Mississippi River. The study developed numerical methods to evaluate levee stability based on the geology at each site. Numerical solutions derived from the field data (i.e., blanket thickness, blanket soil properties, aquifer thickness, and aquifer material properties) were used to calculate exit gradients at the levee toe and to identify seepage entry points as a function of different types of geologic cases. This study concluded that the most viable means of seepage control are riverside blankets, relief wells, and landside seepage berms.

Following the 1973 Flood, Kolb (1975) examined the occurrence of seepage and sand boil activity. The purpose of the study was to evaluate the earlier findings regarding the effect of geologic factors on underseepage, discuss observations of performance issues during the 1973 Flood, and relate the observations to geology. The study concluded that both point bar and channel fill deposits are the primary geologic environments for sand boil formation. Both the ridge and swale features of point bar deposits allow for seepage to propagate under levee foundations and the characteristic clay plugs of swales to impede horizontal flow, driving groundwater to the surface. Channel fill deposits cause similar results as the clay plugs but on a

larger scale. These two cases are relevant to the Buck Chute site because of the proximity of both point bar deposits and channel fill deposits.

USACE (2002) reviewed the methods for the study of underseepage in USACE (1956). The methods selected to better characterize the blanket thickness, other than evenly spaced borings within the levee right-of-way, were the use of Cone Penetrometer Test (CPT) soundings and shallow geophysics. Cone Penetrometer Test (CPT) soundings and shallow geophysics.

The *International levee handbook* (CIRIA 2013) is a comprehensive guide for all parameters of earthen flood-control structures. The document describes the protocol for site assessment, risk assessment, failure mechanisms, emergency management and operations, and non-emergency operations and management. Organizations from France, Germany, Ireland, the Netherlands, the United Kingdom, and the United States collaborated on this project to learn from one another's experiences and to produce solid practice guidance. This guidance recommends increased use of geophysics and CPTs for site assessments and geologic mapping and is intended to be used with relevant local guides for specific procedures.

3.3 Buck Chute studies

Studies focused on the Buck Chute site are limited. Resistivity surveys were conducted by ERDC researchers in 2001 in the vicinity of the 1990s sand boil locations. Resistivity soundings were performed to interpret blanket thickness and to identify potential seepage paths. An in situ resistivity array for long-term monitoring of subsurface flow was also installed within the potential seepage path. CPTs were incorporated to verify the results of the resistivity array data. By monitoring during both low and high water, the study identified a portion of the subsurface that became less resistive during high water. This was interpreted as a possible seepage path. USACE (2011b) described the engineering countermeasures of relief well installation and berm construction at Buck Chute in preparation to the 2011 Flood.

4 Methods

4.1 Electrical resistivity tomography

The resistivity method measures the electrical resistance of the subsurface material. Different subsurface materials have various electrical properties. Clays in particular have low electrical resistance because the phyllosilicate structure and highly charged surface readily transmit electric current. Sands and gravels have a greater resistance because of the pore space between the grains and poor electrical conductivity of the silicate crystalline structure of the grains. The resistivity surveys were conducted to map seepage paths in the subsurface and to continuously map the subsurface features of the alluvial deposits. During high water, the pore space in the subsurface will fill with water, which greatly reduces the electrical resistance. It is possible, by comparing high and low water resistance data, to locate possible seepage paths. Alluvial deposits, such as swales, can be highly varied in geometry. CPT and boring data were obtained at intervals, and the area between the logs was interpreted. It is possible for a feature, such as a swale, not to be detected in a CPT or boring cross section. Resistivity surveys provide a continuous section, ensuring that no subsurface feature that could contribute to sand boil formation is missed.

Electrical Resistivity Tomography (ERT) is a subsurface investigation method that combines the electrical resistivity method with rapid geophysical data acquisition technology. Linear arrays of electrodes, at a set spacing, inserted into the ground are attached to a multiconductor cable, which is in turn controlled by a laptop (Figure 11). A known current is applied to a single electrode; the potential measured at another pair of electrodes, and with the known spacing, allows the resistance to be calculated and recorded. This process is continued until all electrode locations are measured relative to each other. The surveys used the Dipole-Dipole method because of the depth of investigation and the rapid data acquisition time (Reynolds 2011). The 84-channel Advanced Geoscience Inc. Supersting 8 ERT system was used to conduct the surveys. Once data were compiled for a survey line, they were processed using the inversion software RES2DInv. Seven surveys conducted from January to May 2014 were used during interpretation of Buck Chute. Two-meter electrode spacing, which gives vertical and horizontal resolution of approximately 2 m and an investigation depth of 40 m, was chosen.

Figure 11. AGI SuperSting 8 ERT survey equipment.



4.2 Borings

In 1944, USACE drilled numerous borings along the main line Mississippi River levee adjacent to Buck Chute, creating cross section B-B', in support of a levee enlargement project (Figure 12). Auger boring, which USACE (1984) described as limited in the ability to describe complex stratigraphy but useful for preliminary soil investigations, was the method used. Cuttings from the drilling itself are used to identify strata and, as a result, depths to units or soil horizons are subject to interpretation. The records of these borings exist as portfolio sheets in the USACE Engineer Research and Development Center Library and were scanned into electronic format for examination and presentation. Extending to the north and south of the study area, the borings were used to compare regional subsurface data to the more localized CPT and ERT data.

Figure 12. Location of regional boring cross section B-B' (Modified from World Imagery base map downloaded from ESRI ArcMap 10.1 library).



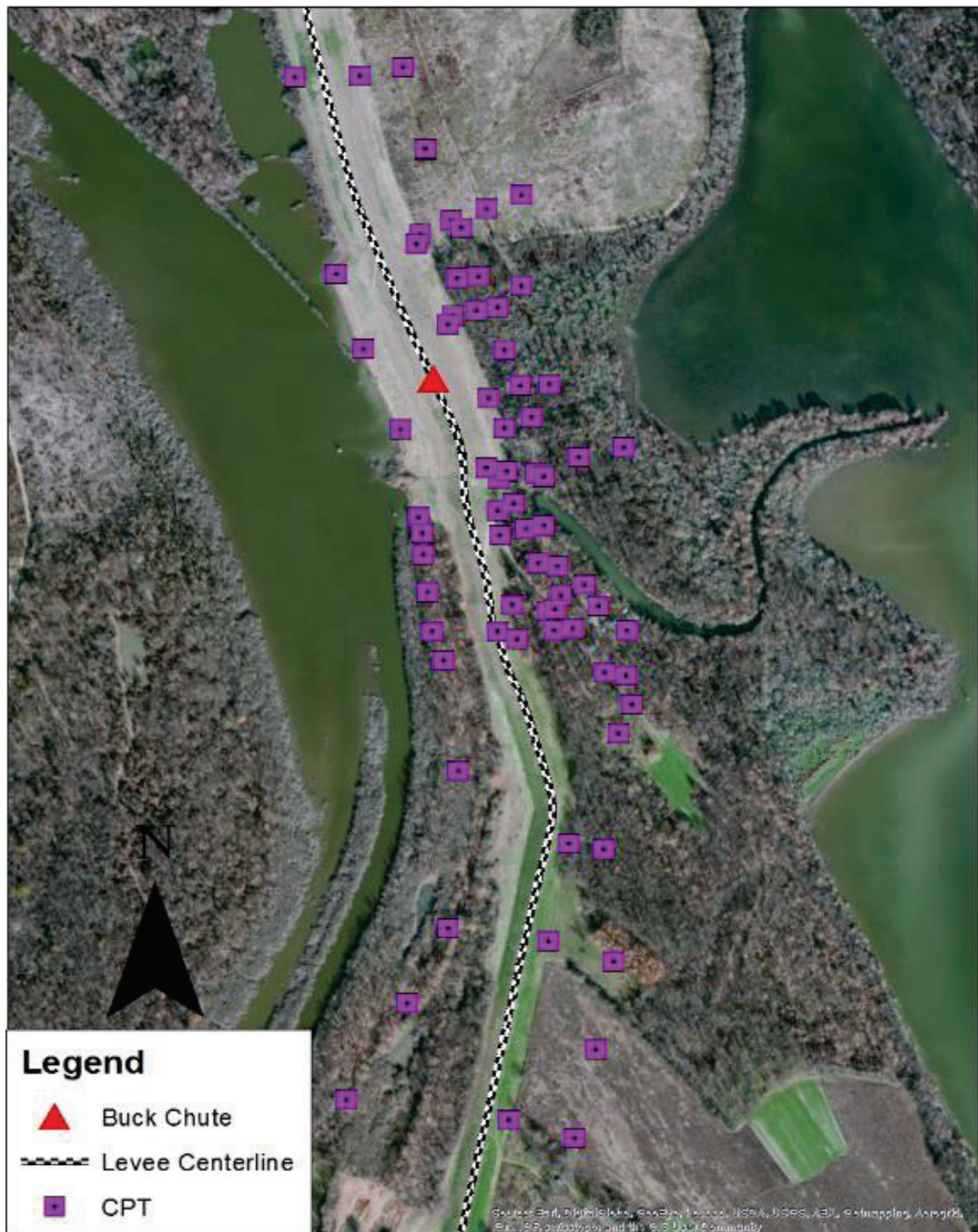
4.3 Cone penetrometer test

In 2002 and 2010, the USACE Vicksburg District performed a number of CPTs in the vicinity of Buck Chute. Figure 13 shows the locations of the CPTs. A CPT involves pushing a 1.4-in.-diam instrumented probe into the ground while simultaneously measuring the cone resistance and sleeve friction on the probe. Cone resistance is the stress acting on the tip of the probe and is an index of the strength of the soil. Sleeve friction resistance, the frictional resistance on a short cylindrical section of steel just above the tip, is an indicator of loose or unstable soil structures (USACE 1994). Results of laboratory testing produced a behavior chart that is used to classify soils by using CPT measurements. The CPT method is a tool of choice for investigators where the site is composed of clays, sands, or soil mixtures containing a small gravel fraction. Cross-section locations were selected to map the extent of the alluvial deposits, and individual CPTs that fall along the cross sections were chosen. The software gINT Professional v8i was used to import the CPT data and produce the cross sections. The CPT cross sections were used to examine the blanket thickness and soil lithology and to map the lateral extent of the alluvial deposits.

4.4 Geographic information system

GIS is a computer system for storing, managing, and displaying both the locations and attributes of spatial features (Chang 2010). For this study, ArcMap version 10.1 was used to compile and interpret spatial data. Because the area has been vital to Mississippi River commerce, historic hydrographic surveys were originally produced to aide in navigating the river. These surveys were digitized and overlain on recent photography and topographic maps. Geologic maps from the Kolb 1968 mapping effort were also digitized and brought into ArcMap. LiDAR data provided accurate elevation information and was brought into the GIS. Additional location data collected in the field during the course of this study, such as ERT survey locations, CPT locations, boring locations, levee stationing, and seepage berm location, were also incorporated into the database.

Figure 13. Distribution of CPTs at Buck Chute (Modified from World Imagery base map downloaded from ESRI ArcMap 10.1 library).



5 Results

5.1 Electrical resistivity tomography

ERT is a subsurface investigation method that combines the electrical resistivity method with rapid geophysical data acquisition technology. The resistivity surveys were conducted to map seepage paths in the subsurface and to continuously map the subsurface features of the alluvial deposits. Seven surveys were conducted from January to May 2014 by using 2-m electrode spacing that provides a subsurface resolution of approximately 2 m.

Five surveys performed from 15 January 2014 through 19 February 2014 were combined during processing. The 7 March 2014 ERT survey was conducted and processed separately from the combined survey. The combined survey begins in the south at the wood line and trends northwest on the seepage berm paralleling the levee at Buck Chute (Figure 14). The line was chosen to intersect the batture channel and seepage paths of the 2009 sand boils. The combined survey results displayed relatively uniform thickness, low-resistivity, top stratum, and more highly resistive substratum (Figure 15). Near the 2009 sand boil activity, an area of higher resistivity values occurs. This is interpreted as coarse, clean sands that have a higher hydraulic conductivity than the surrounding material and therefore is a potential seepage path.

The 7 March 2014 survey was performed to identify possible seepage pathways for the 1990s sand boil occurrences; however, the survey could not be extended far enough south because surface conditions prevented emplacement of electrodes. Due to the orientation of the path through the woods in the southern portion of the study area, the survey was not able to be combined with the 15 January through 19 February surveys. The results are interpreted as a blanket, which thins rapidly from the north to the south (Figure 16).

Figure 14. Location of ERT surveys relative to sand boil activity (Modified from World Imagery base map downloaded from ESRI ArcMap 10.1 library).



Figure 15. ERT results near the 2009 sand boils from January and February.

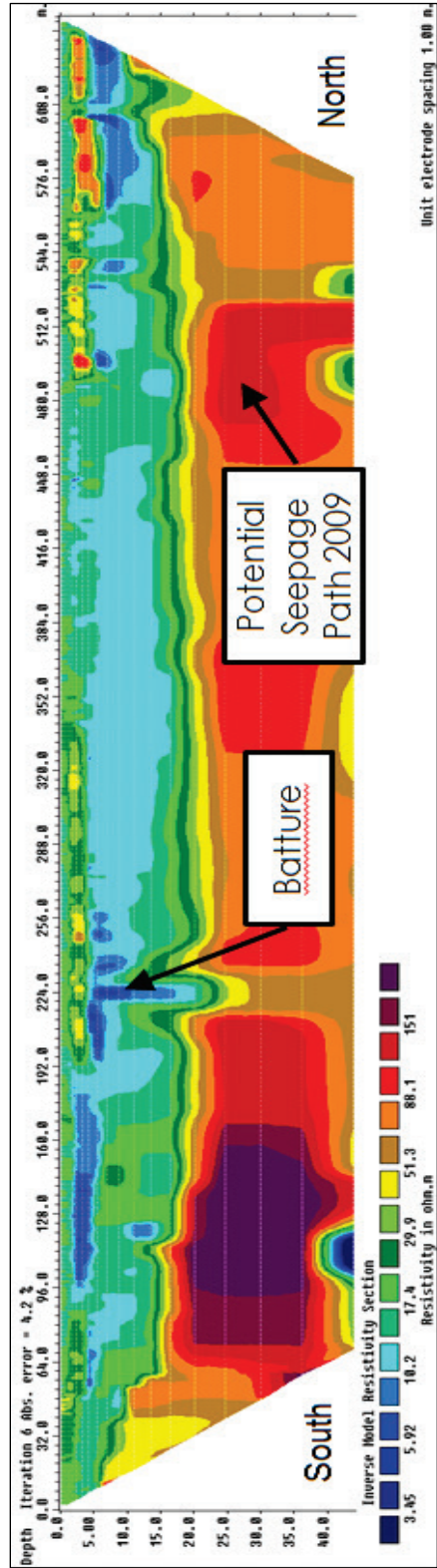
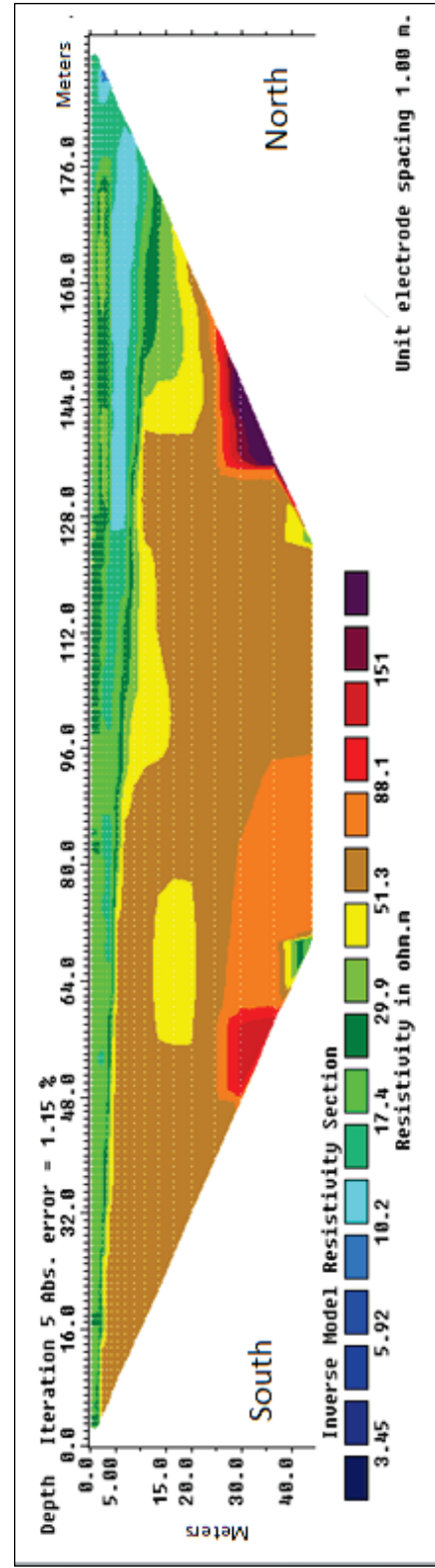


Figure 16. ERT results near 1990s sand boils from March 2014.



5.2 Borings

As part of the levee enlargement project that performed the borings, a cross section was produced that extends from south of the study area through the area and continues to the northeast (Figure 12). The Kolb (1968) cross section is more than 7.4 miles long and compares the stratigraphy of the alluvial deposits in the region. The borings are referenced to Levee Stationing (LS), and the study area extends from LS 100 to 160 (Figure 17). Near boring 105, there is channel fill deposit nearly 60 ft below the approximate mean land surface. This clay plug extending deep into the sands of the aquifer coincides with the area of the 2009 sand boils (Figure 18). It should also be noted that the extremely thin blanket near LS 150 is adjacent to the 1990s sand boils.

5.3 Cone penetrometer test

Five cross sections were produced from the CPT data (Figure 19). Cross sections A-A' and B-B' show the thinning blanket, trending from north to south across the study area, and channel fill deposits. The A-A' section was chosen to run near to the 1990s and 2009 sand boil locations on the land-side of the levee (Figure 20), while B-B' parallels it on the riverside (Figure 21). Near the 1990s boils, the blanket is almost nonexistent; in contrast, the blanket at the 2009 boils is substantial in thickness but begins to thin again toward the north. C-C' is the southernmost west-east cross section; it intersects the batture channel that now is traversed by the levee (Figure 22). C-C' displays an inconsistent blanket in the western portion of the section, which is interfingered with sands and organics, while the eastern portion is more consistent in lithology and thickness. D-D' and E-E' (Figures 23 and 24, respectively) bracket the 2009 boil location. Both show relatively consistent thickness and lithology; however, D-D' does display more lithologic inconsistency toward the northwest portion of the cross section.

5.4 Geographic information system

Once the needed spatial data were compiled, ArcMap 10.1 was used to manipulate and present the data to aid in the interpretation of site development and geologic causes of sand boil formation. Locations of the sand boils were derived from USACE (2011a), and as-built maps and interpretation were overlain on USGS topographic maps or aerial imagery to create area location maps (Figures 25 and 26). The locations of the boils and the location of Buck Chute were used throughout the presentation of the

Figure 17. Location of borings at Buck Chute (Modified from World Imagery base map downloaded from ESRI ArcMap 10.1 library).



GIS results to provide a spatial reference. As discussed in the Buck Chute levee history section, early 1900s hydrographic surveys were analyzed to determine when the Buck Chute levee was constructed (Figures 6 and 7). The 1915 survey shows the location of Buck Chute and the adjacent water bodies but not the levee. The 1926 survey showed the same features but with the addition of the levee. Therefore, the levee was constructed between 1915 and 1926. The area surrounding Buck Chute is found on four Kolb (1968) geologic maps; the color shade representing the alluvial deposits were not uniform due to the age of the maps and the scanning process of the map hard copies. The scanned maps were digitized and georeferenced then each of the alluvial deposit designations were digitized as an individual shape file, and a regional alluvial deposit map was created.

Figure 18. Boring cross section (Modified from Kolb 1968).

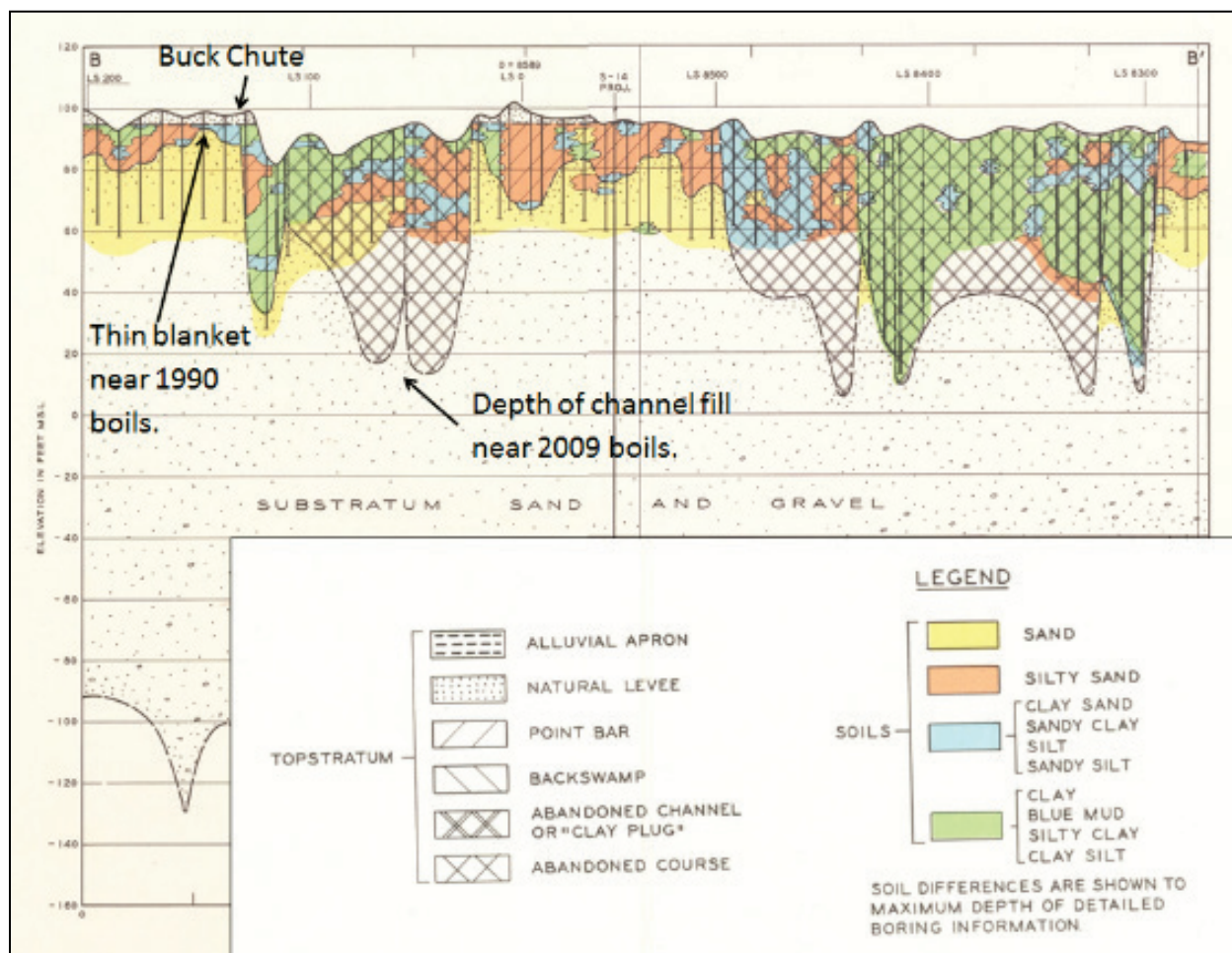


Figure 19. Location map of CPT cross sections (Modified from USGS 1:24000 topographic maps downloaded from ESRI ArcMap 10.1 library).

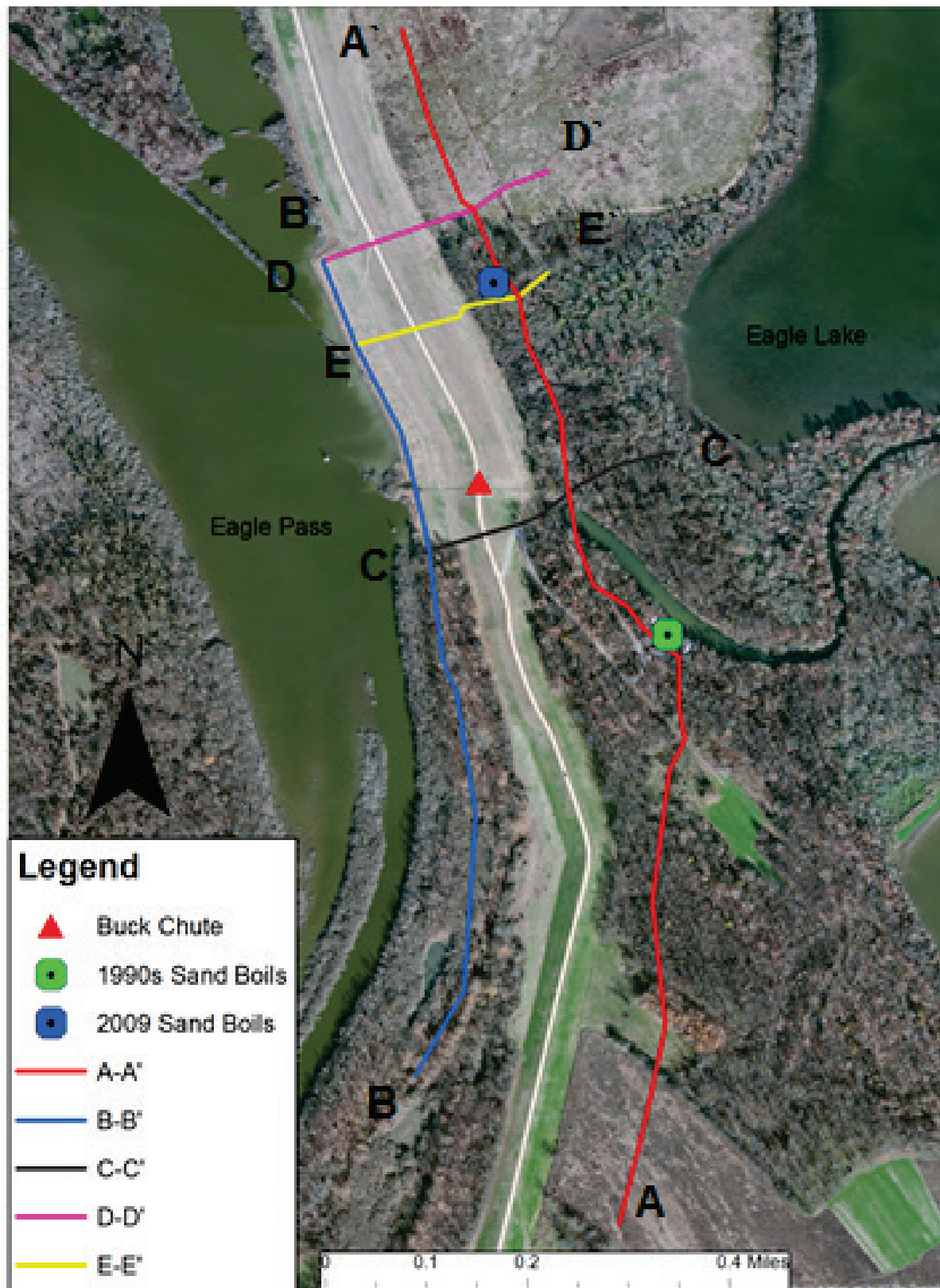


Figure 20. CPT cross section A-A'.

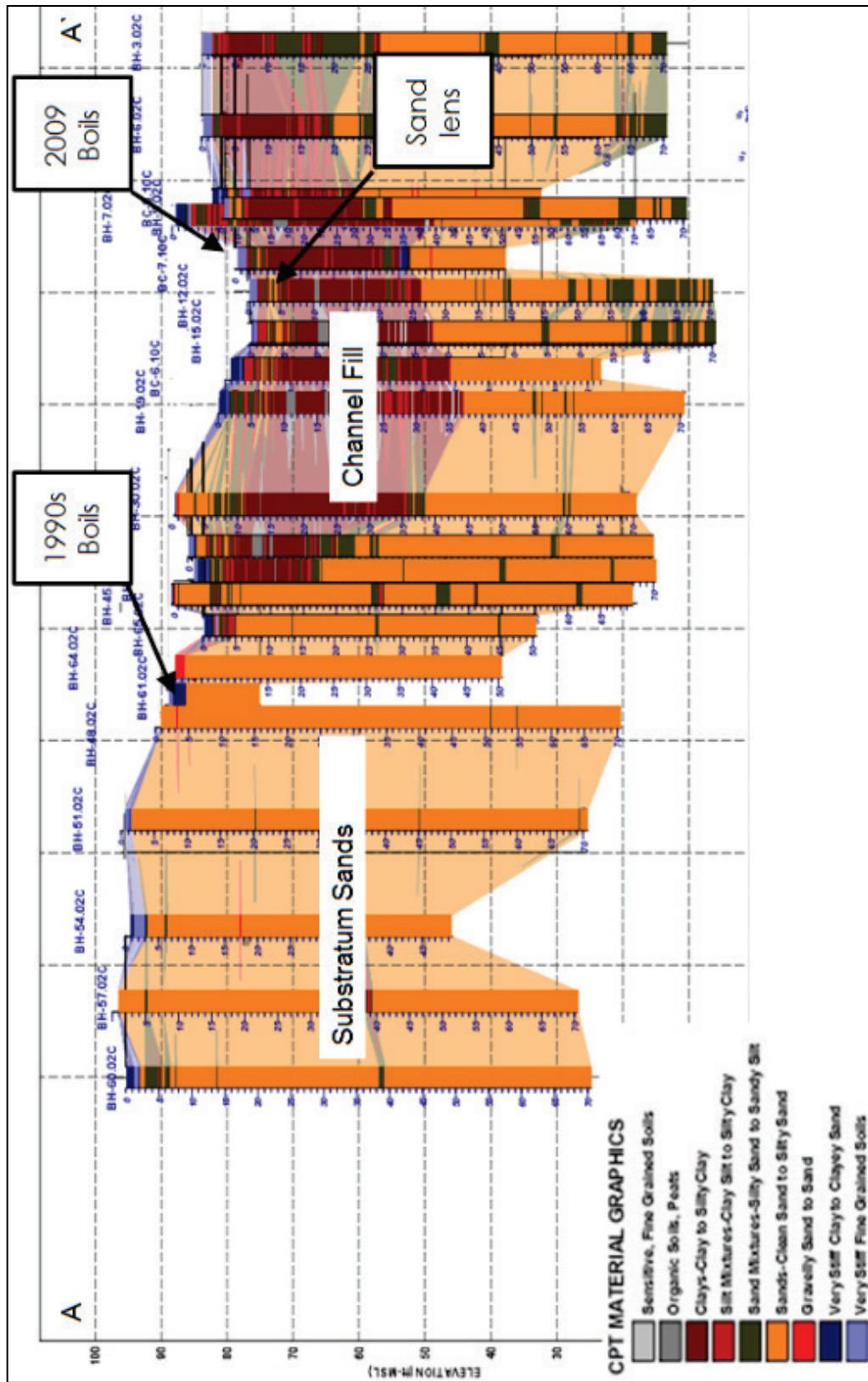


Figure 21. CPT cross section B-B'.

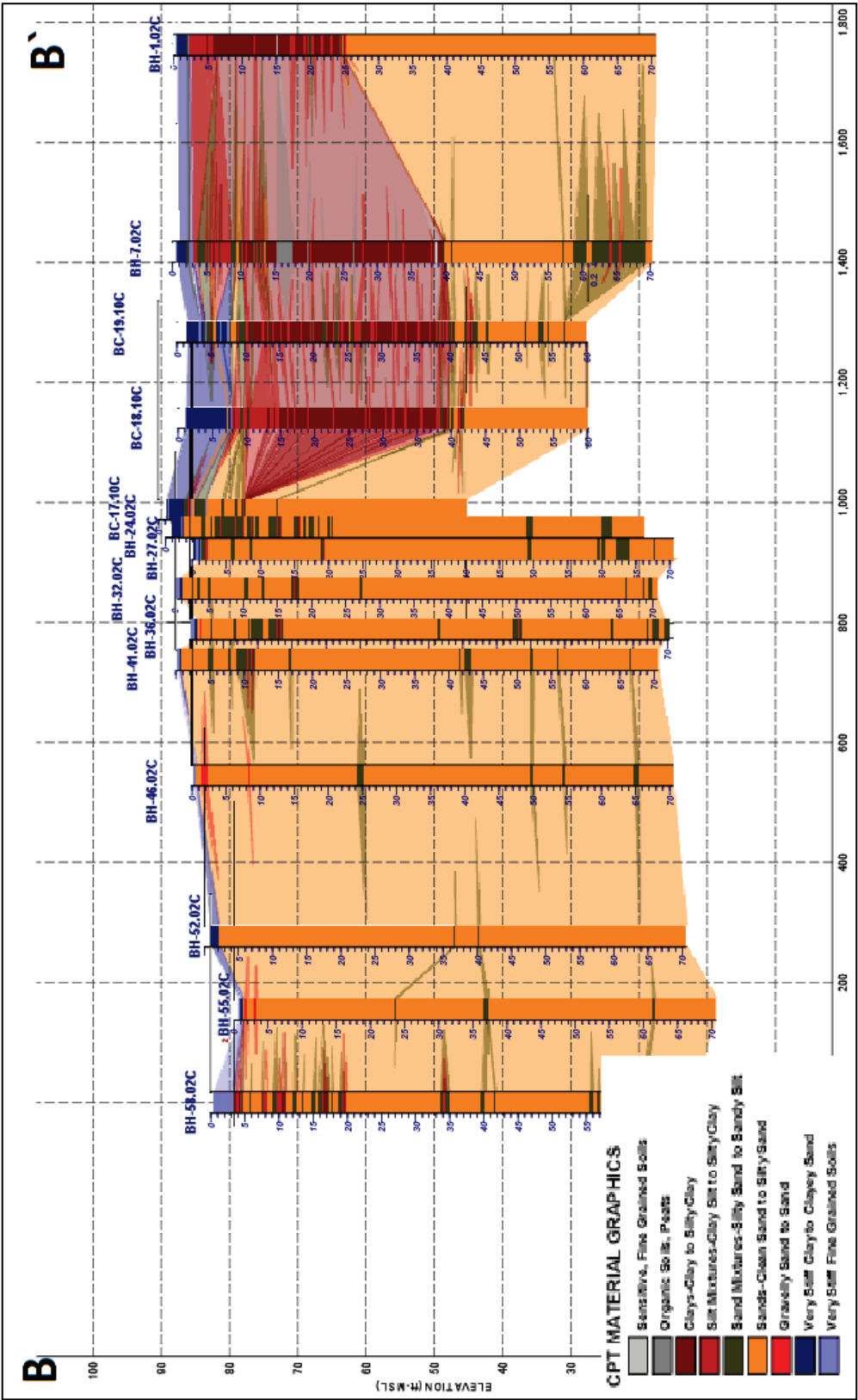


Figure 22. CPT cross section C-C`.

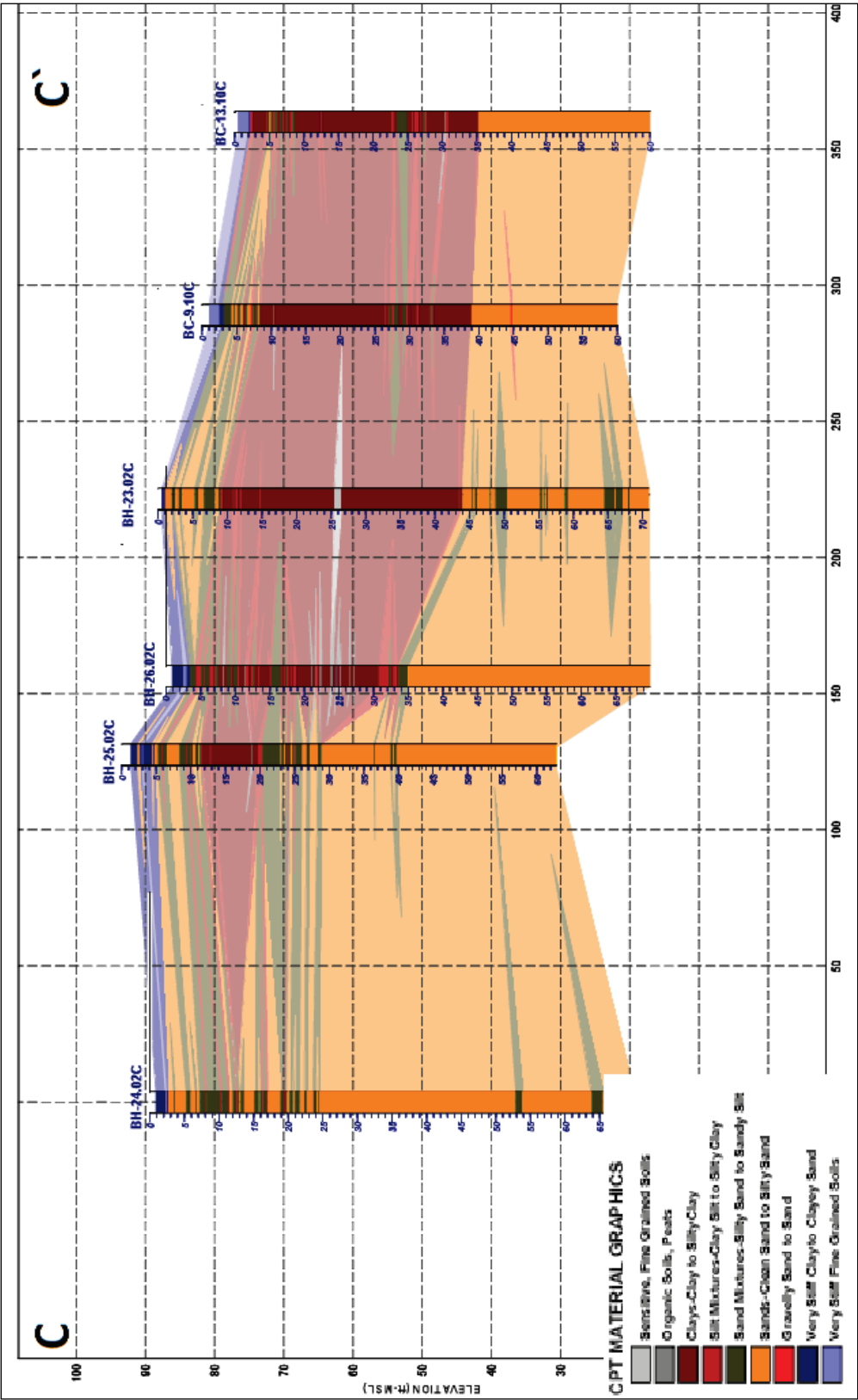


Figure 23. CPT cross section D-D`.

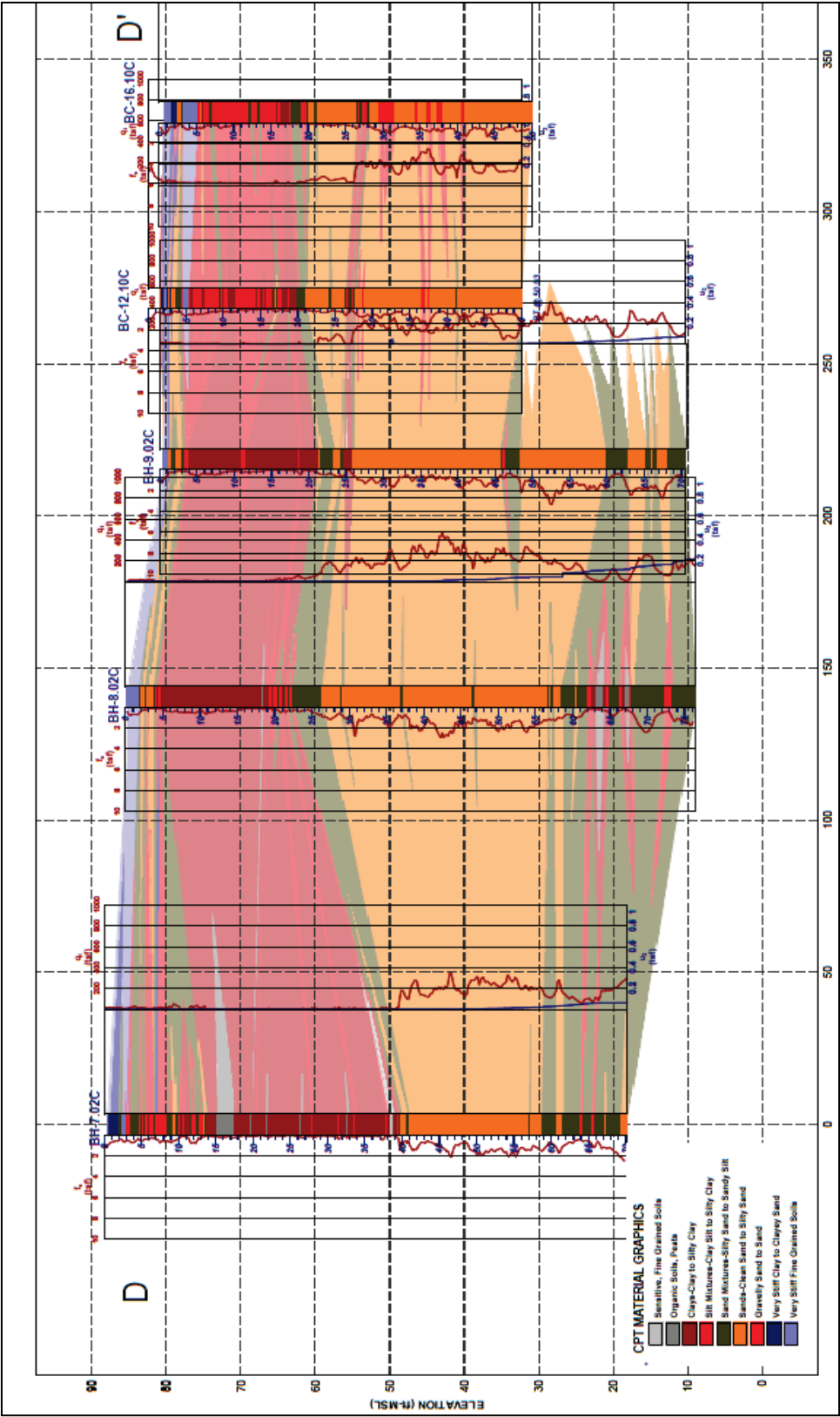
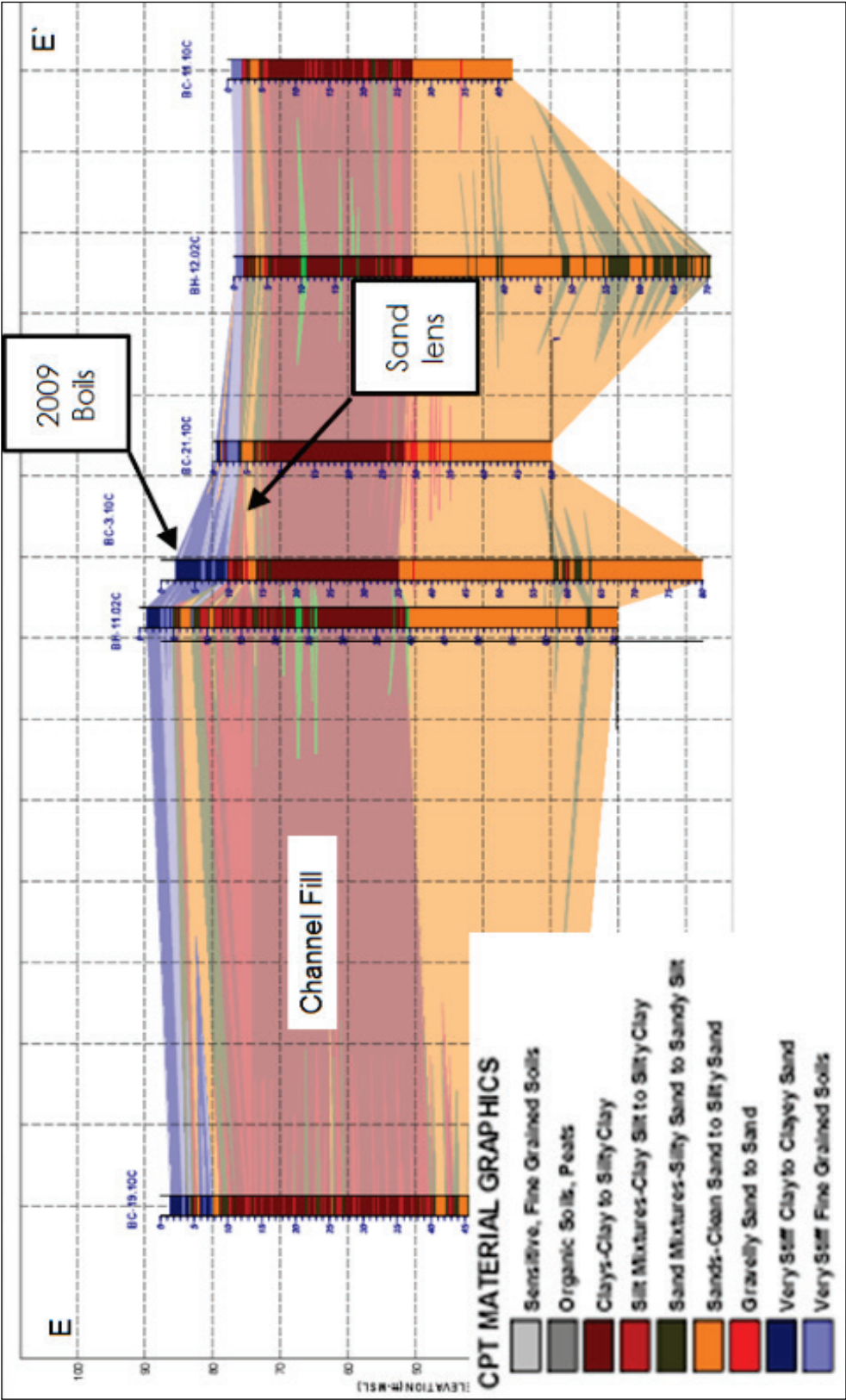


Figure 24. CPT cross section E-E`.



To create elevation profiles, LiDAR data from the riverside of the levee in the west, over the levee, through the locations of the 1990s and 2009 sand boils, and to the landside of the levee (Figures 25 and 26). The locations of these profiles are the same for the combined cross sections discussed in the next section of this report. The LiDAR data date from 2006 prior to the 2011 construction of the landside seepage berm, which is beneficial to the data interpretation because elevations reflect conditions during which the 2009 sand boil formed. The purpose of the profiles was to compare the elevation of the boils relative to the riverside land surface and the landside surface.

Figure 25. 1990s sand boils elevation profile.

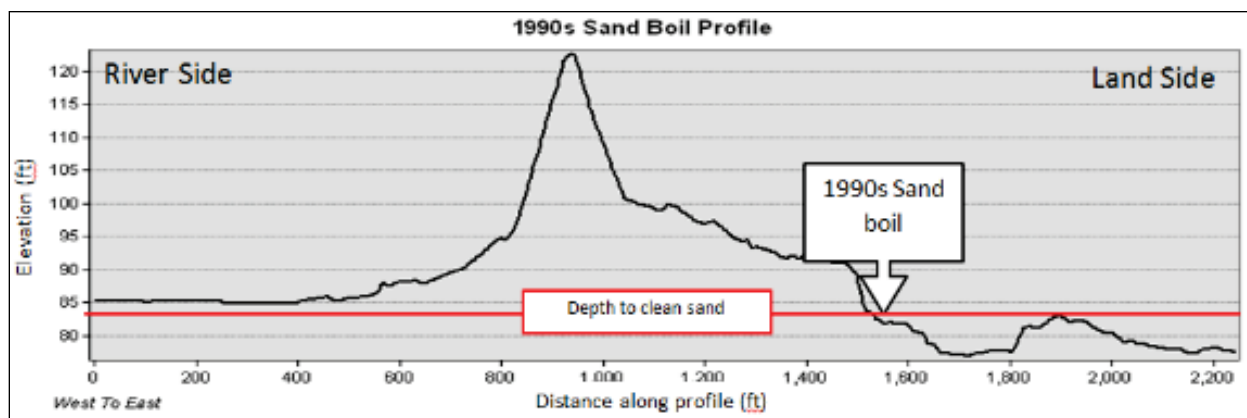
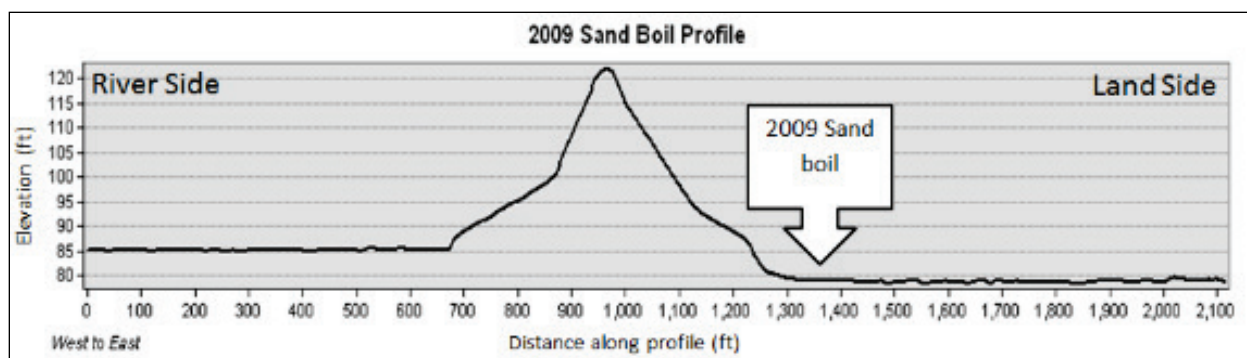


Figure 26. 2009 sand boils elevation profile.



5.5 Summary cross sections

The geologic cross sections are a combination of CPT and GIS results as well as information derived from geologic maps, borings, and alluvial deposit descriptions. CPTs were used in the cross sections to determine depth to silty sand. The GIS database was used to create topographic profiles of the sections and to place the locations of the CPT into the profile. The location, geometry, and composition of the alluvial deposits,

for which there are no direct subsurface data, were interpreted from knowledge of the deposits as discussed in the literature review. Figure 27 is a map view of the cross sections with the CPTs used in the sections. Figures 28 and 29 are the results of the interpreted cross sections.

Figure 27. Location of summary cross sections (Modified from World Imagery base map downloaded from ESRI ArcMap 10.1 library).

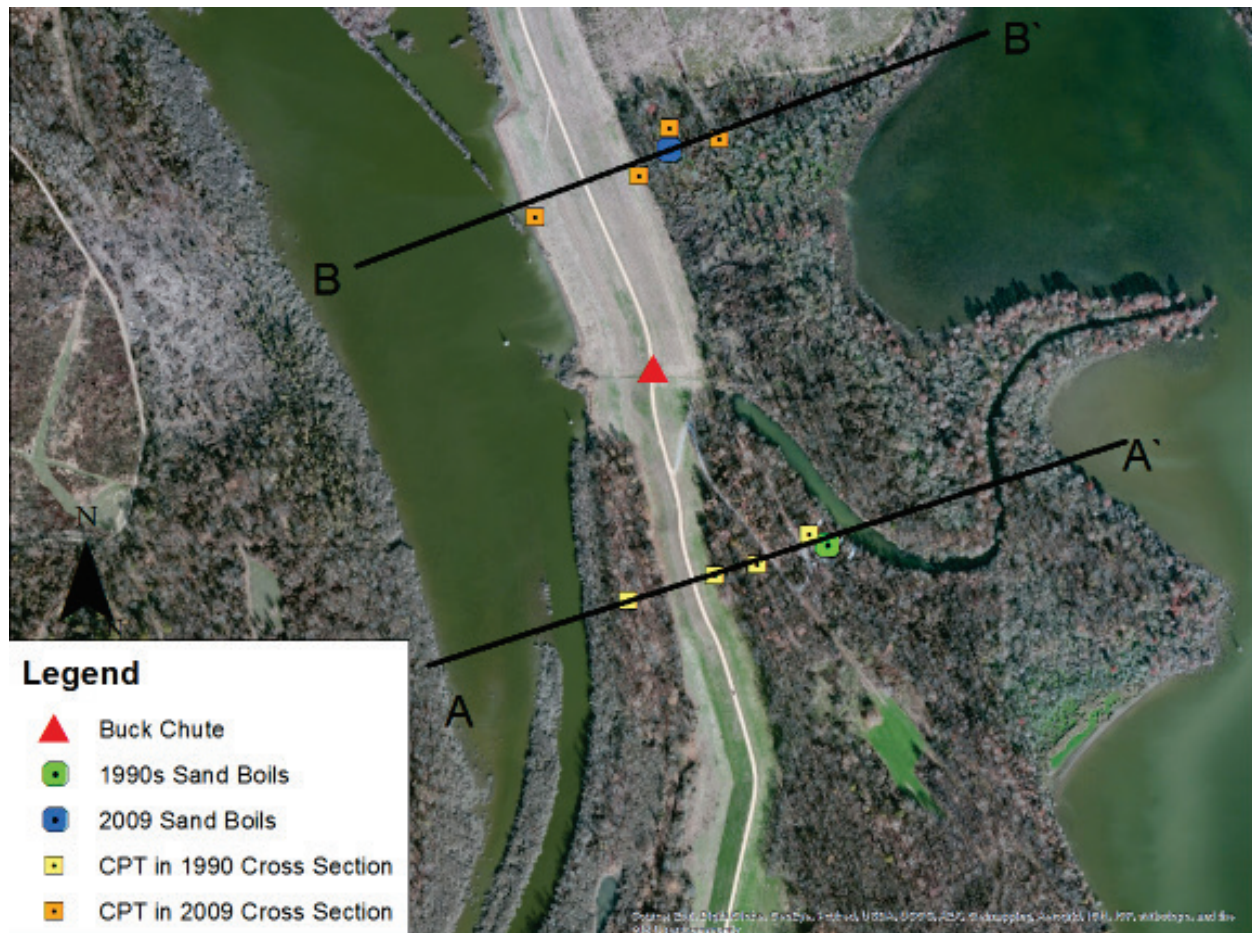
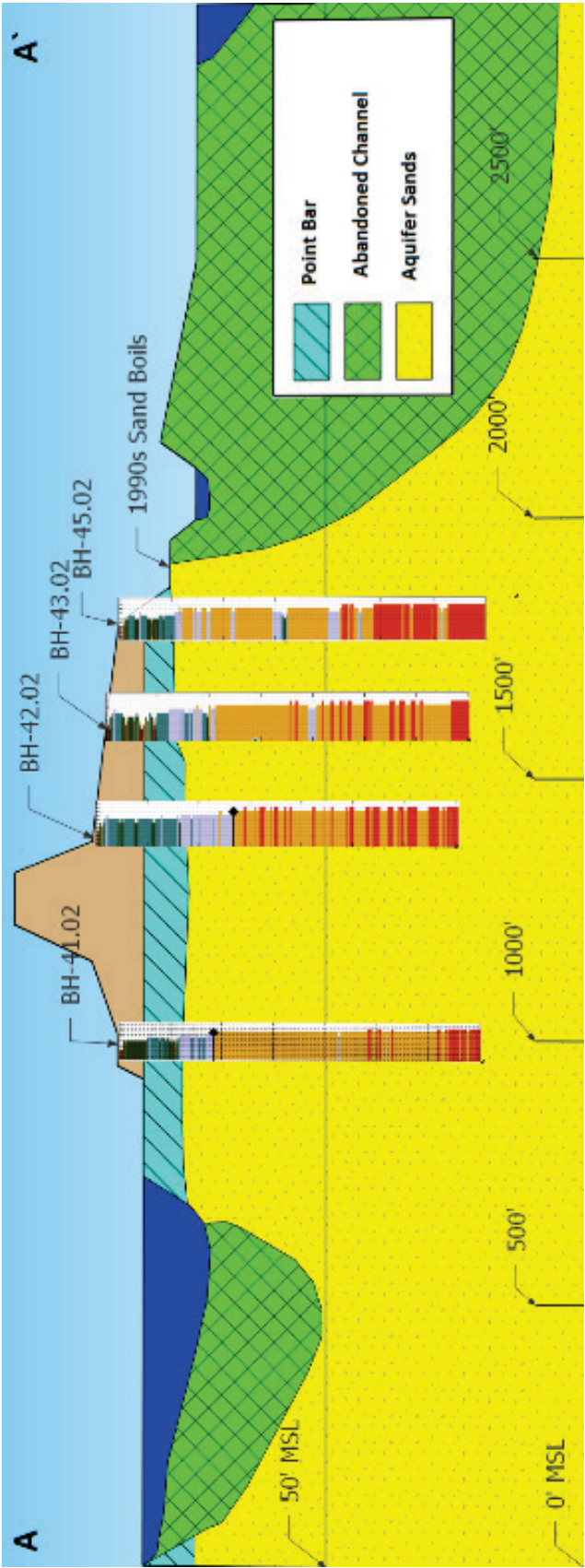
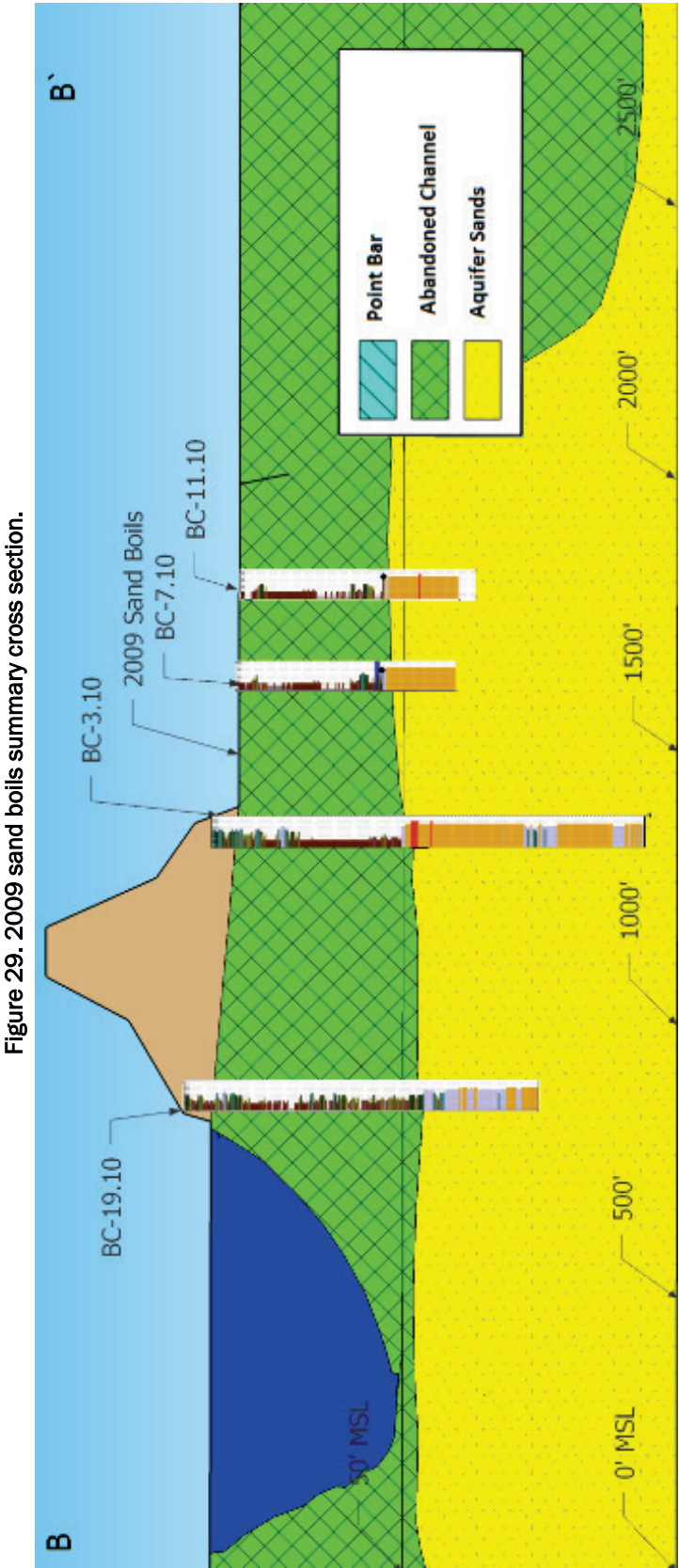


Figure 28. 1900s sand boils summary cross section.





6 Discussion

The record of sand boil formation at Buck Chute begins after the construction of the Muddy Bayou Control Structure and the Yazoo Basin Backwater Levee. The control structure regulates the water elevation in Eagle Lake and was constructed between 1973 and 1979. During the 1973 Flood, no boils were observed due to the height of water in Eagle Lake, which was reported to be at the levee toe. Either there were no boils that occurred during the 1973 Flood, or they could not be observed because of the water level. During the 1979 flood, Muddy Bayou Control Structure was in place, and boils were observed on the landside of the levee along the “chute.” During the 2011 Flood, as part of the sand boil engineer countermeasures, the level of water in Eagle Lake was increased 15 ft in order to prevent a possible levee failure. After the flood and reduction in lake level, no evidence of sand boils was observed as a result of the 2011 Flood. By raising Eagle Lake levels, the head difference was lessened between the riverside and the landside of the levee, preventing the formation of sand boils.

The purpose of the ERT surveys was to provide a continuous cross section of the subsurface, to map potential seepage paths, and to map the batture channel. The cross sections support the results from the CPT and boring data. For the 1990s sand boils, the survey was not extended to the south far enough to capture a seepage path. The survey that intersects the presumed flow path for the 2009 boils does show an area of high resistivity that corresponds to the boil location. To prove that the area was in fact a pathway for subsurface water movement, measurements need to be obtained at both high and low water. The resistance of the pathway would dramatically decrease when filled with water compared to the surrounding material; however, because the surveys were not obtained over a range of stages, confirmation of the flow pathway was not achieved. The location of the batture channel was confirmed by the surveys; however, its influence on sand boil formation is negligible at this location.

The controls of the 1990s sand boil are the point bar deposits, an extremely thin blanket, and a topographic low. The CPT, boring, and ERT data all confirm the geologic map designation of point bar deposit for the 1990s boil location; the subsurface is predominantly sands with little to no blanket

present. The ERT data provided a continuous cross section that shows more resistive material, which coincides with more sandy, unsaturated material near the surface with a very thin silt blanket. Figure 30 is the interpretation of the geologic controls of the 1990s boils derived from data collected and interpretation of literature review. The blanket is non-existent at the location of the boils on the landside; the topographic low where the boils were located is into the sands of the alluvial aquifer. To cause heave and subsequent boil formation at this location, little increase in subsurface hydrostatic pressure is required due to lack of blanket overburden.

At the 2009 sand boil location, abandoned channel deposits are shown on the geologic map at this site. Abandoned channel deposits mostly consist of clays with some silty sands, and these deposits extend to a depth of 60 to 70 ft. The CPT data for this location show the top stratum to be lenses of silts and organics with a thickness of 20 to 30 ft. The control of the 2009 sand boil formation is a blocked seepage path. The abandoned channel deposit in the lacustrine stage (Eagle Lake) acted as a clay plug blocking the subsurface flow and creating localized increase in hydrostatic pressure (Figure 31). The increased pressure, coupled with a likely defect in the blanket, fallen tree, or inconsistency in the blanket, created the heave conditions that led to the sand boil formation.

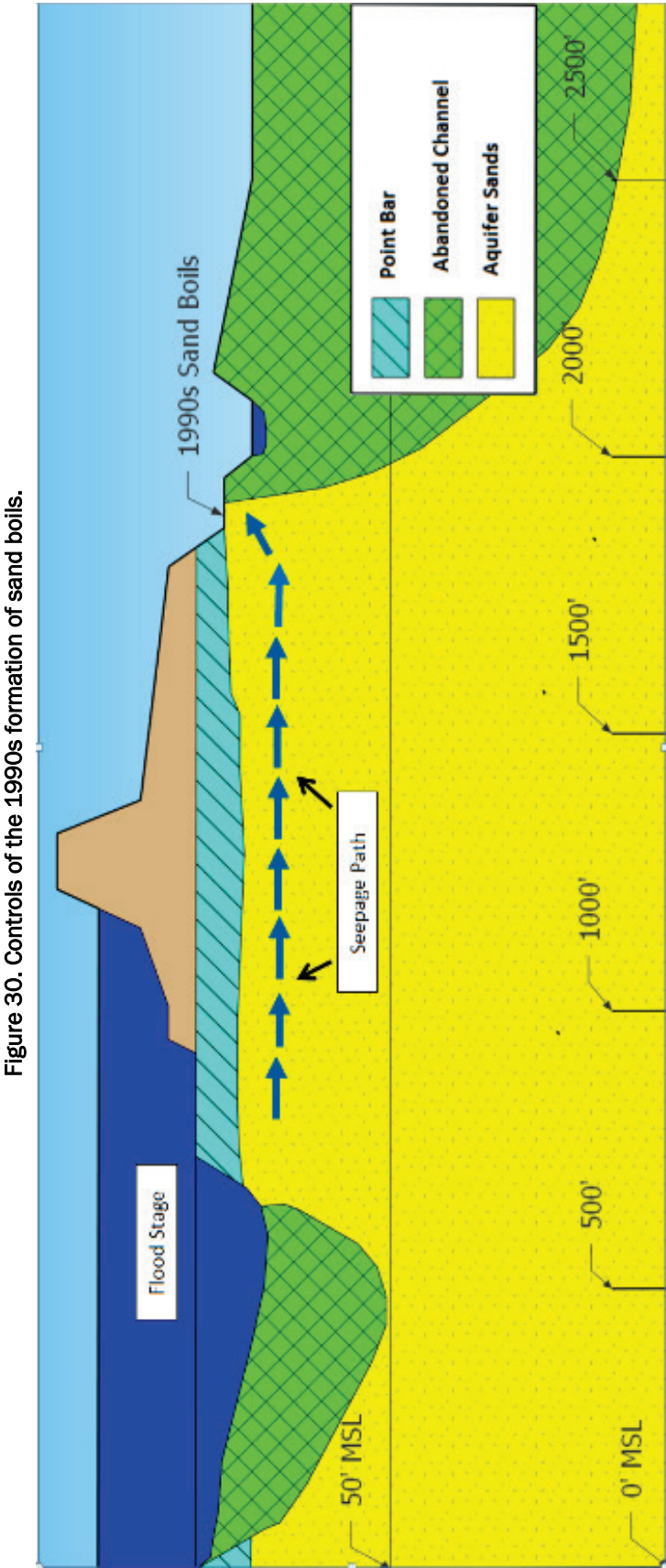
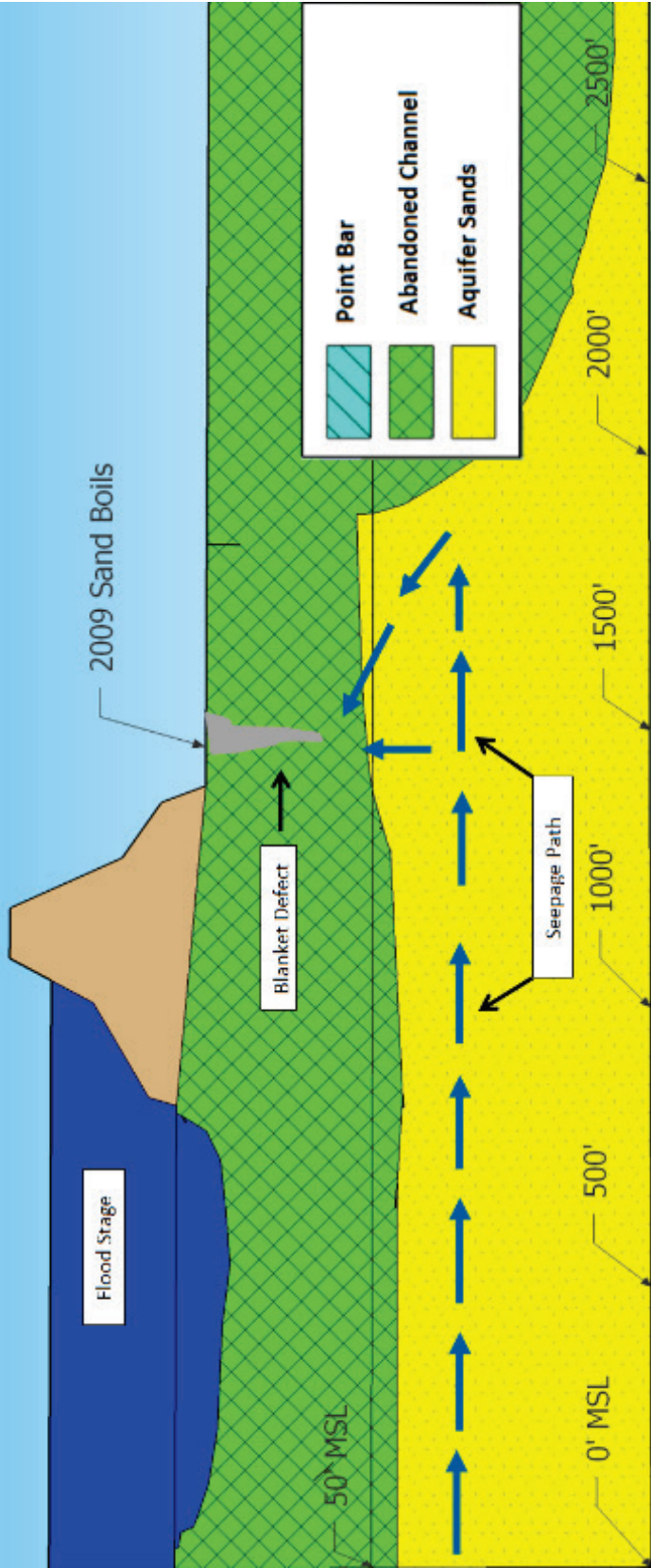


Figure 31. Controls of the 2009 formation of sand boils.



7 Conclusions

By conducting shallow geophysics, collecting CPT and boring data, and compiling a GIS, it was confirmed that the controls of sand boil formation at Buck Chute are not only geologic but also, to some extent, man-made. The construction of the Muddy Bayou Control Structure and the Yazoo Backwater Levee increased the tailwater elevation. Prior to these structures being built between the 1970s to the 1980s, backwater flooding reduced the hydraulic gradient by forming a tailwater at the study site and flooding inhabited areas at Eagle Lake. Geologic control of the 1990s boils was the thin blanket and topographic elevation of the boils relative to the clean substrate sands and the hydraulic gradient present. The 2009 boils were caused by blocked subsurface flow that increased localized hydrostatic pressure and was likely compounded by a blanket defect.

The fundamental control of sand boil formation at both the 1990s boils and the 2009 boils at Buck Chute was head differential. The Muddy Bayou Control Structure and the Yazoo Backwater Levee regulate the water level elevation of Eagle Lake, which prior to regulation rose and fell in response to Mississippi River high-water events. By preventing the lake level from rising, a greater head differential is now generated. This translates to an increase in the subsurface hydrostatic pressure on the landside of the levee, which promotes heave and sand boil formation.

The 1990s boils in the southern portion of the study area are controlled by the point bar top stratum and the topography. Adjacent to the boil locations, the blanket is composed of a silty point bar top stratum and is extremely thin. The composition of this material and its thickness (or thinness) means that it is not very resistant to heave. When examined in topographic cross-section view, the elevation of the boils is actually below the top stratum and into the clean sand. To create a heave at this location would take very little head difference between the riverside and the landside of the levee. The conditions for the sand boils to form are evident by the 1979 flood report of boils near this location at the similar elevation. The first year (1979) that the Muddy Bayou Control Structure was operational, the tail waters from Eagle Lake were prevented from rising.

The boil activity from 2009 is attributed to blocked seepage pathways. The blanket near the boil location does show a somewhat uniform thickness but not necessarily uniform composition. The proximity of the abandoned channel deposit that is now Eagle Lake reduces the subsurface flow from the riverside landward. This reduction increases the hydrostatic pressure behind the clay plug of the abandoned channel deposit, straining any imperfections present in the blanket causing heave. Possible imperfections of the blanket are as complex as the inconsistencies shown in CPT data or as simple as a hole left by a fallen tree's root ball.

The findings of this investigation can be used in the broader analysis of sand boil formation in the LMRV. Historic assessments found that the majority of boil occurrences correspond to point bar deposits; however, in-depth geologic assessments such as this are bringing to light the complexity of the underseepage phenomena. By using shallow geophysics and CPT data, this investigation determined that the controls of sand boil formation at Buck Chute were a combination of many factors. This depth of investigation should be conducted when examining levee performance cases in the future to accurately assess the geology and man-made causes of sand boil formation.

Current seepage analysis software often uses generic levee and geologic profiles in the model. These profiles assume a simple geometry of the top stratum in relation to the substratum and may not include modifications to a levee, such as seepage berms. A site such as Buck Chute exhibits the need for detailed site evaluations because a generic cross section does not represent real-world conditions. A topic of future research would be comparing the results from generic model sections to real world sections. If the difference is great enough between the two, this could cause the seepage analysis modelers to call for accurate site investigation so that the models represent real-world conditions.

References

- Bragg, M. 1977. *Historic names and places on the Lower Mississippi River*. Vicksburg, MS: Mississippi River Commission.
- Camillo, C. A., and M. T. Percy. 2004. *Upon their shoulders*. Vicksburg, MS: Mississippi River Commission.
- Chang, K. 2010. *Introduction to geographic information systems. 5th ed.* New York, NY: McGraw-Hill Companies, Inc.
- Construction Industry Research and Information Association (CIRIA). 2013. *The international levee handbook*. London, UK: Construction Industry Research and Information Association.
- Fisk, H.N. 1944. *Geologic investigations of the alluvial valley of the Lower Mississippi River*. Vicksburg, MS: Mississippi River Commission.
- . 1947. *Fined-grained alluvial deposits and their effects on the Mississippi River activity*. 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*. American Society of Civil Engineers.
- Kolb, C.R. 1968. *Geological investigation of the Yazoo Basin, Lower Mississippi Valley*. Technical Report No. 3-480. Vicksburg, MS: U.S. Army Engineer Research and Development Center.
- . 1975. *Geologic control of sand boils along the Mississippi River levees*. Misc. Paper S-75-22. Vicksburg, MS: U.S. Army Engineer Waterways Experiment Station.
- Mississippi River Commission (MRC). 1975. *Upper and Lower Mississippi River surveys for the period 1879-80 to 1928*. Vicksburg, MS: Mississippi River Commission.
- Reynolds, J. M. 2011. *Introduction to applied and environmental geophysics*. West Sussex, UK: John Wiley and Sons Ltd.
- Saucier, R.T. 1994. *Geomorphology and Quaternary geologic history of the Lower Mississippi Valley*. Vicksburg, MS: U.S. Army Engineer Research and Development Center.
- U.S. Army Corps of Engineers (USACE). 1941. *Investigation of underseepage: Lower Mississippi River levees*. Technical Memorandum No. 184-1. Vicksburg, MS: U.S. Army Engineer Research and Development Center.
- . 1949. *Flood control: Mississippi River and tributaries, Eagle Lake enlargement*. Item 453 L-A & B. Vicksburg, MS: U.S. Army Research and Development Center.

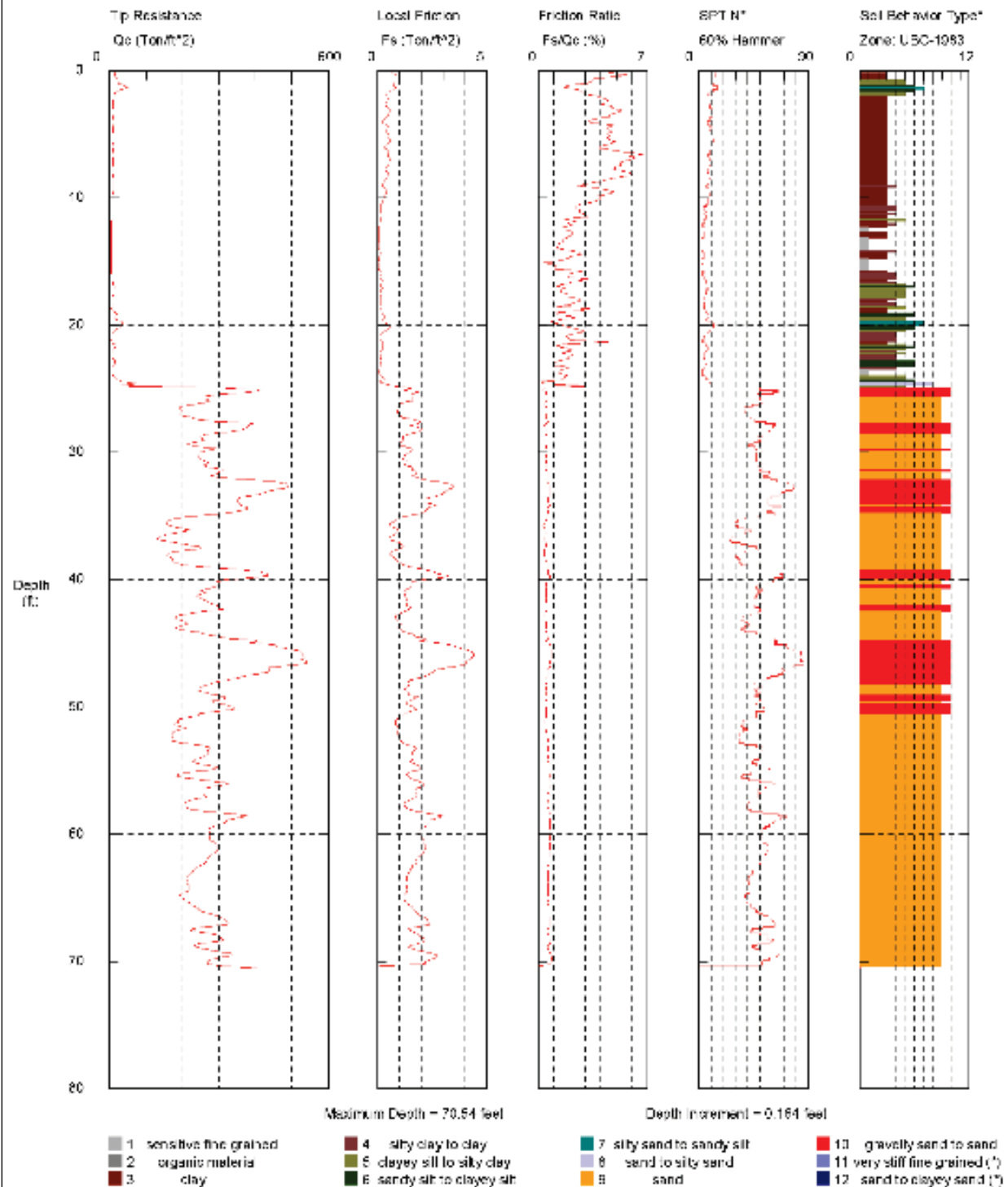
-
- _____. 1956. *Investigation of underseepage and its control, Lower Mississippi River levees*. Technical Memorandum No. 3-424. Vicksburg, MS: U.S. Army Engineer Research and Development Center.
- _____. 1972. *Improvement of the Lower Mississippi River and tributaries*. Vicksburg, MS: Mississippi River Commission.
- _____. 1973. *Mississippi River and Tributaries Post-Flood Report 1973*. Vicksburg, MS: Mississippi River Commission.
- _____. 1979. *Post Flood Report, Flood of 1979*. Vicksburg, MS: U.S. Army Corps of Engineers, Vicksburg District.
- _____. 1984. *Engineering and design geotechnical investigations*. Vicksburg, MS: U.S. Army Engineer Research and Development Center.
- _____. 1994. *Normalization and prediction of geotechnical properties using the cone penetrometer test (CPT)*. Vicksburg, MS: U.S. Army Engineer Research and Development Center.
- _____. 2002. *Performance of levee underseepage control: A critical review*. Tech Report ERDC/GSL TR-02-19. Vicksburg, MS: U.S. Army Engineer Research and Development Center.
- _____. 2011a. *East Bank Mississippi River levees in Mississippi seepage berm and relief wells Item 458- L, Brunswick-Halpino*. Vicksburg, MS: U.S. Army Corps of Engineers, Vicksburg District.
- _____. 2011b. *Mississippi River and tributaries system 2011 Post-flood report*. Vicksburg, MS: Mississippi River Commission.

Appendix A: Cone Penetrometer Test Reports

US ARMY CORPS OF ENGINEERS

Operator: CROSBY
Sounding: CPT-18
Cone Used: 342

CPT Date/Time: 08-07-02 12:53
Location: 5H-1.02C
Job Number: Buck Chute

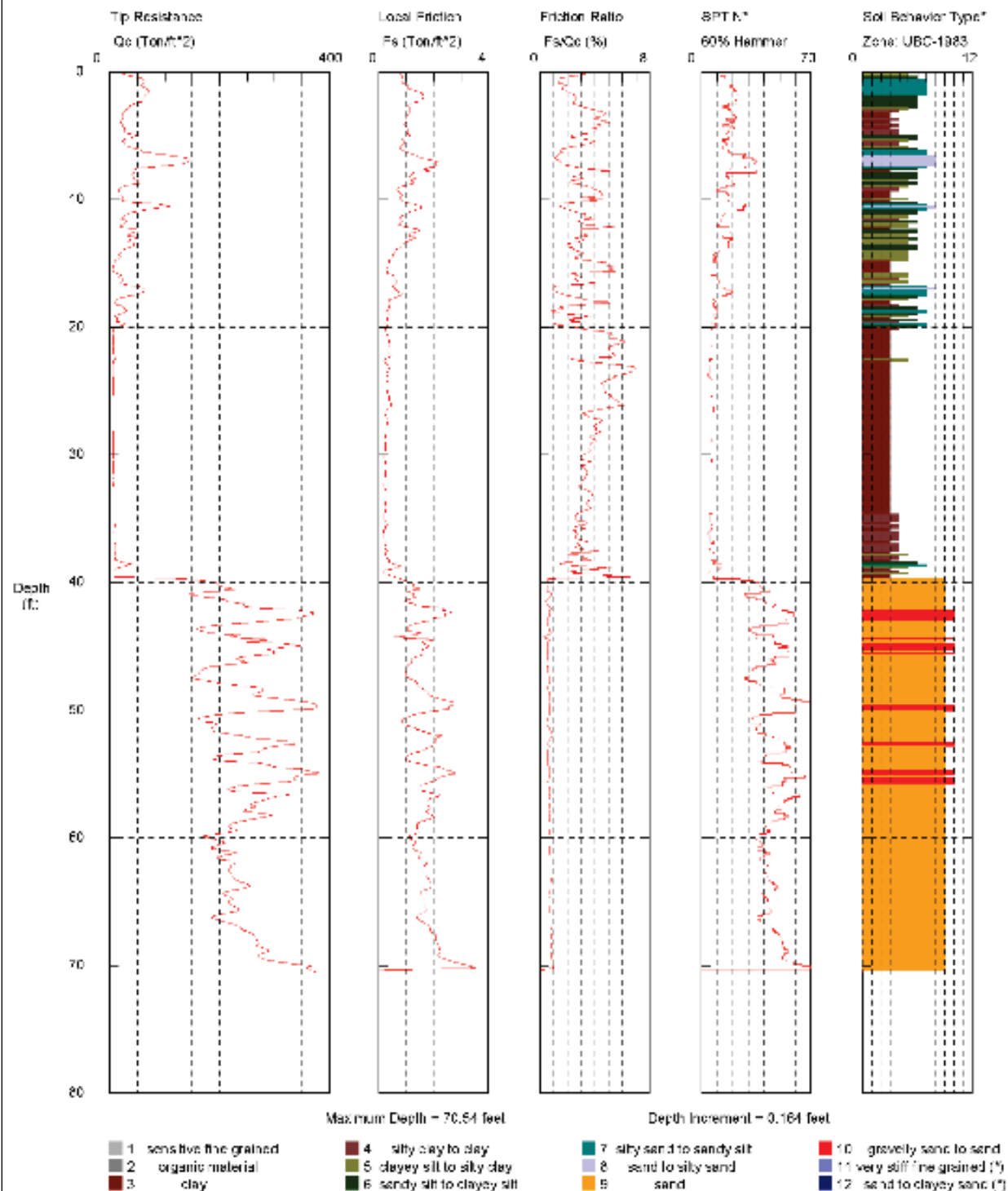


*Soil behavior type and SPT based on data from USC-1083

US ARMY CORPS OF ENGINEERS

Operator: CROSBY
Sounding: CPT-06
Cone Used: 342

CPT Date/Time: 08-06-02 12:18
Location: BH-11.C2C
Job Number: Buck Chute

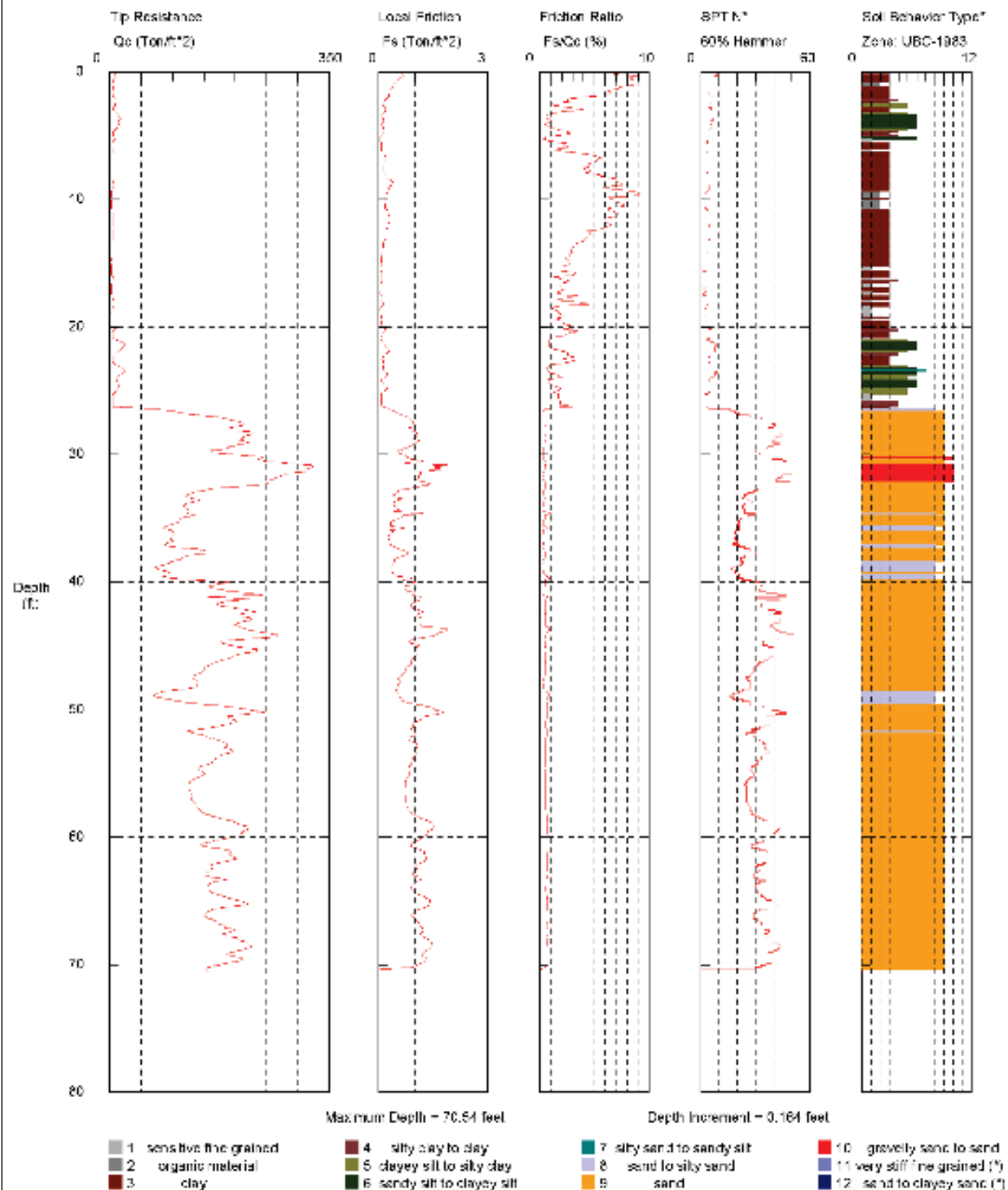


*Soil behavior type and SPT based on data from UBC-1983

US ARMY CORPS OF ENGINEERS

Operator: CROSBY
Sounding: CPT-26
Cone Used: 342

CPT Date/Time: 08-12-02 07:27
Location: BH-12.C2C
Job Number: Buck Chute

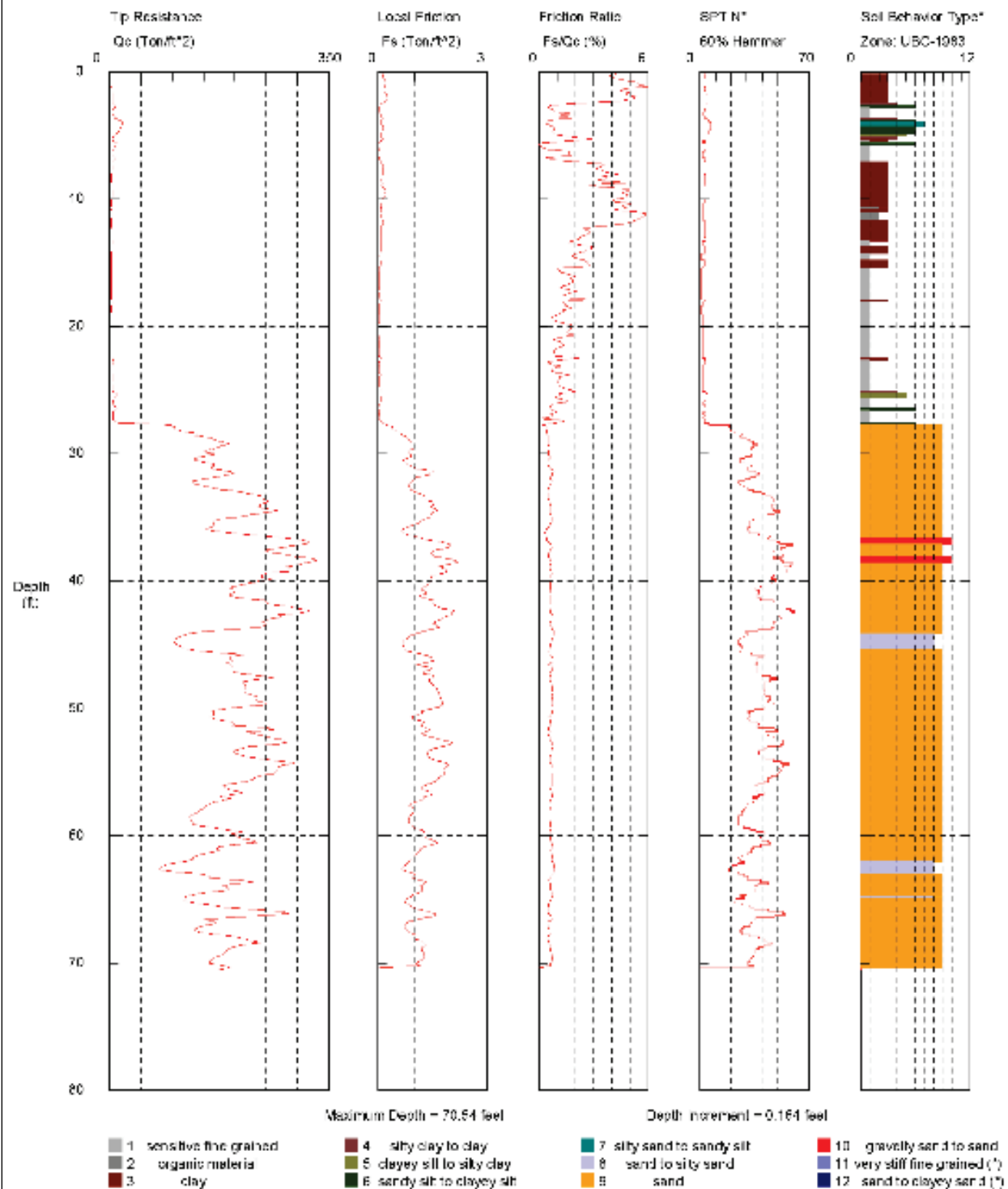


*Soil behavior type and SPT based on data from UBC-1983

US ARMY CORPS OF ENGINEERS

Operator: CROSBY
Sounding: CPT-25
Cone Used: 379

CPT Date/Time: 08-13-02 09:09
Location: BH-15.02C
Job Number: Buck Chute

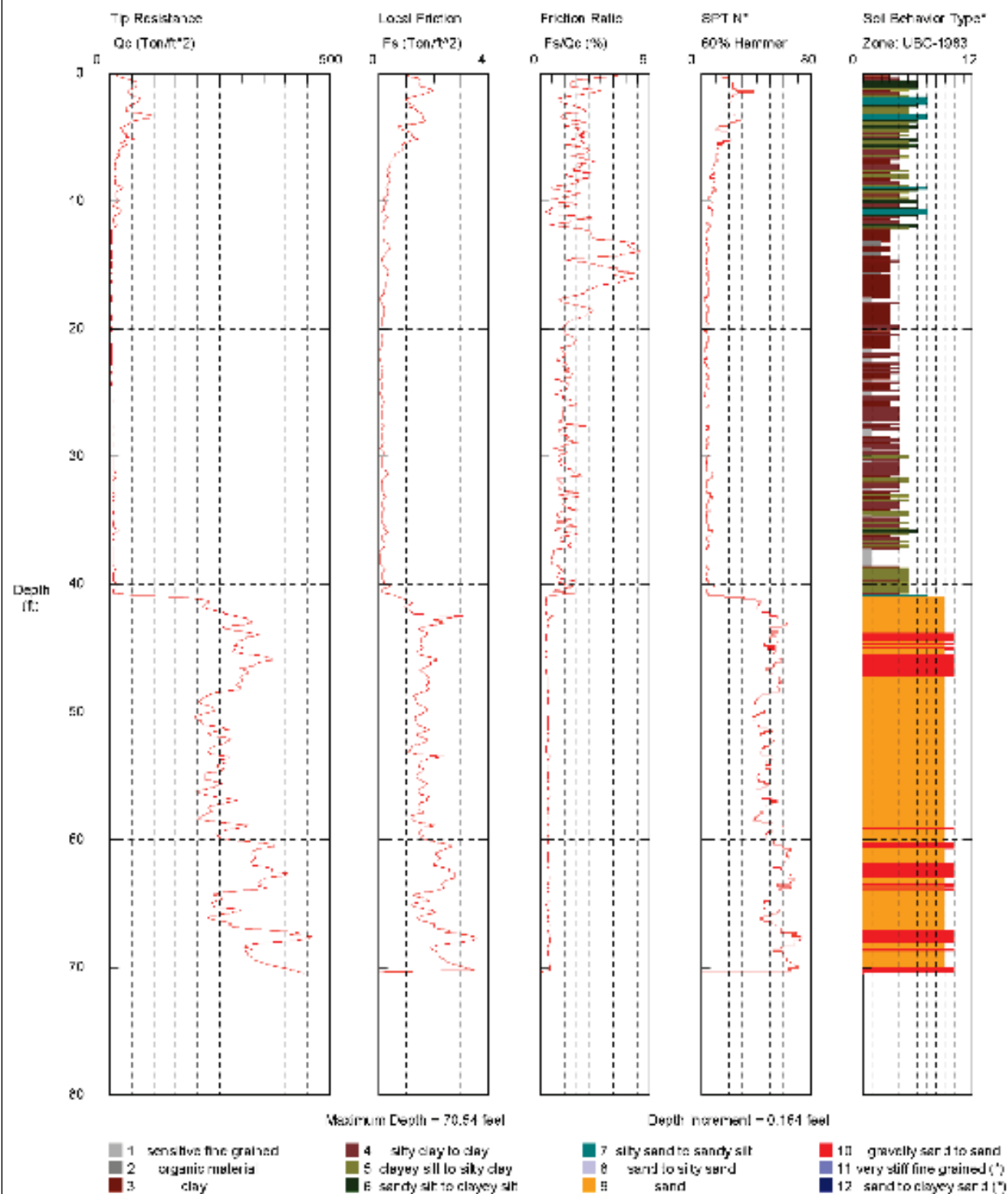


*Soil behavior type and SPT based on data from UBC-1983

US ARMY CORPS OF ENGINEERS

Operator: CROSBY
Sounding: CPT-32
Cone Used: 379

CPT Date/Time: 08-13-02 13:33
Location: BH-15.02C
Job Number: Buck Chute

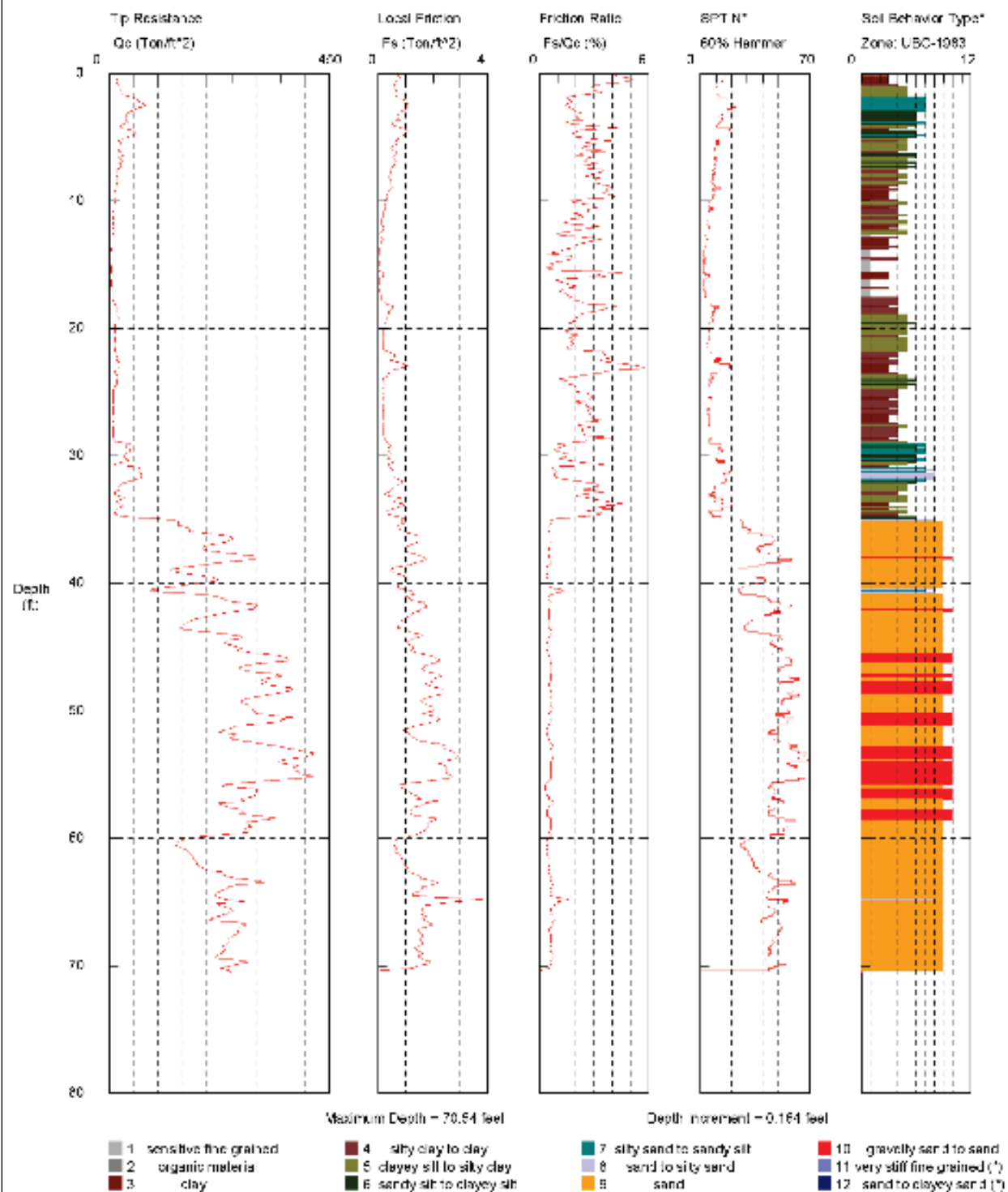


*Soil behavior type and SPT based on data from UBC-1983

US ARMY CORPS OF ENGINEERS

Operator: CROSBY
Sounding: CPT-24
Cone Used: 342

CPT Date/Time: 08-09-02 09:01
Location: BH-23.02C
Job Number: Buck Chute

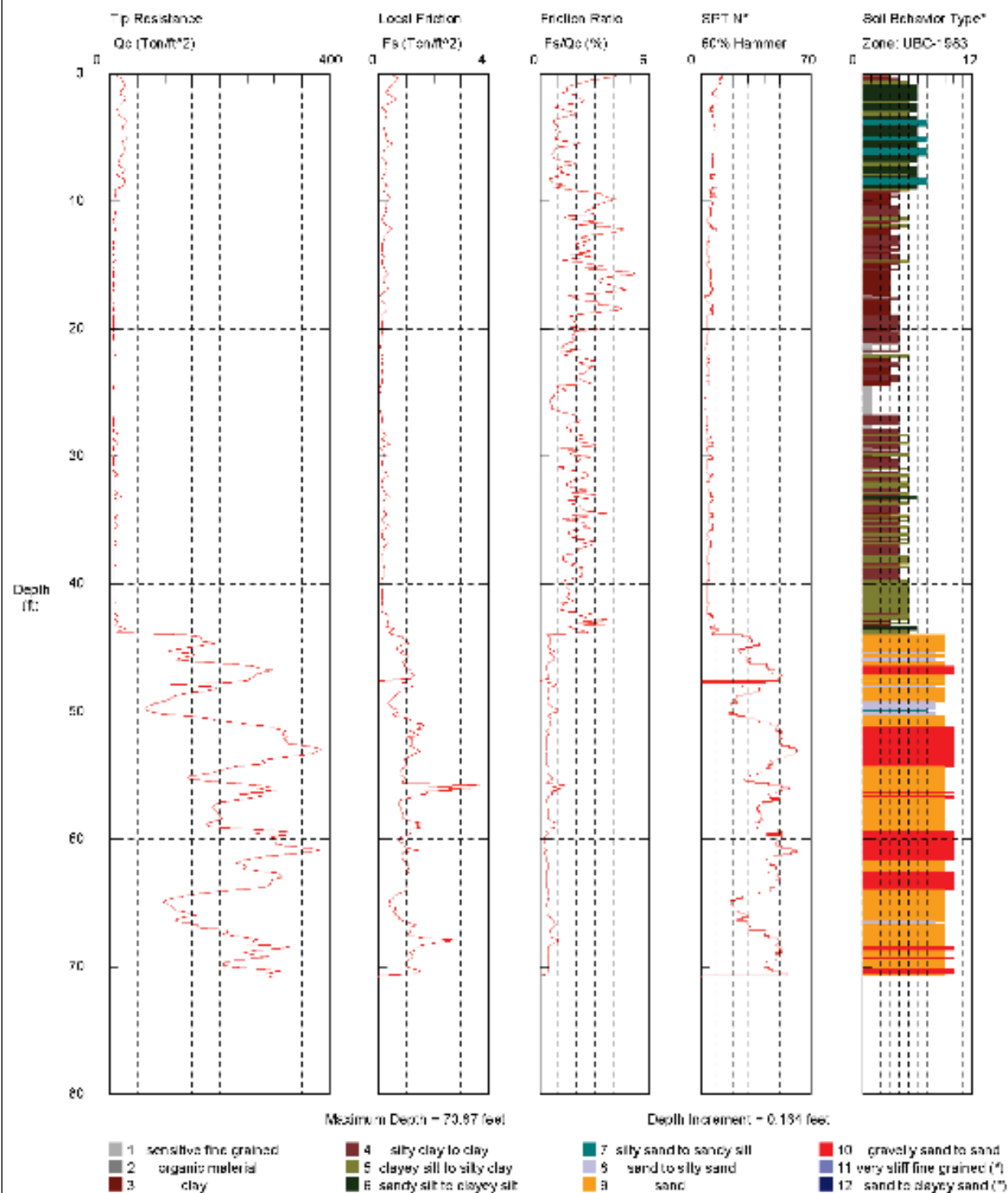


*Soil behavior type and SPT based on data from UBC-1983

US ARMY CORPS OF ENGINEERS

Operator: CROSBY
Sounding: CPT-01
Core Used: 318

CPT Date/Time: 05-19-02 07:22
Location: BH-23.02C
Job Number: Buck Chute

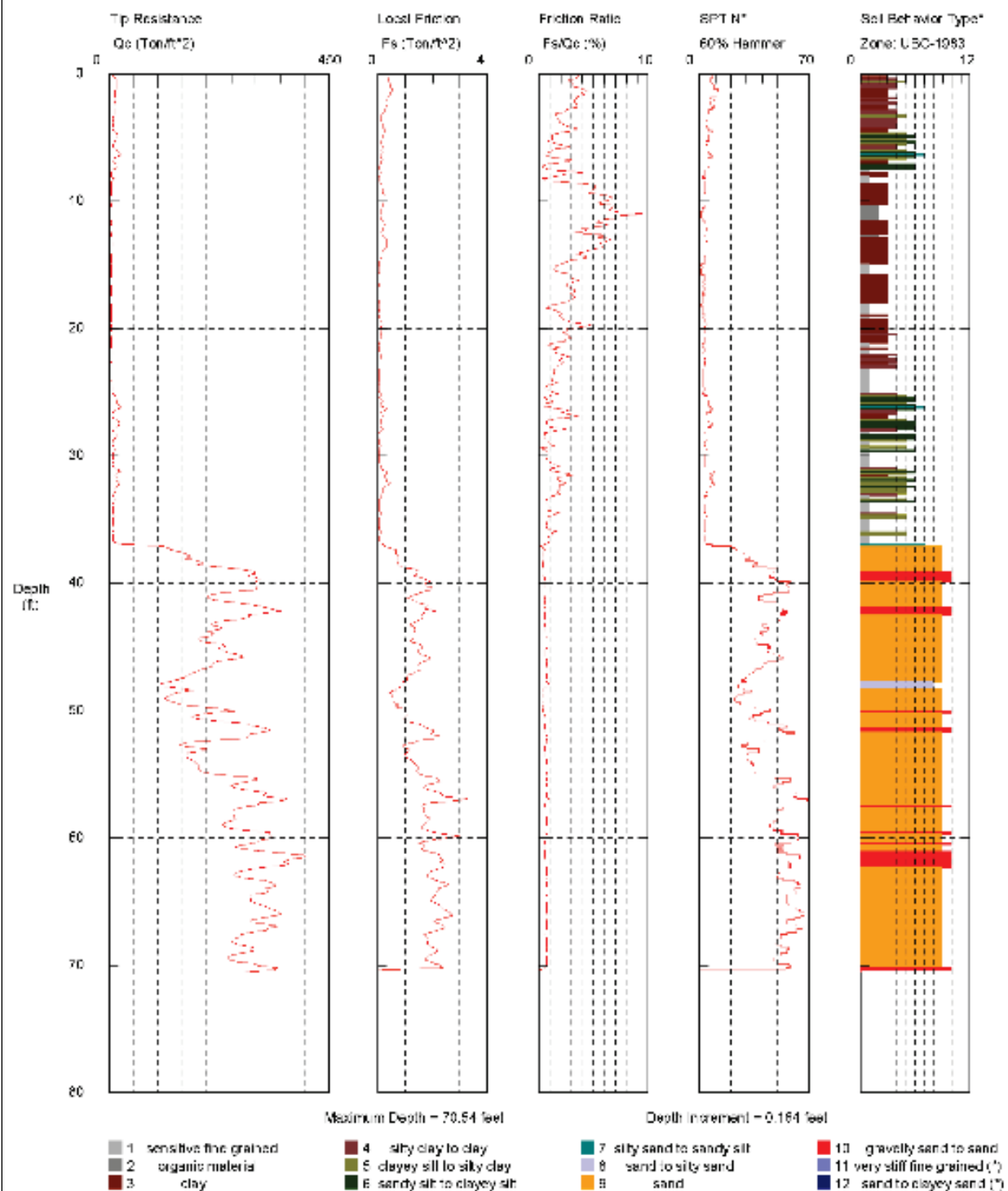


*Soil behavior type and SPT based on data from UBC-1563

US ARMY CORPS OF ENGINEERS

Operator: CROSBY
Sounding: CPT-33
Cone Used: 379

CPT Date/Time: 08-13-02 12:25
Location: 5H-19.02C
Job Number: Buck Chute

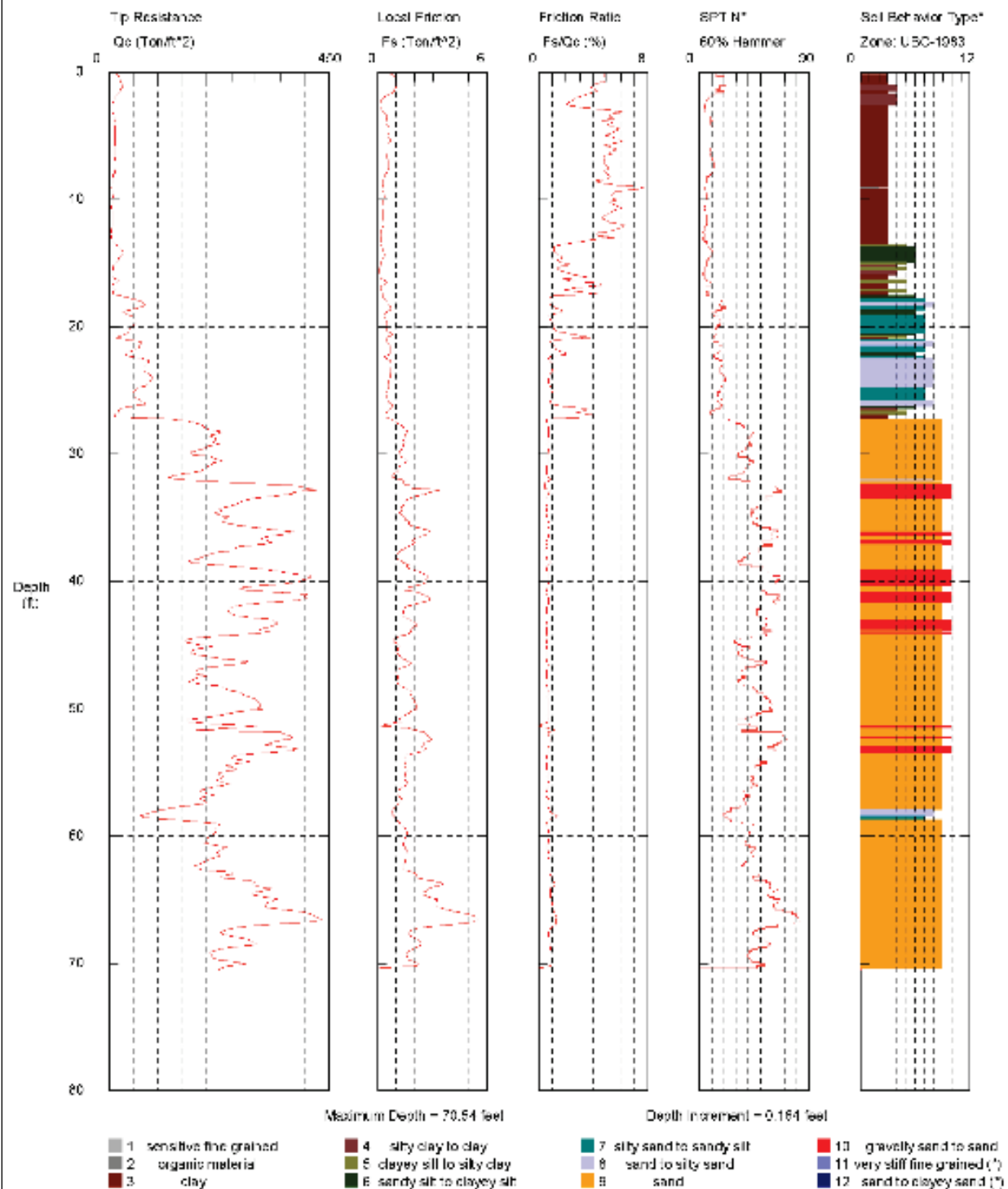


*Soil behavior type and SPT based on data from USC-1083

US ARMY CORPS OF ENGINEERS

Operator: CROSBY
Sounding: CPT-13
Cone Used: 342

CPT Date/Time: 08-07-02 07:51
Location: 5H-2.020
Job Number: Buck Chute

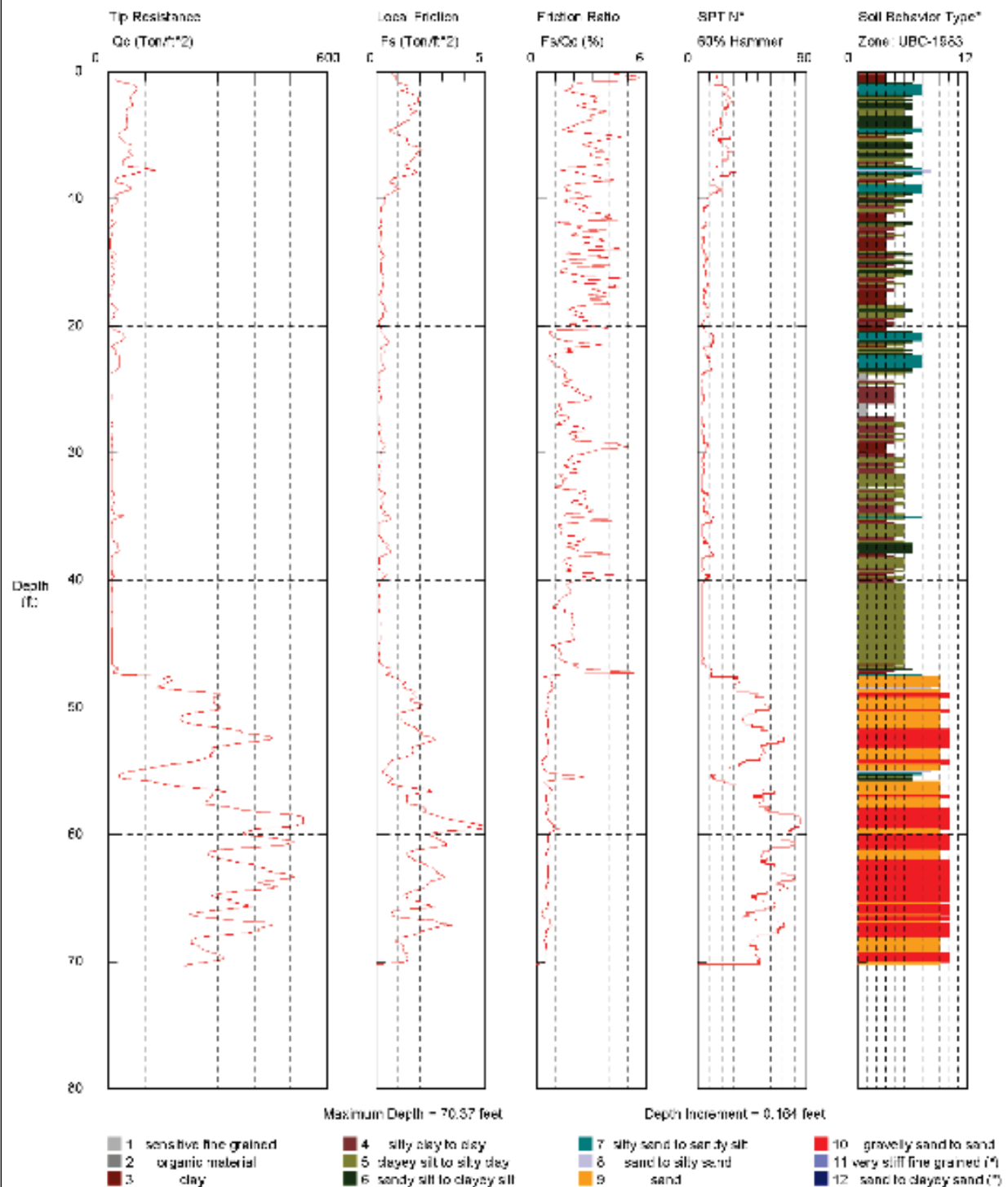


*Soil behavior type and SPT based on data from USC-1083

US ARMY CORPS OF ENGINEERS

Operator: CROSDY
Sounding: CPT-34
Cone Used: 379

CPT Date/Time: 06-14-02 07:29
Location: BH-22.02C
Job Number: Buck Chute

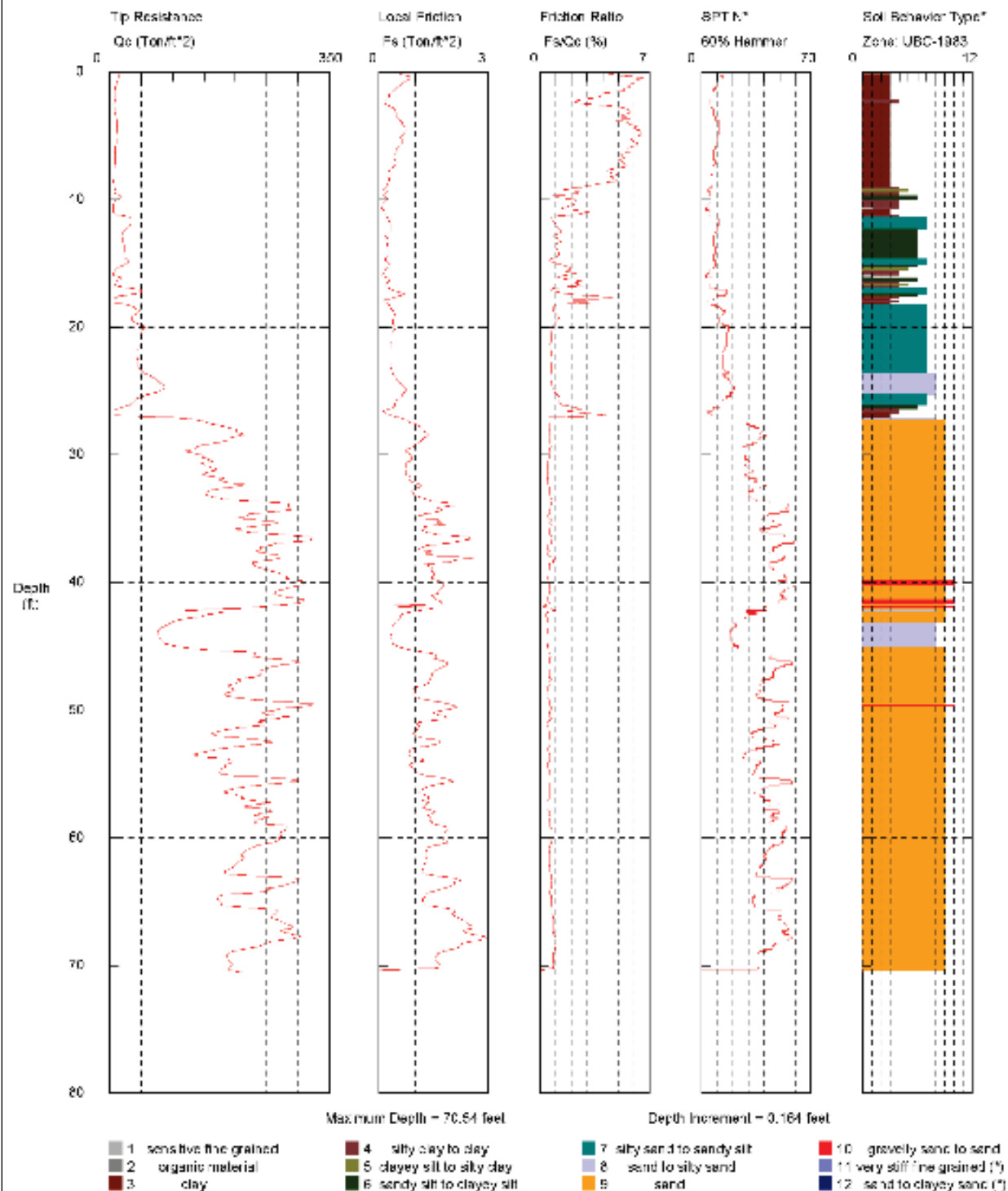


*Soil behavior type and SPT based on data from UBC-1963

US ARMY CORPS OF ENGINEERS

Operator: CROSBY
Sounding: CPT-12
Cone Used: 342

CPT Date/Time: 08-07-02 06:55
Location: BH-3.02C
Job Number: Buck Chute

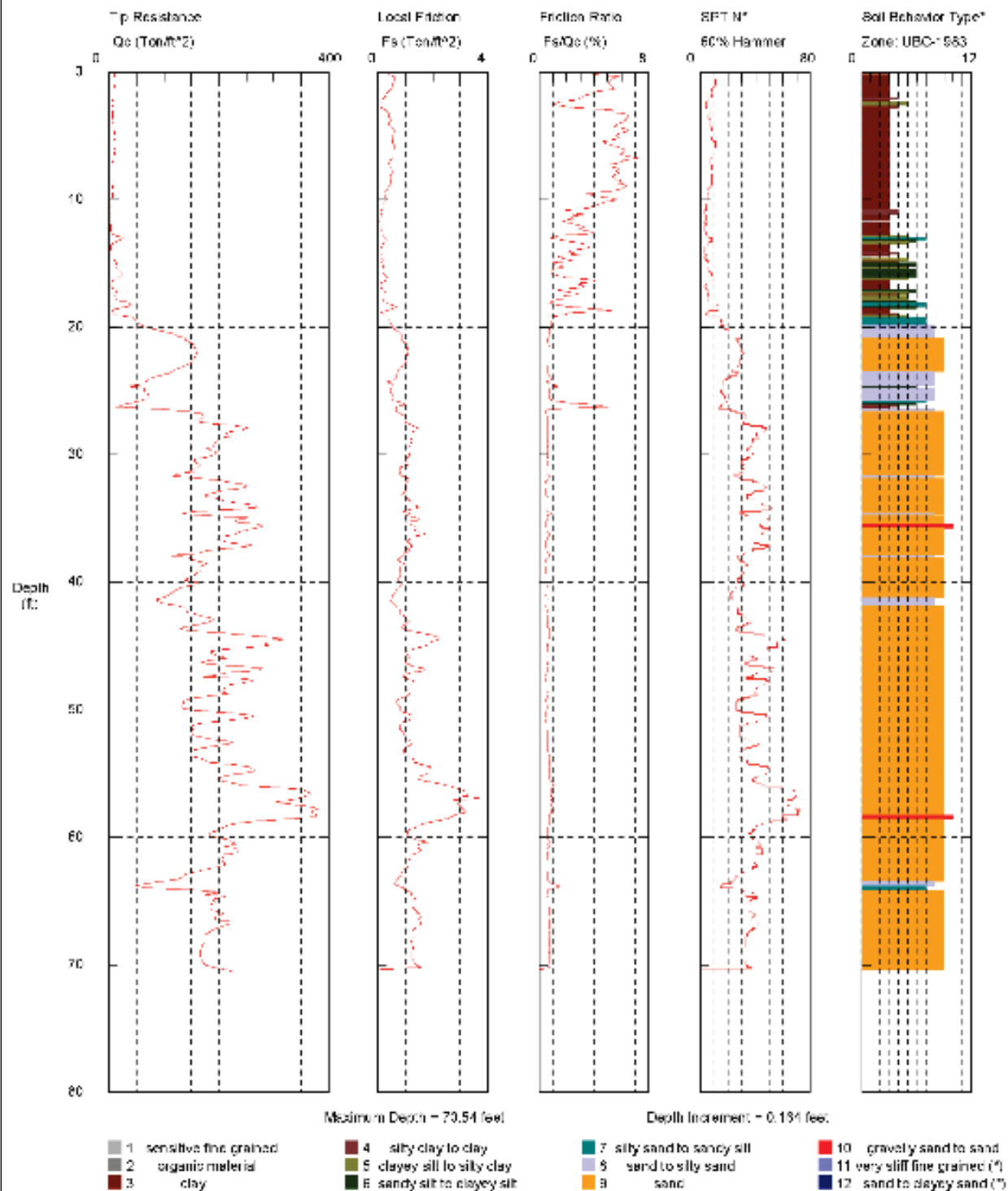


*Soil behavior type and SPT based on data from UBC-1983

US ARMY CORPS OF ENGINEERS

Operator: CROSBY
Sounding: CPT-14
Core Used: 342

CPT Date/Time: 05-07-02 10:54
Location: BH-6 02C
Job Number: Buck Chute

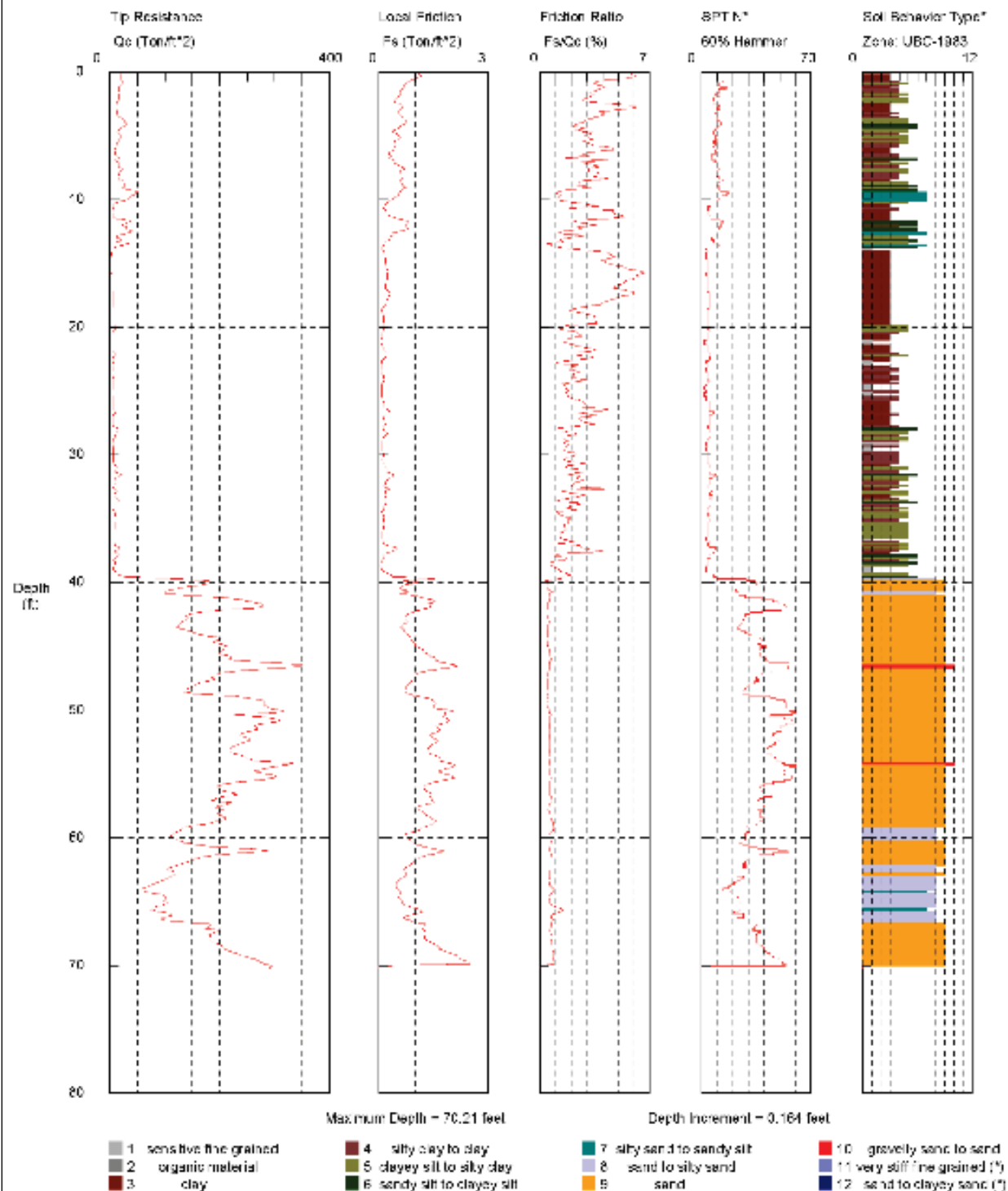


*Soil behavior type and SPT based on data from UBC-1563

US ARMY CORPS OF ENGINEERS

Operator: CROSBY
Sounding: CPT-22
Cone Used: 342

CPT Date/Time: 08-08-02 07:58
Location: BH-7.02C
Job Number: Buck Chute

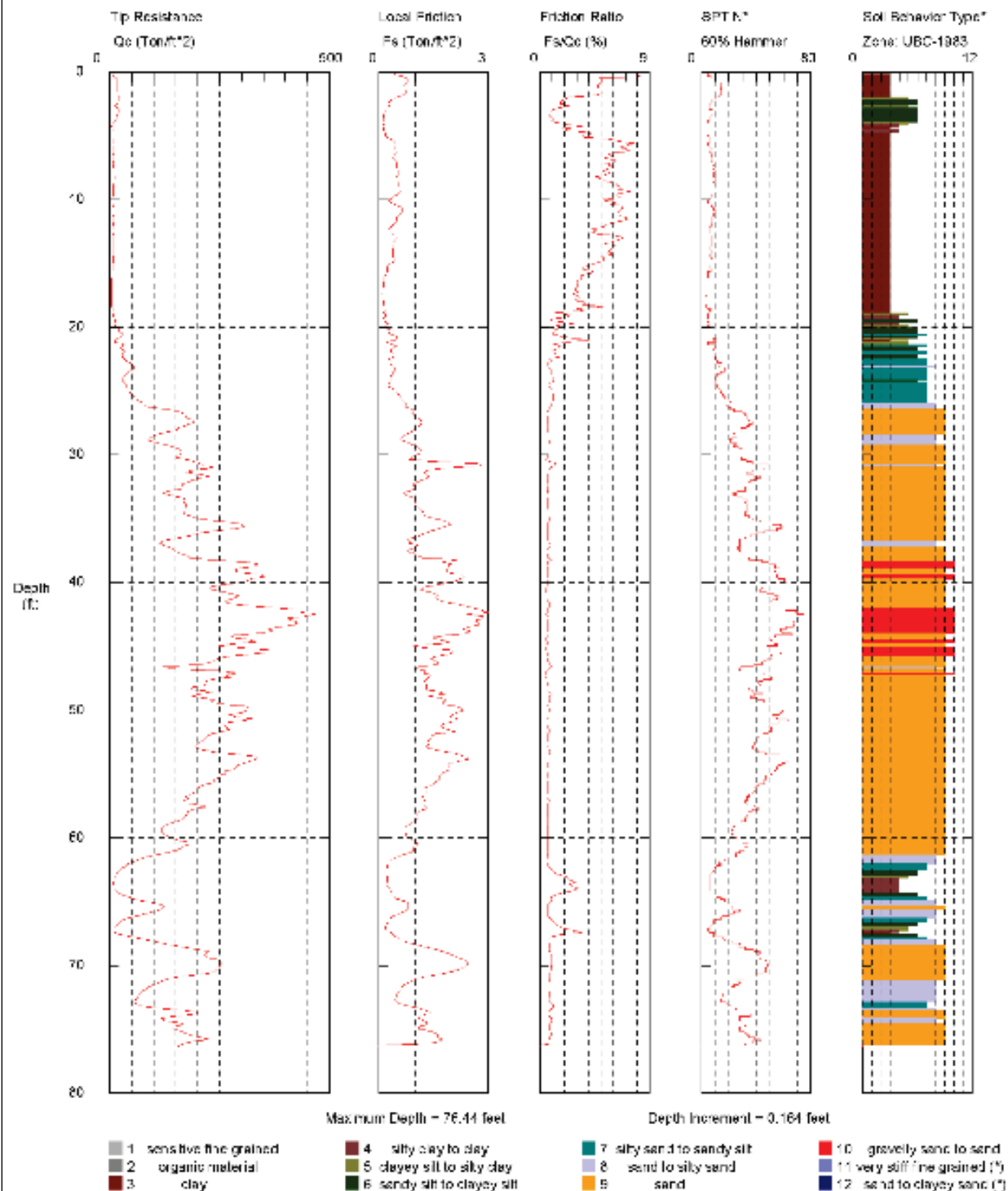


*Soil behavior type and SPT based on data from UBC-1983

US ARMY CORPS OF ENGINEERS

Operator: CROSBY
Sounding: CPT-08
Cone Used: 342

CPT Date/Time: 08-06-02 13:58
Location: BH-5.02C
Job Number: Buck Chute

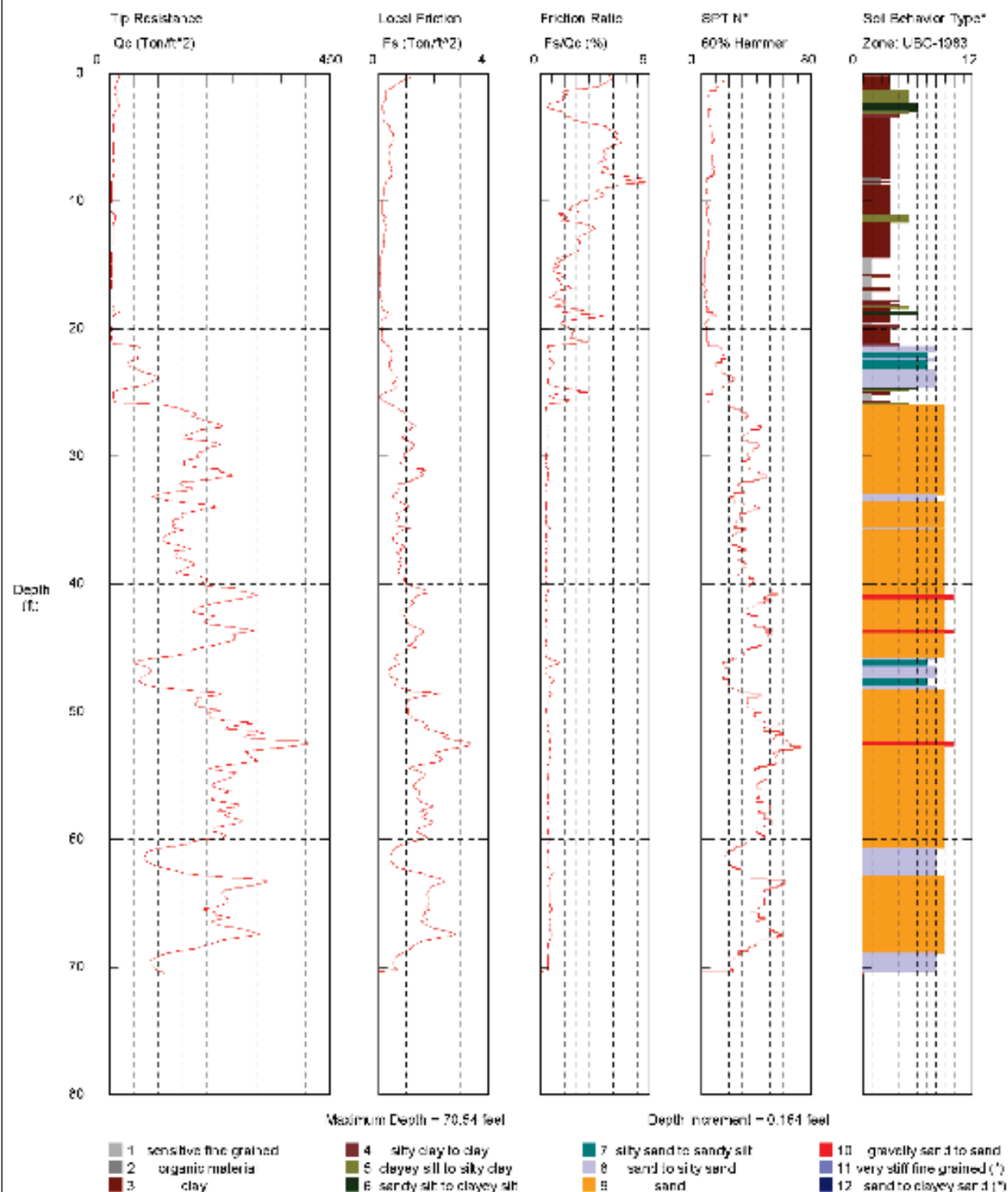


*Soil behavior type and SPT based on data from UBC-1983

US ARMY CORPS OF ENGINEERS

Operator: CROSBY
Sounding: CPT-15
Cone Used: 342

CPT Date/Time: 08-07-02 11:18
Location: BH-0.02C
Job Number: Buck Chute

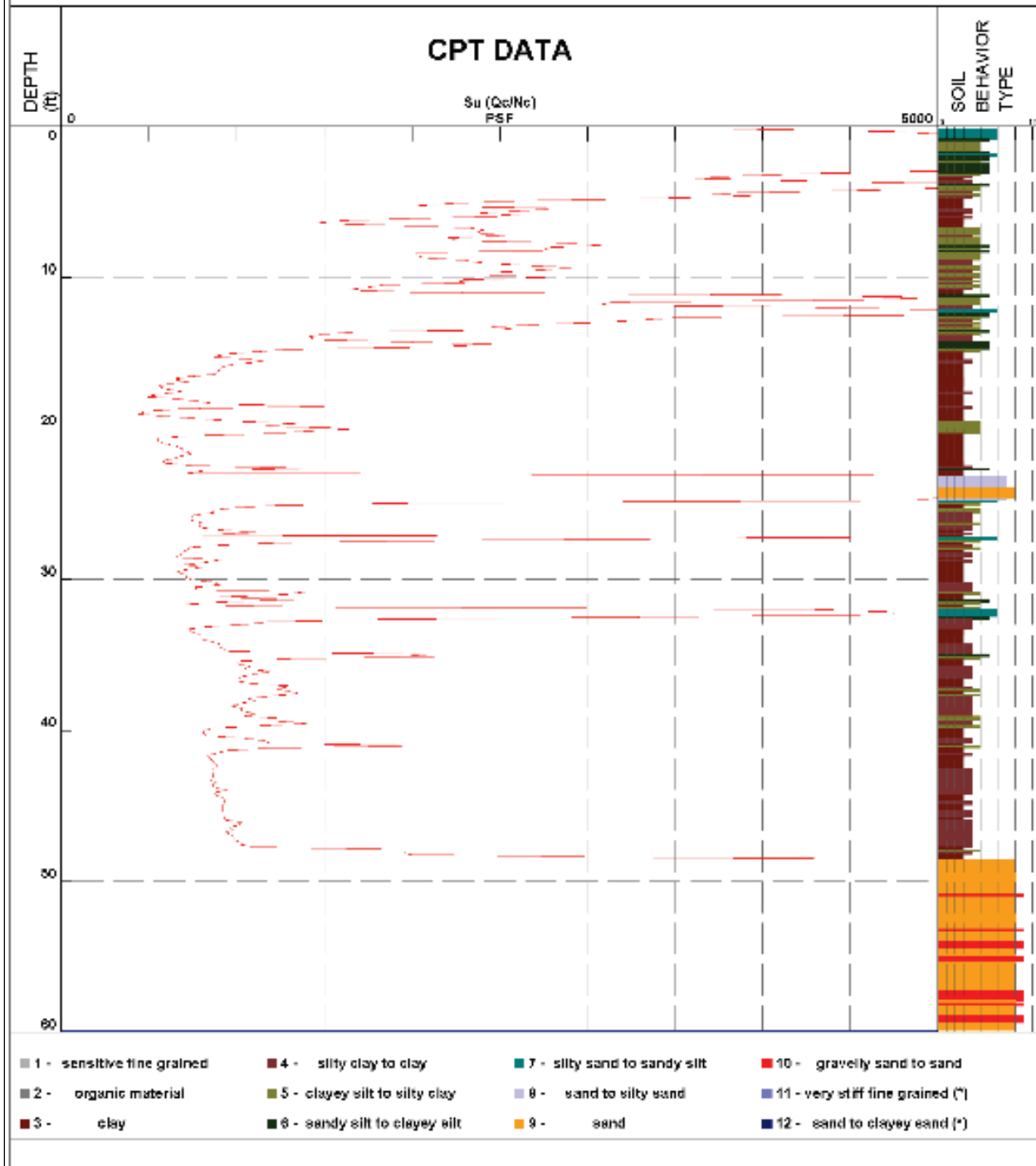


*Soil behavior type and SPT based on data from UBC-1983



VICKSBURG DISTRICT

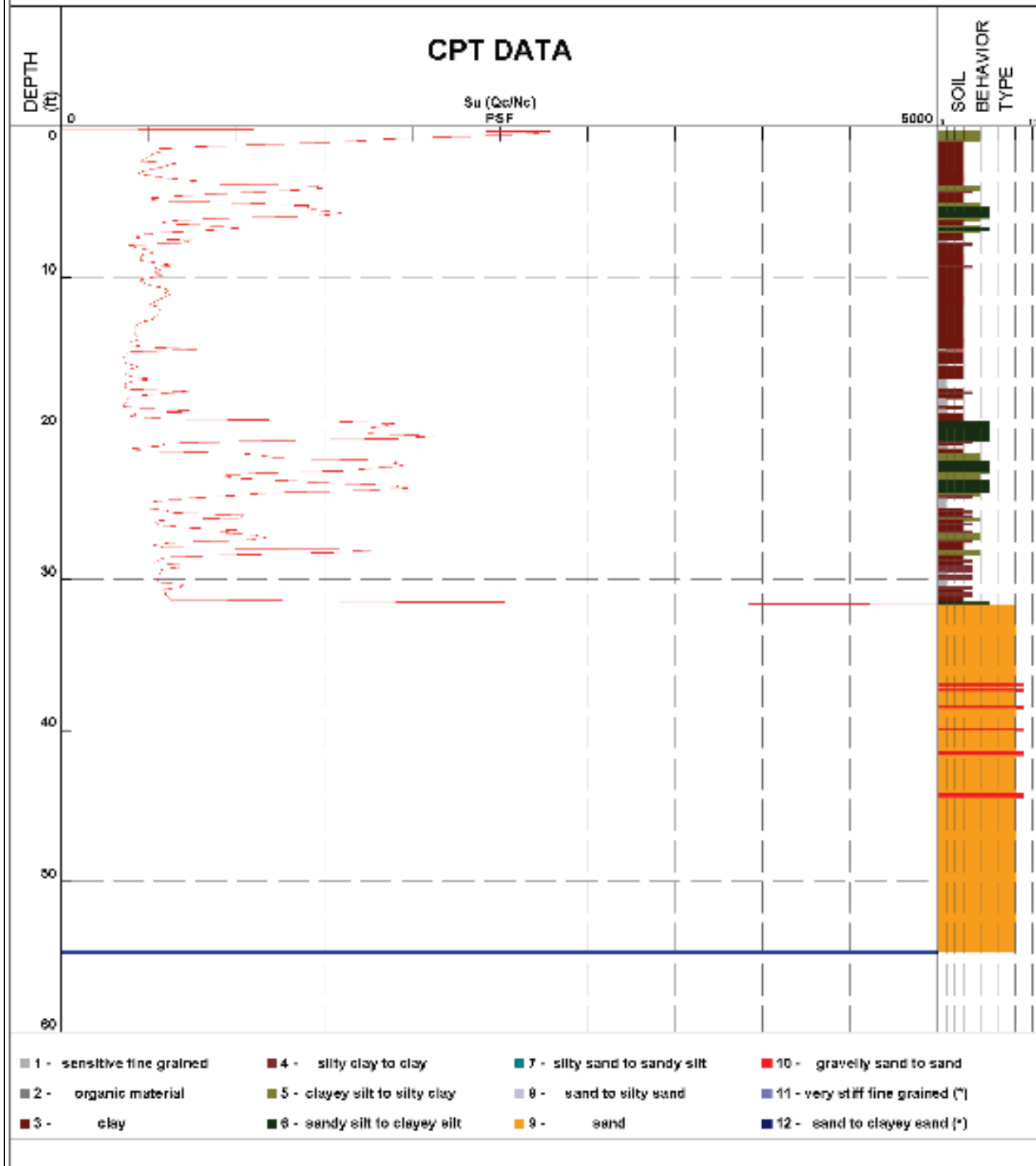
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VICKSBURG DISTRICT

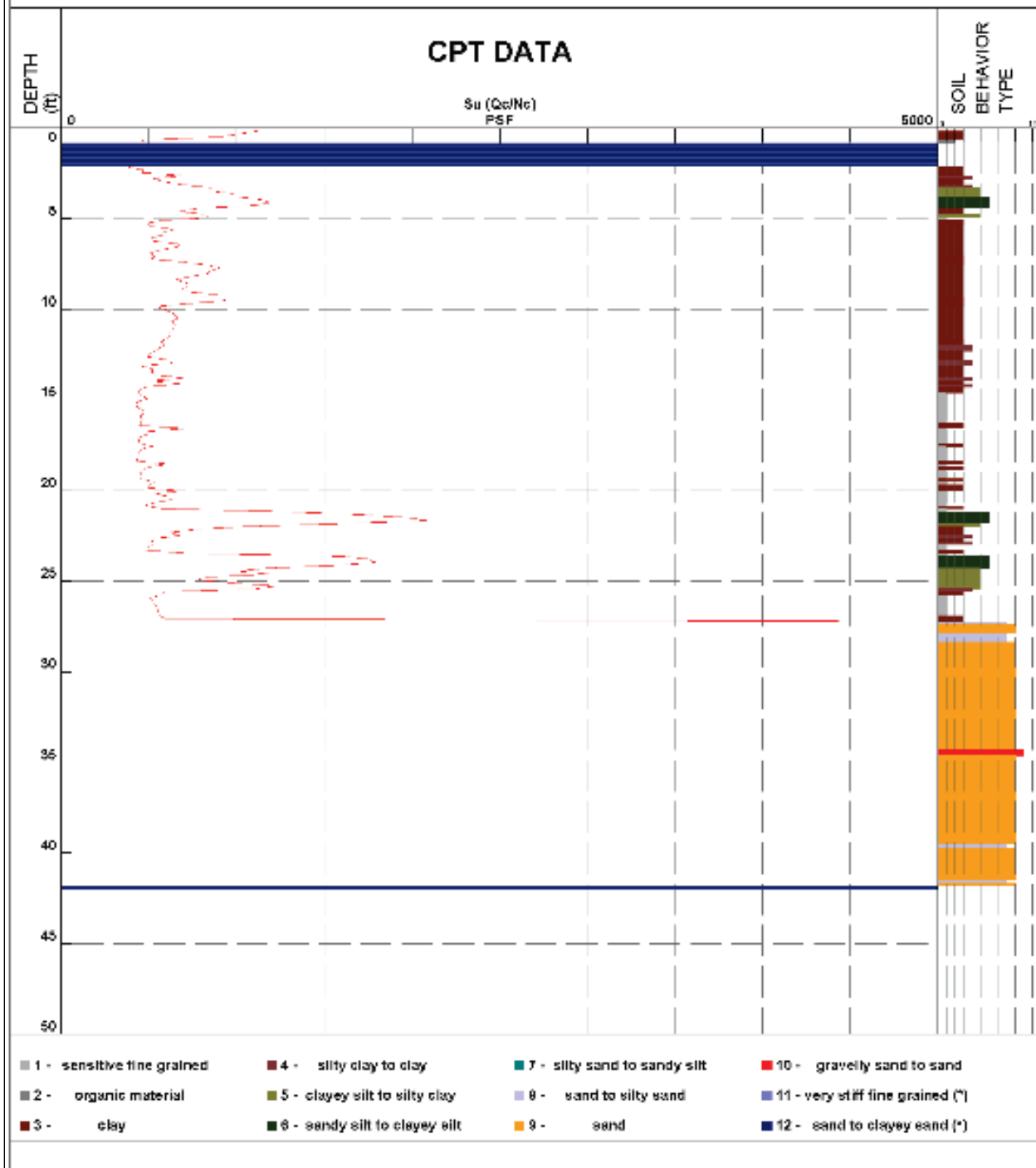
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VICKSBURG DISTRICT

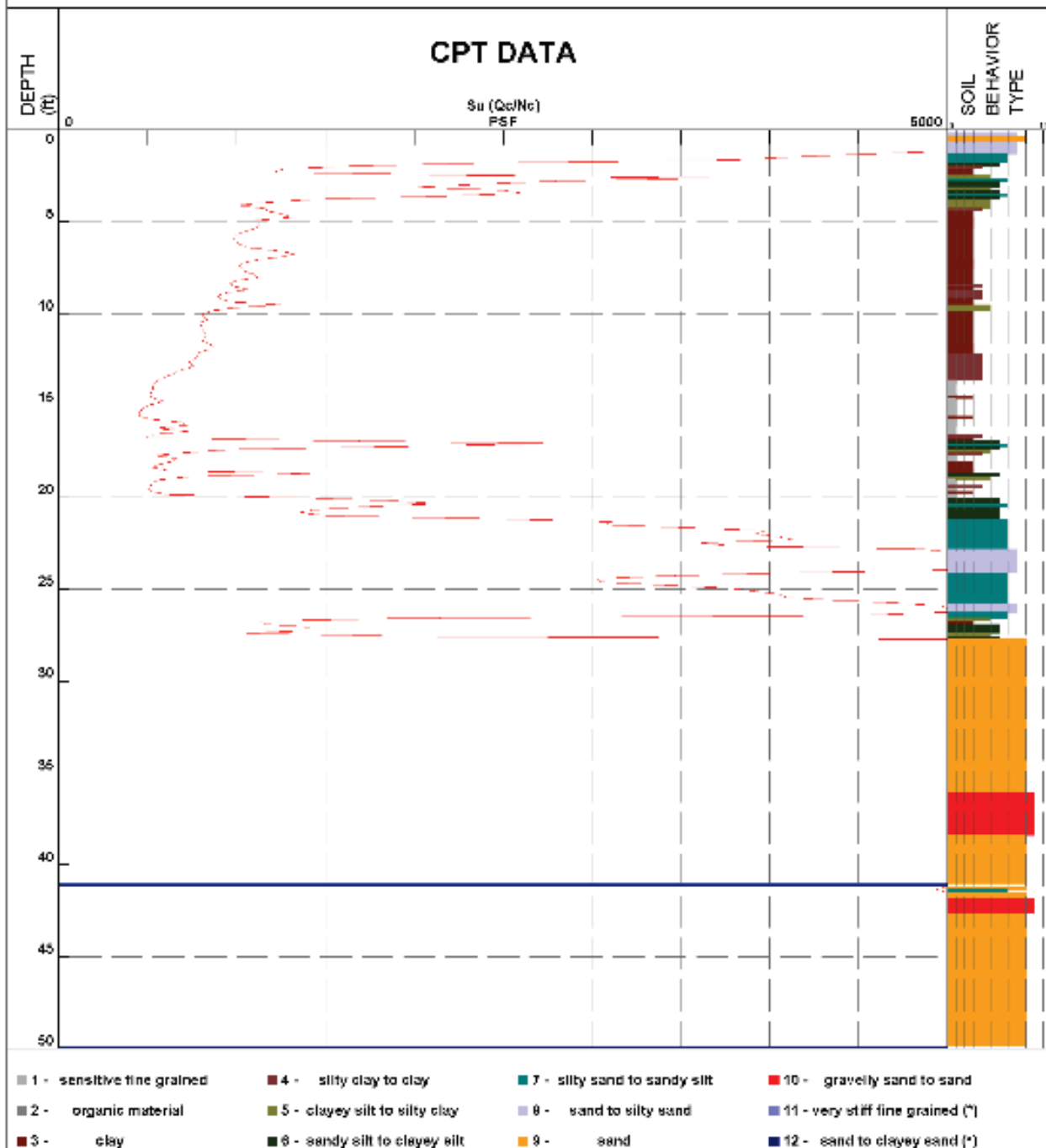
OPERATOR Crosby CONE NUMBER DSA1050 LOCATION 32 31 28.4 81 04 21.2
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VICKSBURG DISTRICT

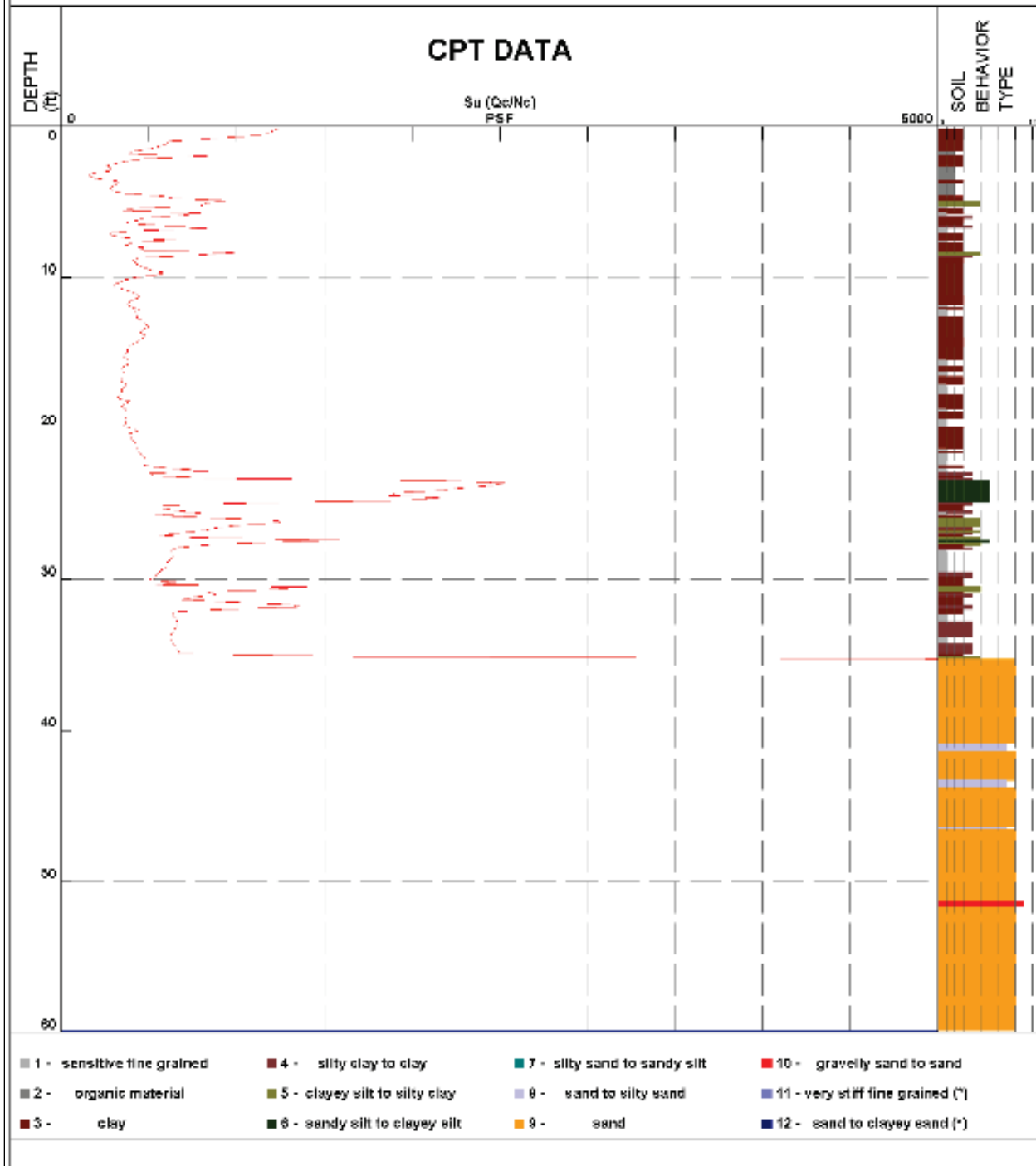
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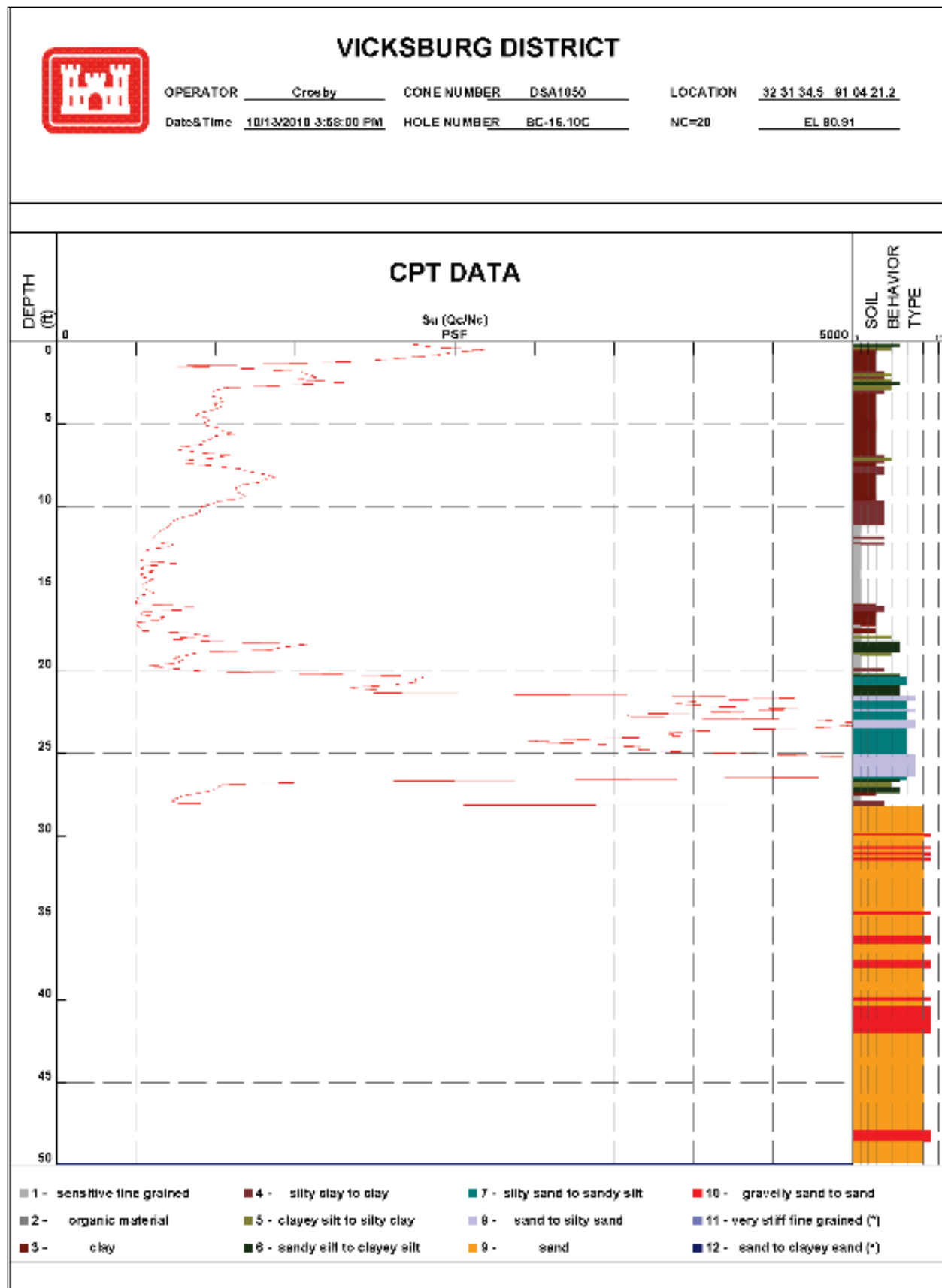




VICKSBURG DISTRICT

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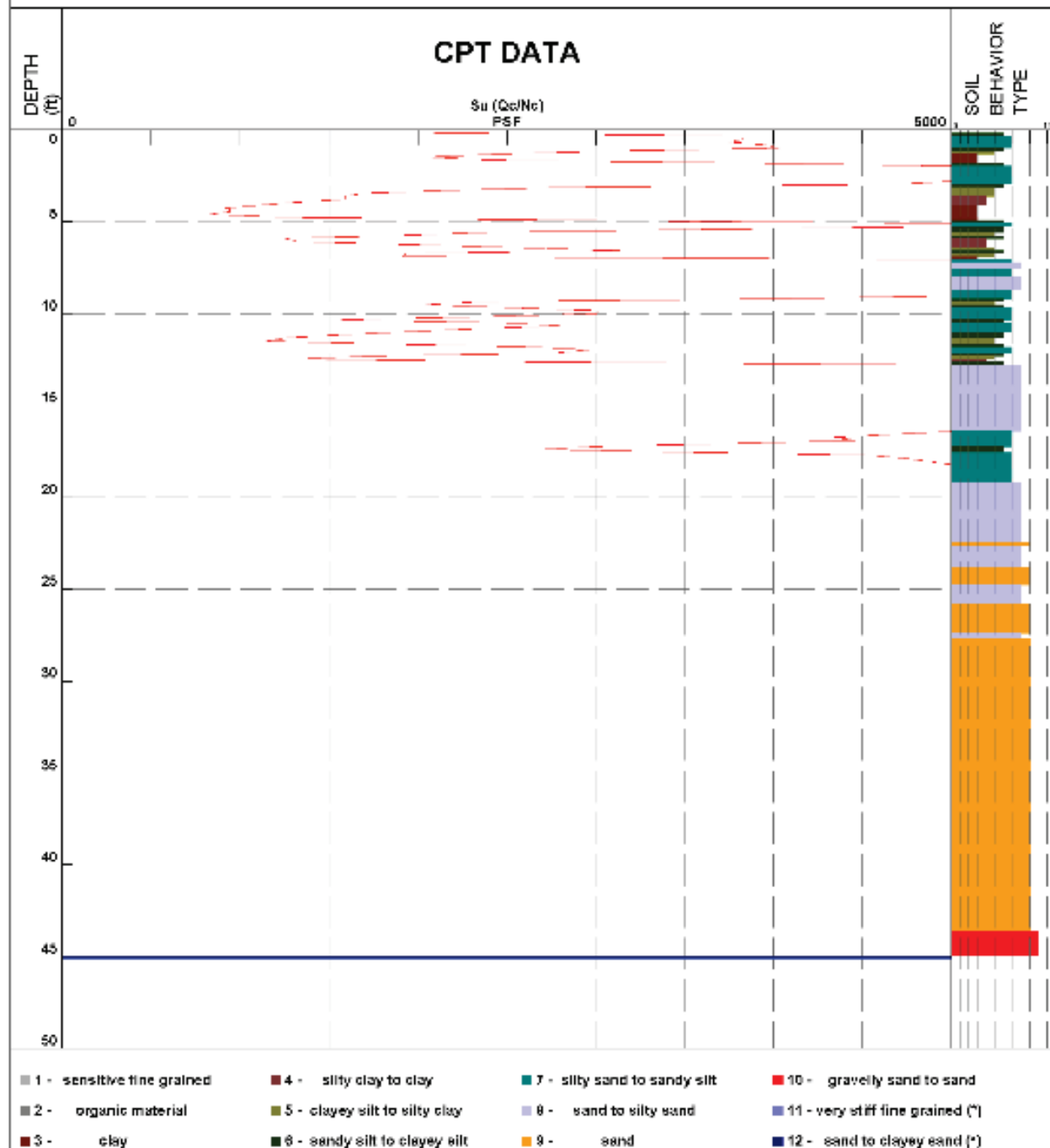






VICKSBURG DISTRICT

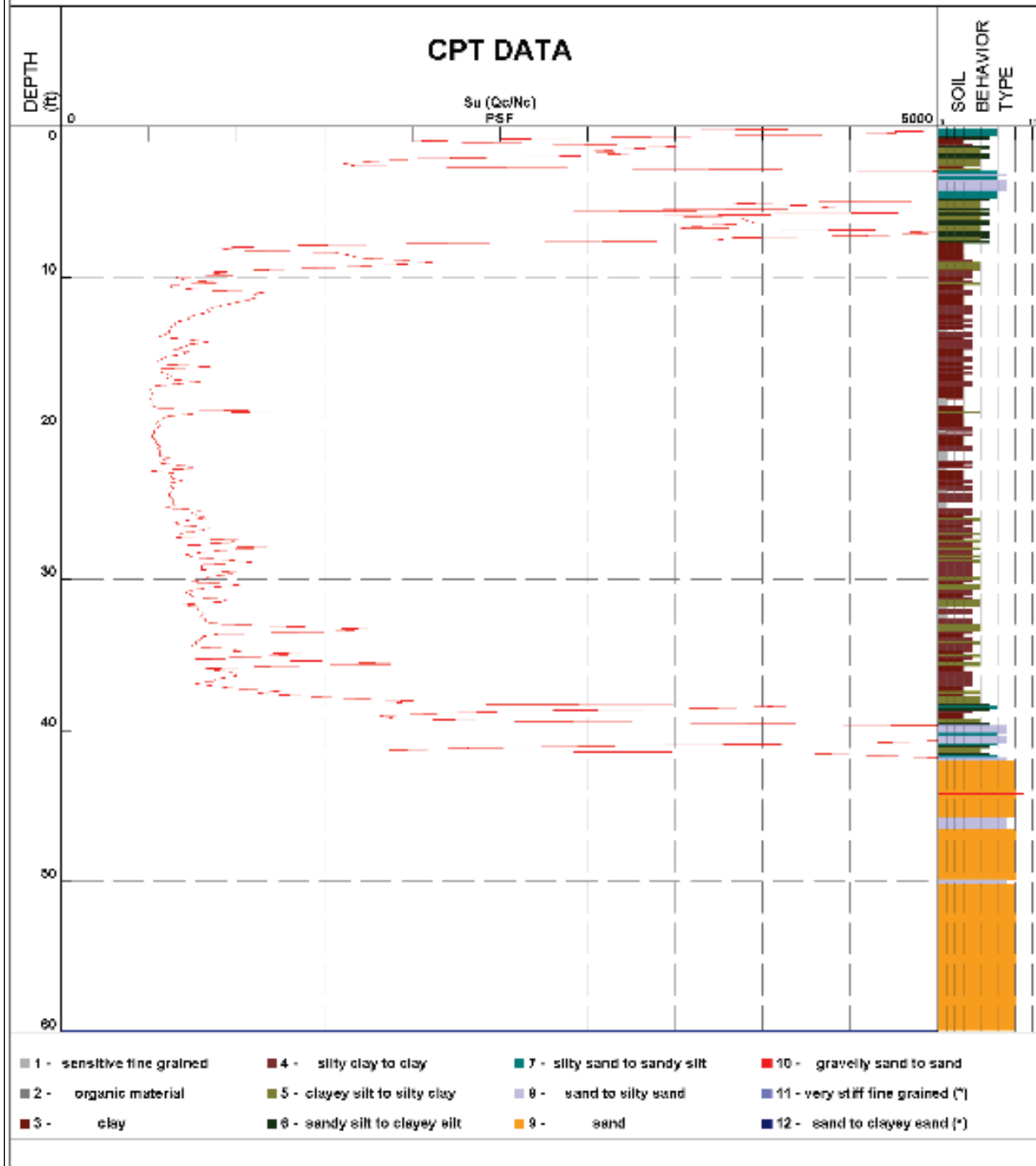
OPERATOR Crosby CONE NUMBER DSA1050 LOCATION 32 31 16.4 91 04 27.5
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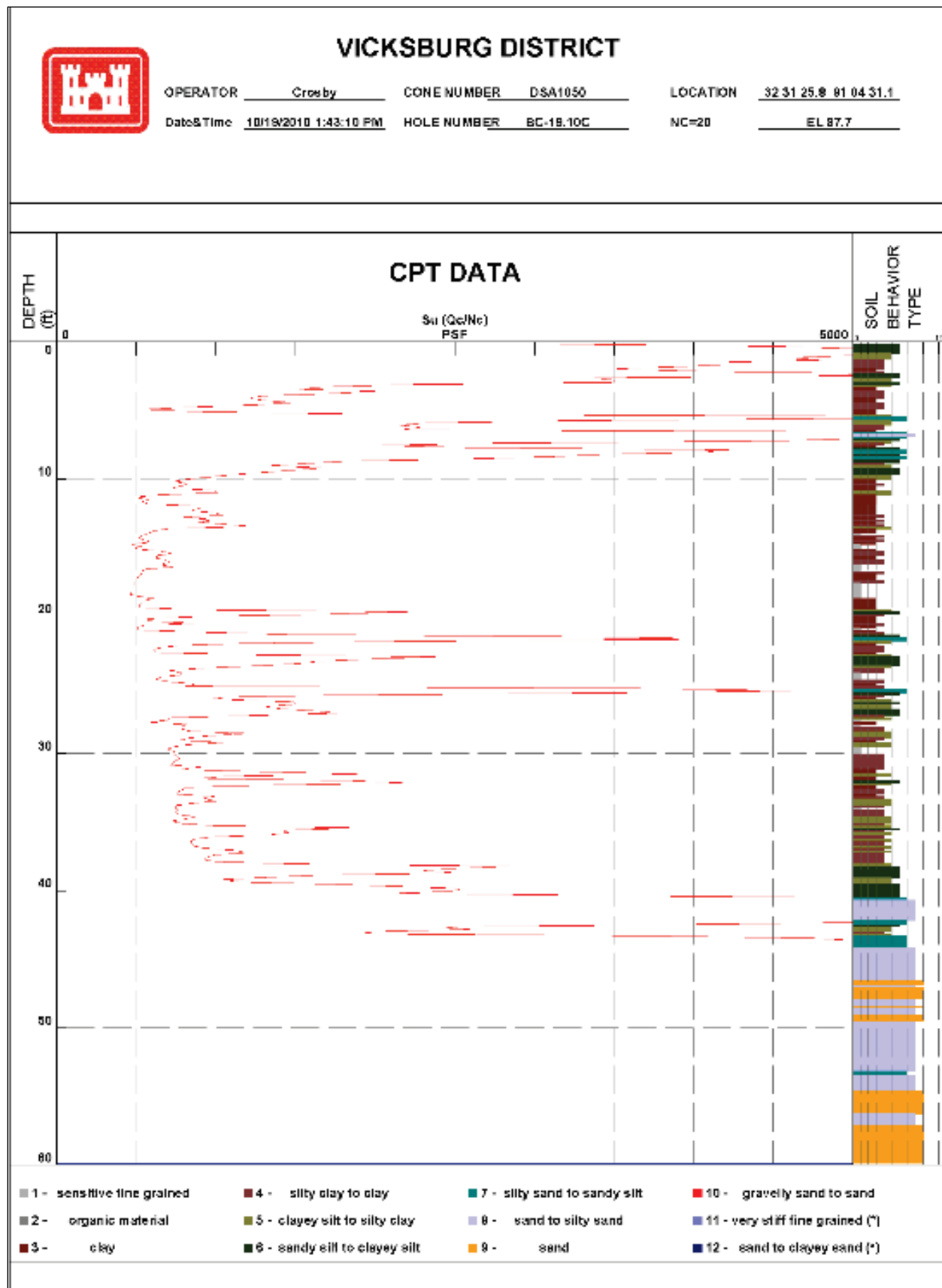




VICKSBURG DISTRICT

OPERATOR Crosby CONE NUMBER DSA1050 LOCATION 32 31 21.3 81 04 28.7
 Date&Time 10/19/2010 12:57:38 PM HOLE NUMBER BC-18.10C NC=20 EL 87.5

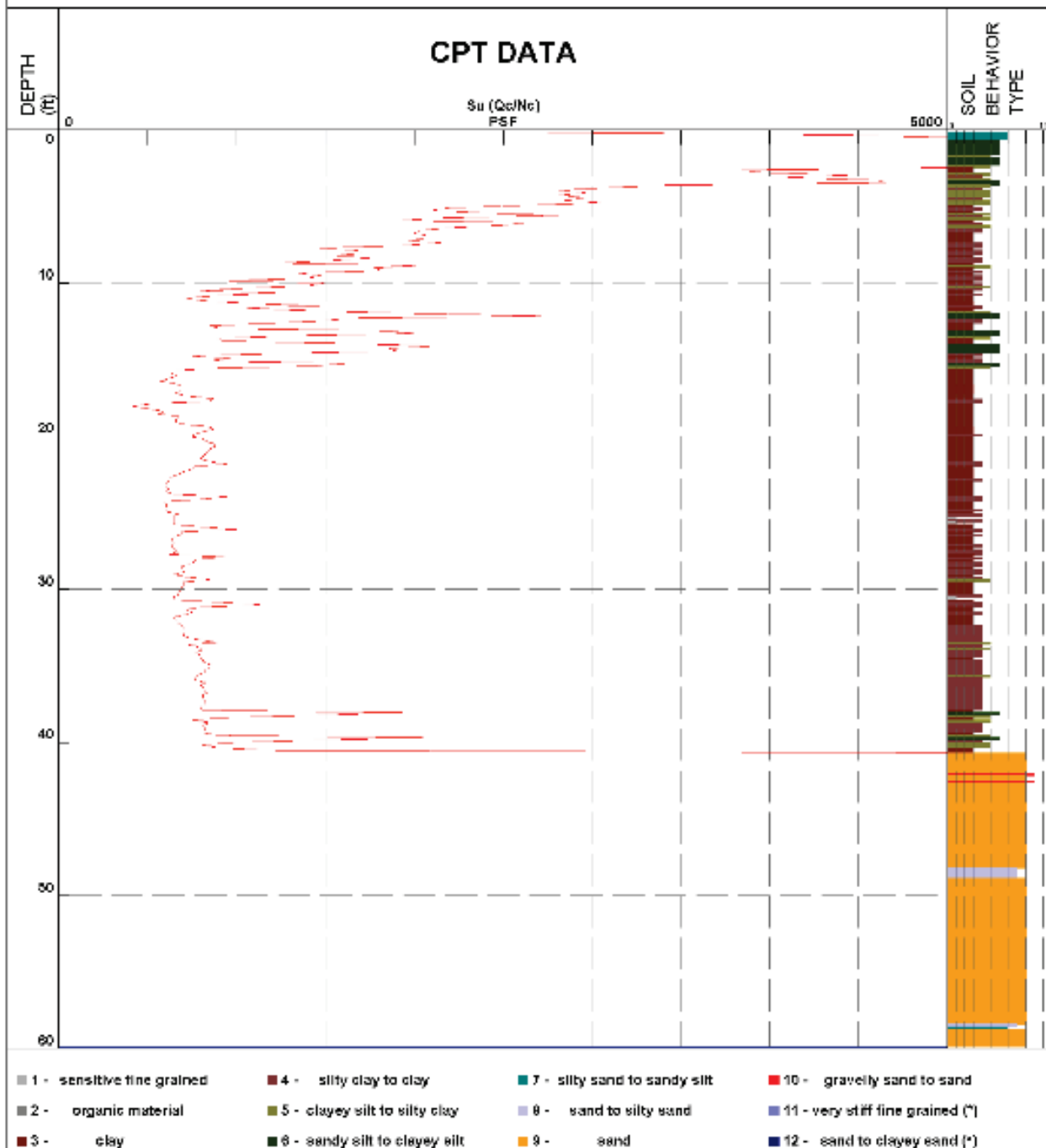






VICKSBURG DISTRICT

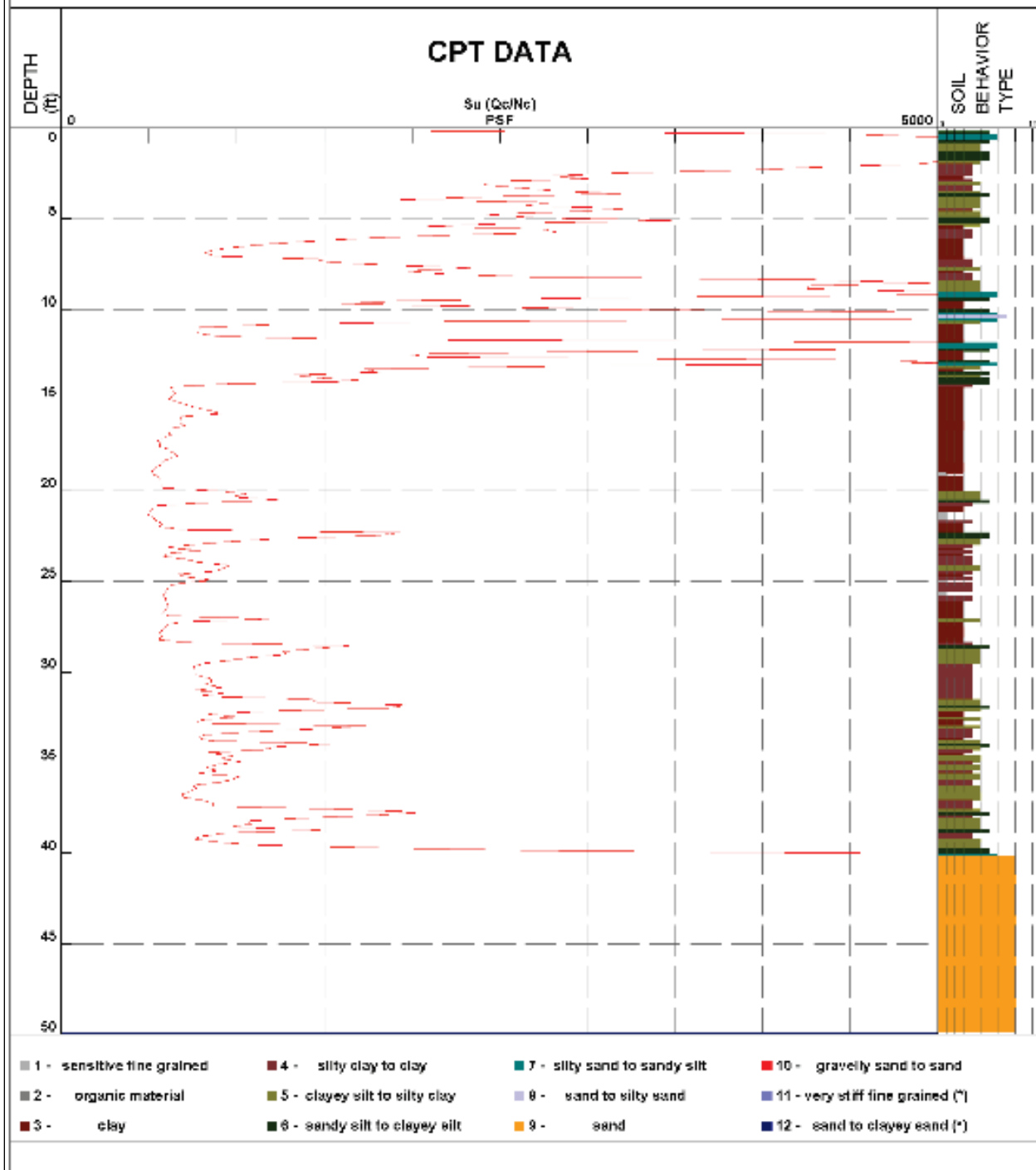
OPERATOR Penley CONE NUMBER DSA1050 LOCATION 32 31 23.1 81 04 23.2
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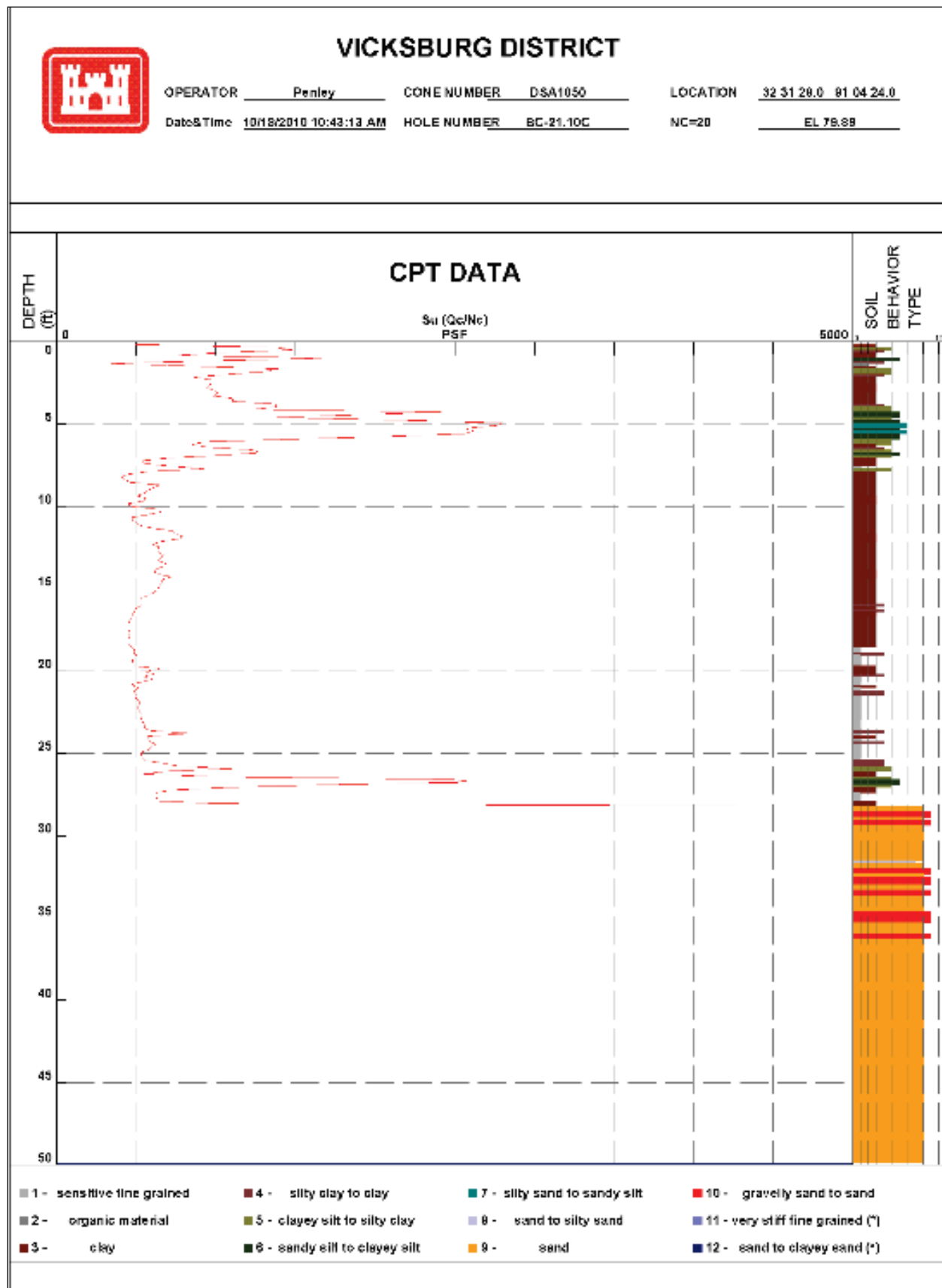




VICKSBURG DISTRICT

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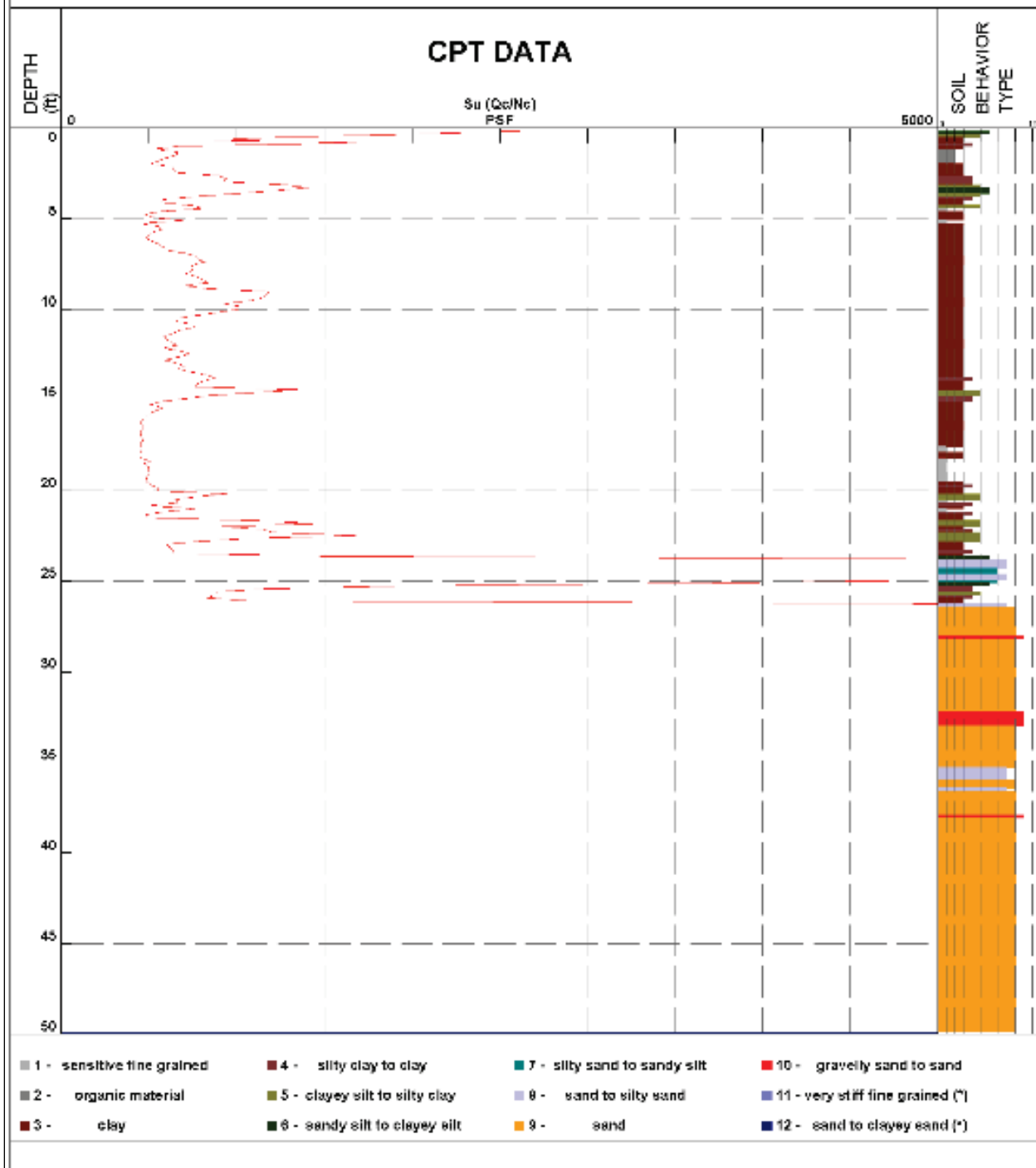


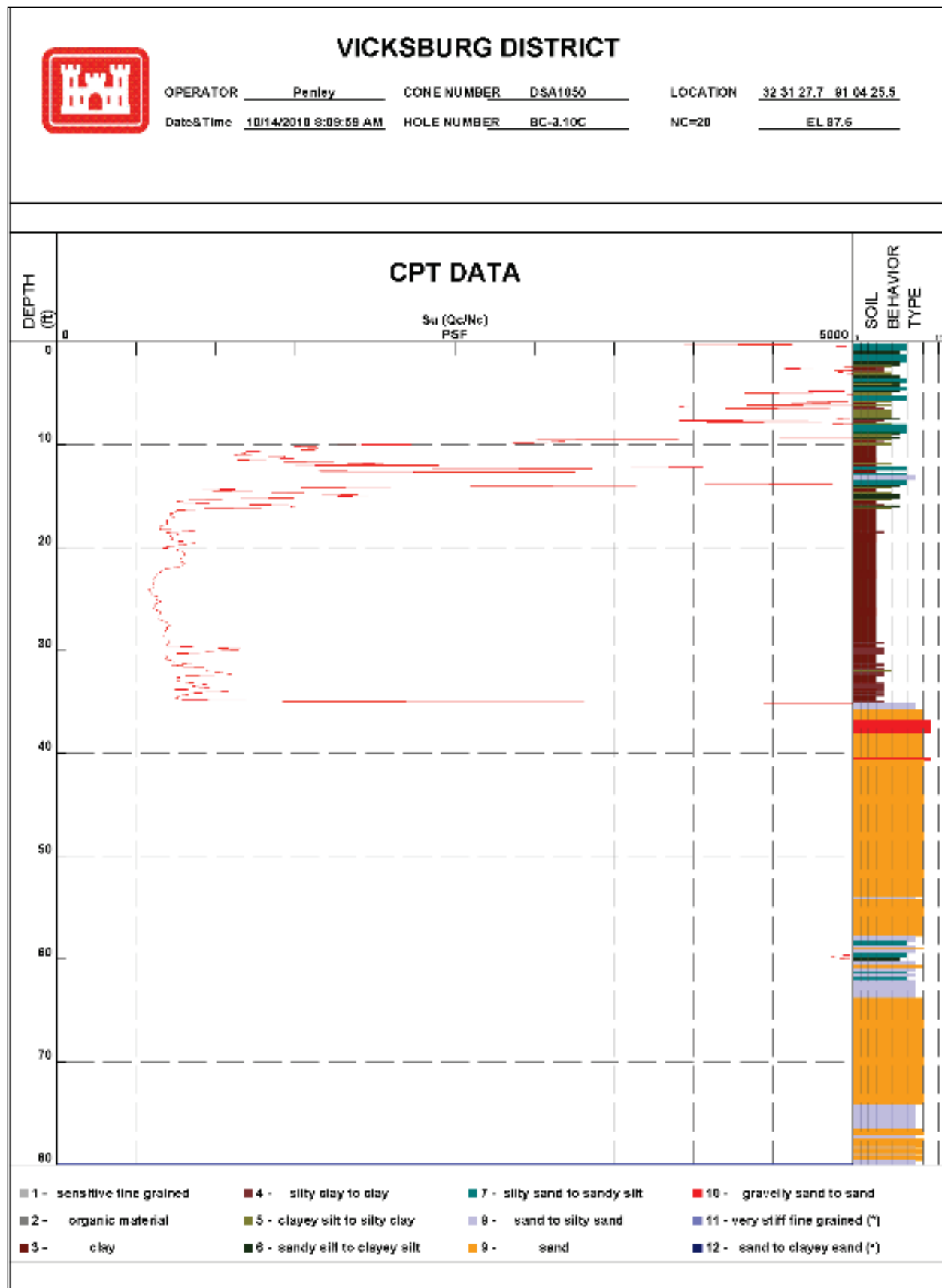




VICKSBURG DISTRICT

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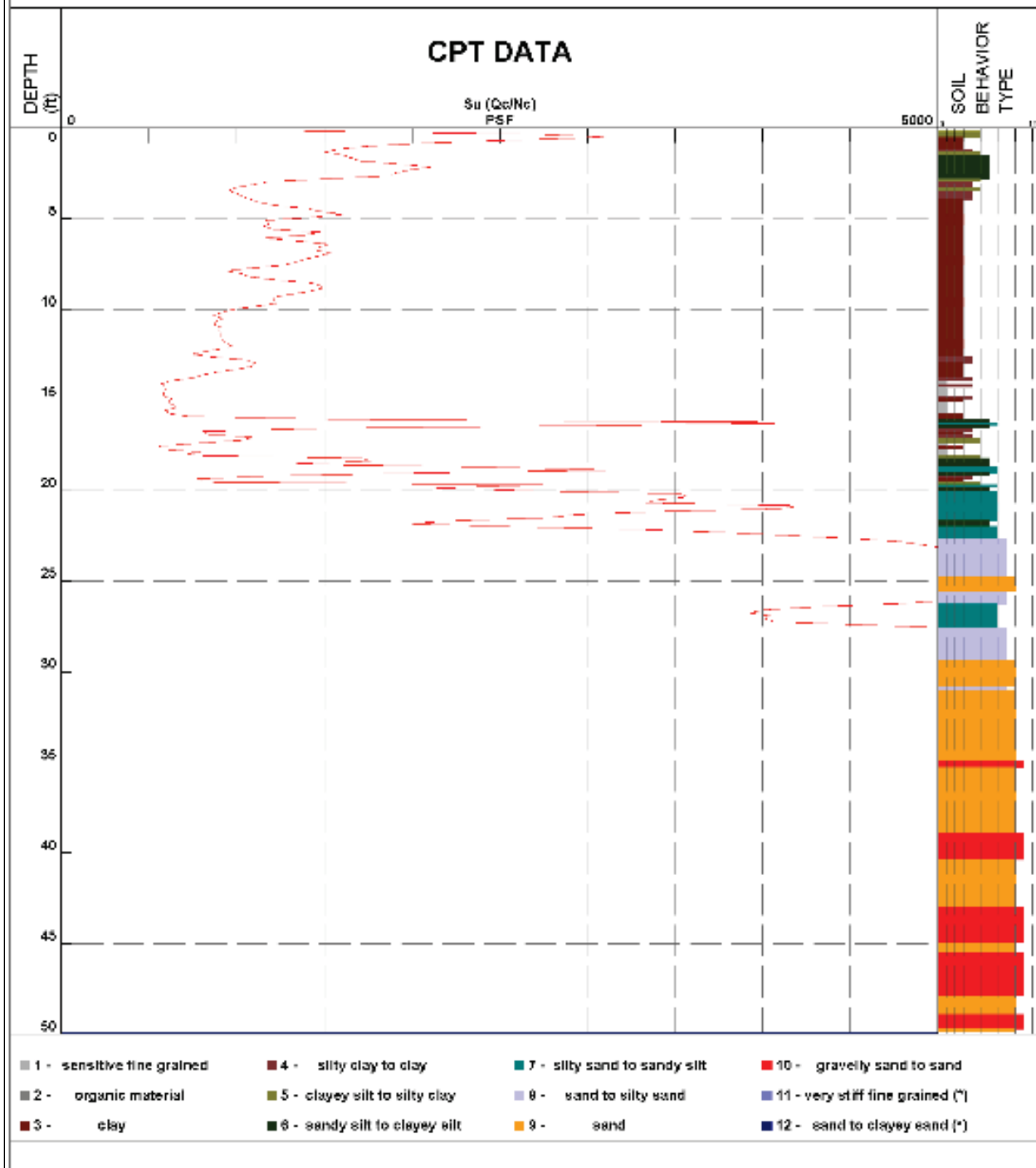






VICKSBURG DISTRICT

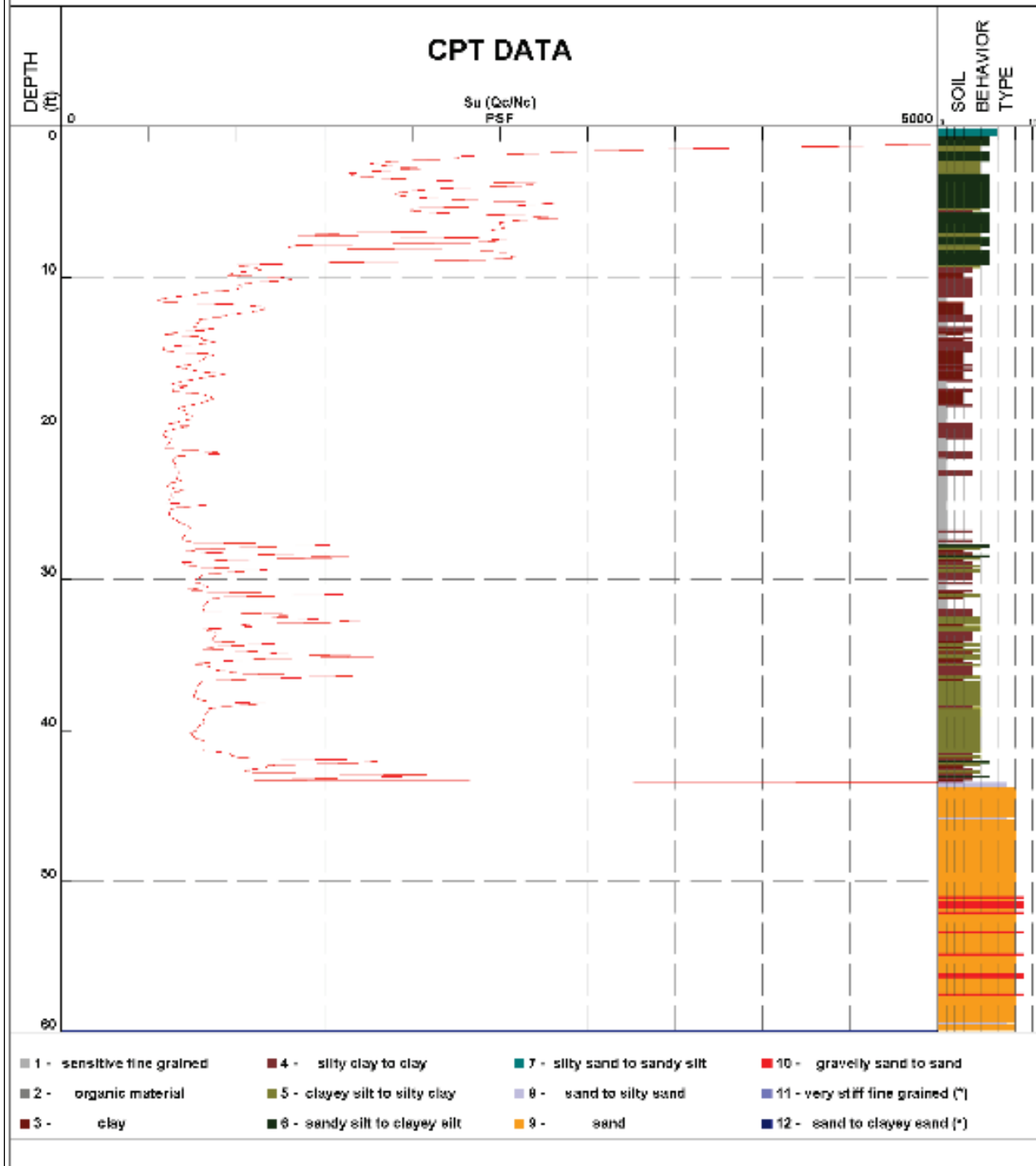
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VICKSBURG DISTRICT

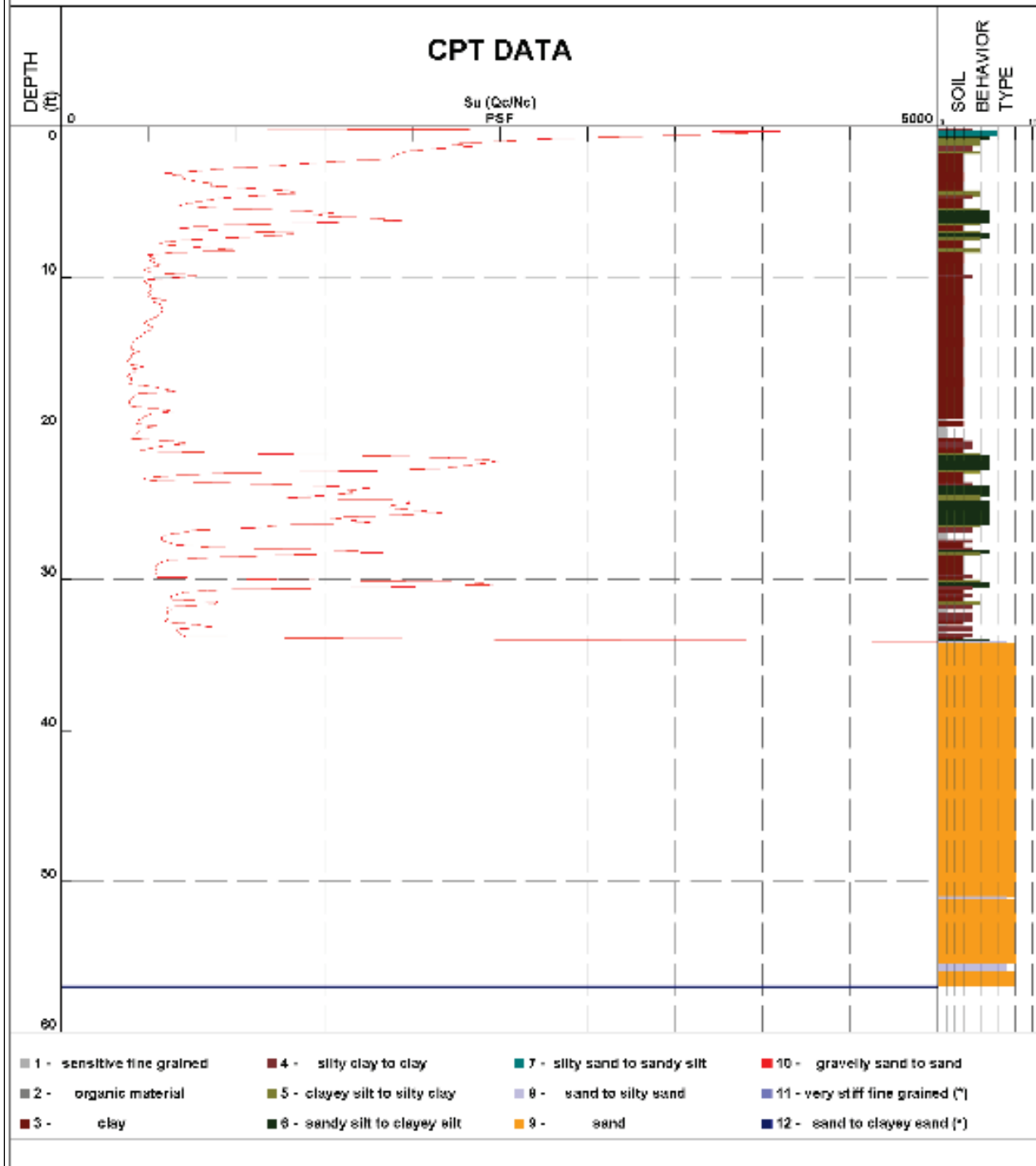
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VICKSBURG DISTRICT

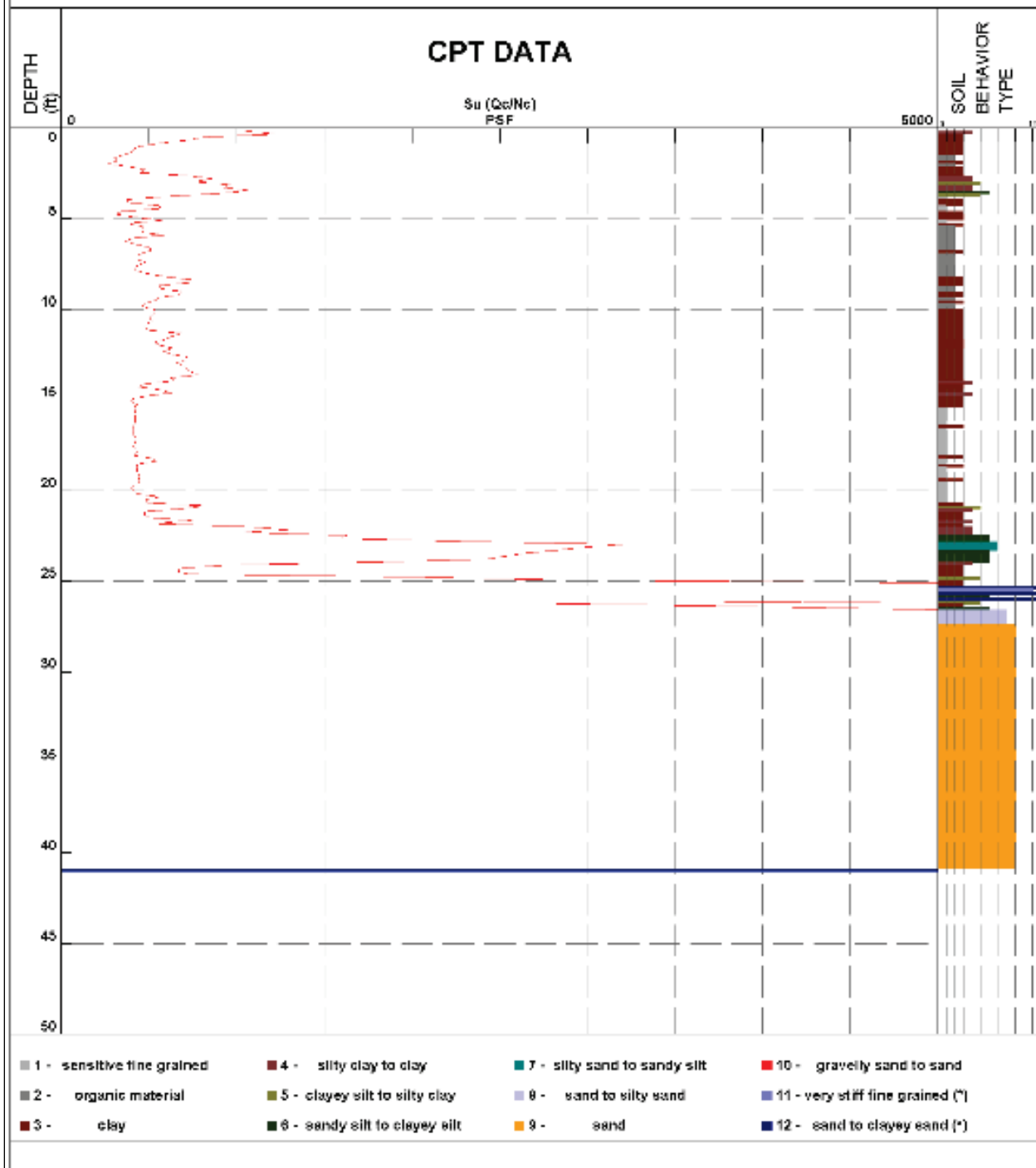
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VICKSBURG DISTRICT

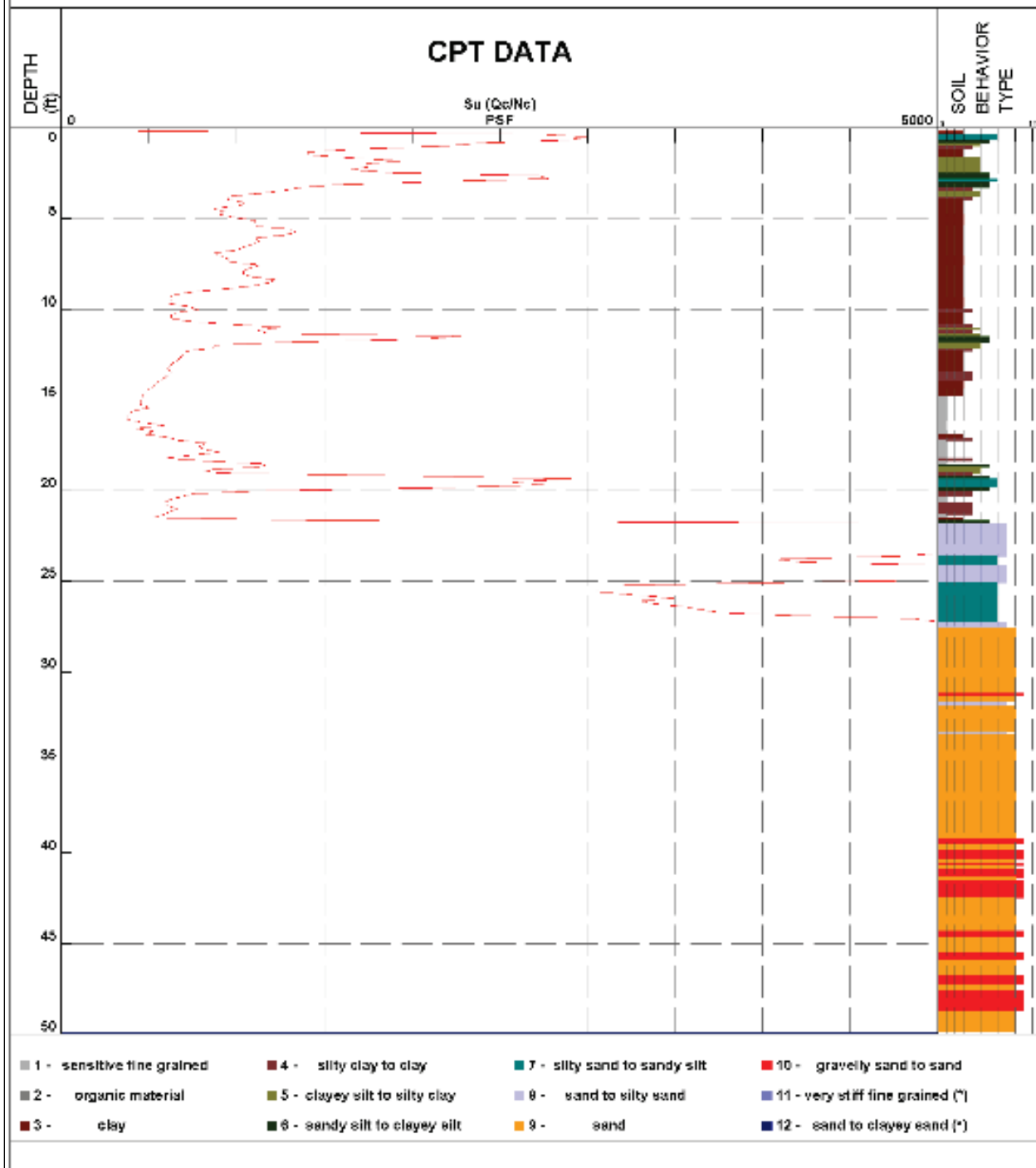
OPERATOR Penley CONE NUMBER DSA1050 LOCATION 32 31 28.8 81 04 23.8
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VICKSBURG DISTRICT

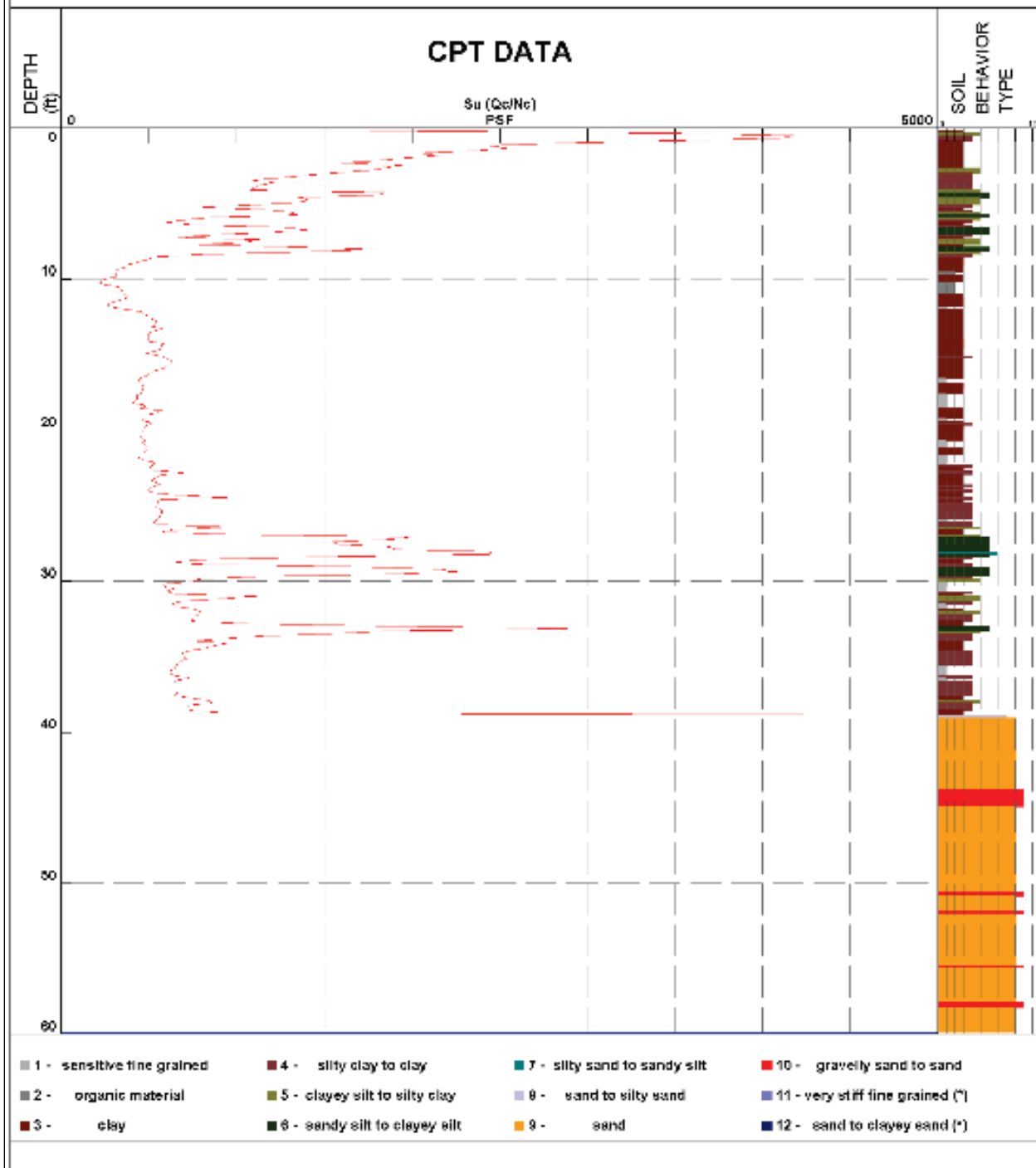
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VICKSBURG DISTRICT

OPERATOR Penley CONE NUMBER DSA1050 LOCATION 32 31 18.8 81 04 17.5
 Date&Time 10/14/2016 2:22:50 PM HOLE NUMBER BC-8.10C NC=20 EL 81.8



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				5b. GRANT NUMBER	
				5c. PROGRAM ELEMENT NUMBER 3121	
6. AUTHOR(S) Seth M. Martin, Joseph B. Dunbar, Maureen K. Corcoran, and Darrel W. Schmitz				5d. PROJECT NUMBER 462582	
				5e. TASK NUMBER A1290	
				5f. WORK UNIT NUMBER J22621	
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14. ABSTRACT Sand boil formation due to underseepage is a potential failure mechanism for levees in the Lower Mississippi River Valley. Sand boils were identified in the Buck Chute study area in the 1990s during high-water events and during the 2009 Flood. The site is unique due to the presence of point bar and abandoned channel deposits. To understand the role of these alluvial deposits on sand boil formation at the site, a geologic investigation of the subsurface was conducted. Using shallow geophysics, cone penetrometer tests (CPT), borings, and a geographic information system (GIS), researchers concluded that the thin blanket associated with point bar deposits, abandoned channel deposits causing a blocked seepage path, and head differential changes caused by the Muddy Bayou Control Structure were the controls of sand boil formation at Buck Chute.					
15. SUBJECT TERMS Seepage, Sand boil, Levee, Underseepage, Mississippi River Soil surveys--Geophysical methods Alluvial plains					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES 93	19a. NAME OF RESPONSIBLE PERSON
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