THE APPLICATION OF GROUND PENETRATING RADAR AT THE KANORADO LOCALITY, NORTHWEST KANSAS

BY

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Master's of Arts.

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ABSTRACT

Geophysical studies of Paleoindian archaeological sites are rare because the sparse cultural remains at such sites cannot be detected by such methods. Though cultural remains cannot be imaged directly, ground penetrating radar (GPR) is still useful for conducting research concerning the site setting by mapping shallow soil horizons that contain archaeological deposits. GPR survey methods are advantageous because data can be collected rapidly over extensive areas without causing ground disturbance. The Kanorado locality in northwestern Kansas consists of three Early Paleoindian sites with cultural deposits 1-2 m beneath an alluvial terrace. A GPR survey of site 14SN106 was conducted in an attempt to delineate the site stratigraphy. High attenuation rates at the site limited the depth of imaging and resolution of the survey. However, the survey was successful because it helped to delineate the extent of the site as well as an unknown arroyo under the terrace.

ACKNOWLEDGEMENTS

Although this thesis bears my solitary name, the research would not have been possible without a great many number of my instructors, colleagues, friends, and family. I would first like to thank my advisor, Rolfe Mandel, for all his help, support, and guidance on this project. I give special thanks to George Tsoflias, Jack Hofman, and Dan Hirmas for all of their valuable suggestions on every step of this research. This project was funded through the Odyssey Archaeological Research Fund and I am grateful for all of the assistance that I have received. I also want to thank Scott Hooker who provided the University of Kansas, the Odyssey Archaeological Research Fund, and me access to his land, without which this research would never have been possible.

There are numerous people who helped out with data collection. Dan Keating and Kris West put in a great amount of their personal time into helping me collect data. Shannon Ryan assisted with many hours of mapping locations out at Kanorado and provided me with her data from the previous field seasons at the locality. The KU 2009 field school students (James Krpan, Alex Norton, Kat Rocheford, Caitlin Curry, Lydia DeHaven, Pam Boulware, Les Hardin, Jordan Jennings, Jeff Ryan, Theresa Royston, John Miller, and Wes Gibson) all helped with data collection as part of the class. Additionally, Craig Hoit and Galen Worthington volunteered their time at Kanorado and assisted me with data collection. William Johnson gave lab space so I could process my samples and Aaron Young conducted my grain-size analysis. I give great thanks to everyone who helped out on any aspect of this project.

CONTENTS

LIST OF FIGURES

LIST OF TABLES

TABLE PAGE

CHAPTER I

INTRODUCTION

The Kanorado Locality is a cluster of three stratified Early Paleoindian archaeological sites (14SN101, 14SN105, and 14SN106) near the town of Kanorado in northwest Kansas (Figures 1 and 2). The cultural deposits at each of the sites are buried in silty alluvium beneath the T-1 terrace of Middle Beaver Creek in Sherman County (Mandel et al., 2004). The sites are significant archaeological resources for a number of reasons. First, the archaeological materials recorded at Kanorado date to the Pleistocene-Holocene transition (11,000-10,000 ^{14}C yr B.P.). No sites dating to this period had been recorded on the High Plains of western Kansas prior to the discoveries at Kanorado. Therefore, the Kanorado Locality is an important resource for understanding the lives of some of the first people to inhabit North America. Second, the Kanorado Locality is the only recorded archaeological sites in the region that contains both Clovis-age and Folsom materials in a stratified context. This makes the site important for studying the differences in the lifeways between these two cultural periods. Finally, the sites at Kanorado have yielded paleoenvironmental data that are being used to reconstruct bioclimatic change during the Pleistocene-Holocene transition.

The archaeological deposits at Kanorado are contained within a distinctive buried soil, informally referred to as the Kanorado paleosol (Mandel et al., 2004). This soil represents a period of landscape stability (see Mandel and Bettis, 2001), and

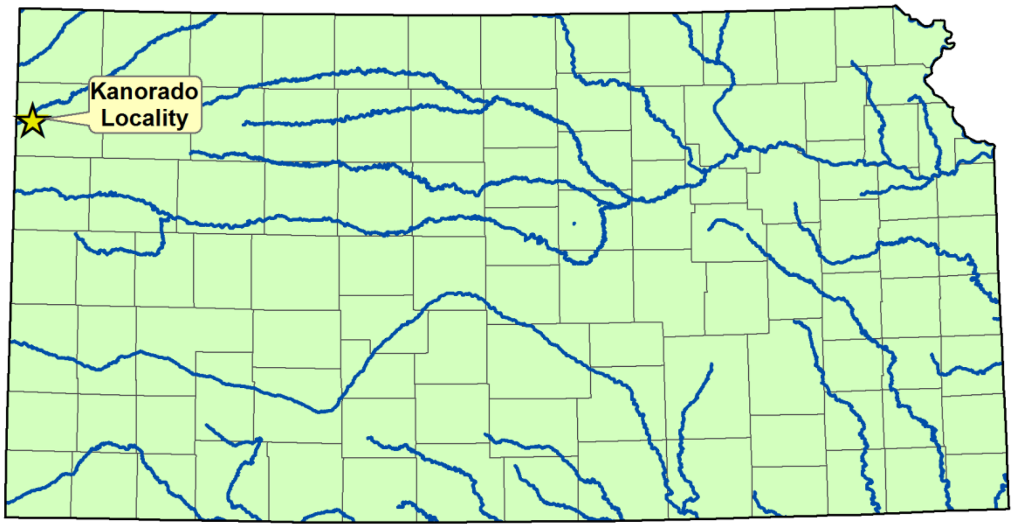

Figure 1. Location of the Kanorado Locality in western Kansas.

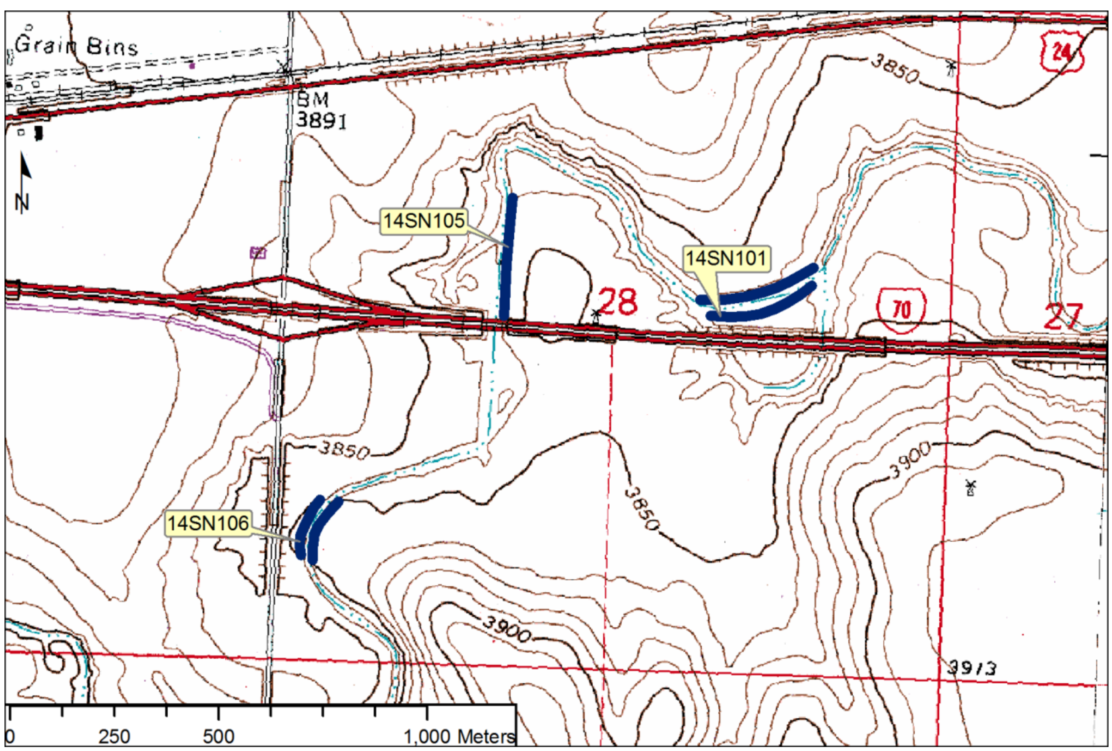

Figure 2. Archaeological site locations at the Kanorado Locality.

it is an important stratigraphic marker for the Pleistocene-Holocene transition in draws on the High Plains of western Kansas (Mandel, 2008a). Archaeologically significant buried soils are often traced by excavating trenches with heavy machinery, a slow and destructive method. The application of geophysical techniques, such as ground penetrating radar (GPR), is advantageous because these techniques are non-destructive and data can be collected rapidly across landscapes.

GPR has proven to be an effective non-destructive method for imaging soil features in a variety of contexts. Just as trenching and coring techniques have their limitations, so too does GPR. Where backhoe trenching may be of limited use in sandy environments, these settings tend to be relatively well suited for GPR. However, in alluvial settings that are rich in electrically conductive clays, GPR is less effective due to signal attenuation. In those settings, other geophysical methods, such as electromagnetic conductivity or electrical resistivity, may be more useful than GPR for non-destructive investigation.

This thesis demonstrates the use of ground penetrating radar (GPR) as a tool for investigation at the Kanorado Locality. Geophysical methods are rarely employed as an investigative technique at Paleoindian sites, such as Kanorado, because the sparse cultural remains are thought to be invisible in such data. This project demonstrates that GPR can be a useful technique for imaging the buried landscape that would have been an active part of the lives of Early Paleoindian people.

Research Objectives

An initial goal of this project was to use GPR as a method to non-destructively map the lateral occurrence of the buried Kanorado paleosol at site 14SN106 at the Kanorado Locality (Figure 3). This site was selected for investigation for two reasons:

1. The Kanorado paleosol is situated about 2 m below the broad T-1 terrace of Middle Beaver Creek. Since the terrace is generally flat and free from obstructions, the GPR survey could be conducted with little interference.
2. Preliminary coring at the site indicated that the Kanorado paleosol was not continuous across the T-1 terrace. Instead, the paleosol was found to pinch out within 50 m of the cutbank. It was thought that the GPR survey would delineate the site boundary at a higher resolution than was already obtained through the coring survey.

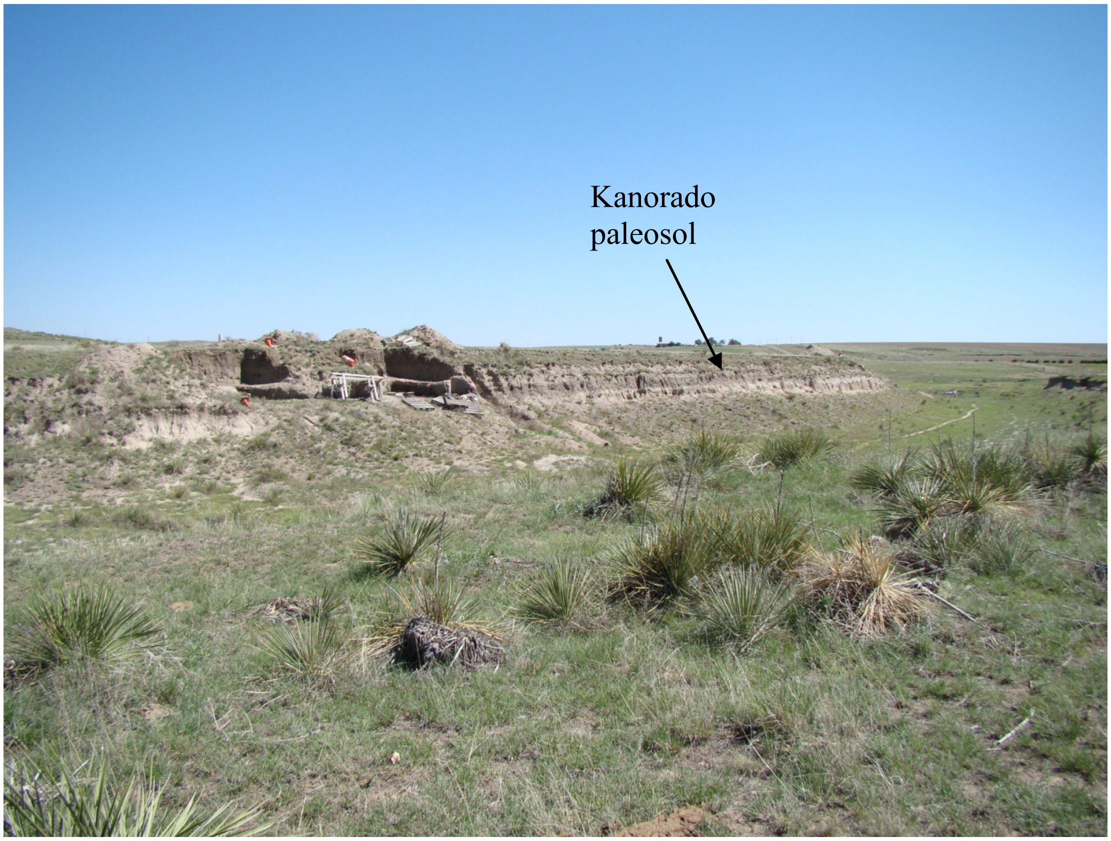

Figure 3. A view of the cutbank and main block excavations at site 14SN106.

Soils represent periods of relative landscape stability; hence the recognition of buried soils can be used to assess the geologic potential for buried cultural deposits (Mandel and Bettis, 2001). The use of GPR to map soil horizons has been demonstrated by the Natural Resources Conservation Service (NRCS) and other researchers in a number of studies (Collins and Doolittle, 1987; Rebertus et al., 1989; Doolittle and Collins, 1995; van Dam and Schlager, 2000; van Dam et al., 2002). The NRCS has produced a generalized map depicting the areas where GPR is more or less suitable for study (Doolittle et al., 2002; Doolittle et al., 2007). The NRCS prediction map relies heavily on the clay content, electrical conductivity, salt content, and mineralogy reported in soil surveys to estimate the amount of GPR signal attenuation that would be likely at a given area. The soils near the Kanorado were depicted as "Moderately Suited" for GPR. This indicated that GPR penetration would likely be over 2 m (Doolittle et al., 2007). The buried archaeological deposits at Kanorado are contained within a paleosol at a depth of about 2 m below the modern T-1 surface. Thus, it was initially concluded that Kanorado may be a good place to demonstrate the technique.

During the initial stages of data collection at Kanorado, it became clear that the sediments were electrically conductive. The high electrical conductivity caused rapid attenuation of the GPR signal and prevented the use of the high-frequency, high-resolution, antennae that would have enabled the clear distinction of soil horizons. After this problem was recognized, the project shifted goals to extract as much information pertaining to the T-1 terrace fill at 14SN106 as possible from the lower frequency, lower resolution antennae. The entire terrace was mapped with a 100 MHz antenna in order to define the extent of a paleoarroyo that is known to contain butchered bison remains that date to the Early Paleoindian occupation of the site (Figure 4).

Figure 4. A view of the excavations within the paleoarroyo at site 14SN106.

In order to aid interpretation of the data, two profiles were described and sampled at 14SN106 and 14SN105. The samples were processed for grain-size, soil moisture content, and electrical conductivity. The results of the laboratory analysis were used as inputs for a finite-difference time-domain (FDTD) model to predict GPR signal response. The FDTD model was then used to help interpret how the GPR signal was influenced by the stratigraphy at the site.

Significance of Research

Blackmar and Hofman (2006) suggested that Paleoindian research in Kansas needs to be oriented towards three specific goals: (1) understanding the origins of the first Kansans, (2) understanding the domestic life and organization of hunter-gatherer groups by exploring large areas around hearths and structures, and (3) understanding the range of technology, land-use patterns, health, and diets of Paleoindian groups. Increased employment of geophysical methods can help with the first two goals. Geophysical methods can be employed to aid in mapping buried late-Pleistocene land surfaces, which may lead to the discovery of archaeological sites. Currently, buried landscapes can be mapped through coring, destructive trenching, or GIS modeling. My study attempted to accomplish this in a rapid, nondestructive manner. Geophysical methods should provide efficient means to identify and target areas surrounding hearths and structures in order to guide efficient excavation strategies. Effectively driving the cost down on expensive excavation has been cited as specific reason for more studies involving geophysical methods (Mandel, 2000; Kvamme, 2003).

The GPR survey at site 14SN106 proved to be particularly useful in identifying the location of a buried paleoarroyo beneath a featureless terrace. Recent excavations within the paleoarroyo revealed bison remains dating to 10,854 ± 40 ^{14}C yr B.P. Although no artifacts have been recovered with the bison remains, the bones show evidence of butchering in the form of cutmarks and selective removal of elements. Paleoindian and Archaic hunters commonly employed natural traps, such as arroyos, to funnel game (Frison, 1976; Frison et al., 1976; Frison and Stanford, 1982; Frison, 1984, 1998; Hofman and Graham, 1998). Although the walls of the paleoarroyo at site 14SN106 were not vertical, they were sufficiently steep to restrain the bison. It has been noted that arroyo traps may have been effective in slowing the animals, thereby allowing hunters to dispatch them (Frison and Stanford, 1982; Hofman and Graham, 1998). The results of this study demonstrate a nondestructive technique for mapping buried arroyo features for the purpose of identifying areas that may represent bison kills.

Thesis Outline

The remainder of this thesis is organized into five chapters. Chapter 2 is an overview of the physical setting of the research area at Kanorado and includes descriptions of the physiography, local climate, soils, and vegetation. Chapter 3 focuses on the historical and archaeological context of the research. Chapter 4 describes the specific methods used in this study, and Chapter 5 presents the results of the GPR surveys, soil analysis, and GPR models at 14SN106 and 14SN105. Finally, Chapter 6 provides a summary of the results, considers the implications of the findings, and offers possible directions for future research.

CHAPTER II

SETTING

Physiography

The Kanorado locality is in the High Plains subprovince of Fenneman's (1931) Great Plains physiographic province that encompasses the majority of western Kansas (Figure 5). This region is dominated by flat uplands with poorly developed surface drainage. Fenneman (1931:5) was particularly struck by the "phenomenal flatness" of the area near the Kansas-Colorado border.

The dominant west to east slope of the High Plains was established during the Tertiary (Merriam, 1963). Throughout the Paleogene the uplift and subsequent erosion of the Rocky Mountains choked the river systems with alluvium. By the end of this period the Rockies as we know them were "buried up to their chins" in their own sediment (McPhee, 1998). During the Miocene Epoch another uplift increased the regional slope, allowing the rivers to once again exhume the Rockies. Much of this sediment was spread east across the High Plains to form the Ogallala Formation (Frye et al., 1956; Gutentag, 1988). The Ogallala Formation consists of heterogeneous clastic deposits, ranging from coarse gravels to clays. In northwestern Kansas, the thickness of the Ogallala ranges from over 100 m to less than 1 m (Frye et al., 1956). Because the Ogallala is a major aquifer, springs are common where it is exposed in the valley walls (Mandel, 2006a). Although many of these springs are dry now due to an artificial lowering of the Ogallala aquifer from agricultural practices, Wedel (1986) noted that springs would have been an important water source in times of drought for prehistoric people.

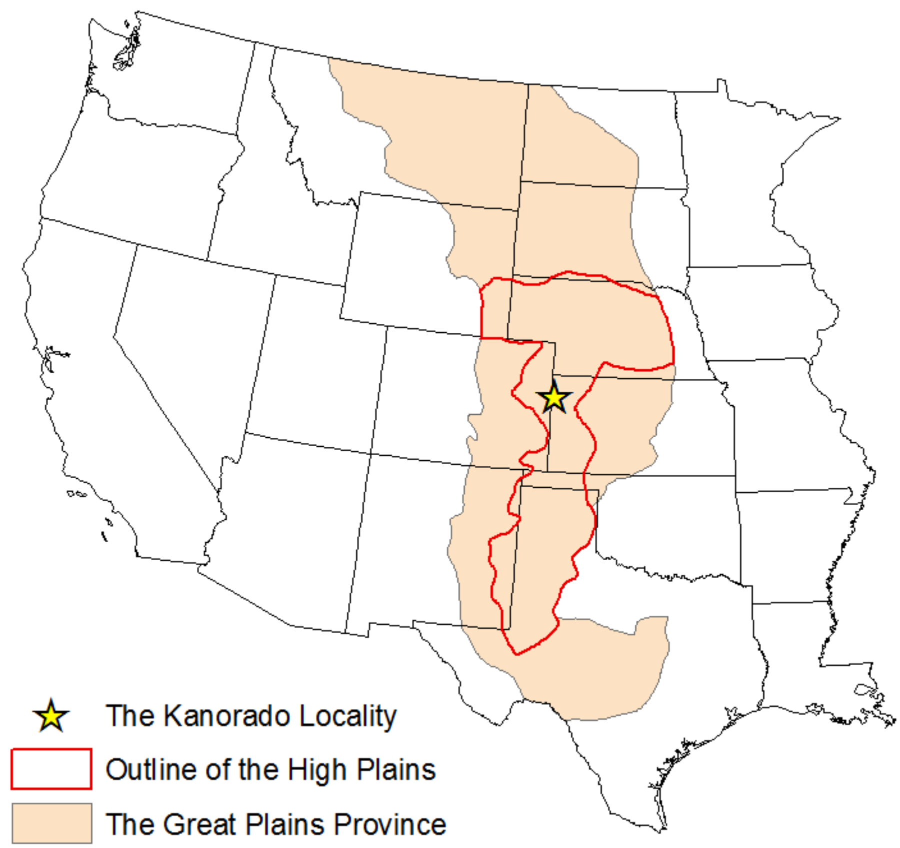

Figure 5. Map of the Western United States showing the extent of the Great Plains physiographic province and the location of the Kanorado Locality (Fenneman, 1931).

There is a 2-3 m-thick mantle of late-Quaternary loess on the uplands at Kanorado and across most of the High Plains (Mandel, 2006a). Shallow, closed depressions, or playas, are formed in the loess. Most of the playas are less than 3 m deep, but some of the larger ones are 15-20 m deep (Mandel et al., 2004). Like springs associated with the Ogallala Formation, playas would have attracted game and people during prehistoric times, including the Paleoindian period (Holliday and Mandel, 2006).

Climate

The modern continental climate of Kanorado is characterized by hot summers and cold winters (Mandel, 2006a). According to the High Plains Regional Climate Center (2009), the hottest month is typically July, with daily maximum average temperatures of 18.6°C (65.4°F). The coldest month is January, where minimum daily temperatures average –9.2°C (15.5°F). The study area falls within the semiarid moisture region defined by (Thornthwaite, 1948). Mean annual precipitation is 48 cm (18.9 in). Most precipitation typically occurs in July, with an average of 7.4 cm (2.9 in), and the driest month is January with an average of 0.9 cm (0.3 in). Prolonged droughts are common in this region and can have a significant effect on the ecosystem (Mandel, 2006a, 2008a).

Soils

The surface soils in the study area consist mainly of the Goshen, Bridgeport, Colby, and Ulysses series (Soil Survey Staff, 2008; [Figure 6]). At 14SN106, the soil on the T-1 terrace is mapped as the Goshen silt loam, which occurs on many alluvial terraces in the area. The Goshen typically has an A-Bt-Bk profile to a depth of 150 cm (see Tables 1 and 2 for soil horizon nomenclature). Compared to the A horizon, the increase in clay content of the Bt horizon is sufficient to qualify it as an argillic horizon. The mineralogy of the Goshen is mixed, and although the soil is typically well drained, the shrink-swell potential is considered moderate. Soils with mixed or montmorillonitic mineralogy and moderate to high shrink-swell potential are problematic for GPR surveys (Doolittle and Collins, 1995).

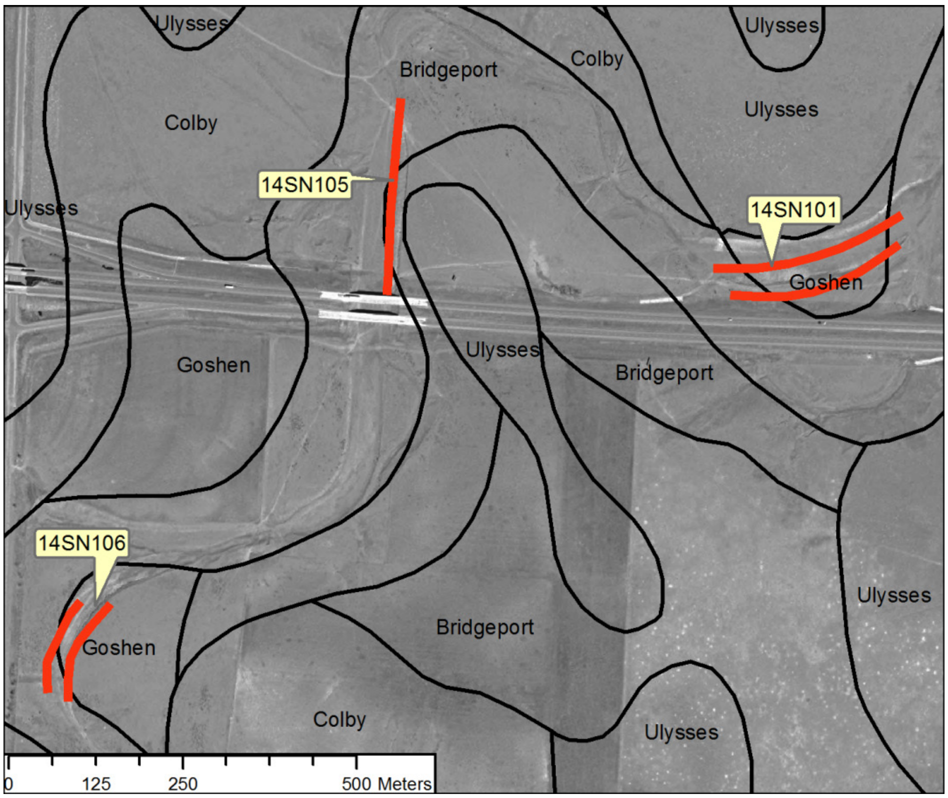

Figure 6. Soil series map at the Kanorado Locality (Soil Survey Staff, 2008).

Table 1. Soil Master Horizon Nomenclature (adapted from Holliday, 2004)

A	Mineral horizon that formed at the surface that exhibits 1) obliteration of all or much of the original rock structure and 2) an accumulation of humified organic matter intimately mixed with the mineral fraction.
B	Horizon that forms below an A horizon and is dominated by obliteration of all or much of the original rock structure and shows one or more of the following: 1) illuvial concentration of silicate clay, iron, aluminum, humus, carbonates gypsum, or silica, alone or in combination; 2) evidence of removal of carbonates; 3) coatings of sesquioxides that make the horizon conspicuously lower in value, higher in chroma, or redder in hue than overlying and underlying horizons without apparent illuviation of iron; 4) alteration that forms silicate clay or liberates oxides or both and that forms granular, blocky, or prismatic structure; or 5) brittleness.
C	Horizon or layer, excluding hard bedrock, that is little affected by pedogenic processes and lacks properties of A, or B horizons. The material of C layers may be either like or unlike that from which the solum formed. The C horizon may have been modified even if there is no evidence of pedogenesis. Included as C layers are sediment, saprolite, unconsolidated bedrock, and other geologic materials that commonly are uncemented.

Table 2. Soil Subhorizon Nomenclature (adapted from Holliday, 2004)

c	Used in mineral soils to indicate identifiable buried horizons with major genetic features that were formed before burial. Genetic horizons may or may not have formed in the overlying material, which may be either like or unlike the assumed parent material of the buried soil.
k	Carbonates: Accumulation of calcium carbonate.
t	Accumulation of illuvial silicate clays in films, threads, or coatings, visible on ped faces and/or pores.
w	Development of Color or Structure: Used with “B” to indicate the development of color or structure or both, with little or no apparent illuvial accumulation of material.

At site 14SN105, the soil on the T-1 terrace is incorrectly mapped as the Bridgeport silt loam, with 2 to 5 percent slopes (Soil Survey Staff, 2008). The Bridgeport series typically occurs on modern floodplains in northwestern Kansas and has a thick, mollic (dark, organic-rich) A horizon above a C horizon. However, the setting at site 14SN105 is a narrow (20–30 m) T-1 terrace that has been mostly removed by mechanized channelization of Middle Beaver Creek, and the surface soil has an A-Bw-Bk profile (Mandel et al., 2004). Because the terrace at site 14SN105 is so narrow, the NRCS combined it with the floodplain and extended the Bridgeport across the T-1 surface.

The upland soils in the immediate area of the Kanorado Locality are the Ulysses and Colby series (Soil Survey Staff, 2008). The Colby silt loam occurs on the upland immediately east of the T-1 terrace at site 14SN106. The Colby soil typically consists of a thin, (~10 cm) A horizon over a thick, calcareous C horizon. The hill slope at site 14SN105 is mapped as the Ulysses silt loam. The Ulysses soil is relatively shallow, and has an A-Bw profile to a depth of 50 cm. The GPR survey at each site included a portion of the upland soils, though their occurrence, in place of the Goshen soil, does not appear to have significantly affected the data.

Vegetation

The study area is in the short-grass prairie and is dominated by two species of grass: blue grama (*Bouteloua gracilis*) and buffalograss (*Buchloë dactyloides*) (Küchler, 1974). Soapweed Yuccas (*Yucca glauca*) and plains prickly pears (*Opuntia polycantha*) are also common at the Kanorado locality. The immediate area of the Kanorado locality is currently used for grazing cattle. Prairie dogs (*Cynomys sp.*) are active in the immediate area, and their burrowing activity has affected vegetative cover.

CHAPTER III

ARCHAEOLOGICAL CONTEXT

History of Investigations at the Kanorado Locality

The Kanorado locality consists of three sites: 14SN101, 14SN105, and 14SN106. These sites are significant for a number of reasons. First, all three sites contain stratified Clovis-age and Folsom cultural deposits. Hence, they are among the few recorded sites in Kansas with stratified Early Paleoindian cultural deposits, and they are likely to shed new light on the peopling of the Central Plains. Second, the remains of camel and mammoth at site 14SN105 that date to 12,200-12,350 ^{14}C yr B.P. may represent pre-Clovis cultural deposits. Also, sites 14SN101 and 14SN105 are important because camel remains were found in the same stratigraphic position as lithic artifacts; hence the sites may represent evidence of camel procurement by Clovis people. In addition, most of the lithic materials recovered at the three sites came from distant sources (e.g., Alibates from the Texas Panhandle, Edwards chert from central Texas, Hartville chert from eastern Wyoming, Smoky Hill jasper from northwest Kansas and/or northeastern Colorado, and White River Group silicates from western Nebraska). Consequently, the sites are important for understanding lithic procurement and mobility strategies of Early Paleoindians. Finally, the sites at Kanorado have yielded paleoenvironmental data that are being used to reconstruct bioclimatic change during the Pleistocene-Holocene transition.

In the sections that follow the history of investigations at the Kanorado locality are discussed. The information was synthesized from short published papers (Mandel et al., 2005; Warren and Holen, 2007) and unpublished reports on file at the Kansas Geological Survey (Mandel, 2003; Mandel, 2004, 2005, 2006b, 2007, 2008b). Only sites 14SN105 and 14SN106 were surveyed as part of my thesis, so emphasis is placed on discoveries at those locations.

Early Investigations and Archaeological Discovery

The Kanorado locality was initially studied by paleontologist K. Don Lindsey of the Denver Museum of Natural History (now the Denver Museum of Nature and Science). The landowner's son reported large bones eroding out of a channelized bank of Middle Beaver Creek. Lindsey visited the site in 1976 and 1981 and conducted salvage excavations of deeply buried mammoth bones. The 1976 excavation recovered mammoth remains from sandy deposits near the base of the cutbank. In addition, Lindsey found one large cobble that he thought appeared out of place with the fine-grained alluvium. Also, a mammoth tooth was found higher in the profile, indicating that there were at least two mammoths. In 1981, Lindsey brought Robin Boast, an archaeology graduate student and employee of the Denver Museum to the site to perform additional salvage excavations. Cultural materials were not recovered during the 1981 salvage excavations, though spiral fractured limb bone fragments were recovered from the upper mammoth level. Lindsey noted that the wear patterns on some of the bones did not appear to be caused by natural processes. He also reported the discovery of camel vertebrae during the 1981 excavation.

In 2001, Steve Holen, Curator of Archaeology at the Denver Museum of Nature and Science, examined the collection of bones from the Kanorado locality and noticed unnatural fractures on some of the specimens. He suspected that the spiral fractures and wear patterns were caused by human modification. Holen, Jack Hofman of the University of Kansas, and two avocational archaeologists visited the area in February 2002. They discovered mammoth bones and burned bone fragments on a talus slope in the location where Lindsey excavated. An *in situ* unidentifiable bone fragment was found in light tan silt about 40 cm below the top of the A horizon of a buried soil. Also, camel remains were found at the base of the same buried A horizon about 30 m north of Lindsey's original mammoth locality. Throughout the Kanorado locality, the A horizon of the buried soil is a prominent stratigraphic marker and is ~0.7-2.0 m below the T-1 surface. Although no cultural materials were found with the camel remains, the camel bones were estimated to be Clovis age (11,000-11,500 ^{14}C yr B.P.).

Later in 2002, Holen and a museum volunteer conducted a surface survey at the Kanorado locality. One thin Alibates endscraper was discovered on a talus slope below the same buried soil that contained the camel remains. The endscraper was discovered ~400 m east of the original mammoth locality. Holen excavated a test unit in the buried A horizon at the site where the endscraper was found and discovered *in situ* lithic flakes. This site was designated the number 14SN101.

In the spring of 2003, Holen discovered the first direct evidence of human occupation at the locality where Lindsey conducted his excavations. Three lithic flakes were found eroding from the base of the buried A horizon in an area located ~50 m south of the original mammoth locality. This area was designated as site 14SN105 (Figure 7). During the test excavations in June of 2003, Holen and Rolfe Mandel (University of Kansas) were walking along a nearby, channelized portion of Middle Beaver Creek south of Interstate 70 when Mandel noticed a diagnostic Folsom endscraper made of Hartville chert. After additional flakes were discovered in the area surrounding the Hartville endscraper discovery, the site was designated as 14SN106.

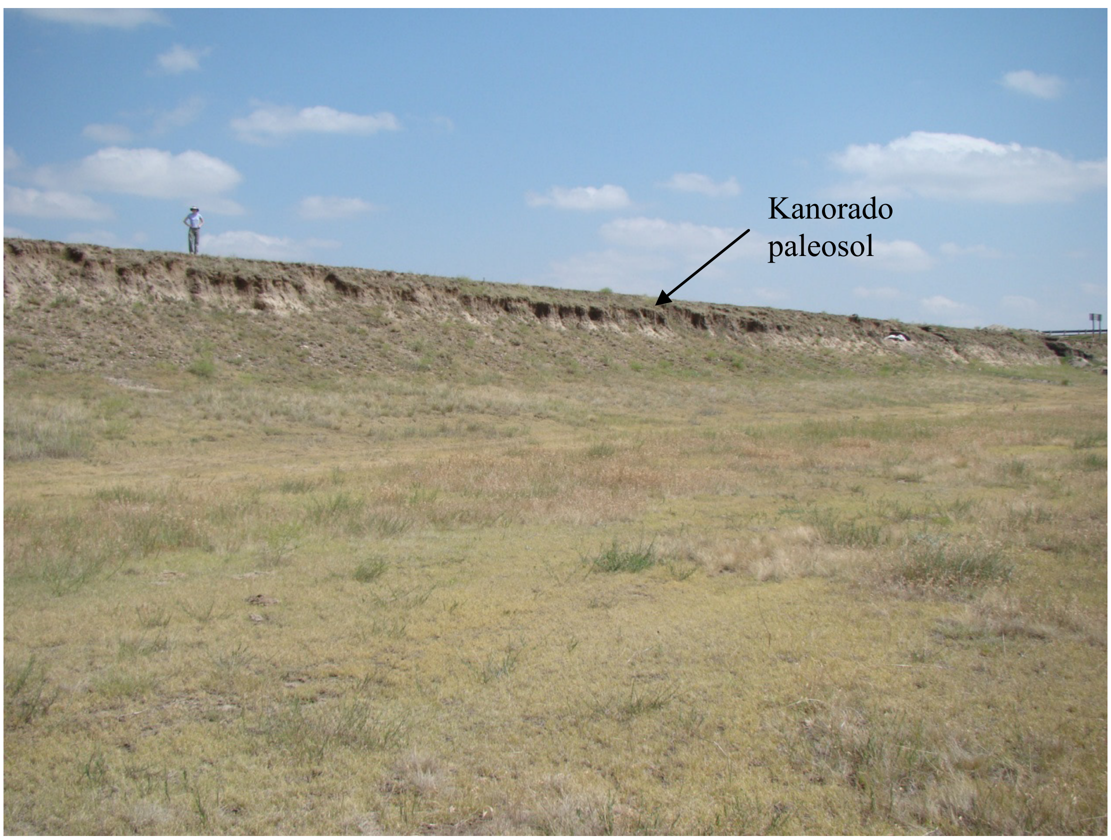

Figure 7. Facing southwest toward the cutbank at site 14SN105.

The archaeological materials recovered at the Kanorado locality are contained within a prominent buried soil informally referred to as the Kanorado paleosol. The Kanorado paleosol is found in draws throughout the High Plains of western Kansas and serves as a prominent stratigraphic marker for the Pleistocene-Holocene transition (Mandel, 2008a). The buried soil usually consists of a thick, cumulic Ak horizon formed in silty alluvium, but it also occurs as part of a pedocomplex of multiple, closely stacked buried A horizons. In some locations, such as site 14SN106, a weakly developed soil that is informally referred to as the Beaver Creek paleosol occurs in silty alluvium above the Kanorado paleosol (Figure 8).

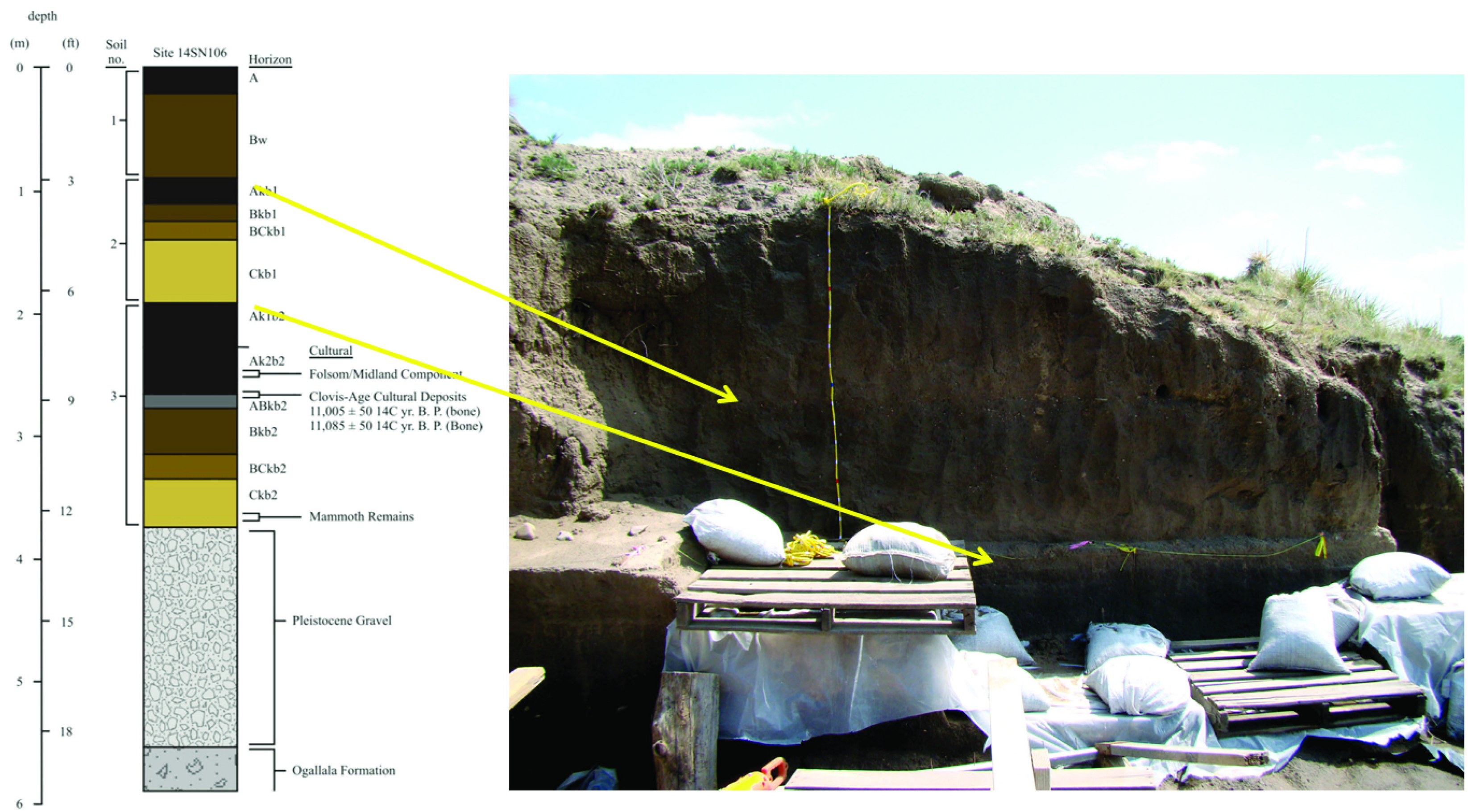

Figure 8. A view of the east wall of the main block excavations and graphical depiction of the soils at site 14SN106.

Site 14SN105

Archaeological excavations have occurred at site 14SN105 each summer from 2003 to 2008. In 2003, four locations were defined at the site (Figure 9). The area where Lindsey initially excavated the mammoth remains is designated Area A. The location where the three lithic flakes were found is called Area B. Area C is located north of Area A and includes the location where the camel bone was recovered. A final area, Area D, was defined in 2006 and is located immediately north of Area A. Each area has been excavated with multiple $1m^2$ units. The results of the excavations at each of these blocks are summarized below.

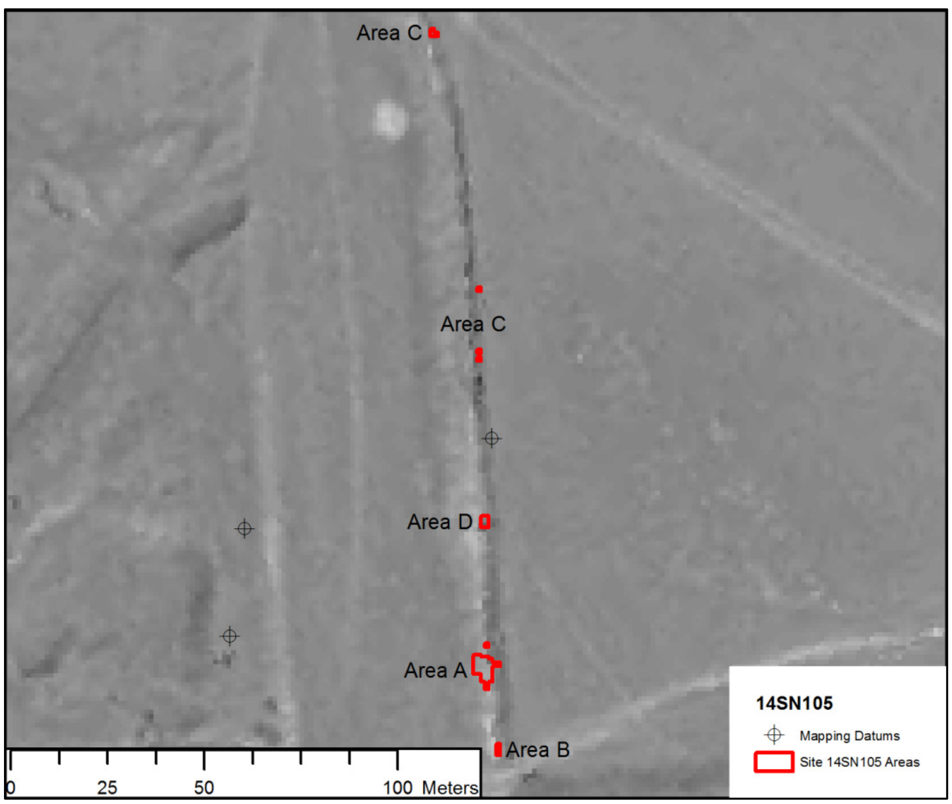

Figure 9. Map of the designated areas at site 14SN105.

The main bulk of excavation has focused on the location where Lindsey excavated the mammoth remains in 1976 and 1981 (Area A). The excavations uncovered mammoth and camel remains dating to ca. 12,200-12,350 ^{14}C yr B.P. The fracture patterns from both the upper and lower mammoth and camel horizons may be products of human activity, but no conclusive evidence in the form of stone tools or cutmarks on bone has been found. The lower mammoth/camel component is positioned at the contact between silty alluvium that contains the Kanorado paleosol and the underlying sandy alluvium. The spatial pattern of the bones and the eastward dip of the sandy deposit suggest that the bone fragments were resting on the surface of a point bar.

Area B is ~50 m south of Area A and is the location where lithic flakes were found eroding out of the base of the A horizon of the Kanorado paleosol. Three 1 m^2 units were excavated in this area in 2003. The excavations yielded only three additional chipped-stone flakes within the Kanorado paleosol, and the area has not been investigated further.

The north end of site 14SN105, beginning about 100 m north of Area A, is designated as Area C. In this area, the Kanorado paleosol and underlying sandy deposits are closer to the surface than at the southern end of the site. Three test units were excavated at the extreme northern end of the site near a two-track trail. The excavations in Area C yielded two chipped stone flakes and ungulate limb bone elements at the base of the Kanorado paleosol. Overall, the excavations in Area C have yielded a low density of artifacts. However, numerous spirally fractured bone fragments, likely camel or bison, and lithic flakes have been recovered from lower part of the buried A horizon of the Kanorado paleosol in this area.

In contrast to Area A, numerous chipped stone flakes have been found in excavations in Area D, only ~50 m north of Area A. Along with the chipped stone flakes, one Hartville chert endscraper, the base of a second endscraper, and one Flattop chalcedony endscraper resharpening flake were found within the middle of the A horizon of the Kanorado paleosol. A bison limb bone from the cultural component at Area D yielded a date of 10,395 ± 45 ^{14}C yr B.P. (NZA-27864). A bison metacarpal from the A horizon of the Kanorado paleosol found at Area A was dated to 10,350 ± 20 ^{14}C yr B.P. (CURL-9002). The artifact assemblage and associated radiocarbon dates suggest that the cultural component within the Kanorado paleosol at site 14SN105 likely represents a Folsom-age campsite.

Site 14SN106

Excavations have occurred at site 14SN106 each summer from 2004 to 2008. Four locations have been identified at the site: Main Block, Mammoth Area, Area C, and Area D (Figure 10). Each area has been excavated with multiple 1 m^2 units. The results of the excavations at each of these blocks are summarized below.

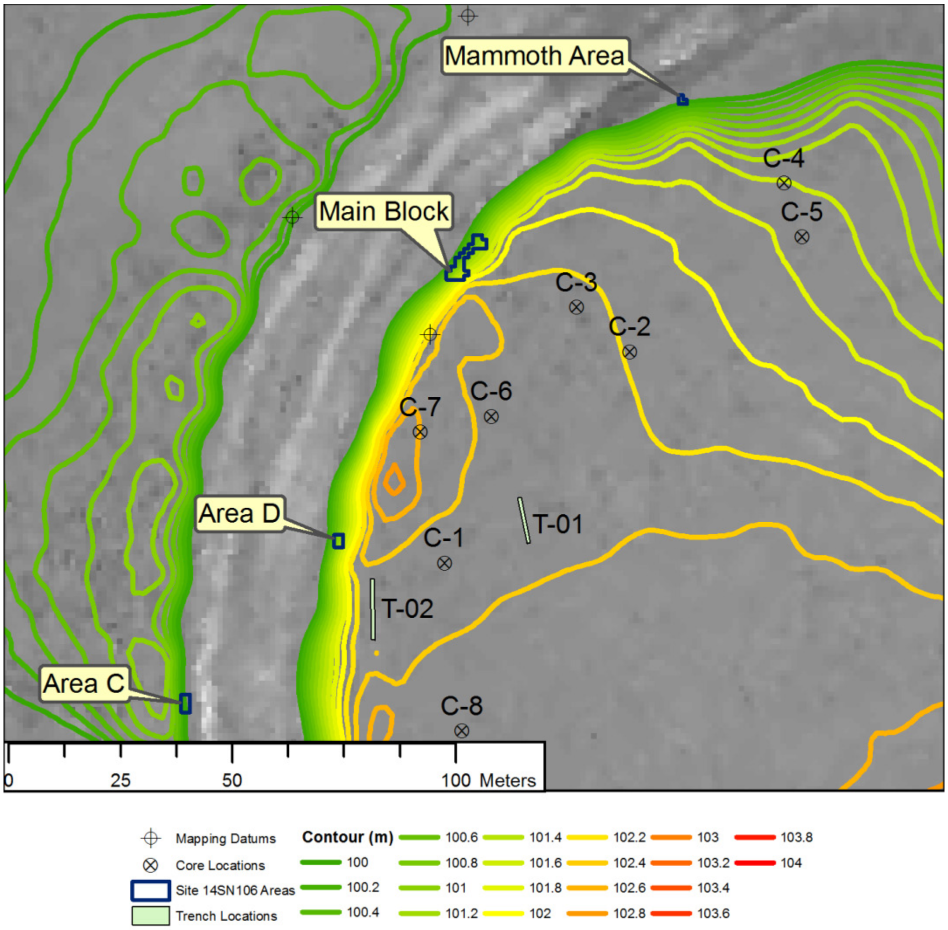

Figure 10. Map of the designated areas of site 14SN106.

The Main Block area has been extensively tested and is the location where the Hartville chert endscraper was first discovered on a talus slope at the site. A total of 25 m^2 have been excavated from the Main Block. The excavations have revealed numerous diagnostic Folsom endscrapers located 10-15 cm above the bottom of the buried A horizon of the Kanorado Paleosol. Based on the presence of numerous endscrapers and resharpening flakes, the Folsom component at the Main Block has been interpreted as a specialized hide processing area where endscrapers were used and resharpened. A lower component at the base of the Kanorado paleosol also has been identified and consists primarily of quartzite flakes. Two dates have been obtained from this component. A metapodial from an elk or camel, found below the Folsom component, was AMS dated to 11,005 ± 50 ^{14}C yr B.P. (CAMS-112742), and an AMS age of 11,085 ± 20 ^{14}C yr B.P (CURL-9009) was determined on bison bone associated with the lower lithic component. Based on these two dates, the lower component probably represents a Clovis-age occupation.

The Mammoth Area is located ~50 m north of the Main Block at site 14SN106. Poorly preserved mammoth bone fragments were found nearly 4 m below the T-1 terrace. The fragments were at the top of the Pleistocene gravel that underlies the fine-grained alluvium in which the Kanorado paleosol formed. No cultural materials were discovered accompanying the bones in this area.

A paleoarroyo filled with mostly sandy and gravelly alluvium is located at the southern end of the site, ~100 m south of the Main Block excavations. The paleoarroyo fill has yielded the remains of at least four bison. On the western bank of the channelized stream (Area C), the remains of one partially articulated bison have been recovered and AMS dated to 10,854 ± 40 ^{14}C yr B.P. (NZA-27348). This bison had distinct butcher marks and may represent part of a kill site. Area D is located just north of the paleoarroyo on the east bank where flakes were found eroding from the Kanorado paleosol. Two bison skulls were recovered from this area and collagen from one of the skulls yielded an AMS age of 8,137 ± 35 ^{14}C yr B.P. (NZA-28180). In 2006, two backhoe trenches were excavated into the T-1 terrace east of the paleoarroyo to assess the stratigraphy and search for additional bison remains. Although the trenches yielded important stratigraphic information, additional bison remains and cultural materials were not recovered. It is likely that the channelization of Middle Beaver Creek has removed the majority of the paleoarroyo fill that may have contained a Folsom bison kill.

History of Archaeogeophysical Prospection

Geophysical methods have been employed for archaeological site surveying since the middle 1940's (Clark, 1990). The first widely cited geophysical investigation at an archaeological site was an electrical resistivity survey at Dorchester-on-Thames in 1946 (Atkinson, 1953). Since its initial use, the electrical resistivity method has proven to be a reliable archaeological prospection technique. The most commonly applied geophysical methods for archaeology are electrical resistivity, electromagnetic induction, magnetometry, and ground penetrating radar. Since my study employed only GPR as a prospection technique, special attention will be given to outlining the history of this method as a geoarchaeological tool.

Ground Penetrating Radar and Archaeology

The potential for ground penetrating radar to aid archaeological prospection was recognized relatively early after its invention. The first widely cited application of GPR was conducted at Chaco Canyon, New Mexico (Vickers et al., 1976). A number of experimental traverses were collected at four different Pueblo sites at

Chaco Canyon. The results of the survey indicated that some of the anomalous radar reflections, referred to as "echoes," revealed the location of buried walls.

Following the Chaco Canyon study, GPR was used to locate historic archaeological features such as stone walls and underground storage cellars at different areas in the eastern United States (Bevan and Kenyon, 1975; Kenyon, 1977) and Cyprus (Fischer et al., 1980; Conyers and Goodman, 1997). These early studies were ideal settings because that the soils were extremely dry, thus buried archaeological reflections were easily interpreted (Conyers and Goodman, 1997).

One of the more significant early studies was conducted by C. J. Vaughan (1986) at the Red Bay archaeological site in Labrador, Canada in 1982 and 1983. That study attempted to locate 16th Century Basque graves at a whaling station on the Labrador coast. Archaeological features were buried by up to 2 m of beach deposits and peat. The interpretation of cultural features in such a setting was challenging because large gravels and other natural features obscured cultural reflections. Vaughan concluded that grave contents, such as bone and metal artifacts, did not contrast enough with the beach deposits to cause reflections. However, the study was successful in detecting buried house walls and the disturbed fill of some graves. This study is also notable because, for the first time, velocity tests were performed on site, which enabled radar travel times to be converted to accurate depths. The earlier studies estimated velocities from local soil characteristics, rather than actually performing velocity tests on site.

During the mid-1980's, a number of 120 MHz GPR surveys were conducted in Japan in order to locate 6th Century pit houses buried in pumice, burial mounds and associated ditches, and "cultural layers" (Imai et al., 1987). This study remains significant because it identified numerous cultural features that have potential for imaging with GPR. What the authors termed "cultural layers" were actually buried stratigraphic units that contained abundant stone artifacts associated with multiple periods of occupation during the Japanese Stone Age. The authors noted that although the stone artifacts could not be recognized individually, GPR could be used to map the strata that contained the archaeological deposits. The lowest cultural layer, approximately 4 m below the surface, was bracketed below a dipping pumice layer that yielded a strong reflection. The upper cultural deposit was contained within a "black soil" at a depth of approximately 2 m. A weaker GPR reflection at the top of the buried soil was used to delineate the potential extent of the archaeological deposit.

During the 1990's, GPR began to be more widely used in archaeology for several important reasons. During this decade, computer processing speeds were greatly increased and software programs were developed specifically for archaeological application (Conyers and Goodman, 1997; Conyers, 2004). Since GPR data began to be collected digitally, this also had the effect of eventually driving down the cost of GPR equipment and survey time (Gaffney and Gater, 2003). Many of the studies during this time were still conducted by a relatively small number of archaeological geophysicists and most initial studies were conducted in Japan (eg. Goodman and Nishimura, 1993; Goodman, 1994; Goodman et al., 1997). This lead to a standardization of processing and visualization techniques, including amplitude slice maps, computer-simulated two-dimensional models, and three-dimensional reconstructions of buried features (Goodman, 1994; Conyers and Goodman, 1997; Conyers and Cameron, 1998).

Over the past 10 years there has been a push for archaeologists to consider geophysical methods, including GPR, as a primary data source for archaeological inquiry (Kvamme, 2003; Aspinall et al., 2008). Traditionally, geophysical methods have been employed only as a prospection technique, and many considered "real archaeology" as an investigative science that begins with a shovel and trowel. Kvamme (2003) and Conyers (2004) have hinted that this view essentially is counterproductive to the archaeological ethical imperative for preservation. Since a greater number of archaeologists are now trained with at least a basic understanding of geophysical methods and properties, such methods should be considered as a basis for hypothesis testing. Geophysical methods are particularly useful for testing hypotheses concerning differences in settlement patterns and identifying behavioral or activity zones since such methods are entirely non-destructive (eg. Bales and Kvamme, 2005; Kvamme and Ahler, 2007).

One recent GPR project was focused on the Sny Magill mound group in northeast Iowa (Whittaker and Storey, 2008). Sny Magill is one of the largest Woodland mound groups in North America and is managed by the National Park Service. Whittaker and Storey (2008) demonstrated that GPR can be a particularly useful and completely non-destructive technique to answer questions about mound construction techniques, mound integrity, and to highlight possible preservation issues. Although it is unlikely that geophysical methods will ever completely replace traditional archaeological investigation, it is important to note that this may be the desired direction that many archaeo-geophysisicts identify as a goal for the coming years.

Paleoindian Geophysical Studies

The application of geophysical surveys at Paleoindian sites is remarkably sparse. To date there is not a single published paper documenting the successful use of GPR at a Paleoindian site. There are two reasons for the lack of published literature on Paleoindian geophysical studies. First, Paleoindian sites tend to have a low density of cultural deposits compared to later Native American village and historic sites. Thus, there is much less potential for GPR to directly image cultural features (Bales and Kvamme, 2005). Second, there is an admitted bias in the archaeogeophysical literature to publish the "successes" of the method rather than equally highlighting the limitations (Conyers and Goodman, 1997; Conyers, 2004).

My study is not the first attempt at applying GPR to Paleoindian studies. For example, a near-surface geophysical survey was conducted at the Gault Paleoindian site in central Texas (Hildebrand et al., 2007). Clovis materials at Gault are contained in clay-rich deposits. A GPR survey was attempted, but high attenuation prevented a meaningful signal and the null results were not published as a part of the report. However, a high-frequency seismic survey was successful in delineating the depth to bedrock at approximately 5 m below the surface. This survey also detected a paleochannel cut into bedrock. A core placed over the channel suggested that the paleochannel fill contained possible pre-Clovis sediment. An electrical conductivity survey was used to map out the horizontal variations in soil water content surrounding the seismic survey lines.

Geophysical methods were also used at the Lime Creek site in southwestern Nebraska (Conyers, 2000). The Lime Creek site is one of several important Paleoindian sites located on a small tributary to Medicine Creek. The sites are located beneath 7-15 m of alluvium and are often covered by water from Harry Strunk Lake. In 1947 and 1948, the extraordinary amount of overburden was removed before excavation by dynamite and bulldozer (Frankforter, 2002). In 1993, a 'slightly' less destructive method was employed that utilized wire-line geophysical tools extended down recently excavated bore holes (Conyers, 2000). Three geophysical surveys were run in each bore hole: natural gamma ray, electromagnetic, conductivity, and single point resistance. The bore hole survey was successful in delineating the vertical and horizontal boundaries of a buried paleochannel that was likely active during Paleoindian occupation of the site. The geophysical logs were useful in correlating the stratigraphy and occurrence of buried soils between bore holes.

CHAPTER IV

METHODS

Ground Penetrating Radar

GPR instruments provide reflective cross sections of the subsurface, and it is important to understand subsurface properties that affect the resulting GPR images. GPR instruments operate by sending an electromagnetic wave through the subsurface from a transmitting antenna. A receiving antenna records the amplitude of the reflected wave and its travel time in nanoseconds (ns). The fundamental physical property that determines wave behavior is known as the permittivity (ε). The velocity (v) that a wave will travel through a medium is a function of the relative permittivity (ε_r) and can be approximated by:

$$v = \frac{c}{\sqrt{\varepsilon_r}}, \text{ (Davis and Annan, 1989)}$$

where *c* is the speed of light in a vacuum (~0.3 m/ns). The relative permittivity is expressed by the ratio of the permittivity of the medium to the permittivity of free space ($\varepsilon_r=\varepsilon/\varepsilon_0$, with $\varepsilon_0=8.85\text{x}10^{-12}$ Farads/meter). When a radar wave encounters a change in the permittivity between two different mediums a portion of the wave is reflected off the interface. When the interface is located directly below the antennas (i.e., normal incidence), the proportion of energy reflected back toward the receiver can be estimated by the reflection coefficient (*RC*):

$$RC = \frac{\sqrt{\varepsilon_1}-\sqrt{\varepsilon_2}}{\sqrt{\varepsilon_1}+\sqrt{\varepsilon_2}}, \text{ (Davis and Annan, 1989)}$$

where ε_1 and ε_2 are the relative permittivities of the first and second mediums respectively. Cases where the relative permittivity of the second medium is greater than the first cause the reflected wave to change its polarity. A change in reflection magnitude and polarity can be useful in identifying marker beds, such as soil horizons, in GPR data.

There are many methods for estimating the relative permittivities of different materials (eg., Topp et al., 1980; Greaves et al., 1996; Martinez and Byrnes, 2001). At frequencies used in this study, the relative permittivity of a given material is a function of its total water saturation (S_w). This is, in turn, related to the grain size and porosity (ϕ) of the sediment (Davis and Annan, 1989). The Complex Refracted Index Method (CRIM) is one method that can be used to approximate permittivity values (Annan, 2005). This method assumes that a sediment sample consists of only mineral grains, water, and air and does not take into account other properties such as mineral composition or soil structure. The sum of the refracted indices of each of the parts describes the relative permittivity of the sample:

$$\sqrt{\varepsilon_s} = \phi S_w \sqrt{\varepsilon_w} + (1 - \phi)\sqrt{\varepsilon_g} + \phi(1 - S_w)\sqrt{\varepsilon_a}, \text{ (Annan, 2005)}$$

where ε_s, ε_w, ε_g, and ε_a are the relative permittivities of the soil sample, pore water, sample grains, and air, respectively.

Determination of relative permittivity values can also be obtained from a regression from starting volumetric water content (Topp et al., 1980). Because the dielectric properties of water are so great relative to solid particles, the relative permittivity can be usefully expressed as a function of volumetric water content (θ_v) alone.

$$\varepsilon_s = 3.03 + 9.3\theta_v + 146.0\theta_v^2 - 76.7\theta_v^3, \text{ (Topp et al., 1980)}$$

As radar energy propagates through the subsurface, the depth of penetration is negatively affected by dispersion and attenuation. Signal dispersion is a resulting loss of amplitude and high frequencies due to energy reflecting obliquely off subsurface interfaces (Conyers and Goodman, 1997). The most limiting property that affects the depth of penetration of radar energy is attenuation. As radar energy propagates through the ground, energy will be lost through attenuation that is largely controlled by the electrical conductivity (σ) of a substance. Most soils and sediments are only very weakly electrically conductive. Clays and fine silts have a tendency to be more electrically conductive than coarse sands. Attenuation (α) can be approximated by:

$$\alpha = \frac{1.69 \text{ x } 10^3 \sigma}{\sqrt{\varepsilon}}, \text{ (Davis and Annan, 1989)}$$

The resulting attenuation value is a loss of signal given in decibels per meter (dB/m). The common values of permittivity, conductivity, velocity, and attenuation have been widely studied and published (Table 3).

Table 3. Electromagnetic Properties of Common Geologic Materials (Davis and Annan, 1989).

Material	ε	σ (mS/m)	*v* (m/ns)	α (dB/m)
Air	1	0	0.30	0
Distilled water	80	0.01	0.033	2×10^{-3}
Fresh water	80	0.5	0.033	0.1
Sea water	80	3×10^{4}	0.01	10^{3}
Dry sand	3-5	0.01	0.15	0.01
Saturated sand	20-30	0.1-1.0	0.06	0.03-0.3
Limestone	4-8	0.5-2	0.12	0.4-1
Shales	5-15	1-100	0.09	1-100
Silts	5-30	1-100	0.07	1-100
Clays	5-40	2-1000	0.06	1-300
Granite	4-6	0.01-1	0.13	0.01-1
Dry salt	5-6	0.01-1	0.13	0.01-1
Ice	3-4	0.01	0.16	0.01

Field Methods

GPR Methods

A GPR reflection survey was conducted over the T-1 terrace at 14SN106 to produce a three-dimensional image of the subsurface. A Sensors & Software PulseEKKO Pro ground penetrating radar system was employed. This system is designed to allow the operator to choose from a number of different antenna frequencies as needed for the research location. Four frequencies of antennas (500, 250, 200, and 100 MHz) were used to determine which, if any, could image to a depth of at least 3 m, thereby penetrating the archaeological deposits at the site. A test line spanning the entire length of the terrace was surveyed in discrete intervals with each of the antennas (Figure 11). The lower frequency antennas are capable of imaging to greater depths at the expense of both vertical and horizontal resolution. The goal was to identify and select the frequency that achieves the desired depth with the maximum possible resolution. Unfortunately, only the 100 MHz antenna was able to image near the desired depth requirement for this survey.

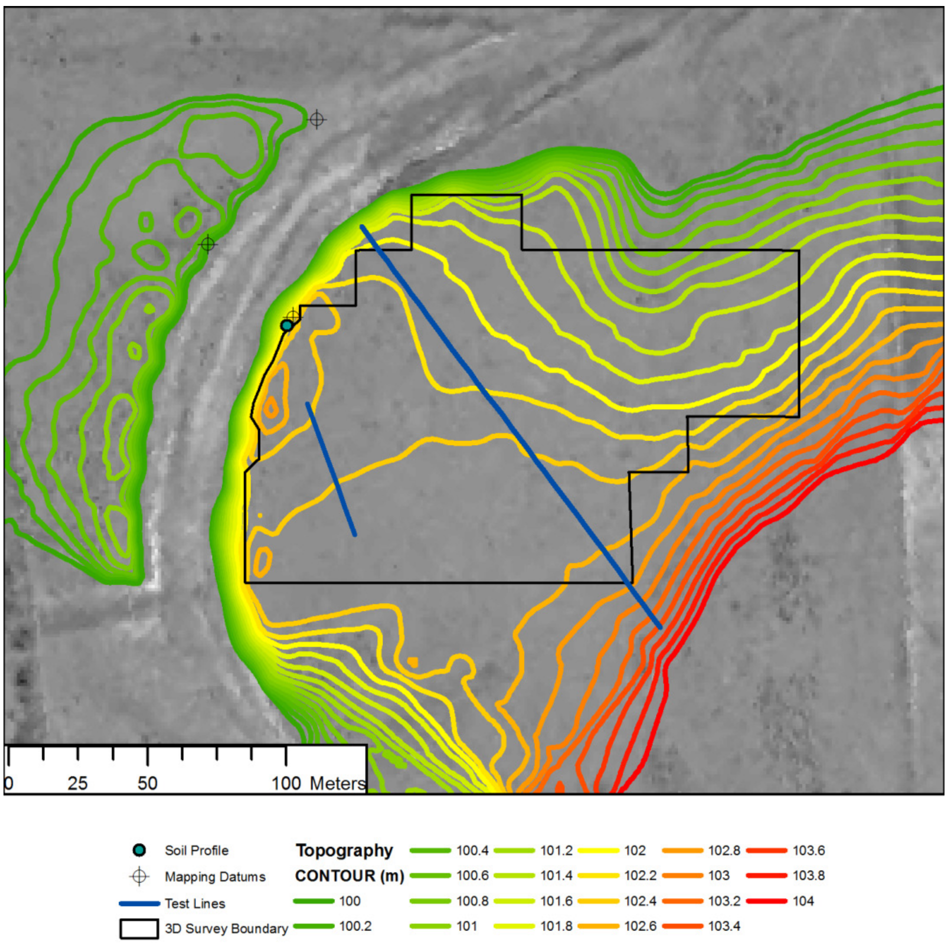

Figure 11. Location of the GPR test lines, the 3D survey boundary, and the soil profile at site 14SN106.

The test line was also used to perform a common midpoint (CMP) survey with the multiple antennas. The CMP survey allows for a determination of the average velocity as radar energy propagates through the ground. The velocity is necessary in data interpretation for converting measurements recorded in two-way travel time to corresponding depths below surface.

The 3D survey at site 14SN106 was conducted by placing wooden grid stakes in 20 m intervals across the terrace. The grid was positioned using a total station and was oriented identical to the excavation grid for future reference. The data were collected using marked survey ropes as guides for each 20 m-long transect. The PulseEKKO Pro antennas radiate the GPR signal in an oblong cone, so the antennas were constantly oriented horizontal to each transect and each other. This was done to minimize any geometric irregularities created by the antennas between transects. Data was recorded in continuous sampling mode along each transect and the antennas were moved at a constant speed to achieve a 25 cm sample spacing.

At the end of each transect the guide ropes and instruments were moved to the beginning point of the next transect. The five m spacing between transects was determined based on the field time available. Transects oriented perpendicular to the original transect lines were collected in an attempt to maximize the possibility of delineating linear features that may not be detected due to their orientation relative to the grid.

At site 14SN105, a test line was also established parallel to the stream bank (Figure 12). Less sediment overlies the Kanorado paleosol in the northern portion of the site than in the southern portion. The test line was collected in an attempt to indicate maximum depth at which the soil is visible.

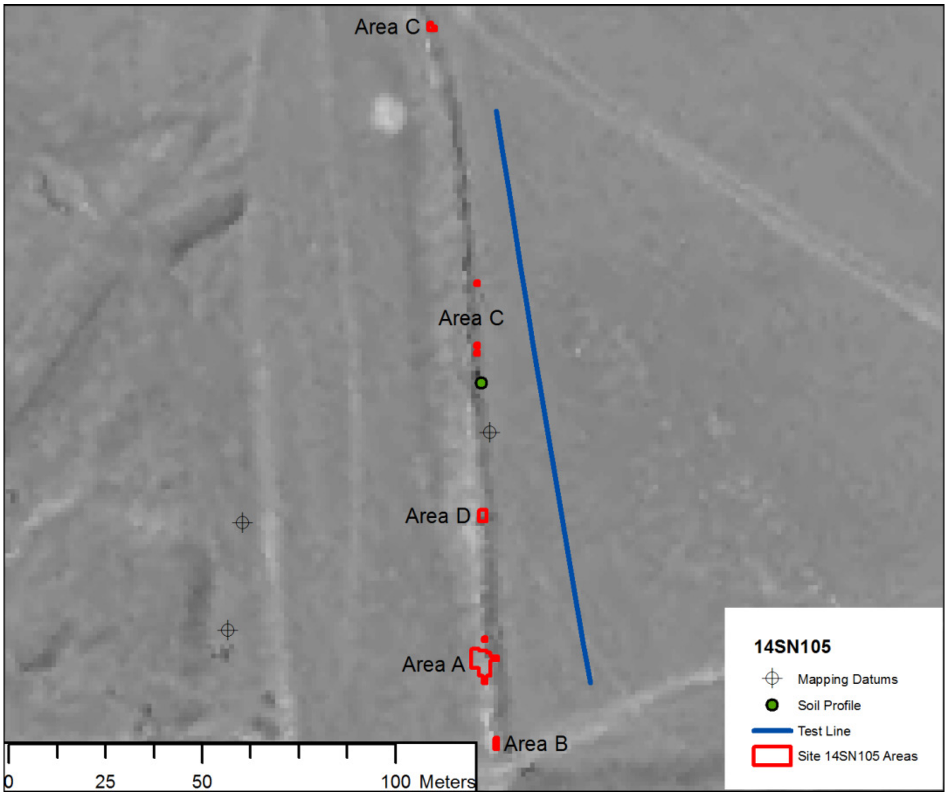

Figure 12. Location of the GPR test line and soil profile at site 14SN105.

Sample Collection Methods

Soil samples were collected for grain-size and electrical conductivity analysis from two profiles, one at site 14SN105 and the other at 14SN106 (Figures 11 and 12). The samples were collected at 5 cm intervals down each profile. Maximum sampling depths reflected the estimated depths of penetration of the GPR signal. At site 14SN105, the profile was located at the northern end of the site in order to accurately characterize the boundary between the Pleistocene gravel and the overlying fine-grained alluvium. At site 14SN106, the profile was collected along an exposure located south of the main excavation block. Samples were collected through the A horizon of the Kanorado paleosol in order to accurately characterize the differences in physical properties between the paleosol and the overlying sediments. In order to collect samples from a clean face, the outcrop was cut back at least 50 cm. All samples were collected with a bulk density sampler designed to preserve natural pore space.

Laboratory Methods

Data Processing and Display

All data processing was done in the EKKO View Deluxe software package by Sensors & Software. The survey transects were collected in the field in 20 m segments. Extra points at the end of each segment were first removed from the file. The short segments were then merged to adjacent segments to form long transects across the length of the terrace (Figure 13). To account for receiver time drift, the Datum Timezero function was then applied to each transect. A low-pass filter was then applied to the data to remove high-frequency noise above 125 MHz (>20% of the nyquist frequency). The Dewow filter was then used to remove unwanted low-frequency noise due to instrument interference. Two datasets were then exported to Kingdom Suite for interpretation. The first dataset was imported after an AGC gain was applied to the data to enhance signal strength. The AGC gain does not preserve relative amplitude information, so an additional dataset was imported to Kingdom without gain for amplitude interpretation.

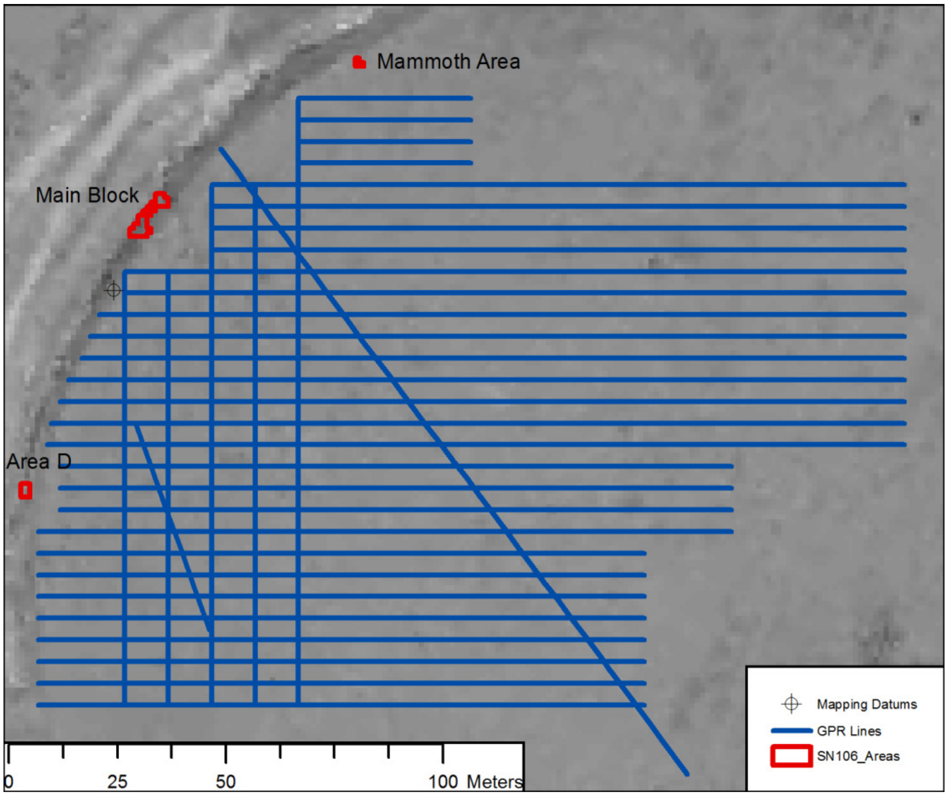

Figure 13. Map of the GPR transects surveyed at site 14SN106.

In Kingdom Suite, a number of horizons were chosen based on amplitude information in each survey line. The accuracy of each horizon was then determined by evaluating the vertical location of equal horizons in cross-lines. The arrival time of each horizon was then interpolated horizontally using a kriging function. This grid was then exported to ArcGIS for further interpretation and integration with existing site spatial data.

Grain-Size Analysis

The ultimate goal for the grain-size analysis data was to estimate the field relative permittivity (ε_r) of the samples. This was estimated through a number of steps (Figure 14). The samples were analyzed for grain-size with a Malvern Mastersizer. This system uses a laser diffraction technique for determining particle diameter. The analysis was completed by Aaron Young in the KU Geography department soils laboratory. The laboratory procedures for the Malvern tend to result in an underestimation of the clay-sized fraction. Thus, a lab correction factor was applied to the data in order to estimate the textural classes of the samples. According to the correction, the clay fraction was determined as the percent of particles under 0.008 mm (Aaron Young, 2008 personal communication). As a further check of this correction factor, a subset of samples was analyzed with the pipette method at the University of Iowa Quaternary Materials Laboratory. The pipette data was in general agreement with the laser diffraction data, however the comparison indicated that the Mastersizer was underestimating the clay content of the samples by as much as 7%.

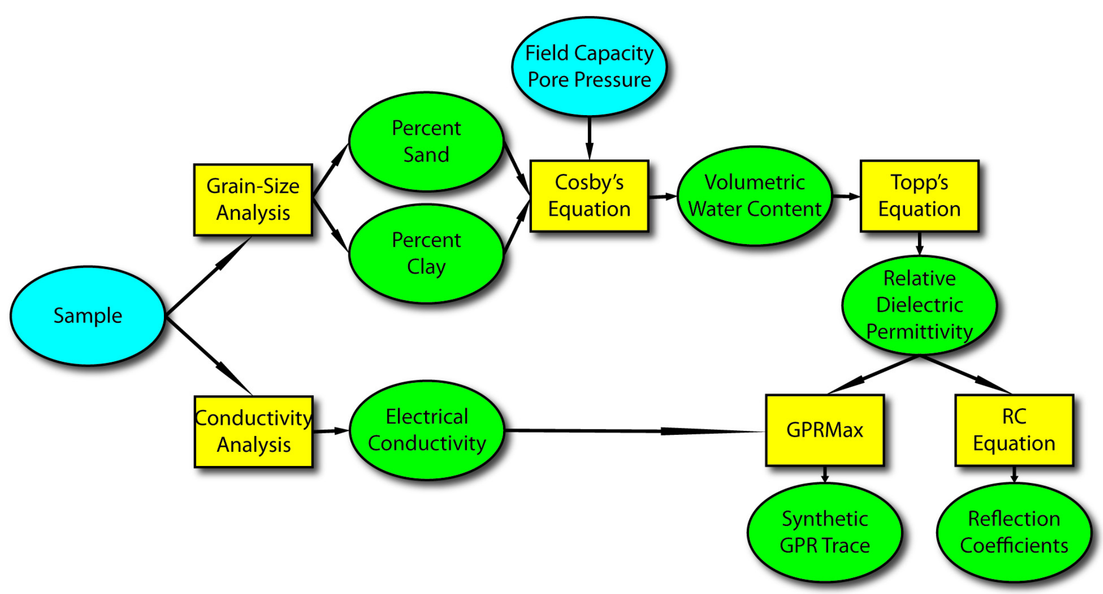

Figure 14. Parameters for the GPR model.

Electrical Conductivity Analysis

The bulk electrical conductivity of a soil is the result of the electrical conductivity of pore fluids, the concentration of dissolved ions in pore fluids, and the type and amount of specific clay minerals in the soil (Santamarina et al., 2005). Determination of electrical conductivity of the samples was necessary to estimate the attenuation of the radar signal through the profile. The conductivity measurements were made from a saturated paste by following procedure 8A in the Soil Survey Laboratory Methods Manual (Soil Survey Staff, 1996). Following the procedure, deionized water was added to ~20 g of air-dried sample until the sample was completely saturated. The viscous paste was then left to stand for at least four hours to ensure that all soluble salts were completely dissolved within the fluid. The electrical conductivity measurements were then collected in microsiemens per cm (μS/cm) with an ECTestr11 by Eutech Instruments. The wet soil samples were then weighed, oven dried, and reweighed for determination of moisture content. This procedure is widely used by soil scientists to estimate soil salinity. Since the paste contains far more water than normal field conditions, the total ionic concentration is lower than field conditions. Thus, the resulting measurements are considered minimum estimates of field conductivity.

Moisture Retention Modeling

For this study, it was important to make an estimation of the volumetric water content through the profile as it likely existed during the GPR survey (Figure 14).

When the GPR survey took place, there had not been rain for at least a week, so the moisture conditions were likely between field capacity and the wilting point. Moisture values for both these two field conditions were estimated using a set of equations from Cosby et al. (1984). The Cosby equations allow for the matric potential (Ψ) of a given sample to be estimated by:

$$\Psi - \Psi_s(\frac{\theta_v}{\theta_s})^{-b}$$

Where Ψ_s is the saturated matric potential, which can be determined by the empirical relationship to the percent sand of the sample ($\%_{sa}$):

$$\Psi_s = 10^{1.88-0.0131(\%_{sa})}$$

The saturated water content (θ_s), or sample porosity, can also be predicted with confidence by the sand content by:

$$\theta_s = 48.9 - 0.126(\%_{sa})$$

The slope of the water retention curve (b) can be predicted with the clay content ($\%_{cl}$) by:

$$b = 2.91 + 0.159(\%_{cl})$$

The equations can be solved for θ_v by inputting the matric potential, expressed in hydraulic head units, at field capacity (102 cm-water) and the permanent wilting point (15300 cm-water). The result is an estimation of the volumetric water content at a specified field moisture condition.

Synthetic GPR Modeling

GPRMax is a free GPR modeling software that uses a finite-difference time-domain (FDTD) method for predicting radar response (Giannopoulos, 2005). In the field, GPR waves are propagated through a theoretical infinite space. This space is simulated with the FDTD method by setting up a model inside a space that is sufficiently large so that the propagated wave never reaches the boundary. Thus, the models were run inside a 20 m grid. The spatial accuracy of this method is entirely dependent on the size of the input cells in the model. Generally specifying smaller input parameters yields more accurate results. The tradeoff is drastically longer computational times. A cell size of 1 cm was chosen for the simulations. GPRMax calculates the corresponding wave amplitudes, velocities, and losses for each cell and the appropriate time that a signal would be received. The high frequencies of any field data attenuate at a faster rate than low frequencies, thus the field data ended with a center frequency near 75 MHz. To help account for these losses, a 75 MHz ricker wavelet was used as the source wave in the GPRMax simulations.

CHAPTER V

RESULTS

<u>Site 14SN106</u>

Test Line

The initial test line at site 14SN106 was set up to help determine the research strategy at the site. The line began near the main block excavations and extended 180 m to the far edge of the terrace (Figure 11). In order to determine the best frequency for imaging across the terrace, the line was surveyed with multiple antenna frequencies (500, 250, 200 and 100 MHz). The results indicated that the attenuation was great enough that the subsurface could only be imaged to a depth greater than 1 m with the 100 MHz antenna. A common midpoint (CMP) survey was conducted with each antenna frequency to estimate the radar velocities. This enabled the radar travel times to be converted to depths. The CMP surveys indicated that the radar velocity was near 0.06 m/ns. This value is near the expected values for saturated silty sediments (Davis and Annan, 1989). The wavelength (λ) of the GPR data was estimated to be 0.8 m since the ending GPR signal was 75 MHz and the velocity was estimated to be 0.06 m/ns ($\lambda = v/f$). Since the GPR method requires that the thicknesses of the stacked horizons are generally greater than one quarter of the wavelength (0.2 m), it was determined that this method would not likely yield very informative results considering the boundaries of individual soil horizons.

The 100 MHz test line was successful in imaging a strong reflector that appeared to rise toward the surface beginning around 20 m from the bank (Figure 15). From 20 to 65 m there is visible stratigraphy, possible cross-bedding, under the strong reflection. This appears to be interrupted from ~65 to 75 m by an anomalous area that resembles a channel fill. This channel area is located in the center of the terrace at 14SN106 and it was initially unknown whether it connected to the known paleoarroyo at the southern end of the site.

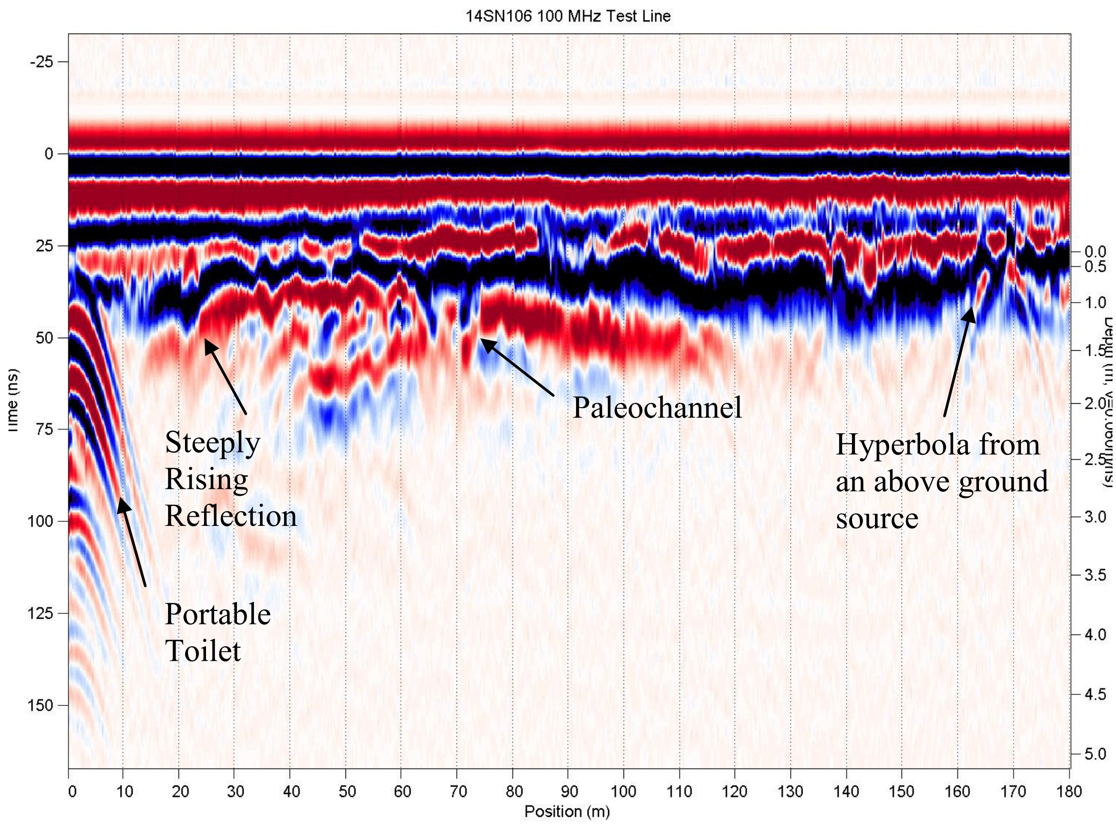

Figure 15. Results of the 180 m test line at site 14SN106.

In order to quickly assess how the southern paleoarroyo would appear in the data, a shorter test line was surveyed at the southern end of the site (Figure 16). The line was positioned between two backhoe trenches that were excavated during the 2006 field season. The trenches were placed based on what appeared to be a slight depression in an aerial photograph that was interpreted as indicating the direction of the paleochannel. In Trench 01, rounded fluvial gravels were encountered below a depth of 1.5 m; hence it was assumed that the trench was positioned within the paleochannel (Rolfe Mandel and Jack Hofman, personal communication, 2008). However, the GPR test line in this area contained a dipping reflection south of Trench 01 (Figure 17). The paleoarroyo is visible in the cutbank and has multiple inset channel fills. Thus, it is possible that the dipping reflection in the GPR data relates to another paleoarroyo that is unrelated to the one found within Trench 01.

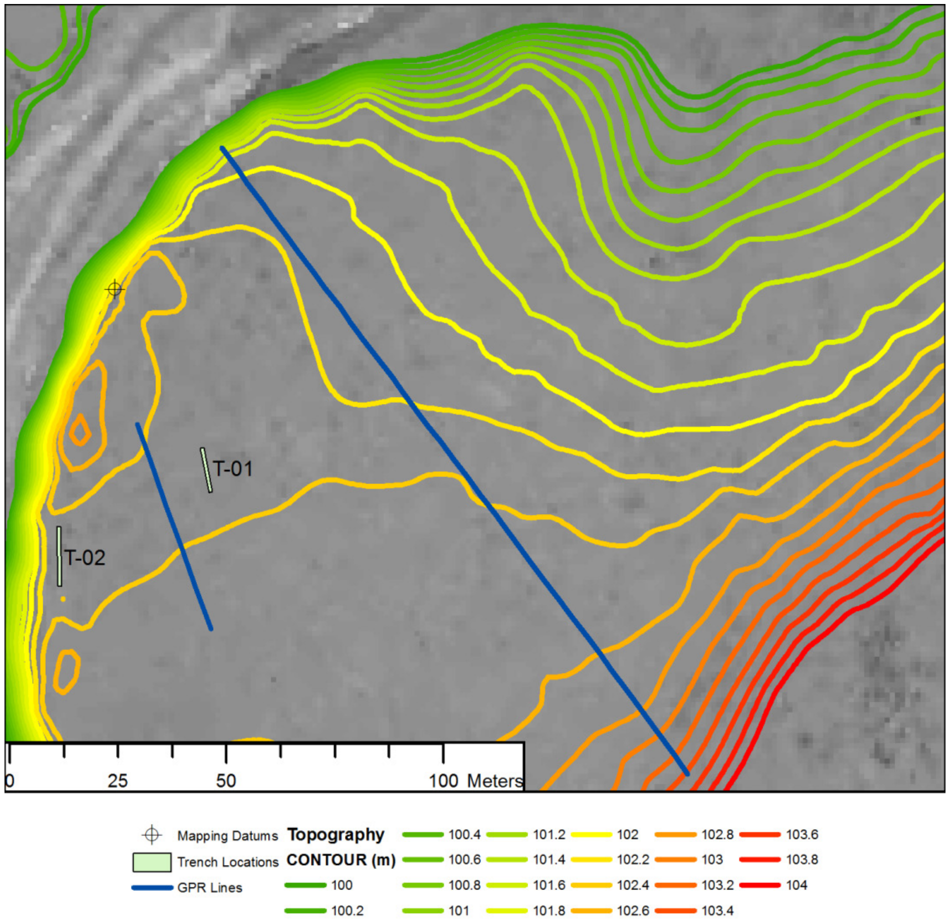

Figure 16. Map of the trench locations and GPR test lines at site 14SN106.

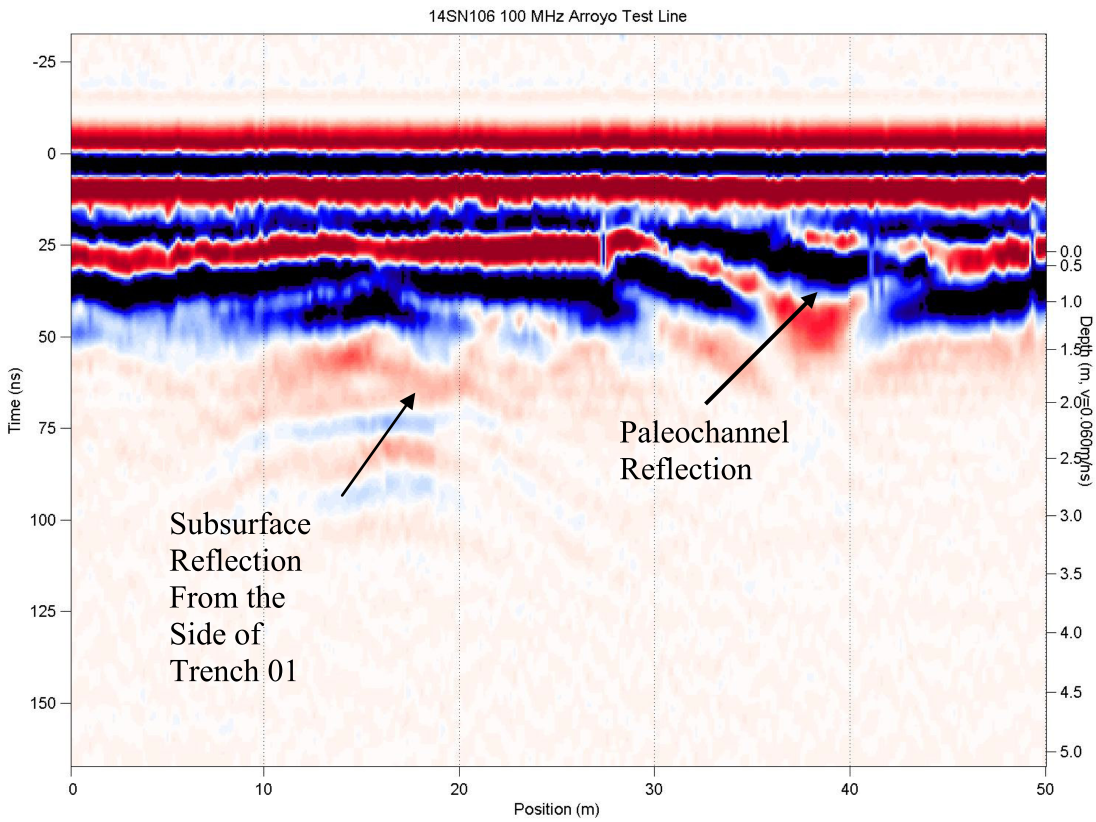

Figure 17. Results of the paleoarroyo test line at site 14SN106.

3-Dimensional Map

The survey lines at 14SN106 consistently showed that in spite of very high attenuation, a reflection was visible across the terrace (Figures 18 and 19). Although the reflection appears generally flat across the terrace, its strength and thickness is variable. Toward the western portion of the survey grid, the reflection generally appeared slightly later in time than in the center of the grid. In most survey lines, there appears to be a slight gap in the reflection that suggests there may be multiple events causing a similar reflection (Figure 19). Interference from metal excavation equipment at the surface made it difficult to interpret the absolute continuity of the reflection in the western portion of the grid. In places, especially in the eastern portion of the terrace, the lower boundary of this reflection is very irregular. This irregularity generally coincides with areas where the reflection appears later in time and is influenced by greater attenuation. There are considerable variations in both the thickness and amplitude of the reflection across the survey grid. In the center of the survey grid, the reflection generally appears earliest in time. The reflection also tends to be the thinnest in this area (Figure 20). In places there appears to be inclusions of small troughs within the larger reflection. This is probably a result of multiple reflective horizons that have caused both constructive and destructive interference in the data. It is likely that this is caused by a disconformity between the fine-grained sediments and the underlying Pleistocene-aged gravels.

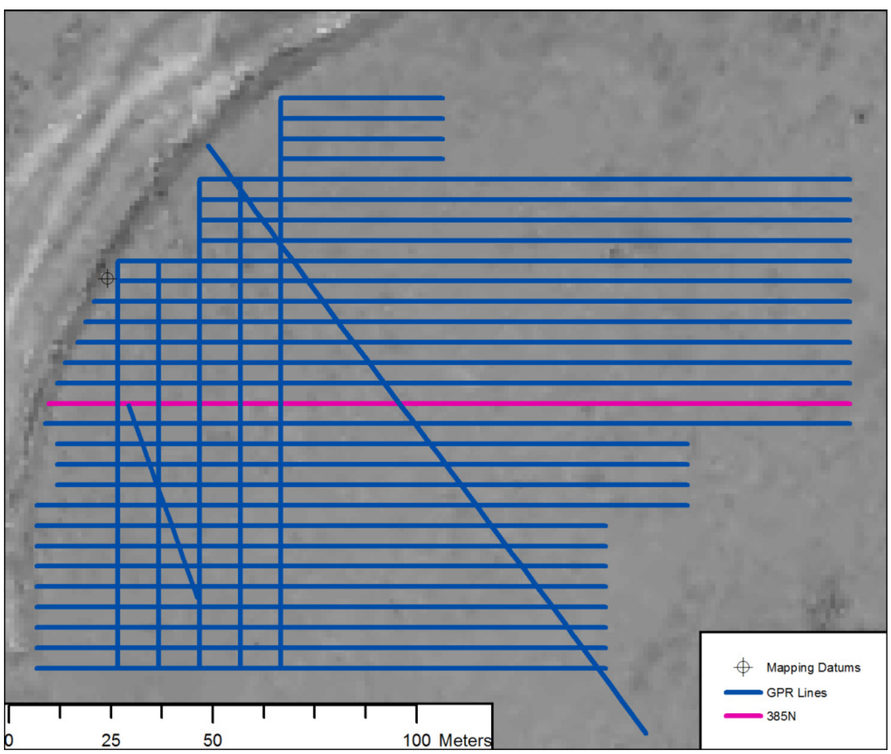

Figure 18. Map showing the location of line 385 N at site 14SN106.

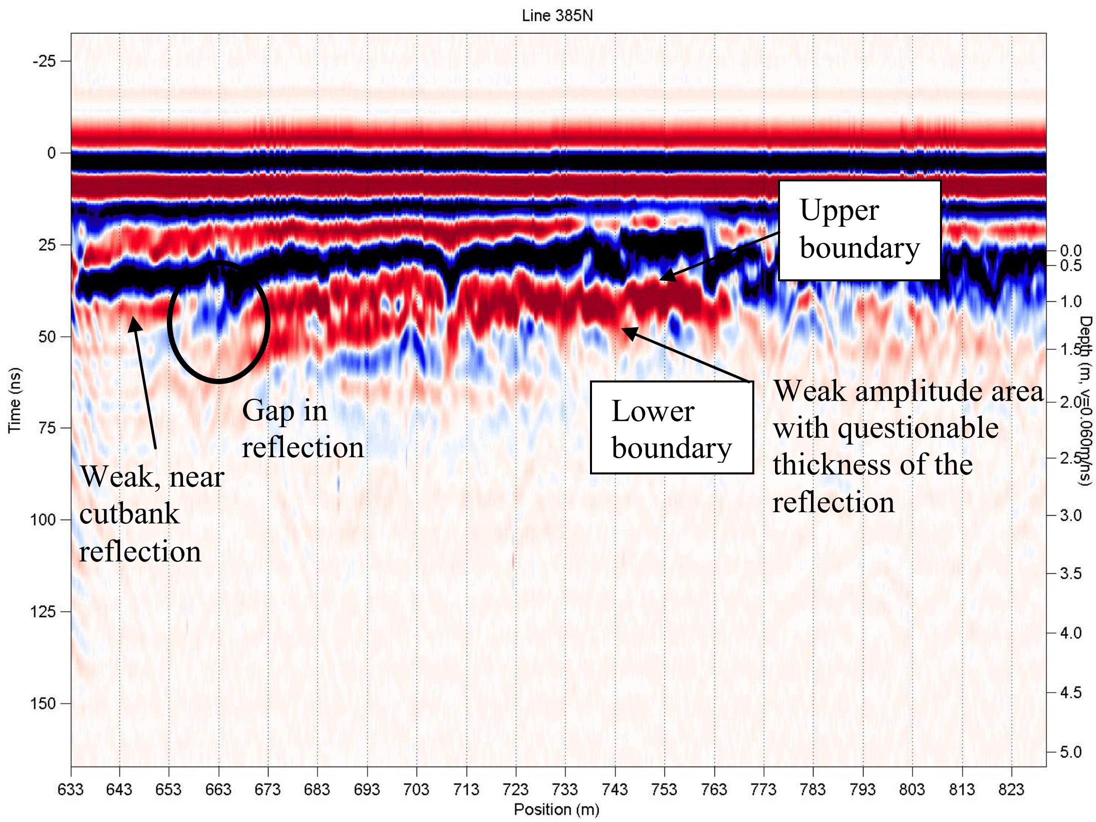

Figure 19. Results of line 385 N at site 14SN106.

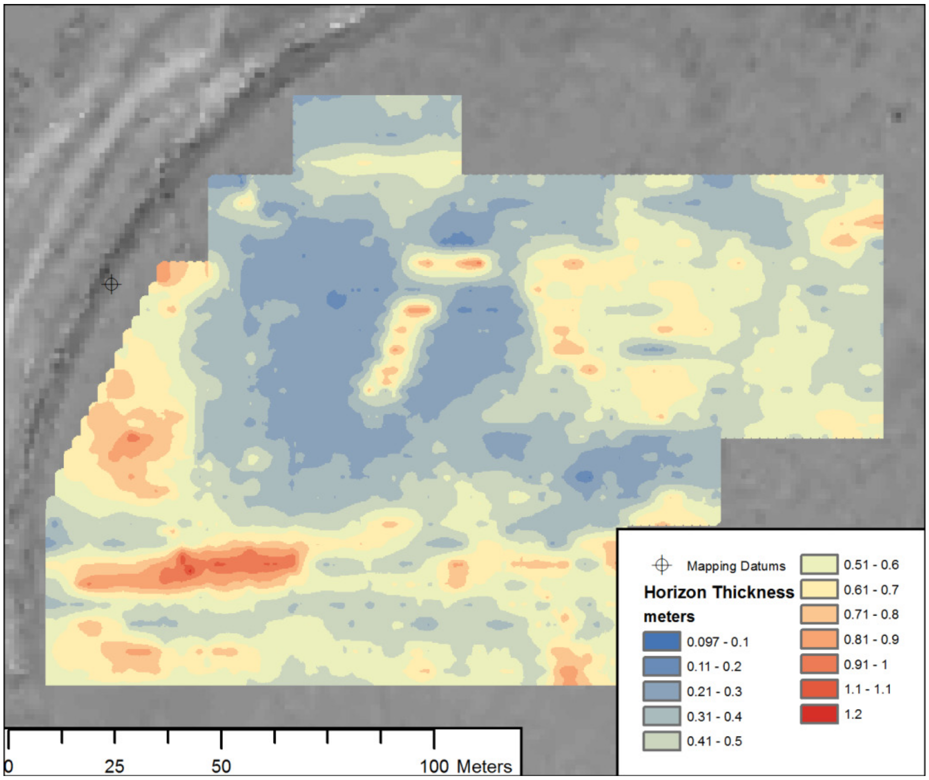

Figure 20. Map showing the thickness of the GPR reflection across the terrace at site 14SN106.

The AGC-gained data was used in KINGDOM Suite to identify the zero crossing of both the upper and lower boundaries of the reflection. The upper boundary of the reflection clearly shows that the reflection appears later in time near the western portion of the survey (Figure 21). The lower boundary shows two localized low areas that relate to two different paleoarroyos at the site (Figure 22). The southern arroyo is clearly visible in the cutbank and is known to contain butchered bison remains that date to the time of the Paleoindian occupation at the site. This feature appears in the data as a 10 m-wide linear area that extends 60 m east from the western edge of the survey grid. The GPR map in this area also shows Trench 01 was not located within this paleoarroyo. Instead, the trench appeared to be located over an area where the underlying fluvial gravel deposit rises steeply toward the surface. This will aid in further evaluation of the paleoarroyo.

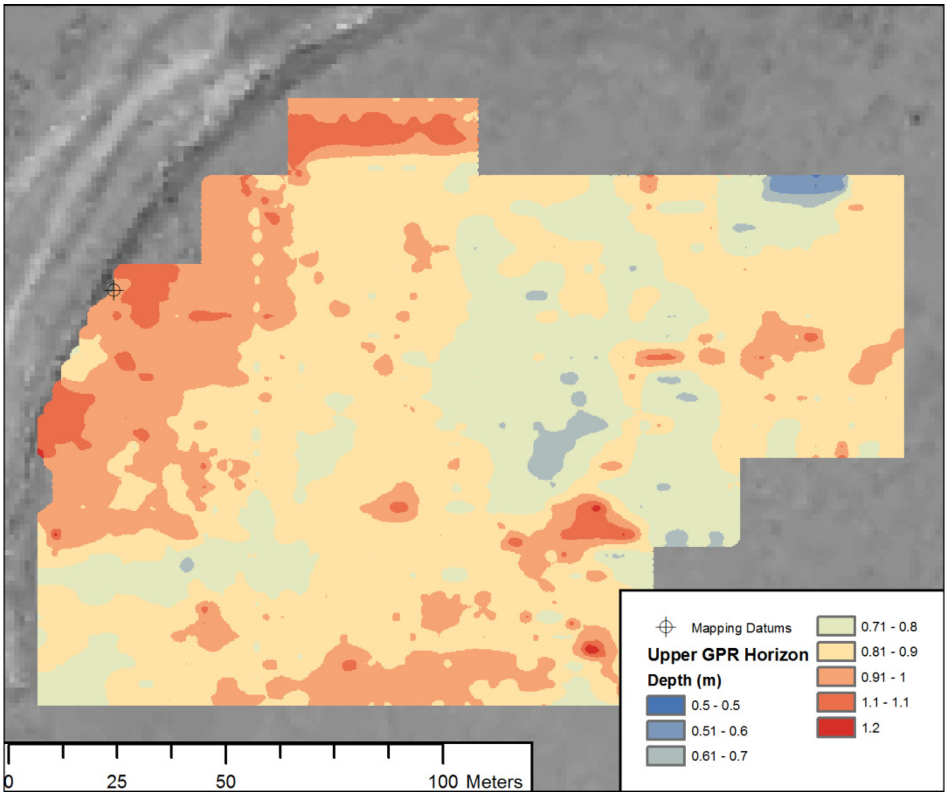

Figure 21. Map showing the approximate depth below surface of the upper boundary of the GPR reflection.

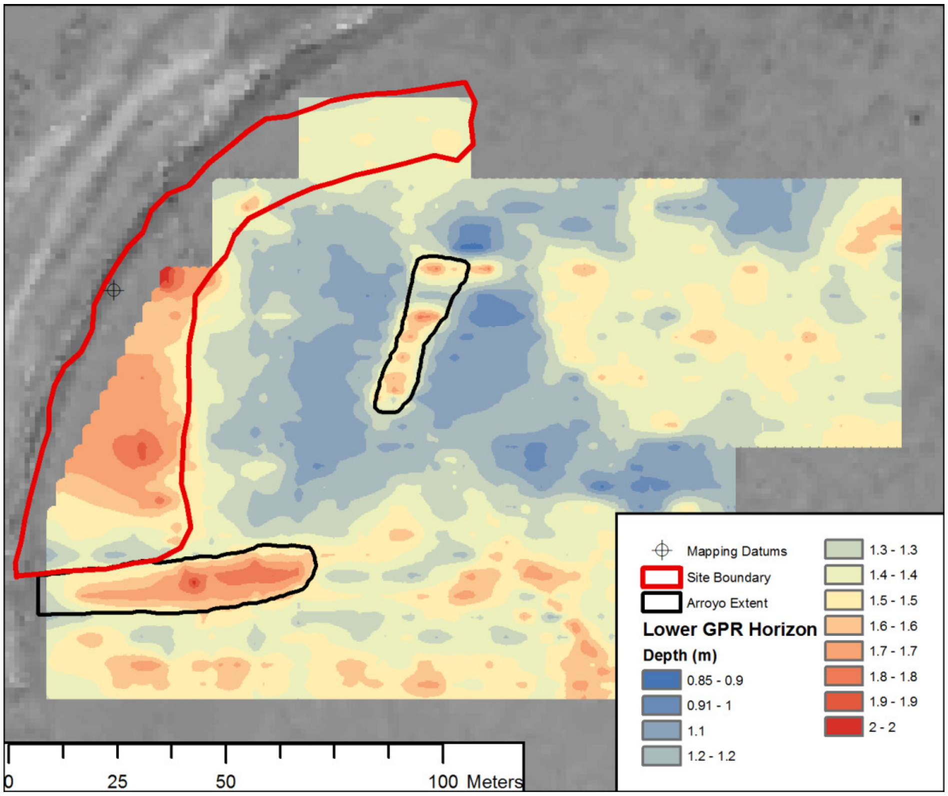

Figure 22. Map showing the depth to the lower boundary of the GPR reflection, approximate site boundary, and paleoarroyo locations.

A similar channel anomaly was also visible in the center of the survey grid (Figure 22). This second paleoarroyo is a 7 m wide by 30 m long linear feature that runs generally to the northeast. The anomaly is located within an area of the survey that showed the highest amplitudes from the ungained dataset (Figure 23). Based on this information, it is likely that the second arroyo cut into coarser materials, resulting in a much higher reflection coefficient. Five auger holes were placed in a transect over this area and the depth to gravel was recorded (Figure 24). There is generally good agreement between the augered depth to gravel and the depth of the GPR horizon (Figures 25 and 26). Additionally, a buried soil was detected in the three auger cores within the paleoarroyo, but it was not detected in the auger cores located on either side of the paleoarroyo. These data will aid further evaluation of the buried cultural deposits at the site.

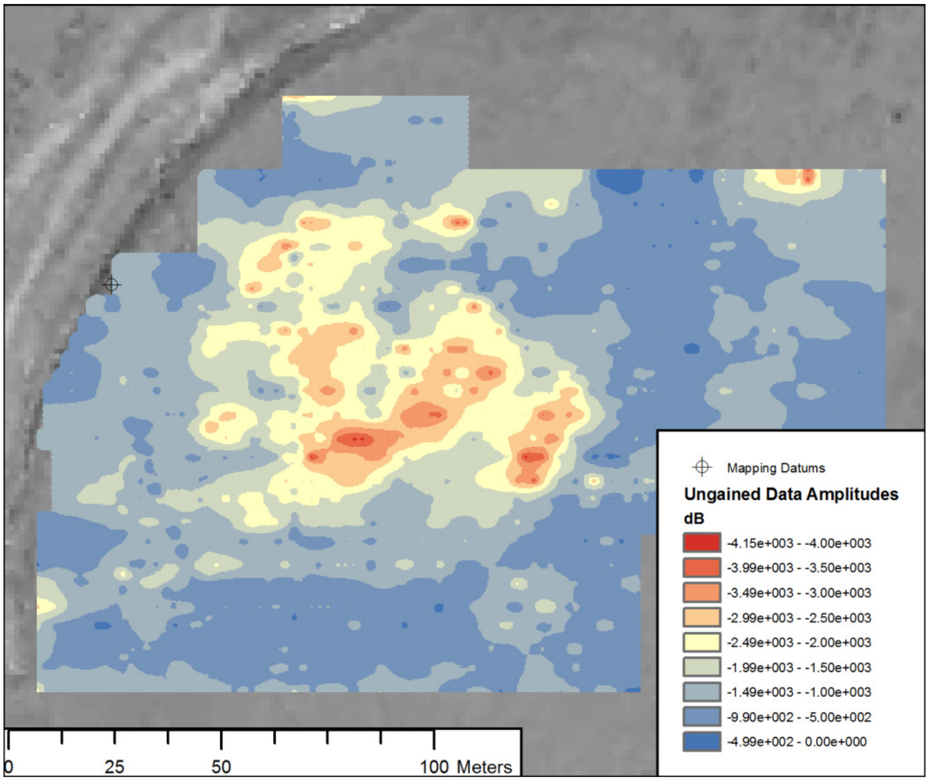

Figure 23. Map showing the ungained amplitudes of the GPR reflection.

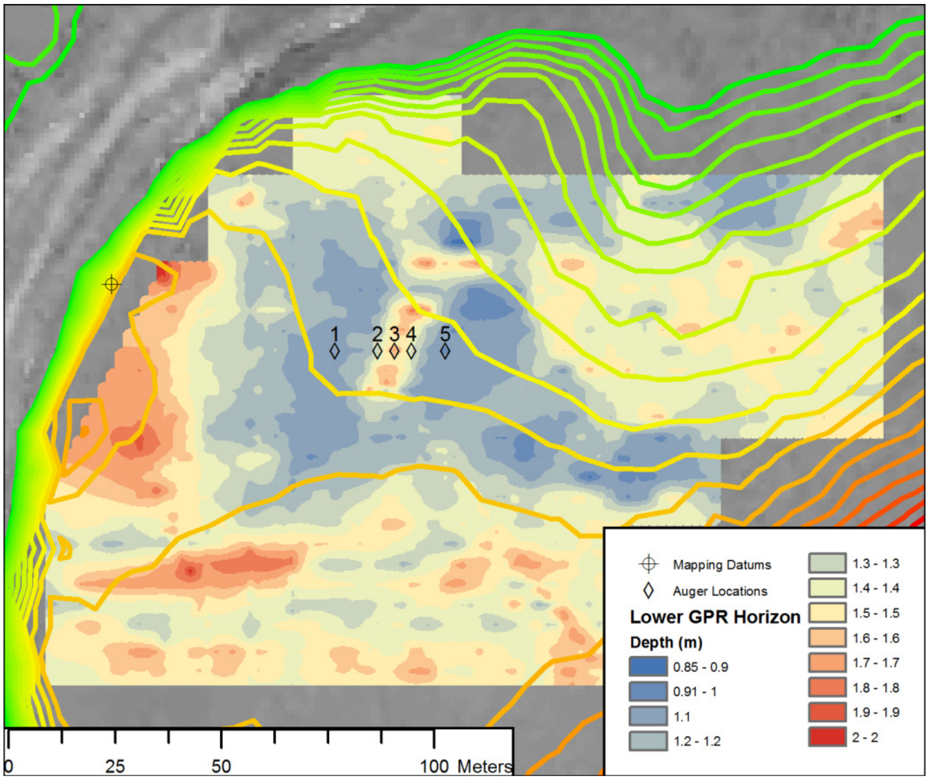

Figure 24. Map showing the locations of the auger cores along line 400 N.

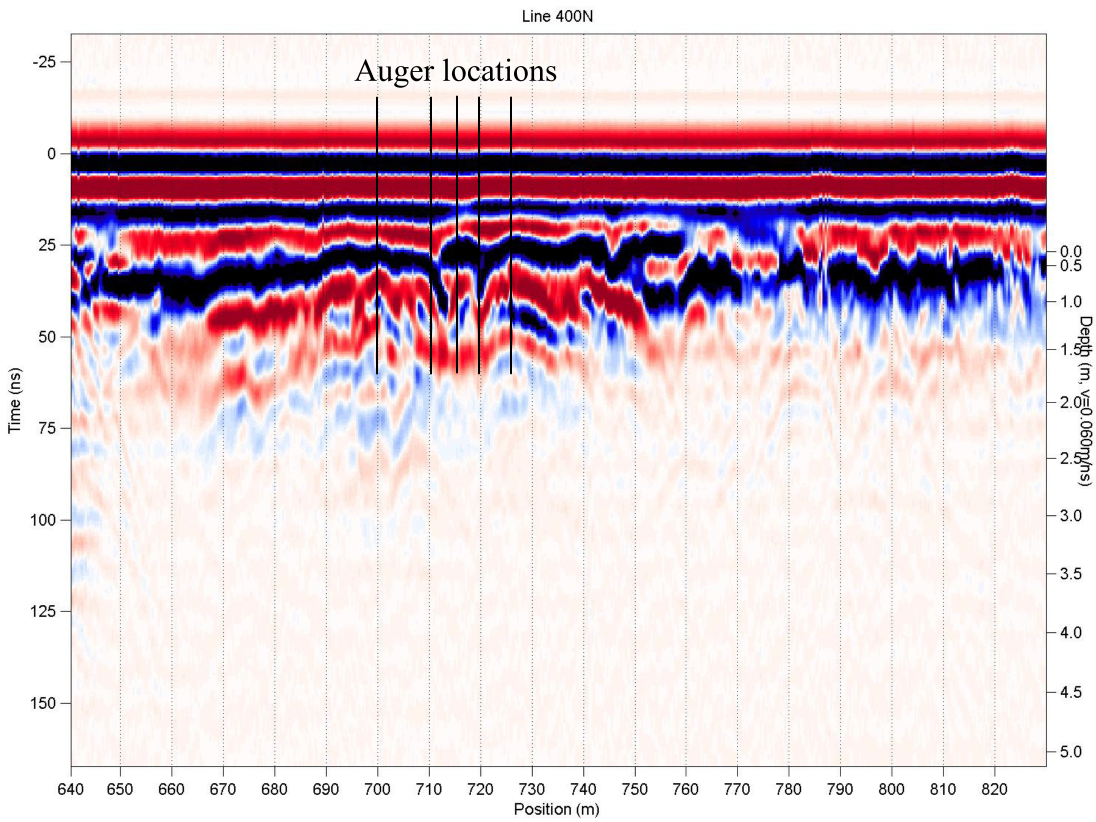

Figure 25. Results of line 400 N showing locations of the auger cores.

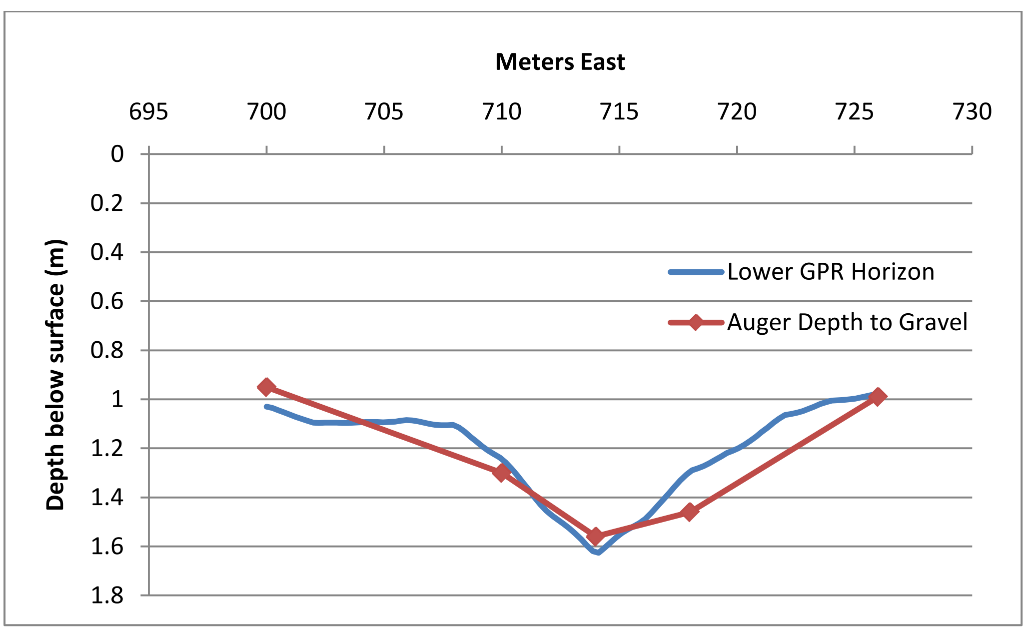

Figure 26. Comparison of the estimated depth to the lower boundary of the GPR horizon and the recorded depth to gravel in the auger cores.

Site 14SN105

A single transect was surveyed parallel to the bank across most of the length of site 14SN105 (Figure 12). As observed at site 14SN106, the Kanorado paleosol formed in silty sediments above Pleistocene sand and gravel. The Kanorado paleosol and the underlying sand and gravel are closer to the surface at the northern end of the site than at the southern end of the site. Hence, the depth of the Kanorado paleosol varies along the length of the site. The GPR transect was surveyed to determine the maximum depth to which the paleosol could be imaged (Figure 27). The radar energy attenuated beyond a depth of about 1.5 m. At the southern end of the site, the Kanorado paleosol is deeper than could be imaged. From 50 m-north to 75 m-north there is a reflection that rises toward the surface to a depth of about 1 m. From 75 m-north to 100 m-north this reflection maintains a relatively constant depth of 1 m below the surface. The reflection then dives deeper below the surface until 125 m-north, where attenuation prevents a clear image. This reflection corresponds to the change in depth of the Kanorado paleosol across the length of the site. Between 75 and 100 m-north, where the Kanorado paleosol is shallowest, there is another deeper reflection that appears at approximately 1.5 m that corresponds to the approximate depth of the underlying coarse sands.

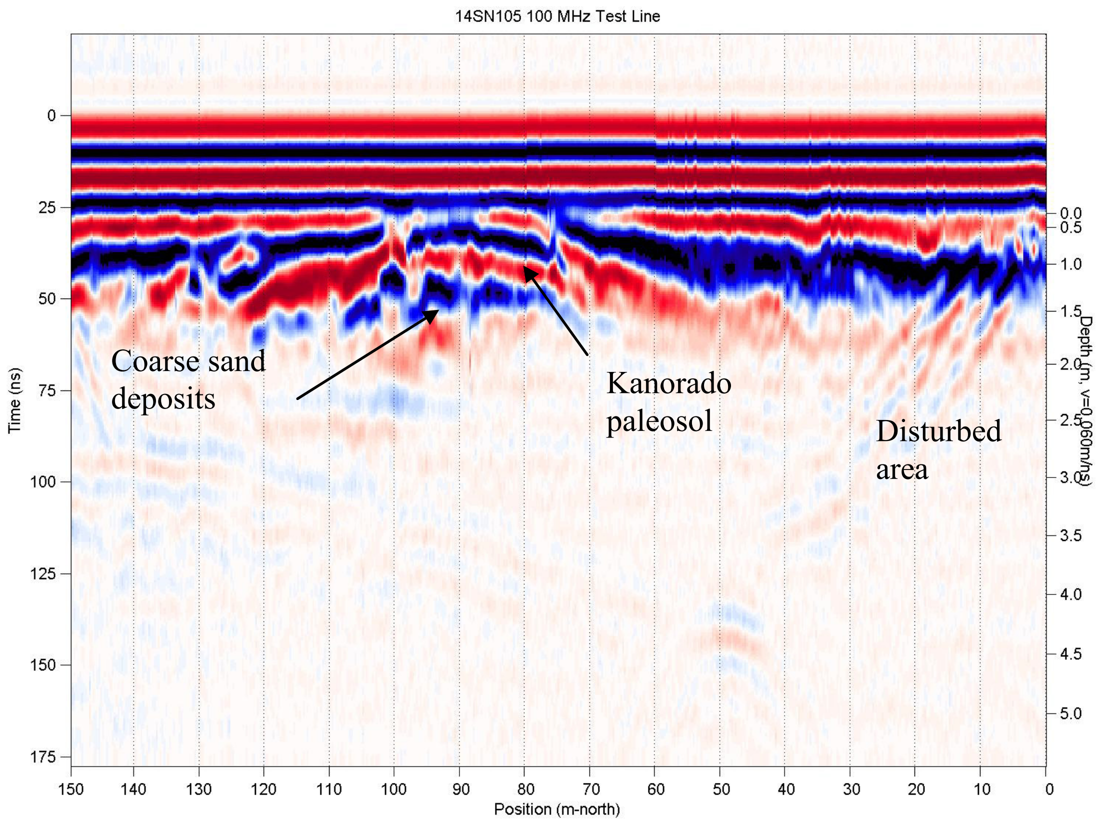

Figure 27. Results of the test line at site 14SN105.

<u>GPR Model</u>

A total of 67 samples were collected from profiles at sites 14SN106 and 14SN105 and were described and analyzed for grain-size and electrical conductivity . The data were then used as inputs for an FDTD model that predicts GPR signal response. The estimation of the relative permittivity of each sample relied heavily on the results of the grain-size analysis, while attenuation was primarily a function of electrical conductivity. The results of the grain-size analysis indicated that the majority of the samples were within the loam, silt loam, and silty clay loam textural classes (Figures 28 and 29). The lowest two samples at 14SN105 were determined to be sandy loam. The results of the grain-size analysis are in general agreement with earlier work, in which grain-size analysis was conducted at 14SN105 by pipette (Mandel et al., 2004). The recognition of small changes in grain-size was important for determining the potential sources of GPR reflections through the profile.

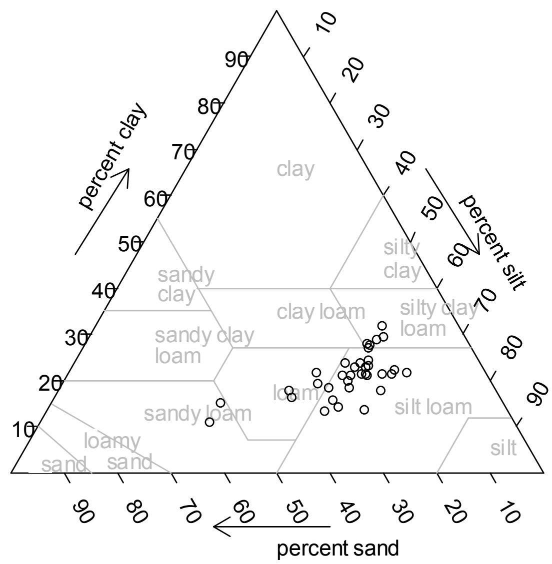

Figure 28. Grain-size results from the profile at site 14SN105.

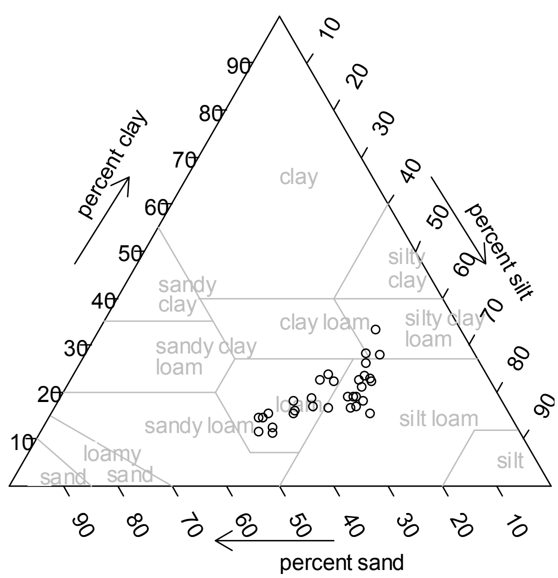

Figure 29. Grain-size results from the profile at site 14SN106.

Site 14SN106

The profile at site 14SN106 was sampled through three stacked soils: the surface soil (0-100 cm bs), the Beaver Creek paleosol (100-155 cm bs), and the A horizon of the Kanorado paleosol (155-195 cm bs) (Figure 30). The grain-size data for site 14SN106 show a general decrease in the sand content through the A and Bw horizons of the surface soil (Figure 31). This corresponds with an increase in clay content to the bottom of the Bw horizon. Sample number 10 was located within the boundary between the Bw and Bk horizons at ~60 cm below the surface. This sample shows a dramatic decrease in the sand content and a corresponding increase in clay content, which resulted in a large estimated increase in the relative permittivity. The grain-size data show a gradual increase in sand content and an equally steady decline in clay content from the top of the Bk horizon to the top of the Kanorado paleosol (155 cm bs). The estimated reflection coefficients between 60 and 140 cm are at or below 0.01. The low reflection coefficient indicates that substantial reflections would not be caused by the upper boundary of the Beaver Creek paleosol. This result is actually quite surprising since, at several locations at the site, there are visible deposits of sand and pebbles just above the Beaver Creek paleosol. However, pebbles were not present in the sampled profile. Within the Kanorado paleosol, the grain-size data show a very subtle decline in the sand content, which corresponds to an increase in silt content. This change in grain-size resulted in a large increase in the estimated relative permittivity below 160 cm.

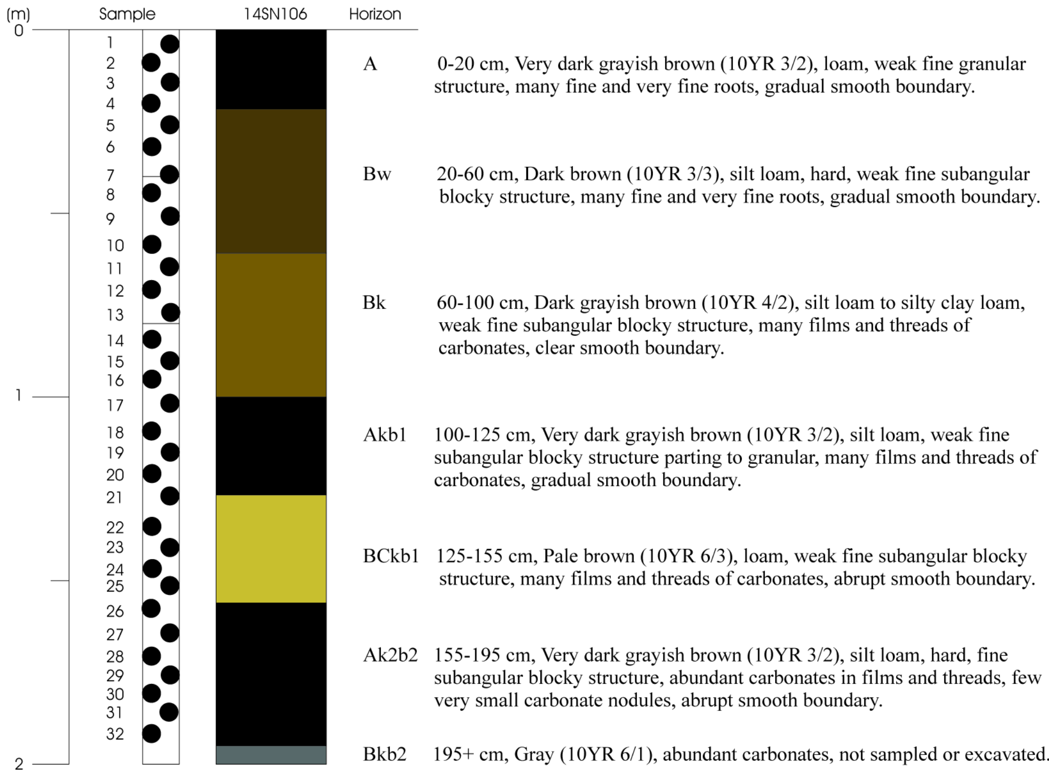

Figure 30. Soil description of the profile at site 14SN106 showing sample locations.

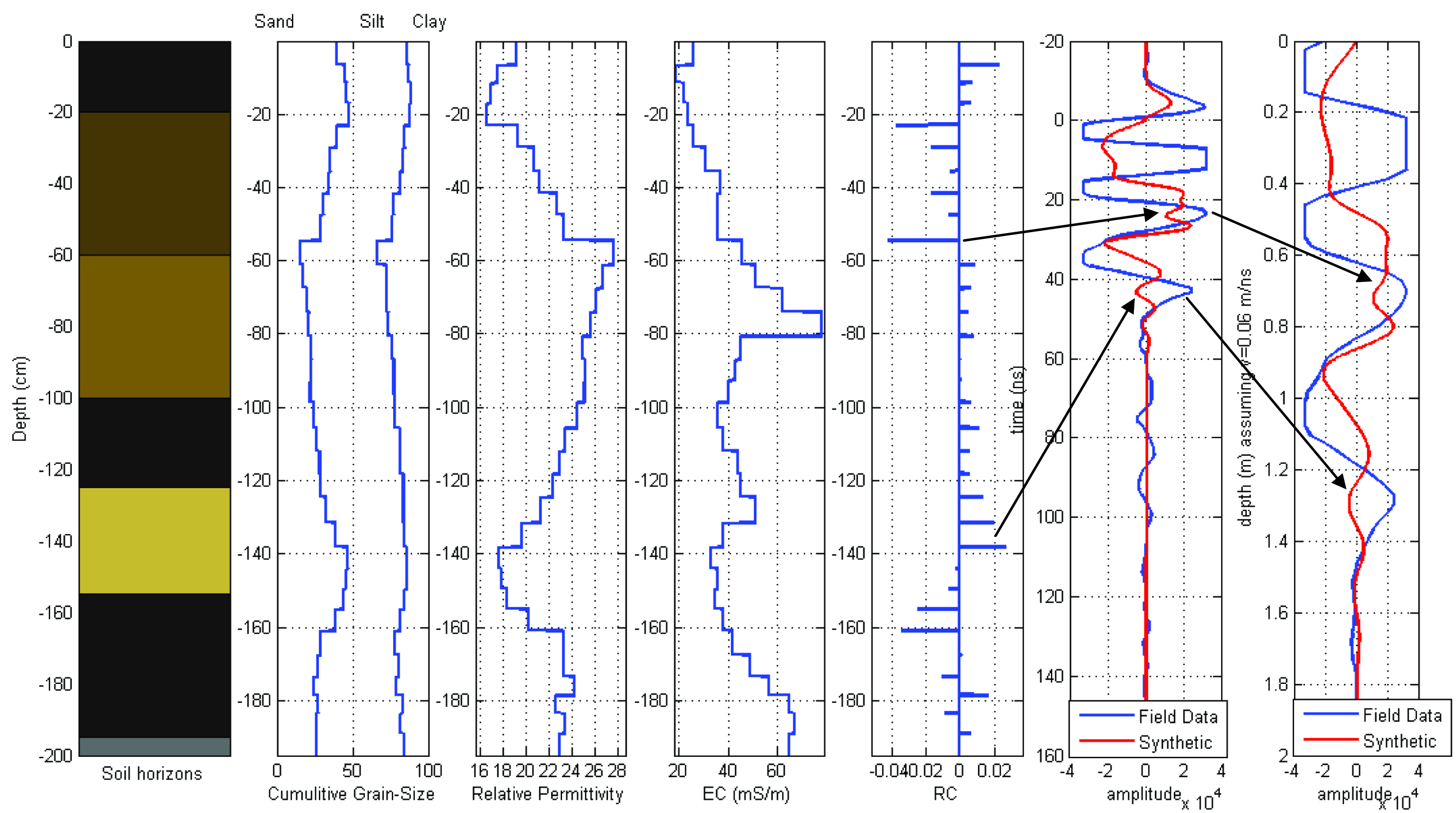

Figure 31. Sample analysis results for the profile at site 14SN106.

The estimated apparent conductivity values for the surface soil appear slightly out of phase with the measured changes in clay content. There is a peak in electrical conductivity in the Bk horizon of the surface soil at 80 cm. The peak in electrical conductivity may be attributed to an increase in salt content in conjunction with an increase in carbonates within this horizon.

The estimated relative permittivities and sample conductivities were used as inputs for GPRMax. The results of the GPRMax simulations were then overlaid with nearby, relatively noise free, traces from the field data. The simulated GPR trace was subjected to less attenuation than the field data, though the signal did need to be gained for display. The low attenuation results indicated that the methods used for the electrical conductivity analysis yielded minimum estimates for attenuation. The field data trace and GPRMax model trace each has similar reflections near 20 ns (0.6 m bs), though the polarity of the reflection in the two traces differs. The reverse polarity indicates that there is a change in moisture conditions at roughly 0.6 m, though the field data indicated a decrease in moisture, while the model predicted an increase in moisture. The time the signal was received indicates that this reflection occurred above the Beaver Creek paleosol (100 cm bs). Thus, the weak reflection near the terrace cutbank is interpreted as caused by an increase in clay content at the top of Bk horizon of the surface soil.

Site 14SN105

The profile at site 14SN106 was sampled through two stacked soils: the surface soil (0-105 cm bs) and the Kanorado paleosol (105-203 cm bs) (Figure 32). The results of the grain-size analysis of the surface soil for site 14SN105 were very similar to the results for the surface soil at site 14SN106 (Figure 33). Like site 14SN106, the grain-size data from site 14SN105 also show a general decrease in sand content and an increase in clay content through the A and Bw horizons. A sample collected within the Bk1 horizon (60 cm bs) had an increase in sand content compared with samples from adjacent horizons. This was the only sample collected completely within the Bk1 horizon at the site. The local increase in sand content resulted in an estimation of two relatively large reflection coefficients surrounding this sample. The grain-size data show a gradual increase in the sand content and a corresponding decline in clay from the top of the Bk2 horizon to the top of the Kanorado paleosol (70-100 cm bs). At 100 cm there is a slight increase in sand content that causes a relatively large estimated reflection coefficient. This is the only reflection coefficient within the range of the Kanorado paleosol that would likely cause a reflection. The grain-size data below the Akb horizon of the Kanorado Paleosol show an increase in the sand content with a corresponding decrease in silt content. This change in grain-size resulted in numerous large estimated reflection coefficients within the Bkb2 and BCkb horizons (180-220 cm).

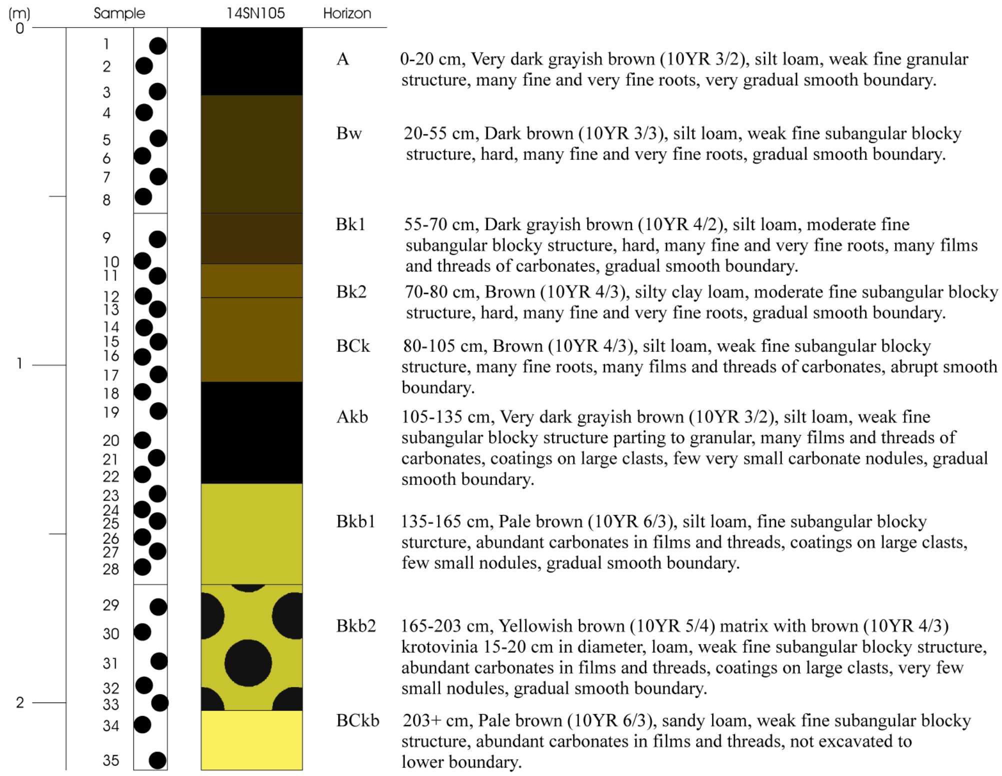

Figure 32. Soil description of the profile at site 14SN105 showing sample locations.

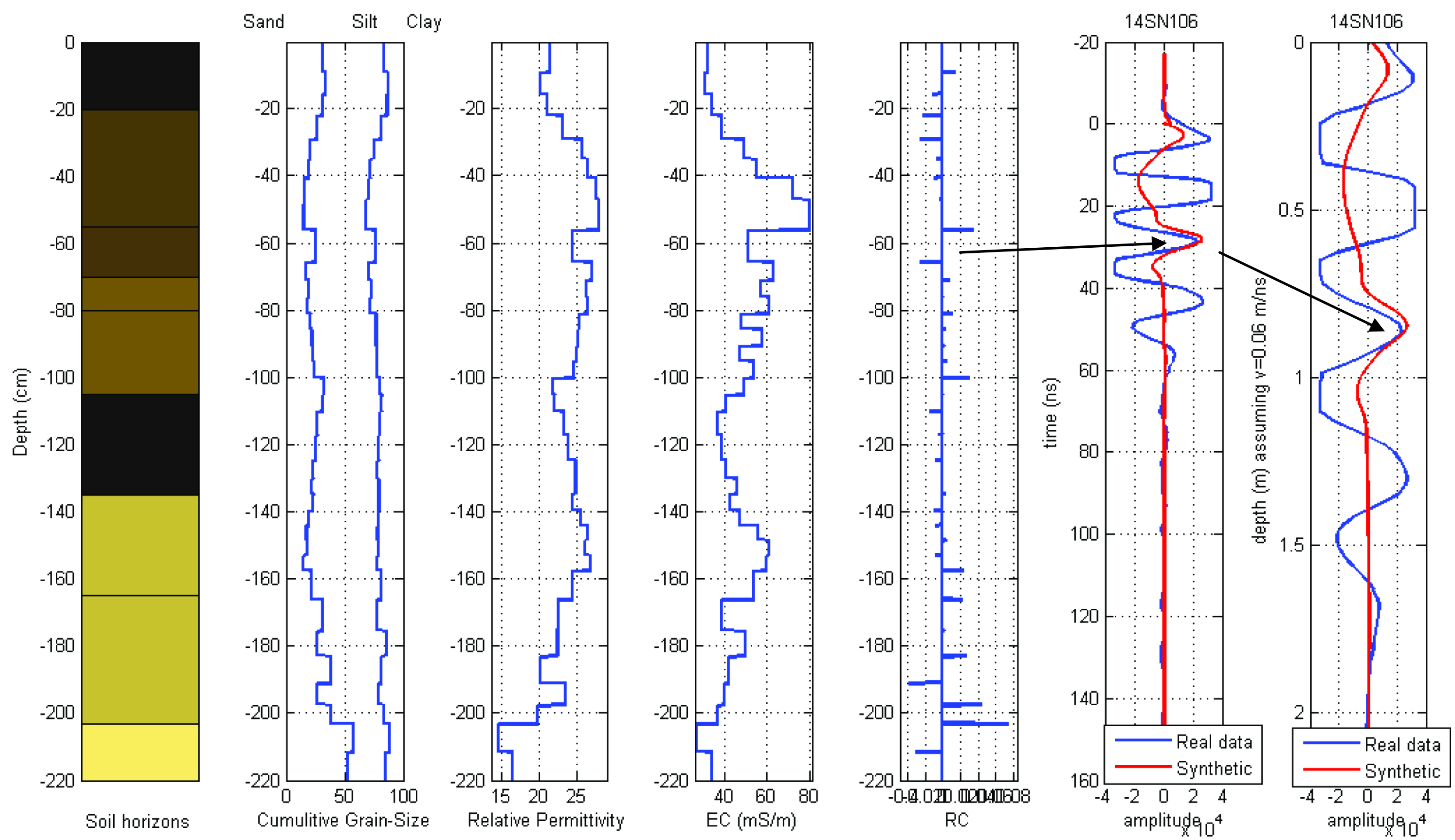

Figure 33. Sample analysis results for the profile at site 14SN105.

The gradual increase in the electrical conductivity values for the A and Bw horizons correlates well with the gradual increase in clay in these horizons (R^2=0.87). However, below 60 cm there were numerous shifts in the electrical conductivity that do not appear to be correlated with any major changes in clay content. Secondary carbonate accumulation was observed in every sample below 60 cm and was represented by films, threads, and small nodules in the matrix and by coatings on some clasts. Hence, the change in electrical conductivity throughout the profile probably reflects changes in dissolved salt content instead of abundance of negatively charged clay minerals.

The relative permittivity of each sample was estimated from the grain-size analysis and used as inputs for GPRMax trace simulation. The results of the GPRMax simulations were then overlaid with nearby, relatively noise free, traces from the field data. At site 14SN105, the simulated GPR trace was subjected to greater attenuation than the field data. The field data trace and GPRMax model trace each has similar reflections beginning near 25 ns (0.75 m). This position roughly corresponds to the anomalous sample collected within the Bk1 horizon at 60 cm. Since the field data had less attenuation, there was also an additional reflection visible near 50 ns (1.5 m). The lower reflection in the field data was interpreted as caused by the boundary between the sandy deposits and the overlying Kanorado paleosol. Unfortunately, the GPRMax simulated trace attenuated before this interface.

CHAPTER VI

SUMMARY AND CONCLUSIONS

The results of the investigations at the Kanorado locality demonstrate the successful use of GPR for non-destructively mapping of a buried landscape at an Early Paleoindian site where cultural materials are contained within silty deposits. Geophysical surveys are rarely conducted at Paleoindian sites because the sparse cultural remains are thought to be invisible to these techniques. The initial goal of the project was to use GPR to image the Kanorado paleosol, a buried soil containing Early Paleoindian deposits, at site 14SN106. This site was chosen for two reasons:

1. The cultural deposits are ~2 m below the surface of the broad T-1 terrace of Middle Beaver Creek. Since the terrace is generally flat and free from obstructions, the GPR survey could be conducted with little interference over the broad area.
2. Preliminary coring at this site in 2006 indicated that the Kanorado paleosol was not continuous across the broad T-1 terrace. Instead, the Kanorado paleosol was found to pinch out about 50 m east of the cutbank. It was thought that the GPR survey would delineate the site boundary at a higher resolution than was already obtained through the coring survey.

An initial test line was conducted across the terrace at site 14SN106. The test line was surveyed with multiple antenna frequencies to determine which antenna would best image the subsurface. The results of the test-line survey revealed that the sediments at the site were electrically conductive, which caused rapid attenuation of the GPR signal. The high attenuation prevented the use of the high-frequency, high-resolution antenna that would have enabled the clear distinction of the soil horizons at the site. None of the antennas used at the site were able to image through the Kanorado paleosol. After this problem was recognized, the project shifted goals to extract as much information as possible pertaining to the T-1 terrace fill by using the low frequency antenna. The results of the test line revealed an anomalous area in the center of the terrace that appeared to be caused by a paleoarroyo. At the southern end of site 14SN106, a paleoarroyo extends across the T-1 terrace and is known to contain butchered bison remains dating to ca. 10,850 ^{14}C yr B.P. A 3D survey grid was set up over the terrace to determine if the paleoarroyo anomaly in the center of the terrace was connected to the known paleoarroyo at the southern end of the site.

The entire T-1 terrace at site 14SN106 was mapped at a 5 m transect spacing and 0.25 m sample spacing to produce a 3D image of the subsurface. The results of the 3D survey confirmed that the fine-grained alluvial deposits are replaced by coarse sand and gravel deposits no more than 40 m east of the cutbank. This was indicated by a steeply rising strong reflection that interrupted a weaker reflection near the western survey edge. It is estimated that only 3,500 m^2 of the Kanorado paleosol remains within the T-1 terrace fill at 14SN106, excluding the area of the paleoarroyo at the southern end of the site.

The results of the 3D map also gave a clear reflection of one of the multiple inset fills within the southern paleoarroyo. The arroyo anomaly covers an area 700 m^2 and the bottom of the channel anomaly is estimated to be ~1.8 m below the surface. The southern arroyo anomaly in the GPR map was shown to be oriented in an eastward direction and not a northeast direction as previously thought. A trench excavated in 2006 (Trench 01) was positioned ~10 m north of this anomaly. Within the trench, channel gravels were located at 1.5 m below the surface and a buried soil was present about 2.5 m below the surface. Based on the information from the trench stratigraphy and the arroyo anomaly in the GPR map, it is likely that the paleoarroyo visible in the GPR data needs further testing.

The results of the 3D survey also successfully identified the extent of a previously unknown paleoarroyo in the center of the T-1 terrace at site 14SN106. This feature has an area of ~320 m^2 and the bottom of the channel is estimated to be ~1.6 below the surface. Unlike the southern paleoarroyo, multiple inset fills were not detected by the GPR. The width of the paleoarroyo anomaly in the center of the T-1 terrace (~7 m) is also shorter than the width of the southern paleoarroyo (~12 m). A transect consisting of five auger cores revealed what appeared to be a buried soil within the paleoarroyo. This buried soil was not present in the two auger cores located on either side of the paleoarroyo. The fill within the paleoarroyo may date to the Pleistocene-Holocene transition or it may post-date that period. Excavations are needed to explore the area of this newly discovered paleoarroyo.

A single test line also was collected with a 100 MHz antenna that was moved along a transect parallel to the cutbank at site 14SN105. At site 14SN105, the depth to the Kanorado paleosol varies considerably from north to south. At the northern end of the site, the Kanorado paleosol is ~0.7-1 m below the T-1 surface, but at the southern end of the site the paleosol is ~2 m below the surface. The GPR test line was collected to determine the maximum depth to which the Kanorado paleosol could be imaged. The results of the test line appeared to successfully image the Kanorado paleosol at the north end of the site. The radar energy attenuated near 1.5 m below the surface, so the paleosol could not be imaged near this depth.

In order to aid interpretation of the GPR data, soil samples were collected from two profiles. One profile was located at site 14SN106, and the other was at site 14SN105. The samples were analyzed for grain-size and electrical conductivity information. The data from the laboratory analysis were then used as inputs for a finite-difference time-domain model to predict GPR signal response. The GPR model from site 14SN106 indicated that neither the Kanorado paleosol nor the overlying Beaver Creek paleosol were the cause of a shallow reflection in the GPR data. Instead, the weak reflection is interpreted as the result of an increase in clay within the Bk horizon of the modern surface soil. In the GPR model from site 14SN105, there was a weak reflection above the top of the Kanorado paleosol and the signal attenuated before the interface of the Pleistocene sand deposits and the overlying fine-grained alluvium.

Future Research

There are many different ways to expand this study. First, the results of the 3D survey at site 14SN106 can be used to direct future excavations. The GPR survey successfully delineated the extent of two paleoarroyos at the site. Butchered bison remains have been found within the paleoarroyo fill at the southern end of the site. Future excavations should be placed within the southern paleoarroyo anomaly to search for additional bison remains. It is still unknown whether the fill within the northern paleoarroyo dates to the Pleistocene-Holocene transition. Future excavation should also be directed in this area to determine the relationship between the northern paleoarroyo and the Paleoindian site.

The methods used in this project have potential for guiding research at other Paleoindian sites. Future GPR surveys need to be performed in areas that are not as electrically conductive as Kanorado. Also, GPR surveys focused on mapping buried soils should be conducted in sandy environments. Paleoindian sites have been found in sandy dune settings (e.g., May and Holen, 2003; Mayer, 2003). In sandy settings backhoe trenching is of limited use, thus alternative methods of investigation are needed. These settings tend to be well suited for GPR because the electrical conductivity of sand tends to be relatively low. Future GPR surveys focused on mapping pedo-stratigraphic markers, such as the Kanorado and Brady paleosols, in sandy settings will likely be more successful than at the Kanorado locality.

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