Report

Landform Sediment Assemblages in the Anoka Sand Plain for Support of Cultural Resource Investigation

Project I.D.: 06M058

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16. Abstract (Limit: 200 words) This report presents results of geomorphic and landscape sediment assemblage mapping in the upper Anoka Sand Plain, Minnesota. The purpose is to provide a context for evaluating the geologic potential for both buried and surficial prehistoric cultural deposits in this reach of the Mississippi Valley. The project was done for the Minnesota Department of Transportation as an enhancement to the Mn/Model project. Mn/Model is a GIS database designed as a planning tool to help avoid pre-contact archaeological deposits.			
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Management Summary

This report presents results of geomorphic and landscape sediment assemblage mapping in the Anoka Sand Plain physiographic province, Minnesota. The purpose of the report is to provide a context for evaluating the geologic potential for buried and surface prehistoric cultural deposits in this region of Minnesota. The project was completed for the Minnesota Department of Transportation and Federal Highway Administration as an enhancement to the Mn/Model project in support of future cultural resource evaluation and mitigation projects.

The geomorphic mapping was conducted directly within the GIS project utilizing ArcMap software; U.S. Geological Survey (USGS) digital raster graphics of 7.5' quadrangle maps; scanned, orthorectified and georeferenced images of USGS NAPP color infrared high altitude aerial photography; scanned, orthorectified and georeferenced images of historic U.S. Department of Agriculture (USDA) black-and-white aerial photography; available USDA digital soil maps for Anoka, Hennepin, Isanti, Ramsey, Sherburne, and Wright counties; and, 10-meter interval digital elevation models. Delineation of landforms was completed by "heads-up" digitizing, and coding of landforms was conducted using the techniques and code key developed for Mn/Model geomorphology mapping (Hudak and Hajic 1999; Hajic et al. 2000). Thirteen (13) landscape sediment assemblages (LsSA's) are identified in the project area: undifferentiated uplands, glaciofluvial, catastrophic flood, valley terrace, floodplain, lacustrine, and valley margin. Thirty-four cores were collected to obtain datable material from, and to characterize, different Landform Sediment Assemblages (LfSA's). Sixteen radiocarbon samples were selected and assayed at Beta Analytic, Inc. radiocarbon laboratory using the accelerator mass spectrometer (AMS) technique. A history of landscape evolution was developed for the project area. LfSA's were then assigned a Landscape Suitability Ranking (LSR) for different depth intervals. The suitability ranking of an LfSA represents a measure of the potential for geological strata to contain and preserve cultural resources with respect to depositional and post-depositional environments and geologic age.

The main part of the Anoka Sand Plain in the Stacy Basin between the Mississippi and St. Croix Rivers, as well as remnants on the southwest side of the Mississippi River, is dominated by a collapsed sand plain landscape. Stagnant ice was buried by a substantial body of very fine sand sometime after about 12,000 C^{14}yrBP. The sand plain is comprised of multiple levels due to the collapse of underlying stagnant ice. Stages in the collapse include ice-walled lakes, linked depressions from glacial karst, and ice-block melt-out kettles. Four outwash plain levels also are represented. The youngest of the four is contemporaneous with the collapsed sand plain, and all are very late Wisconsin in age. The Holocene history of the project area takes place on the modified collapsed sand and outwash plain platform. The key early Holocene event is the development of lakes that in the middle Holocene evolve to wetland basins within the collapsed meltwater troughs, ice-block meltout depressions, and meltwater paleochannels. Long term fluctuations in precipitation shifted water levels with a concomitant shift in shore positions. As the shorelines migrated, so did the near-shore habitation and other sites used by the prehistoric

people. Streams tend to occupy reaches of collapsed meltwater troughs and meltwater paleochannels, but there are alluvial reaches as well. Terraces are very limited; the floodplain landscape is dominated by one or more meander belts. Higher levels of the collapsed sand and outwash plains were buried locally by isolated dunes to eolian dune fields on several occasions during the Middle Holocene to early-late Holocene.

The platform of collapsed sand plain and youngest two outwash plains is old enough to have cultural deposits of Middle Paleoindian and younger periods on its surface with little geologic potential for buried cultural deposits beneath this platform surface. Older, higher landscapes can have Early Paleoindian deposits on the land surface as well. However, a discontinuous eolian dune mantle can bury the collapsed sand plain and youngest two outwash plains, and any cultural deposits that pre-date the dunes. The geologic potential for buried cultural deposits on the plains beneath and within dunes, particularly Middle Archaic and older, is high. In addition to the dunes, another high geologic potential for burial and preservation of prehistoric cultural deposits is within basins of linked depressions, collapsed meltwater troughs, and former meltwater channels, especially around the basin margins.

1 Introduction

The Minnesota Department of Transportation (Mn/DOT) requested an assessment of the geomorphology and landform sediment assemblages (LfSAs) of the Anoka Sand Plain in the Stacy Basin, a basin north of the Twin Cities between the Mississippi River and St. Croix River valleys, plus sandy areas up and down the Mississippi Valley between Crow Wing State Park and the mouth of the Minnesota Valley that fell outside of previous Mississippi River Valley mapping (Figure 1). The assessment is an enhancement to the geomorphic contributions to Mn/Model (Hudak and Hajic 1999). This location is rapidly developing north and northwest of the Twin Cities. Results of the investigation will benefit planning and environmental assessment, particularly in the evaluation of prehistoric cultural resources for which the investigation is designed, but for other applications as well.

The Anoka Sand Plain project abuts two previous smaller project-specific geomorphic and LfSA study areas on the Anoka Sand Plain (Hajic 1999; Hudak and Hajic 1999). It also abuts two similarly assessed study reaches of the Mississippi River Valley between Brainard and the mouth of the Minnesota River Valley, one in the original Mn/Model (Hudak and Hajic 1999), and a previous Mn/Model enhancement project (Hajic 2002). Also, the project area has a small interface with the St Croix River Valley study area, which was geomorphically mapped and evaluated as part of the original Mn/Model (Hudak and Hajic 1999). Given this key geologic and geographic position, assessment of the Anoka Sand Plain will further our understanding of the landscape evolution of this rapidly developing part of the state, as well as some major river valleys, paleoenvironments, and the geologic potential for the burial and preservation of prehistoric cultural deposits.

2 Objectives

The objectives of the investigation are to:

- Build a GIS database for the project area useful for geomorphic mapping;
- Digitize (map) and describe the project area geomorphology and landform sediment assemblages (LfSA’s), and assess the age, stratigraphy and depositional environments of the LfSA’s; and
- Determine the geologic potential for the location, burial and preservation of intact prehistoric cultural deposits in terms of Landscape Suitability Rankings (LSR’s) for LfSA’s.

3 Quaternary Geologic Overview

The Anoka Sand Plain project area is defined primarily by the ecological boundary of Hanson and Hargrave (1996), developed under the guidance of the US Forest Service, and locally by the boundaries of previous Mn/Model geomorphic and LfSA mapping projects (Figure 1). Excluding previously mapped areas, the project area includes the majority remaining area of a sandy plain in a basin that slopes overall to the south and southeast between the Mississippi and St. Croix River valleys. It also includes a series of discontinuous areas of small to moderate size, mostly lower reaches of valleys, on either side of the Mississippi River Valley between Crow Wing State Park and the mouth of the Minnesota River Valley. Within this area, tributaries of the Mississippi and St. Croix rivers drain a largely collapsed glacial landscape. In the past, the project area was covered by two different glacial lobes during the Late Wisconsin Stage, but ice did not fully retreat from the basin. A sheet of generally fine grain sand was introduced into the basin, covering most of the area and leading to its name as a sand plain. Since deposition of the sand, the project location continued to undergo dynamic geologic and geomorphic changes from the latest Pleistocene to the present, albeit not at the magnitude of a glacial advance. Many of the geologic changes have implications for predicting the location of, finding, and interpreting the archaeological record. During the last two millennia of the Pleistocene, when Paleoindian people may have been in the area, these changes include the youngest glaciation, deglaciation and ice stagnation, and systematic collapse of stagnating ice; shifts in the activity and location of meltwater channels and establishment of new drainage systems; development of an extensive wetland and lacustrine system; and, responses to entrenchment of the Mississippi River into its valley, and to major downstream geomorphic events in the Minnesota and River Warren Valley, and St. Croix Valley.

To provide a Quaternary geologic context for the current investigation, the following paragraphs summarize the phases of late Quaternary landscape change for the project area and vicinity, based on conclusions of previous geologic investigations. The outline follows the narrative of Meyer (1998), but is augmented with some additional references. This outline serves as a starting point for further development of the history of landscape evolution of the basin between the Mississippi and St. Croix valleys.

- The Superior lobe of glacial ice advanced southwestward (St. Croix Phase) into the Stacy basin (Meyer 1998), which is a southwest–northeast oriented depression on Paleozoic bedrock (Mossler 1983) that extends from northeast Hennepin County to southwest Burnett County in Wisconsin. Ice then advanced to the position of the St. Croix moraine that surrounds the west, south and southeast sides of the basin and current project area (Figure 1). In parts of Stearns and Hennepin counties, ice pushed beyond the location of the modern Mississippi River, but in general the ice margin paralleled the east side of the current Mississippi River channel. North of the project area, meltwater flowed southward down the Long Prairie River and west of the western margin of the St. Croix moraine (Wright 1990). Meltwater cut numerous channels in the moraine in Dakota, Hennepin, Ramsey, Washington and Chisago counties, and ultimately drained into the Mississippi (Meyer 1992: Figure 3). Ice retreated and left an ice-cored St. Croix moraine.

- Glacial Lake Lind next formed behind the St. Croix Moraine over the Stacy basin (Johnson 1992). The southwestern part of the lake covered part of Hennepin County west of the present Mississippi River and north of Minneapolis. Reddish brown lake sediment with a Superior basin source was deposited in the lake over the next approximately one thousand years. Outlet locations of the lake are uncertain.

- The Superior Lobe readvanced southwestward (Automba Phase, Wright 1972; Wright et al. 1973) to at least the inner margins of the St. Croix Moraine, overriding Glacial Lake Lind sediment (Wright 1972; Clayton 1984; Johnson and Mooers 1998; Meyer 1998), and pushing west of the modern Mississippi River in Hennepin County. The lobe had a subglacial drainage system of tunnel valleys that in places cut channels beneath the bed of the ice (Wright 1972, 1973). Tunnel valley fans were deposited at the mouths of these streams at the St. Croix Moraine and in recessional positions (Patterson 1994). Glacial Lake Lind may have continued to exist up the valley of a precursor to the Mississippi (Meyer 1998). Ice then retreated back to the Superior basin.

- A lake re-formed as ice vacated the basin (Johnson 1999; Meyer 1998). The lake may have been a distinct basin, or may have been a continuation of Glacial Lake Lind. Outlet locations are uncertain, as is the timing of lake drainage relative to the advance of the Grantsburg Sublobe ice over the basin.

- The Grantsburg Sublobe of the Des Moines lobe advanced northeast across the Anoka Sand Plain project area (except for parts adjoining the Mississippi Valley north of about Becker), overriding the St. Croix Moraine on the west side of the Stacy basin, entering the basin, and stalling at the position of the Pine City Moraine (Hobbs and Goebel 1982). The shaded relief map developed for the current mapping project shows that the Pine City Moraine consists of a well-defined end moraine and several minor recessional moraines. The morphology also suggests ice terminated in at least three different stubby sublobes, with the eastern one perhaps arriving at, or readvancing to, its maximum position after the middle sublobe (Figure 1). The southeast flank of the Grantsburg sublobe followed the inner margin of the southeast flank of the ice-cored St. Croix Moraine. To the northwest, advancing ice blocked the Long Prairie River course, reversing flow to the north, then east and south to form an early course of the Mississippi River (Schneider 1961; Goldstein 1998). Ice crossed the location of the present Mississippi in the vicinity of easternmost Stearns County. Glacial Lake Grantsburg, a small proglacial lake, fronted advancing ice at this position for only about 100 years (Johnson 1994; Johnson and Hemstad 1998). However, when and at what ice position the lake originally formed depends on where the outlet of the preceding glacial lake was located (Meyer 1998). If located in the vicinity of the Mississippi River at the southwest end of the Stacy Basin, a lake would have formed as ice entered the basin. If located to the northeast, in the vicinity of the current St. Croix River valley, no lake would have formed until advancing ice blocked that valley outlet. Although Grantsburg sublobe meltwater is thought to have coursed through troughs in the St. Croix Moraine, no outlets for Glacial Lake Grantsburg have been identified, possibly because the outlet(s) was over the ice terminus (Cooper 1935) or beneath the ice (Meyer 1998). Ice retreated slightly, possibly opening outlets allowing the lake to drain through the St. Croix Moraine, before stagnating. Ultimately, meltwaters coursing down the Mississippi Valley northwest of the Grantsburg sublobe location are interpreted as having been diverted eastward across Sherburne and Anoka counties, then northeastward across Chisago County, before turning southward along the position of the St. Croix Valley (Meyer 1998: Figure 10). Wright (1972) estimated the age of advance of the Grantsburg sublobe to be about 16,000 C^{14}yrBP. Clayton and Moran (1982) estimated an age of 12,300 C^{14}yrBP. Meyer (1998:41) considers a radiocarbon age of about 11,900 yrBP that is from material stratigraphically below the till to be "somewhat younger than the probable age of the Grantsburg-sublobe maximum." He suggests either the silt beneath till from which dated material was retrieved was buried by till deposited by a late surge of the sublobe, or that the "till" represents mass wasting of stagnant ice debris.

- As the Grantsburg sublobe margin retreated, and then wasted, meltwater from the northern part of the lobe escaped eastward, then southward down the location of the St. Croix River Valley (Meyer 1998: Figures 9 and 10). The gap in the moraine in north Minneapolis through which the Mississippi River now flows presumably was not available for meltwater discharge at this time. Extensive sand deposits that form the Anoka Sand Plain in the Stacy basin originally were interpreted as outwash sand (Cooper 1935) derived from the retreat and wasting of the Grantsburg sublobe. Currently, these deposits are interpreted as lacustrine in origin (Stone 1965, 1966; Meyer 1985; Meyer and Hobbs 1989; Meyer and others 1990; Patterson 1992; Lehr 1992; Meyer and others 1993; Meyer 1993; Meyer 1998). Meltwaters coursing through the Stacy basin are believed to have been impounded by the Barrens fan (Meyer et al. 1993; Meyer 1998), an hypothesized alluvial fan believed to have emanated from the readvanced Superior Lobe ice, perhaps when ice occupied the position of the Nickerson Moraine (Wright 1972; Clayton 1984), in the position of the modern St. Croix Valley on the northeast side of the basin. Glacial Lake Anoka ensued, with two levels (Hugo and Fridley) recognized below its maximum level (Eginton 1975; Meyer and others 1990; Meyer 1993; 1998). Lake levels presumably were controlled by outlets in eastern Chisago County with drainage (catastrophic at times) down the St. Croix Valley. The morainal gap along the Mississippi River in north Minneapolis presumably had not yet opened. Meyer (1998) cites a radiocarbon age of 11,710 +/- 80 C^{14}yrBP (Beta-37418) on wood from sand below the area covered when the lake was at the Fridley level. The depth of the sample in sand is unclear, as is the relationship, if any, to till deposited by the Grantsburg sublobe. Final drainage of Glacial Lake Anoka occurred when a southern outlet in north Minneapolis opened (Meyer and Hobbs 1989), possibly by melting of stagnant ice occupying a buried valley (Meyer 1998). Hajic (2002) has presented additional radiocarbon evidence that suggests the north Minneapolis gap was open prior to Glacial River Warren (by about 10,700 C^{14}yrBP [Fisher 2001]) at the latest, possibly was open prior to about 11,880 C^{14}yrBP, and was almost certain open by about 11,470 C^{14}yrBP. If this is the case, then the latest history of the Stacy basin, namely Glacial Lake Anoka and its different levels, needs reevaluation, which we will do in part here by presenting an alternative hypothesis.

- With drainage of Glacial Lake Anoka, the Mississippi developed a broad, high "upper" terrace across part of the Anoka Sand Plain (Meyer 1998). In the Red River Valley, Lake Agassiz formed, episodically draining as Glacial River Warren through its southern outlet, episodically cutting and filling the Minnesota River Valley and the Mississippi Valley downstream of the tributary Mississippi River (Upham 1895; Teller and Clayton 1983; Clayton 1983; Matsch 1983; Kehew and Lord 1986; Smith and Fisher 1993; Johnson et al. 1998). Hudak and Hajic (1999) suggest that the majority of significant downcutting was not necessarily episodic, but could have occurred during a single catastrophic event. Glacial River Warren may have begun functioning around 11,700 C^{14}yrBP., based on a radiocarbon age associated with the Herman level of Glacial Lake Aggasiz (Teller 1985). When the Minnesota River Valley was tributary to Glacial River Warren, it was lowered to the "middle" terrace level (Meyer and Hobbs 1989; Meyer 1998). Wood and peat collected in 1923 (Cooper and Foot 1932), presumably related to slackwater deposits ponded in the lowest reach of the Mississippi Valley by Glacial River Warren (Meyer 1996), yielded radiocarbon ages of 11,790 +/- 200 C^{14}yrBP (W-454) and 10,200 +/- 300 C^{14}yrBP (W-445), respectively. Lower terraces were also built during later, more restricted flows of Glacial River Warren (Meyer et al. 1990; Meyer 1998). During downcutting of Glacial River Warren, St. Anthony Falls was initiated and migrated 7 miles upstream (Winchell and Upham 1888; Sardeson 1916; Wright 1990; Wright et al. 1998).

- The St. Croix Valley was cut from a high level to its present trench by catastrophic flooding of discharge out of the Lake Superior Basin simultaneously via the Brule and Kettle Rivers around 9,900 C^{14}yrBP (Hudak and Hajic 1999; Hajic and Hudak 2005).

4 Methods

Methods follow those outlined for Mn/Model geomorphological investigations (Hajic et al. 2000), modified to take advantage of methodological, technical and software advances. Available relevant literature and source data were assembled and assessed for utility toward mapping in the GIS and evaluating geologic models.

4.1 Data Acquisition

Multiple GIS basemap datasets were constructed for the project. Refer to Table 1 for data lineage and project coverage information.

Both Historical and modern color-infrared aerial photography mosaics were generated from individual 9x9-inch photo frames, to create seamless aerial photography basemap layers.

All basemap layers were projected to the UTM (Universal Transverse Mercator) Zone 15 coordinate system, with a horizontal datum of NAD83 (North American Datum 1983), and all units are established in meters.

4.2 GIS Workflow and Hardware/Software Setup

A combination of both desktop GIS and server-based GIS processing was utilized to complete the project. Due to the length of the project, the range of versions of ESRI's (Environmental Services Research Institute) ArcGIS Desktop, ArcSDE, and ArcGIS Server spanned from versions 9.1 to 9.3.

GIS desktop operations were performed on HP workstations with dual LCD displays. Server-based GIS operations consisted of versioned geodatabase replication, web-based GIS hosting (for project status site), and nightly geodatabase backups.

All features for the geomorphology layer were constructed through heads-up digitizing over various basemap layers and combinations at a minimum of 1:24,000 scale. Topology rules were developed and utilized during every editing session to detect and repair gaps and overlaps between features throughout the extent of the geomorphology layer.

4.3 Software Bugs and Temporary Workaround Procedures

During the early stages of the project, a serious ESRI software "bug" was suspected with version 9.1 and detected in version 9.2. The software bug created thousands of polygon slivers and gaps less than a scaled meter in width within the geomorphology feature class during topology validation. The software bug would maintain true curves (parametric curves) on the concave side of a shared polygon arc, but not on the convex side. Foth requested that ESRI support staff work on a corrective patch during the 6-month period after subsequently determining that the problems were caused by a bug. During that time, temporary workaround procedures had to be developed and employed by Foth staff to avoid generating sliver and gap polygons while continuing mapping operations. The effects of the software bug created significant project delays, and required extensive data repair operations to restore the geomorphology layer after the bug was fixed by ESRI in a stand-alone software patch.

4.4 Quality Control Checking

Quality control operations were performed on the statewide LfSA models as part of another project, checked and updated for attribute consistency against the most current LfSA Code Key listing. As a result, the Anoka Sand Plain project benefited from this extensive attribute quality control check operation, which was not possible because of software limitations during the earlier Anoka Sand Plain model productions. Various minor attribute value discrepancies were identified and corrected within the 28,000+ existing LFSA polygon attribute records. Examples of the minor discrepancies include: white spaces, missing hyphens, capital "O" in place of a zero, incorrect asterisk character count, etc. This operation was necessary to ensure that correct attribute values were assigned to all lookup table attribute records used by the custom map symbol assignment tools during the mapping stage of the project.

4.5 Custom Map Symbol Assignment Tools

To promote efficiency, accuracy, and ensure that the geomorphologists could focus their efforts on mapping instead of attribute management, a set of custom GIS tools were developed. The custom GIS tools utilize lookup tables and drop-down box user interfaces to nearly eliminate manual typing, and automate the task of assigning and creating new map symbol records as much as possible. This concept also guarantees uniqueness of new map symbols and code key values, and at the end of the project, makes it far easier to extract all new attribute records created during the project.

4.6 Digital Mapping

Heads-up digital mapping was conducted on-screen. In general, geomorphic mapping proceeded by layering various coverages in various degrees of transparency over a DEM or shaded relief base, toggling layers on and off as needed. Utility of the various photographic based layers varied by county and by landscape or landform. The earlier aerial photography, in particular, revealed detail in tonal contrasts with geomorphic implications that have since been lost with urbanization. However, margins of wetlands and lake levels vary between the historic photography and the later color infra-red (CIR) and color photography. LfSA polygons were tagged using the custom tools. The final geomorphology coverage had a final topology validated, and was smoothed, then edge-matched with mapping from earlier projects, and trimmed to the project boundary. Edge-matching with previous digital mapping was completed at the end of mapping. Advances in methods, techniques, available data layers, and interpretations between 1999 and now have created some discontinuities at adjoining project boundaries. Mapping or re-mapping of the various pre-existing and adjoining project areas can be updated to resolve these discontinuities at a later date. Modifying these pre-existing models was not part of our current scope of work.

The geomorphic mapping was digitally proofed by two different people for map labels, geomorphic location, and geologic continuity. The Map Unit (LfSA) Field Code Key was updated (Appendix A).

4.7 Groundtruth - Sediment/Soil Coring and Analysis

Because subsurface investigations would be limited, and the project area is large, the subsurface coring program targeted several landforms that are key to understanding terminal Wisconsin – very early Holocene landscape evolution within that part of the project area between the Mississippi and St. Croix Valleys. This period is critical because it is during this interval of time that the geologic underpinnings of the Holocene landscape are established. Subsequent geomorphic change would occur on the geologic platform established during this interval. Several different landforms were sampled in an attempt first and foremost to collect organic remains that would provide minimum ages or actual ages for some features in different parts of the basin. Sampling also was designed to begin to document the stratigraphy and sedimentology of underlying sediment assemblages of some landforms. Two transects of tightly spaced cores were taken to begin to understand depression margin stratigraphy and variability because these locations are seen as potentially important archaeologically, in particular because of the potential for buried soils, and thus buried prehistoric cultural deposits. Core locations were recorded with a Trimble GeoExplorer XH GPS unit.

Thirty-four solid continuous sediment/soil cores were collected with a track-mounted GeoProbe unit utilizing liners in a 1.23 m (4 ft) long barrel that is about 4.6 cm (2 in) in diameter. Recovery was generally good, but packing of sand and peat within the liners prevented cutting and full recovery in some cores. Liners were extracted from the barrel, capped and labeled. In the lab under uniform conditions, cores were removed from the liners, split longitudinally along natural planes of fracture and cleavage, and described by Curtis Hudak utilizing slightly modified standard pedologic and sedimentologic techniques and terminology (Scheoneberger et al., 2002). Core descriptions are located in Appendix B. Graphic sediment soil logs were constructed from the descriptions, and utilized in cross-sections.

Generally small samples of very fine organic material were extracted from cores. In some cases, sediment samples were washed through nested sieves to recover fine organic detritus. Residual organic material was rinsed with distilled water, air dried, and shipped to Beta Analytic for assay using the AMS technique. Radiocarbon laboratory data are in Appendix C.

4.8 Remote Sensing Analyses - Pilot Project for Buried Soils Detection

To augment the planned geomorphology mapping for this project, an ancillary pilot project was initiated. The pilot project involves attempting to detect buried soils through a combination of LANDSAT 7 ETM+, and RADARSAT 1 data utilization. Two LANDSAT scenes, and one RADARSAT scene were acquired, and extensive classification operations were performed on the data.

A training area in Anoka County was identified that included extensive depression margins, a depositional environment likely to have buried soils due to both colluvial wash off sandy basin sideslopes, and fluctuations in hydrologic conditions within the basin that resulted in extensive lateral movement of basin environments in the past. The mapped geomorphology layer polygons within this area were used to train the remote sensed data. Spatial relationships between pairs of map symbols within the geomorphology layer were used to isolate specific edges within the training area.

5 Landscape and Landform Sediment Assemblages

Thirteen landscapes are involved within the limits of the project area, including the Mississippi River Valley. Landscapes and the major landform sediment assemblages (LfSA) within each landscape are outlined below, in general from oldest to youngest.

5.1 Active Ice Landscape (Superior Lobe)

The project area is surrounded mostly by till and morainal topography of the Superior lobe, and in some places, the Anoka Sand Plain boundary crosses into this landscape. Thus, small parts of the St. Croix end moraine, and the Pierz Drumlin Field of the ground moraine to the north are mapped in the model. The Superior lobe till is sandy and stony, exhibits a characteristic reddish brown color, and belongs to the Cromwell Formation (Wright 1970).

Many units are related to the Pierz Drumlin Field. The northern boundary of the project area in parts of Benton, Sherburne and Mille Lacs counties more or less corresponds with the boundary of the Pierz Drumlin Field. Much of this boundary has been accentuated by truncation caused by past meltwater stream activities. Along this meltwater-modified boundary, drumlins (IDRX:21), relatively steep hillslopes developed on truncated drumlins (IHX:21), inter-drumlin troughs (IIDX:21), and some supporting wetland deposits (IIDMA<X:21), fall within the project area. Also in this area, there are two benches eroded into Superior Lobe till by meltwater channels. Meltwater-modified drumlins (IDRTX:21) rise above these flood-scoured plains, and drumlins occur between some meltwater channels. Some smaller isolated hummocks of Superior lobe till rise above other surfaces and these are simply mapped as undifferentiated hummocks (IHUX:21).

5.2 Meltwater Trough Fan Landscape (Superior Lobe)

In the vicinity of some termini of the collapsed meltwater troughs (see Collapsed Meltwater Trough Landscape discussion below), Patterson (1994) has identified tunnel valley fans consisting of irregular, generally elongated deposits of sand and gravel with thin lenses of Superior Lobe till that are generally elongated parallel with the collapsed meltwater trough landscape. They usually rise above the surrounding, younger sand plain; larger meltwater trough fans are the highest features projecting above the sand plain. These features were also interpreted to compose much of the terminal St. Croix moraine, and were further identified in terminal extra-morainic positions and in association with recessional moraines (Patterson 1994).

The largest meltwater trough fan in the project area, the Elk River fan complex (Patterson 1994), is located on either side of the central to southern part of the eastern boundary of Sherburne County. The fan may have originally extended southwest to a position just southwest of the later highest terrace of the Mississippi Valley as well. It is considered to have been fed by three different tunnel valleys at various times; at least two morphologically distinct fans are evident. The eastern and youngest fan, referred to as the Blue Lake fan (Patterson 1994), spans the Isanti – Anoka County boundary immediately east of the Sherburne County boundary. The Blue Lake fan is characterized by crude ridges, oriented with the collapsed meltwater troughs, that are eroded into smaller, sometimes oriented hills with relatively steep and short hillslopes. Overall, the hilly landscape is mapped as MFHX:21. Toward the south, the fan is mantled by younger till of the Grantsburg Sublobe and is mapped with the stagnant ice landscape of that younger sublobe. At the southern end of the Blue Lake fan there is a series of short, narrow ridges in lower landscape positions, apparently between, and possibly climbing onto the flanks of, some isolated remnants of the fan. The ridges might be esker segments related to the younger (Grantsburg Sublobe) field of eskers to the west-southwest. Small depressions on this large meltwater trough fan are numerous, but most are too small to map. Depressions large enough to map are differentiated on the basis of the type and thickness of material overlying sand and gravel. Marshes occupy some of the depressions, and less than 1 m of peat or organic muck is interpreted to overlie sand and gravel (MFDMA<X:21). Where sand to loam overlies sand and gravel, the depression is mapped as MFD<X:21.

The larger western part of the fan complex contrasts sharply with the morphology of the Blue Lake fan. On both its larger northern remnant and smaller southern remnant it has a broad top of comparatively low relief (MFPX:21) marked by few shallow depressions (MFD<X:21). Surrounding hillslopes (MFHX:21) are relatively steep. To the north, the northern remnant descends to a lower level of the complex that exhibits more relief due to a series of depressions of modest size that host marshes and lakes. In addition to the aforementioned depression map units, MFDMAX:21 is used in this area to distinguish those depressions with more than 2 m of peat and muck. There also is one relatively small kettle lake.

From this surface, there is a slight descent northward to another distinct geomorphic surface of limited area to the north. It is distinguished from the previously described surface by a narrow, arcuate depression. Beneath this lower surface, glaciofluvial sand of the Grantsburg Sublobe overlies a veneer of meltwater trough fan sand-and-gravel over Superior Lobe till. This lower surface is pitted mostly by small depressions. However, there are a few slightly larger depressions. Depressions are mapped as previously noted.

There are other, smaller, meltwater trough fans that are similarly mapped, some of which are overlain by till deposited by the Grantsburg Sublobe. The smallest of these meltwater trough fans are considered hummocks (MFHUX:21). The area of meltwater trough fans may be greater than it appears in the model where mapped Grantsburg Sublobe till overlies fan deposits.

5.3 Glaciofluvial Landscape (Superior Lobe)

The Cromwell Formation also includes outwash from the Lake Superior Lobe till. The outwash is a minor component of the current project area. There are several segments of outwash plains (OPX:21) within the project boundary. Outwash ranges from a thin veneer over till to thick sequences found locally along the margins of the east side of the Mississippi Valley, and to thick sequences within the northeastern part of the Anoka Sand Plain where it can be scoured by later meltwater channels. Locally, relatively steep hillslopes are developed in the outwash (OHX:21). Depressions on the outwash reflect the type and thickness of post-outwash fill: ODMAX:21 for peat greater than 2 m thick; ODMA<X:21 for peat less than 1 m thick; ODBX:21 for poorly drained coarse material <1 m thick; and ODX:21 for well drained coarse material <1 m thick.

5.4 Stagnant Ice Landscape (Grantsburg Sublobe)

Loamy till deposited by the Grantsburg Sublobe, the New Ulm Formation (Matsch 1972; Meyer and Patterson 1997), is generally thin. Within the Stacy Basin it is usually buried, but is exposed on the flank of the St. Croix end moraine on the west side of the Mississippi River. Exceptions are where remnants overlie Superior Lobe till and various ice-contact deposits such as those of the Superior Lobe meltwater trough fan landscape. The till is mapped as either hills (SH:21) or hummocks (SHU:21). In these positions, there may also be depressions on the till. Depressions on the till reflect the type and thickness of fill that accumulated through time: SDMA:21 for peat greater than 2 m thick; SDMA<:21 for peat less than 1 m thick; SDB:21 for poorly drained coarse material <1 m thick; and, SD:21 for well drained coarse material <1 m thick.

To the north of the basin, where distinct and indistinct lobes of the Grantsburg sublobe advanced, there are defined moraines and more subtle minor or 'push' moraines behind the end moraine. The few areas where they fall within the project area are treated simply as an undifferentiated plain (SP:21). Along the west side of the Mississippi River Valley, there are also areas where till of the Grantsburg Sublobe overlie the earlier St. Croix end moraine. These are mapped as either hills, hummocks or undifferentiated moraine.

5.5 Ice-Contact Landscape (Grantsburg Sublobe)

On the west side of the Elk River tunnel valley fan, actually within a collapsed meltwater trough, there is a belt of coarse material. The morphologically striking part of the belt exhibits a series of parallel to subparallel narrow esker-like ridges. Although there are other possible origins, such as a series of ice-marginal valleys (David Mickelson, personal communication, June, 2009), or a kame terrace, they are here considered eskers (NEK:21), although individual ridges are not distinguished. Other parts of the belt are simply mapped as undifferentiated hills (NH:21). Eskers also occur on the southeast side of the Elk River tunnel valley fan, in places overtopping hills associated with the fan.

There is a distinct series of kettle lakes, ice contact in origin, which are differentiated and discussed under the lacustrine landscape.

5.6 Glaciofluvial Landscape (Grantsburg Sublobe; Contemporaneous and Younger Mississippi Valley)

Northeast of the Mississippi River Valley, there are essentially four levels of outwash plain. The oldest occurs as a high bench, is located just south of the Pierz Drumlin Field in western Sherburne and southern Benton Counties, and has drumlins protruding through the channeled surface which is developed on till of the Superior Lobe. Original inter-drumlin troughs were modified by younger outwash. To the east, also crossing the Sherburne – Benton County line is a similar smaller and narrower bench that lies at a slightly lower elevation and lacks the strong protruding drumlin forms. The next youngest surface occurs to the east of this bench, and continues to the east across what was probably the width of a sublobe of the Grantsburg Sublobe. The LfSA associated with this surface is comprised of outwash that drained southward and southwestward behind the terminal ice position. There is a west to east trending meltwater channel that heads eastward from area. The youngest outwash plain is the largest, south of the next-to-youngest outwash plain, and distinguished from it by a multi-threaded meltwater channel. The west end of the youngest plain is truncated and inset by the highest outwash plain in the Mississippi Valley, although at the head of the youngest plain in this location, the oldest braids of the highest Mississippi Valley outwash plain appear to head into the project area. This youngest plain is marked by features of meltwater flow, and is cut by one or more meltwater channels. All outwash plains essentially represent ice-marginal streams between higher ground to the north and stagnating ice to the south. Each of the two younger plains have some areas that are collapsed. On the lowest plain, the collapsed area is toward the south and east. On the east side of the collapsed part of the lowest plain, there is an indistinct boundary with the collapsed sand plain landscape that comprises most of the landscape in the Stacy basin. Some east – west oriented meltwater channels extend in segments across the north part of this plain. They appear to be temporally most closely related to the two youngest outwash plains in the basin.

Where not in an obvious dune field, eolian sand (dunes, discontinuous sheets) mantles the two youngest outwash surfaces and is considered as an overlying discontinuous deposit.

Major landforms associated with these four outwash surfaces are generally similar. Rather than list four different versions of the same map label, the number sign (#) will be substituted for the number (relative age, database Code Number 25) of the outwash plain level in this more generic description. Similarly, in the following, a ‘C’ is inserted into all map labels for those parts of the youngest two levels that are collapsed. Coarse texture is to be assumed unless otherwise noted in the labeling. Where not in an obvious dune field, eolian sand (isolated dunes, discontinuous sheets; denoted with an ‘E’ in the labels) mantles the two youngest outwash surfaces and is considered as an overlying discontinuous deposit.

Northeast of the Mississippi Valley, the main elements of outwash surfaces are plains and meltwater channels. In general, the outwash plains are mapped as OP#:21. Where discontinuous eolian dunes or sand sheets are present, the map label is OPE#:21. There are places where outwash is relatively thin over older surfaces (OP<#:21; OP<E#:21). Locally, the arrangement of dunes resulted in shallow depressions and or poorly drained swales (ODE#:21; ODMA#:21; ODMA<#:21) on the two youngest outwash plains. Meltwater channels are treated as paleochannels (OPC#:21). They can have a sandy floor, or have a range of thickness of overlying wetland deposits: OPCMA#:21 for peat greater than 2 m thick; and, OPCMA<#:21 for peat less than 1 m thick. Where depressions are present in the floor of the channels, they can have a similar range in thickness of secondary fill: ODMA#:21 for peat greater than 2 m thick; ODMA<#:21 for peat less than 1 m thick; ODB#:21 for poorly drained coarse material <1 m thick; and, OD#:21 for well drained coarse material <1 m thick.

Elsewhere in the project area around the edges of the previously mapped reaches of the Mississippi Valley, there are remnants of outwash plains (OP:21; OPX:21 for Superior Lobe outwash), and outwash terraces of both the Mississippi and tributary valleys (OT:21; OT#:21) that once served as outwash streams. Terrace ordering in this project and other adjacent project areas has yet to be formally unified with the Mississippi Valley terraces. Depressions that occur on the terrace surfaces use the same labeling scheme as above.

5.7 Collapsed Sand Plain Landscape

Formerly in Mn/Model mapping projects, the Anoka Sand Plain was treated as a combination of stagnant ice and glaciofluvial landscapes (Hudak and Hajic 1999; Hajic and Hudak 1999). The Minnesota Geological Survey considers it basically to be a lake plain of Glacial Lake Anoka, with the main body of sand having been deposited in the lake from Grantsburg Lobe meltwaters (Meyer 1993; Meyer et al. 1993; Meyer and Hobbs 1993; Meyer 1998). Because sedimentological documentation of the origin of the sand is sparsely developed, we have taken a more conservative, descriptive approach here, simply referring to that part of the Anoka Sand Plain lacking obvious outwash features as a Collapsed Sand Plain. Regardless of the original depositional environment of the body of sand in the Stacy Basin, be it glaciofluvial, lacustrine, a combination of the two, or some additional set of processes, the morphologic form of the plain is due to the wastage of buried ice resulting in differential collapse. Thus it is treated as a collapsed sand plain landscape rather than included in the stagnant ice landscape, or a lacustrine landscape. This landscape accounts for the majority of the Anoka Sand Plain between the Mississippi and St. Croix Valleys. Other sandy areas within the project area beyond the Stacy Basin are mostly related to glaciofluvial activity of tributaries, with main surfaces appearing to accord with the lowest outwash plain on the east side of the Mississippi River, and the Mississippi River operating at mostly lower levels of the landscape.

In the Stacy Basin, although individual landform shapes tend to be irregular in form, the main landforms reflect an overall pattern of landscape evolution with progressive ice melting and collapse. Positive features in the Collapsed Sand Plain landscape were once the beds of ice-walled lakes. Linked depressions probably reflect the subsequent development of a glacial karst system. The transition was complex as both positive features and depressions occur at multiple levels locally. In turn, kettle lakes (LK), pocked the plain as final ice blocks melted. The collapsed sand plain is further complicated as it was modified by eolian reworking of the surficial sand.

Positive areas constitute a plain (DPE:21) and are inset below outwash and ice contact landscapes of the earlier St. Croix phase of the Superior Lobe. On a sub-regional level, the positive landscape areas are divided into distinct tracts defined by some of the collapsed meltwater troughs, larger meltwater channels, and alluvial valley segments. Some hillslopes are extensive and steep enough along these linear features to differentiate them in mapping (DH:21). Overall texture of the landscape within a tract, defined by the orientation, spacing and relief of landforms, can vary among different tracts across the basin. These differences in landscape texture among some tracts suggest some underlying factors, beyond simply the melting of ice, were established prior to emplacement of the sand body and controlled to some degree some aspects of the evolution of the collapsed sand plain. Nevertheless, the landform elements remain similar among the different tracts.

Within a given tract of the plain, local positive features tend to be comprised of one to three levels, with intervening transitions ranging between well defined discontinuous steps to gentle slopes. Some of these levels are distinguished in the mapping, but not the labeling of the polygons; thus some adjacent polygons can share the same map attributes. The highest local level is variable in plan view form, ranging from ovoid to a segment of an oval to irregular to having one or multiple rather straight bounding segments. More often than not, where eolian dunes are minimal, surface relief of the highest local levels is relatively flat to shallow basinal, typical of relict ice-walled lake beds. Regardless of whether eolian dunes are present, usually isolated, discontinuous hills often ring parts or all of the outer limits of the highest level, also a feature that can be common to relict ice-walled lakes. More continuous slightly higher areas occur on occasion, and may have a preferred orientation, sometimes independent of depression boundaries. This combined highest level makes up the bulk of the positive aspect of the collapsed sand plain landscape. Lower positive levels share similar relief characteristics, although tend to be less regular. Regardless of the number of levels, the lowest level tends to have fewer hills projecting above that level of the plain.

Aside from the just-mentioned hills, the plain has a largely discontinuous cover of eolian dunes, and may also have localized sweeps of sand sheet. There are areas of substantial dune accumulation, discussed later as an eolian landscape. However, there are also patterns seen on early black and white aerial photographs that are more difficult to explain by eolian processes and appear to be more related to ice stagnation.

Within a given tract, depressions at a range of scale occur across the plain. They are abundant throughout nearly all of the collapsed sand plain, but cover the greatest area in Anoka and southern Isanti Counties, in the area covered by Grantsburg Sublobe ice, as well as the preceding Superior Lobe of ice that entered the basin during the Automba Phase. Some fraction of the apparent changing frequencies of depressional areas must in part be due simply to the overall south and southeast slope of the landscape and thus a relatively higher intersection of the landscape with the shallow groundwater system in the downslope direction. Depressions range in size from over 6 km^2 to less than 1000 m^2; the smallest depressions were not mapped. If interconnected basins are considered, some basins within a tract can eclipse tens of square kilometers in area.

Depressions range from ovoid to irregular in form, a trend that tends to increase with size of the depression. The smallest depressions are almost entirely ovoid in form and identified at all positive levels of the landscape. Slightly larger depressions have margins defined by multiple arcuate segments. These types of depressions are distinguishable at all positive levels of the plain as well, but tend to be isolated only on the highest positive levels of the plain. Some of these can have a linear trend. From these forms, there is then a pattern of linkage between depressions of progressively larger size down the landscape in the style of linked depression systems associated with glacial kart (Kemmis 1991). Linkages among depression basins range from saddles and sills through short drainageways and slightly broader connections now occupied by wetlands. The linkages between smaller basins are for the most part relict in the higher parts of the landscape. Linkages between larger basins where no stream is present today are typically ditched. In this manner, smaller depressions are linked to progressively larger depressions at progressively lower local levels of the landscape. To a large degree, this discussion applies to depressions of the collapsed parts of the lower two outwash plains of the glacialfluvial landscape (Grantsburg Sublobe) as well.

Individually or collectively, the shape, orientation, distribution and pattern of linked depressions, beyond the limits of the previously discussed outwash plain landscapes and discussion of the meltwater trough landscape to follow, reflects some structural or other form of control. For example, in Anoka County, in the tract southeast of the meltwater trough occupied by Cedar Creek and northwest of the middle chain of kettle lakes, where depressions account for a large area of the collapsed sand plain, the depressions form a pattern of concentric arcs, with the convex part of the arc pointing to the southwest. In the northeastern third or so of this pattern, the orientation of the southeast limbs of these arcs shift somewhat. Overall, the pattern suggests a relationship between the coarser arrangement of linked depressions and structure influencing collapse of the Superior Lobe ice of the Automba Phase. This patterning may or may not have been significant to the activities of prehistoric inhabitants.

Wetlands occupy, or occupied, all of the larger, lower depressions, and some of the smaller and higher depressions. Lakes generally much smaller in area than the depressions they occupy, are not uncommon in the depressions of intermediate to larger size. In our view, the likely resource-rich depressions, and particularly depression margins, are of particular potential significance to the archaeological record. The margins are the interface between better drained higher ground and the depressions and thus a likely focus for food-related activities, among others. However, the position of depression resources and depression margins can vary spatially from depression to depression. Furthermore, they would not have been static in the past, but rather would have varied among basins due to differing basin geometries coupled with the effects on water level due to changing climatic and water table conditions. Relict beach ridges within some of the larger basins, coprogenous and marly lake sediment seen in cores and inferred from soil series descriptions attest to higher water levels in depressions in the past. A wetter period or simply accumulation of depression sediment through time, organic or otherwise, could result in burial and preservation of any potential prehistoric cultural deposits that were discarded at basin margins of an earlier time when water or wetland levels were lower.

Because of the potential significance of depression margins and basin geometry to fully understanding the archaeological record, most basins were mapped as three distinct landforms related to the presence, absence, and thickness of wetland and lacustrine deposits, using patterns evident on aerial photography and mapped soil series.

Distinguishing these different linked depression subdivisions follows the same conventions as for other depressions in other landscapes: DLDMA:21 for peat greater than 2 m thick; DLDMA<:21 for peat less than 1 m thick; DLDB:21 for poorly drained coarse material <1 m thick; and, DLD:21 for well drained coarse material <1 m thick. Individual depressions are not specified as linked depressions.

5.8 Collapsed Meltwater Trough Landscape

A series of northeast – southwest trending troughs crosses the project area (Wright and Rubin 1956, Lehr 1991, Mooers 1989, Savina et al. 1979, Goebel et al. 1983, Patterson 1992, Meyer 1993, Meyer and Hobbs 1993). At a coarse scale, the troughs are more or less linear and for the most part parallel with one another across the project area. At an even coarser scale, the troughs radiate from the southwest tip of Lake Superior southwestward to, and across, the Mississippi River Valley in the vicinity of the Twin Cities and northward, basically within the area overridden by the Superior Lobe of Late Wisconsin ice (Wright, 1973). At the coarse scale, troughs tend to be extensive yet still discontinuous, but in the more distal position they tend to be more numerous and relatively short. In the northern third and western part of the project area, troughs intersect with outwash channels and are crossed in places by stream valleys, partitioning the project area into an irregular grid. Although reflecting conditions established during advance of the Superior Lobe ice during the St. Croix phase, collapse and expression of the troughs appear to be coeval with, and/or post-date, the outwash channels.

Originally referred to as “drainageways” (Wright 1956), and then interpreted as subglacial channels (Cushing 1963), the troughs are currently referred to as tunnel valleys that formed beneath the Superior Lobe during catastrophic discharges of stored basal meltwater and subsequently collapsed from melting of later Grantsburg Sublobe ice that filled the valleys (Wright 1973). Patterson (1994) refers to the troughs resulting from collapse of the subglacial drainageways as ‘tunnel valleys,’ but her use of the term is intended to describe the landform as opposed to carrying any of the genetic implications which the term ‘tunnel valley’ can convey. Here, the more descriptive term ‘collapsed meltwater trough’ is used to refer to the landscape generated from collapse related to these subglacial ice contact drainageways. Treating the troughs at the landscape scale acknowledges that they are composed of a range of landforms, related both to original collapse as well as subsequent modification by potentially younger glaciofluvial processes, followed by alluvial, colluvial and lacustrine processes. Furthermore, collapsed meltwater troughs were likely important to prehistoric inhabitants of the sand plain because of the varied and resource-rich environments within the troughs, including a strong association with the relative large and deep kettle lakes.

Trough morphology varies. Some are defined primarily by a string of ovoid ice block meltout kettles and associated basins, often with kettle basins oriented with long axes in line with the overall trough trend and often at contrasting orientations with other landscape features into which they are set. Some are short, relatively shallow, with gradual to steep trough walls. Others are characterized by a more continuously and sharply defined trough or valley bounded by steep walls that can be greater than 15 m in height. In plan view, trough width and trough wall form are irregular; original tunnel valley widths have generally been interpreted to be slightly wider than the currently expressed troughs to encompass this valley wall variation. In this mapping project, however, only the physically expressed troughs, and not the inferred limits of former tunnel valleys, are mapped in this landscape.

A range of features result in the variability seen in trough form both within a single trough and among troughs. These features include protrusions from trough walls, beading of the trough, relict valley wall slumps, intersections with previously formed depressions, ovoid basins from late ice-block meltout, relict eskers, and isolated hummocks within troughs, originally probably with an ice-contact origin. Further modifications are introduced by younger watercourses that occupy reaches of some troughs. Benches may represent outwash terraces or exhumed kame terrace remnants.

Within the troughs, primary landforms are depressions, eskers, and hummocks that could be kame terrace remnants, or broader eskers. Depressions are what give the meltwater troughs their essential form. Their distribution appears discontinuous, in part because of the irregular form of trough walls, but also because substantial areas of trough floors are mapped with the younger floodplain landscape where streams flow through troughs, and the lacustrine landscape. Depressions are differentiated on the basis of thickness and type of material that underlies them. Where peat or organic muck is greater than 2 m thick, the depression is mapped as TDMA:21. Where peat or organic muck is less than 1 m thick and overlies sand, it is mapped as TDMA<:21. Where sand underlies the floor of the trough, it may represent outwash, ice contact material, or even washed wall slump. At this point, the landform is still considered to be a depression. Where poorly drained and underlain by sand, the depression is mapped as TDB21, and where somewhat better drained, as TD:21.

Segments of eskers (TEK:21) are evident within lower reaches of several of the meltwater troughs. In general, the long, narrow ridges with some degree of sinuosity are mapped as eskers, using various MNGS maps as a guide. Broader and/or shorter segments of ridges within meltwater troughs could be esker remnants or kame terraces. Here, they are mapped using the descriptive term hummock (THU:21).

5.9 Valley Terrace Landscape

Streams within the Stacy Basin exhibit few terrace remnants. Where present, they are generally small in area and limited to the largest few watercourses. Two levels were identified: VT1 and VT2.

5.10 Floodplain Landscape

Collapse of the sand plain affected the development of the Holocene surface drainage system as well as the subsurface drainage system. Lowest order elements of the surface drainage tend to be short connections between depressions, and steeper, yet still relatively short drainageways along tract margins into meltwater troughs and larger order stream valleys. The overall course of larger order elements of the surface drainage system across the Anoka Sand Plain is almost entirely inherited from pre-Holocene glacial and outwash trends, although there are some alluvial valley segments of larger streams that jump from one collapsed meltwater trough to another.

From the west side of the Anoka Sand Plain, east of the Mississippi River valley, east to the Elk River tunnel valley fan, and south of the Rum River, streams cross the plain oriented a little west of south, for the most part normal to the trend of former meltwater channels higher in the basin to the north. The Rum River and streams to the east, south of the meltwater channels occupied in part by West Branch Sunrise River and South Branch Sunrise River, flow toward the southwest. In both cases, most of these south to southwest flowing streams occupy collapsed meltwater troughs for much of their reaches in the project area, with waters making their way to the Mississippi River. In the northeast part of the project area, various branches of the Sunrise River flow eastward and northeastward to the St. Croix River Valley.

Most rivers and creeks draining the Anoka Sand Plain are too narrow to map, but several river channels (FR:21) are wide enough for mapping. The largest river crossing the Anoka Sand Plain is the Rum River. It flows southward in one of the meltwater troughs through the town of Milaca on the south flank of Superior Lobe till, and then into the project area through the lower west flank of the moraine deposited by the Grantsburg sublobe. The Rum River is joined from the west by the West Branch. At the town of Princeton, it is captured by a former meltwater channel crossing the collapsed glaciofluvial landscape and heads eastward to where it angles sharply southward in another meltwater trough. From there it heads south-southwest, jumps southward where it hits a discontinuity in the meltwater trough to flow in what appears to be a mostly alluvial cut valley segment. Upon encountering the next meltwater trough to the south, it angles within it to the southwest for a short reach before heading southward again to the Mississippi River in another reach of what appears to be an alluvial valley. When within meltwater troughs, the river at times courses through linear wetlands and enters and exits kettle lake basins. This occurs with smaller creeks and their meander belts as well. Other creek channels large enough to map that ultimately flow to the Mississippi River via the Elk River are Lilly Creek (the outlet of Rush Lake), the unnamed outlet of Eagle Lake, and the St. Francis River. The St. Francis River occupies one of the meltwater troughs immediately south of Elk Lake where it is joined by Bottle Brook, a tributary. One tributary of the St. Croix River, the North Branch Sunrise River, has a channel wide enough to map.

There are a number of narrower rivers that cross parts of the Anoka Sand Plain that flow in definable meander belts. The larger rivers also exhibit meander belts. In most cases, these meander belts are active as opposed to relict. In some valleys and troughs, two meander belts, an older and a younger, are evident. Faint traces of meander belts are seen coursing through some of the larger depressions, and it is likely they were more extensive than mapped here. Meander belts are distinguished in the mapping based primarily on the apparent sediment sequences: FMBC>>:21 for coarse textures in the alluvium greater than 2 m thick; FMBC<:21 for coarse alluvium less than 1 m thick; FMBFC>>:21, FMBFC>>1:21, and FMBFC>>2:21 for fine over coarse alluvium >2 m thick; FMBFC<:21 for fine over coarse alluvium <1 m thick; FMBF>>:21 for fine alluvium > 2 m thick; FMBF<:21 for fine alluvium <1 m thick; FMBMAPC>>:21 and FMBPC>>:21 for peat over coarse alluvium >2 m thick, with or without a marsh; FMBMAPC<:21 for peat over coarse alluvium <1 m thick; and, FMBMAP>>:21, FMBMAP>>1:21, and FMBMAP>>2:21 for peat > 2 m thick.

Floodplain segments in many valleys are sparse because of the extent of meander belts. Variations on type x (FFX:21) and type y (FFY:21) floodplains are present in limited areas. There are also some areas of floodplain undifferentiated beyond texture.

Paleochannels (FPCFC<<:21) are present in the way of cutoff meanders in the few larger rivers in the project area, but only a small fraction of these are distinguished. Floodplain backwater lakes (FLNFC>>:21) are rare.

5.11 Lacustrine Landscape

The lacustrine landscape is limited in this report to extant lakes (LNF>>:21), modern and relict beaches (LSHC>>1:21, LSHC>>2:21, respectively), deltas (LDEF>>:21) and some reservoirs (LLRF>>:21). Lakes are found throughout most of the Anoka Sand Plain. They are most common in linked depressions where they can occur at different levels in the landscape, but are usually in the lowest landscape position. Excluding kettle lakes, lakes generally occupy a small percentage of the linked depressions that they occupy, with the exception of some lakes in small basins in higher landscape position. In some of the larger linked depressions, there are relict beach ridges (LSHC>>2:21) beyond modern lake margins. Some linked depressions undoubtedly hosted lakes in the past larger than today, but they are treated as linked depressions rather than relict lake beds. Coupled with lacustrine deposits identified in some basins from coring, or inferred from soil series descriptions, the relict beach ridges point to more extensive lakes in the past. Lakes also occur in some reaches of abandoned meltwater channels and in the meltwater trough landscape where many, but not all, of the kettle lakes occur. On that part of the oldest outwash plain cut into Superior Lobe till, there are several small relict lake beds (LLBC<:21) that filtered coarse sediment drained off the Superior Lobe by low order valleys. In the same vicinity, there is another relict lake bed (LLBF>>:21) in a shallow basin behind some scoured Superior Lobe drumlins. Backwater lakes in floodplains are considered part of the floodplain landscape.

Kettle lakes (LK:21) that fill or nearly fill clearly definable ovoid basins (LDK:21) are distinguished because of their distinct form, origin and relatively great depth. Additionally, they have significance to both evolution of the collapsed meltwater troughs and understanding prehistoric settlement patterns. Most, but not all, of the kettle lakes occur along the lines of collapsed meltwater troughs and are elongated within and parallel to the troughs. This led to the interpretation that Grantsburg Sublobe ice was forced into the troughs as it advanced, and then wasted to help give the troughs their current surface expression (Wright, 1973). The kettle lakes are inset into, and therefore younger than, linked depressions of the collapsed sand plain landscape.

The kettle lakes are further distinguished from other lakes occupying linked depressions by their morphology and the morphology of their basins. The lakes tend to fill most of the basin they occupy. Both the lakes and basins tend to be ovoid in form with smoother curvilinear boundaries than other lakes in the region, and relatively deep. Bathymetry maps of some of the basins suggest some may have related ice-block kame terraces below water levels. Where kettle lakes are not immediately against their basin wall, the intervening depression (LDKMA:21; LDKMA<:21) is occupied by wetland, generally underlain by peat or organic muck in excess of 2 m thick.

Because Holocene creeks and rivers utilized reaches of some of the meltwater troughs within which many kettle lakes formed, the later watercourses deposited deltas (LDEF>>:21) at the heads of some of the kettle lakes.

5.12 Eolian Landscape

The collapsed sand plain and glaciofluvial landscapes are generally covered discontinuously by eolian dunes and possibly in places a thin veneer of sheet sand. Dunes appear to decrease in the northernmost part of the Anoka Sand Plain, and are absent, or nearly so, on the higher glaciofluvial benches where meltwater channels are cut into drumlinized till of the Superior Lobe. In east-central Sherburne County in and around Sand Dunes State Park, and western Anoka County, there are distinguishable dune fields (EED:21). In the former location, dunes have encroached into the west side of the large collapsed meltwater trough mouth that is west of the Elk River tunnel valley fan complex. The dune field locations are close to and downwind of the Mississippi Valley, but the collapsed sand and outwash plain landscapes could have served as sand sources as well. Within the Sherburne County dune fields, eolian sand can be in excess of 10 m thick, and some of the steeper, taller dune hillslopes are distinguished in the mapping (EH:21). Dune fields are not as thick in Anoka County. In some locations, depressions formed within the dune fields, in some cases supporting ponds or wetlands. Depressions range from having less than a meter of peat and organic material (EDMA:21) or fine material (ED<:21) over sand to simply sand throughout (ED:21).

5.13 Valley Margin Landscape

At the interface between the truncated foot of the Superior Lobe till and the two highest glacialfluvial surfaces, there are a couple of features on the latter that appear to be fans. Until further investigation, they are considered alluvial fans (MAF:21), but it is possible, given the extent of Glacial Lake Grantsburg, that they could be fan deltas as well. Relict distributary channels (MPC:21) are evident on the main example of this feature.

6 Sedimentology and Stratigraphy of the Anoka Sand Plain

The limited coring program was designed to sample beneath different surfaces across the project area in an effort to 1) examine, although preliminarily, sediment assemblages of the collapsed sand plain landscape; 2) obtain datable material to provide minimum ages for certain features and deposits, and information on the timing of landscape evolution; and, 3) examine in slightly more detail depression margins, in part to provide information for the investigation of the utility of RSAT imagery to identify and classify boundary characteristics that was initiated in preliminary form during the project. Cores were taken in ten (10) areas, for the most part focusing on the collapsed sand plain landscape and meltwater channels.

6.1 Area 1

Four cores were taken in Area 1 located in the southeasternmost collapsed meltwater trough in the vicinity of Rice Creek Chain of Lakes County Regional Park (Figure 2), an area relatively rich in known archaeological sites. Three cores were located in a depression on the trough floor between kettle lakes, and the forth was taken on the flank of an isolated low hummock rising above surrounding wetlands.

Cores from the depression revealed unoxidized sandy clay loam to silty clay loam till is overlain by a discontinuous bed of unoxidized, laminated silty clay loam that is at least 0.5 m thick (Figure 3). This is overlain by up to about 1.4 m of laminated to indistinctly bedded unoxidized very fine sand to very fine loamy sand, with occasional interstratified thin beds of marl. In core 09AN-03, the basal thin bed (0.16 m thick) consists of pebbly very fine sandy loam and it abruptly overlies the silty clay loam. In turn, the pebbly bed is conformably overlain by the well sorted very fine loamy sand. Isolated fine pebbles are rarely present within the sand. Sandy loam is overlain by a marl bed and capped by about 0.9 m of peat that can have at least one interstratified discontinuous thin bed of loam to fine to medium loamy sand with a 7.5YR hue. In cores 09AN-01 and -03, the upper 1.5 to 1.7 m is likely fill.

Beneath the hummock, at least 2 m of unoxidized laminated to indistinctly bedded very fine sand is overlain by a thin bed of laminated coarse silt loam. Silt loam is in turn overlain by faintly bedded very fine loamy sand and the sequence is capped by about 1.4 m of peat.

The till belongs to the New Ulm Formation (Meyer and Patterson, 1997) and was deposited during advance of the Grantsburg Sublobe. The basin records a lacustrine phase following deposition of till during which silty clay loam was deposited. A >45,000 C^{14}yrBP age was obtained on a sample of wood charcoal from the lacustrine bed, but it is clearly too old for the sediment assemblage and represents reworked material. In the one core where the upper contact was sampled, pebbly sandy loam abruptly overlies the silty clay loam. There is no evidence of exposure of either the lacustrine deposit or the overlying bed, and it is possible these were deposited in a subglacial environment. Interstratified marl and possibly the interstratified peat in core 09AN-01 suggest a lacustrine origin for the overlying body of sandy loam to loamy sand. There is considerable distance between cores 09AN-03 and -04, and any correlations between sand bodies are speculative. The body of sandy loam to loamy sand overlying fine grain lacustrine deposits either grades laterally into the fine sand body in the lower part of core 09AN-

04, or seemingly more likely, it pinches out against the flank of this fine sand body. A radiocarbon age of 9,170 ± 40 C^{14}yrBP (Table 1) from lacustrine marl immediately above the top of the sand suggests the sand was deposited sometime before this date, and certainly no later. This age indicates a lacustrine system was well developed in at least some examples of the collapsed meltwater trough landscape by the first millennium of the Holocene, and hints at the possibility that collapse of the meltwater troughs could have actively continued into the Holocene. Fine grain lake sediments are overlain by peat which suggests wetland conditions throughout most of the Holocene. Whether the intervening bed of lacustrine sand correlates to an upper bed of very fine sandy loam to loamy sand in core 09AN-04 is open to question (Figure 3). The fill is road embankment material.

6.2 Area 2

A series of eight cores were taken across a large wetland linked depression between the two southeasternmost collapsed meltwater troughs in the Carlos Avery State Wildlife Management Area (Figure 4). Isolated small hummocks rising above the wetland could be eolian dunes. Cores reveal a thick sequence (> 5 m) of unoxidized, laminated to thinly bedded very fine sandy loam and loamy very fine sand capped by up to 1 m of peat (Figure 5). The base of sand was not encountered. In the middle to lower increments of sand, some cores had laminae enriched in mica and heavy minerals suggesting some degree of sorting by currents. Core 09AN-12 has two beds of silt loam separated by fine sand. Toward the southwest, several cores have some silt laminae interstratified with very fine sandy loam, mostly in the middle increments. In one core (09AN-08), peat lenses are interstratified within the upper 0.5 m of very fine sand. Peat is overlain by less than 1.6 m of deoxidized to oxidized, thinly bedded to laminated, very fine loamy sand to sandy loam.

A radiocarbon age of 32,360 ± 340 C^{14}yrBP (Beta-258837) (Table 1; Figure 5) was obtained on charcoal collected about 2.4 m into the thick sand unit in core 09AN-07. The charcoal is clearly redeposited. However, an age on basal peat collected from core 09AN-11 indicates it began accumulating in this location shortly before 3940 ± 340 C^{14}yrBP (Beta-258838).

The transect suggests that the linked depressions landform sediment assemblages are dominated by very fine sandy loam and loamy sand that appear to have a lacustrine origin. The latter radiocarbon age suggests a transition to wetland was certainly accomplished in the slightly lower landscape positions from which the sample was derived during the early late Holocene. Wetland conditions may have appeared earlier in the higher linked depressions.

Although more ages will be required to draw more definitive conclusions regarding the spatial and temporal evolution of individual linked depressions, as well as wetlands on the collapsed sand plain, this latter age, coupled with the aforementioned age from lake sediment beneath marl in Area 1 suggests peat accumulation in linked depression wetlands began millennia later than in the collapsed meltwater troughs. If this pattern holds the test of additional dating, one archaeological implication is that substantial wetlands, and kettle lakes, would have been attractive exploitable resources by Late Paleoindian through Middle Archaic groups during the early and middle Holocene in collapsed meltwater troughs, whereas linked depression wetlands may not have fully developed for utilization by prehistoric groups until much later.

6.3 Area 3

Seven cores were taken in Area 3 in the northeastern part of the project area (Figure 6). Four cores sampled an area of little collapse, and two sampled two likely stagnant ice-marginal meltwater channels close to the modern drainage divides within the channels. One meltwater paleochannel is occupied and drained to the east by North Branch Sunrise River. The final core was taken near the axis of a collapsed meltwater trough to the north of the paleochannels.

Cores sampling the questionable lake plain (09IA-01 – 09IA-04) indicate that nearly the entire sediment assemblage is oxidized and exhibits colors with both 10YR and 7.5YR hues. Fine pebble gravel rapidly fines upward to thinly bedded medium sand with and without pebbles, very fine sand with and without pebbles, and pebbly loamy fine sand in the lower meter or so of 09IA-04 (Figure 7). This crude upward fining sequence is overlain by thinly bedded to laminated very fine sandy loam to very fine and fine sand that contains occasional thin beds of coarse silt loam, and rare angular to rounded fine pebbles (some are basalt), and has a thickness of at least 4 m. The upper 2 m or so of the sediment assemblage consists of laminated to thinly bedded very fine sandy loam to very fine sand that exhibits 7.5YR hues, oxide accumulations with 7.5YR and 5YR hues, occasional leisengang bands, and a few very weak incipient buried soils with AC or CA horizonation.

Uncarbonized, perhaps partially charred wood, from a very fine sand bed above gravel in core 09IA-04 yielded a >45,000 C^{14}yrBP (Beta-258839) age (Figure 7; Table 1).

The cores on the uncollapsed plain in the Area 3 vicinity suggest a different origin from the unoxidized to deoxidized sand body seen elsewhere throughout the project area where the sand plain is collapsed. Oxidized conditions and the hues of soil colors suggest the material may even have a Superior Lobe source. At least the lower increments are glaciofluvial in origin; the origin of the remainder of the sequence remains unclear. There is a silt increment above pebbly sand near the base of core 09IA-03, suggesting at least some of the sediment assemblage may have a lacustrine origin. The rest of the sequence has textures and bedding characteristics the same as seen in unoxidized sediment assemblages elsewhere beneath the sand plain where it has collapsed. In these positions, the very fine sandy sediment has been interpreted to have a lacustrine origin. In any case, cores from fill in paleochannels cutting into this part of the plain yielded radiocarbon ages that indicate this sediment assemblage is older than about 11,000 C^{14}yrBP.

In the former meltwater channels that cut into the surface sampled in cores 09IA-01 – 09IA-04, cores 09IA-05 and -07 indicate the location is underlain by a coarse sandy loam diamicton with 5YR hues strongly suggesting it is the Cromwell Formation deposited by the Superior Lobe (Figure 7). Diamicton is truncated by channel gravel that in the northern paleochannel is more of a lag, being less than a decimeter thick, and in excess of 1.8 m thick in the southern southern paleochannel. In this latter location, gravel is overlain by deoxidized coarse to very coarse sand and then deoxidized to oxidized very fine and fine sand forming an upward fining sequence. The uppermost 1.3 m consists of two sandy loam – peat sequences. In the other paleochannel where only a gravel lag is present, about 1.0 m of unoxidized fine sand overlies gravel and in turn is overlain by about 0.3 m of marl and organic-enriched silty clay loam lake deposits. The sediment assemblage is capped by about 3.3 m of peat. Near the top of peat is a thin bed of deoxidized fine and medium sand. About a meter of fill overlies the sequence.

Two radiocarbon ages were obtained from material sampled in core 09IA-05 (Figure 7; Table 1). An age of 9,960 ± 40 C^{14}yrBP (Beta-258841) is from just above the gravel bed that lies on till. An older age of 10,980 ± 60 C^{14}yrBP on peat incorporated in lacustrine beds comes from about a meter higher in the core.

Fill in the two paleochannels represents initial glaciofluvial channel activity. When the channels were abandoned, the northern channel is occupied temporarily by a lake, and both channels are subsequently occupied by a wetland within which peat accumulated. At some point late in the history of the wetland, there was a pulse of alluvial sand. The two ages from the northern, presumably slightly older, of these meltwater channels are about 1000 years apart and inverted. The older age is from peaty material in lake sediment from an interval that occurs in the middle of a sampling core liner; contamination during coring is not an issue with this sample because it is associated with the only marl encountered within the core. If it is in place, the age suggests glaciofluvial activity in the paleochannel ceased just prior to about 11,000 C^{14}yrBP, implying stagnant ice still occupied much of the basin at this time. If redeposited, it likely was derived locally from elsewhere within the paleochannel, given its lacustrine context, pointing toward a similar conclusion as to the age of channel abandonment. The younger age is from just above basal gravel in deoxidized fine sand. If this sample is in situ, it suggests fluvial or glaciofluvial activity was going on in the paleochannel at the time. If the fine sand was deposited under lacustrine conditions, then glaciofluvial activity had ceased, and a lake existed within the paleochannel, at a minimum, around 10,000 C^{14}yrBP. Regardless of the depositional environment of the fine sand, the shift to finer lake sediment would post-date this age. It is possible that this sample is on material picked up higher in the core during a reentry of the core barrel into the hole; casing was not used for sampling. The older of the two ages is more in line with the nascent evolving geochronology of the basin.

In the collapsed meltwater trough north and upslope of the previously discussed meltwater channels, core 09IA-06 reveals at least 3.9 m of marl is overlain by at least 1.6 m of peat, with an uppermost increment of stratified peat and pebbly sandy loam beds (Figure 7). The marl has interstratified laminae and thin beds of coprogenous earth and peat, particularly in the lower increments. The near-surface peat has at least one thin bed of silty clay loam.

Two radiocarbon ages, in stratigraphic order, were obtained from core 09IA-06 (Figure 7; Table 1). At the base of the core, peat interstratified with lacustrine sediment yielded an age of 9,840 ± 40 C^{14}yrBP (Beta-258843) (Table 1; Figure 7). Fine lenses of peat in the stratigraphically youngest marl bed, immediately below thick peat, yielded an age of 5,930 ± C^{14}40 yrBP (Beta-258842).

Lake and wetland sediment coupled with radiocarbon ages indicate the collapsed meltwater trough was occupied by a lake and wetland for at least the entire Holocene. Although there are differences in stratigraphic details between Areas 1 and 3, it appears that collapsed meltwater troughs were essentially occupied by substantial lakes and wetlands throughout the Holocene.

6.4 Area 4

In Area 4, the northern end of one of the elongated depressions along the northern boundary of the Elk River meltwater trough fan complex was sampled in core 09SH-01. In this case, the depression supports a lake that nearly fills the basin. Also, a short transect of four cores, 09SH-02, 09SH-08, -09 and -10, sampled an interior margin of a depression in a moderately expressed collapsed meltwater trough immediately northwest of the Elk River tunnel valley fan (Figure 8).

In the isolated core 09SH-01, unoxidized, laminated silty clay loam is overlain by about 0.5 m of silt loam that is pedogenically altered, and capped by an unoxidized fine sandy loam (Figure 9). The overlying 3.6 m is interpreted as road embankment material. A thin bed of fine sandy loam buries the soil, and in turn is buried by about 1.6 m of silt loam of indeterminate origin. The silty clay loam and silt is lacustrine in origin. The overlying sand is probably some lake margin veneer, with sand derived from surrounding basin footslopes. A thin, weakly expressed soil is developed in the lake deposits. It exhibits an A – Cg profile.

The transect of cores in Area 4 indicates the underlying sediment assemblage to the depth sampled consists of an unknown thickness of unoxidized silt loam, overlain by 3.3 m of unoxidized very fine loamy sand (Figure 9). This is conformably overlain by about 1.3 m of deoxidized very fine sand to loamy sand. A thin bed of interstratified peat and very fine loamy sand caps the sequence. The surficial interstratified unit thickens and in general peat becomes more prominent, although nowhere is organic-rich sediment thick along the transect. Very fine sand in core 09SH-09 may have an eolian origin, and account for the slight rise and presence of an interior margin transition.

Along the short transect, there is limited variable between basin and the slight rise that was sampled. Peat in the basin transitions through peaty fine loamy sand, ultimately becoming interstratified with primarily thin beds of very fine loamy sand. The transect, although not the ideal setting, suggests slight lateral variability with the possibility of shallowly buried soils at basin margins.

6.5 Area 5

At this location, two cores were taken within the link between two adjacent linked depressions (Figure 10). The eastern basin is slightly higher. The floor of this basin is segmented by narrow 'ribs' of slightly higher ground into sub-basins that contain discrete wetlands. The western basin is slightly lower and occupied by Diann Lake. Core 09SH-04 was taken in the eastern higher part of the link between the two basins, and core 09SH-03 in the western lower part.

All of core 09SH-04, except for the uppermost 0.4 m, consists of unoxidized up to deoxidized thinly bedded to laminated (very weakly expressed) very fine loamy sand (Figure 11). At least one cross-bed in slightly coarser sand was observed between a depth of 4.9 and 5.6 m. Beneath this bed, irregular, sometimes angular bedding was observed. The uppermost 0.4 m consists of peaty very fine sandy loam. In Core 09SH-03, at least 2.9 m of the unoxidized very fine loamy sand is overlain by at least 1.5 m of peat, with thin beds of fine loamy sand in the lower 0.25 m.

This is overlain by at least 0.1 m, and no more than about 0.3 m, of unoxidized very fine loamy sand. This in turn is capped by peaty very fine sand and finally peat (Figure 11).

A radiocarbon age on basal peat in core 09SH-03 yielded an age of 10,270 ± 40 C^{14}yrBP (Beta-258847) (Table 1; Figure 11). This radiocarbon age indicates that introduction of the sand body into the Stacy Basin predates about 10,300 C^{14}yrBP. It further indicates that development of the linked depression system was advanced enough to be supporting a wetland by about 10,300 C^{14}yrBP.

6.6 Area 6

This area is within a large complex depression relatively low on the landscape within a very large mouth of a collapsed meltwater trough (tunnel valley); just west of the Elk River meltwater trough fan (Figure 12). Four cores were taken in the depression. One (09SH-05) was taken on the northwest side, and three were collected at the depression margin along the south side of the depression (Figure 12). In the latter location, there is a low sandy rib adjacent to a small basin to the northeast. The southernmost two cores (09SH-11, 09SH-12) were taken just on and just off the end of this spur. The northernmost core (09SH-09) may be in a northwest extension of this depression.

In core 09SH-05, at least 1.7 m of unoxidized sandy clay loam diamicton is overlain by a thin bed of very fine sandy loam with a 7.5YR hue (Figure 13). This bed is in turn overlain by about 1.7 m of oxidized very fine loamy sand to sandy loam. The hue of the sandy loam is suggestive of a Lake Superior basin source, but the underlying diamicton, interpreted as a sandy clay loam till, lacks any hint of reddish brown hue which often shows even under unoxidized conditions. The relatively high clay content and lack of reddish brown hue of the diamicton suggests it belongs to the New Ulm Formation deposited by the Grantsburg Sublobe. The sandy loam bed with 7.5YR hue may be a thin supraglacial deposit. The overlying oxidized loamy sand to sandy loam is interpreted as lacustrine in origin related to the collapsed sand plain.

In the short transect at the south margin of the depression, the two cores in close association with the sandy rib revealed a base of unoxidized sandy clay loam diamicton overlain by at least 2 m of unoxidized very fine sandy loam to very fine sand (Figure 13). An upward fining sequence that is about 2 m thick overlies the first sandy unit. This fining sequence consists of unoxidized fine and medium to coarse sand that grade upward to oxidized very fine loamy sand. Fill caps the sequence. The sediment assemblage beneath the adjacent local basin is quite different (Figure 13). The unoxidized sandy clay loam diamicton is overlain by a thick unit of high-angle cross-bedded pebbly fine to medium loamy sand with sandy loam to loam interbeds, and capped by an unoxidized bed of very fine loamy sand. This very fine loamy sand is conformably overlain by unoxidized, very firm, silty clay loam that has weakly expressed laminae and is capped with a thin bed of peat. About 2.7 m of unoxidized to oxidized very fine sandy loam caps the sequence beneath fill.

Till that floor the sequence is likely the New Ulm Formation. Overlying deposits in cores 09SH-11 and -12 are sandy lacustrine deposits overlain by an upward-fining sand sequence. Most likely this sequence is glaciofluvial, having been deposited between to ice block remnants late in the history of the basin. However, a considerably younger alluvial origin cannot be ruled out as streams coursed through this and other basins, at least during the late Holocene.

In core 09SH-06, taken in the local sub-basin, unoxidized, cross-bedded, pebbly sand and loam is overlain by about 0.75 m of unoxidized silty clay loam with at least two thin peat beds in the upper half of the deposit (Figure 13). The pebbly beds above till represent glaciofluvial channel deposits, subglacial or otherwise. The silty clay loam is lacustrine in origin, and could have accumulated within the channel when abandoned, or be more extensive within the larger basin. Silty clay loam is capped by 0.2 m of peat. The sequence is capped by about 2.7 m of oxidized down to unoxidized, laminated to massive, very fine loamy sand. This sand is likely lacustrine in origin.

This transect of three cores indicates that small, subtle changes in landscape position within a basin can result in significantly different stratigraphic sequences.

One radiocarbon age of 26,570 ± 180 yrBP (Beta-258848) was obtained on charred organic material recovered from the diamicton in core 09SH-05. The age is probably too old for the till, whether it belongs to the Cromwell or New Ulm formation. However, the age likely provides an approximate age for the landscape over which the Superior Lobe advanced.

6.7 Area 7

Core 09BN-01 was taken in what appears to be a possible collapsed depression in a cross-over chute from one meltwater channel to another where meltwater channels scour drumlinized Superior Lobe till on the oldest outwash surface (OP4) (Figure 14). The sampled sediment assemblage consists of thinly bedded marl lacustrine sediment of unknown thickness that is overlain by about 1.4 m of massive wetland peat. The base of the sediment assemblage was not attained. One thin bed (3 cm-thick) of unoxidized fine sandy loam diamicton is interbedded within the peat. The sequence is capped by about 1.5 m of road embankment fill. The soil profile is thick, very poorly drained, and exhibits an Oab – Cg – Oeb – Oab – Cg profile.

Peat at the contact of lacustrine marl and basal peat yielded a radiocarbon age of 7,340 ± 40 C^{14}yrBP (Beta-258844) (Table 1; Figure 15). The core records a transformation from lacustrine conditions to wetland peat around this time, perhaps reflecting the warming and drying influence of the Hypsithermal climatic episode in this relatively high landscape position.

6.8 Area 8

One core, 09SH07, was taken at this location. The core was sited within one of the narrow channels that is part of a relict multi-channeled system on a fan that appears to have connected flow at one time between inter-drumlin channels on the drumlinized Superior Lobe till, and the next-to-oldest outwash surface in the project area (Figure 14). These channels are oblique to both the interdrumlin troughs from which flow for these channels derived, as well as outwash channel trends on the OP3 surface which are truncated by the sampled channels. Flow in these channels coalesced in a former outwash channel on the oldest part of the youngest outwash plain (OP1). This relict channel at one time flowed into the St. Francis River valley.

The sediment assemblage down to the sampled depth consists of a lower deoxidized upward fining alluvial sequence culminating in about 0.4 m of laminated peat, that in turn is overlain by oxidized fine sand that fines upward to fine loamy sand, with and without pebbles (Figure 15). The sequence is capped by 1.1 m of road embankment fill. The lowest two beds encountered in the core fine upward from medium to very fine sand, with few peat and black sand laminae. Pebble-rich beds in silty clay loam, and in the fine loamy sand above, are locally derived from the adjacent till uplands.

The lower alluvial sequence is pedogenically altered by a moderately thin, poorly drained buried soil that exhibits an OAb – ACb – Cg profile. The younger sequence has an incipient, very weakly expressed soil developed in its top. It exhibits a CA – C profile.

One radiocarbon age was obtained on peat collected from the laminae in the basal sampled alluvial bed. It yielded an age of 6,910 ± 60 C^{14}yrBP (Beta-258849) (Table 1; Figure 15). The age suggests the fan was mostly active prior to this age if the peat is not redeposited; the number of alluvial sequences above till is unknown. The younger upward fining sequence points to a later interval of alluvial activity in this channel. If the channeled landform is indeed some type of alluvial fan, the radiocarbon age confirms the youngest outwash plain predates this age.

6.9 Area 9

One core, 09ML-01, was taken in a less-than-ideal position in a wetland developed in meltwater channels on the next-to-oldest outwash plain (OP3) at the Kunkel State Wildlife Management Area. This core was an attempt to collect organic material to obtain a minimum age on a set of ill-defined meltwater channels that drained the outer northwest flank of a western lobe of the Grantsburg Sublobe (Figure 14). The lower 1.1m consists of an upward fining deoxidized sequence of medium and fine pebble gravel overlain progressively by beds of pebbly medium sand, interstratified beds of coarse and fine loamy sand, and capped by a thin bed of peat (Figure 15). Peat is buried abruptly by what is most likely road embankment fill.

The lower upward-fining sequence is very weakly altered by a thin, poorly drained soil that exhibits an OAb – Cg profile. No buried soils were encountered, but basal till was not encountered in the core.

Peat at the top of the lower upward fining sequence yielded an age of 3,100 ± 40 C^{14}yrBP (Beta-258845) (Table 1; Figure 15).

6.10 Area 10

One core was taken in this location to examine the sediment assemblage beneath an ice-walled lake bed in the southern part of the project area in one of the broader collapsed meltwater troughs (Figure 14). The lake bed has a slightly depressional central area, and it is here that the core was taken.

To the depth core 09RA-01 was taken, it shows the lowest bed of the ice-walled lake bed sediment assemblage consists of at least 0.25 m of deoxidized very fine loamy sand to sandy loam (Figure 15). Few thin laminae have concentrations of heavy minerals indicating the presence of currents strong enough to perform some sorting. Loamy sand is overlain by 5.8 m of silty clay loam, with a surficial thin bed of silt loam. Lower strata of silty clay loam are mottled (except for the lowest beds), deoxidized, laminated (very weakly expressed) and very firm. Upper strata are mottled, deoxidized to oxidized, massive, and firm. At a minimum the silty clay loam beds represent lacustrine deposits. The sequence is topped by about 0.7 m of fills.

Despite evidence of some sorting of heavy minerals, the lowest sampled loamy sand to sandy loam is likely lacustrine in origin as well. The surface soil profile exhibits an Ap (fill) – A – C profile, with some oxidized colors in the upper C horizons.

Wood charcoal was washed from the lowest bed of silty clay loam. It yielded a >45,000 C^{14}yrBP age (Beta-258846) (Table 1; Figure 15); clearly the charcoal was detrital, and redeposited from elsewhere.

7 History of Landscape Evolution

This section focuses on the history of landscape evolution of the basin between the Mississippi and St. Croix Valleys for that time period relevant to potential human occupation. Thus, the introductory synopsis of events at the beginning of this report will suffice up until the time of advance of the Grantsburg Sublobe. Of particular concern is the interval of time between several centuries before the Paleoindian period through the Early Archaic period as this is when the major configuration of the landscape is established. All subsequent changes later in the Holocene occur on the general landscape pattern established during the latest Wisconsin and early Holocene. The remainder of the project area is up- and down-valley, adjacent to the Mississippi Valley. For glaciofluvial and alluvial history of this reach of the Mississippi Valley, see Hudak and Hajic (1999) and Hajic (2002).

A few of the positive features of the Anoka Sand Plain were sampled, and their stratigraphy is summarized in Figure 18A. Topographic highs (hummocks, hills) in collapsed meltwater troughs (core 09AN-04, Area 1; 09SH-04, Area 5; 09SH-05, Area 6) are similar to the one sampled topographic high in linked depressions on the collapsed sand plain landscape. Unoxidized to deoxidized very fine sand, loamy sand and sandy loam comprises all or nearly all of the sequences. Locally, there are one or more thin beds of silt loam. The sand in these sequences is tentatively interpreted as having been deposited in a lacustrine environment. Two surfaces interpreted as ice-walled lake plains were sampled. A classic example in the southern part of Ramsey County (Area 10) is underlain by a thick unoxidized silty clay loam lacustrine deposit. It overlies basal very fine sandy loam to loamy sand, and is capped by a thin increment of lacustrine silt loam (Figure 18A). Although finer in texture, the sequence is fairly uniform and mostly unoxidized, as with the sediment assemblages beneath the other topographic highs. The other example originally thought to be an ice-walled lake is the uncollapsed part of the sand plain in Area 3 (Figure 18A). The sediment assemblage is similar to that beneath the other topographic highs in having a thick sequence of more or less uniform texture (very fine loamy sand to very fine sand), but it is oxidized to deoxidized.

Collapsed meltwater troughs yielded some of the thickest fills inset into the more positive landscape elements and associated sediment assemblages. These troughs also yielded the oldest radiocarbon ages likely to be in stratigraphic position. The summary stratigraphic sequence of collapsed meltwater troughs (excluding Historic deposits) is similar to that sampled in meltwater channels, linked depressions of the collapsed sand plain, and the channel on the oldest outwash plain, to the depths they were sampled (Figure 18B). Till of either the Cromwell or New Ulm formations is overlain by discontinuous unoxidized glaciofluvial gravel, discontinuous unoxidized lacustrine silty clay loam, and then rarely (core 09SH-06; Area 6) peat. This sequence is then abruptly overlain by unoxidized very fine sandy loam, very fine loamy sand or very fine sand, sometimes with some indication of traction currents in the lowest increments. The sand body is interpreted primarily as lacustrine. It is possible that this sand increment is stratigraphically correlative to lower increments of aforementioned sediment assemblages underlying topographic highs (Figure 18A). Only one of the aforementioned sediment assemblages of topographic highs was taken to basement material (New Ulm formation), so basal stratigraphy beneath topographic highs is still in question. The sand increment could be younger as well. In the basins, the sand body is overlain, apparently conformably, by lacustrine marl, silt loam, and/or coprogenous earth that has a short transition to peat. Peat sedimentation was interrupted in the upper third by a bed of either lacustrine or alluvial sand.

No reliable temporal information on the sediment assemblages of the topographic highs is available from sampled sites, but the major components of the landscape almost certainly post-date about 11,900 C^{14}yrBP. The youngest glacial advance into the Stacy Basin is that of the Grantsburg Sublobe. Within the Stacy Basin, there are three relevant radiocarbon ages relative to the age of advance into the basin by the Grantsburg Sublobe. In Chisago County, near the eastern margin of the sublobe, till overlies organic silt at one site reported by Meyer (1998). Wood from the organic silt yielded an age of 11,900 +/- 70 C^{14}yrBP (Beta-47804). Wood from the base of overlying till yielded an age of 11,850 +/- 60 C^{14}yrBP (Beta-47059), statistically the same age as the underlying silt. Wood from sand overlying till from another site in Chisago County yielded an age of 12,030 +/- 200 C^{14}yrBP (W-354) (Wright and Rubin 1956). Again, the age is statistically indistinct from the other two. Despite Meyer's (1998) reservation that the first age on material from silt seems too young, the suite of three nearly identical ages seem to suggest that the surface over which the ice rode, or the vegetation growing on lower slopes of the St. Croix end moraine and subject to entrainment into the advancing ice, is about 11,900 radiocarbon years old. Currently, there is no clear evidence to discount such an interpretation. The sediment assemblages above till of topographic highs (ice-walled lake beds, hummocks and hills in collapsed meltwater troughs and in linked depressions on the collapsed sand plain, and presumably beyond the limits of depressions in both) is younger than about 11,900 C^{14}yrBP. At this time, the Des Moines Lobe of ice in Iowa was stagnating. The St. Croix Moraine and Stacy Basin offered the least resistance to what probably represents a last-gasp surge of the downstream end of active glacial ice at the time.

The Grantsburg Sublobe advanced up the south flank of older Superior Lobe till where it formed several sublobe end moraines, the spacing of which reflect the influence of local morphology of the older till. While at its maximum position, a proglacial Lake Grantsburg formed between ice and older till to the northwest, deposited a thin veneer of lacustrine silt and clay, and after about 100 years, drained (Johnson 1994; Johnson and Hemstad 1998). The ice retreated somewhat and then stagnated. This would represent the earliest possible age for the oldest outwash plain (OP4) preserved in the basin, in the western part of Sherburne and southern part of Benton Counties. The position of this surface suggests that it was shaped by either the Mississippi River of the time as it flowed into the basin, or by an ice-marginal meltwater stream, or a combination of both. The next younger bench (OP3) would likely be close in age to this older surface. With some further retreat or wastage, some components of the next-to-youngest outwash plain (OP2) would probably have formed as drainage coalesced off the southeast-facing flank of the older till and residual ice in the Grantsburg Sublobe moraines. Some of this water was likely funneled eastward through the large meltwater channels in Isanti County.

There are no radiocarbon ages that bear conclusively on how long it took the Grantsburg Sublobe, once in the basin, to advance, retreat slightly, and stagnate. The fact that Glacial Lake Grantsburg lasted about 100 years suggests ice occupied the maximum position only briefly before retreat and opening of an eastward drainage outlet. Coupling this with the likelihood that Grantsburg Sublobe ice was thin, relatively clean ice, it is likely that it surged into the basin once it initially overrode the St. Croix Moraine. Several hundred years for advance and slight retreat is not an unreasonable timeframe.

If this temporal scenario approximates reality, then the sublobe was beginning to stagnate around the time Early Paleoindian people were populating North America, and after any potential earlier explorers were present. Reasonably habitable ground would have been found on the surrounding moraines and highest outwash benches.

From this period until some undetermined time before the Holocene, a period that certainly would include the Early, probably the Middle, and maybe even the Late Paleoindian periods, the standing model for landscape evolution in the Stacy Basin (Meyer et al. 1993; Meyer 1998) includes these salient interpretations:

1. After the Grantsburg Sublobe ice dissipated, the drainage was eastward through the basin utilizing multiple proglacial and possibly supraglacial stream courses with drainage to the St. Croix valley; any southern outlet was blocked.
2. Blockage of the St. Croix valley outlet by deposition of the Barrens outwash fan, a feature deposited by meltwater from the Superior lobe to the northeast of the project area.
3. Establishment of the extensive and locally deep, Glacial Lake Anoka in the now-closed basin that sat at three different levels controlled by the opening of various eastern outlets.
4. Deposition of the main sand body of the Anoka Sand Plain within Glacial Lake Anoka from wasting Grantsburg Sublobe ice and outwash from the retreating margin of the Des Moines Lobe.

It is during this interval of time that the main sand body of the Anoka Sand Plain is introduced into the basin. Although a definitive sedimentological investigation of the origin and depositional mode of the sand has yet to be conducted, we can accept a lacustrine origin, but offer an alternative interpretation that requires no Glacial Lake Anoka as proposed by Meyer (1998). Regardless of how or from where the sand body was introduced into the basin, if it was introduced rapidly on top of the ice shortly after stagnation began, the sand would have cycled through the formation and evolution of large ice-walled lakes early during the stagnation process. In this manner, the sand acquires bedding characteristics compatible with a lacustrine origin without the necessity of an extensive lake in the basin.

The other requirement for a Glacial Lake Anoka is blockage of lower outlets or a relatively high outlet to the St. Croix River valley. At its highest level, Meyer et al. (1993) and Meyer (1998) propose blockage by the Barrens fan. The configuration of the Barrens fan, particularly the western edge of the fan and southwestern margin of the fan nose (Meyer 1998; his Figure 11), conforms to the western margin of the current western margin of the St. Croix Valley. However, this margin is no older than about 9,850 C^{14}yrBP, having been cut around this time by catastrophic drainage of Glacial Lake Duluth (Hudak and Hajic 1999; Hajic and Hudak 2005). The sand of the 'Barrens' across the valley in Wisconsin was also deposited at this time, not earlier. This flood and the features related to it were thought by Meyer to have occurred as the earliest, highest lake stand lowered to the 'Hugo' level of Glacial Lake Anoka. Among these features is the broad water-washed surface west of the St. Croix Valley north of Franconia.

A St. Croix Valley outlet for the basin may have been active at times, but if either the North Minneapolis gap in the Mississippi Valley, or one of the two large collapsed meltwater channels breaching the St. Croix Moraine were opened beneath the stagnant ice, the basin would not necessarily be closed, thus negating the necessity to propose a large lake that has no definitive morphologic evidence of shore and nearshore features. The few east-west oriented valleys that cross Isanti and Anoka counties in particular were likely flowing originally as stagnant ice-marginal streams. Subsequent development of a linked depression system suggesting glacial karst after ice-walled lakes suggests a sub-ice meltwater drainage system. This can account for the unoxidized glaciofluvial sedimentological evidence overlying till.

This chain of events may have happened relatively rapidly. Radiocarbon and geomorphic evidence suggest the North Minneapolis gap of the Mississippi Valley was open by about 11,470 C^{14}yrBP (Hajic 2002). Remnants of stagnant ice and collapse, however, may have remained and continued for some time afterwards in the basin. The overall distribution patterning of linked depressions in Anoka County suggests the possibility that Grantsburg Sublobe ice could have overrode Superior Lobe ice of the Automba Phase that was already stagnating in the basin. Although this advance of Superior Lobe ice is generally considered to be an earlier event, it remains undated.

The radiocarbon-dated chronology picks up as link-depressions of the collapsed sand plain and collapsed meltwater troughs are developed and beginning to infill. Lacustrine marl, coprogenous earth and silt loam are accumulating in lakes within some collapsed meltwater troughs from at least as early as about 10,270 C^{14}yrBP (Figure 18B). This phase of isolated lakes in the Stacy Basin was almost certainly time-transgressive depending on specific meltwater trough geometry and development. The youngest radiocarbon age associated with the contact between very fine sand and overlying lake marl is about 9,200 C^{14}yrBP. The northern sampled meltwater channel similarly supported a lake locally beginning around either 11,000 or 10,000 C^{14}yrBP, depending on the interpretation of the inverted pair of radiocarbon ages. This lake phase appears to have lasted into the middle Holocene. A shift to peat sedimentation in basins across the plain appears to have occurred between at least about 7300 and 5900 C^{14}yrBP (Figure 18B). The time-transgressive character of this shift may be related to basins occupying differing landscapes, basin infilling, and other factors. This shift may represent a change from lake to shallower wetlands. Peat accumulated more or less continuously throughout the remainder of the middle and late Holocene and into the Historic period. There appears to be one exception. In the upper third or so of several of the peat sequences, there is a thin bed of coarser material, usually sand. This may represent a brief interval of increased precipitation and runoff into basins. Within many of the wetlands there is evidence on Historic aerial photography of extensive meander belts, even of very low order streams, coursing through basins of all sizes. A period of increased precipitation would activate these systems as well as wash material into wetlands from surrounding, easily erodible, sandy hillslopes. One radiocarbon age from the top of peat beneath one such bed suggests this event happened shortly after about 3900 C^{14}yrBP (Figure 18B).

Fluctuations in water levels, accumulation of lake and wetland sediment, and deposition of colluvium in footslope and toeslope locations would have altered the configuration of lake shorelines and lead to potential burial of prehistoric cultural deposits along inner basin margins.

Uncollapsed parts of the sand plain and two younger outwash plains were essentially relict features by the earliest Holocene as the various types of basins developed and partially filled with lacustrine and wetland deposits. While relict landforms, they were by no means static. Sandy soils were eroded and much of the sand plain is covered by a discontinuous mantle of eolian dunes and perhaps sheet sands. In some locations, substantial dune fields formed. As a result of investigations of the contribution of eolian activity to lake sediment in Lake Ann, which is a kettle lake in a collapsed meltwater trough amidst dune fields in eastern Sherburne County, Keen and Shane (1990) suggest there were three episodes of dune activity initiated by drought, significant water table lowering and drying of the soil. The earliest decrease in precipitation began around 8,000 C^{14}yrBP and allowed substantial eolian dune fields to form by about 7,400 C^{14}yrBP. Major dune reactivation occurred by about 5,800 C^{14}yrBP, and again sometime between about 5,100 and 4,000 C^{14}yrBP. Thus, Middle Archaic and older prehistoric cultural deposits could be buried by or within eolian dunes. Dunes essentially stabilized after 4,000 C^{14}yrBP, although there are Historic records of minor destabilization from the late 1800's and 1930's (Keen and Shane 1990).

8 Remote Sensing Pilot Project Initial Results

Within Anoka County, an area with abundant depressions (Figure 16) was selected for assessment and to train the remote sensed data. Boundaries between map units at the interface between linked depressions and surrounding hillslopes were used to isolate edges most likely to be associated with buried soils around interior basin margins, if present at all. After numerous classifications, the LANDSAT data proved to be far more effective than the RADARSAT, and figure 17 illustrates the best LANDSAT classification output relative to the isolated polygon edges.

Although there were no ground reference points for buried soils available to conduct a proper accuracy assessment, visual interpretation of the output shows this approach has good potential and further research is likely worth pursuing.

9 Landscape Suitability Rankings for Surface and Buried Archaeological Sites

In Mn/Model, the geologic potential for surface and buried prehistoric cultural deposits is discussed in terms of landscape suitability rankings (LSR's) (Hudak and Hajic 1999). The LSR index is objectified to the extent possible by considering the age of the deposits as too old, too young or old enough to host intact prehistoric cultural deposits, and the degree to which depositional environments, based on depositional energy, are likely to bury and preserve intact cultural deposits.

The majority of the project area was established during the terminal Wisconsin, and landform sediment assemblages associated with higher surfaces of the active and stagnant ice, ice contact, meltwater trough fan, collapsed sand plain, glaciofluvial, and collapsed meltwater trough landscapes are too old to host buried prehistoric cultural deposits, except for early and possibly middle Paleoindian in the latter three landscapes. Furthermore, most of these sediment assemblages accumulated in depositional environments unfavorable for occupation. Some sediment assemblages, such as the collapsed sand plain, may represent environments of deposition favorable for burial and preservation of artifactual material (i.e. lacustrine), but were unfavorable for significant occupation in the first place.

In general, where till mantles the landscape, the geologic potential for buried prehistoric cultural deposits is nil due to depositional environments, but also for the most part age. For similar reasons, the ice contact and meltwater trough fan LfSAs also are assigned a nil LSR. In the glaciofluvial landscape, represented by the four outwash plains and outwash surfaces within the Mississippi Valley, depositional environments would not have been conducive to burial or preservation of intact cultural deposits because of the dynamic nature and energy of the braided stream environment, particularly in channeled areas. However, there is a low possibility that intact cultural material may be on, or very shallowly buried in, fine sandy bar-top deposits. The collapsed sand plain and hummocks, hills and better drained flats within the collapsed meltwater trough LfSAs might have been conducive to burial and preservation early in their formation when ice-walled lakes were present, but the discovery of any early Paleoindian artifactual record in such an environment would be purely happenstance.

Depressions and stream valleys, and more specifically their margins and lower sideslopes with adjoining higher landscape positions, as well as younger eolian deposits that mantle the youngest two outwash plains and the collapsed sand plain, are of much greater concern in the landscapes of the project area. Linked depressions, lake basin depressions, other depressions, along with the margins and some meander belts of creeks and rivers, associated with all major landscapes, can have a moderate to high geologic potential for hosting buried prehistoric cultural deposits. Depositional energies of hillslope colluviation, lacustrine and wetland sedimentation, and fluvial overbank sedimentation are conducive to burial and preservation of prehistoric cultural deposits. Shifts in wetland margins and lake shorelines, along with the evidence of prehistoric utilization of these environments, likely occurred in response to climate shifts during the Holocene. Beach ridges also have a high landscape suitability ranking, even though depositional energies can be relatively large and cause some archaeological deposits to be disturbed.

Although the collapsed sand plain and outwash plains have a very limited to no geologic potential for hosting buried prehistoric cultural deposits, there are large areas where substantial percentages of these landscapes are buried to varying depths by younger eolian deposits. Keen and Shane (1990) have demonstrated that most of the dunes are middle to early-late Holocene in age. Thus, any potential Late Archaic and earlier cultural deposits on these surfaces could be buried by dune sand with a high potential for being preserved intact. Even younger cultural deposits can be buried where dunes were reactivated during Historic time.

Given the general terminal Wisconsin age of the collapsed sand plain and various outwash plains, and the overwhelming percentage of Woodland sites and sites of indeterminate cultural affiliation on high ground, it is unsurprising that there are no discrepancies in known site age and landform or landscape in the existing archaeological site database as of 2006.

Sherburne County has the most Paleoindian and Archaic sites. There are two Paleoindian sites recorded, one possible and one definite. A possible Folsom point was found in an artifact scatter associated with the margin of the paleochannel complex in which the St. Francis River occupies the main paleochannel. The other occurs 1.8 km to the north on a fan complex adjacent to a wetland in a former fan channel. This latter site has yielded a Clovis and an Alberta point. The site is multi-component, with Archaic, Woodland and Mississippian artifacts, so the cultural curation of older points by younger occupants is a possibility. Four Archaic sites are in the database. They include the one site at the aforementioned multi-component scatter, one kill site that is in a creek cutbank, one on a hummock within a collapsed meltwater channel, and one unconfirmed artifact scatter on a meander belt of a smaller creek.

In southeast Anoka County, one Paleoindian site is recorded on a hummock within the southeasternmost collapsed meltwater trough. This site has yielded a Cody and Agate Basin point. It is also multi-component, with a Woodland occupation as well. Close by, there are two Archaic sites, one confirmed, and the other unconfirmed. The former is on the tip of a plunging esker remnant, immediately adjacent to the wetland in the axis of the trough. The latter is on a hummock overlooking the same wetland and former Archaic site from the opposite side of the wetland. The hummock site is multi-component with confirmed Woodland and suspected Mississippian artifacts.

The remaining sites in the project area are Woodland or with an indeterminate affiliation, with a small number of Mississippian sites. A substantial number of sites with a Woodland affiliation are earthworks. The majority of these younger sites occur on the collapsed sand plain and outwash terraces. However, these larger landscape positions are unimportant in terms of site location selection. The vast majority of these late Holocene sites are focused along and within collapsed meltwater troughs and surrounding associated kettle lakes.

In the Mississippi River Valley beyond that part of the project area between the Mississippi and St. Croix River valleys, sites are sparse on Mississippi River surfaces. Where affiliations have been determined, they are relatively young. Just south of Little Falls, immediately south of the mouth of Pike Creek, two Woodland sites are located between the Mississippi River and a terrace scarp that descends to the river. It is likely these sites are located on the footslope; any floodplain or low terrace is too narrow to map. One of the sites has unconfirmed Archaic material. If the location proves to be floodplain, the presence of Archaic material, if confirmed, may provide an approximate limiting age.

There are more sites on surfaces adjacent to the Mississippi River outwash plains that fall within the project area. On the east side of the valley, there is a dissected belt of outwash and alluvial fans, both comprised of material derived from the Cromwell Formation underlying the Pierz Drumlin field to the east. Probably only the highest level is underlain by outwash, with lower levels representing coalesced alluvial fans. It is on these latter features that sites are situated within the project area. These fans are still for the most part likely to be pre-Holocene in age because of the level of the surfaces they mantle, and the relatively high Mississippi River valley terrace levels that truncate some of them. In Morrison County, nine of these sites, all within 7.5 km of one another, are situated on hummocks rising above an enveloping wetland in a collapsed basin, or on the surrounding outwash plain which is at an intermediate level. Five of the sites are multi-component, with the oldest component at five of them being Paleoindian represented by Cody and other lanceolate points. Archaic artifacts are recognized at two of the scatters and Woodland artifacts and earthworks exist at all of them. In Benton County, eight sites occur on intermediate to lower levels of the belt; all consist of Woodland mounds.

Remaining sites west of the Mississippi River valley include one on an outwash plain along the Sauk River, a number associated with remnants of the youngest outwash plain of the Stacy Basin that includes one Archaic site, several on till-cored hummocks, and three on a catastrophic flood surface within the mouth of the Minnesota River valley.

10 Conclusions

The main part of the Anoka Sand Plain in the Stacy Basin between the Mississippi and St. Croix Rivers, as well as remnants on the southwest side of the Mississippi River, are dominated by a collapsed sand plain landscape. Stagnant ice was buried by a substantial body of very fine sand sometime after about 12,000 C^{14}yrBP. The sand plain is comprised of multiple levels due to the collapse of underlying stagnant ice. Stages in the collapse include ice-walled lakes, linked depressions from glacial karst, and ice-block melt-out kettles. Four outwash plain levels also are represented. The youngest of the four is contemporaneous with the collapsed sand plain, and all are very late Wisconsin in age. Several distinct, probably stagnant ice-marginal, meltwater paleochannels cross both outwash and collapsed sand plains. The collapsed sand and outwash plains surround several higher areas of older meltwater trough fan, ice-contact, and stagnant ice landscapes. Plains are altered by linear collapsed meltwater troughs of which relatively large kettle lakes are a prominent feature. Formation of the troughs is roughly contemporaneous with, to slightly younger than the collapse of the sand plain.

The Holocene history of the project area takes place on the modified collapsed sand and outwash plain platform. The key early Holocene event is the development of lakes that in the middle Holocene evolve to wetlands in basins within the collapsed meltwater troughs, ice-block meltout depressions, and meltwater paleochannels. Lakes in linked depression systems may have a slightly younger initial age, but subsequent basin history is similar among the different basin types suggesting overall climatic control. Long term fluctuations in precipitation shifted water levels with a concomitant shift in shore positions. As the shorelines migrated, so did the near-shore habitation and other sites used by the prehistoric people. Streams tend to occupy reaches of collapsed meltwater troughs and meltwater paleochannels, but there are alluvial reaches as well. Terraces are very limited; the floodplain landscape is dominated by one or more meander belts. Higher levels of the collapsed sand and outwash plains were buried locally by isolated dunes to eolian dune fields on several occasions during the Middle Holocene to early-late Holocene.

The platform of collapsed sand plain and youngest two outwash plains is old enough to have cultural deposits of Middle Paleoindian and younger periods on its surface with little geologic potential for buried cultural deposits beneath this platform surface. Older, higher landscapes can have Early Paleoindian deposits on the land surface as well. However, a discontinuous eolian dune mantle can bury the collapsed sand plain and youngest two outwash plains, and any cultural deposits that pre-date the dunes. The geologic potential for buried cultural deposits on the plains beneath and within dunes, particularly Middle Archaic and older, is high. In addition to the dunes, another high geologic potential for burial and preservation of prehistoric cultural deposits is within basins of linked depressions, collapsed meltwater troughs, and former meltwater channels, especially around the basin margins. Burial could also have occurred beyond interior basin margins because basin floors, at least of linked depressions, have some relief. What at one time were low rises on floors of depressions are now buried by peat.

Despite the early age of the plains, Paleoindian and Archaic sites comprise a tiny fraction of archaeological sites for which affiliations have been determined. One of the Paleoindian sites occurs on a hummock in the southeasternmost collapsed meltwater trough, one is near a paleochannel on the youngest outwash plain, and one is on a higher, older surface. Archaic sites are about as sparse. Interestingly, two of four sites are located very low on the landscape in association with stream meander belts. Woodland sites comprise the greatest percentage of known sites. Most occur on the collapsed sand plain and outwash plains, but their distribution is clearly focused on collapsed meltwater troughs, and kettle lake basins in particular. Nearly all of these sites are on high, well-drained ground within 300 m of a scarp leading into a trough, meltwater paleochannel, stream valley, or kettle lake basin.

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