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THE CHARACTERIZATION AND POSSIBLE ORIGINS OF
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THE CHARACTERIZATION AND POSSIBLE ORIGINS OF TWO LOESS SHEETS IN THE UPPER GREAT LAKES REGION, USA

By

Michael Edward Bigsby

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ABSTRACT

THE CHARACTERIZATION AND POSSIBLE ORIGINS OF TWO LOESS SHEETS IN THE UPPER GREAT LAKES REGION, USA

By

Michael Edward Bigsby

In this thesis, I investigate two loess deposits - one in north-central Wisconsin and the other in northeastern Wisconsin and the western Upper Peninsula of Michigan. Loess thickness is typically less than 1 m across each of these two regions. The goal of this research is to determine the possible origins of these loess deposits by examining their spatial characteristics. Five sampling transects were utilized, each extending away from a possible loess source area, onto the loess sheet proper. A total of 113 loess samples were collected from these transects. Data indicate that the loess in north-central Wisconsin had two likely source areas: 1) the Late Wisconsin terminal moraine and 2) Cambrian sandstone outcrops in Clark County, WI. The Late Wisconsin terminal moraine was the primary silt source; fine sands were largely derived from the sandstone landscape. The northeastern Wisconsin and western Upper Peninsula loess deposit is surrounded by four potential loess sources: 1) the Watersmeet Moraine, 2) the Republic Moraine, 3) the Sagola Moraine, and 4) the Vilas County Outwash Plain. Loess data indicate that all of these landforms may have been contributing various types of eolian sediment to the loess sheet. This study provides evidence that landscapes that have previously not been recognized as loess sources may, in fact, have provided substantial amounts of eolian sediment to stable, upland landscapes in immediate post-glacial times.

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Images in this thesis are presented in color.

1. Introduction

Loess is eolian, or wind-blown, silt (Smalley, 1966; Follmer, 1996). It is composed mainly of quartz and feldspar minerals typically ranging in size from 20-60 micrometers (μm) (Smalley and Cabrera, 1970; Pye, 1995), however loess can also be finer or coarser textured. Loess is commonly tan or buff in color (Smith, 1942; Frye *et al.,* 1962; Pye, 1995). Thick and aerially extensive deposits of loess are found in parts of North America, South America, central and eastern Europe, and central Asia (Pye, 1995; Bettis *et al.*, 2003). It is the most extensive surficial deposit in central North America (Roberts *et al.* 2003), where it extends as an almost continuous, upland deposit from the Upper Great Lakes region to Louisiana, and from eastern Ohio to eastern Colorado (Smith, 1942; Frye *et al.,* 1968; Pye, 1995; Follmer, 1996; Bettis *et al.,* 2003).

To date, most loess research in the continental USA has been conducted in the Great Plains region (Lugn, 1962; Pye *et al.,* 1995; Maat and Johnson, 1996; Mason, 2001; Mason *et al.,* 2003; Roberts *et al.,* 2003) and Central Lowlands (Smith, 1942; Frye *et al.,* 1962; Frye *et al.,* 1968; Ruhe *et al.,* 1971; Mason *et al.,* 1999; Muhs and Bettis, 2000). Collectively these studies have provided information on loess texture, chronology, and source areas. These studies generally show that loess in these regions is derived from glacial or periglacial sources.

Loess has also been recognized in the Upper Great Lakes region, especially in Minnesota, Iowa, Indiana, Ohio and Wisconsin (Fehrenbacher *et al.,* 1965; Hole, 1968; Ruhe, 1969; Cahow, 1976; Attig and Muldoon, 1989; Mason and Nater, 1994; Mason *et al.*, 1994; Stanley, 2008) and more recently, in Michigan (Schaetzl, 2008; Schaetzl and Hook, 2008; Schaetzl and Loope, 2008). In contrast to the thick, extensive deposits in the central United States, loess deposits in the Upper Great Lakes region are relatively thin, and they are not spatially extensive and/or continuous (Hole, 1968). Perhaps for this reason, they have not been studied as extensively. However, studying these deposits may lead to a better understanding of late Pleistocene paleoenvironments near the margin of the Laurentide Ice Sheet (LIS).

Unlike many loess deposits in the Great Plains and Central Lowlands, loess in the Upper Great Lakes is usually not located near large meltwater valleys, and therefore, has probably not been sourced from them. Without obvious meltwater valley source areas for this loess, research in the Upper Great Lakes has focused on determining which landscapes could have potentially provided silt to be deflated, and as a result, several non-traditional loess sources have recently been discovered in this region. For example, Schaetzl (2008), working in the Lower Peninsula of Michigan, concluded that the source of loess in the Grayling Fingers was the nearby Port Huron outwash plain. Schaetzl and Loope (2008) determined the source of loess on the uplands in the eastern Upper Peninsula of Michigan (U.P.) to be the surrounding silt-rich glaciolacustrine plain of Lake Algonquin. Stanley (2008) concluded the north-central Wisconsin loess sheet had two sources: (1) ice-walled lake plains perched atop the Late Wisconsin terminal moraine to the north and (2) Cambrian sandstone outcrops to the west, rendered unstable by permafrost.

This thesis investigates two regionally important loess deposits in Wisconsin and the U.P. of Michigan: the north-central Wisconsin loess sheet and the Iron County loess sheet (Figure 1.1). The north-central Wisconsin loess sheet is located primarily in Clark, Marathon, and Taylor Counties, Wisconsin (Hole, 1942; Stanley, 2008). This loess sheet is bordered on the north by the Late Wisconsin terminal moraine and on the west by Cambrian sandstone bedrock outcrops in western Clark County (Stanley, 2008). On its southern and eastern margins, the loess deposit gets progressively thinner, until it is no longer detectable. Thus, these margins are more diffuse and harder to define. Although the north-central Wisconsin loess sheet was recently studied by Stanley (2008), a different sampling method was used in this thesis in order to compare and contrast the results from Stanley (2008) with the results from this thesis.

Figure 1.1. Locations of north-central Wisconsin and Iron County loess sheets (shaded areas).

The Iron County loess deposit is part of a larger area of loess that has been referred to as the northeast Wisconsin loess sheet, which is located primarily in Florence, Forest, Oneida, and Vilas Counties in Wisconsin and Iron County, Michigan (Figure 1.2). This study area is bordered on the north by the Watersmeet Moraine, on the east by the Sagola Moraine, and on the west by the Vilas and Oneida County, WI outwash plains (Black, 1976; Peterson, 1986). This loess sheet is unique in that it is located within an interlobate-like, re-entrant area along the Laurentide Ice Sheet (LIS) margin. This type of setting provides an excellent opportunity to study the paleowind regime of an area that was likely experiencing strong katabatic winds coming off the LIS.

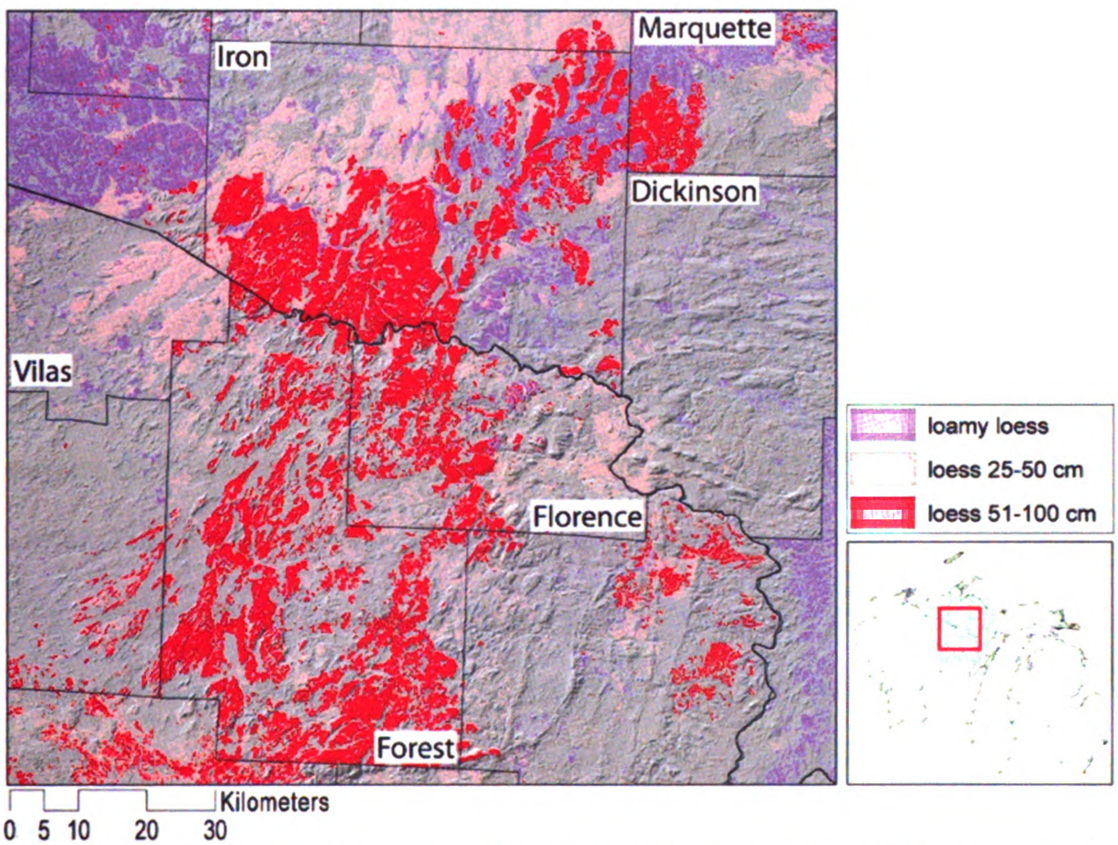

Figure 1.2. Regional loess distribution and loess thickness (cm) in northeast Wisconsin and the western U.P.

My research hypothesis for this thesis is that glacial drift located on the broad moraines was the source areas of loess in north-central Wisconsin, while moraines and outwash plains were the sources of loess that covers Iron County. Ice-walled lake plains on the Late Wisconsin moraine in north-central Wisconsin contain a large amount of silt, perhaps the most silt of any glacial landform in this region (Clayton and Cherry, 1967; Ham and Attig, 1996; Clayton *et al.,* 2008). These landforms are also typically located in high elevations, because they are perched on top of the topographically high moraine (Clayton and Cherry, 1967; Ham and Attig, 1996; Clayton *et al.*, 2008). Thus, after the water on these features drained, the lake floor sediments could have easily been deflated by winds. The topography of the moraines in Iron County is consistent with stagnant ice margins. Stagnant ice typically contains an abundance of supraglacial drift; of which silt is a large component. This silt could have been deposited in the ICLS while local outwash plains also provided eolian sediment to the loess sheet.

A typical method for sampling loess in the Great Plains and Central Lowlands regions has been to establish one or more transects away from a possible loess source to determine the character of the deposit (Smith, 1942; Hutton, 1947; Ruhe, 1954; Frye *et al.,* 1962; Frazee *et al.*, 1970; Maat and Johnson, 1996; Muhs and Bettis, 2000; Mason, 2001). I applied the same method to my research in the Upper Great Lakes region by establishing transects away from several prominent Late Wisconsin end moraines that border the loess deposits, on the assumption that they could have been source areas for the loess. Data from these transects will be used to help determine source area for each loess deposit.

1.1 Research Objectives

This thesis will increase our knowledge of loess in the Upper Great Lakes region by focusing on two regionally important loess deposits. The research will also advance our understanding of non-traditional loess sources and deposits, in general. The goals of this research are to (1) document and characterize these two loess deposits, and in so doing, (2) establish the likely source area(s) for each loess deposit. With the completion of these objectives, I hope to demonstrate that recently de-glaciated landscapes, such as moraines and outwash plains, were important loess sources in the Upper Great Lakes region. Because loess sheets change in predicable spatial patterns, I also propose to establish the paleowind direction in the study areas, at the time of loess deposition, and near glacial margins in general.

2. Literature Review

Loess deposits provide an excellent record of Late Quaternary climate change; thus, loess and related eolian deposits are important areas of study in geomorphology. Worldwide, extensive loess deposits appear to have a geographic relationship with areas of Pleistocene continental and alpine glaciations (Smalley, 1966). According to the geologic record, parts of the Quaternary Epoch were marked by loess deposition and non-deposition, creating several distinct loess units in the process. However, a single loess unit does not provide a complete paleoenvironmental record. To interpret the loess record, researchers must be able to correlate between two or more units in order to complete the record (Pye, 1984). Additionally, it is imperative for investigators to correlate between loess units and their source area(s) (Mason *et al.,* 1999).

Smalley (1966) stated that three operations influence a sedimentary deposit: (1) P actions (production), (2) T actions (transportation), and (3) D actions (deposition). In this literature review, I will discuss how production, transport, and deposition affect loess deposits and how they can provide information about paleoenvironmental conditions. I will then explain how the spatial characteristics of loess can be used to infer its possible source area. Next, I will discuss recent research on loess in the Upper Great Lakes region. This chapter will conclude with a discussion of ice-walled lake plains; a potential loess source for this thesis.

2.1 Background

Loess is an eolian deposit consisting mainly of quartz and feldspar minerals of predominately silt-sized particles (Smalley, 1966; Smalley and Cabrera, 1970; Pye, 1984). Pecsi (1990, 1-2) provides a more detailed definition of loess as, "… a loose deposit with coarse silt predominate in grain size, unstratified, porous, permeable, stable in steep walls, easily erodible by water, "structured light loam" of pale yellow color due to finely dispersed limonite (iron hydroxides), quartz as main mineral constituent (40-80%), subordinate feldspar content, variable amounts of clay minerals (5-20%) and carbonates (1-20%)". According to Pye (1995), four requirements are necessary for loess formation: (1) a dust source, (2) wind to transport dust, (3) a stable landscape for accumulation, and (4) time. Loess is common throughout the world especially North America, South America, central and eastern Europe, and central Asia (Pye, 1995). In the United States it extends as an almost continuous deposit from the Upper Great Lakes region to Louisiana, along major river valleys, and from southern Ohio to eastern Colorado (Figure 2.1) (Bettis *et al.*, 2003). Isolated deposits are also found in Washington, Idaho and Alaska (Roberts *et al.* 2003).

2.2 Loess Production

Loess in the North America can generally be divided into two varieties based on providence: (1) glacial and (2) periglacial (Grimley, 2000). Geological records indicate that silt production is high during glacial periods (Pye, 1995) and that most loess in the Central Lowlands region and eastern Great Plains is glaciogenic in origin (Bettis *et al.*, 2003). Weight and shearing deformation of glaciers sometimes crush and grind rocks into silt-sized sediments (Smalley, 1966; Pye, 1984) that are carried away from the ice margin by meltwater. Alternatively, in the western Great Plains, loess is often associated with eroded and weathered shale and siltstone bedrock, associated with

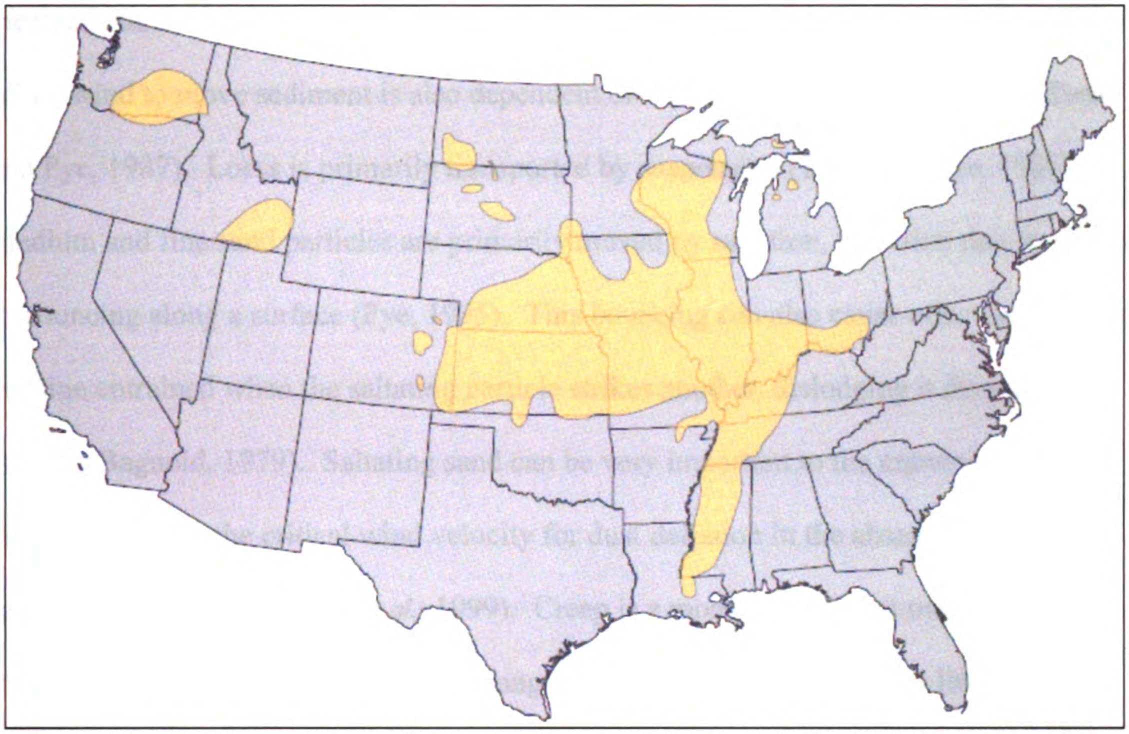

Figure 2.1. Map of general loess distribution (brown shaded area) in the USA (after Hole, 1968; Bettis *et al.*, 2003; Schaetzl, 2008; Schaetzl and Hook, 2008; Schaetzl and Loope, 2008).

periglacial environments (Lugn, 1962). Loess in this region is thought to have formed mostly from the weathering of outcrops of the White River Group siltstone, which exist northwest of large loess deposits in the Great Plains (Mason, 2001; Bettis *et al.,* 2003). The White River Group is an Oligocene age rock unit found in Nebraska, South Dakota, Wyoming, and Colorado (Mason, 2001). This weathering was likely caused by freeze/thaw cycles associated with paleotundra climates (Lugn, 1962).

2.3 Loess Transportation

Wind will move sediment from a source if the velocity is fast enough to overcome the frictional and gravitational forces holding the sediment in place (Smalley, 1966, Pye, 1984). Once these forces are overcome, eolian sediment is transported by (1) suspension, (2) saltation, (3) creep, or any combination thereof (Bagnold, 1979). These three mechanisms are responsible for the entrainment of particles of various sizes. The ability of the wind to move sediment is also dependent on the grain size of the sediment (Tsoar and Pye, 1987). Loess is primarily transported by suspension (Tsoar and Pye, 1987). Medium and fine sand particles are primarily moved by saltation, an action that is similar to bouncing along a surface (Pye, 1995). This bouncing can also cause other particles to become entrained when the saltating particle strikes another, dislodging it from the ground (Bagnold, 1979). Saltating sand can be very important to the entrainment of silt particles because the critical wind velocity for dust deflation in the absence of saltating sand is much higher (Mason *et al.,* 1999). Creep is a mode of sediment transport that involves coarse sand particles rolling along a surface (Pye, 1995) and has little effect on dust transport. During eolian transport, particle size sorting takes place with the finer fractions moving further downwind, leading to wedge-shaped loess deposits in cross-section (Ruhe, 1954).

Smalley (1966) outlined three ways in which loess can be transported. In the first scenario, subaerially exposed bedrock is weathered and the eroded silt particles are deflated by wind and deposited. The second scenario involves transport of silts from weathered bedrock by a fluvial system and then deflated out of the stream valley by eolian processes. These first two scenarios are commonly cited as mechanisms for loess deposition in the western Great Plains where the source of loess is the White River Group (Lugn, 1962; Pye *et al.,* 1995; Maat and Johnson, 1996; Aleinikoff *et al.,* 1998; Grimley, 2000; Mason, 2001).

In the third scenario, silt produced by glacial erosion gets transported from the terminus of the glacier by meltwater (Smalley, 1966; Follmer 1996; Bettis *et al.*, 2003).

Loess deposits in the Central Lowlands, which formed mainly in this manner, are generally thickest on the east side of river valleys, suggesting strong westerly winds during deposition (Ruhe, 1954; Frazee *et al.*, 1970; Pye, 1984; Muhs and Bettis 1998). Some of the thickest loess deposits in the United States are associated with the Missouri and Mississippi River Valleys, both of which were large, glacial meltwater valleys (Bettis *et al.*, 2003). During the winter months when the LIS was not producing meltwater, the outwash channels were likely at low flow or frozen, exposing floodplain sediments to eolian processes (Dawson, 1992; Pye, 1995). Silt produced initially from glacial erosion was then blown up and out of these outwash channels by wind and deposited downwind, tens of kilometers from the source (Frye *et al.*, 1962; Smalley, 1966; Frazee *et al.*, 1970). Meltwater channels are particularly important for eolian sediment in the coarse and medium silt range (Pye, 1995). This scenario is the dominate mechanism for loess transport and deposition in the Central Lowlands.

Along with dry river beds and outwash plains, erosional surfaces under periglacial conditions are subject to dust deflation (Pye, 1984, Mason *et al.,* 1994). Although most loess in the Central Lowlands is associated with major river valleys, the Iowan Erosion Surface (IES), located in southeastern Minnesota and northeastern Iowa was a locally important loess source during the Late Wisconsin (Ruhe, 1969; Mason *et al.,* 1994, 1999). During the last glacial maximum (LGM), the IES was ice-free and was subjected to eolian and fluvial erosion (Hallberg *et al.,* 1978). Loess is absent across most of the IES, but 1–1.5 m of Peoria loess caps its eastern and southern margins (Bettis *et al.,* 2003).

Recently, loess research in the Upper Great Lakes region has focused on non-traditional source areas. There is a lack of large meltwater valleys and few friable bedrock outcrops exist in the region; causing the need to look elsewhere for possible source areas. Research in Michigan and Wisconsin has revealed that lake plains (Schaetzl and Loope, 2008) and moraines (Stanley, 2008) have contributed eolian sediment to the surrounding landscapes. The two study areas that are the focus of this research also has no obvious source area adjacent to the loess deposit. For this reason, attention was given to the moraines bordering the study areas.

2.4 Loess Deposition

Loess particles are deposited when wind velocity and/or turbulence decreases. With a decrease in wind velocity or turbulence, larger dust particles fall out of suspension first in accordance with Stokes' Law (Pye, 1995). Three mechanisms exist to halt loess transport: (1) particle transport is interrupted by vegetation and/or a topographic barrier, which decrease the wind velocity; (2) particles are washed out of atmospheric suspension by precipitation; and (3) gravitational settling of particle aggregates formed by build-up of electrostatic charges (Ruhe, 1954; Tsoar and Pye, 1987; Mason *et al.,* 1994, 1999). Of these scenarios, the most effective mechanisms for loess deposition are vegetation and topographic barriers (Tsoar and Pye, 1987; Mason *et al.,* 1994). A vegetation or topographic barrier will only allow the smallest particles, suspended high in the air, to continue downwind (Mason *et al*., 1994, 1999; Schaetzl and Loope, 2008). Above the vegetation canopy, a near-surface zone of low wind velocity is formed, causing dust particles to fall out of suspension (Bagnold, 1979). Vegetation effectively prevents the dust particles from re-entrainment, allowing for the accumulation of loess. Local topography plays a major role in the potential for loess accumulation through its effect on the movement of saltating eolian sand (Mason *et al.,* 1999). If the amount of sand transport is higher than the rate of loess deposition, significant accumulation of loess may only occur downwind of the topographic barrier (Mason *et al.*, 1994, 1999). Steep, windward-facing escarpments and narrow valleys can act as sand traps. This mechanism may have been especially important to the Upper Great Lakes region due to the severe periglacial climate during much of the Pleistocene in the region (Mason *et al.*, 1999). The absence of loess adjacent to source areas suggests re-entrainment of dust (Tsoar and Pye, 1987), possibly due to the lack of a vegetation or topographic barrier.

Loess units often contain paleosols because its accumulation is highly episodic (Ruhe *et al.*, 1971; Hayward and Lowell, 1993; Jacobs and Mason, 2007). Generally, loess units represent glacial episodes, and paleosols represent interglacials and periods of soil formation and non-deposition (Muhs *et al.*, 2003). If the accumulation rate of loess is too low, pedogenesis will incorporate the sediment into the soil (Tsoar and Pye, 1987). If accumulation reaches a critical rate, loess will overwhelm pedogenesis, forming a loess unit. The critical rate of loess accumulation ranges between 0.5 and 1.0 mm yr^{-1}, depending on climate (Pye, 1984).

2.5 Spatial Characteristics

A major concern and goal in loess studies is determining the source area (Frazee *et al.*, 1970; Handy, 1976; Mason, 2001; Mason *et al.*, 2003; Schaetzl and Hook, 2008). Loess deposits display predicable spatial characteristics that serve as important proxies for paleowind direction, which can be used to infer source area. The geographic relationship between loess source and loess deposits depends on the type of landscape and the climate and vegetation gradients in an area (Pye, 1995). Many studies have shown that loess thickness and certain particle sizes decrease from the source area while coarser sediments tend to decrease (Krumbein, 1937; Smith, 1942; Hutton, 1947; Ruhe, 1954; Simonson and Hutton, 1954; Fehrenbacher *et al.,* 1965; Frazee *et al.*, 1970; Rutledge *et al.,* 1975; Handy, 1976; Putman *et al.,*1988; Aleinikoff *et al.,* 1998; Mason *et al.*, 1999; Muhs and Bettis, 2000; Bettis *et al.*, 2003; Jacobs and Mason, 2007; Schaetzl and Hook, 2008; Schaetzl and Loope, 2008). Multiple geochemical decay functions have also been used to indicate loess source areas (Ruhe, 1954, 1969; Aleinikoff *et al.,* 1998; Mason *et al.*, 1999; Grimley, 2000; Muhs and Bettis, 2000). This distance-decay trend is the result of winnowing of coarse particles and heavy minerals/elements (Ruhe, 1954; Muhs and Bettis, 2000). In the Great Plains and Central Lowlands, loess is usually thickest to the east of source areas due to prevailing westerly winds (Smith, 1942; Smalley, 1966; Fehrenbacher *et al.,* 1965; Handy, 1976; Muhs and Bettis, 2000). However, a narrow band of westward thinning loess occurs on the west side of river valleys in the Central Lowlands (Ruhe, 1954; Handy, 1976; Mason, 2001; Bettis *et al.,* 2003). This phenomenon has been attributed to variable easterly winds or anticyclonic winds (Hobbs, 1943; Fehrenbacher *et al.*, 1965; Handy, 1976; Putman *et al.,* 1989). In the case of the Mississippi Valley as a source, it appears that most loess accumulation occurred within 100 km of the river (Pye, 1984).

Additionally, the general topographic characteristic of the surface upon which loess was deposited influences the thickness (Ruhe, 1954). The ability of loess to resist erosion is heavily influenced by landscape position, and subsequent erosion can make interpretations of loess deposits difficult (Schaetzl, 2008). When loess is deposited, it generally covers a landscape evenly (Pye, 1984). However, the process of erosion causes loess covered landscapes to become highly dissected with the loess being persevered only on the flat uplands (Ruhe, 1954; Schaetzl, 2008). Loess on side slopes is preferentially eroded which causes these deposits to be thinner or non-existent (Ruhe, 1954). Thus, the valleys and footslopes may contain thicknesses of loess, known as reworked loess (Pye, 1984), that are artificially high.

2.6 Loess Chronology

Once a source area has been identified, the next step is to determine the span of time the source area was active. Often, the age of a loess deposit is needed to fully understand the paleoenvironmental conditions at the time of deposition. Establishing an accurate age is complicated by the fact that loess deposits are time transgressive (Ruhe *et al.,* 1971). Both relative and absolute dating techniques are used to differentiate between loess units. Paleosols are often used to separate loess units (Ruhe *et al.,* 1971). These buried soils have known stratigraphic positions which are used to obtain both relative and absolute age dates. The methods utilized by researchers to give accurate absolute age dates to loess formations include radiocarbon dating (^{14}C), thermoluminescence (TL) dating, and optically stimulated luminescence (OSL) dating (Pye *et al.,* 1995; Maat and Johnson, 1996).

Radiocarbon, TL and OSL dating of loess in the Great Plains and Central Lowlands indicate that much of it was deposited during the Late Wisconsin glacial period (Pye, 1984). Loess deposited during this period is known as Peoria loess. Generally, Peoria loess was deposited between 25.0 and 13.0 years ka (Pye, 1984; Bettis *et al.,* 2003). Peoria loess is volumetrically and geographically the most extensive loess unit in North America (Frye *et al.*, 1968). It is the uppermost loess unit in the Central Lowlands and Upper Great Lakes region. Thick (>10 m) deposits of Peoria loess are found on the east side of major river valleys that drained the LIS (Bettis *et al.*, 2003). The thickest deposits (> 40 m) of Peoria Loess lie along the Missouri River Valley in western Iowa (Bettis *et al.*, 2003). The White River Group appears to be the major source for Peoria loess in the western Great Plains (Grimley, 2000).

2.7 Loess in the Upper Great Lakes Region

Loess deposits in the Upper Great Lakes region are relatively thin when compared to deposits in the Great Plains and other parts of the Central Lowlands, nearer to large meltwater rivers. Recent research has focused on the characteristics, distribution and origins of loess in the Upper Great Lakes region (Schaetzl, 2008; Schaetzl and Hook, 2008; Schaetzl and Loope, 2008; Stanley, 2008). In Wisconsin, loess deposits were first recognized by Hole (1942) while working on his dissertation in north-central Wisconsin. Other geomorphic studies have been carried out in north-central Wisconsin that have recognized the presence of loess (Hole, 1968; Cahow, 1976; Attig and Muldoon, 1989; Attig, 1993).

Although loess has long been recognized in north-central Wisconsin (Hole, 1942, 1968; Cahow, 1976; Attig and Muldoon, 1989; Fiala, 1989; Attig, 1993; Syverson and Colgan, 2004) no research has focused on the loess sheet until recently (Stanley, 2008). She found that loess is thickest (~70 cm) along the Late Wisconsin terminal moraine in northern Clark County, Wisconsin and along Cambrian sandstone outcrops in the western portion of the county. She also noted loess thickness decreases to < 40 cm towards the east/southeast and that the texture of the loess is coarser near the moraine and Cambrian sandstone uplands in the western part of Clark County. The dominant mineral constituent in her study area is quartz followed by plagioclase and K-feldspar (Stanley, 2008). From this information, she concluded the loess in this area is likely derived from two sources: 1) ice-walled lake plains on and behind the Late Wisconsin terminal moraine to the northwest of the study area, and 2) Cambrian sandstone uplands to the west/southwest. Her conclusion that ice-walled lake plains were a loess source area is particularly significant because it is the first time they have been recognized as a loess source. Large portions of the LIS in the Upper Great Lakes region were characterized by stagnant ice margins after the LGM (Ham and Attig, 1996), thus, ice-walled lake plains could be a regionally, more-extensive and important loess source. OSL age estimates from Stanley's study area indicate the period of loess deposition occurred between ~ 15,200 and 12, 000 years ago (Stanley, 2008). At the time of loess deposition, the LIS margin in north-central Wisconsin was characterized by stagnant and likely underlain by permafrost (Clayton, 2001). Stanley suggests loess was not available for deflation until after the ice and permafrost began melting. Therefore, the OSL age estimates do not necessarily reflect the timing of ice margin retreat because ice blocks and permafrost could have persisted for hundreds of years (Stanley, 2008).

Only recently has loess been a recognized deposit in the eastern Upper Peninsula (Schaetzl and Loope, 2008) and northern Lower Peninsula of Michigan (Schaetzl, 2008; Schaetzl and Hook, 2008). Schaetzl and Loope (2008) tested the topographic barrier model developed by Mason *et al.*, (1999) on a regional level at their site in the eastern Upper Peninsula. Loess deposits there are preserved on uplands that were once islands in proglacial lakes formed in the Lake Superior and Lake Michigan basins. They hypothesized that the origin of the eolian silt cap covering the islands was glacial lake bed sediment exposed after the LIS retreated and proglacial lake levels fell. This study also highlighted the fact that saltating eolian sand can have a significant impact on generating loess (Schaetzl and Loope, 2008).

Schaetzl and Hook (2008) examined the origin of silt-rich sediment in an area of northern Michigan known as the Buckley Flats. The Buckley Flats are part of the Outer Port Huron morainic system which consists of several large, gently sloping heads-of-outwash (Schaetzl and Hook, 2008). The silt cap on the Buckley Flats thins and becomes finer textured and siltier from south to north. Based on this evidence, Schaetzl and Hook concluded the silty cap is loess and that its source is likely the Manistee River Valley, which lies south of the study area. The Manistee River carried meltwater during the Port Huron stage, and thus, the loess on the Buckley Flats is similar to loesses in the Central Lowlands, also sourced from meltwater rivers. This study was the first to recognize an extensive, albeit thin, loess sheet in Lower Michigan.

Schaetzl (2008) examined another silty cap that covers parts of the Grayling Fingers region of the High Plains of northern Lower Michigan. The Grayling Fingers region is a large landform assemblage formed mostly by Late Wisconsin glaciofluvial processes (Schaetzl, 2008). The silt cap is preserved only on stable, flat uplands of the Graying Fingers (Schaetzl, 2008) and it was determined to be a loess deposit. Evidence suggests the source area was the Port Huron outwash plain and Manistee River Valley (Schaetzl, 2008). This study reinforces the fact that the Port Huron outwash plain and Manistee River Valley were important regional loess sources. The discovery that the loess is only preserved on the flat, stable uplands was an important contribution of this study.

The Upper Great Lakes region loess research presented above is important because it provides evidence for (1) loess in a region that was previously thought not to contain loess and (2) non-traditional loess source areas. Because there are no major rivers that drained the LIS in the Upper Great Lakes region and easily erodible bedrock outcrops are rare in this area, coupled with the fact that the LIS occupied the Upper Great Lakes longer than most other regions in the United States, this area was overlooked as a landscape where loess could accumulate.

2.8 Ice-Walled Lake Plains

An ice-walled lake plain is an elevated, nearly flat, plateau-like landscape (Clayton, 1967, Cahow, 1987; Clayton, *et al.,* 2008) underlain by horizontally bedded gravel, sand, silt and clay deposited in a glacial lake surrounded by stagnant ice. Ice-walled lakes trap supraglacial sediment washed in from melting, stagnant ice. Sand and gravel are usually found along the margins and the sediments becomes finer toward the center where silt and clay are deposited (Clayton, 1967). When the surrounding ice melts due to thermal erosion (Ham and Attig, 1996), the topography is inverted and the ice-walled lake plain becomes a relatively high, flat surface on the otherwise hummocky landscape associated with stagnant ice topography (Clayton, 1967; Ham and Attig, 1996; Clayton *et al.,* 2008) (Figure 2.2). Ice-walled lake plains are usually less than 5 km in diameter and the laminated offshore sediment is often at least as thick as the elevation between the ice-walled lake plain and the adjacent inter-hummock depressions (Clayton, *et al.,* 2008). These stagnant glacial ice landforms are very common on parts of the Late Wisconsin terminal moraine in North Dakota, Minnesota and Wisconsin (Cahow, 1987; Ham and Attig, 1996; Clayton *et al.,* 2008). Given their common occurrence, large amounts of silt, and high landscape position, ice-walled lake plains may have been significant source areas for loess in the western Upper Great Lakes region, such as north-central Wisconsin (Stanley, 2008).

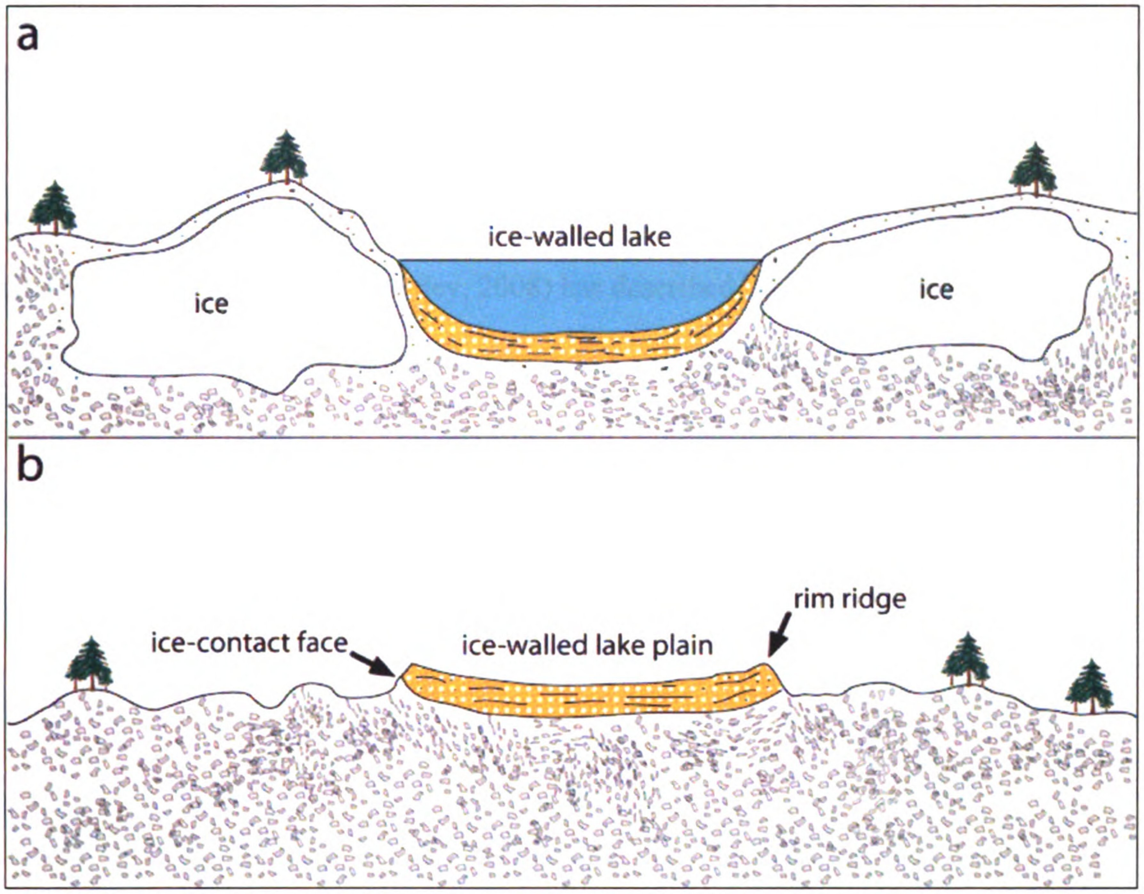

Figure 2.2. Schematic cross sections of an ice-walled lake plain (a) confined by ice and (b) after ice melted. Brown stippled pattern represents Pleistocene glaciolacustrine sediments.

2.9 Summary

Loess can provide information about past wind regimes (Muhs and Bettis, 2000), and the extent and timing of glaciations (Pye, 1995), while buried soils within loess deposits provide a reference for climate and landscape stability (Ruhe *et al.,* 1971; Bettis *et al.,* 2003; Mason *et al.,* 2003). All of these records are critical to understanding the paleoenvironmental conditions during loess deposition. In order to obtain this knowledge, we must be able to understand the basics characteristics and distribution of loess. Loess production and transport is profoundly influenced by climate (Aleinikoff *et al.,* 1998; Kohfeld and Harrison, 2001; Muhs *et al.*, 2003). Loess deposits display characteristic spatial trends with respect to loess thickness, particle size, mineralogy, and geochemistry. These trends can be used to infer paleowind regime; which, in turn, is used to determine the source area for the loess. Most of the knowledge we have of loess comes from research done in the Great Plains and Central Lowlands. Recent work (Schaetzl and Loope, 2008; Stanley, 2008) has described landscapes previously overlooked as possible source areas to be highly significant contributors of loess. New source areas and types have been identified and continue to emerge.

3. Study Areas

This thesis will investigate two loess deposits that occur in the Upper Great Lakes region, the Iron County loess sheet (ICLS) and the north-central Wisconsin loess sheet (NCWLS) (Figure3.1).Loess in north-central Wisconsin has been recognized for decades (Hole, 1942, 1968; Cahow, 1976; Attig and Muldoon 1989; Stanley, 2008). Flint (1971) recognized loess in the western U.P., but it has not been the subject of intensive study. This chapter provides background on the geography, geology, glacial history, soils, modern vegetation and climate, relevant to these two study areas.

Figure 3.1. General locations of study areas (indicated by red boxes).

3.1 The Iron County Loess Sheet

Based on Natural Resource Conservation Service (NRCS) soil surveys (Linsemier, 1997), several areas of northeast Wisconsin and the western U.P. contain soils that are capped by loess that attains thicknesses of a few tens of centimeters to a meter. The Iron County loess sheet is located primarily in Iron County, Michigan, but the deposit extends a few kilometers into Baraga, Gogebic, and Marquette Counties and into bordering counties in Wisconsin. The thickest loess is found in the southwestern portion of Iron County. The study area is bordered on the north by the Watersmeet Moraine, on the northeast by the Republic Moraine, on the east by the Sagola Moraine, and on the west by the Vilas County, WI Outwash Plain (Figure 3.2). The loess in Iron County is discontinuous, being mainly preserved on uplands. This thesis is the first comprehensive study of the Iron County loess deposit.

3.1.1 Geology and Glacial History

The ICLS study area is underlain by Precambrian crystalline bedrock (Peterson, 1986; Schaetzl *et al.*, 2009). The bedrock geology of this area is extremely complex, containing some of the oldest rocks on Earth, dating back 3.5 billion years to the Archaean Era (Schaetzl *et al.*, 2009). Some of the larger units within the study area include the Hemlock Formation, Badwater Greenstone, and Michigamme Formation (Schaetzl *et al.*, 2009). Many outcrops of these and other types of rocks are common in the western U.P. (Schaetzl *et al.*, 2009; Peterson, 1986). During the numerous glacial advances into the Upper Great Lakes region, some of these bedrock outcrops were sculpted into drumlins, especially in Iron County.

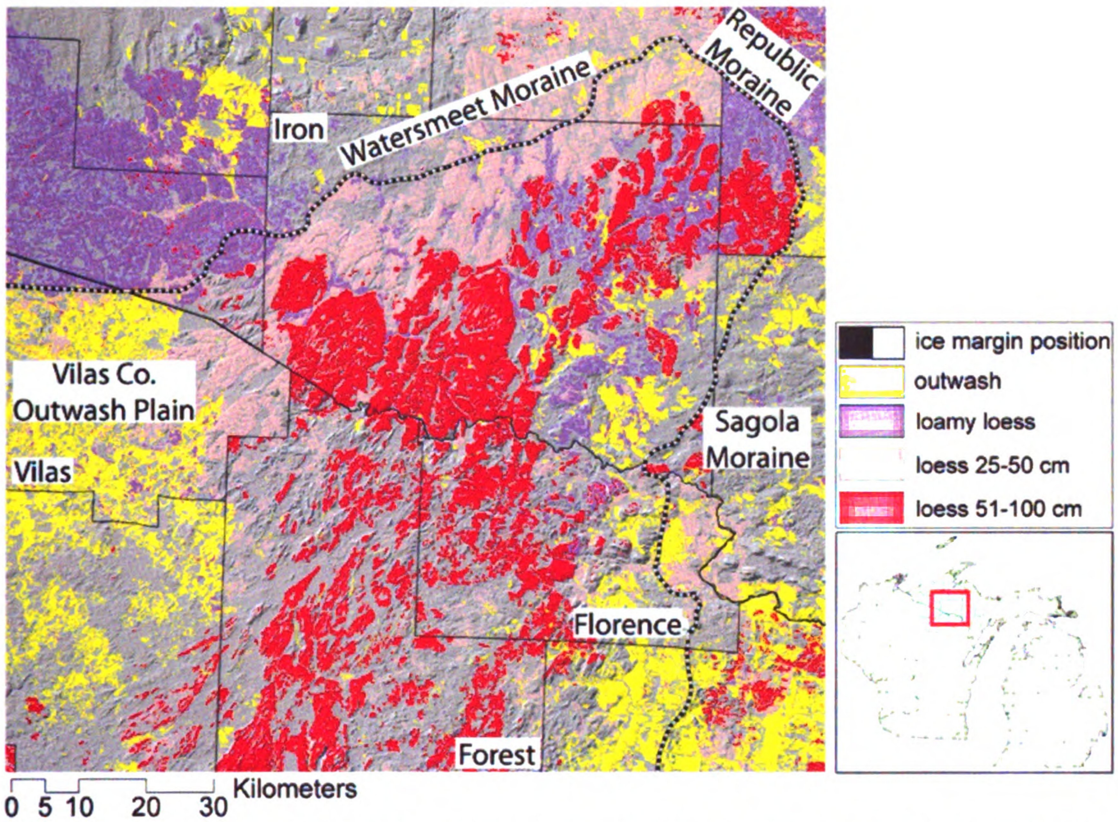

Figure 3.2. Loess distribution and location of outwash deposits near the Iron Co. Loess Sheet

Where the bedrock is not exposed, it is covered by glacial deposits of Late Wisconsin age in the Iron County area. Glacial drift in this area is generally thin, but it can range to 45 m in thickness (Peterson, 1986). There were four major ice lobes that contributed to the construction of the glacial landscape in the western U.P. They are, from west to east: (1) Ontonagon, (2) Keweenaw Bay, (3) Michigamme, and (4) Green Bay (Attig *et. al.,* 1985; Peterson, 1986). These four lobes were generally contemporaneous while building the end moraines of the Winegar-Early Athelstane Phase (Attig *et. al.,* 1985) that forms the northern and eastern boundaries of the ICLS (Figure 3.3). The Winegar-Early Athelstane Phase probably correlates to the Port Huron advance, which occurred approximately 15.0 ka (Attig *et. al.,* 1985; Blewett et al., 1993).

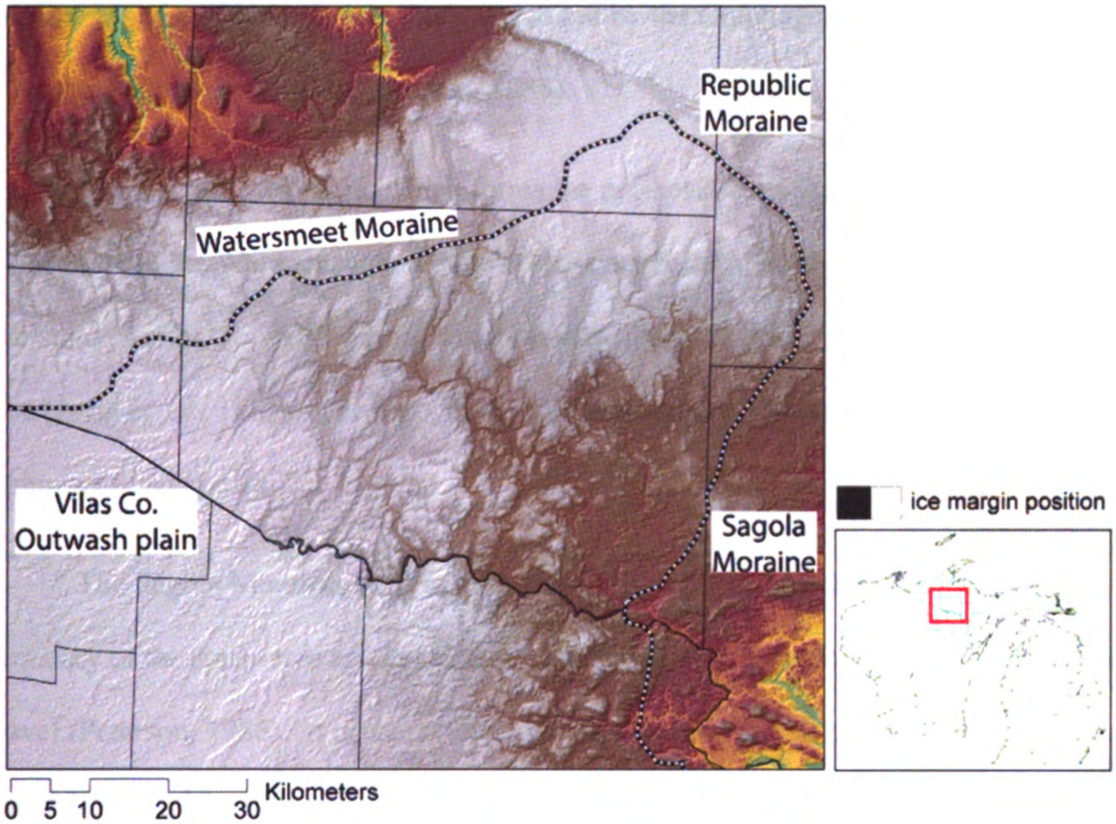

Figure 3.3. Names and location of moraines bordering the Iron County Loess Sheet (Attig et al., 1985; Peterson, 1986).

The Watersmeet Moraine consists mostly of brown colored till, of gravelly sand texture, according to Peterson (1985), who produced a surfical geology map of the Iron River 1° X 2° quadrangle. The NRCS describes the soils on the moraine as being generally well drained and gravely, sand texture (Linsemier, 1997). The landscape associated with the Watersmeet Moraine consists mostly of hummocky, bedrock controlled topography, with numerous closed depressions, and few lakes (Attig *et. al.*, 1985). It is difficult to trace the Watersmeet Moraine for any considerable distance because the drift that comprises the moraine is very thin in most places (Peterson, 1986). The NRCS has also mapped the Watersmeet Moraine and classified it as a disintegration moraine (Jerome, 2006). It was likely deposited by the Ontonagon and Keweenaw Bay lobes approximately 15.0 ka (Peterson, 1986).

The Republic Moraine, which forms the northeast boundary of the study area, is located where the Watersmeet and Sagola Moraines meet in northeastern Iron County. The stony, sandy brown till of this landform was likely deposited by the Michigamme lobe (Attig *et. al.*, 1985). The topography of the moraine is characterized by many hummocks and kettles.

The Sagola Moraine, built by the Green Bay lobe, is located on the eastern boundary of the study area and consists of calcareous, red, ice contact, stratified sand and gravel (Peterson, 1986). It is characterized by hummocky topography with many kettles. The red color of the till suggests that the ultimate source of the drift was most likely the red Precambrian sandstones and shales from the Superior basin area (Attig *et. al.*, 1985; Peterson, 1986). This sediment was deposited into the Lake Michigan basin at an earlier time, and subsequently re-entrained and deposited by the Green Bay lobe ~ 15.0 ka as the Sagola Moraine (Peterson, 1986).

The region where the Iron County loess was deposited generally lies between the Watersmeet, Republic, and Sagola Moraines and is characterized generally by two major landform assemblages. The first is the Iron County Drumlin Field, located mostly in the southwest part of the county (Figure 3.4). A typical drumlin here is ~ 1 km long and ~ 0.5 km wide, and usually has less than 15 m of local relief (Peterson, 1986) (Figure 3.5). The cores of these drumlins are comprised of bedrock, beneath a thin deposit of sandy glacial till. The Iron County drumlins are typically oriented northeast – southwest.

Swales between drumlins are often occupied by lakes, streams or wetlands. Overall, the region is characterized by a deranged drainage pattern.

The other major landform assemblage between the moraines is an area of hummocky, ice-contact, stratified drift and bedrock outcrops known as the Michigamme Bedrock Terrain (Figure 3.4). Drift here is usually thin, but it can be locally thick within lowlands. The drift consists mostly of gravelly sand and gravel which are found in kame terraces, ice-channel fills and pitted outwash plains or bedrock influenced ground moraine deposited by the Michigamme and Green Bay lobes (Peterson, 1986). Like the Iron County Drumlin Field, the Michigamme Bedrock Terrain is characterized by a deranged drainage pattern with many lakes and wetlands.

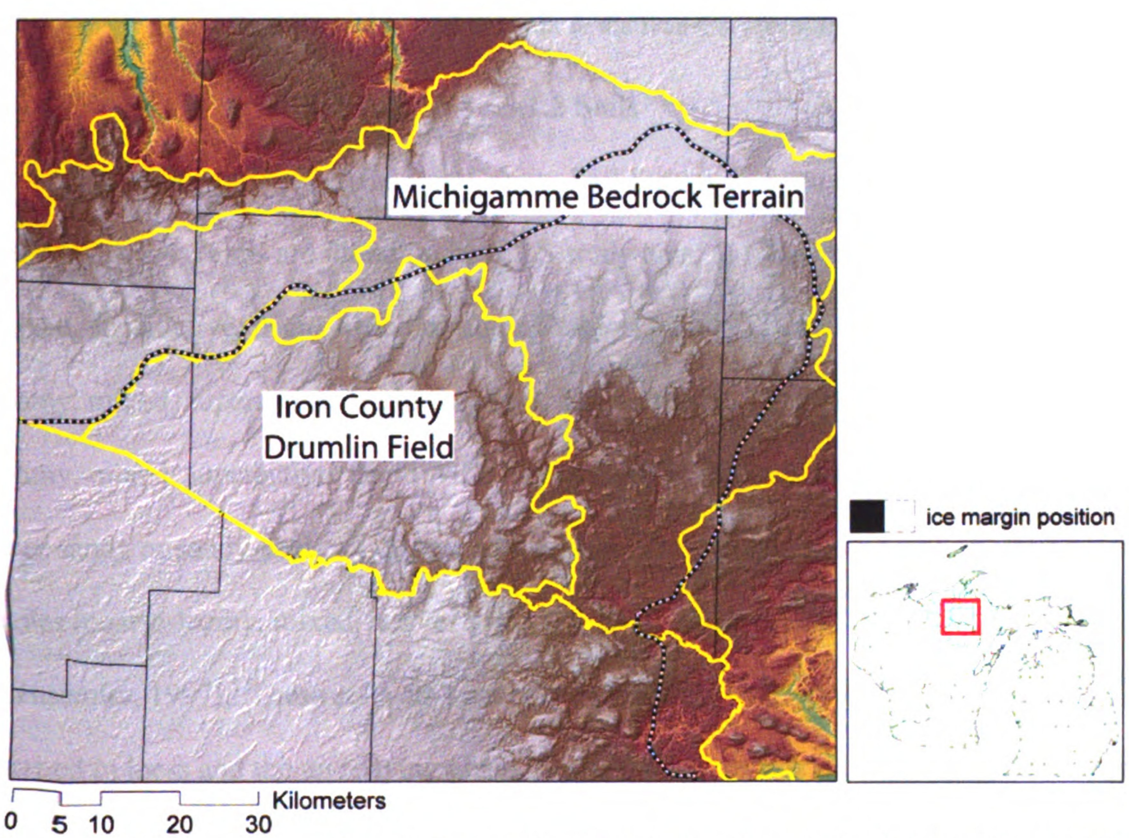

Figure 3.4. Physiographic regions within Iron County, MI where loess is found (yellow line indicates boundary of region).

Figure 3.5. A typical drumlin in the Iron Co. Drumlin Field.

3.1.2 Soils

According to the NRCS Iron County Soil Survey (Linsemier, 1997), five soil series with loess caps are found in the ICLS study area: (1) Wabeno series (coarse-loamy, mixed, superactive, frigid Alfic Oxyaquic Fragiorthods), (2) Champion series (coarse-loamy, mixed, superactive, frigid Oxyaquic Fragiorthods), (3) Goodman series (coarse-loamy, mixed, superactive, frigid Alfic Haplorthods), (4) Petticoat series (coarse-loamy over sandy or sandy-skeletal, mixed, active, frigid Alfic Haplorthods), and (5) Peavy series (coarse-loamy, mixed, active, frigid Oxyaquic Haplorthods) (Figure 3.6) (Linsemier, 1997). These soils are generally moderately well drained to well drained, formed in loess and the underlying glacial till and found on uplands such as end moraines and drumlins (Table 3.1). Loess mantles here generally range from 35 – 70 cm thick (Linsemier, 1997).

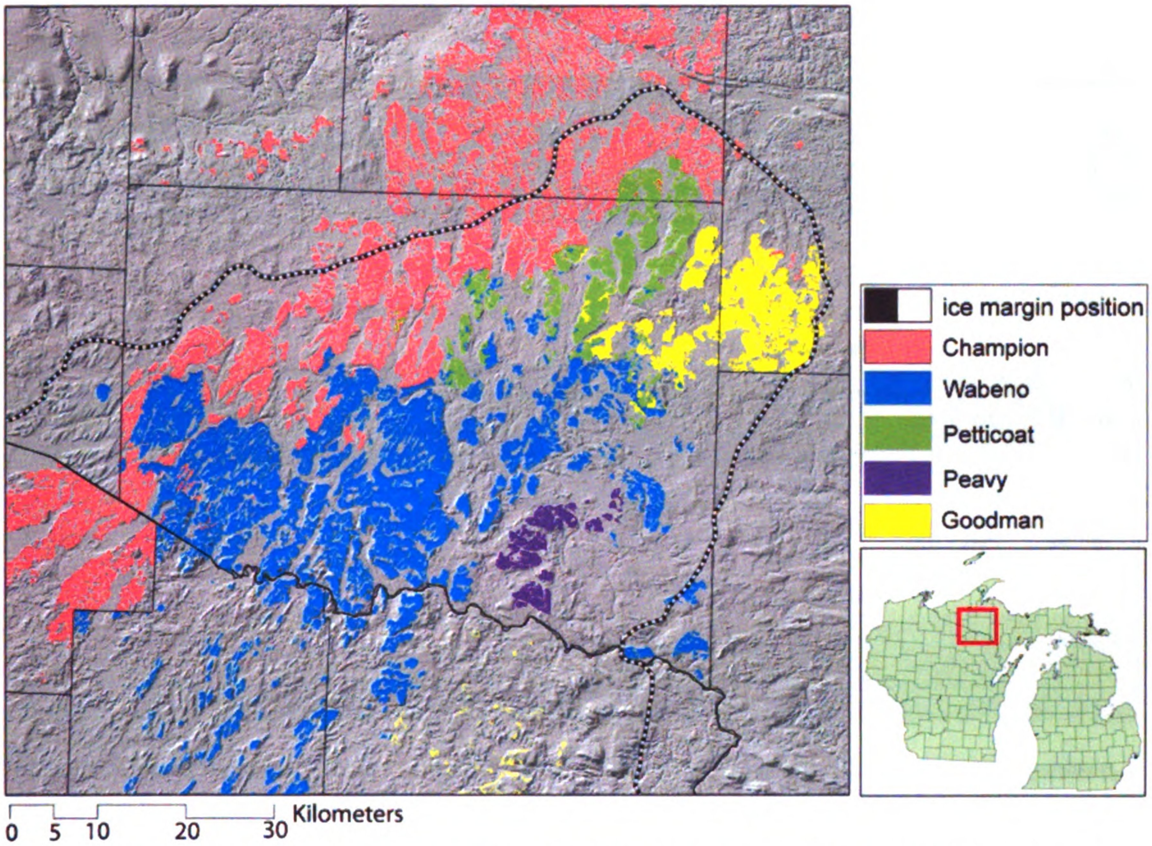

Figure 3.6. Distribution of loess mantled upland soils in Iron County Loess Sheet study area (Linsemier, 1997).

3.1.3 Vegetation and Climate

The mean annual temperature (1971-2000) for Stambaugh, Michigan, located within the ICLS, is ~ 3° C. The mean January temperature of this region is ~ -13°C and the mean July temperature is ~ 18°C (National Climatic Data Center, 2002). The annual mean precipitation at Stambaugh is 77 cm, with a January mean precipitation of ~ 3 cm and a July mean precipitation of ~ 18 cm (National Climatic Data Center, 2002). Average annual snow fall for Stambaugh is 193 cm. The study area is mostly forested with shrub wetlands and some areas of minimal agriculture on drumlins. The uplands are generally occupied by sugar maple, yellow birch, hemlock forests and the lowlands are occupied by conifer swamp species such as spruce and fir (Linsemier, 1997).

Series	Counties	Taxoniomic Class	Drainage Class*	Landform	Parent materials	Surface texture	Depth to LD†
Champion	Iron, MI & Vilas, WI	Oxyaquic Fragiorthods	WD & MWD	ground & end moraines	loess, underlying sandy or loamy till	very fine sandy loam	50 cm
Goodman	Iron, MI & Marquette, MI	Alfic Haplorthods	WD	ground & end moraines	loess, underlying loamy and sandy till	silt loam	63 cm
Petticoat	Iron, MI	Alfic Haplorthods	WD & MWD	ground moraines	loess, underlying sandy till	silt loam	76 cm
Wabeno	Iron, MI & Forest, WI	Oxyaquic Fragiorthods	MWD	moraines and drumlins	loess, underlying loamy and sandy till	silt loam	80 cm
Peavy	Iron, MI	Oxyaquic Haplorthods	MWD & WD	ground moraines	Loess and underlying till	silt loam	68 cm

Table 3.1. Characteristics of loess mantled upland soils in the Iron County Loess Sheet (Linsemier, 1997). * Drainage class: well drained (WD), moderately well drained (MWD) † Lithologic Discontinuity (LD)

3.2 The North-Central Wisconsin Loess Sheet

The north-central Wisconsin loess sheet is located primarily in northeastern Clark, northwestern Marathon, and southern Taylor Counties, Wisconsin (Figure 3.7). The loess sheet is bordered on the north by the Late Wisconsin terminal moraine, and on the west by a sandy landscape dominated by Cambrian sandstone bedrock outcrops, in western Clark County (Mudrey *et al.*, 1982; Ham and Attig, 1996; Stanley, 2008). The loess sheet has no definite topographic boundary on the south and east. Instead the loess thins until it can no longer be recognized; here it is commonly incorporated into the underlying drift. Loess thickness within the study area ranges from 30 – 100 cm; it is commonly thickest near the moraine and thins, away from it (Stanley, 2008).

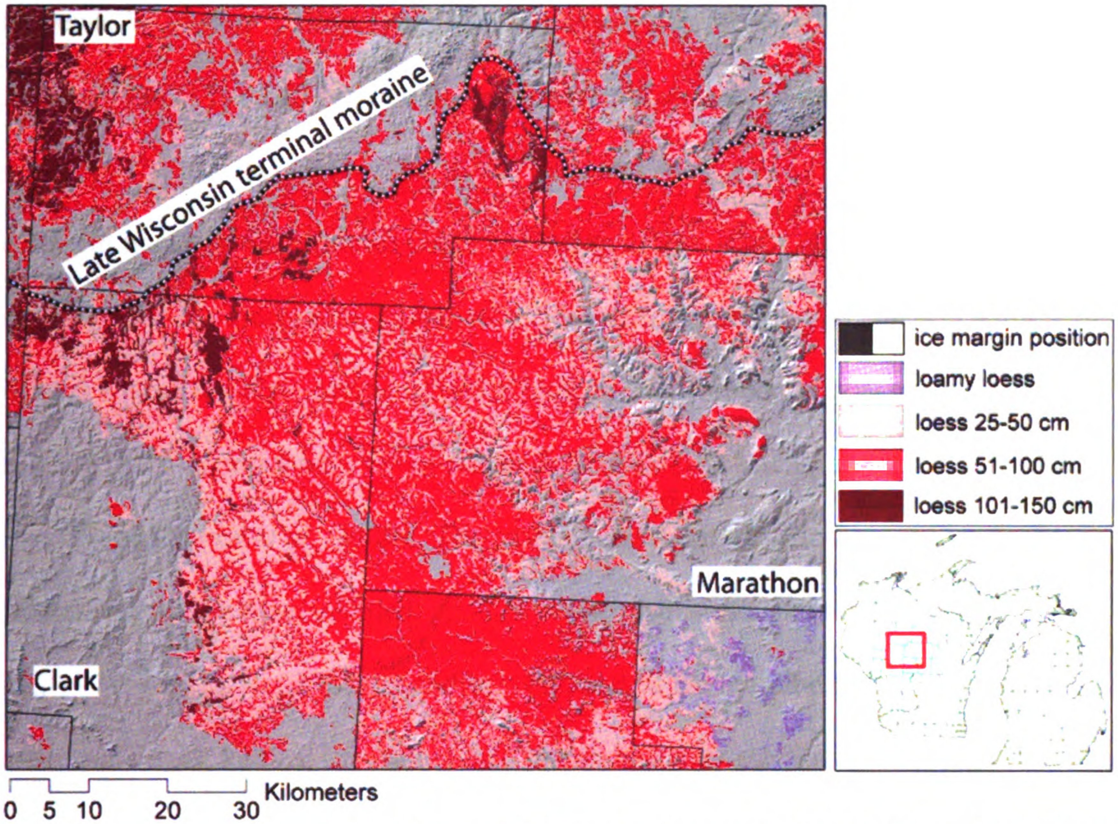

Figure 3.7. Loess thickness and distribution within the North-central Wisconsin Loess Sheet (Fiala et al., 1989).

3.2.1. Geology and Glacial History

The study area lies in a transitional zone between the Canadian Shield and younger, Cambrian-aged, sedimentary rocks. The northern and eastern portions of the study area are underlain by Precambrian crystalline bedrock, while the southern and western portions are underlain by onlapping Paleozoic sandstones (Mudrey *et al.,* 1982). The crystalline bedrock is primarily comprised of basaltic metavolcanics, granite, diorite, and gneiss (Mudrey *et al.,* 1982).

The Late Wisconsin terminal moraine in north-central Wisconsin and its associated features were deposited mainly by four ice lobes that were probably not contemporaneous (Mickelson *et. al.,* 1974). These four lobes were, from west to east, Chippewa, Wisconsin Valley, Langlade, and Green Bay lobes (Attig *et. al.*, 1985; Peterson, 1986). The LIS reached its maximum extent in north-central Wisconsin approximately 20.0 ka (Attig *et. al.,* 1985; Ham and Attig, 1996). By about 18.0 ka the ice margin began to retreat north (Ham and Attig, 1996). The Late Wisconsin terminal moraine within the study area, known as the Perkinstown moraine (Ham and Attig, 1996), is a large ice-disintegration feature built by the Chippewa, Wisconsin Valley, and Langlade lobes during the St. Croix-Hancock Phase of the Michigan Subepisode (Attig *et. al.*, 1985; Karrow *et al.,* 2000). The moraine has a fairly distinct ridge that rises tens of meters above the loess mantled, pre-Late Wisconsin surface to the south. (Mickelson *et al.,* 1974; Attig *et al.,* 1985). Landforms typical of the moraine include hummocks, ice-contact ridges, kettles, ice-walled lake plains, and outwash fans (Peterson, 1986; Ham and Attig, 1996). The moraine itself is mainly comprised of slightly clayey, silty, gravelly sand till (Ham and Attig, 1996).

The NCWLS covers landforms of pre-Late Wisconsin age drift (Stewart and Mickelson, 1974) (Figure 3.8). The exact age of this drift is not known, however, it is probably older than 45.0 ka (Stewart and Mickelson, 1974). Landforms on the pre-Wisconsin drift plain here have low relief, which could best be described as gently rolling with a distinctly dendritic drainage pattern (Figure 3.9). The Edgar Member of the Marathon Formation is located mainly in the southeastern portion of the study area; it is probably the oldest drift in the study area (Syverson and Colgan, 2004). The Bakerville and Merrill Members of the Lincoln Formation are exposed in the western and northern parts of the study area, respectively. Slope gradients on the pre-Late Wisconsin landscape generally do not exceed six percent (Fiala *et al.,* 1989). The subdued nature of this landscape is probably due to accelerated erosion during the Late Wisconsin and to the extreme age of the till (pre-Late Wisconsin) (Attig and Muldoon, 1989).

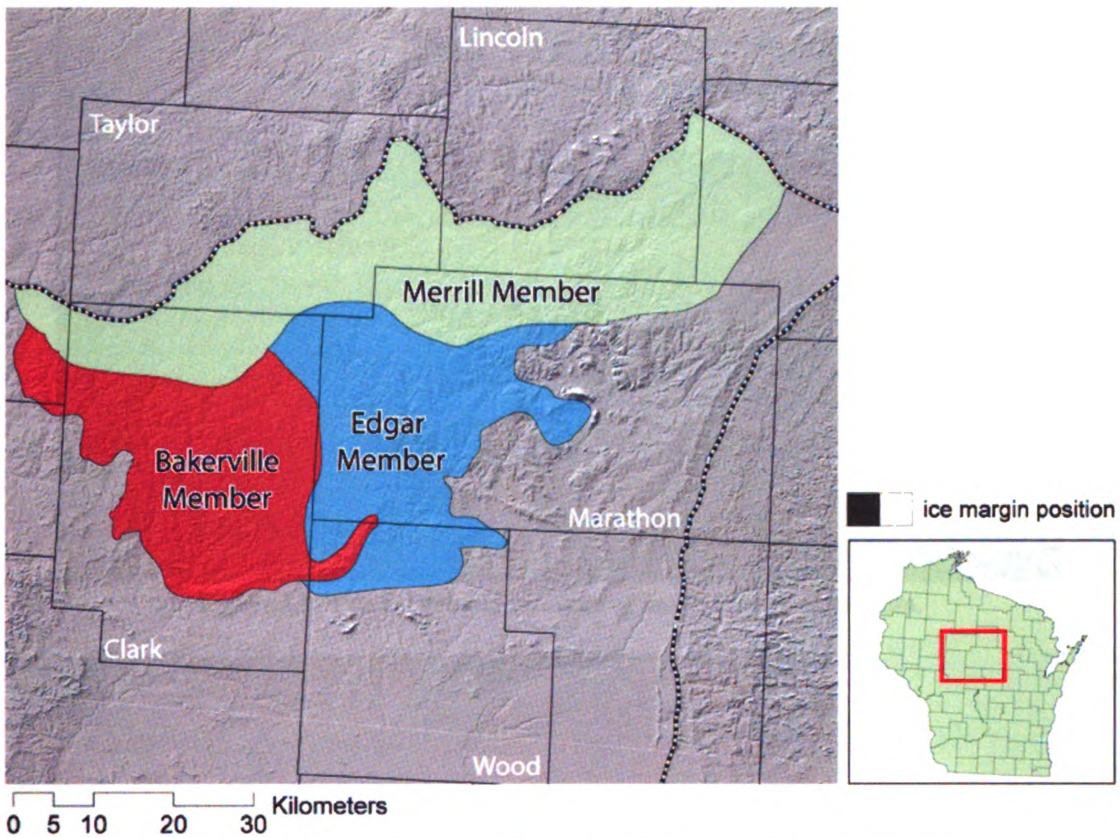

Figure 3.8. Location of pre-Late Wisconsin till members (Clayton et al., 2006).

Previous work in this area has confirmed the presence of loess (Hole, 1942; Cahow 1976; Attig and Muldoon 1989) and NRCS soil surveys have mapped eolian silt caps within many soils (Fiala *et al.,* 1989). However, the most comprehensive study to date has been that of Stanley (2008) whose work on the NCWLS focused mainly on the portion of the loess sheet located in Clark County, WI. The study area in this thesis is located slightly to the northeast of Stanley's study area (Figure 3.10). Stanley (2008) found that, in this general area, loess thickness decreases away from the Late Wisconsin

Figure 3.9. Typical ground moraine of north-central Wisconsin.

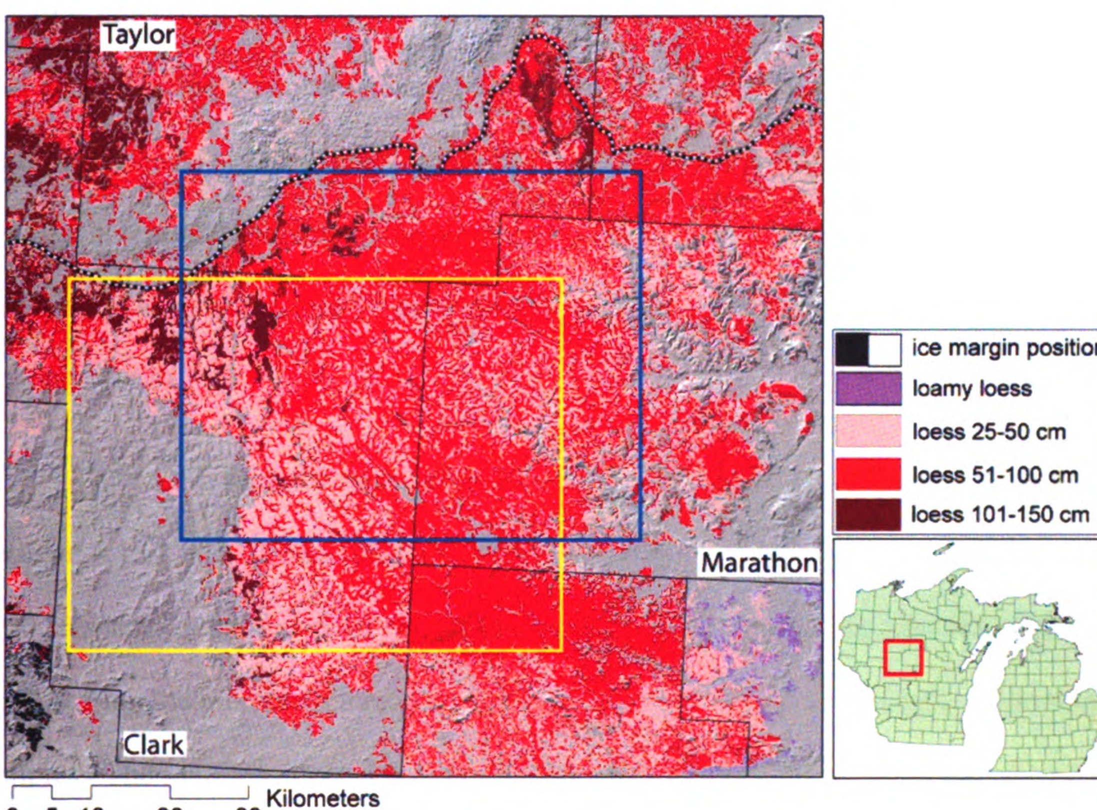

Figure 3.10. Map showing locations of Stanley's (2008) study area (yellow box), and the study area for this research (blue box).

terminal moraine; which is consistent with the classic wedge-shaped thickness trends in the Great Plains and Central Lowlands regions (Smith, 1942; Ruhe, 1954; Frazee *et al.*,1970; Handy, 1976; Aleinikoff *et al.,* 1998; Mason *et al.*, 1999; Muhs and Bettis, 2000; Bettis *et al.*, 2003; Jacobs and Mason, 2007; Schaetzl and Hook, 2008; Schaetzl and Loope, 2008). According to Stanley (2008), the area of thickest loess (>75 cm) is in northern Clark County; loess decreases to approximately 40 cm to the southeast, over a distance of about 30 km. The area of thickest loess lies distal to the Late Wisconsin terminal moraine, which she concluded was a major source area for the NCWLS. An area of slightly thinner loess (60-75 cm) occurs in central Clark County where it thins to the west, to approximately 35 cm over a distance of 40 km. Based on this thickness trend, Stanley concluded there must be a second source area; the Cambrian sandstone outcrops in western Clark County. Stanley also found that loess texture follows the same spatial trend as loess thickness; becoming finer away from the two source areas. Based on these data, she suggested that the NCWLS had two main sources: (1) the Late Wisconsin terminal moraine to the north, including numerous ice-walled lake plains on and behind the moraine, and (2) outcrops of Cambrian-aged sandstones to the west (Stanley, 2008).

Three OSL samples from her study area indicate that loess deposition occurred between ~ 15.2 and 12.0 ka (Stanley, 2008). According to Stanley, these OSL age estimates support her theory of two source areas for the NCWLS. The sample collected furthest from the moraine returned an age of 14.1 ka, the oldest age estimate of the three samples. The sample collected proximal to the moraine returned the youngest age, 12.9 ka. Although the age estimate errors overlap, Stanley postulates that the Cambrian sandstone source in western Clark County was active before the Late Wisconsin terminal moraine. The area farthest from the moraine would have become ice-free first, allowing sediment to be deflated (Stanley, 2008), and thus, the loess associated with the sandstone outcrops is the oldest. Only after the ice margin retreated from the Late Wisconsin terminal moraine and the permafrost in the moraine melted, would sediment from the ice-walled lake plains in the moraine be available for entrainment.

3.2.2 Soils

According to the NRCS (Fiala *et al.*, 1989), four loess mantled, upland soils are found in the NCWLS study area: (1) Magnor (coarse-loamy, mixed, superactive, frigid Aquic Glossudalfs), (2) Marshfield (fine-loamy, mixed, superactive, frigid Mollic Epiaqualfs), (3) Loyal (fine-loamy, mixed, superactive, frigid Oxyaquic Glossudalfs) and, (4) Withee (fine-loamy, mixed, superactive, frigid Aquic Glossudalfs) (Figure 3.11). These soils have drainage classes that range from poorly drained to well drained (Table 3.2). They formed in loess and the underlying loamy glacial till found on ground moraines (Fiala *et al.,* 1989). Loess mantles within the study area range between 40 – 90 cm thick (Table 3.2).

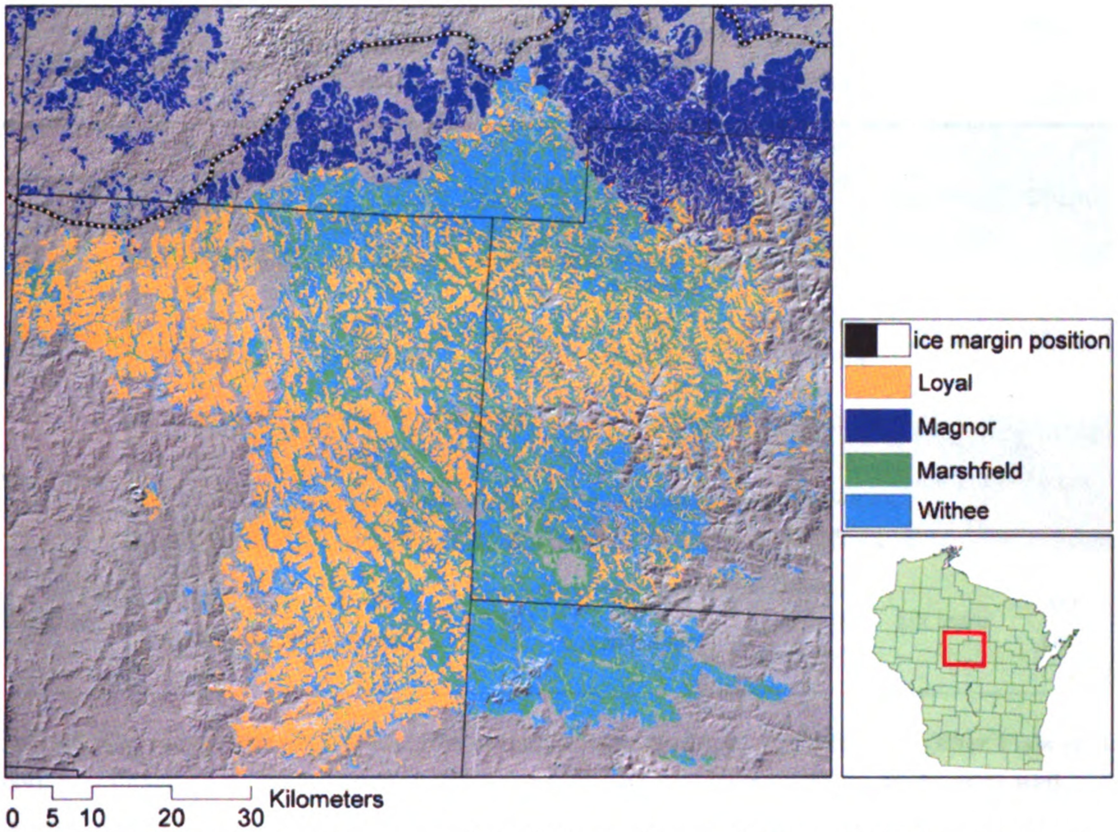

Figure 3.11. Distribution of loess mantled soils in north-central Wisconsin (Fiala *et al.*, 1989).

3.2.3 Vegetation and Climate

The mean annual temperature (1971-2000) at Medford, Wisconsin, located within the study area, is ~ 5° C with a January mean temperature of ~ - 12° C and a July mean temperature of 20° C (National Climatic Data Center, 2002). The mean annual precipitation is 84 cm with a mean January precipitation of ~ 3 cm and a mean July precipitation of ~ 10 cm; average total snowfall for Medford is 101 cm (National Climatic Data Center, 2002). Natural vegetation for this area consists of mixed hardwoods located on the areas underlain by till, and pine and oaks on the sandy soils near sandstone outcrops (Fiala *et al.,* 1989). Presently, suitable soils are under agricultural production either as crop or pasture land (Stanley, 2008). Where farming is not possible due to any number of limitations, the land is usually forested.

Series	Counties	Taxonomic Class	Drainage Class*	Landform	Parent materials	Surface texture	Depth to LD†
Loyal	Taylor, Clark, Marathon, WI	Oxyaquic Glossudalfs	MWD	ground moraines	loess or alluvium, underlying loamy till	silt loam	50 cm
Magnor	Taylor, Clark, Marathon, WI	Aquic Glossudalfs	SPD	ground & end moraines, IWLP	loess, underlying sandy loam till	silt loam	53 cm
Marshfield	Taylor, Clark, Marathon, WI	Mollic Epiaqualfs	PD	ground moraines	loess or alluvium, underlying loamy till	silt loam	86 cm
Withee	Taylor, Clark, Marathon, WI	Aquic Glossudalfs	SPD	ground moraines	loess, underlying loamy till	silt loam	100 cm

Table 3.2. Characteristics of loess mantled upland soils in north-central Wisconsin (after Fiala et al., 1989). *Drainage class: poorly drained (PD), somewhat poorly drained (SPD), moderately well drained (MWD) † Lithologic Discontinuity (LD)

4. Methods

4.1 Preparatory Work

Prior to the start of fieldwork, surfical geology maps from the U.S. Geological Survey and Wisconsin Geological and Natural History Survey were used to identify moraines and ice margins within the study areas. Distal-edge moraine margins were digitized from georectified, digital versions of these maps, aided by a hillshade DEM, in a geographic information system (GIS).

Natural Resource Conservation Service (NRCS) digital soils data (SSURGO, or county scale) for each county in Michigan and Wisconsin were used to make raster mosaics of soils covering the study areas. Each soil series was color-coded based on parent material data gathered from NRCS soil survey official soil series descriptions. Parent material categories used for the study areas included till, outwash, lacustrine sediment, and loess. The loess category was split into three groups based on the thickness of the parent material: (1) loess 25-50 cm, (2) 51-100 cm, (3) 101-150 cm. A fourth category was created for loamy loess (Figure 4.1).

Using these data to display maps of soils that have loess as their parent material, and the moraine margins, sampling transects were drawn in a GIS. Establishing sampling transects has been a common approach for many loess studies (Krumbein, 1937; Smith, 1942; Hutton, 1947; Ruhe, 1954; Simonson and Hutton, 1954; Fehrenbacher *et al.,* 1965; Frazee *et al.,* 1970; Putman *et al.,* 1988; Mason, 2001; Muhs *et al.,* 2008). It is by using this method that these researchers have discovered the distance-decay trends of loess

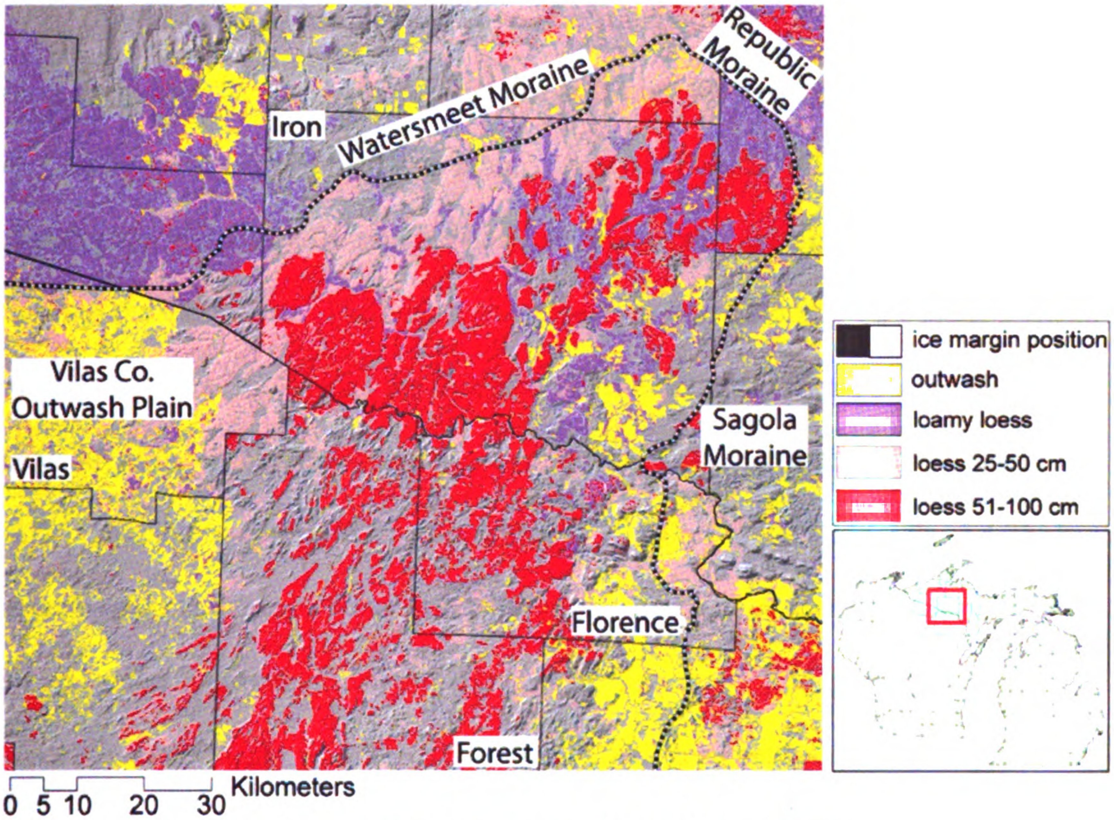

Figure 4.1. Soil parent materials of Iron County, MI.

deposits. This method also allows for a more accurate estimate of area covered in a sampling study. The transect sampling method was chosen for this study in order to obtain data on the rate of change in loess thickness and particle size with distance to a presumed source area.

With this justification in mind, the locations of the five sampling transects were selected based on several criteria. Transects (1) must start at the distal edge of a potential source area (in this case, an end moraine), (2) must generally run perpendicular to the potential source area, and (3) must end at approximately the presumed distal edge of the loess sheet, or at a point where the loess was too thin (<30 cm) to effectively sample.

Three transects were established in Iron county; each ~ 8 km wide (Figure 4.2). One transect, Iron County 1 (IC1), spans the area from the Republic Moraine in northeast Iron County to the edge of the Vilas County Outwash Plain in Vilas County, WI. The outwash plain was viewed as another possible source area, and also represents the distal margin of the loess sheet. The other two transects in Iron County, Iron County 2 (IC 2) and Iron County 3 (IC 3), span the area between the Watersmeet and Sagola Moraines. The width of the two transects in north-central Wisconsin, north-central Wisconsin 1 (NCW 1) and north-central Wisconsin 2 (NCW 2), were ~ 4 km wide (Figure 4.3). Both transects begin at the Late Wisconsin terminal moraine and continue to the southeast until they end at the approximate distal margin of the loess sheet. The greater width of the transects in Iron County was due to the unpredictable road network; many of the roads were two-track gravel logging roads. The loess in north-central Wisconsin is more extensive, making it easier to locate a suitable sample site.

After the five transects were established, potential soil sampling locations within the study areas were identified in a GIS using digitized topographic maps (DRGs), digital elevation models (DEMs), and SSURGO data, coded for loess soils. Potential sampling sites met each of these conditions: (1) presence of soils formed in loess, in map units that were at least 40 ha in size; and (2) located on broad, geomorphically stable uplands, where erosion, subsequent to the original deposition of the loess, would have been minimal. Sample sites within woodlots were preferred because agricultural and other types of disturbances are minimal. Sites within the transects were approximately 4 kilometers apart, to provide a relatively uniform geographic distribution along the transects. Each potential site was recorded in a GIS for navigation purposes.

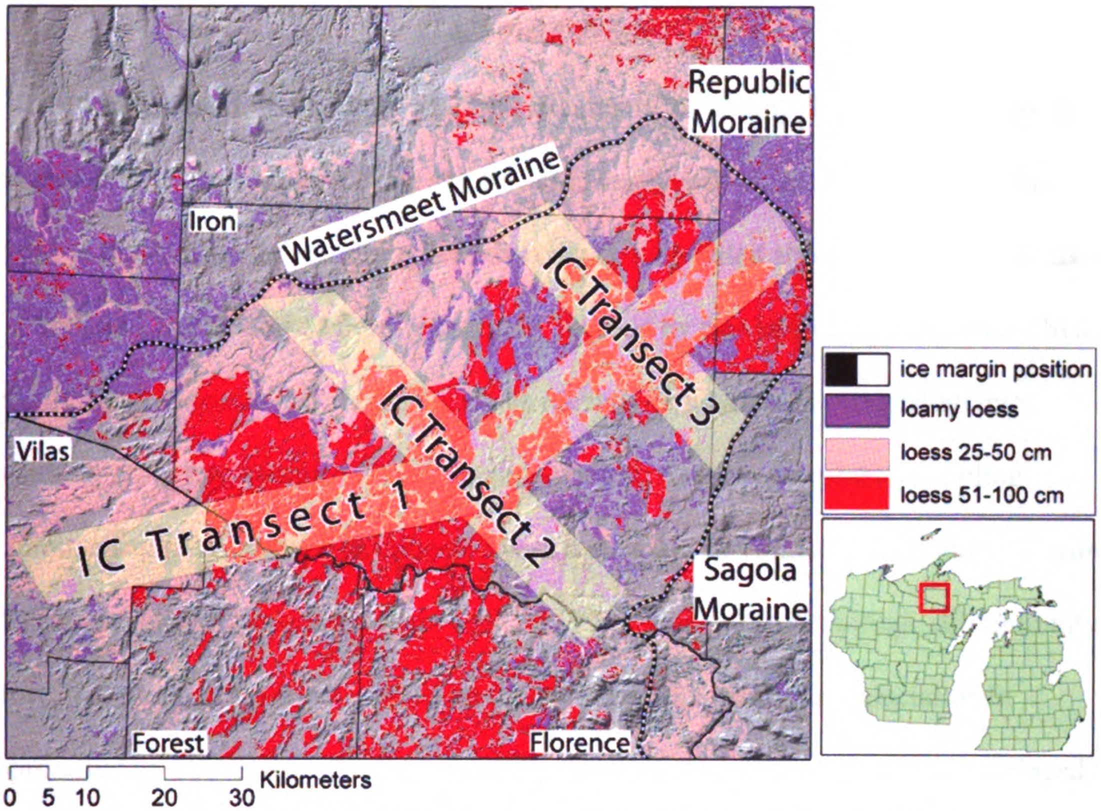

Figure 4.2. Location of Iron County transects and general loess thickness.

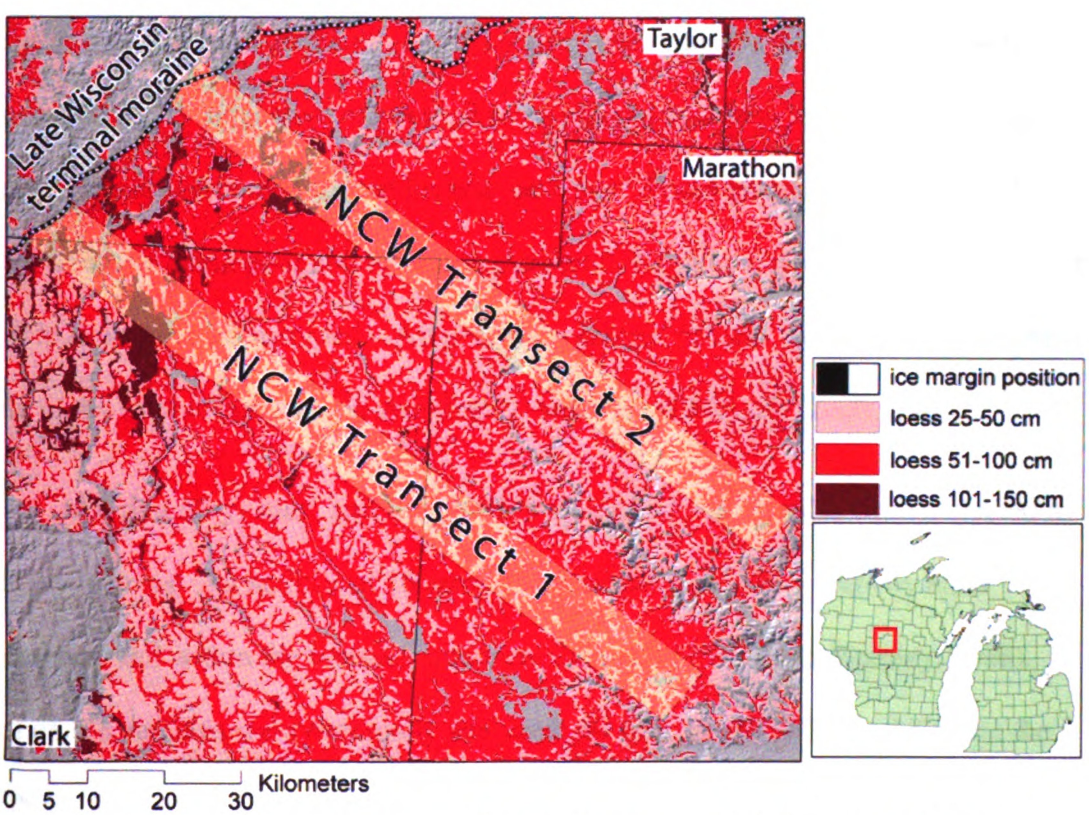

Figure 4.3. Location of north-central Wisconsin transects and general loess thickness.

4.2 Field Work

In the field, if a potential sample site identified during the preliminary work was found to be unsuitable, a more suitable site was identified nearby. For sites that proved to be suitable for sampling, based on the criteria listed above, a sample was taken on a high and flat upland. Micro-topography formed by tree uprooting, and other obvious signs of disturbance on the uplands, such as recently exposed soil, were taken into consideration before sample collection, and avoided. At each acceptable sampling location, a sample of loess was collected with a standard three-inch bucket auger (Figure 4.4). The sample was taken from between the A horizon and the lithologic discontinuity below, that marked the contact between the loess and the underlying glacial drift. Approximately 600-700 g of loess were collected at each sampling location and placed in sample bags for transport to the lab. The thickness of the loess mantle at each sample location was also measured and the site location was recorded with a global positioning system (GPS). A subjective measure of loess quality, based on loess thickness and texture, was also recorded for the loess at each site. Loess quality was measured from one to ten, one being poor and ten being excellent. Landform type and land use at each sample site were also recorded. All data were entered in field notes and into the attribute table of the sample point file in ArcMap 9.3 software (ESRI, Redlands, CA).

During May, June, and July 2009, a total of 87 soil samples were collected in both study areas. An additional 26 samples collected in previous years by other researchers fell within the transects and were included for analysis (Stanley, 2008). A total of 113 samples were eventually analyzed; 40 from the NCWLS and 73from the ICLS.

4.3 Laboratory Methods

After air-drying the samples, they were lightly ground with a mortar and wooden pestle at the Michigan State University Soil Geomorphology Laboratory. Ground samples were passed through a 2 mm sieve and put through a sample splitter three times in order to fully homogenize them. The remaining sediment larger than 2 mm was discarded. Soil samples were prepared for particle size analysis by adding ~ 1 g of soil to a water-based solution with 5 ml of $(NaPO_3)_{13} \cdot Na_2O$ as the dispersant, in a 25 ml vial. The vials were agitated for 2 hours to disperse the sediment in the suspension. Particle size analysis (PSA) was completed using a Malvern Mastersizer 2000E laser particle size analyzer (Malvern Instruments Ltd., Worcestershire, UK). The PSA data were calculated as both actual and clay-free, but only the clay-free data were used in this analysis. This was done to prevent misinterpreting the results because a significant portion of clay particles can be transported and deposited as silt or sand size aggregates (Pye, 1995). Data from laser particle size analyses were added to the attribute table of the sample point file within the GIS.

For analysis purposes, the data from the sampling transects IC 2 and IC 3 were combined for each regression analysis and scatterplot. Likewise, the data from NCW1 and NCW 2 were combined. Both of these sets of transects run parallel to each other (Figure 4.2 and 4.3) and it was determined that combining the data for each set would give a greater sample population and, therefore, a more robust data set. All subsequent analyses were done with the combined data sets. Thickness and particle size data were examined using best-fit linear, logarithmic, and curvilinear regression analysis, performed in Microsoft Excel. From these equations, best-fit line equations, and p-values were determined. The significance of the slope of the line (significantly different from zero, or not) was also determined for each linear regression. Scatterplots of loess thickness, mean weighted particle size, and clay-free particle size fractions were then created, using Microsoft Excel, and linear, logarithmic, and polynomial (curvilinear) regression lines were added to each scatterplot. The origins (X-axis value of zero) of the scatterplots represent the starting point of the transects, often near the presumed source area. A positive trend on the scatterplot represents an increase in that variable, away from the presumed source area; a negative trend represents a decrease. I examined the p-value of each regression line to determine the significance of the regression line equation. I have chosen an alpha value for all statistical analysis of 0.05, therefore a $p\text{-value} < 0.05$ is considered statistically significant and a $p\text{-value} > 0.05$ is non-significant. The Student's t-test was used to determine if the slope of a linear regression line was significantly non-zero. If the t-test value is higher than the critical t-value, then the regression line is considered significantly non-zero, and statistically significant. Generally, I only will be discussing the regression line equation that has the highest p-value, from among the three (linear, logarithmic and polynomial) fits/models. Once this best-fit line has been chosen and found to be statistically significant, it is examined to see if it agrees with our understanding of the spatial characteristics of loess.

Continuous particle size graphs for each loess sample were also created using Microsoft Excel and Adobe Illustrator, in order to better visualize the variation in particle sizes across the study areas and within a sample. Images in this thesis are presented in color.

5. Results and Discussion

The focus of this chapter is to characterize the loess deposits of north-central Wisconsin and Iron County, Michigan, especially their trends away from their hypothesized source regions. I begin by presenting and discussing loess thicknesses and particle size characteristics within transects that span each of the two study areas. I next discuss the spatial characteristics of the loess across the transects in each of the two study areas. This section is important because the spatial characteristics of these loess samples can help determine their possible source areas (Smith, 1942; Ruhe, 1954; Simonson and Hutton, 1954; Frazee *et al.,* 1970; Rutledge *et al.,* 1975; Putman *et al.,* Pye, 1995; Muhs and Bettis, 2000; Schaetzl and Hook, 2008; Stanley, 2008).

In cross-section, loess deposits display a wedge-shaped form, with loess thickness and various particle size fractions, especially coarse silt fractions, decreasing away from the source area, whereas some of the finer particle size fractions increase with distance (Krumbein, 1937; Smith, 1942; Hutton, 1947; Ruhe, 1954; Simonson and Hutton, 1954; Fehrenbacher *et al.,* 1965; Frazee *et al.*, 1970; Rutledge *et al.,* 1975; Handy, 1976; Putman *et al.,* 1988; Mason *et al.,* 1994; Aleinikoff *et al.,* 1998; Muhs and Bettis, 2000; Bettis *et al.*, 2003; Jacobs and Mason, 2007; Schaetzl and Hook, 2008). The regular and predictable spatial trends characteristic of loess have enabled researchers to examine deposits quantitatively, mainly by plotting thickness and particle size changes and using these trends to establish the likely loess source area (Krumbein, 1937; Smith, 1942; Hutton, 1947; Ruhe, 1954; Simonson and Hutton, 1954; Fehrenbacher *et al.,* 1965; Frazee *et al.,* 1970; Putman *et al.,* 1988; Mason, 1994; Mays *et al.,* 2003). Many of these workers were able to demonstrate that their data were suitable for statistical analysis, fitting them to linear, logarithmic and curvilinear models (Krumbein, 1937; Smith, 1942; Hutton, 1947; Ruhe, 1954; Simonson and Hutton, 1954; Fehrenbacher *et al.*, 1965; Frazee *et al.*, 1970; Rutledge *et al.*, 1975; Putman *et al.*, 1988; Mason, 2001). Using similar methods, I created scatterplots showing the changes in loess thickness and in various particle size fractions with distance, in order to visualize the characteristics of the loess along each of three transects, and away from the hypothesized source areas. These scatterplots were then fit to each of three different types of regression line models. Finally, I discuss the possible source area(s) for each loess deposit and, based on my interpretations of the spatial patterns of loess thickness and particle size characteristics along the transects, conclude whether these areas were, in fact, loess sources. A table of all sample data is located in Appendix A, scatterplots for each transect are presented in Appendix B, and particle-size graphs for each loess sample are available in Appendix C.

5.1 The North-Central Wisconsin Loess Sheet

Stanley (2008) concluded that the Late Wisconsin terminal moraine was one of two source areas for loess in north-central Wisconsin - the other being Cambrian sandstone outcrops and the otherwise sandy landscapes in southwestern Clark County. The Late Wisconsin terminal moraine contains many ice-disintegration features, particularly ice-walled lake plains, which are formed on silty sediment and exist at high elevations. Therefore, I am also hypothesizing that the source area for the north-central Wisconsin loess sheet (NCWLS) in my study area is the Late Wisconsin terminal moraine. According to Stanley (2008), the sandstone outcrops contributed mostly fine sand to the loess sheet, but this sediment is unlikely to have been transported long distances. Data from both of my two transects from north-central Wisconsin were combined to create the scatterplots for the NCWLS.

5.1.1 Loess Thickness Data in the North-Central Wisconsin Loess Sheet

In general, loess thickness along both transects in the NCWLS decreases away from the Late Wisconsin terminal moraine, taking on the classic wedge-shape in cross-section (Figure 5.1). This result is in agreement with those of Stanley (2008) from the same loess sheet and with other loess research done in the Great Plains and Central Lowlands (Figure 5.2) (Krumbein, 1937; Smith, 1942; Hutton, 1947; Ruhe, 1954; Simonson and Hutton, 1954; Fehrenbacher *et al.,* 1965; Frazee *et al.,* 1970; Putman *et al.,* 1988; Mason, 2001; Schaetzl and Hook, 2008). Loess thicknesses range from 35 to 95 cm along the ~ 55 km transects. These results are consistent with previous reports of loess thickness in north-central Wisconsin (Hole, 1942, 1968; Fiala *et al.*, 1989; Stanley, 2008). The mean loess thickness in the study area is 58 cm (median = 55 cm). From the northwestern boundary of the loess sheet to ~ 25 km, loess thickness is more variable, ranging from 45 to 95 cm. Samples with thick loess (101-150 cm) are located within the first 25 km of the transects. From ~ 25 to ~ 55 km, loess thickness becomes more predictable, averaging 48 cm in thickness and generally staying within a ±20 cm range. The linear regression line of loess thickness has a p-value of 0.000 and a t-statistic value of 3.301. The critical t-value at 40 degrees of freedom and a level of significance of 0.05 is 2.021. Both the p-value and the t-statistic indicate that the slope of the linear regression line is significantly non-zero, signifying that the expected relationship, a decrease of loess thickness with distance from the source, exists (Figure 5.1). At the start of the transect, the linear regression line predicts a loess thickness of ~ 73 cm. At the southwestern edge

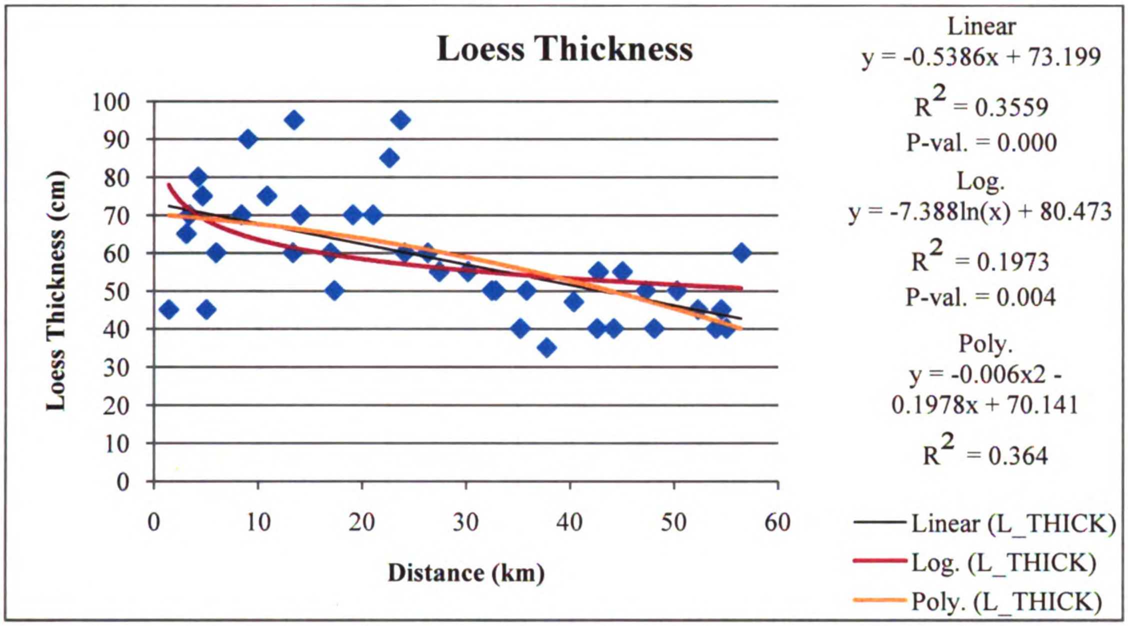

Figure 5.1. Scatterplot of loess thicknesses along the two samples transects in north-central Wisconsin.

of the study area the regression predicts a thickness of ~ 42 cm. This predictable loess thinning pattern indicates that winds were predominately from the north and northwest at the time of deposition, which is not inconsistent with reported paleowind directions elsewhere in the Midwest (Muhs and Bettis, 2000). Immediately to the northwest of the NCWLS in the study area lies the Late Wisconsin terminal moraine. Assuming the prevailing winds were from the northwest, it would seem reasonable to conclude that the Late Wisconsin terminal moraine could have been a source for the loess in north-central Wisconsin, as had been previously suggested by Stanley (2008).

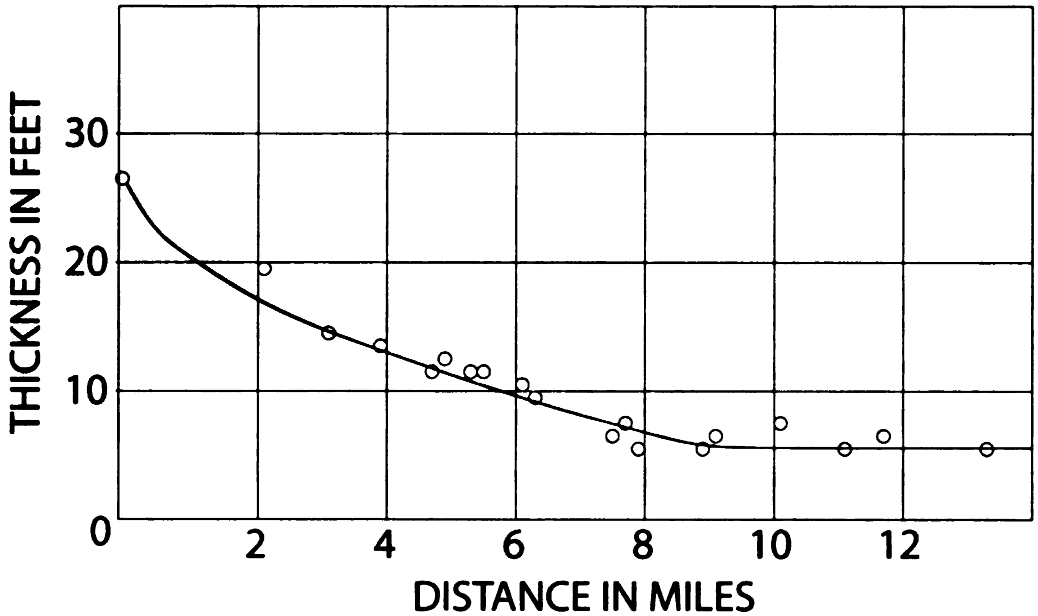

Figure 5.2. Graph comparing observed (open circles) to theoretical (solid line) loess thickness in Illinois (after Krumbein, 1937).

5.1.2 Particle Size Trends in the North-central Wisconsin Loess

The mean sand:silt:clay ratio for all samples from the NCWLS is 20:59:21; the median is 19:60:21. Most loess samples the study area are silt loam in texture. Most individual loess samples have a modal particle size peak near 25 μm (fine silt/medium silt) (Appendix A). Fine silt (12-25 μm) is generally the largest single particle size fraction for all loess samples from the NCWLS transects, making up a little less than one third of the total silt content, followed by medium silt, coarse silt, and lastly, very fine silt (Appendix A). There is also a large component of very fine sand in the north-central Wisconsin loess transect samples, averaging ~ 15%.

The average MWPS (mean weighted particle size) for all NCWLS loess samples is 52 μm (very-very fine sand) and the median is 49 μm (coarse silt), indicating that the loess is generally coarser than many loess deposits in Illinois and Iowa, in which medium silts dominate (Smith, 1942; Ruhe, 1954). Overall, there does not appear to be a significant change in the MWPS of the loess along the transects (Figure 5.3). Results from previous work carried out in the Great Plains and Central Lowlands has indicated an overall decrease in mean particle size away from a loess source area (Smith, 1942; Ruhe, 1954, Fehrenbacher *et al.,* 1965; Muhs and Bettis, 2000). The lack of a significant change in MWPS across the NCWLS transects might be explained by pedoturbation (*i.e.*, cryoturbation and/or bioturbation) in the thin loess area. This process would be most pronounced in thin loess areas, which exist at the far southeastern edge of the study area, near the end of the transects. Pedoturbation would cause the underlying coarser textured till to mix with the relatively finer textured loess. Data from particle size distribution curves for the study area show samples collected within the first ~ 25 km of the transect are fairly uniform, typically with modes peaking in the medium silt fraction (Figure 5.4). Samples collected at a distance of ~ 25 km from the Late Wisconsin terminal moraine to the far end of the transect generally show more variation in the modal peak (Figure 5.4). If the lack of change in MWPS was due to pedoturbation, the particle size distribution curves should show a secondary peak in the sand fraction. None of the particle size distribution curves for the NCWLS show a meaningful secondary peak in sand faction (Appendix C). Thus, I suggest that the lack of change in MWPS over the course of the transects is due to the transects lying normal (or at least not parallel to) to the direction of loess transport (Rutledge *et al.,* 1975). If true, this would suggest that there is a significant amount of eolian contribution from the sandstone outcrops in western Clark County, and that the Late Wisconsin terminal moraine was not the only loess source in this study area. Therefore, it appears the sandstone outcrops in western Clark County are a possible loess source, but probably only a secondary source.

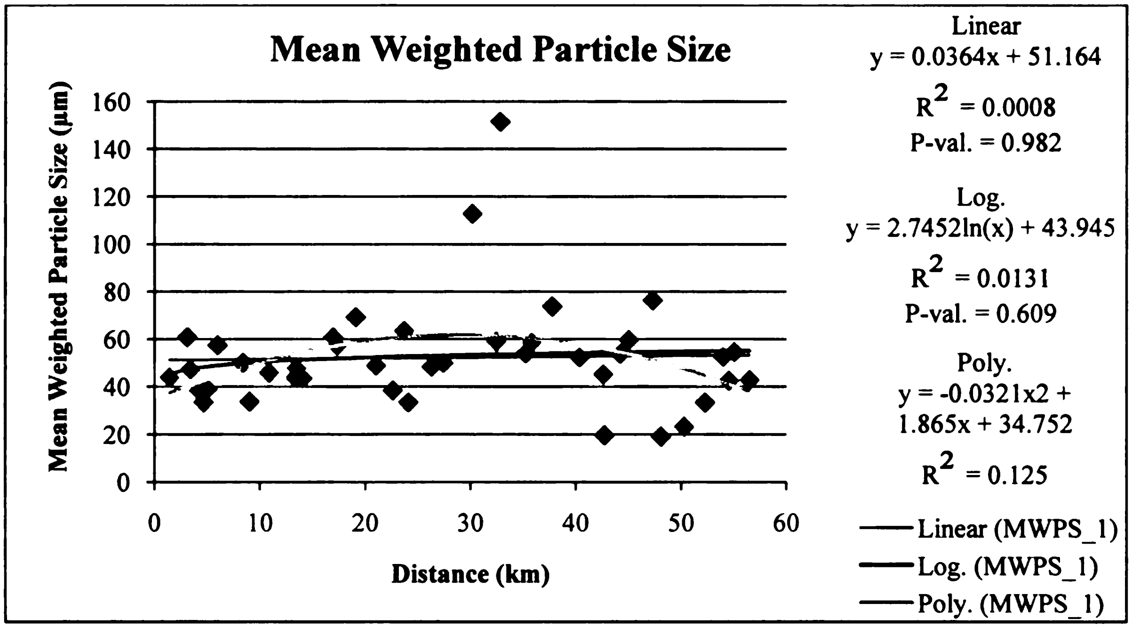

Figure 5.3. Scatterplot of mean weighted particle size values for both sampling transects in north-central Wisconsin.

5.1.3 Spatial Trends in the North-Central Wisconsin Loess Sheet: Silt Content

The overall silt content of the NCLWS does not change significantly with distance away from the Late Wisconsin terminal moraine (Figure 5.5). The p-values indicate that none of the regression lines for this particle size fraction are statistically significant. Additionally, the t-statistic value of the linear regression line is less than the critical t-value, indicating that the slope of the linear regression line is not significantly non-zero. A direct comparison of these silt content results to those of Stanley (2008) cannot be made because she did not provide data on the spatial trends of the overall silt. Results from the Buckley Flats in northwest Lower Michigan by Schaetzl and Hook (2008), the only study from the region to examine overall clay-free silt content, shows clay-free silt content increases from south to north, away from the presumed source area (Figure 5.6).

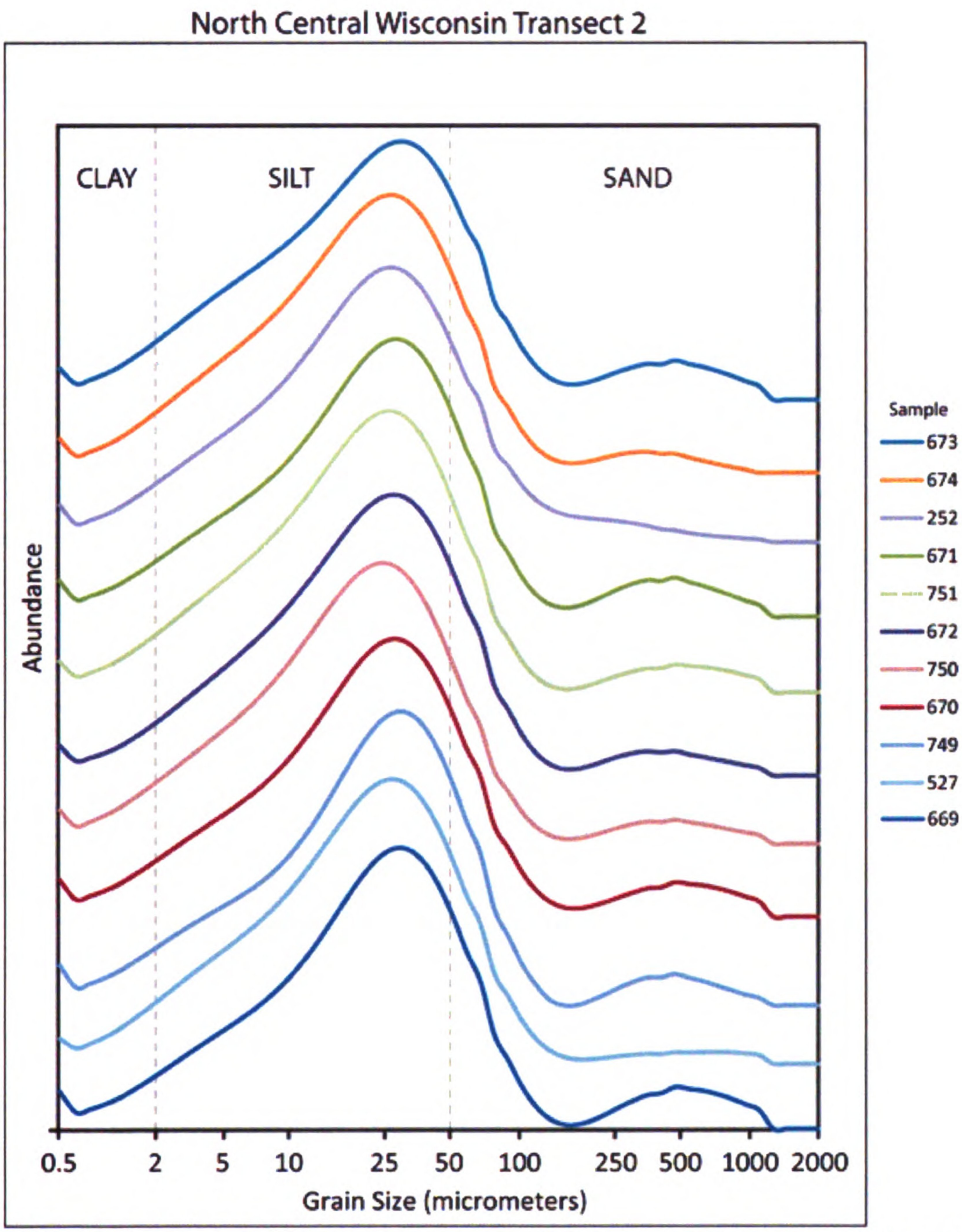

Figure 5.4. Continuous particle size distribution curves for 10 representative samples (673, proximal to moraine; 669, distal to moraine) from north-central Wisconsin transect 2 (NCW2). Curves are offset vertically for clarity.

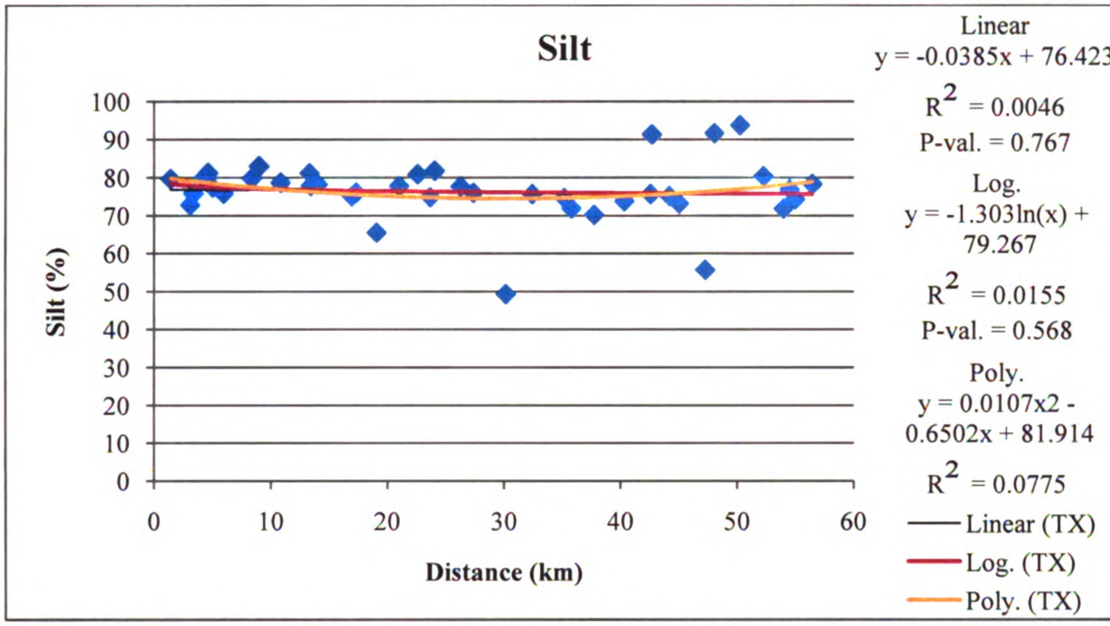

Figure 5.5. Scatterplot of silt contents from both transects in north-central Wisconsin.

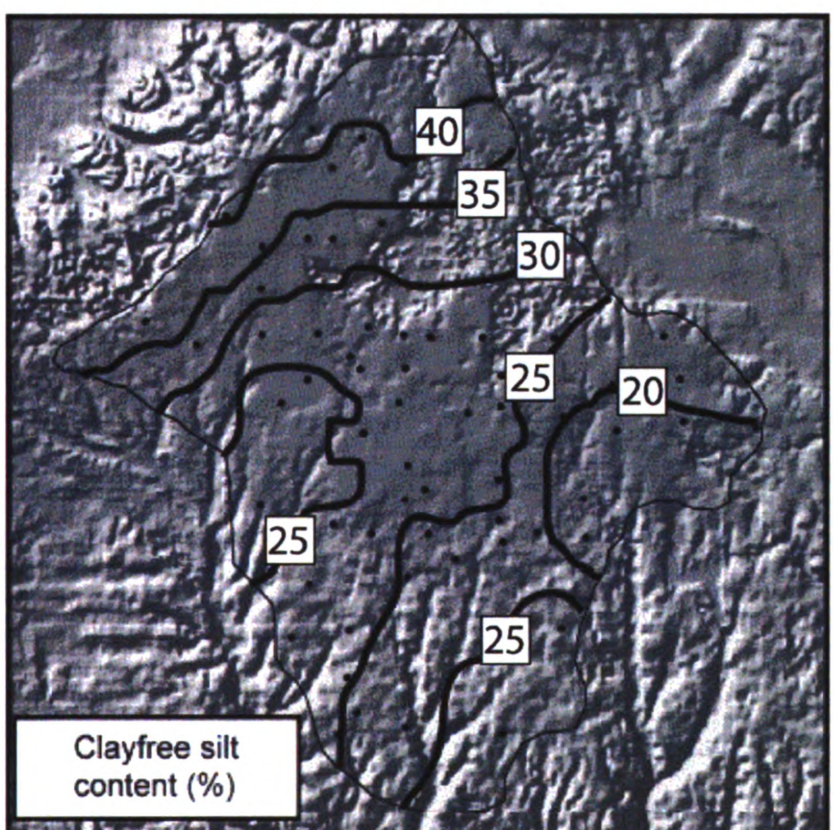

Figure 5.6. Kriged isoline map of clay-free silt content of loess across the Buckley Flats (Schaetzl and Hook, 2008).

Typically, very fine and fine silt increase in content as one progresses away from a loess source (Smith, 1942; Ruhe, 1954; Frazee *et al.,* 1970; Rutledge *et al.,* 1975; Putman *et al.,* 1988; Pye, 1995; Schaetzl and Hook, 2008). For this study, fine silt has been defined as both 12-25 μm and 2-20 μm; a distinction will be made when referring between the two. Data from the NCWLS shows that no significant change occurs along the transect, in either the very fine silt (Figure 5.7) or the fine silt (12-25 μm) fraction (Figure 5.8). The calculated p-values for all six regression lines for the very fine silt and fine silt (2-12 μm) scatterplots are non-significant (Appendix B). The fine silt (2-20 μm) regression lines also proved to be statistically non-significant (Figure 5.9). These results appear to be consistent with those of Stanley (2008) from the southern portion of the NCLWS, where very fine silt and fine silt (12-25 μm) show very little change with

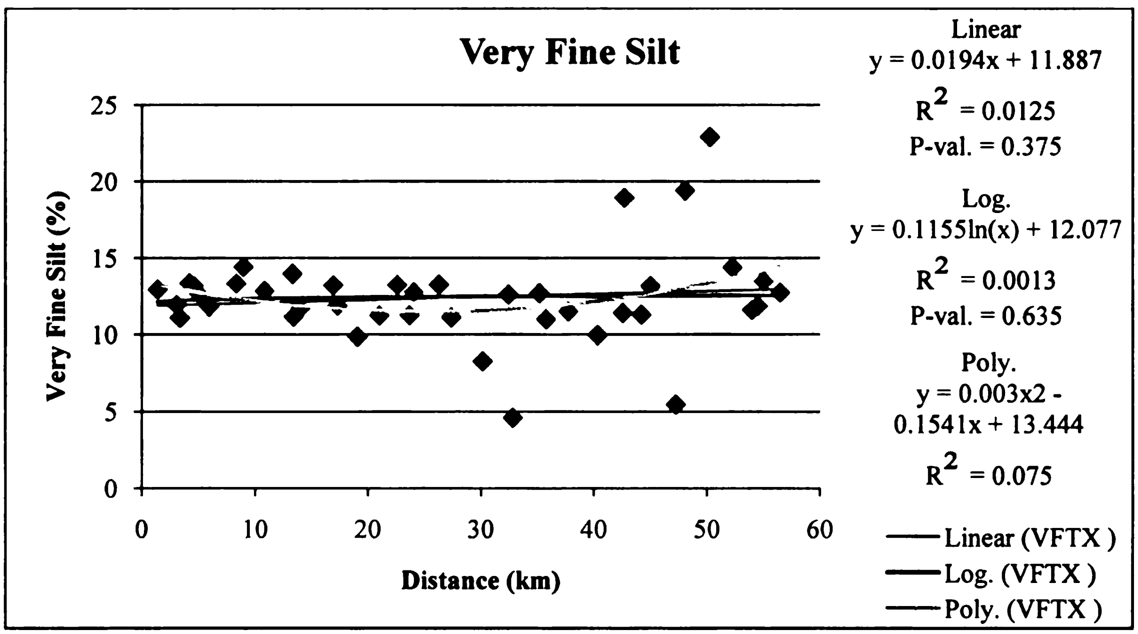

Figure 5.7. Scatterplot of very fine silt contents from both transects in north-central Wisconsin.

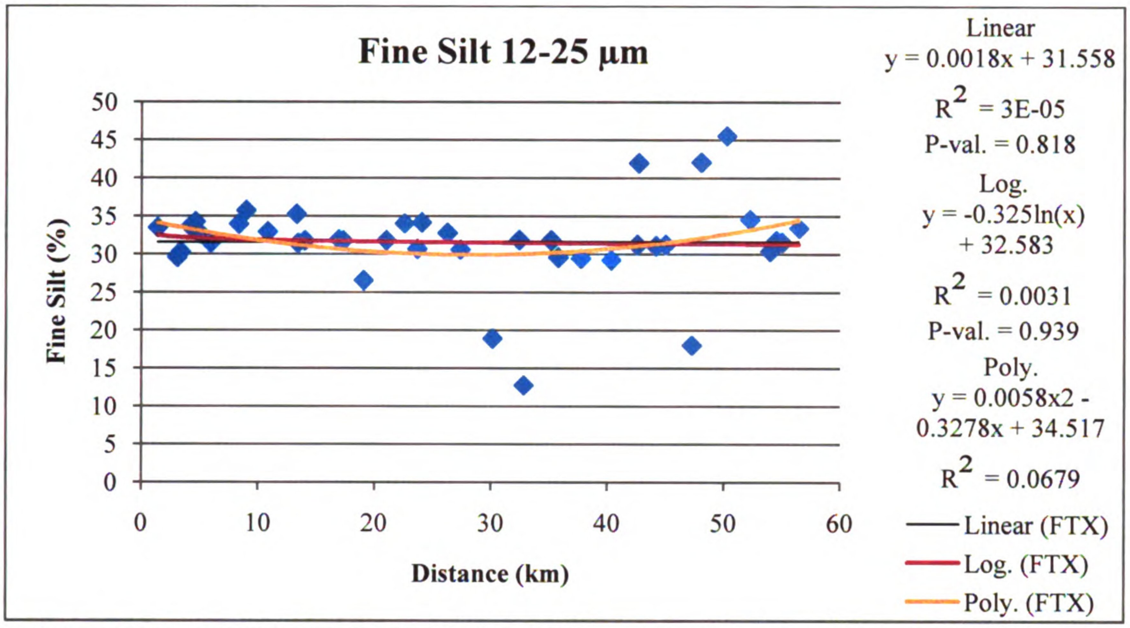

Figure 5.8. Scatterplot of fine silt (12-25 µm) from both transects in north-central Wisconsin.

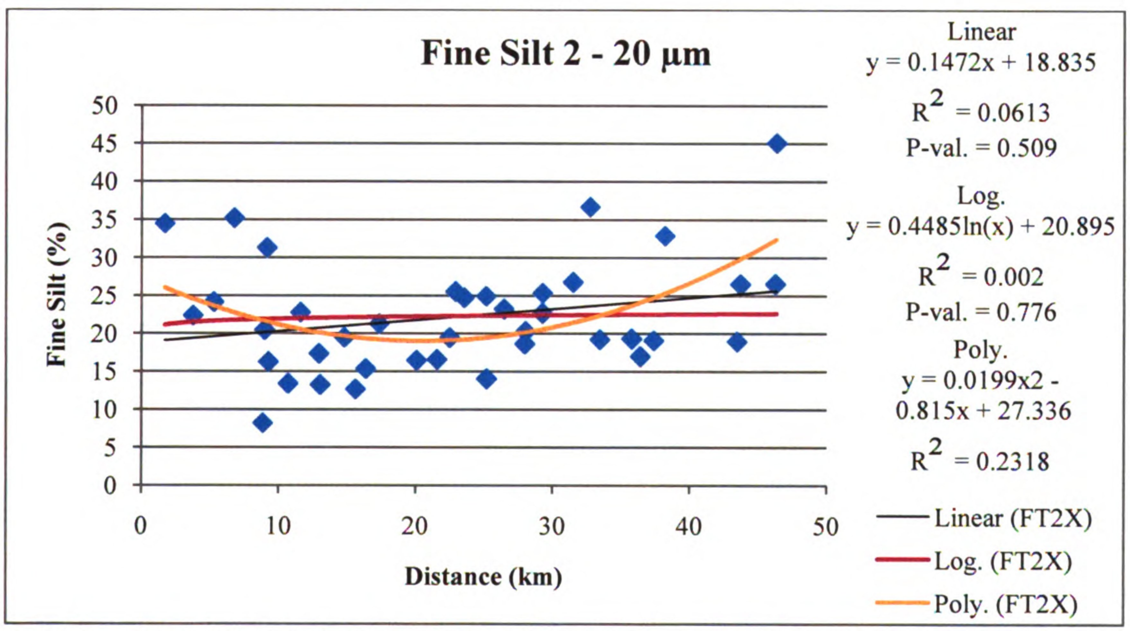

Figure 5.9. Scatterplot of fine silt (2-20 µm) from both transects in north-central Wisconsin.

distance from the Late Wisconsin terminal moraine (Figure 5.10). Rutledge *et al.* (1975) encountered a similar pattern in one of their transects in Ohio, only very small changes in fine silt occurred with distance from the presumed source. Rutledge *et al.* (1975)

suggested two possible reasons for the lack of significant change in particle size distribution: 1) the loess source is approximately normal to the transect, or 2) the loess source is located further west than the presumed source (the beginning point of the transect). Based on Stanley's work and data (Figure 5.10), I support the first hypothesis to explain the pattern of silt fractions in this study. Results from work by Stanley (2008) indicate a very strong pattern of decreasing fine silt and very fine silt concentrations from northeast to southwest, across the NCWLS. The transects for my study lie approximately normal to this trend, again suggesting that the Cambrian sandstone outcrops in western Clark County were a secondary loess source area. If the sandstone outcrops were a

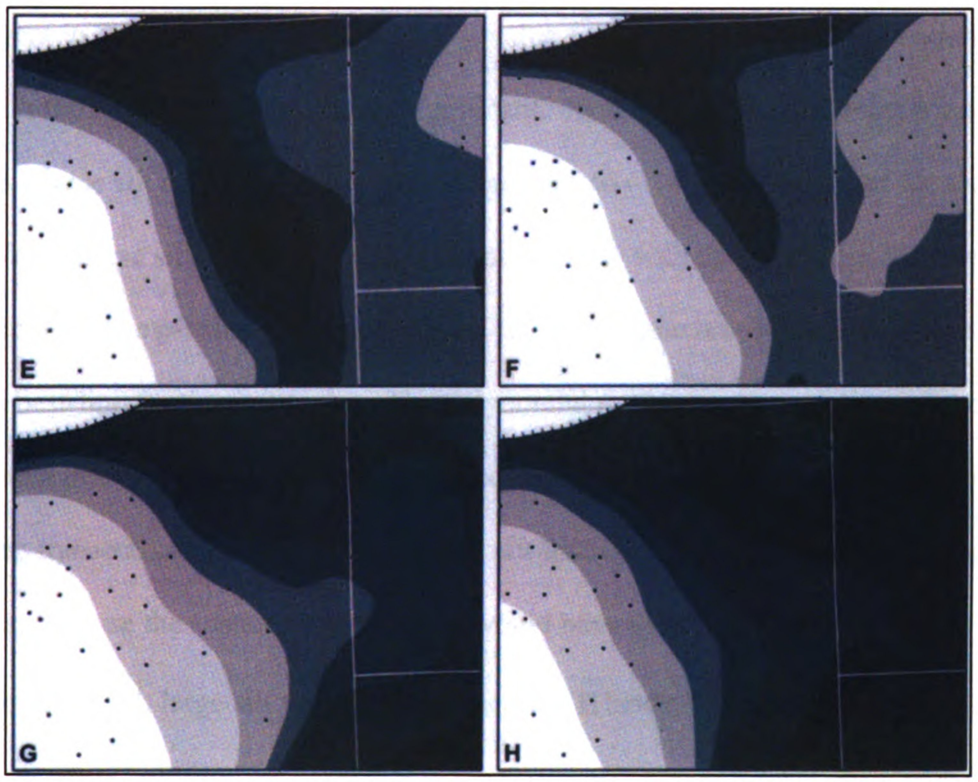

Figure 5.10. Kriged maps of particle size distributions in north-central Wisconsin (from Stanley, 2008). Dark shades represent high concentrations and light shades represent low concentrations. E) coarse silt F) medium silt G) fine silt (12 - 25um) H) very fine silt. The edge of the Late Wisconsin terminal moraine is located in the upper left corner, represented by the hatch marks.

secondary source, this could possibly explain the lack of decrease in fine silt along the transects, perhaps due to dilution of the fine textured sediment with coarser sediment from the southwest via pedoturbation.

Contents of the coarser silt fractions, such as medium (Figure 5.11) and coarse silt (Figure 5.12) do show a significant change with distance from the Late Wisconsin terminal moraine. The linear regression line for medium silt content has a p-value of 0.057, indicating that the linear regression is only marginally significant. The regression line predicts a medium silt content of ~ 17% near the Late Wisconsin terminal moraine and a content of ~ 16% at the terminus of the transect. A much more significant change is apparent in the coarse silt fraction. The p-value for the linear regression of coarse silt content is 0.030, which is statistically significant. Near the moraine the regression line predicts coarse silt contents to be ~ 16%, decreasing to ~ 14% at the edge of the study area. Very coarse silt also shows a significant decrease with distance from the moraine (Figure 5.13). The p-value of the polynomial regression line is 0.048 which indicates that it is the best-line for the scatterplot. The polynomial regression line predicts very coarse silt content near the moraine to be ~ 9.5% decreasing to ~ 8.3% at the terminus of the sampling transect. A decrease in the coarser silt fractions is to be expected in loess deposits, because the sustained wind speed would have to have been very strong (~ 14 m sec^{-1}) to keep such large silt particles in suspension (Handy, 1976). Therefore, they fall out of suspension shortly after entrainment. The results of this study agree with the results from Stanley (2008); medium and coarse silt contents in her study area decreased with distance from the Late Wisconsin terminal moraine (Figure 5.10) suggesting that it is the source for medium and coarse silt to the NCWLS.

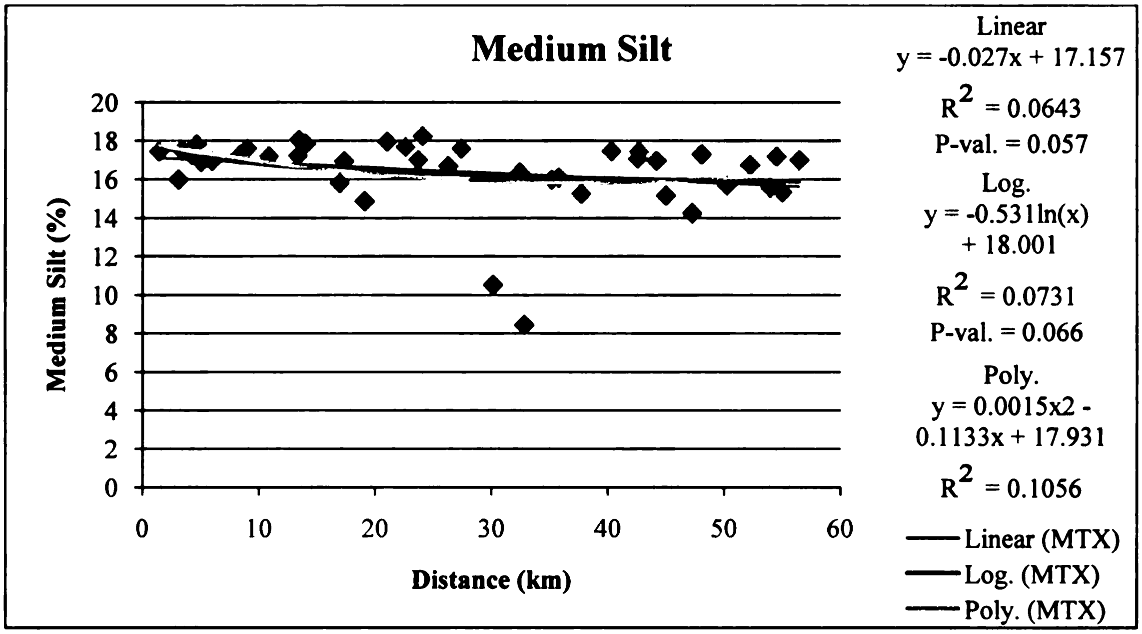

Figure 5.11. Scatterplot of medium silt contents from both transects in north-central Wisconsin.

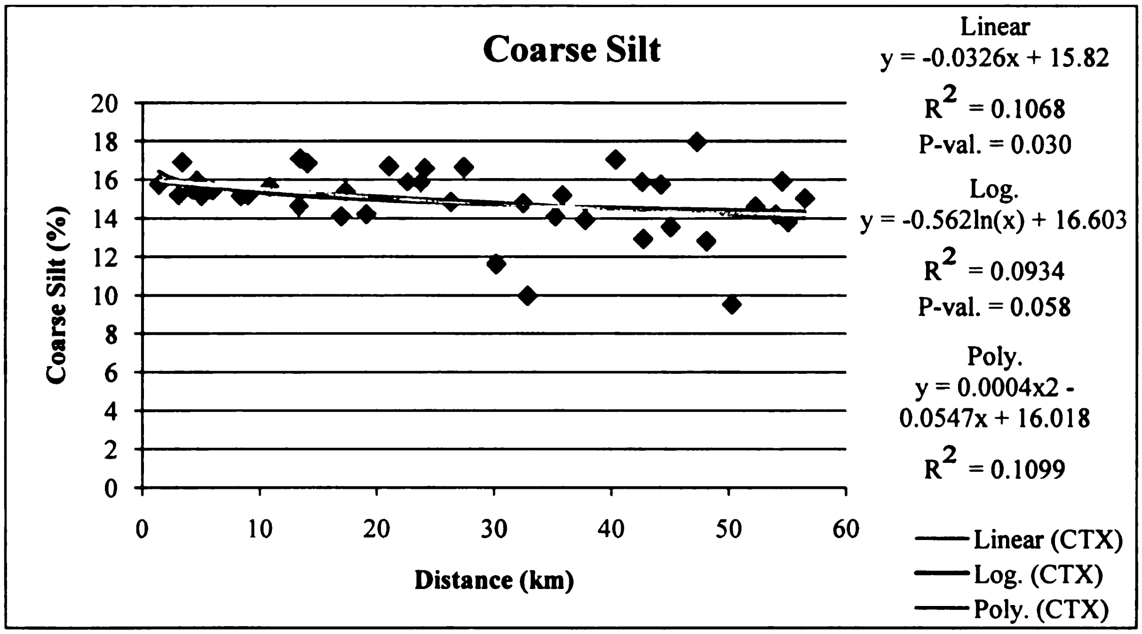

Figure 5.12. Scatterplot of coarse silt contents from both transects in north-central Wisconsin.

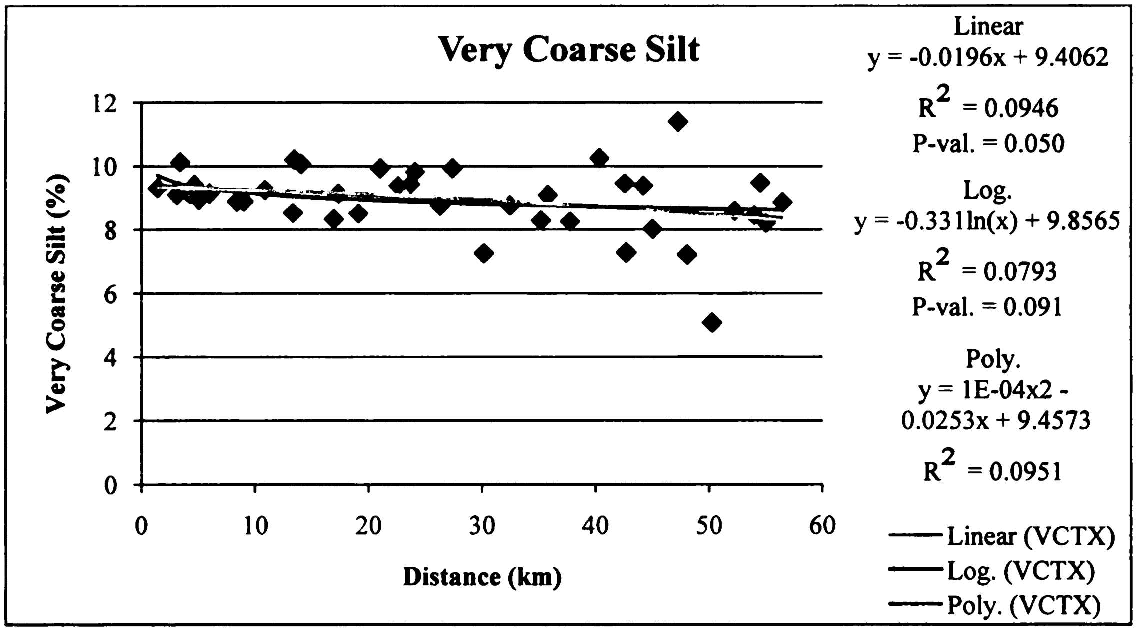

Figure 5.13. Scatterplot of very coarse silt contents from both transects in north-central Wisconsin.

In summary, although most silt fractions do not change significantly with distance from the Late Wisconsin terminal moraine, there does appear to be a general trend toward decreasing coarser silt contents away from this presumed source (Appendix B). For those silt fractions that do show a statistically significant change, it is not more than a 5% change in content over the 55 km distance of the transects. Very fine silt, fine silt defined as 12-25 μm, and fine silt defined as 2-20 μm, do not change significantly with distance from the Late Wisconsin terminal moraine. The lack of change in these silt fractions may be due to the transects lying approximately normal to the direction of sand particle transport from the sandstone outcrops southwest of the study area, even though they lie perpendicular to the possible morainic silt source (Rutledge *et al.,* 1975). Stanley (2008) suggested that the main source for very fine silt and fine silt fractions was the Late Wisconsin terminal moraine. The medium and coarse silt contents in the study area transects does show a slight decrease with distance from the Late Wisconsin terminal moraine, suggesting that the moraine was a source for these loess particle size fractions. Previous studies, however, have generally shown more significant decreases in these silt fractions, from a source area (Smith, 1942; Ruhe, 1954; Frazee *et al.,* 1965; Rutledge *et al.,* 1975; Putman *et al.,* 1988; Schaetzl and Hook, 2008). Based on the results of this study and the results from Stanley (2008), it appears the main source of silt sized particles, especially the coarse silts, in the NCWLS is the Late Wisconsin terminal moraine.

5.1.4 Spatial Trends in the North-Central Wisconsin Loess Sheet: Sand Content

Very fine sand and fine sand are the two sand fractions that are most likely to provide diagnostic information about paleowind regime, because their small grain size makes them most likely to be transported significant distances by eolian processes (Pye, 1987). In the only other study found to examine the sand content of a loess sheet, Schaetzl and Hook (2008) found that the very fine sand and medium sand contents in the Buckley Flats loess decreased with distance from the Manistee River valley, the presumed source. In this study, neither very fine sand (Figure 5.14) nor fine sand (Figure 5.15) change significantly with distance from the Late Wisconsin terminal moraine. Indeed, none of the 17 sand fractions analyzed this study showed a significant change with distance from the Late Wisconsin terminal moraine (Appendix B). In her study area, Stanley (2008) noted an overall decrease in coarse very fine sand, fine-fine sand, and coarse very fine sand contents away from the Cambrian sandstone outcrops in western Clark County Wisconsin (Figure 5.16), but not from the moraine. The lack of significant change among the various sand fractions with distance from the Late

Wisconsin terminal moraine may be due to the transects lying approximately normal to a possible sand source, in this case, the sandstone outcrops.

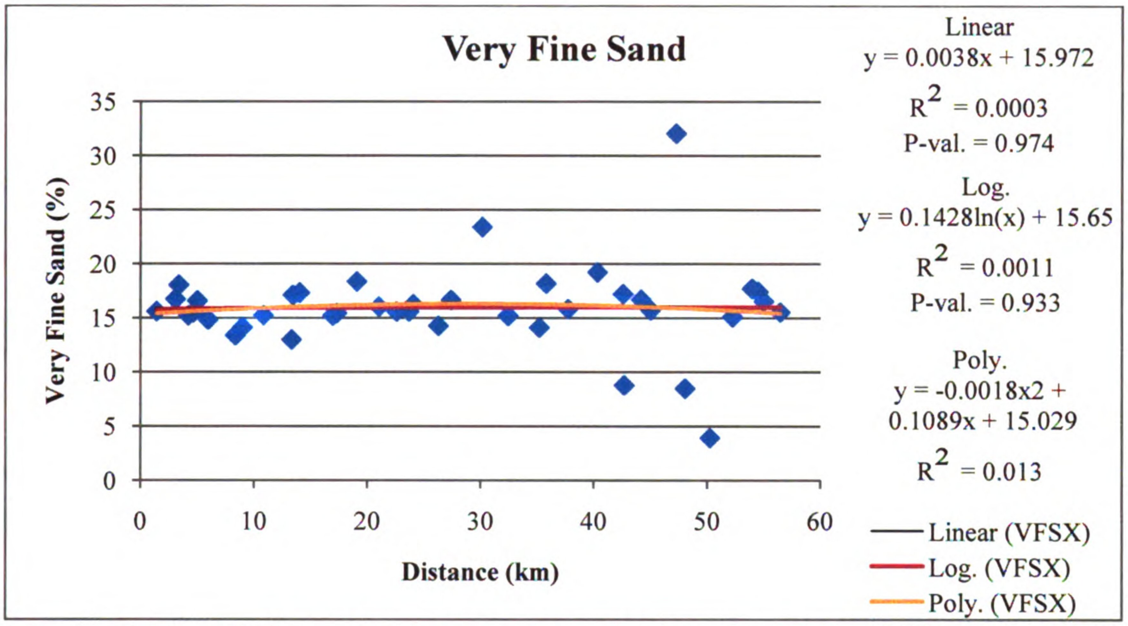

Figure 5.14 Scatterplot of very fine sand contents for all loess samples from north-central Wisconsin.

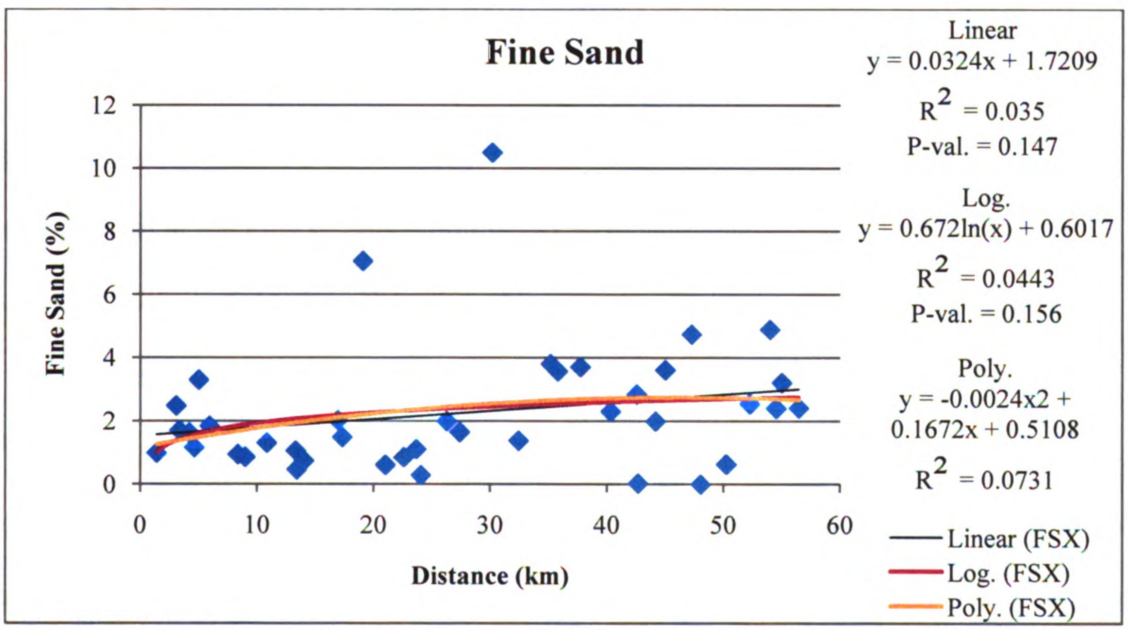

Figure 5.15. Scatterplot of fine sand contents for all samples in north-central Wisconsin

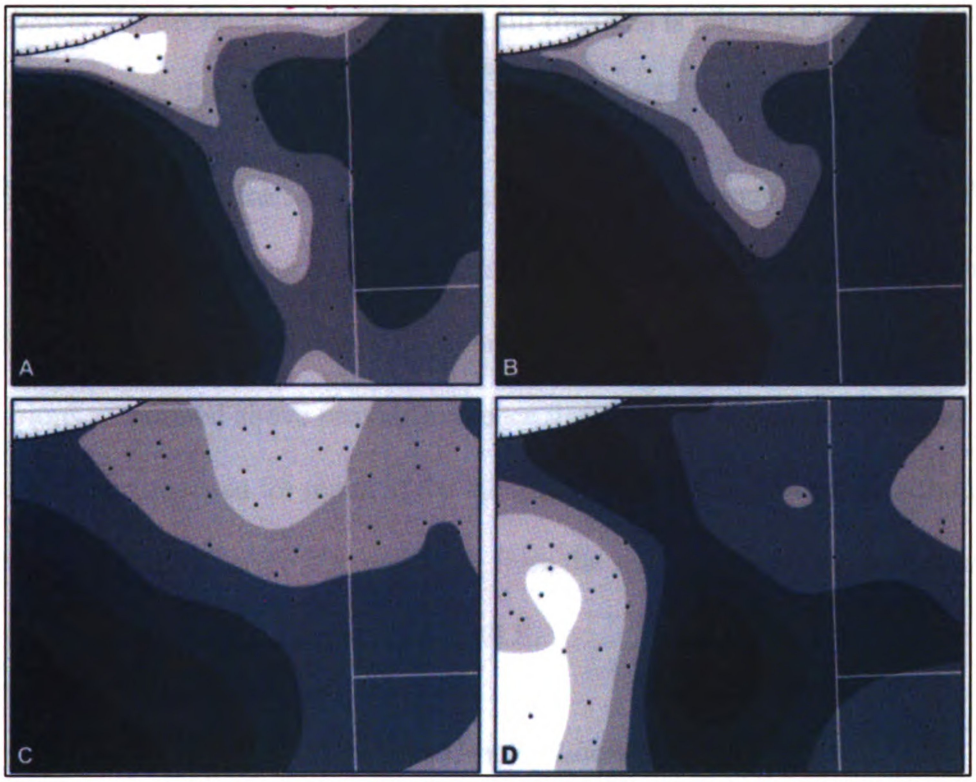

Figure 5.16. Kriged maps of particle size distribution in north-central Wisconsin (from Stanley, 2008). Dark shades represent highest concentrations and light shades represent the lowest concentrations. A) coarse fine sand B) fine-fine sand C) coarse very fine sand D) very-very fine sand

5.1.5 Summary of Loess Characteristics in North-central Wisconsin

In summary, loess thicknesses in the north-central Wisconsin study area generally decrease away from the Late Wisconsin terminal moraine. This pattern of loess thinning indicates that at the time of deposition winds were dominantly from the northwest. Although mean weighted particle size of loess typically decreases away from a source area (Krumbein, 1937; Smith, 1942; Ruhe, 1954; Fehrenbacher *et al.,* 1965; Frazee *et al.*, 1970; Handy, 1976; Putman *et al.,* 1988; Pye, 1995; Muhs and Bettis, 2000), in this study MWPS did not show a significant change with distance from the Late Wisconsin terminal moraine. Only three silt fractions show a statistically significant, but very weak, decrease away from the Late Wisconsin terminal moraine: medium silt, coarse silt and very coarse silt. However, the decrease for each of these silt fractions is relatively small; none of them decrease more than 5 percent over the course of the 55 km long transects.

None of the sand fractions from this study showed a change with distance from the moraine, which may occur because the transects are oriented approximately normal to the direction of likely sand transport. Data on loess thickness and the three silt particle size fractions mentioned above provide evidence that the Late Wisconsin terminal moraine was a source area for much of the loess in north-central Wisconsin, although significant contributions were also occurring from the sandstone outcrops, which may have provided fine textured sand to the NCWLS.

5.2 The Iron County Loess Sheet

The majority of the Iron County loess sheet lies in a re-entrant between three ice-margin positions, each associated with a named end moraine (Figure 5.17). It is believed that the formation of the end moraines that border the ICLS occurred contemporaneously, during the Winegar Phase of the Late Wisconsin (Attig *et al.,* 1985; Peterson, 1986). According to Attig and Clayton (1993), the glacial drift deposited during the Winegar Phase was relatively silty compared to glacial drift associated with earlier Late Wisconsin glacial phases in the area. Furthermore, the NRCS classified the moraines that surround the Iron County Loess Sheet (ICLS) as disintegration moraines, in which silty sediment is a common component (Jerome, 2006). It is between the three moraines, usually on large, broad drumlins, that the majority of the Iron County loess was deposited.

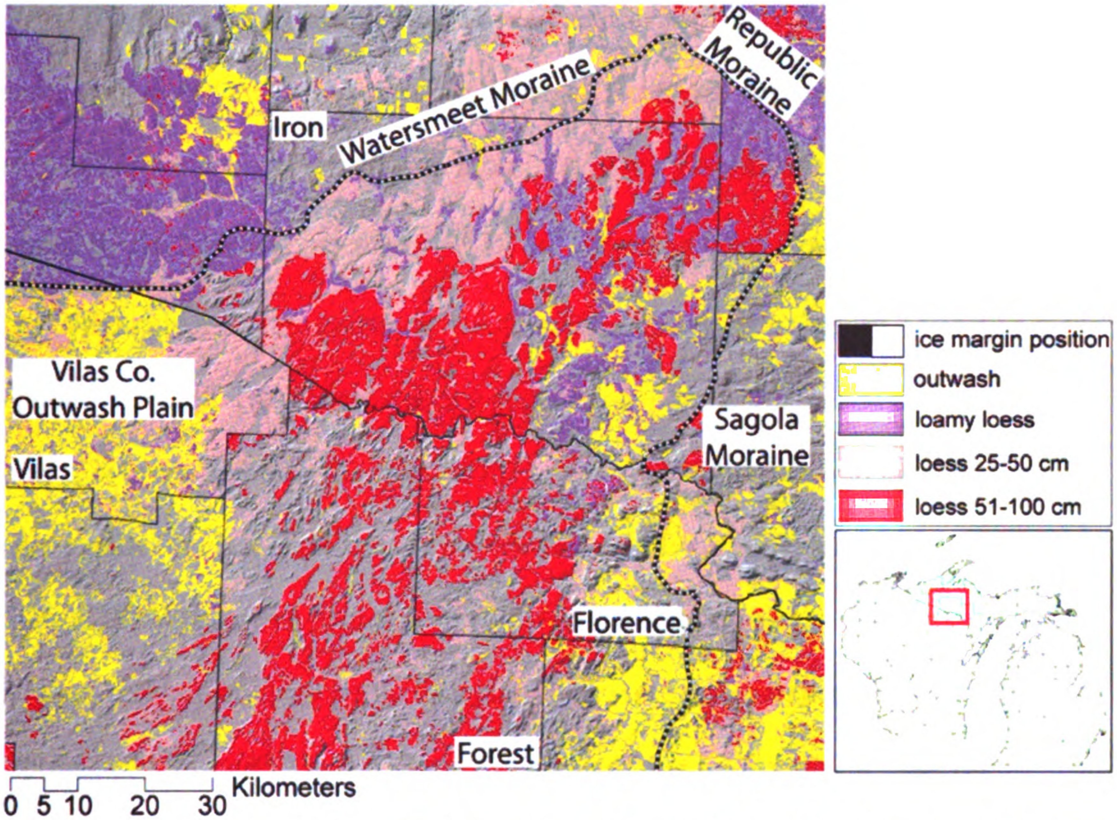

Figure 5.17. Map of loess thickness in the Iron County Loess Sheet and locations of possible source areas.

Glacial meltwater valleys have long been acknowledged to be loess sources (Smith, 1942; Ruhe, 1954; Frazee *et al.,* 1970; Putman, 1988; Pye, 1995; Muhs and Bettis, 2000; Schaetzl and Hook, 2008). Although prominent meltwater valleys do not exist near the ICLS, a large outwash plain, known as the Vilas County Outwash Plain, borders the southwestern edge of the ICLS (Figure 5.17). The location of the outwash plain proximal to and southwest of the loess deposits makes it a possible loess source area. I examined whether the ICLS had multiple source areas, particularly: 1) each of the three surrounding end moraines and 2) the Vilas County Outwash Plain, which lies to the southwest of the study area.

Three sampling transects were developed for the ICLS (Figure 5.18). One transect (IC 1) generally runs from southwest to northeast, approximately midway between the Watersmeet and Sagola Moraines, along the corridor of the thickest loess, as mapped by the NRCS (Linsemier, 1997). IC 1 starts in Vilas County, Wisconsin at the edge of the outwash plain and ends in southwestern Marquette County, Michigan at the Republic Moraine. The transect takes a slight bend to the north midway across Iron County, in order to follow the trend of thick loess. The other two transects (IC 2 and IC 3) are parallel to each other and are oriented in a northwest to southeast direction. Each begins at the Watersmeet Moraine on their northwestern margin, and ends at the Sagola Moraine; both are oriented perpendicular to these two end moraines. For analysis purposes, data from IC 2 and IC 3 were combined in order to create a more robust data set. The following data are the first to be reported for the Iron County loess sheet.

A total of 77 loess samples were collected within these transects in Iron and Marquette Counties in Michigan, and in Forest and Vilas Counties in Wisconsin (Figure 5.19). IC 1 contains 47 sample locations, IC 2 contains 24 sample locations, and IC 3 contains 15 sample locations. Samples from locations that lie at the intersection of the transects were used twice in the analyses, once for IC 1 and once for IC 2 or IC 3.

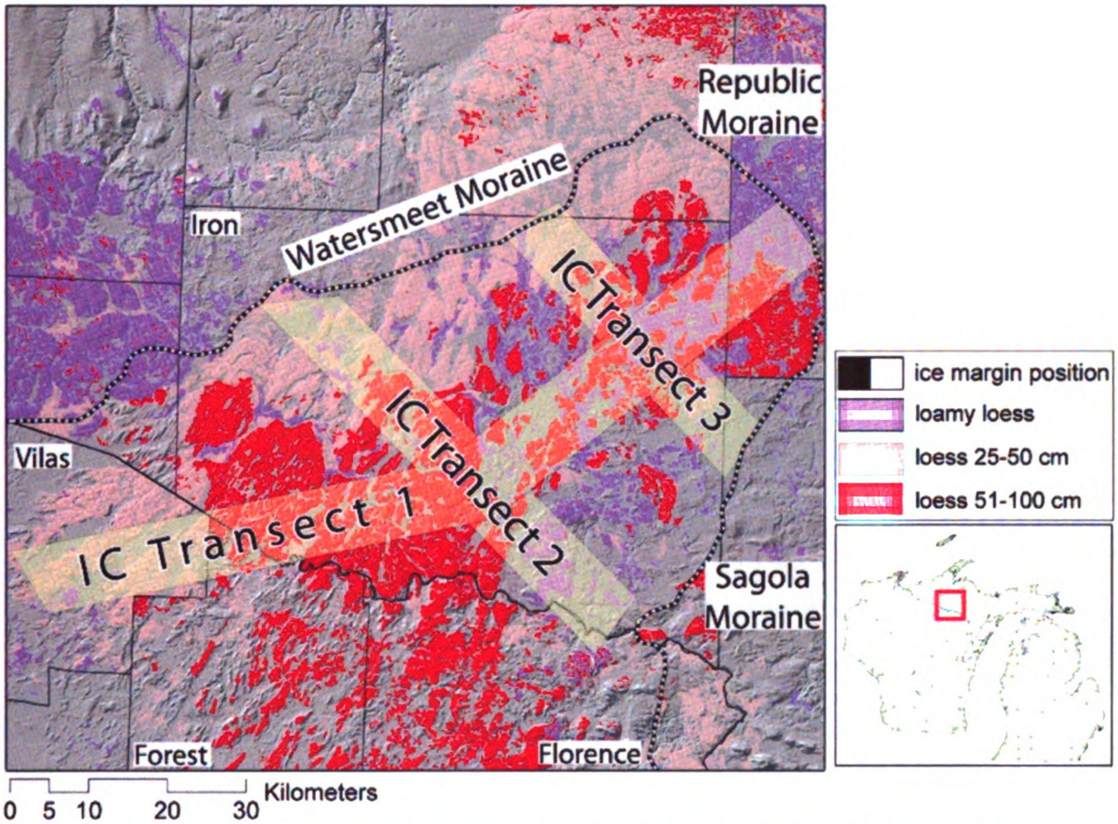

Figure 5.18. Location of sampling transects in the Iron County Loess Sheet study area.

5.2.1 Loess Thickness Data in the Iron County Loess Sheet

Loess thickness in the ICLS, as indicated by the transect data, ranges from 30 to 95 cm. The mean thickness is 52 cm and the median is 50 cm (Appendix A). The thickest loess (51-100 cm) is generally found in the center of the study area, along an axis running southwest to northeast (Figure 5.19). Areas of thick loess are also found in southwestern Marquette County, southeastern Baraga County and northern Forest and Florence Counties. Thinner loess is usually found at the edges of the study area - near the ice margin (end moraine) positions and near the northeastern edge of the outwash plain in Vilas County, WI.

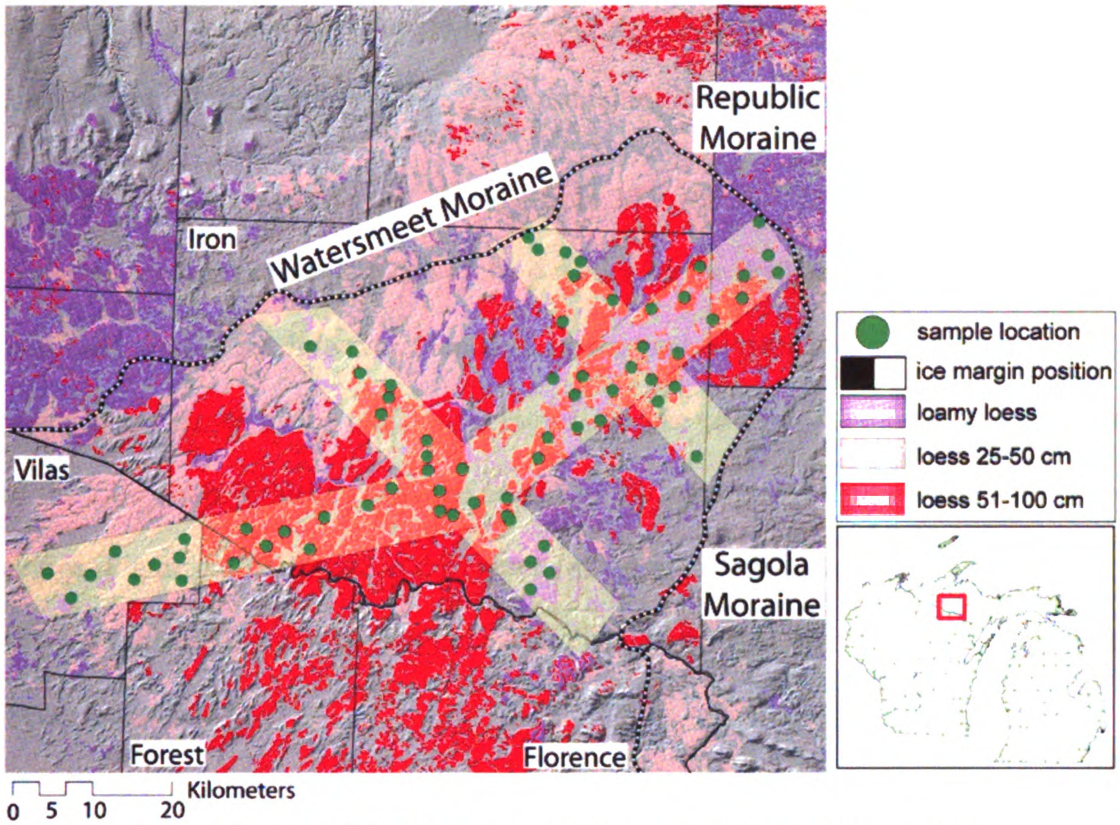

Figure 5.19. Map of Iron County Loess Sheet sample locations (green dots).

As stated previously, much of Iron County is occupied by the Iron County Drumlin Field. These drumlins are typically 15 m high, with broad summits (Peterson, 1986). Additionally, the drumlins are located on a regional bedrock high that separates the Great Lakes drainage basin from the Mississippi River drainage basin. This bedrock high may have caused the ice covering the study area to be relatively thin, as ice flow directions (and moraine configurations) indicate that southerly flowing ice would have been diverted around the sides of the drumlin field (Peterson, 1986). Given their high elevation and relatively thin ice cover, it is likely that these drumlins were some of the first landforms to be exposed when ice began melting at the end of the Late Wisconsin advance. Their early exposure could have allowed for an overall longer period of loess deposition compared to the surrounding landscapes. Not surprisingly, these high, broad drumlins typically coincide with the areas of thickest loess in Iron County.

Loess thicknesses along IC 1 range from 30 to 95 cm. The mean thickness is 51 cm and the median is 50 cm. None of the p-values for the thickness regression lines were statistically significant, however. Nonetheless, the general pattern of points on the scatterplot, as shown by the polynomial regression (the best-fit of the three lines), shows that the loess sheet is thickest near the middle of the transect and thins toward both margins (Figure 5.20). Based on this pattern of loess thickness, it does not seem that either the outwash plain or the Republic Moraine was the sole source of loess to the Iron County Loess Sheet.

Loess thickness across IC 2 and IC 3 ranges from 30 to 95 cm. The mean thickness if 55 cm and the median thickness is 55 cm. Similar to the loess thickness regressions for IC 1, none of the p-values for IC 2 and IC 3 were statistically significant. The general pattern of loess thickness in these two transects is, however, similar to IC 1 (Figure 5.21). Loess is generally thickest near the middle of the transects and thinner at the edges. This pattern suggests that neither the Watersmeet nor the Sagola moraines, were the main source areas for loess in Iron County.

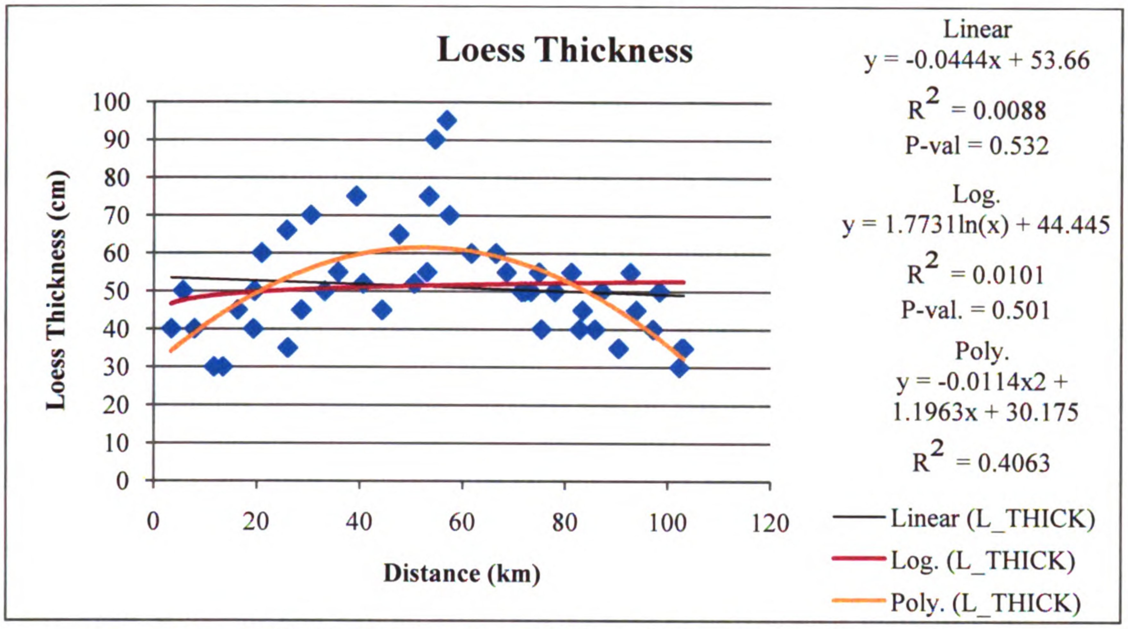

Figure 5.20. Scatterplot of loess thickness in Iron County Transect 1.

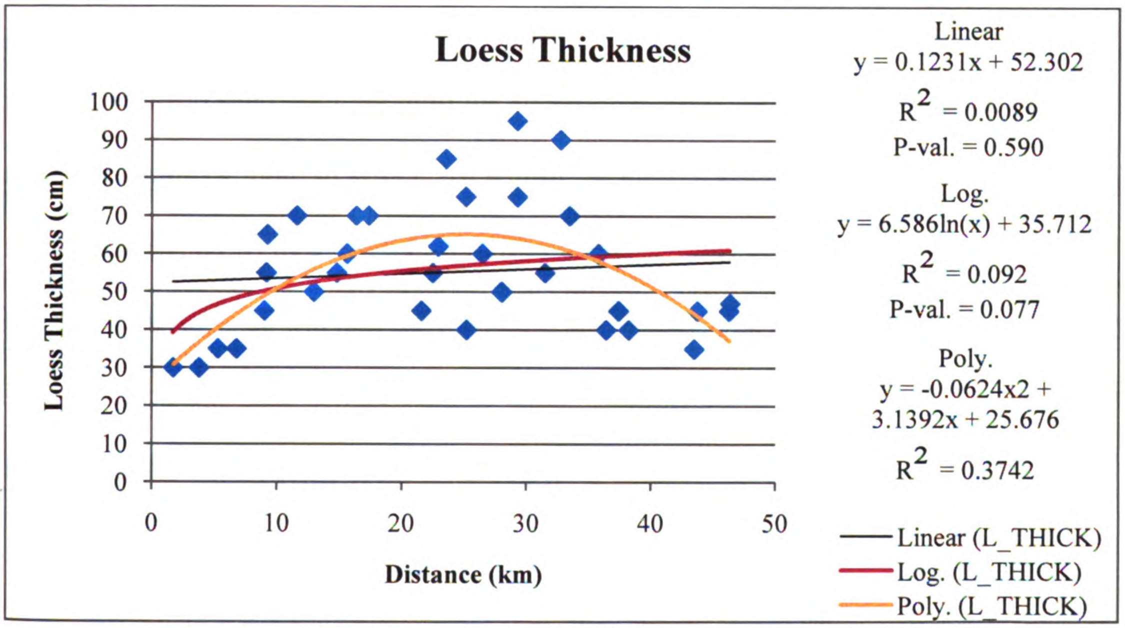

Figure 5.21. Scatterplot of loess thickness in Iron County Transects 2 and 3.

Although the loess scatterplots for IC 1 and IC 2 and 3 do not provide conclusive evidence for a source area when examined separately, together they suggest that multiple source areas were contributing loess to the ICLS. Both transects exhibit thick loess near the middle of the transect, and thinner loess near the margins. This pattern of loess thickness indicates that loess was being deposited by winds from multiple directions, and likely, from multiple sources. It also suggests that no one of the four possible sources was dominant. The study area is surrounded on all sides by landscapes that could have served as source areas for the loess mantle in Iron County. This evidence suggests that the Watersmeet, Republic and Sagola Moraines, as well as the outwash plain in Vilas County, WI, all contributed some eolian sediment to the ICLS.

5.2.2 Particle Size Trends in the Iron County Loess Sheet

The mean sand:silt:clay ratio for all samples from the ICLS is 36:50:14 and the median is 38:48:14; both of which are within the loam texture class. The mean weighted particle size (MWPS) of the samples ranges from 22 – 221 μm. The average MWPS for all ICLS samples is 88 μm and the median is 84 μm, both of which are in the coarse very fine sand category. The texture class of most loess samples from the ICLS is either loam or silt loam; however, some samples are notably finer or coarser textured (Appendix B).

Mean weighted particle size in IC 1 ranges from 22 μm – 221 μm along the 105 km transect. The average MWPS is 85.2 μm and the median is 77.9 μm, both of which are in the coarse very fine sand fraction. As stated previously, MWPS typically decreases with distance from a source area (Smith, 1942; Ruhe, 1954, Fehrenbacher, *et al.,* 1965; Muhs and Bettis, 2000). The scatterplot of MWPS in IC 1 does not display a significant change with distance from either the Vilas County Outwash Plain or the Republic

Moraine (Figure 5.22). However, the pattern of scatterplot points seems to show that MWPS is higher near the edges of the transect, with a notable decrease near the middle. This pattern suggests that both the outwash plain to the southwest and the moraine to the northeast contributed some eolian sediment to the loess mantle in Iron County. The mode of particle sizes along IC 1 increases away from the outwash plain, suggesting that the Republic Moraine contributed slightly more silt, and/or the Vilas County Outwash Plain contributed more fine sands to the ICLS (Figure 5.23). Both seem to be reasonable conclusions, based on these data. Some particle size curves feature obvious secondary peaks in the sand fraction. These bi-modal particle size curves are likely cause by in-mixing of sand from below the loess mantle.

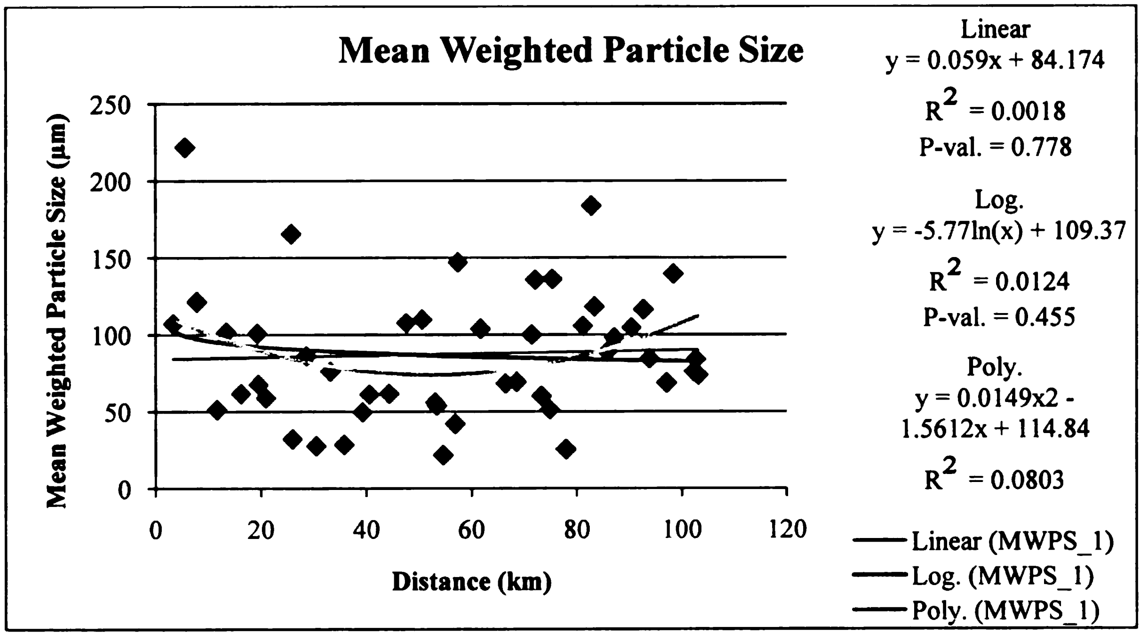

Figure 5.22. Scatterplot of mean weighted particle size for Iron County transect 1.

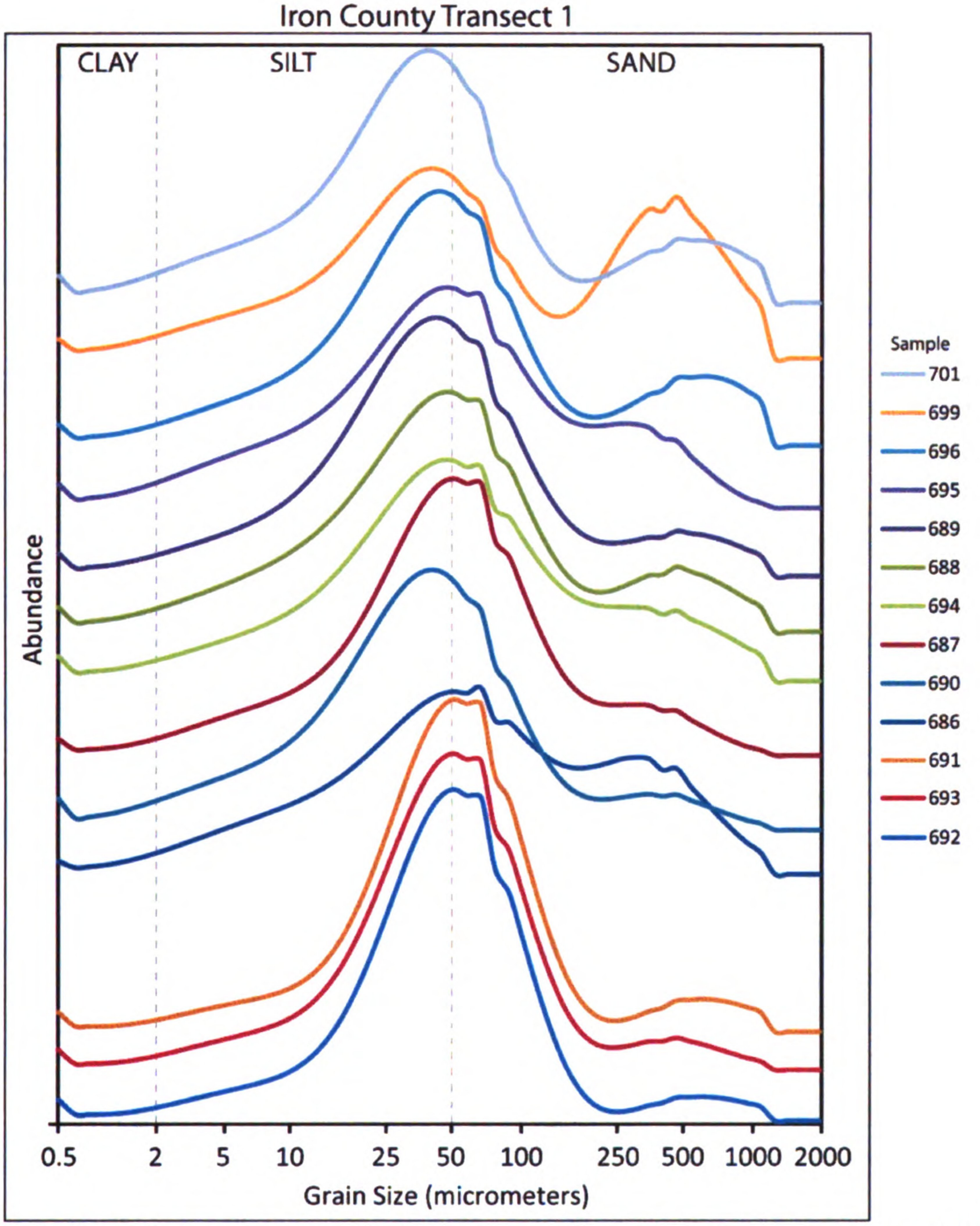

Figure 5.23. Continuous particle size distribution curves for representative samples (701, proximal to outwash plain; 692, distal to outwash plain) from Iron County transect 1 (IC 1). Curves are offset vertically for clarity.

Mean weighted particle size along IC 2 and 3 is highly variable over the length of the transects (Figure 5.24). This may be due, in part, to greater mixing near the Watersmeet Moraine compared to the area near the Sagola Moraine (Figure 5.25). Additionally, none of the p-values for the three regression lines are statistically significant and there is no discernable pattern evident in the scatterplot. As such, no conclusion can be drawn as to the likely source area, with respect to the Watersmeet and Sagola Moraines. The lack of a pattern may be due to loess coming from both the Watersmeet Moraine to the west of the study area and the Sagola Moraine to the east, or perhaps little loess was derived from these moraines. Another explanation may be that increased pedoturbation near the Watersmeet Moraine, where loess is generally thinnest, is increasing the MWPS near the western edge of the transects.

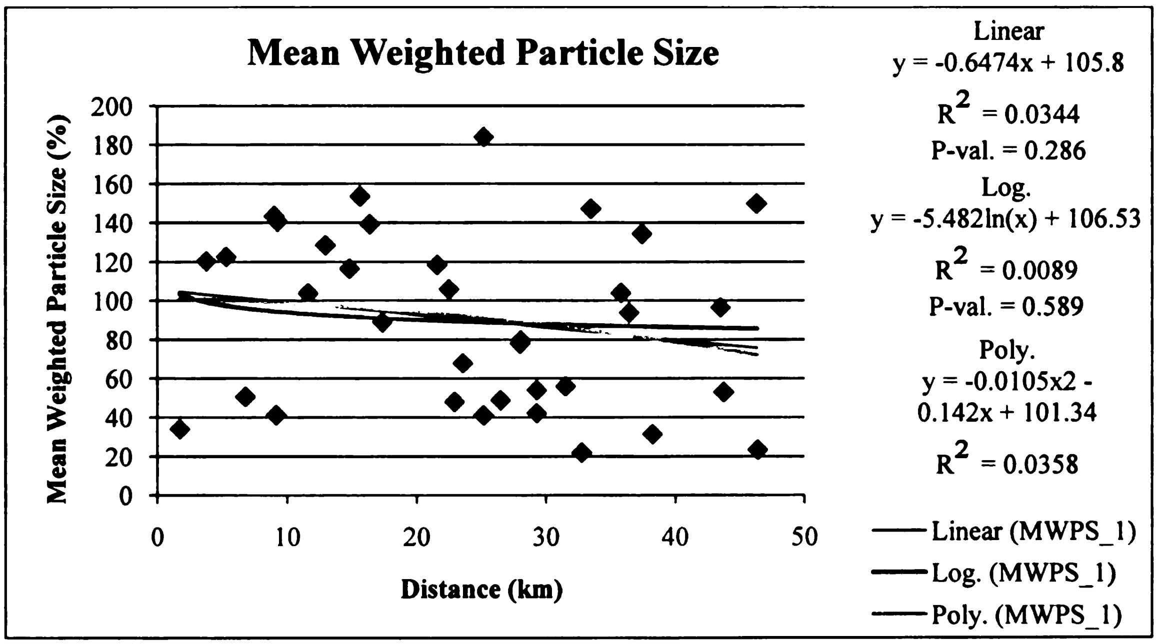

Figure 5.24. Scatterplot of mean weighted particle size in Iron County transect 2 and 3.

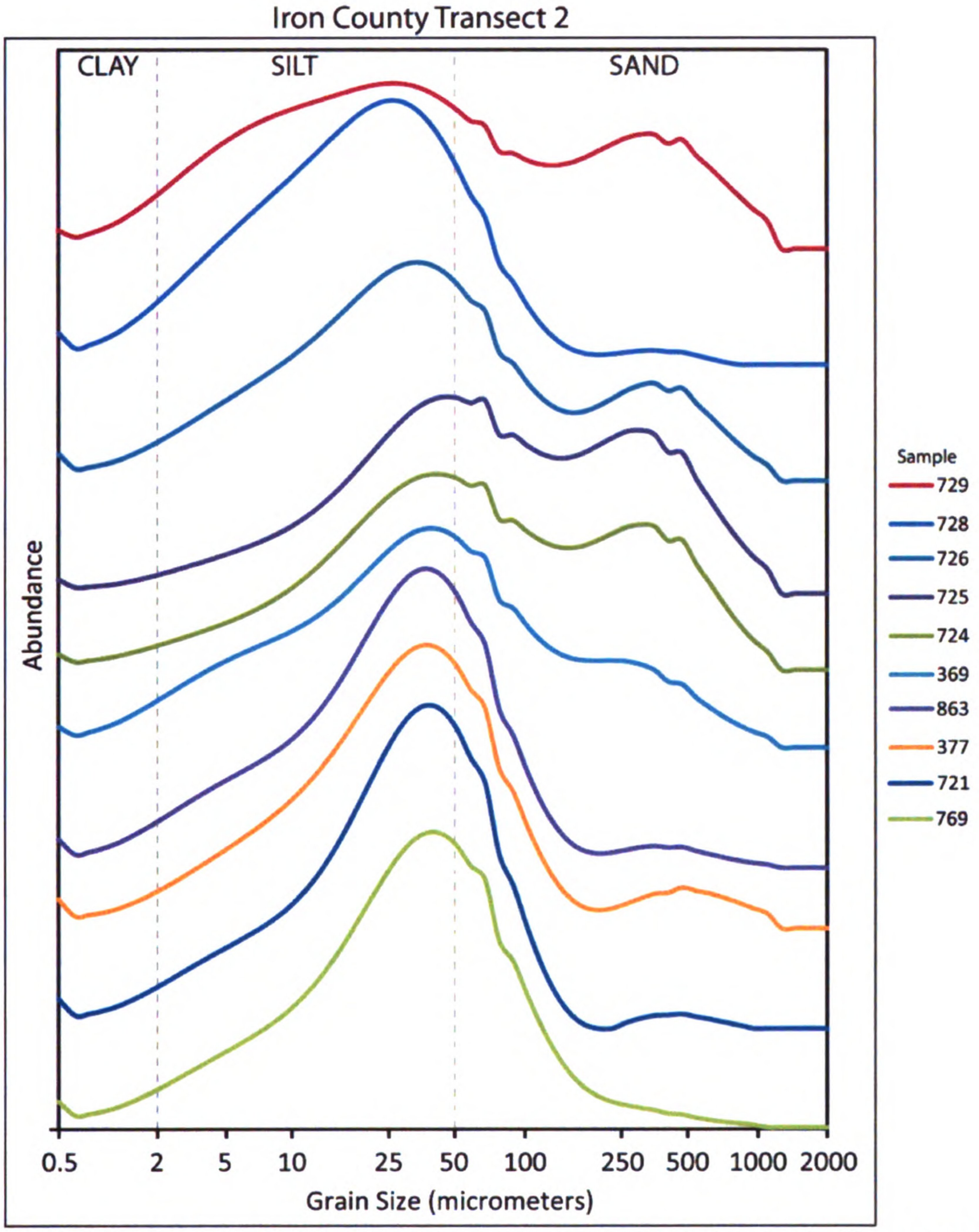

Figure 5.25. Continuous particle size distribution curves for representative samples (729, proximal to the Watersmeet Moraine; 769, distal to the Watersmeet Moraine) from Iron County transect 2 (IC 2). Curves are offset vertically for clarity.

It has long been recognized that the prevailing winds that deposited much of the loess near the Mississippi and Missouri River valleys were westerly (Smith, 1942; Ruhe, 1954, Fehrenbacher *et al.,* 1965; Frazee *et al.,* 1970; Handy, 1976; Putman *et al.,* 1988; Muhs and Bettis, 2000), thereby depositing the majority of loess to the east of these river valleys. However, these loess deposits have also been observed on the west sides of the same river valleys, due to frequent variations of wind patterns (Ruhe, 1969; Frazee *et al.,* 1970; Handy, 1976; Putman *et al.,* 1988, Muhs and Bettis, 2000). Considering that the ICLS has possible source areas to the east, west, north, and south, all of these could have provided some eolian sediment, and as a result, destroyed any obvious pattern of MWPS distance-decay from any one individual source. The loess thickness data for IC 2 and 3 seem to lend support to this explanation, as they also indicate winds were multi-directional in the ICLS (Figure 5.21).

Another possible explanation for the apparent lack of decrease in MWPS from either source is pedoturbation (*i.e.,* bioturbation and/or cryoturbation). Both transects are characterized by thinner loess near the edges, usually less than 50 cm. The underlying glacial till could have easily mixed with the relatively thin loess. Evidence for this type of pedoturbation can been seen in the particle size distribution curves for IC 2 and IC 3 (Appendix C) where several loess samples have significant secondary peaks in the sand fraction (Figure 5.25). It is probable that both variable winds and pedoturbation have had an impact on the ICLS spatio-textural properties, but neither can be identified as the main reason for the lack of spatial trend in MWPS.

5.2.3 Spatial Trends in the Iron County Loess Sheet: Silt Content

Total silt contents for IC 1 samples range between 26 and 71%. The mean and median silt contents are both 51%. The p-value for overall silt content (polynomial regression) is 0.029, which is statistically significant. According to the trend of the polynomial regression line, overall silt content first increases, then decreases with distance from the outwash plain (Figure 5.26). The regression line predicts silt content near the outwash plain to be ~ 55%, increasing to a maximum of 65% at 40 km, then decreasing to ~ 45% near the Republic Moraine. The trend of the regression line shows that silt first increases away from the Vilas County Outwash Plain before it decreases, nearer the Republic Moraine. This result is similar to that found by Smith (1942) in Illinois, where intermediate fractions first increase, then decrease, with distance from the source. Smith did not define what he meant by "intermediate fractions," nor did he offer an explanation for the trend. The initial increase, then decrease, in silt in this study is probably due to the samples near the outwash plain having higher amounts of sand. This trend suggests that samples near the southwestern edge of the transect are receiving sand sized particles from the Vilas County Outwash Plain. Because all particle sizes are calculated clay-free, silt and sand are inversely related.

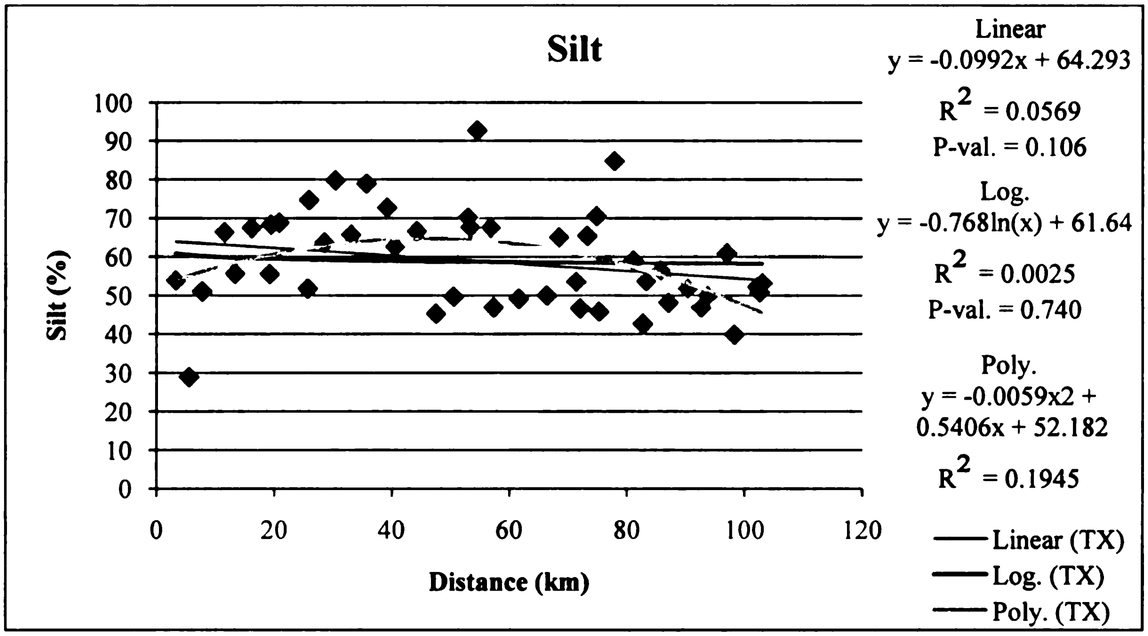

Figure 5.26. Scatterplot of silt contents from Iron County transect 1.

Very fine silt first increases then decreases with distance from the outwash plain, similar to the trend displayed in the silt content scatterplot (Figure 5.27). The polynomial regression line has a highly statistically significant p-value of 0.000. Near the outwash plain, the polynomial regression line predicts very fine silt content to be ~ 7%, increasing to a maximum of 9% at 40 km from the outwash plain, and then finally decreasing to ~ 3.5% near the Republic Moraine. Fine silt defined as 12-25 μm and fine silt defined as 2-20 μm also display similar trends to silt and very fine silt (Figures 5.28, 5.29). Fine silt (12-25 μm) has a polynomial regression line with a p-value of 0.001, indicating a statistically significant trend. The regression line predicts fine silt (12-25 μm) content near the outwash plain to be ~ 20%, increasing to a maximum of 25% at 45 km from the outwash plain, then decreasing to ~ 13% near the northeastern edge of the transect. Fine silt (2-20 μm) shows an almost identical polynomial regression line to fine silt defined as 12-25 μm. In general, the finer silt fractions discussed all show an initial increase then overall decrease with distance from the outwash plain. Because finer silt fractions are usually underrepresented in loess that is near the source area, these results suggest that the ICLS received sediment from multiple sources; the Vilas County Outwash Plain, the Republic Moraine and possibly other source areas. Based on the linear regressions, which are also statistically significant, each of the silt fractions mentioned above, it appears the majority of the fine silt content is derived from the Republic Moraine.

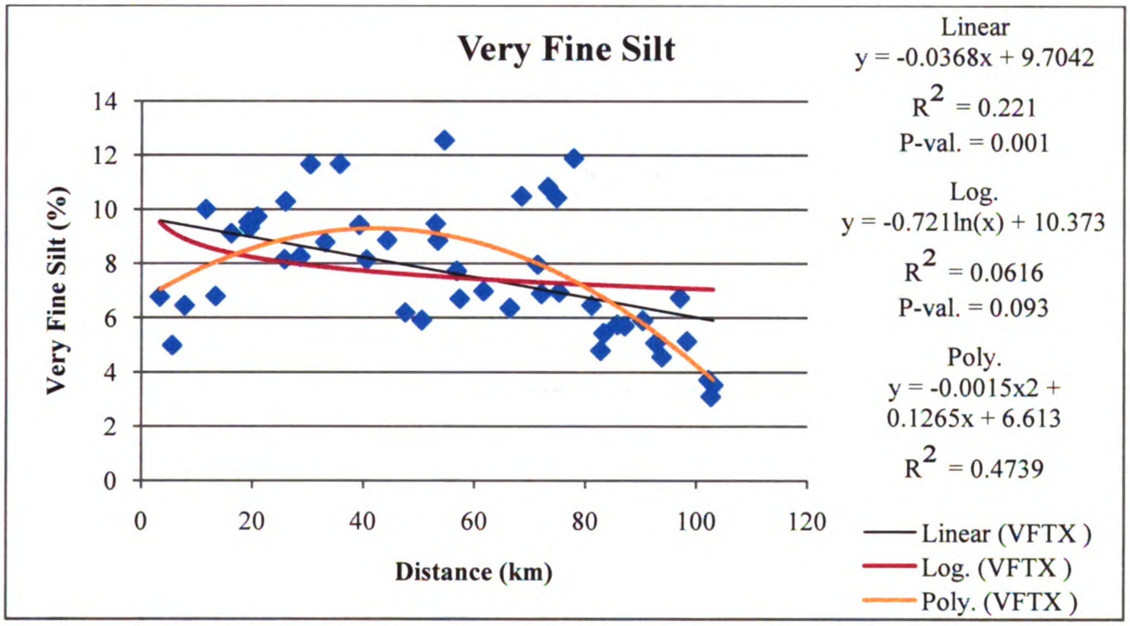

Figure 5.27. Scatterplot of very fine silt contents in Iron County transect 1.

Coarse silt and very coarse silt contents, typical of near-source loess deposits, also show a significant change along the length of the IC 1 transect. However, unlike the various finer silt fractions discussed above, coarse silt and very coarse silt show positive trends on the scatterplots. Of the three regression lines for the coarse silt scatterplot, only the logarithmic regression had a statistically significant p-value (0.044) (Figure 5.30). The trend of the regression line predicts coarse silt content near the southwestern edge of

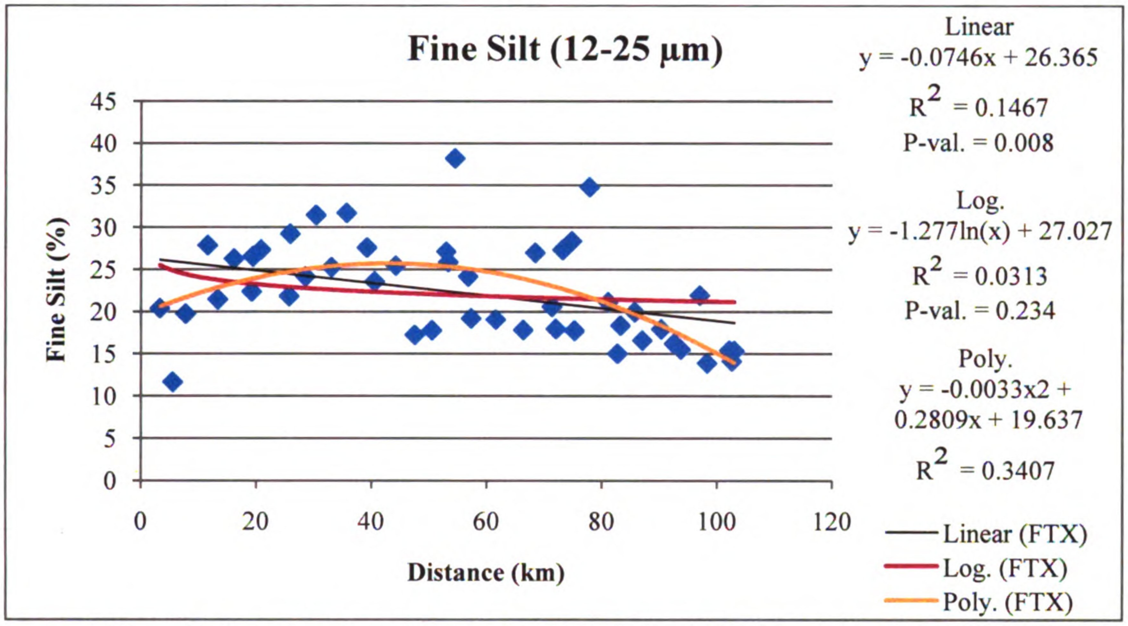

Figure 5.28. Scatterplot of fine silt (12-25 µm) content in Iron County transect 1.

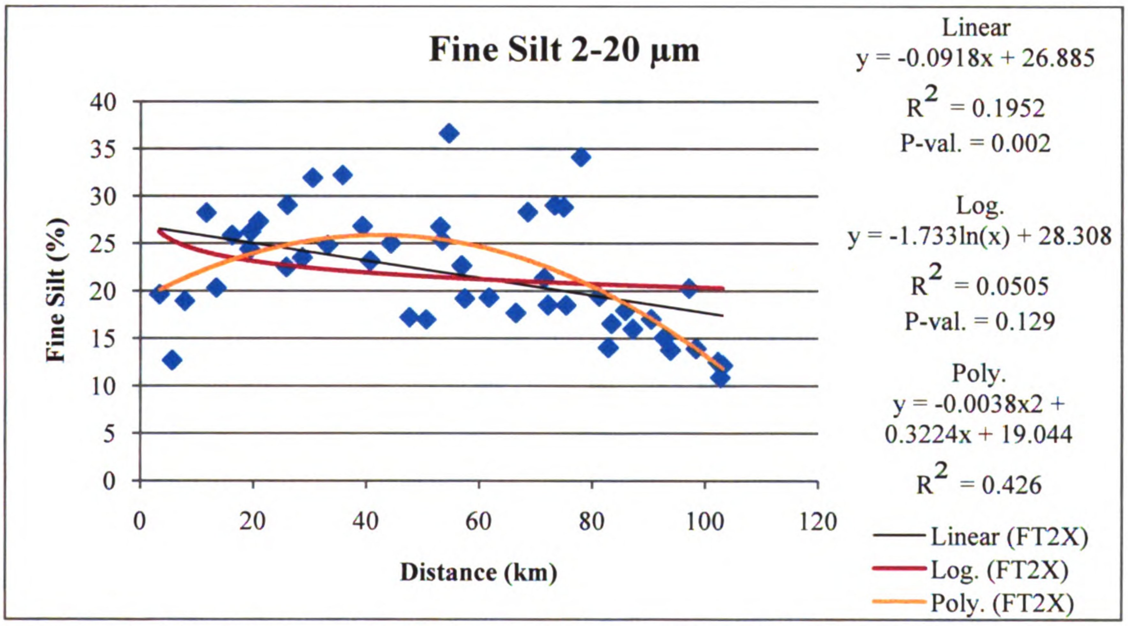

Figure 5.29. Scatterplot of fine silt (2-20 µm) contents in Iron County transect 1.

the transect to be ~ 13% increasing to ~ 16% at the northeastern terminus. The overall trend in very coarse silt content is similar to the trend for coarse silt, and it also has a statistically significant logarithmic regression p-value (0.019) (Figure 5.31). The regression line predicts very coarse silt content at ~ 7% on the southwestern edge of the transect increasing to ~ 10% on the northeastern edge. Previous studies have shown that coarse silt typically decreases with distance from a source (Figure 5.32) (Smith, 1942; Ruhe, 1954; Rutledge *et al.,* 1975; Putman *et al.,* 1988). The results of both coarse silt and very coarse silt scatterplots suggest that the Republic Moraine on the northeastern edge of the study area was a source for these sediments.

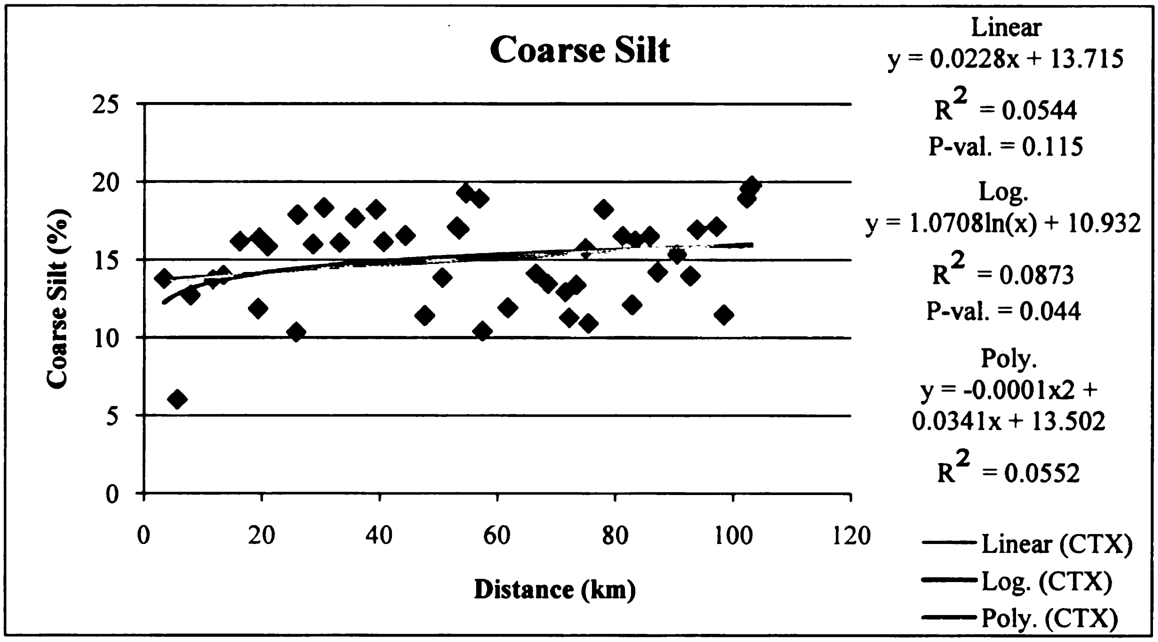

Figure 5.30. Scatterplot of coarse silt contents along Iron County transect 1.

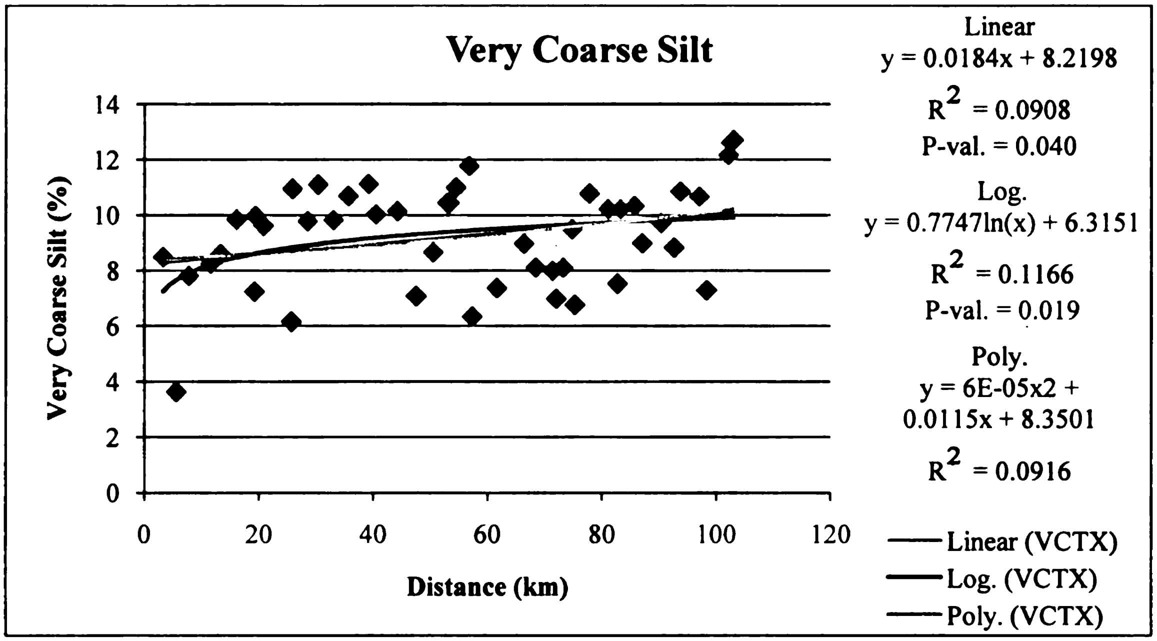

Figure 5.31. Scatterplot of very coarse silt contents in Iron County transect 1.

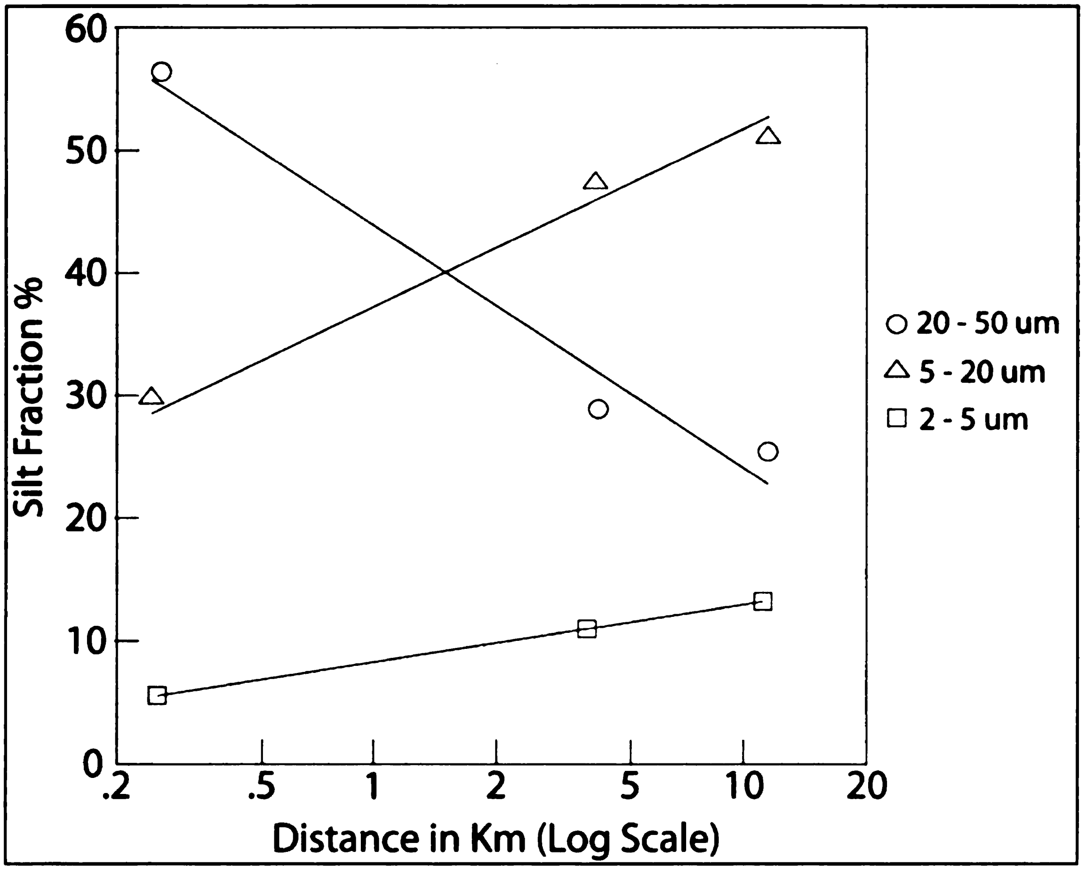

Figure 5.32. Means of loess silt fractions in relation to distance from a source (after Rutledge *et al.,* 1975).

Unlike the regression analysis for IC 1, none of the regression lines for the various silt particle size fractions from IC 2 and 3 are statistically significant. However, some scatterplots display recognizable patterns that could nonetheless be used to imply a source area. The very fine silt scatterplot shows the highest concentrations near the edges of the transect, coupled with lower contents in the middle of the transect (Figure 5.33). Fine silt defined as 12-25 μm displays the same pattern (Figure 5.34). Typically, very fine silt and fine silt increase with distance from a source. Because the contents of these silt fractions decrease with distance from both moraines, these patterns suggest that neither moraine was the dominant source of very fine silt or fine silt for the ICLS.

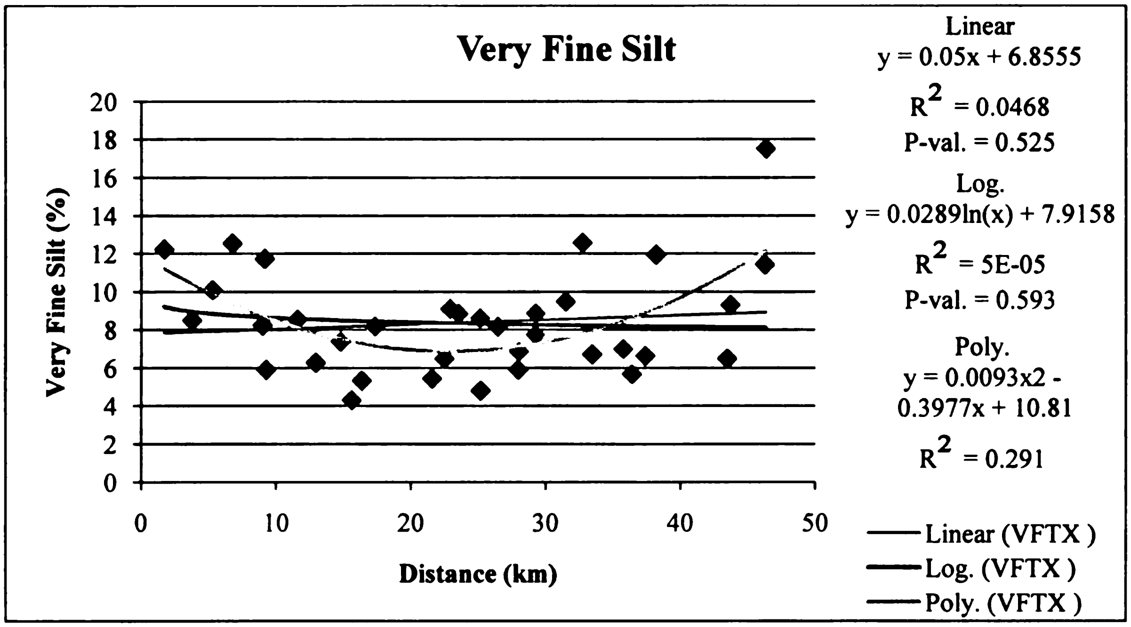

Figure 5.33. Scatterplot of very fine silt content in Iron County transect 2 and 3.

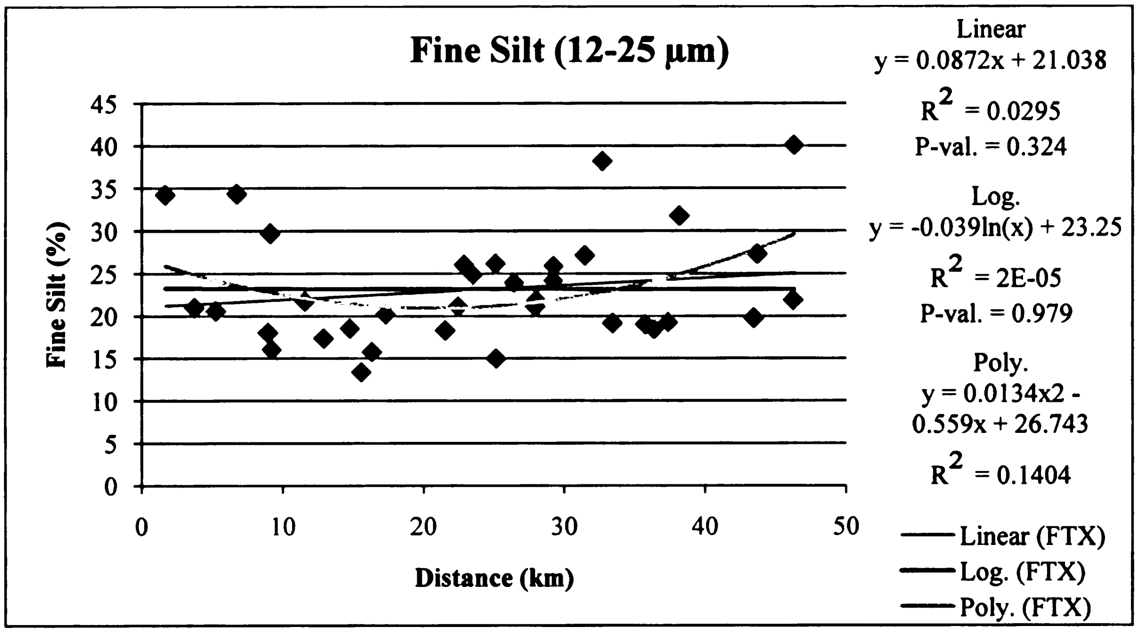

Figure 5.34. Scatterplot of fine silt in Iron County transect 2 and 3.

5.2.4 Spatial Trends in the Iron County Loess Sheet: Sand Contents

The very fine sand and very fine and fine sand fractions of IC 1 both feature statistically significant polynomial regression lines (Figure 5.35 and 5.36). The p-value of the polynomial regression for very fine sand is 0.000 and it also has an R^2 value of 0.391 indicating that it is a better fit than the linear regression which also has a p-value of 0.000. The regression line shows that the predicted very fine sand content at the southwestern edge of the transect is ~ 22%, decreasing to 20% at 40 km from the outwash plain, and then increasing to ~ 32% at the northeastern margin of the transect. This pattern indicates that very fine sand was being transported from both the Vilas County Outwash Plain and the Republic Moraine, to the ICLS. The same trend is apparent with related particle size fractions when the very fine sand content is subdivided into very, very fine sand, medium very fine sand and coarse very fine sand (Appendix A). The p-value of the very fine and fine sand polynomial regression line is 0.000, similar to that for very fine sand. The line predicts very fine and fine sand contents at the southwestern edge of the transect to be ~ 30%, decreasing to ~ 25% at 40 km from the outwash plain before increasing to ~ 42% near the northeastern edge of the transect. This scatterplot also shows a distinct pattern that indicates that the Vilas County Outwash Plain and the Republic Moraine were both contributing finer sands to the loess sheet, but the Republic Moraine appears to have been a larger source, according to the linear and logarithmic regression lines (Figures 5.35 and 5.36).

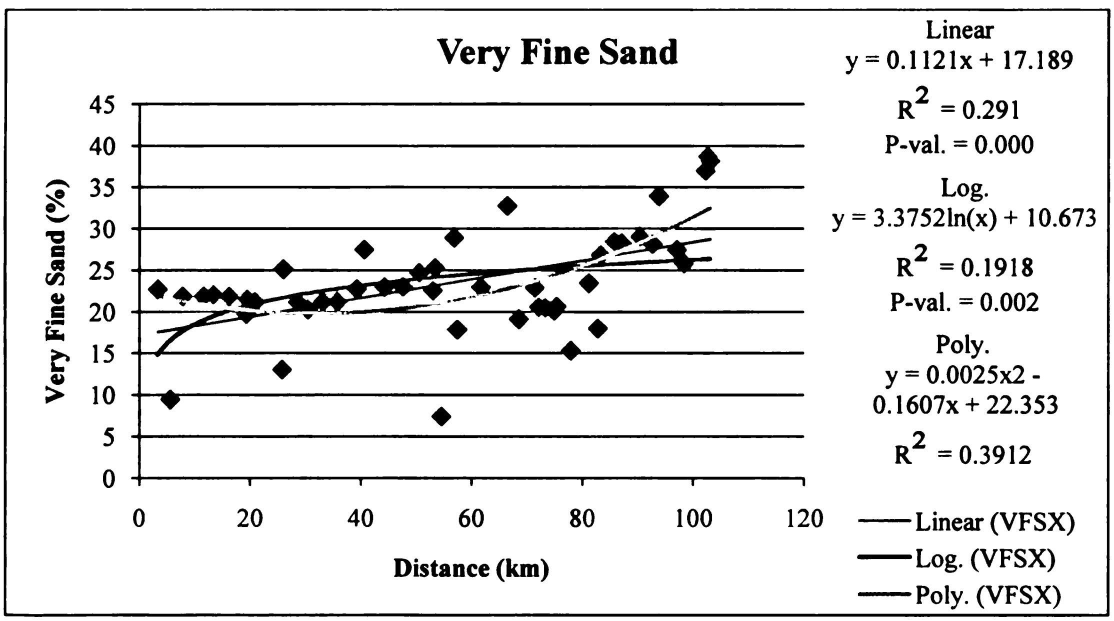

Figure 5.35. Scatterplot of very fine sand contents in Iron County transect 1.

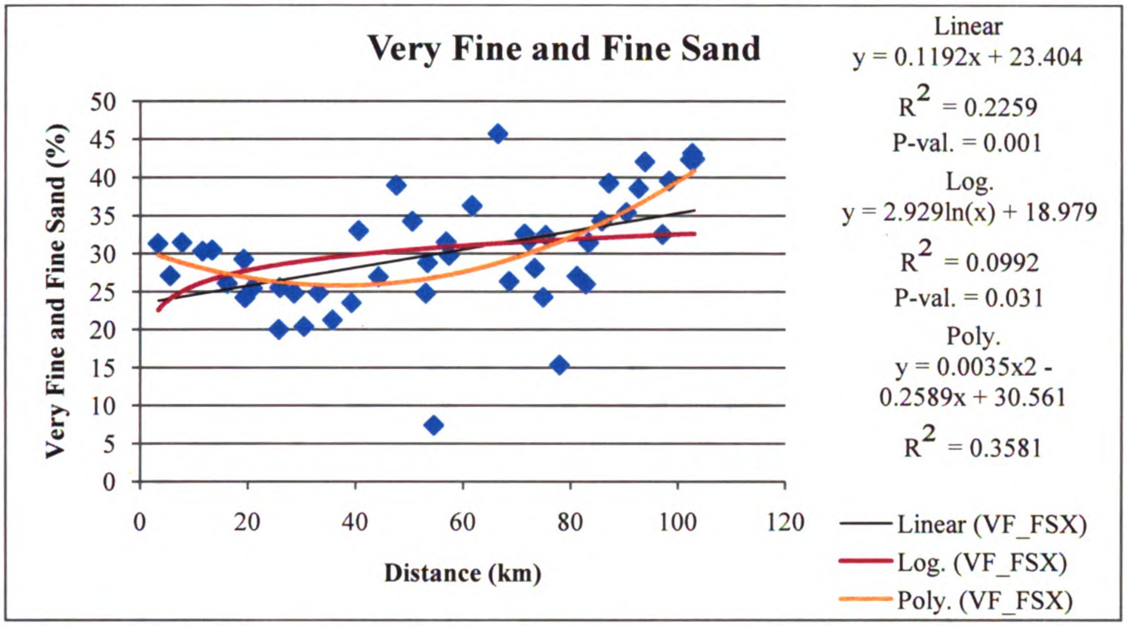

Figure 5.36. Scatterplot of very fine and fine sand contents in Iron County transect 1.

Although the regression analysis for all of the sand fractions for IC 2 and 3 proved to be non-significant, very fine sand does seem to show a distinct pattern in the sediment concentrations over the length of the transects, being highest in the middle of the transect and lowest at the edges (Figure 5.37). Very fine sand typically decreases away from a loess source (Smith, 1942; Ruhe, 1954; Rutledge *et al.,* 1975; Pye, 1984; Putman *et al.,* 1988; Mason, 2001). If the Watersmeet Moraine and the Sagola Moraine were both contributing very fine sand to the ICLS, we would expect to see a high concentration of very fine sand content near the edges of the transect. Instead, the opposite pattern emerges from the data. A similar, but somewhat weaker pattern is apparent when very fine sand is subdivided into very, very fine sand (Figure 5.38) and coarse very fine sand (Figure 5.39). These results indicate that neither the Watersmeet nor the Sagola Moraine was the primary source of very fine sand, very, very fine sand, or coarse very fine sand for the ICLS. It is possible that these particle size fractions were coming from different source(s).

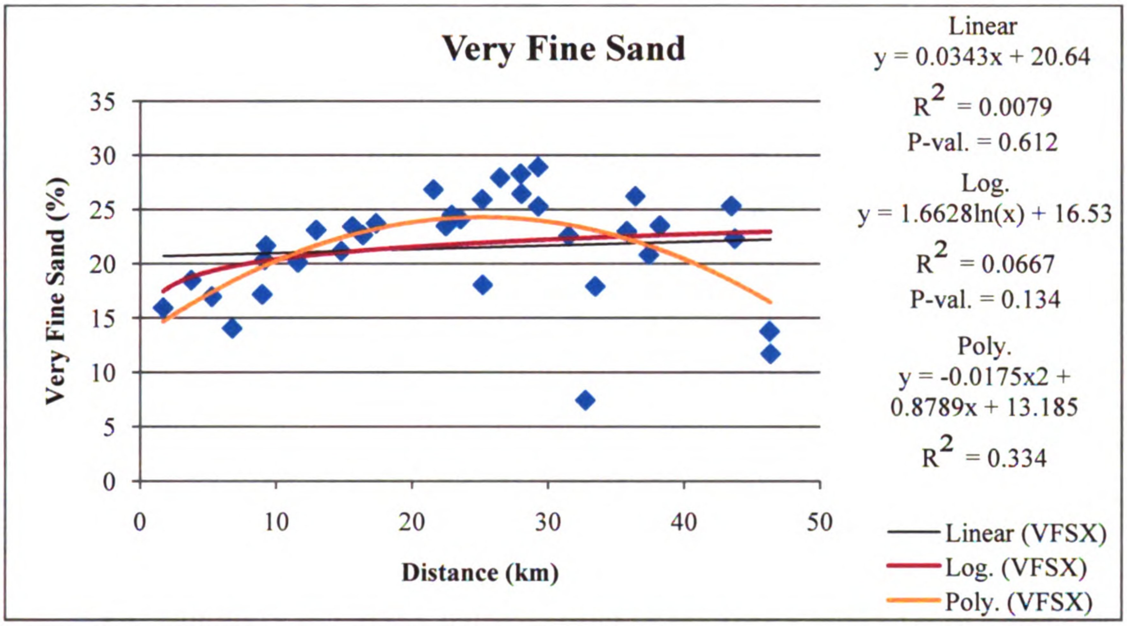

Figure 5.37. Scatterplot of very fine sand contents for Iron County transect 2 and 3.

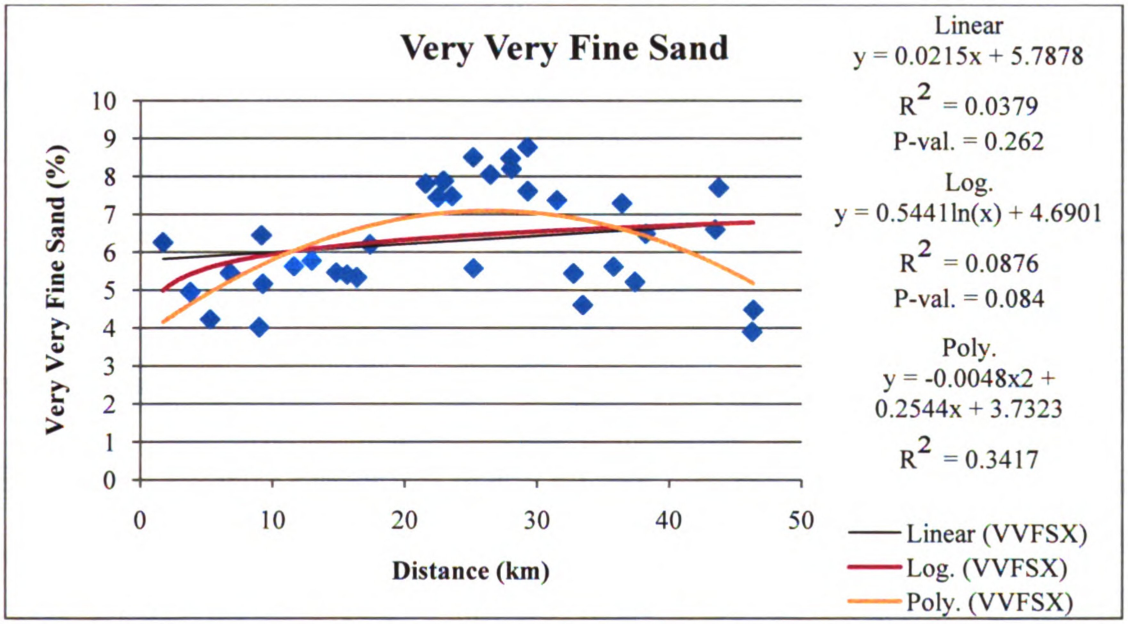

Figure 5.38. Scatterplot of very, very fine sand contents from Iron County transect 2 and 3.

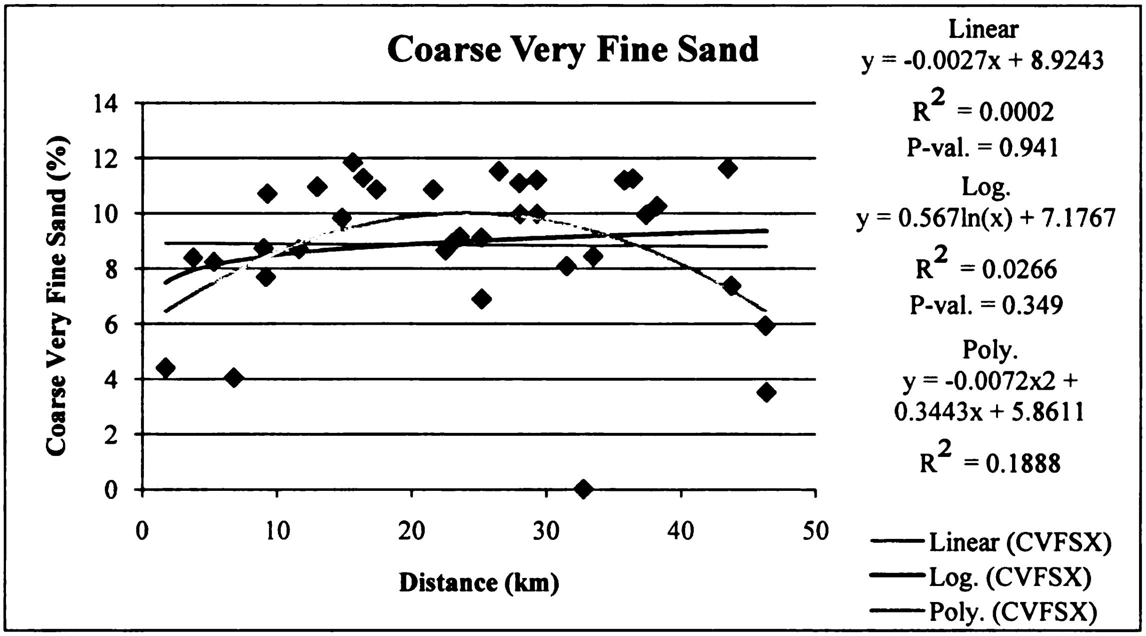

Figure 5.39. Scatterplot of coarse very fine sand contents from Iron County transect 2 and 3.

5.3.4. Summary of Loess Characteristics of the Iron County Loess Sheet

In summary, the spatial patterns of loess thickness, MWPS, and the various particle size fractions indicate that the ICLS seems to have been receiving loess inputs from all sides: the Watersmeet Moraine, Republic Moraine, Sagola Moraine, and the Vilas County Outwash Plain. Loess is thickest near the middle of IC 1 and thins away from the middle in both directions. The pattern of loess thickness in IC 2 and 3 is similar - thickest in the middle of the transect and thinner at the edges. These results imply that multiple source areas existed for the ICLS.

Mean weighted particle size in IC 1 is highly variable, with no discernable pattern evident in the scatterplot. Similar to loess thickness, this pattern might be explained by inputs of sediment from multiple source areas, and may have been complicated by bioturbation of underlying sediment into the loess. Normally, MWPS decreases from a source, but if multiple source areas were contributing sediment, the deposits from each source could potentially overlap with sediment from other source areas, destroying any spatial pattern that could be used to determine the direction of loess transport. Mean weighted particle size data from IC 2 and IC 3 are also inconclusive. However, because the study area is surrounded by potential loess sources, it is possible that loess was transported from several different directions.

When loess thickness and MWPS fail to definitively point to a source area, individual particle size fractions can usually provide some insight to the direction of transport, and help identify which source may have been contributing more or less of one particle size fraction. The polynomial trends of the IC 1 particle size contents of very fine silt, fine silt defined as 12-25 µm, and fine silt defined as 2-20 µm, all indicate that the Vilas County Outwash Plain and the Republic Moraine were both contributing loess to the ICLS (Figure 5.40). A steady decrease away from the northeastern edge of the transect in both the coarse silt and very coarse silt contents from IC 1 suggests that the Republic Moraine was contributing more of the coarser textured silt particles to the ICLS (Figure 5.40). None of the silt fractions from IC 2 or 3 have regression lines that are statistically significant. However, some of the silt particle size fraction trends from IC 2 and 3 show high concentrations near the edges of the transects.

Fine textured sand particles are capable of being transported by high winds (Schaetzl and Hook, 2008) and can provide some diagnostic evidence used to determine source area. The very fine sand and very fine and fine sand polynomial regression lines from IC 1 indicates that those particles were blowing onto the ICLS from multiple directions, but it appears that the Republic Moraine was a larger source (Figure 5.40). Each subdivision of very fine sand, including very-very fine sand, medium very fine sand

and coarse very fine sand, also support this conclusion. All other sand fractions from IC 1 proved to be non-significant. Likewise, all regression lines for each sand particle size fraction from IC 2 and 3 were non-significant. However, the scatterplots of very fine sand content from IC 2 and 3 exhibits a trend with a peak near the middle of the transect. This pattern indicates that neither the Watersmeet nor the Sagola Moraines were contributing very fine sand to the ICLS. Instead the pattern suggests that the source of very fine sand particles must be coming from a direction that is approximately normal to IC 2 and 3.

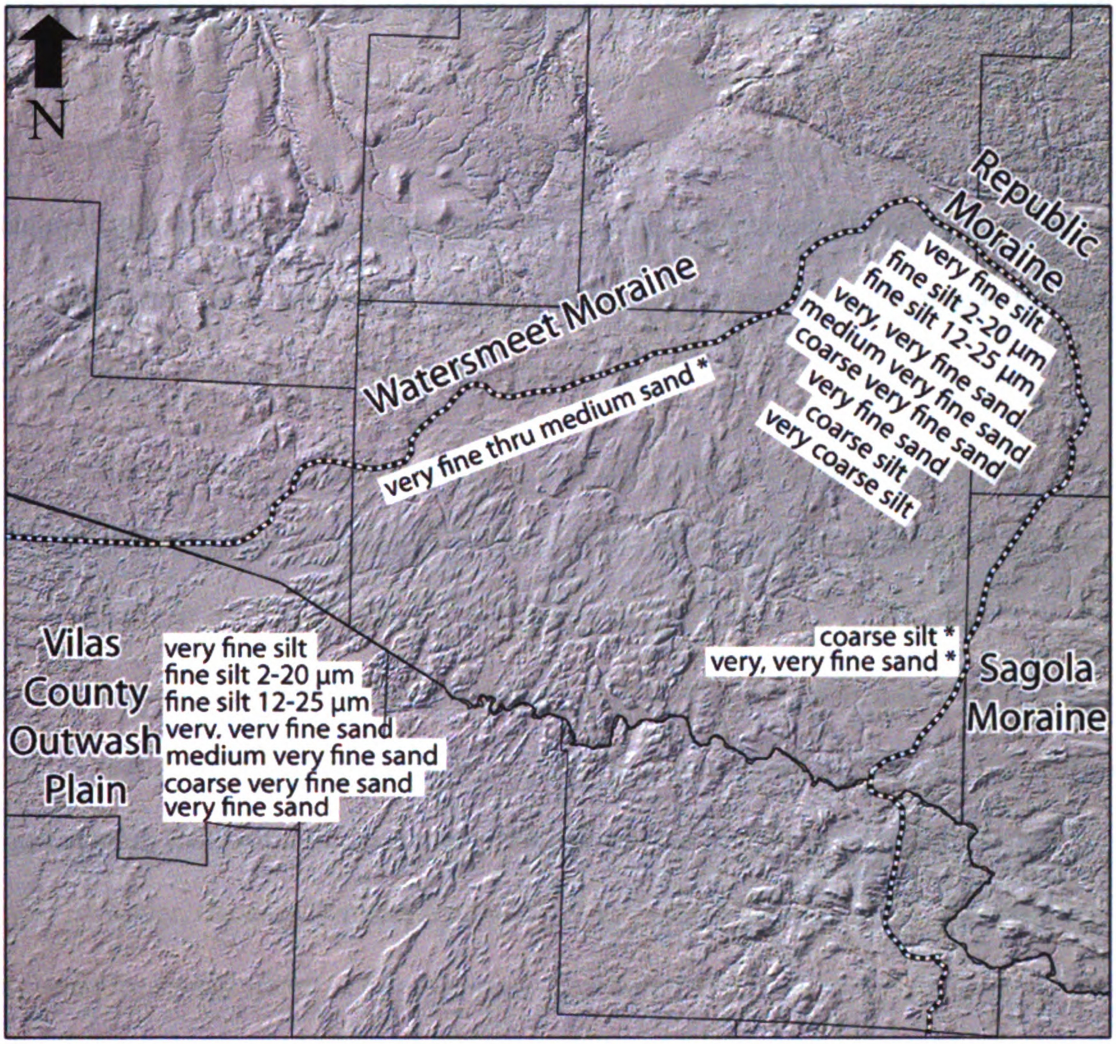

Figure 5.40. Summary of source area contributions to the Iron County loess sheet based on regression analysis. Particle size fractions denoted with an astrisk (*) are based on visual inspection of apparent trends of sample points on the scatterplots

6. Conclusions

Based on the results of this study as discussed above, I conclude that the NCWLS had two source areas: 1) the Late Wisconsin terminal moraine and 2) the Cambrian sandstone outcrops in western Clark County. This finding agrees with Stanley's (2008) conclusion that the Cambrian sandstone outcrops and the Late Wisconsin terminal moraine were both source areas for the NCWLS. Although there are many ice-disintegration landforms that comprise the Late Wisconsin terminal moraine, ice-walled lake plains, in particular, are silt-rich and their position on top of the moraine make them obvious sources for loess. After the ice-walled lakes drained, fine textured, dominantly silt-textured sediment could easily have been deflated and deposited as loess, downwind. Stanley (2008) noted that the sandstone outcrops to the southwest of the NCWLS are very friable and could have easily experienced increased physical weathering in the harsh periglacial environment of the Late Pleistocene.

Although I used different sampling methods in this thesis than did Stanley (2008), my results, conclusions and interpretations appear to be in general agreement with her. Each method has its own advantages and shortcomings. The cluster/mapping/interpolation method used by Stanley (2008) (and Schaetzl and Hook, 2008) is useful when the possible loess source area is not known. Practically, this method requires more fieldwork, because more data are necessary to produce reliable kriged maps. However, the data from the method used by Stanley is usually only visually inspected for spatial trends. The advantage of sampling along transects lies in the option to use regression models to determine the statistical significance of the spatial trends of loess thickness, MWPS, and individual particle size fractions, across space, in a more quantitative manner. However, the interpretability of the transect data regressions is optimized if they have been oriented parallel to the main direction of loess transport, or nearly so.

The results from the ICLS reveal a complex and dynamic environment at the time of loess deposition, which began at approximately 15.0 ka (Peterson, 1986). Because loess is thickest and generally finest in the center of the study area, it appears that the ICLS was receiving various particle size textures of eolian sediment from multiple source areas: 1) the Watersmeet Moraine, 2) the Republic Moraine, 3) the Sagola Moraine, and 4) the Vilas County Outwash Plain. Several regression analyses support this conclusion by showing peaks in sediment contents in the center of the study area. Loess may also be thickest in the center of the ICLS because this area is a re-entrant characterized by ~15 m high, bedrock cored, drumlins that would have become ice-free and stable earlier than the surrounding areas. The uplands in the ICLS were likely the first landscape positions to be invaded by vegetation, which could have acted as a sediment trap foe eolian dust. Once the center of the ICLS became ice-free, it would allow the opportunity for a longer period of loess deposition, thus increasing loess thickness.

The moraines surrounding the study area are generally characterized by landforms associated with ice stagnation. Stagnant ice typically has an abundance of supraglacial drift. Once the ice melted, silt particles from the supraglacial drift could have been entrained by wind and transported to the study area. Because the ICLS is located within an interlobate re-entrant, it is probable that katabatic winds were frequent and strong. Katabatic winds could have come off of each of the three ice margins, causing a chaotic regional wind pattern to persist for many years in the ICLS region. This chaotic paleowind regime may have resulted, in part, in the rather chaotic spatial patterns of loess thickness, MWPS, and individual particle size fractions of the ICLS. The variability of wind direction and strength in this interlobate region probably caused silt particles to be re-entrained over and over again before their final deposition. The constant re-entrainment likely would have mixed sediments from several source areas. The variability of scatterplots for the ICLS supports the conclusion that katabatic winds were prominent in the interlobate area, along with whatever the more regional wind regime was at the time of loess deposition.

The importance of this research is demonstrated by the conclusion that loess was derived from sources that had previously not been considered as significant contributors of eolian sediment. This may lead future workers to consider silt mantled soils, far from meltwater streams, as having been derived from eolian sediment. It also helps to increase the knowledge of Quaternary geology in the Upper Great Lakes, particularly in the western Upper Peninsula by providing more quantitative surficial geology data for the region. The results from north-central Wisconsin support earlier conclusions that the loess was sourced from the Late Wisconsin terminal moraine and sandstone outcrops southwest of the study area (Stanley, 2008). The work carried out in Iron County, MI is significant because it is the first data reported from that loess sheet and it seems that it is the only loess sheet located within an interlobate re-entrant.

APPENDIX A

Scatterplots

All particle size data for this study were calculated on a clay-free basis.

Scatterplots presented in the text are omitted from the appendix.

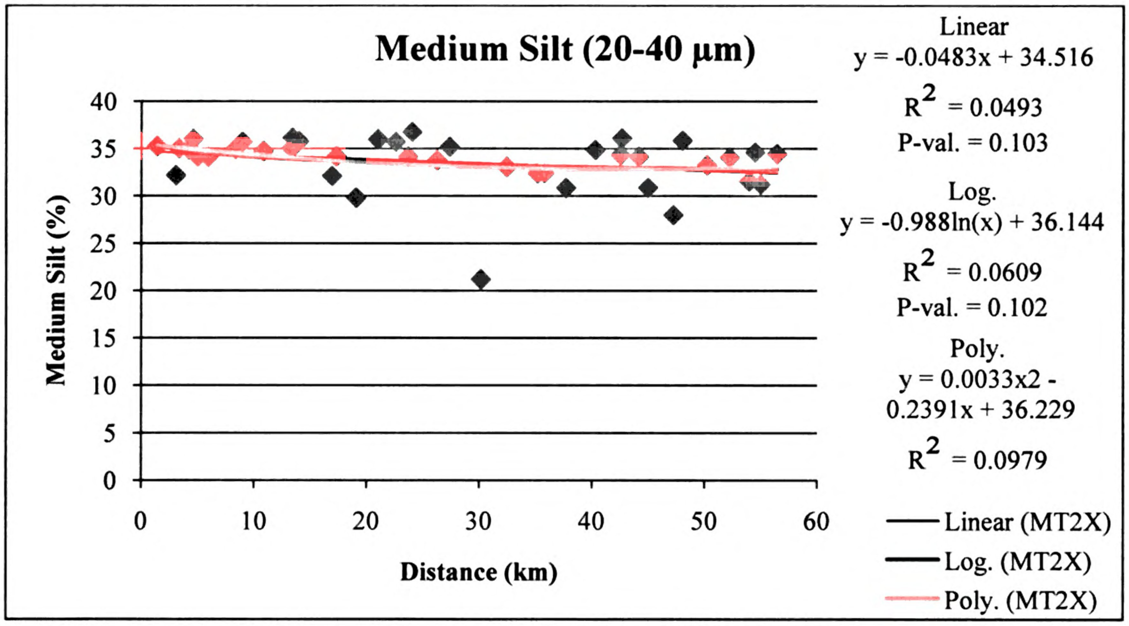

Figure A.1. Scatterplot of medium silt content from north-central Wisconsin transects 1 and 2

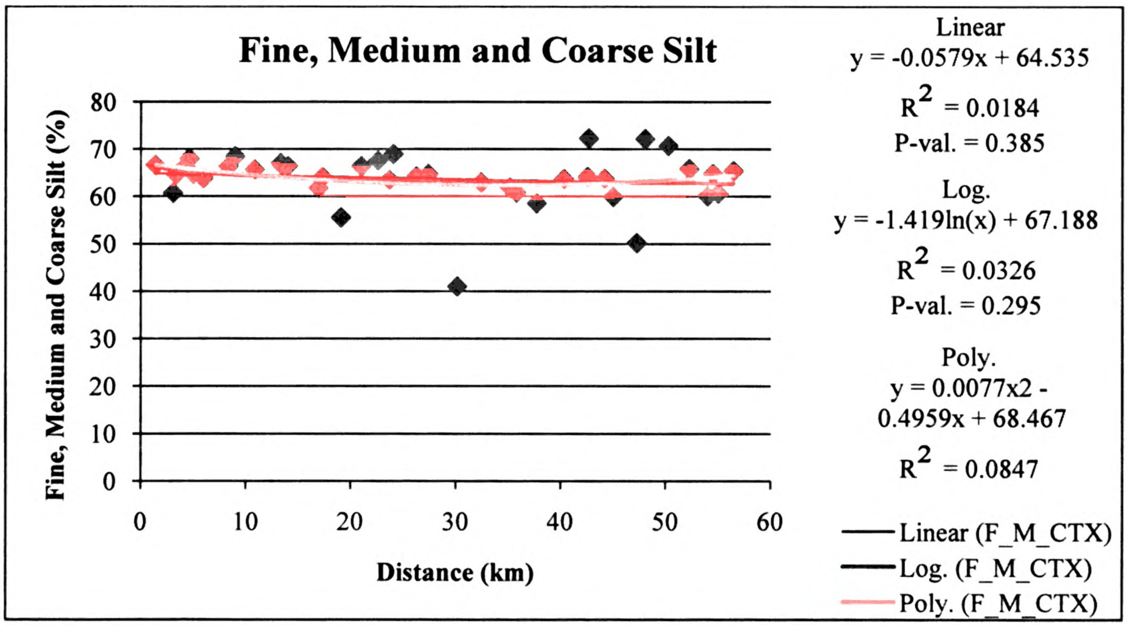

Figure A.2. Scatterplot of fine, medium and coarse silt content from north-central Wisconsin transects 1 and 2

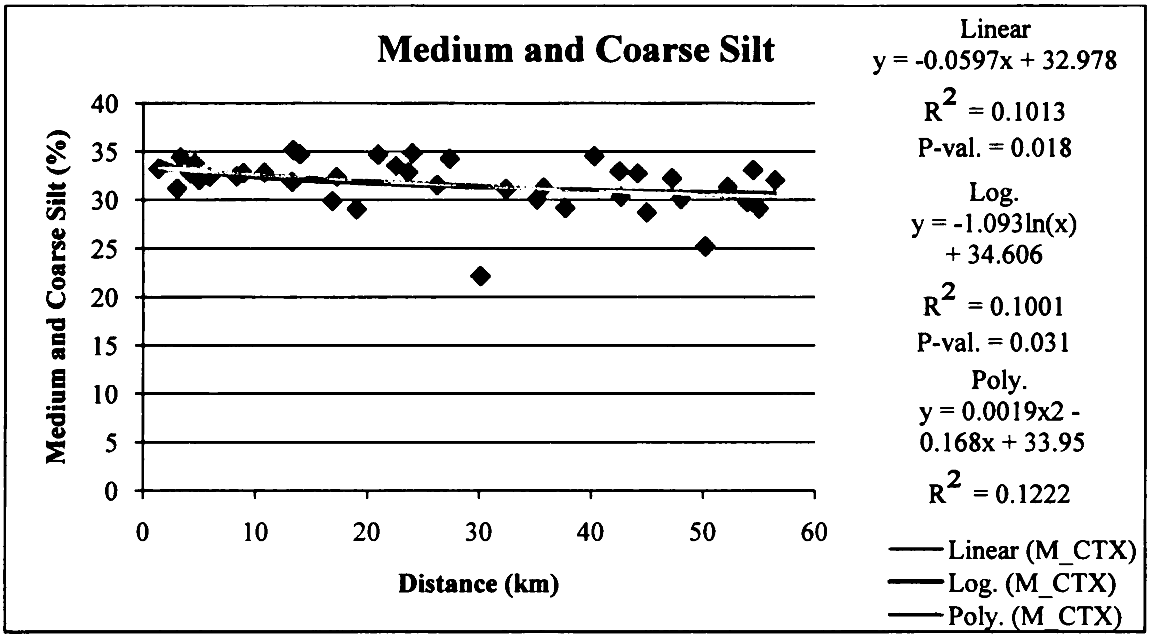

Figure A.3. Scatterplot of medium and coarse silt content from north-central Wisconsin transect 1 and 2

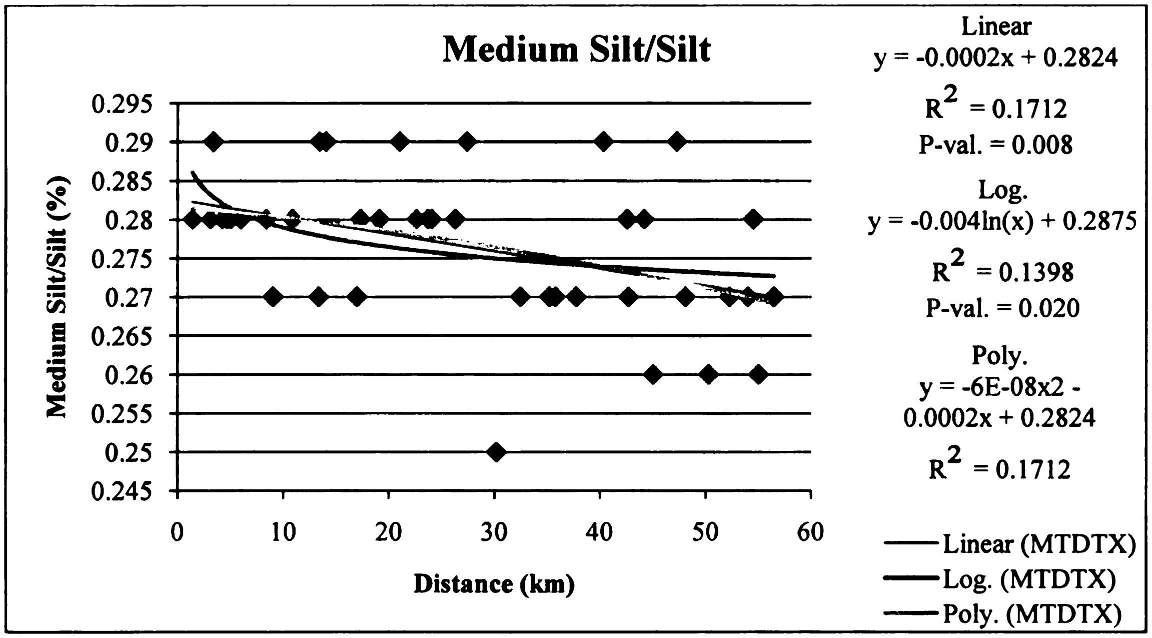

Figure A.4. Scatterplot of medium silt/silt content from north-central Wisconsin transects 1 and 2

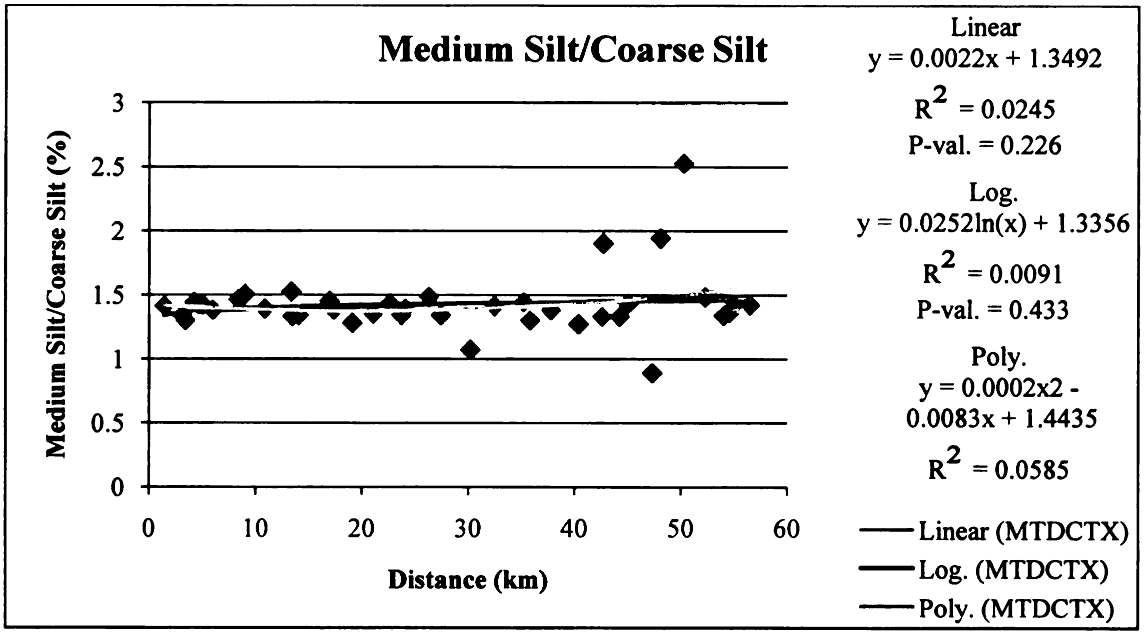

Figure A.5. Scatterplot of medium silt/coarse silt from north-central Wisconsin transects 1 and 2

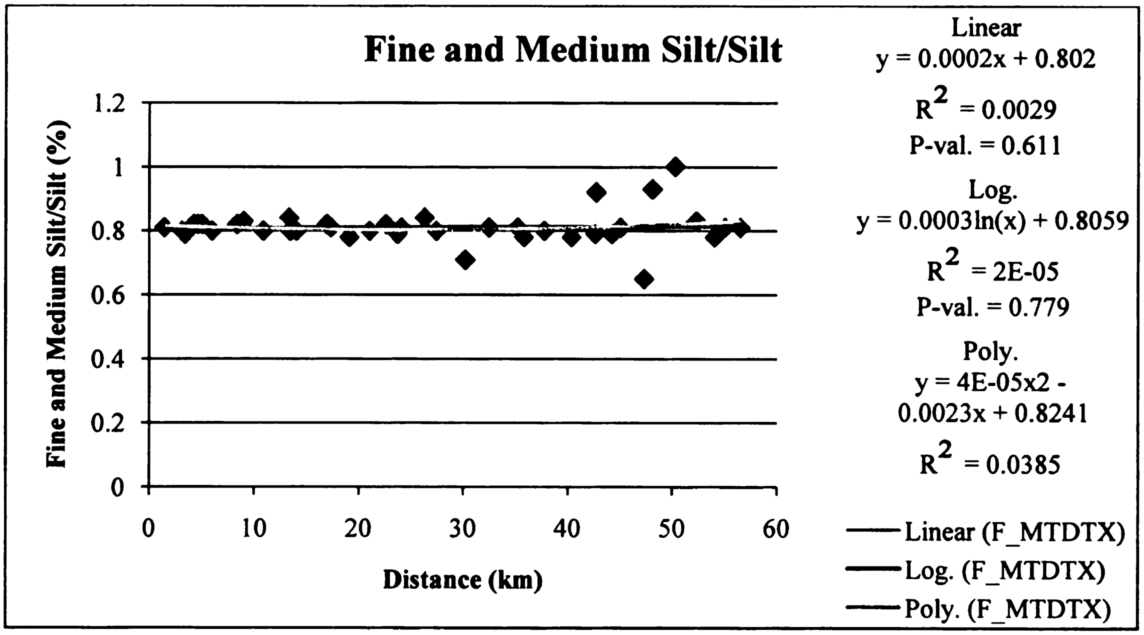

Figure A.6. Scatterplot of fine and medium silt/silt from north-central Wisconsin transects 1 and 2

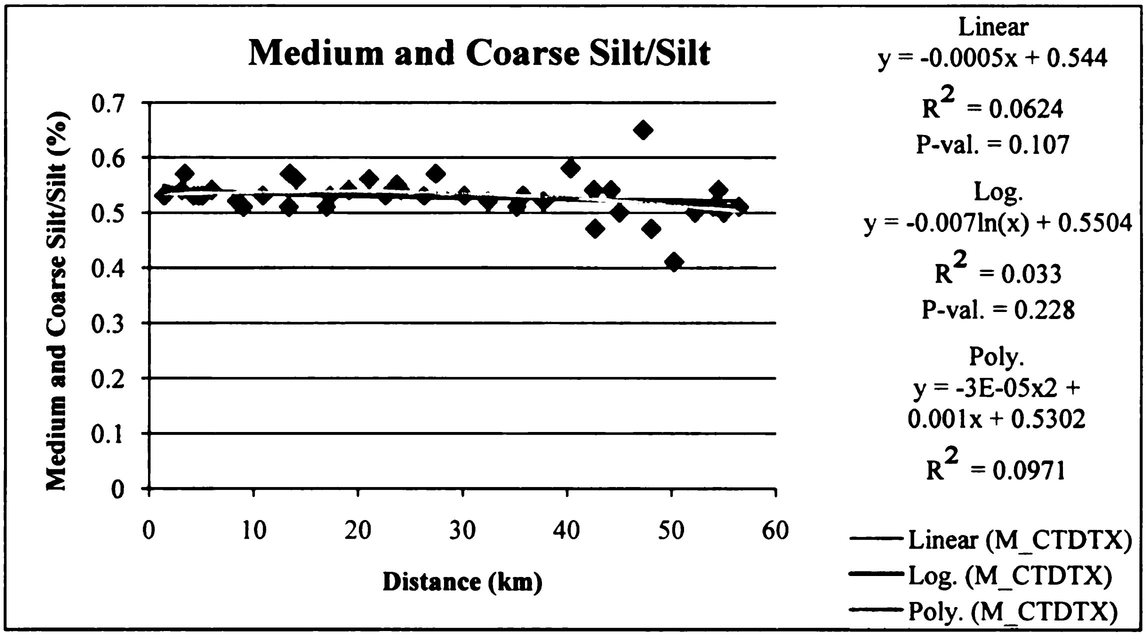

Figure A.7. Scatterplot of medium and coarse silt/silt contents from north-central Wisconsin transects 1 and 2

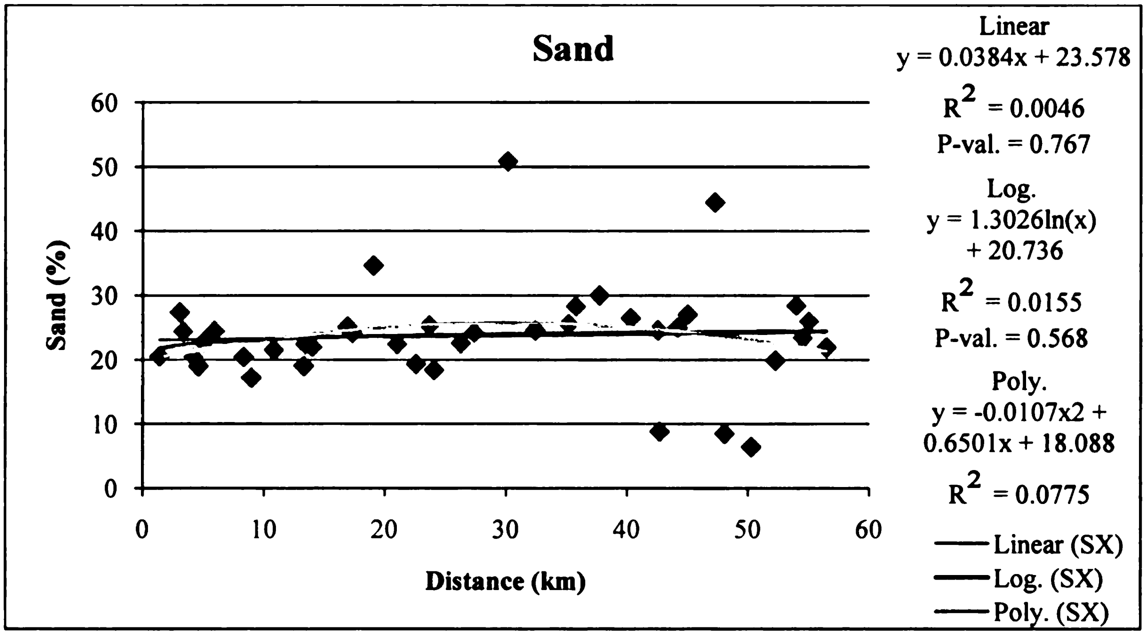

Figure A.8. Scatterplot of sand content from north-central Wisconsin transects 1 and 2

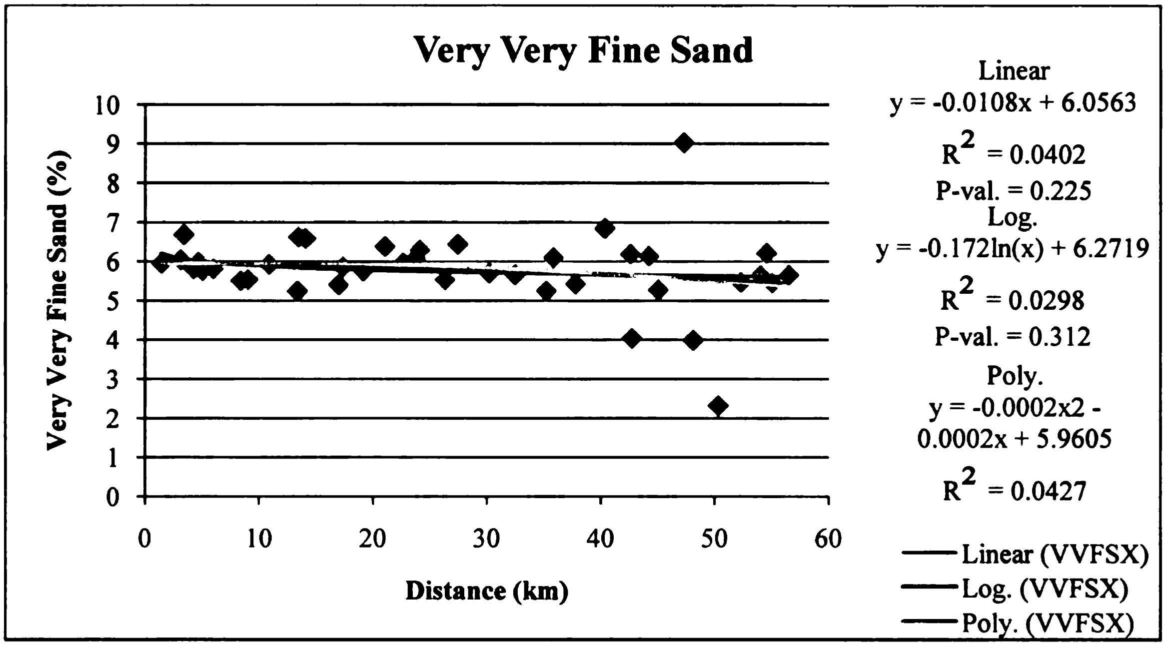

Figure A.9. Scatterplot of very-very fine sand content from north-central Wisconsin transects 1 and 2

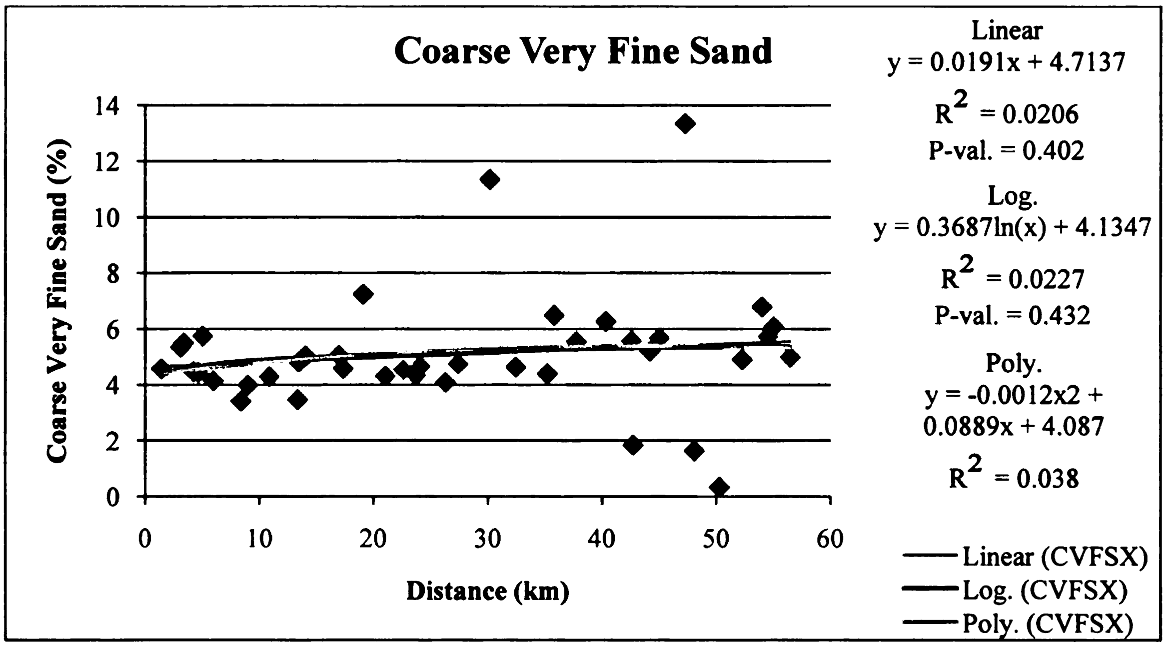

Figure A.10. Scatterplot of coarse very fine sand contents from north-central Wisconsin transects 1 and 2

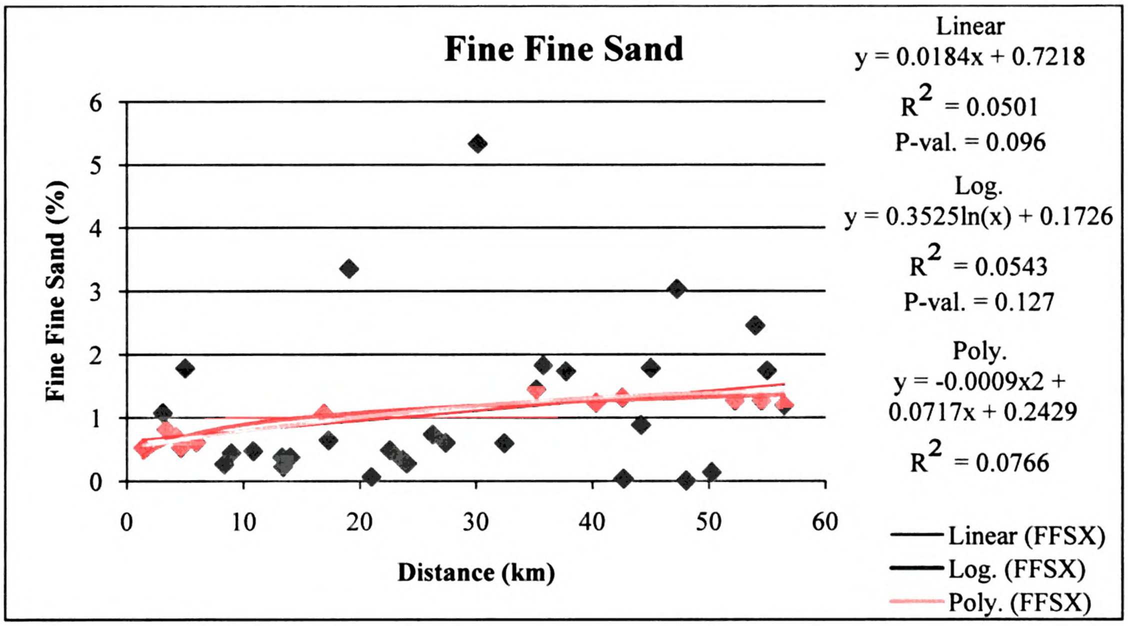

Figure A.11. Scatterplot of fine-fine sand content from north-central Wisconsin transects 1 and 2

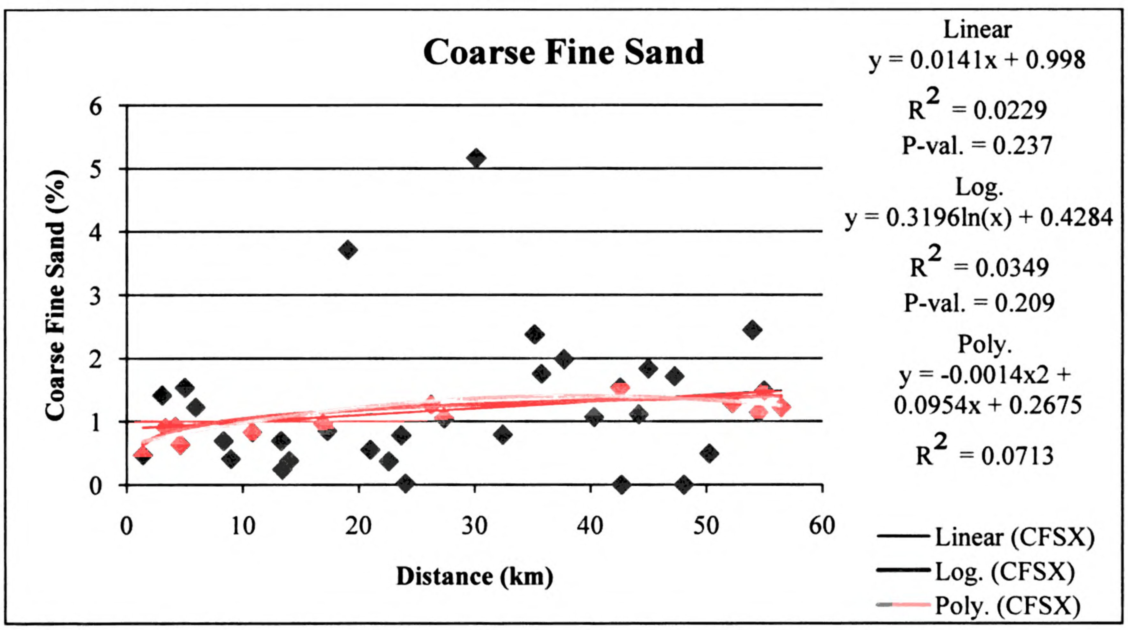

Figure A.12. Scatterplot of coarse fine sand content from north-central Wisconsin transects 1 and 2

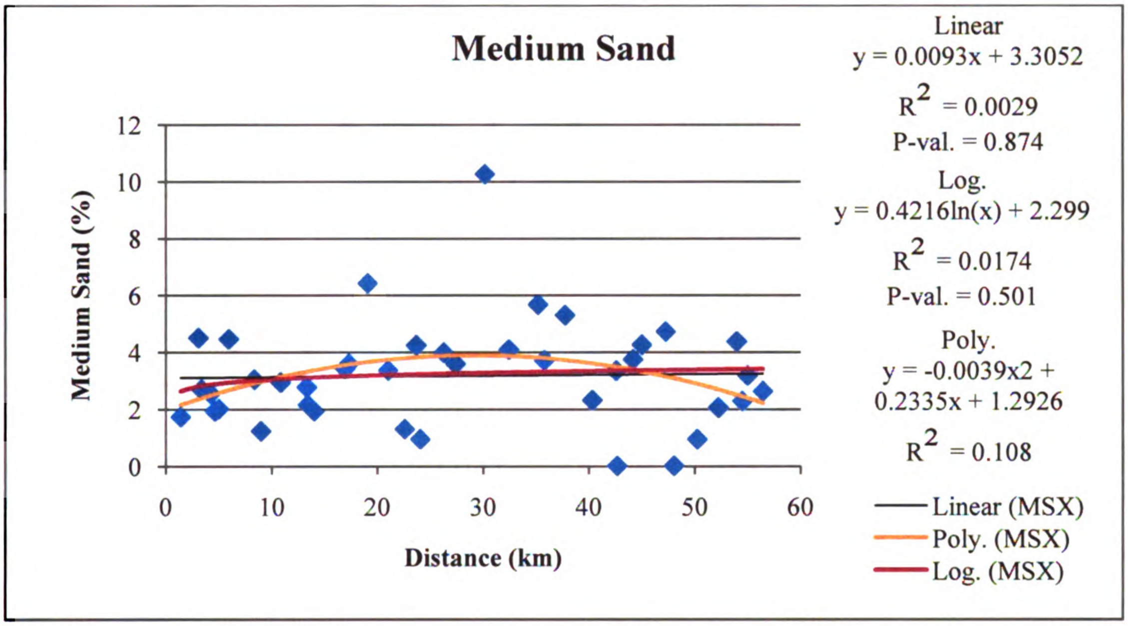

Figure A.13. Scatterplot of medium sand content from north-central Wisconsin transects 1 and 2

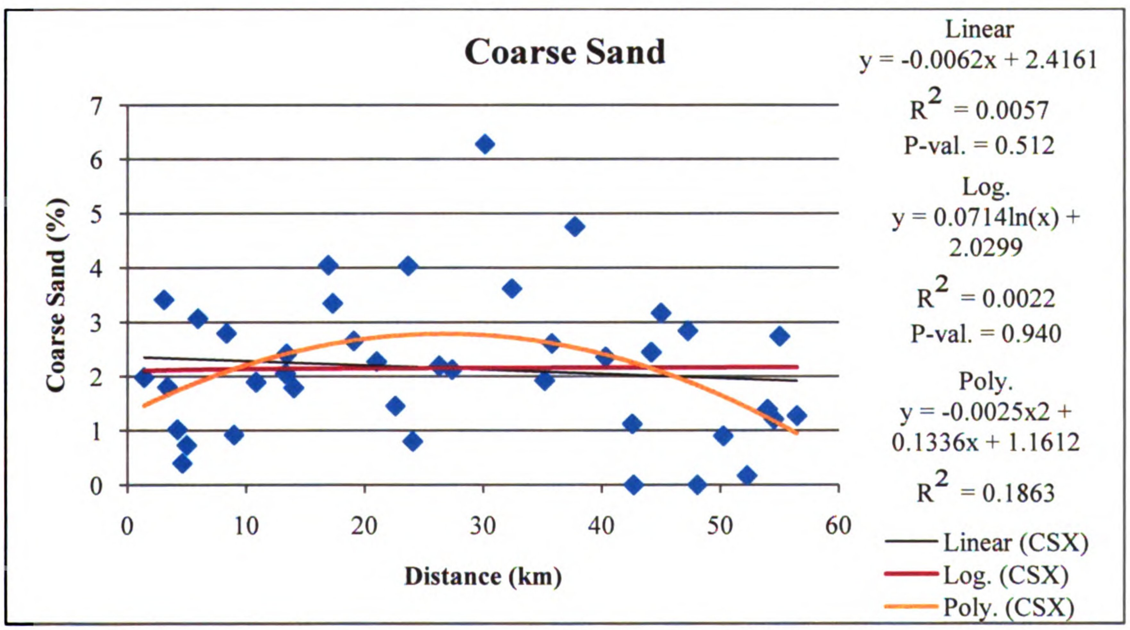

Figure A.14. Scatterplot of coarse sand content from north-central Wisconsin transects 1 and 2

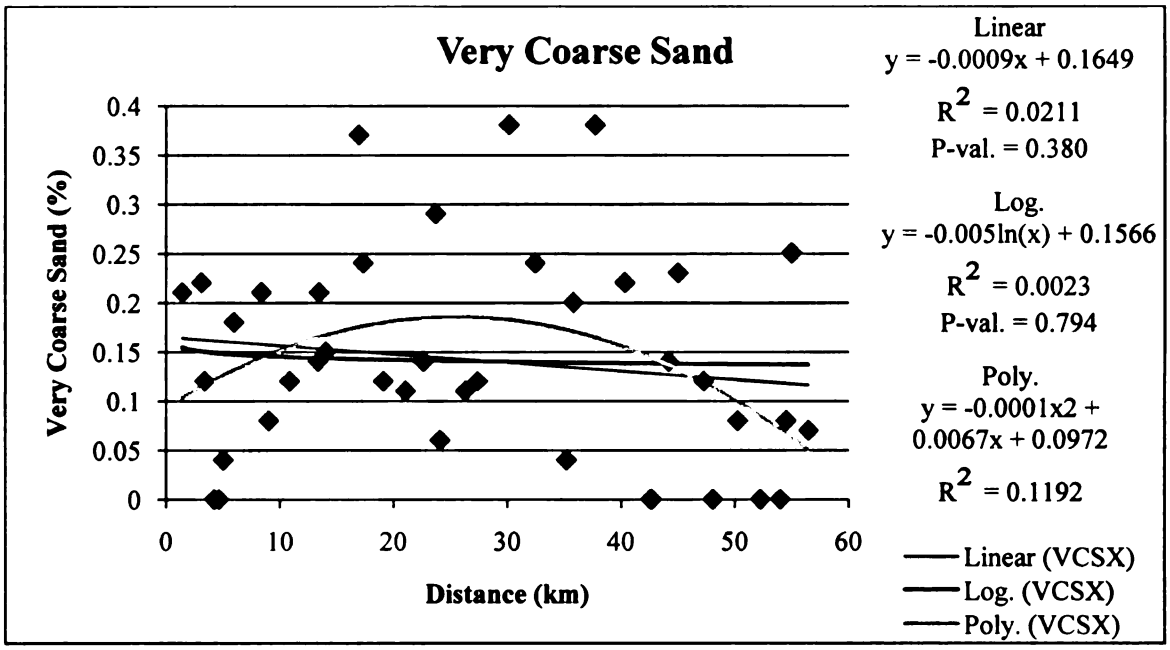

Figure A.15. Scatterplot of very coarse sand content from north-central Wisconsin transects 1 and 2

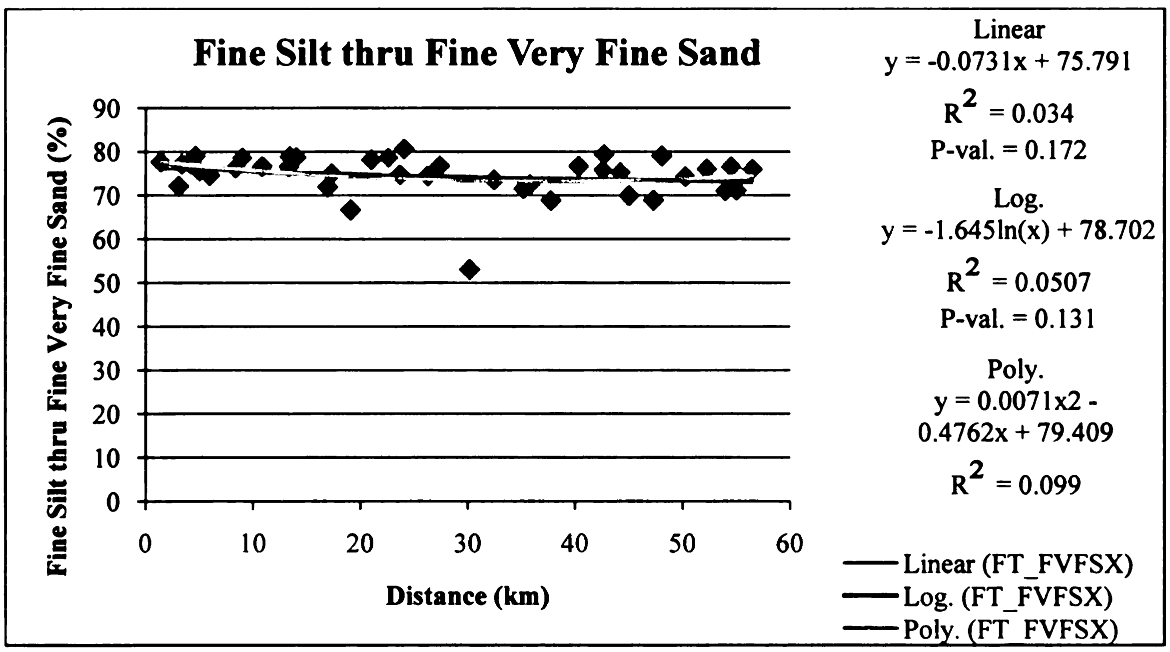

Figure A.16. Scatterplot of fine silt thru very fine sand contents from north-central Wisconsin transects 1 and 2

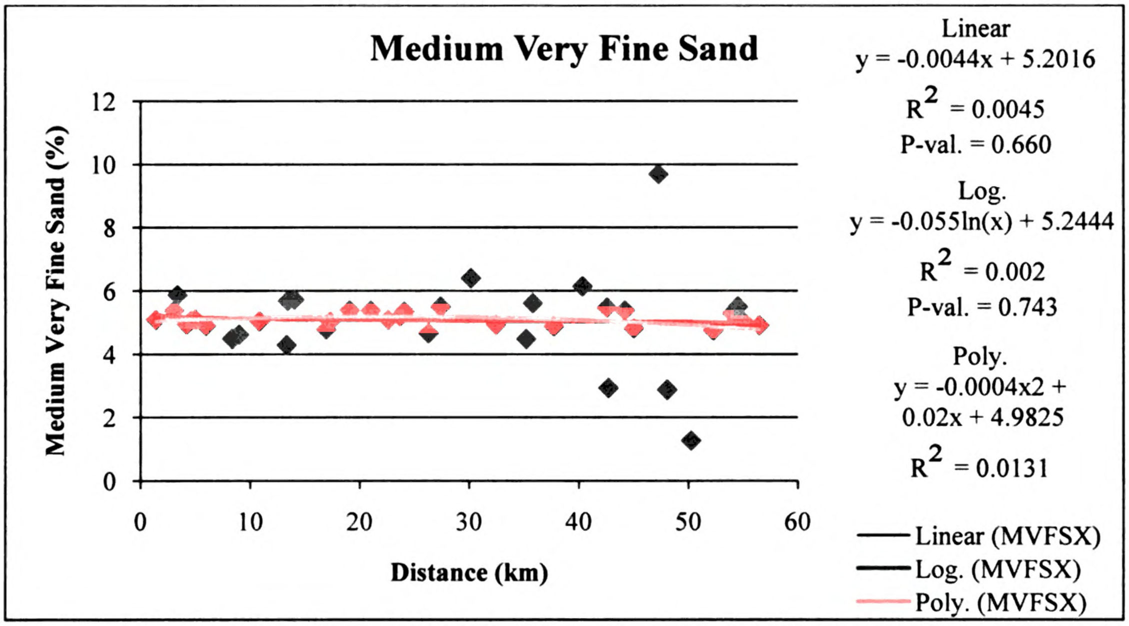

Figure A.17. Scatterplot of medium very fine sand content from north-central Wisconsin transect 1 and 2

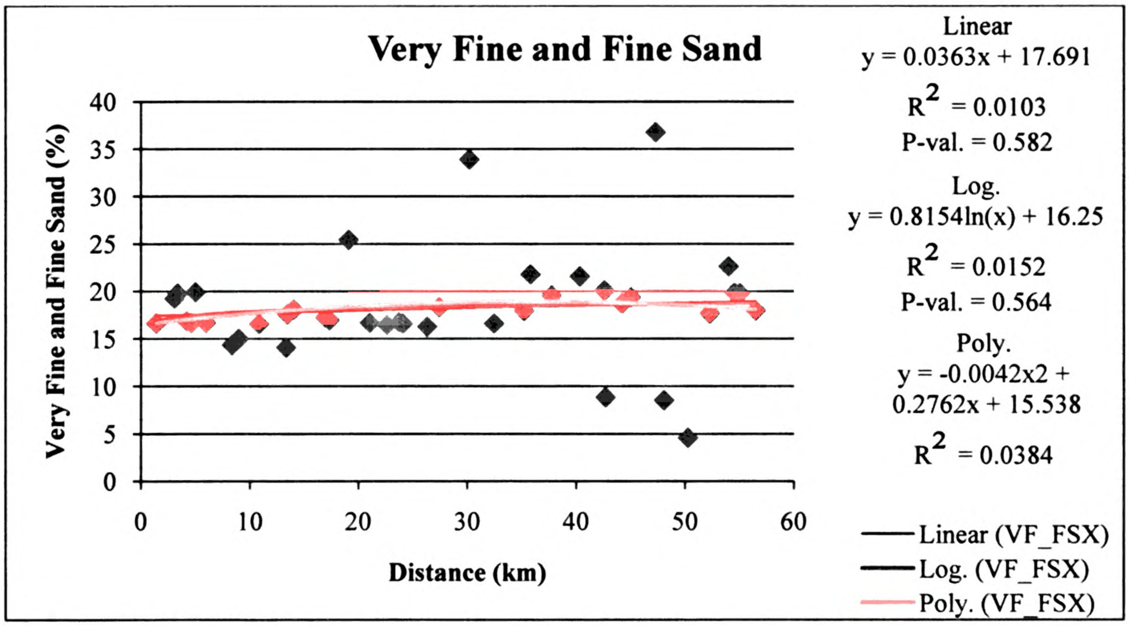

Figure A.18. Scatterplot of very fine and fine sand content from north-central Wisconsin transect 1 and 2

North-central Wisconsin transect 1 & 2

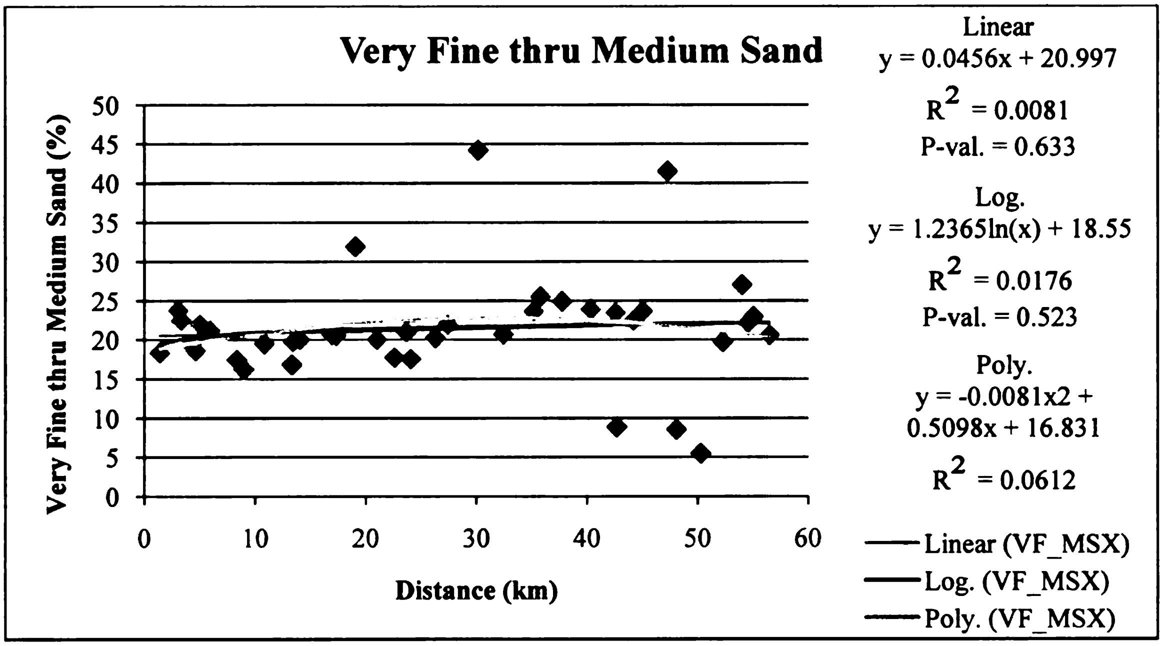

Figure A.19. Scatterplot of very fine thru medium sand content from north-central Wisconsin transect 1 and 2

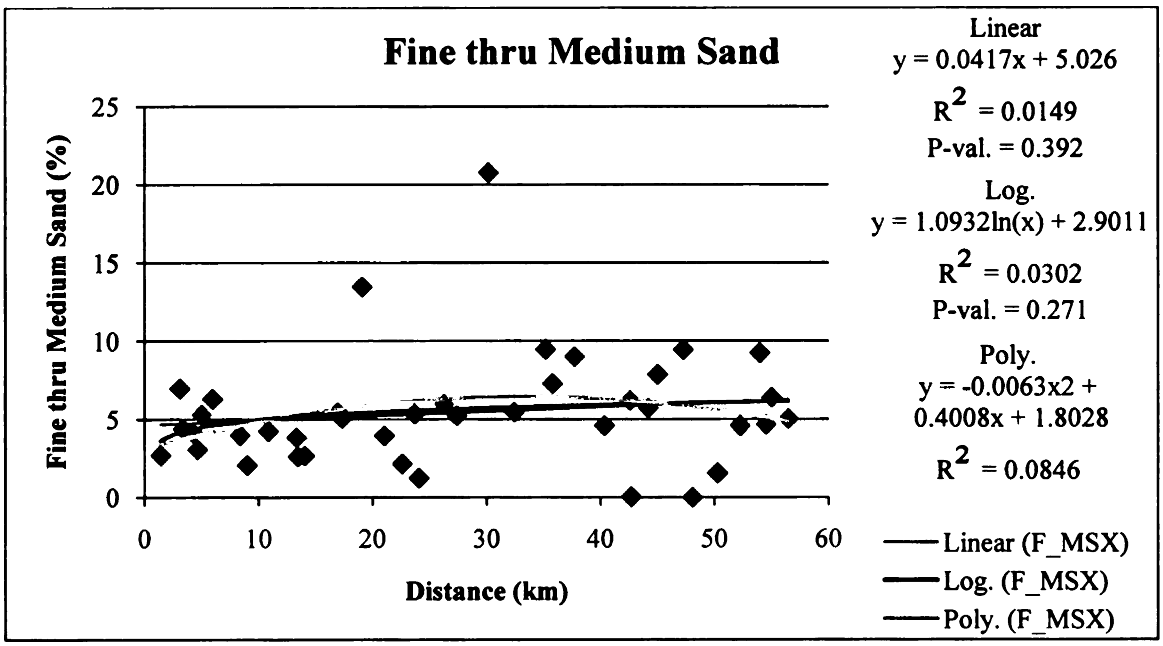

Figure A.20. Scatterplot of fine thru medium sand content from north-central Wisconsin transect 1 and 2

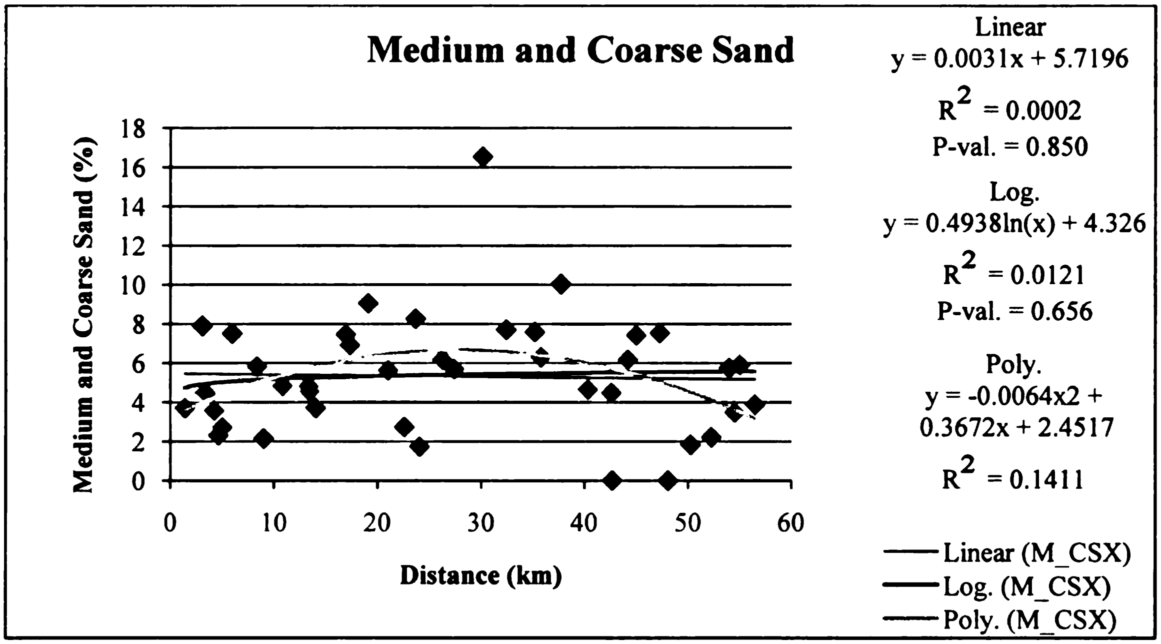

Figure A.21. Scatterplot of medium and coarse sand content from north-central Wisconsin transect 1 and 2

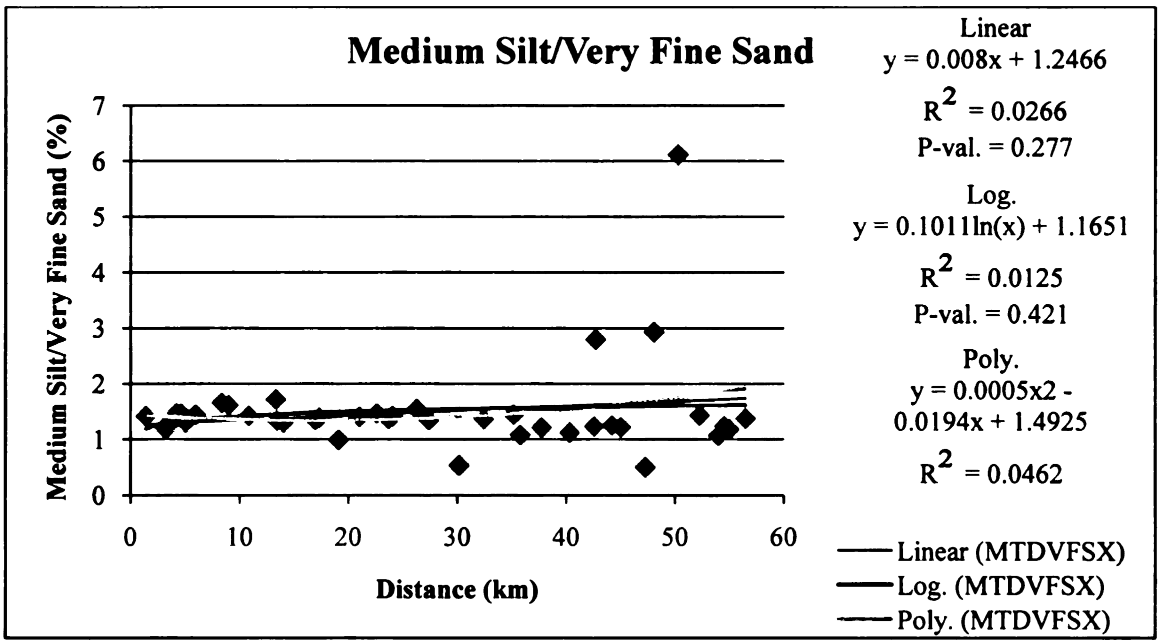

Figure A.22. Scatterplot of medium silt/very fine sand content from central-Wisconsin transect 1 and 2

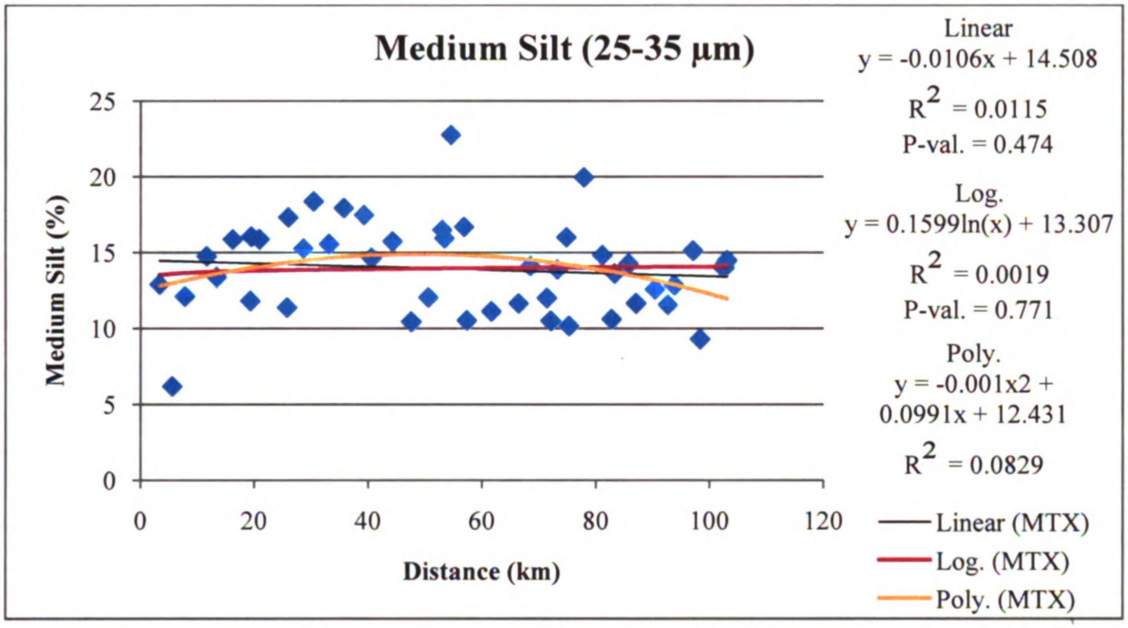

Figure A.23. Scatterplot of medium silt content from Iron County transect 1

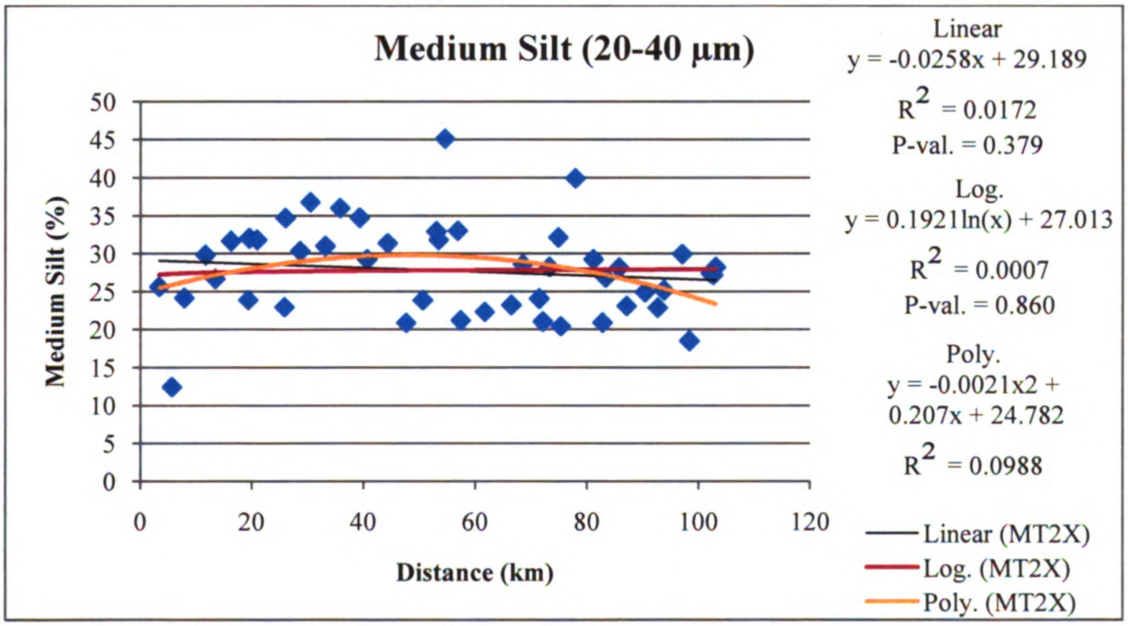

Figure A.24. Scatterplot of medium silt content from Iron County transect 1

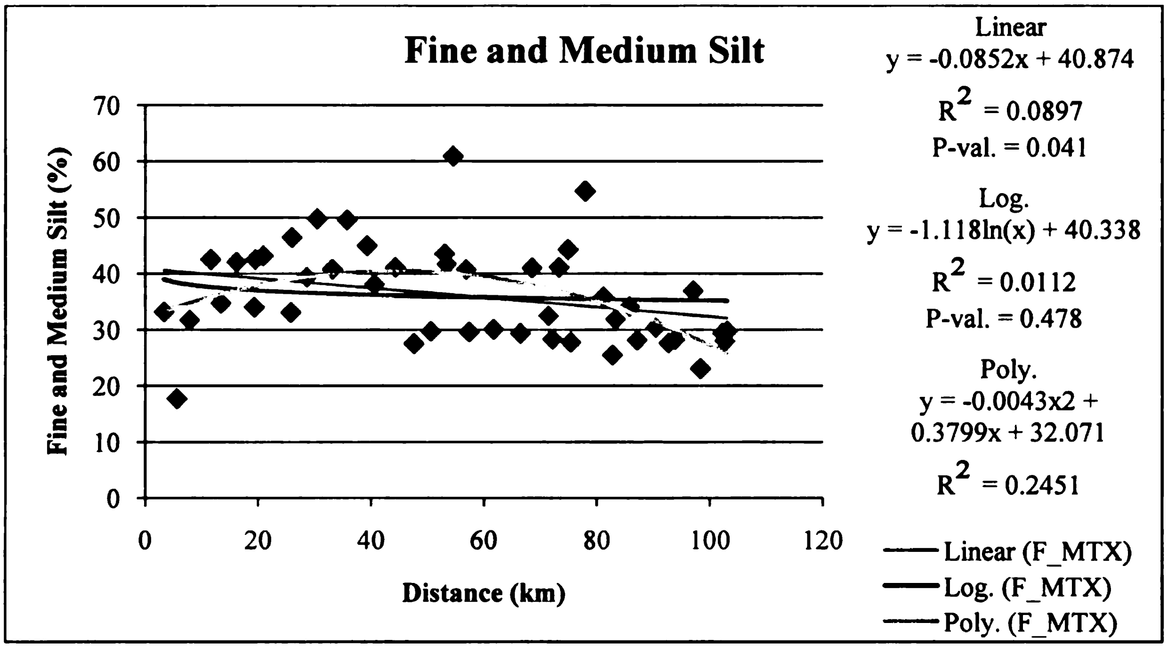

Figure A.25. Scatterplot of fine and medium silt content from Iron County transect 1

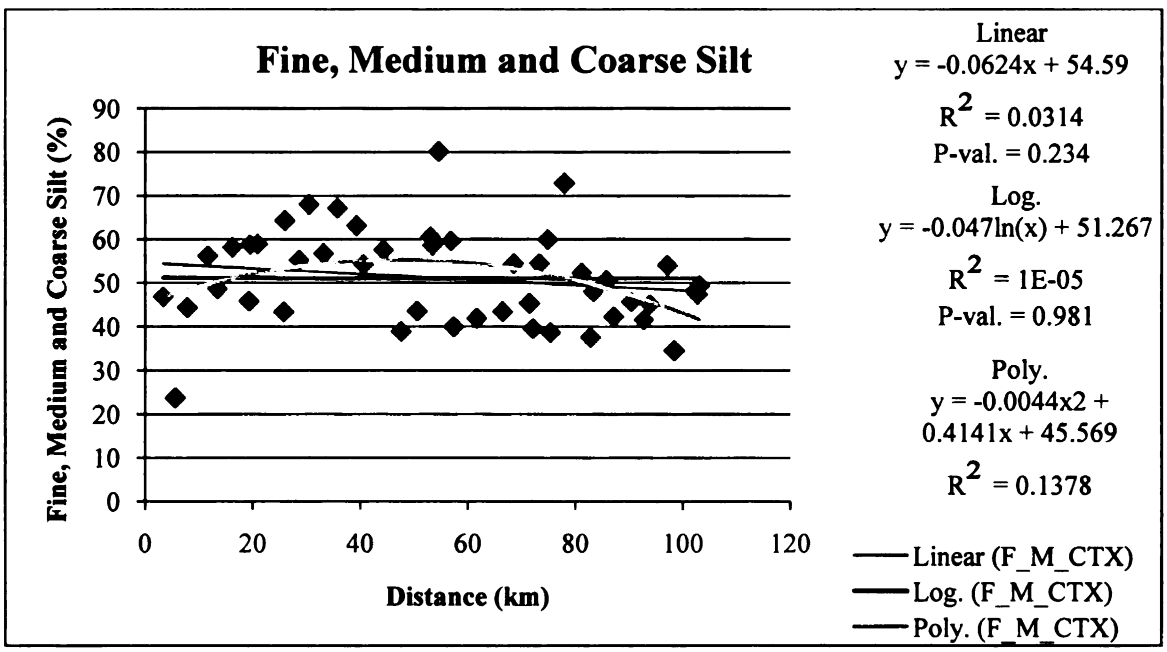

Figure A.26. Scatterplot of fine, medium and coarse silt content from Iron County transect 1

Iron County Transect 1

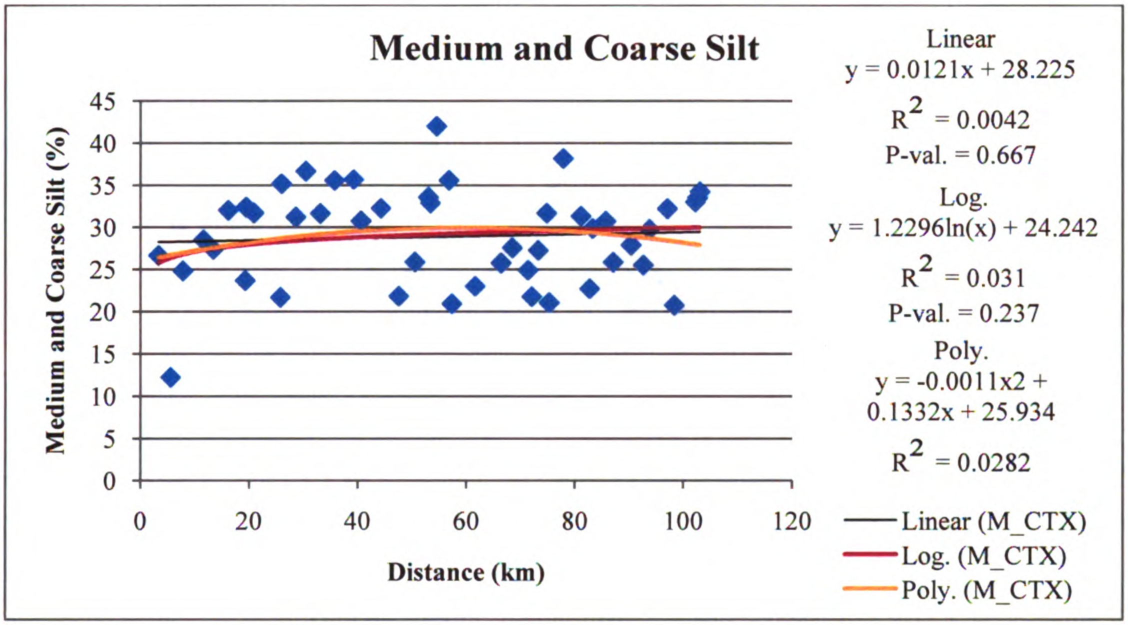

Figure A.27. Scatterplot of medium and coarse silt content from Iron County transect 1

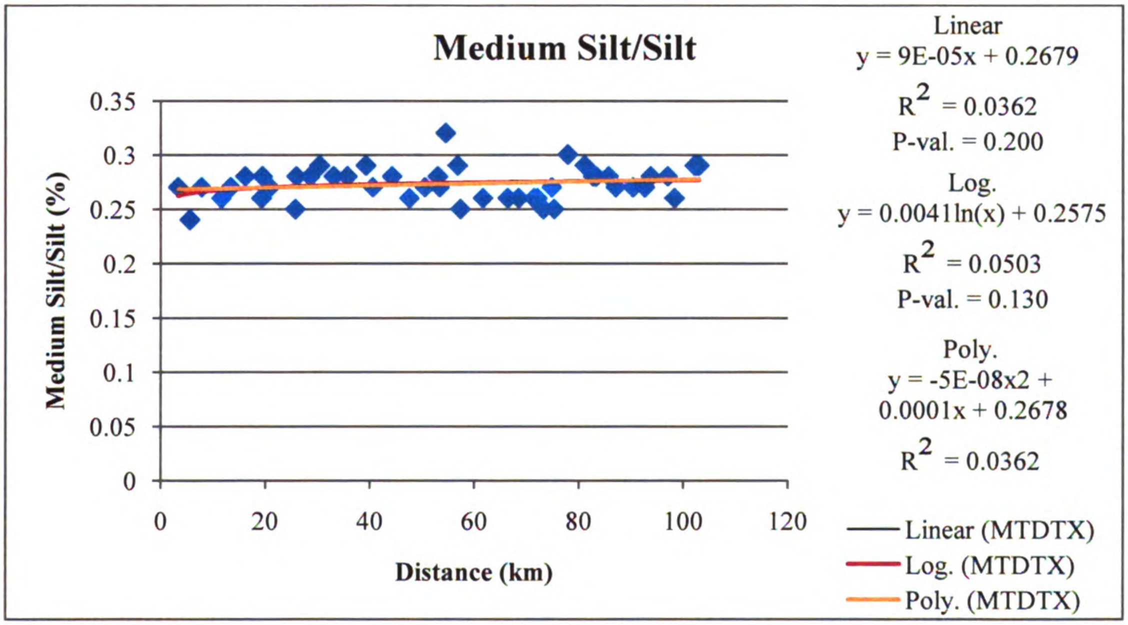

Figure A.28. Scatterplot of medium silt/silt content from Iron County transect 1

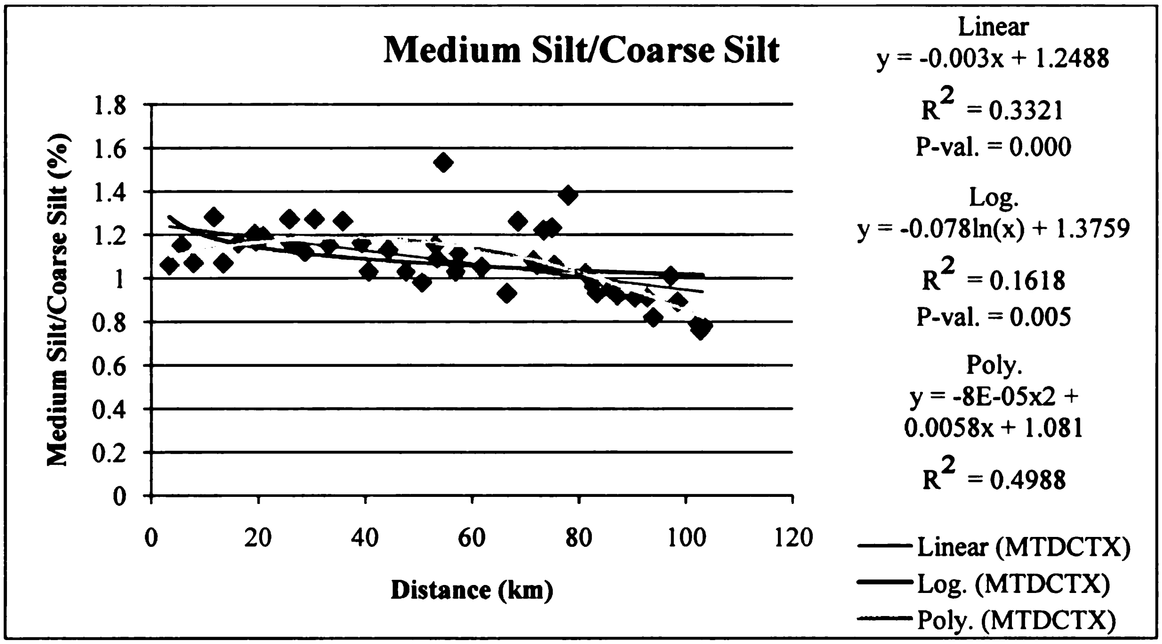

Figure A.29. Scatterplot of medium silt/coarse silt content from Iron County transect 1

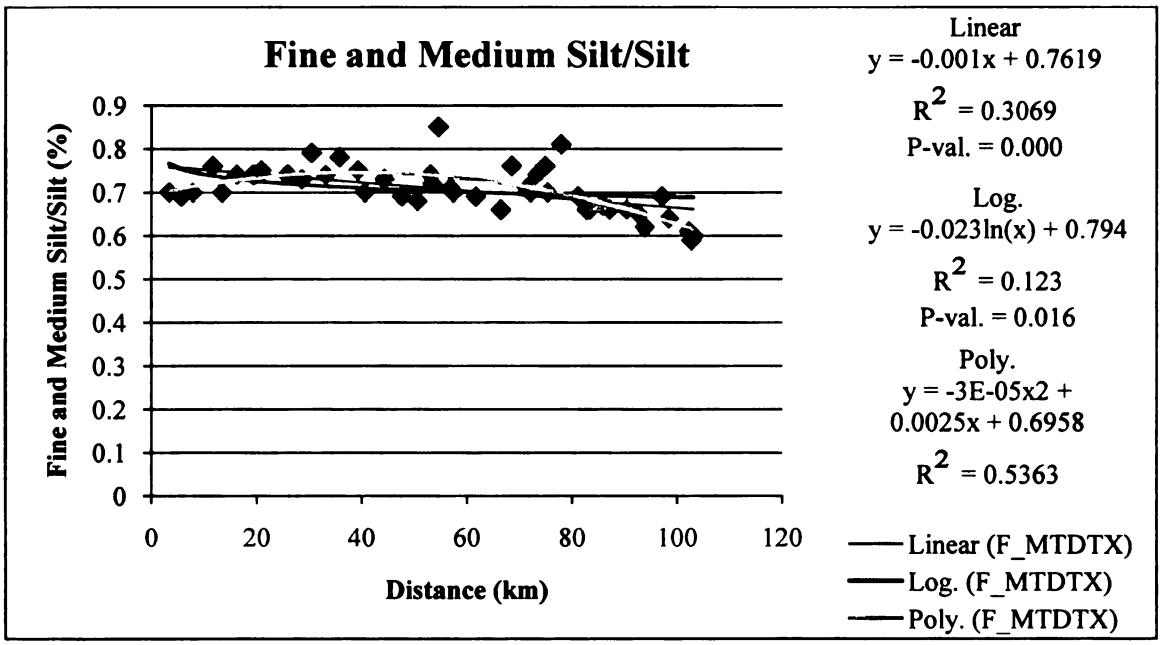

Figure A.30. Scatterplot of fine and medium silt/silt from Iron County transect 1

Iron County Transect 1

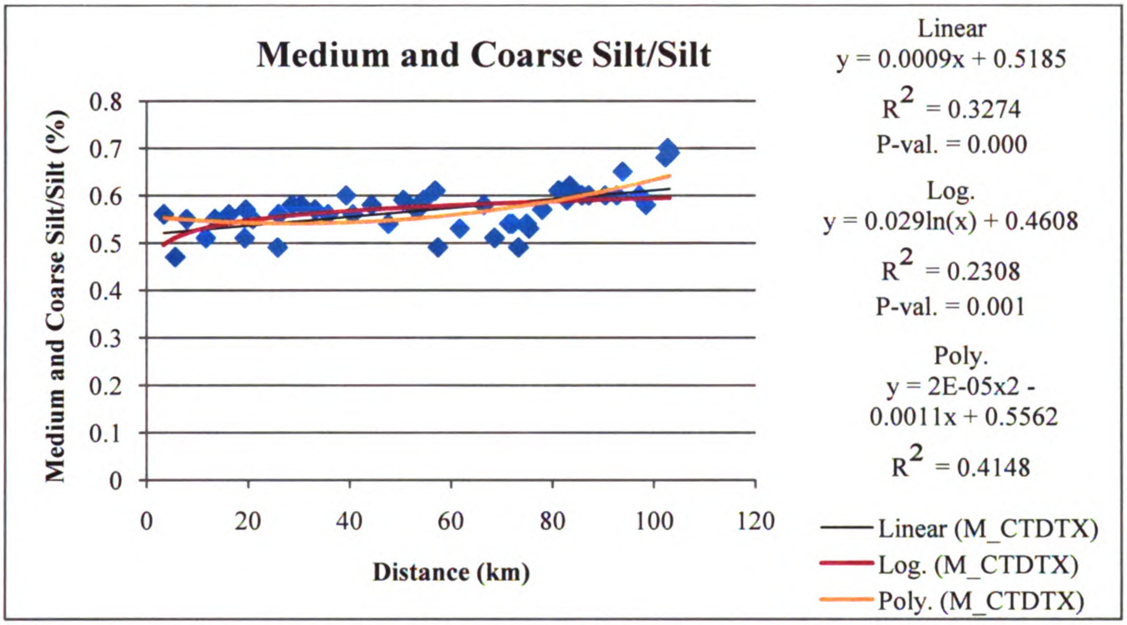

Figure A.31. Scatterplot of medium and coarse silt/silt from Iron County transect 1

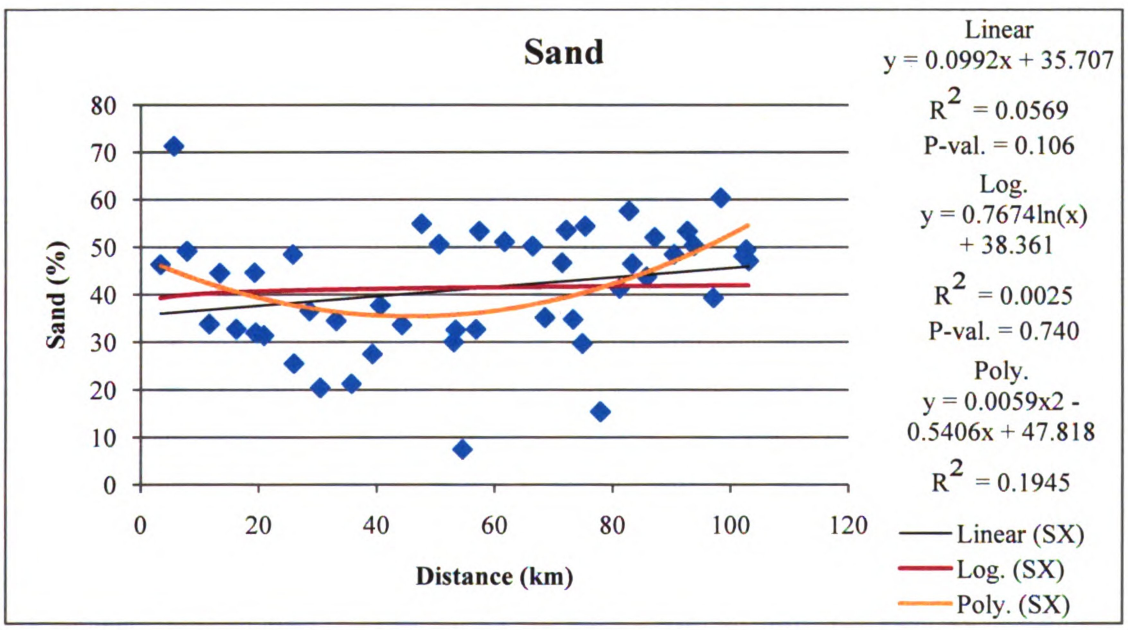

Figure A.32. Scatterplot of sand content from Iron County transect 1

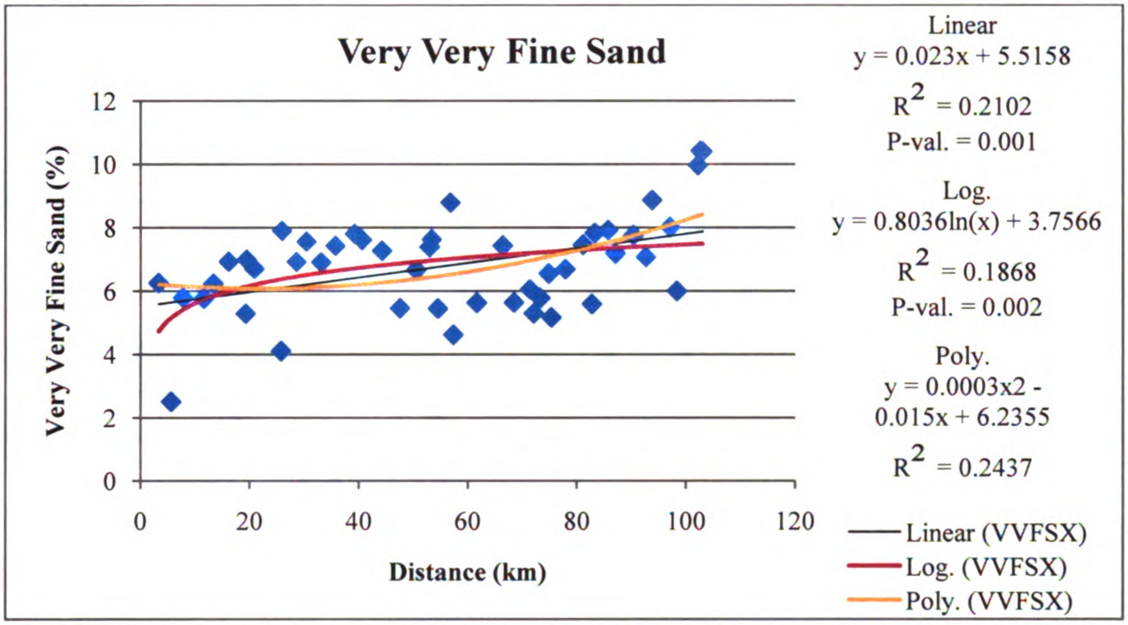

Figure A.33. Scatterplot of very-very fine sand content from Iron County transect 1

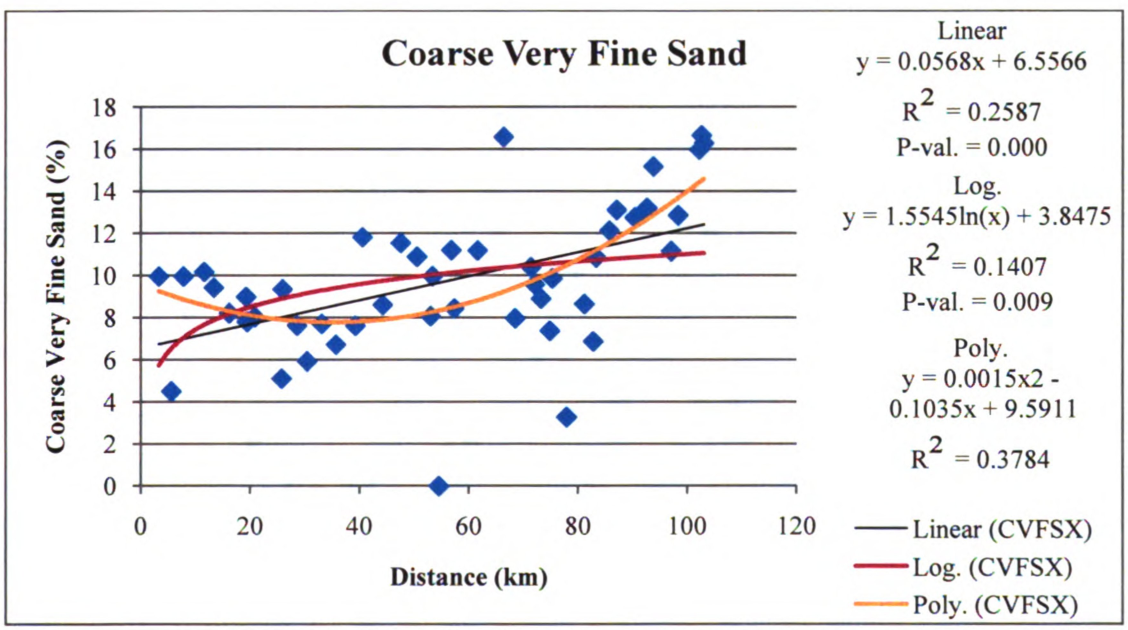

Figure A.34. Scatterplot of coarse very fine sand content from Iron County transect 1

Iron County Transect 1

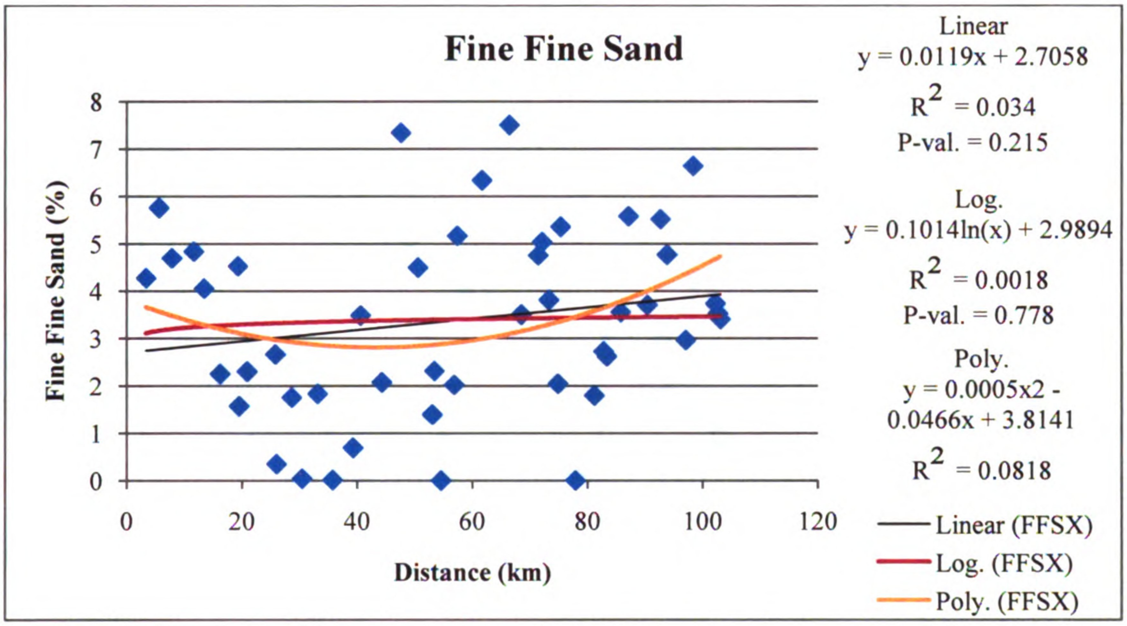

Figure A.35. Scatterplot of fine-fine sand content from Iron County transect 1

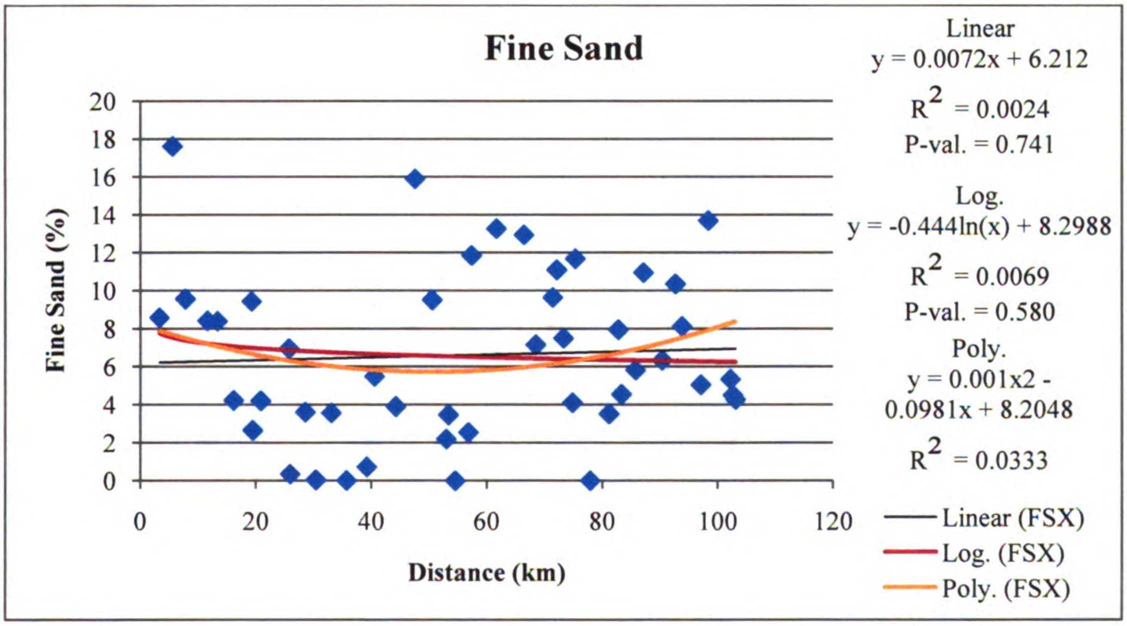

Figure A.36. Scatterplot of fine sand content from Iron County transect 1

Iron County Transect 1

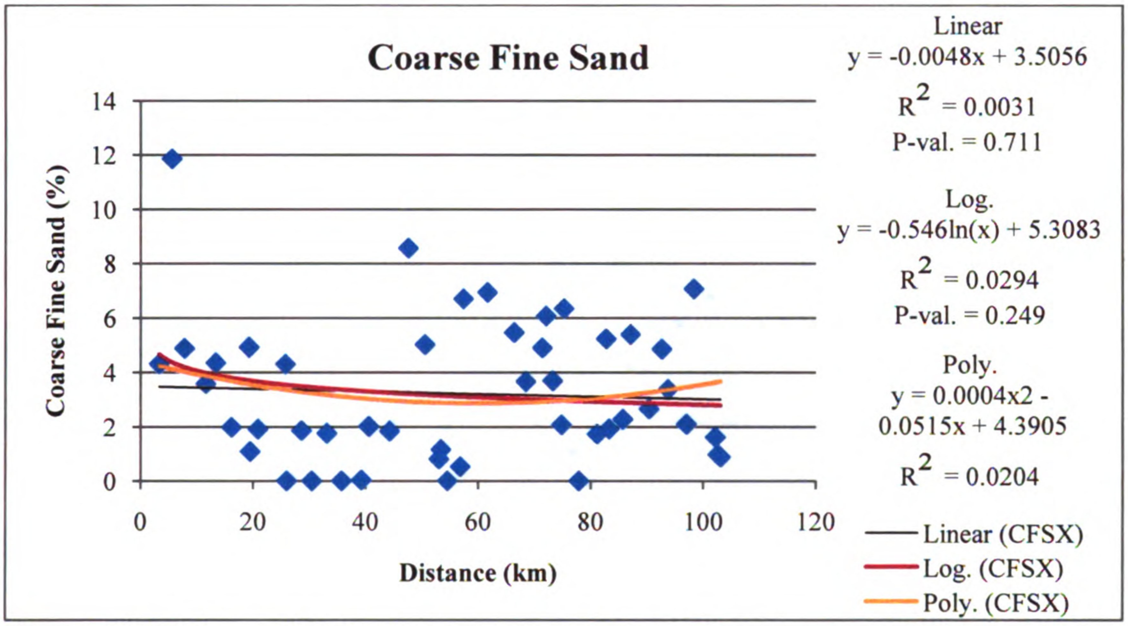

Figure A.37. Scatterplot of coarse fine sand content from Iron County transect 1

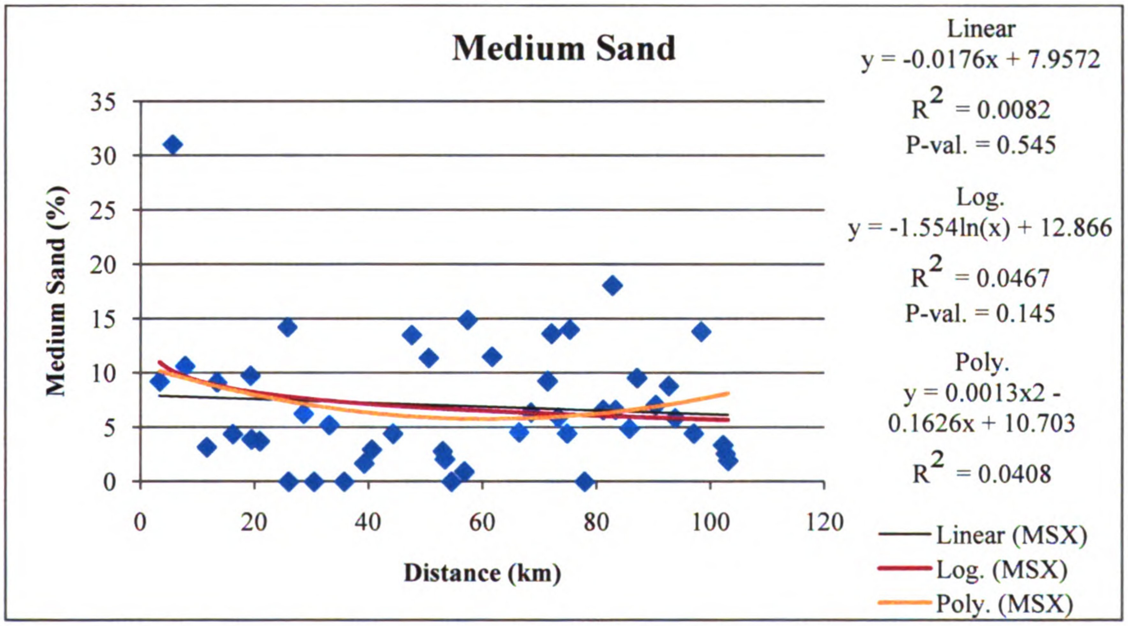

Figure A.38. Scatterplot of medium sand content from Iron County transect 1

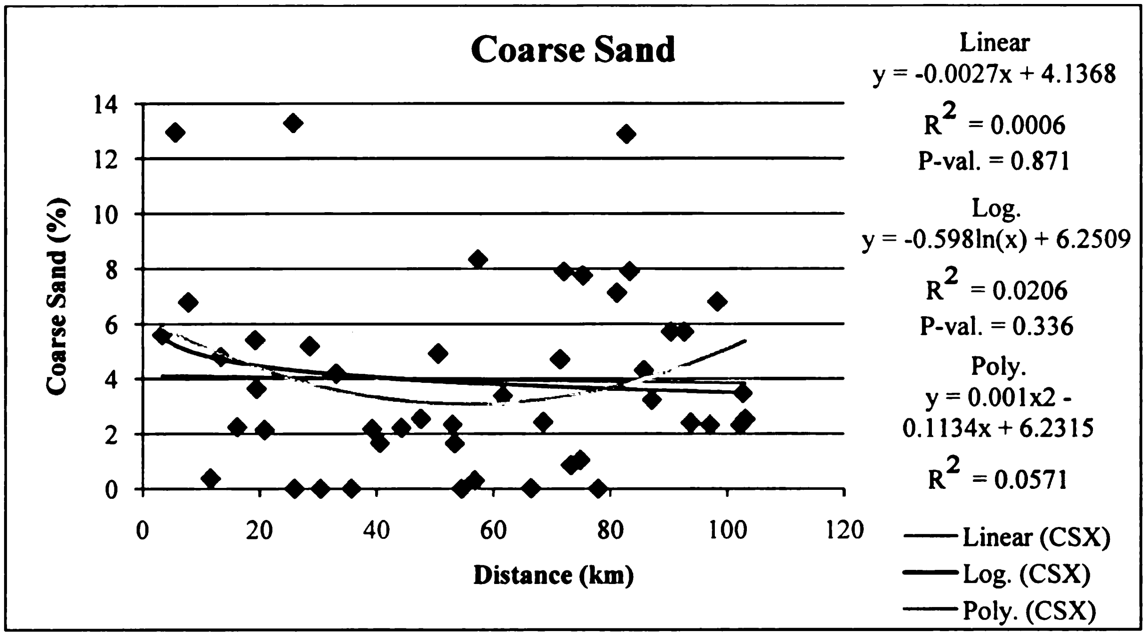

Figure A.39. Scatterplot of coarse sand content from Iron County transect 1

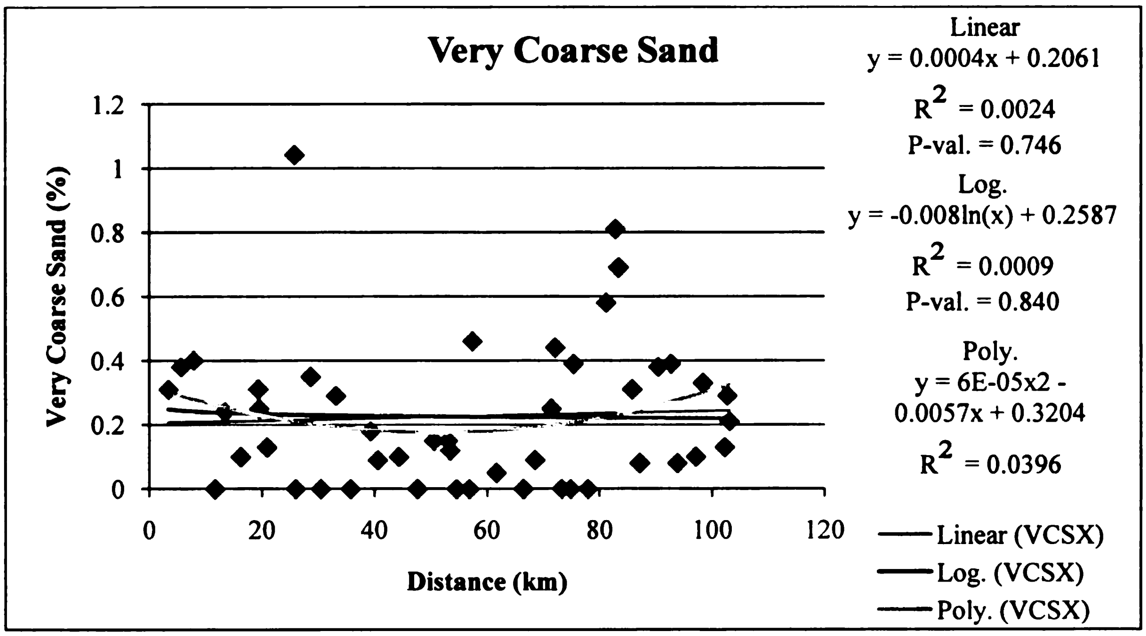

Figure A.40. Scatterplot of very coarse sand content from Iron County transect 1

Iron County Transect 1

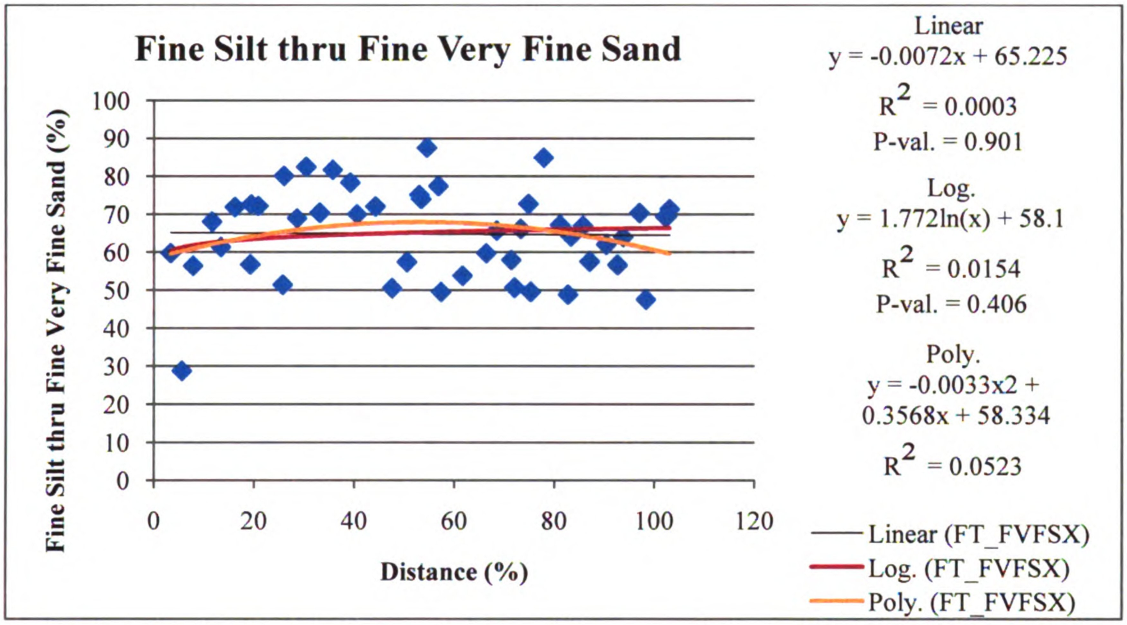

Figure A.41. Scatterplot of fine silt thru fine very fine sand content from Iron County transect 1

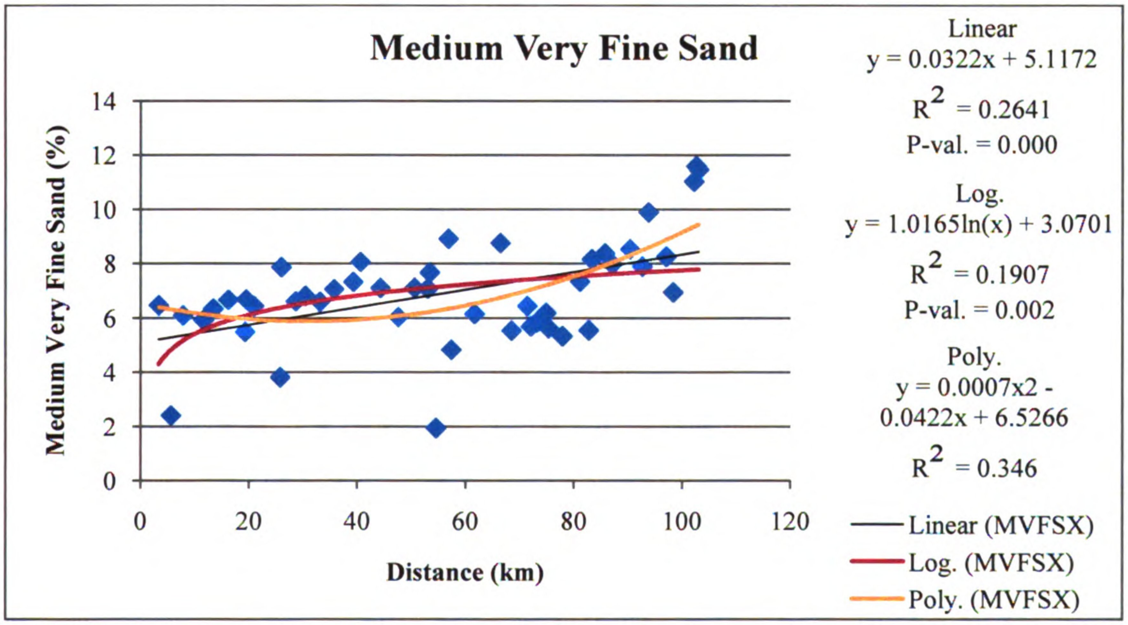

Figure A.42. Medium very fine sand content from Iron County transect 1

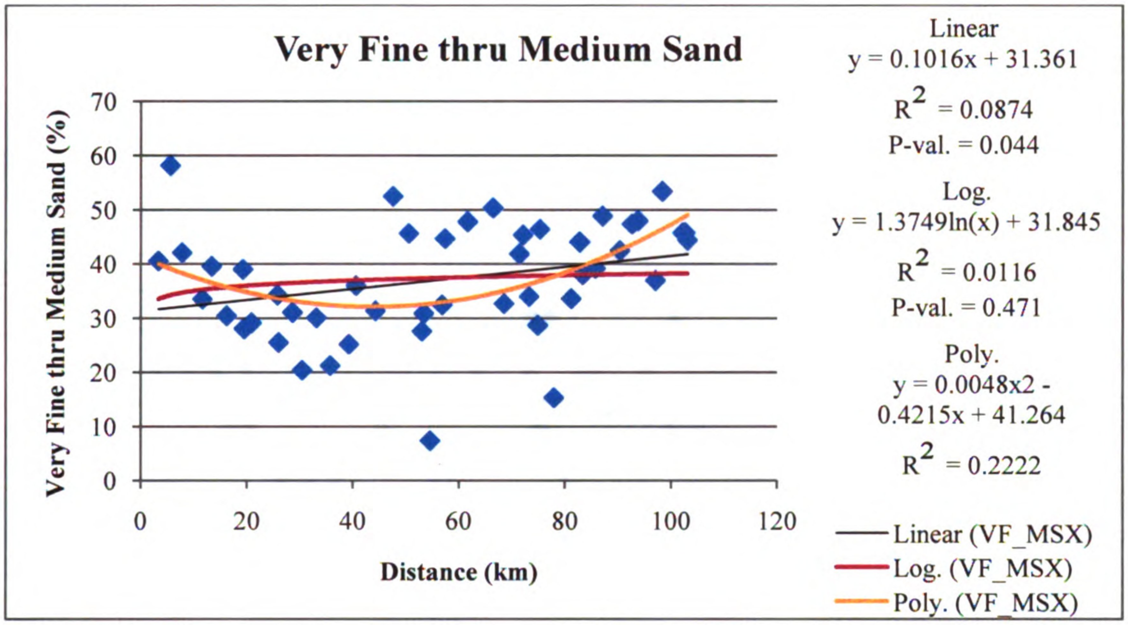

Figure A.43. Scatterplot of very fine thru medium sand content from Iron County transect 1

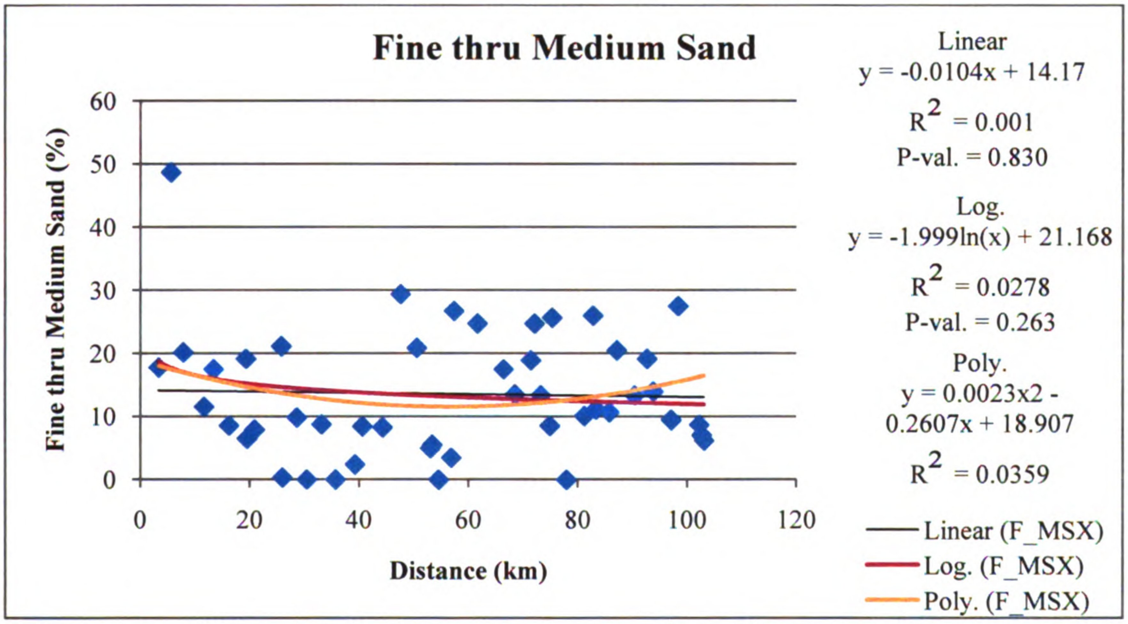

Figure A.44. Scatterplot of fine thru medium sand content from Iron County transect 1

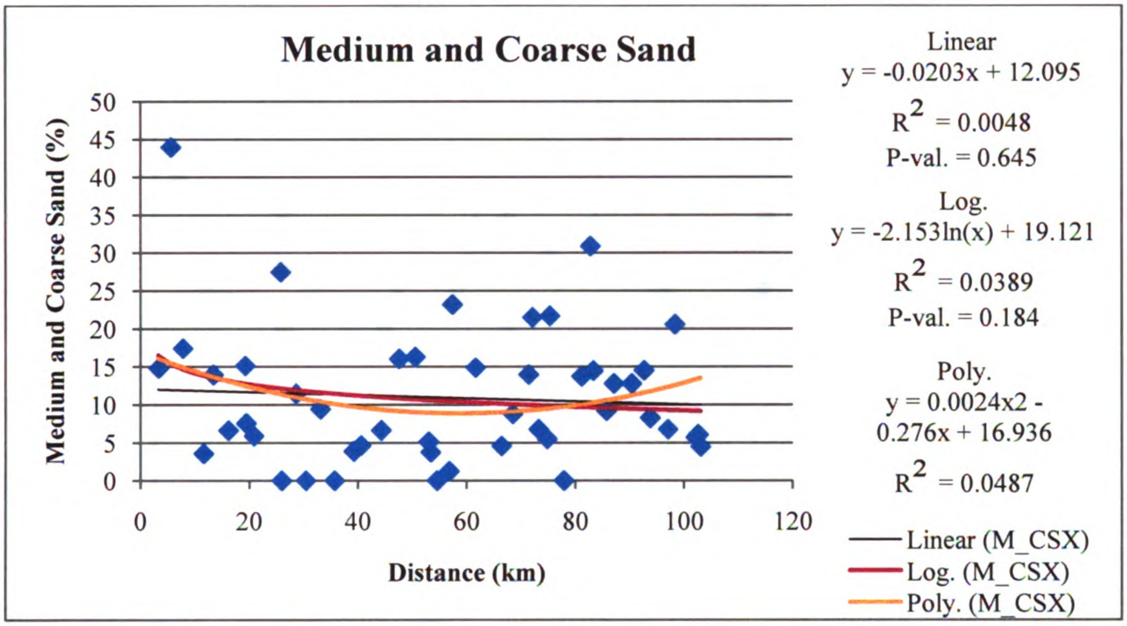

Figure A.45. Scatterplot of medium and coarse sand content from Iron County transect 1

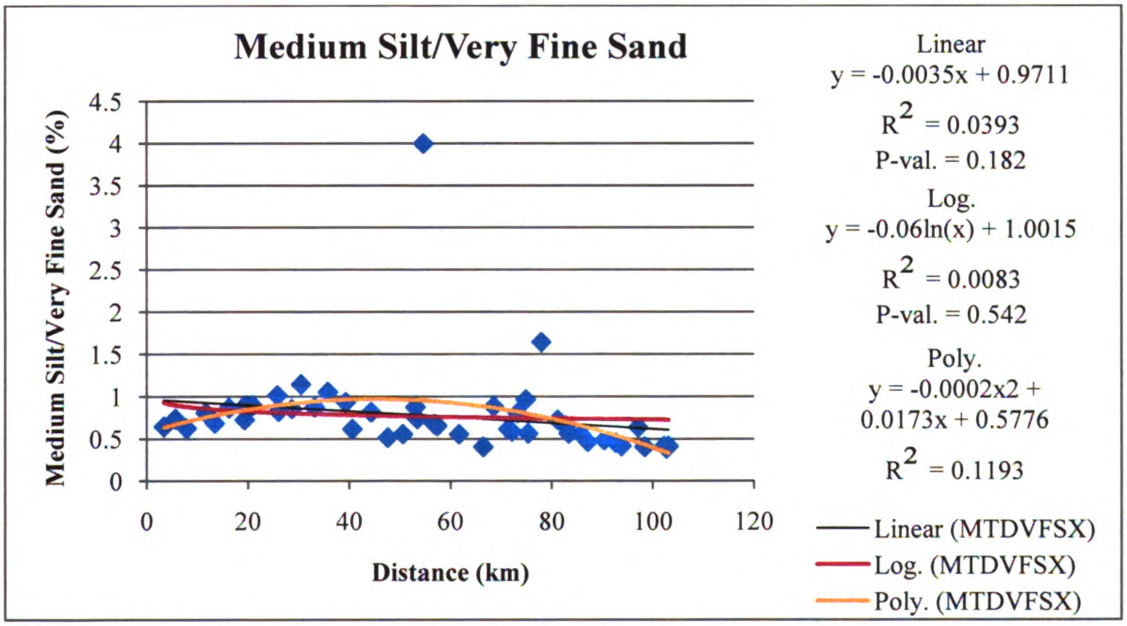

Figure A.46. Scatterplot of medium silt/very fine sand content from Iron County transect

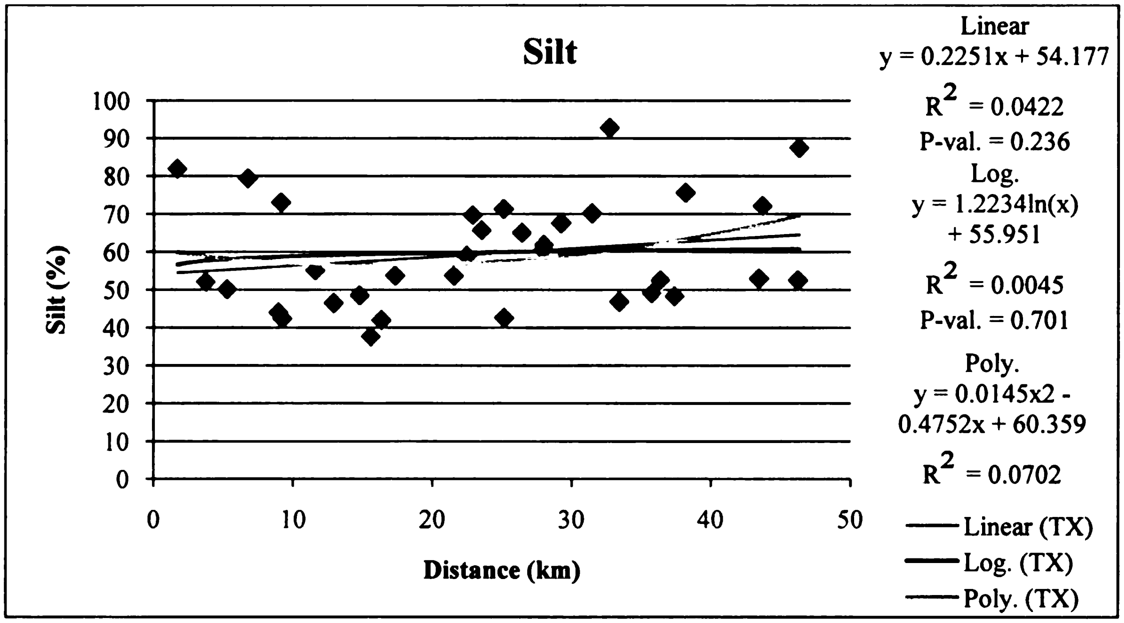

Figure A.47. Scatterplot of silt content from Iron County transects 2 and 3

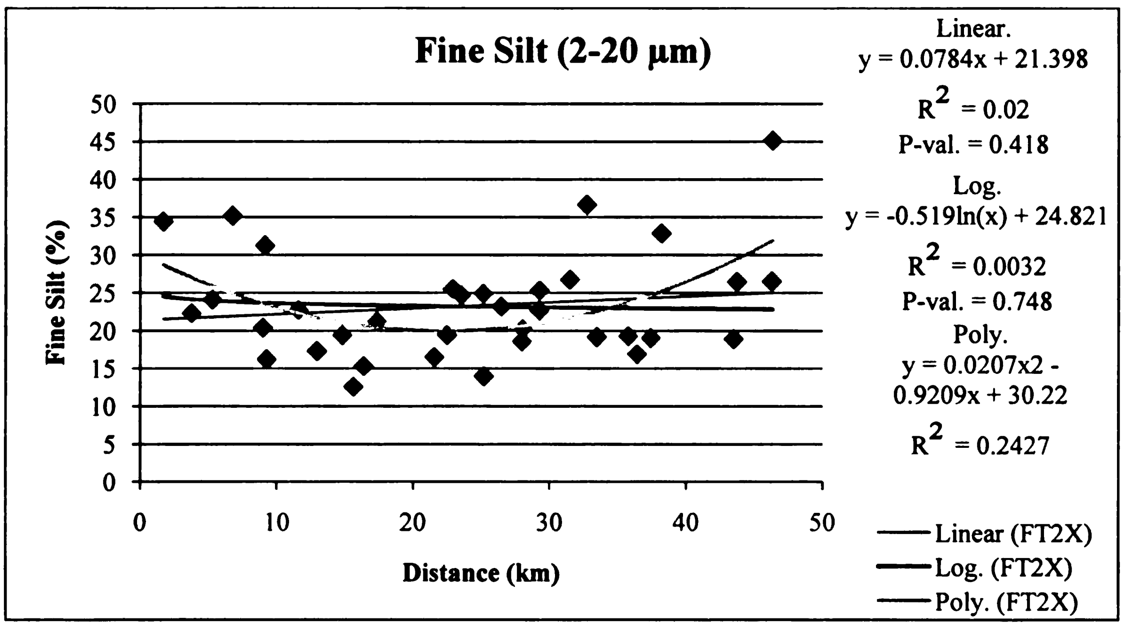

Figure A.48. Scatterplot of fine silt content from Iron County transects 2 and 3

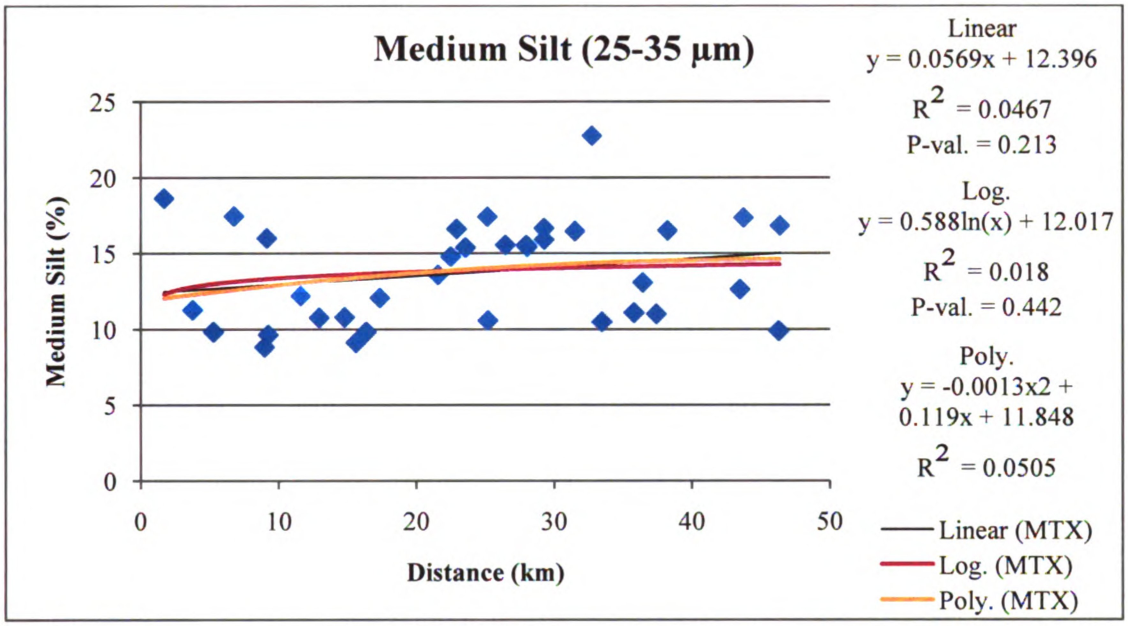

Figure A.49. Scatterplot of medium silt content from Iron County transects 2 and3

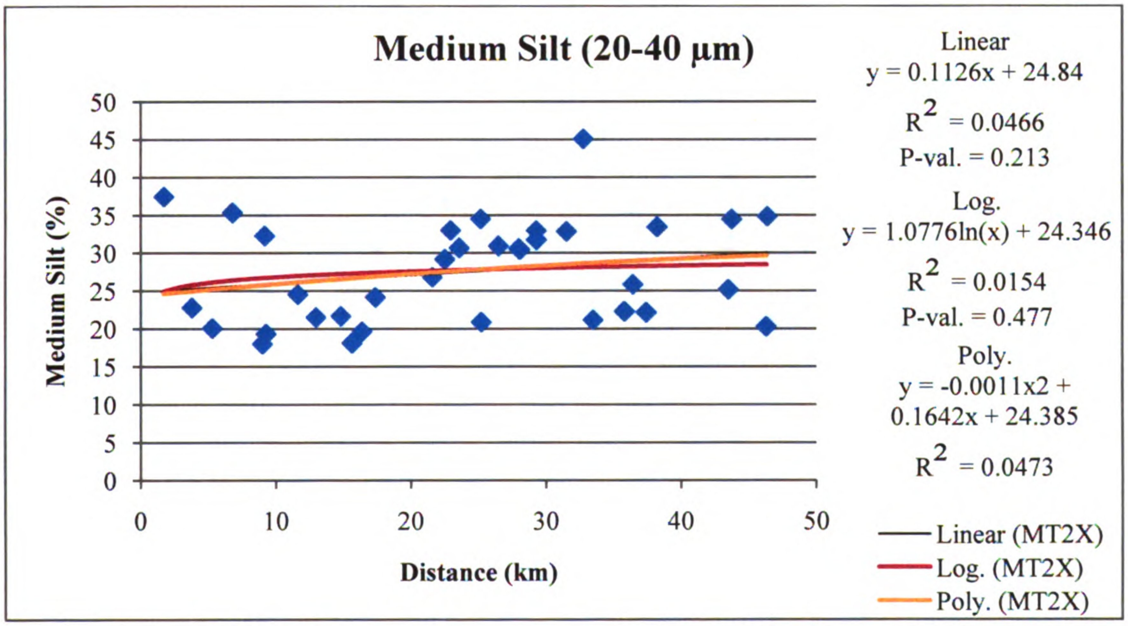

Figure A.50. Scatterplot of medium silt content from Iron County transects 2 and 3

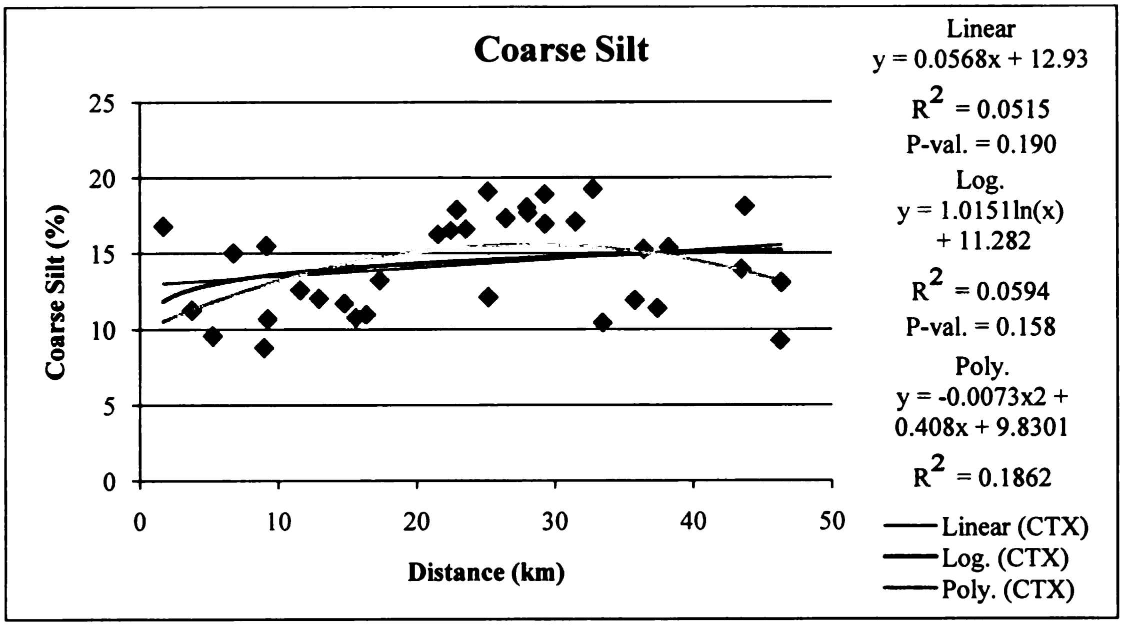

Figure A.51. Scatterplot of coarse silt content from Iron County transects 2 and 3

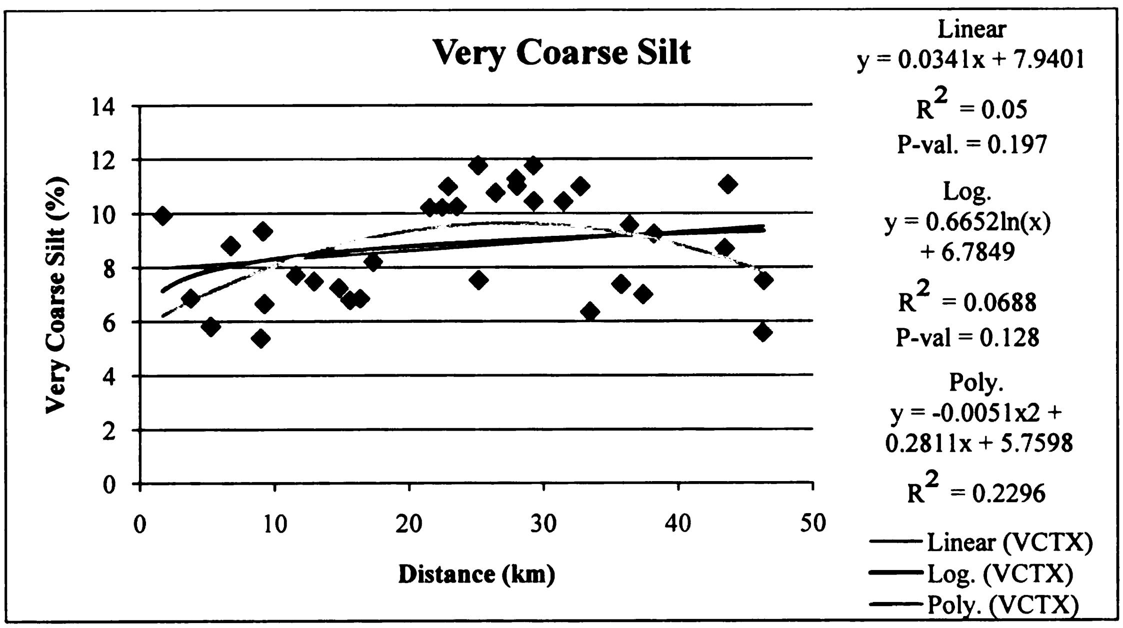

Figure A.52. Scatterplot of very coarse silt content from Iron County transects 2 and 3

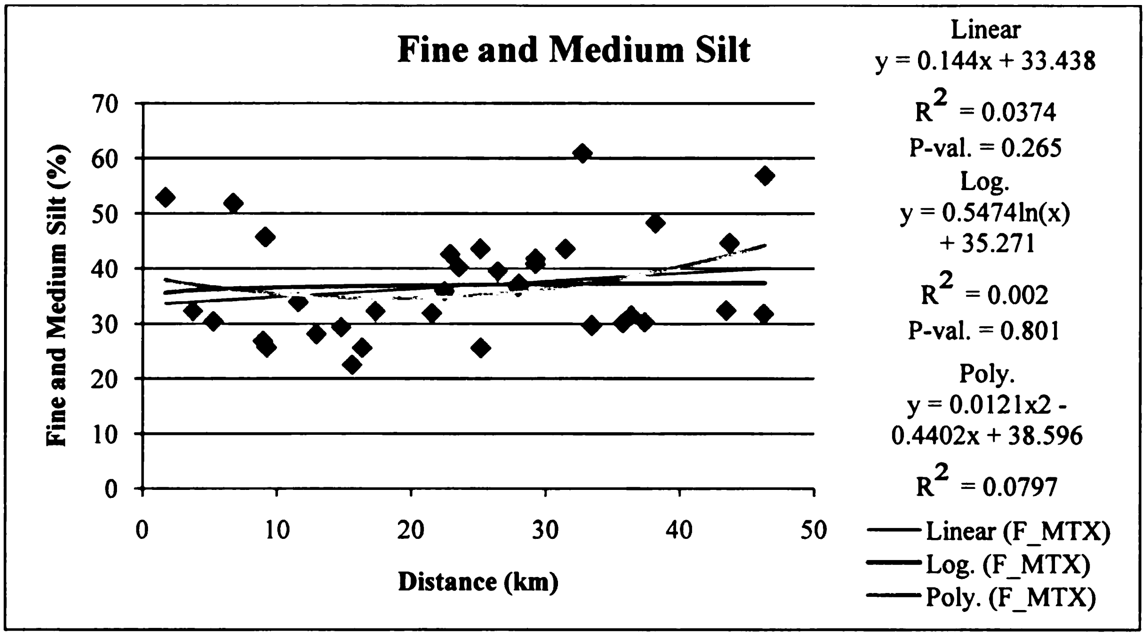

Figure A.53. Scatterplot of fine and medium silt content from Iron County transects 2 and 3

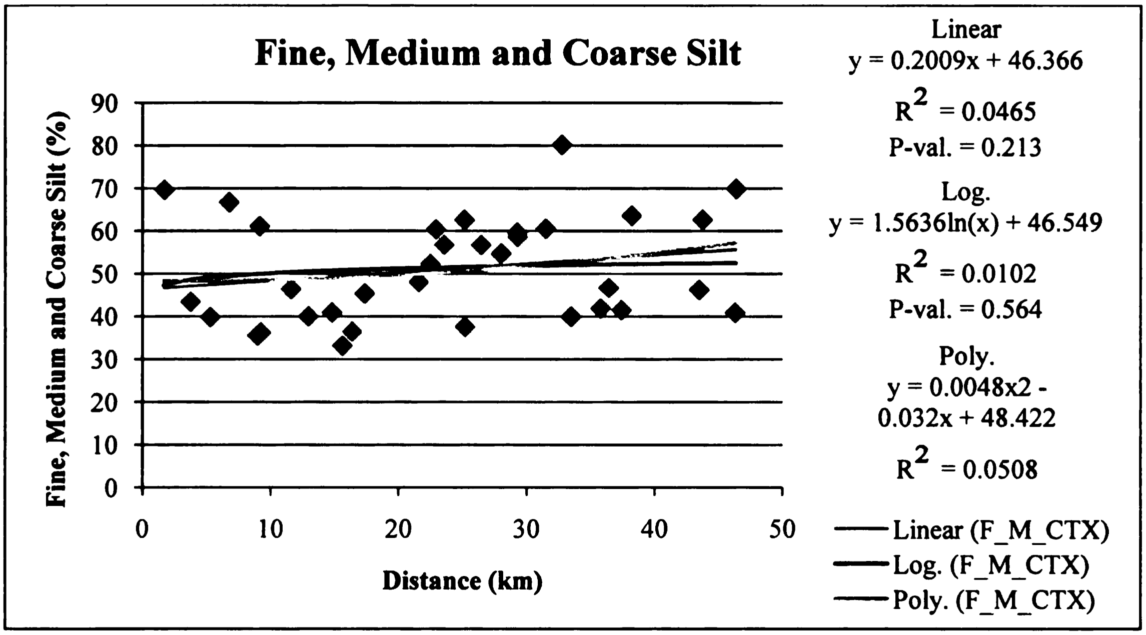

Figure A.54. Scatterplot of fine, medium and coarse silt content from Iron County transects 2 and 3

Iron County Transect 2 & 3

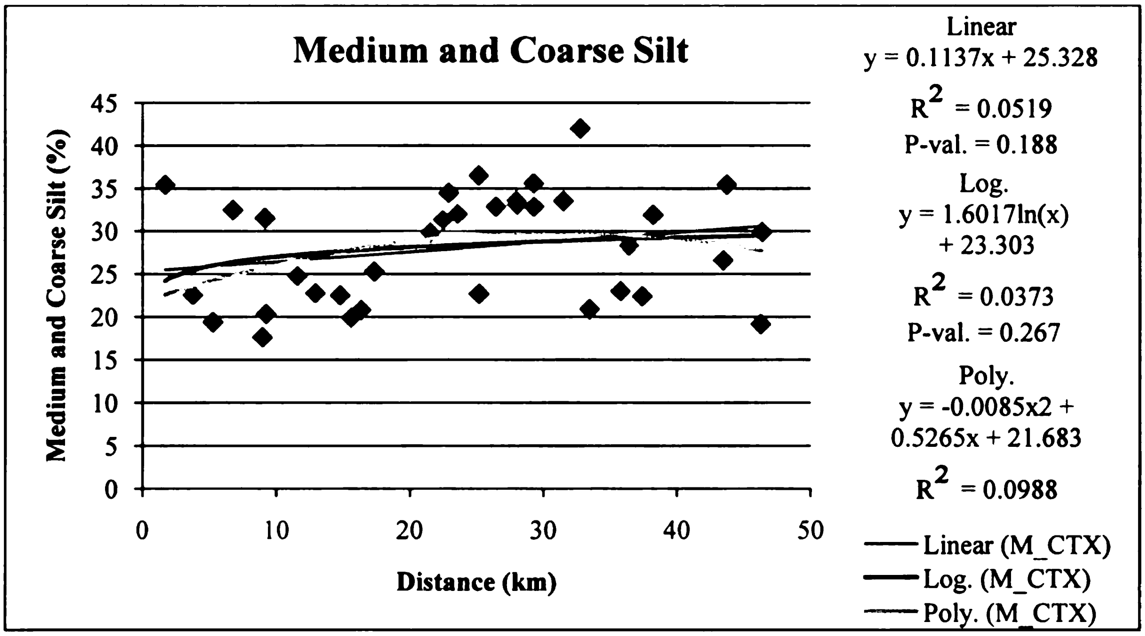

Figure A.55. Scatterplot of medium and coarse silt content from Iron County transects 2 and 3

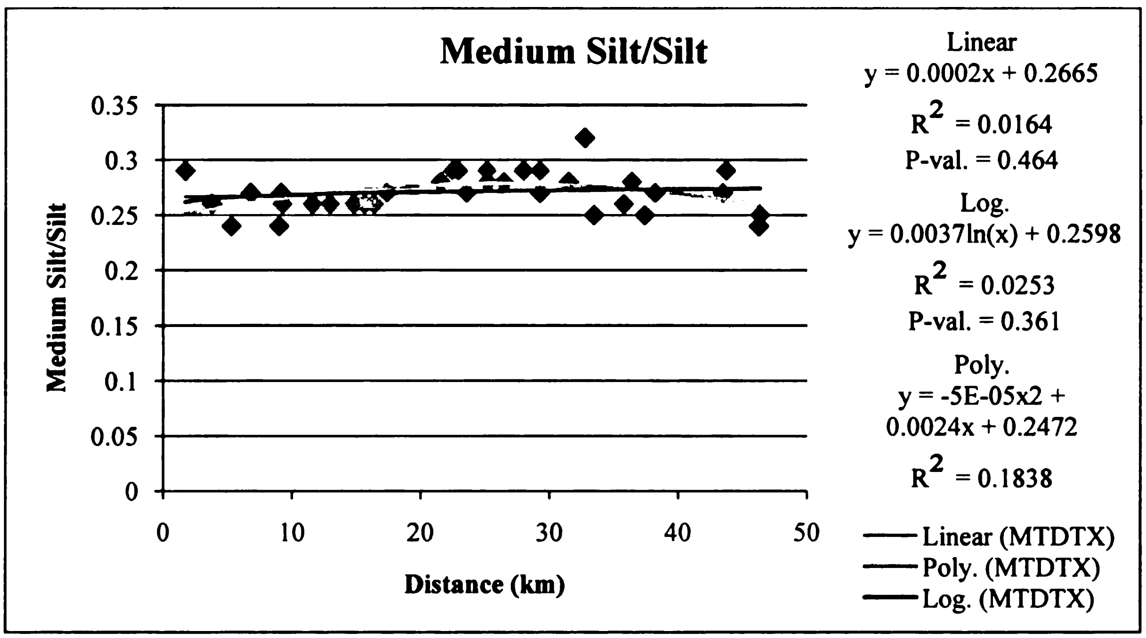

Figure A.56. Scatterplot of medium silt/silt content from Iron County transects 2 and 3

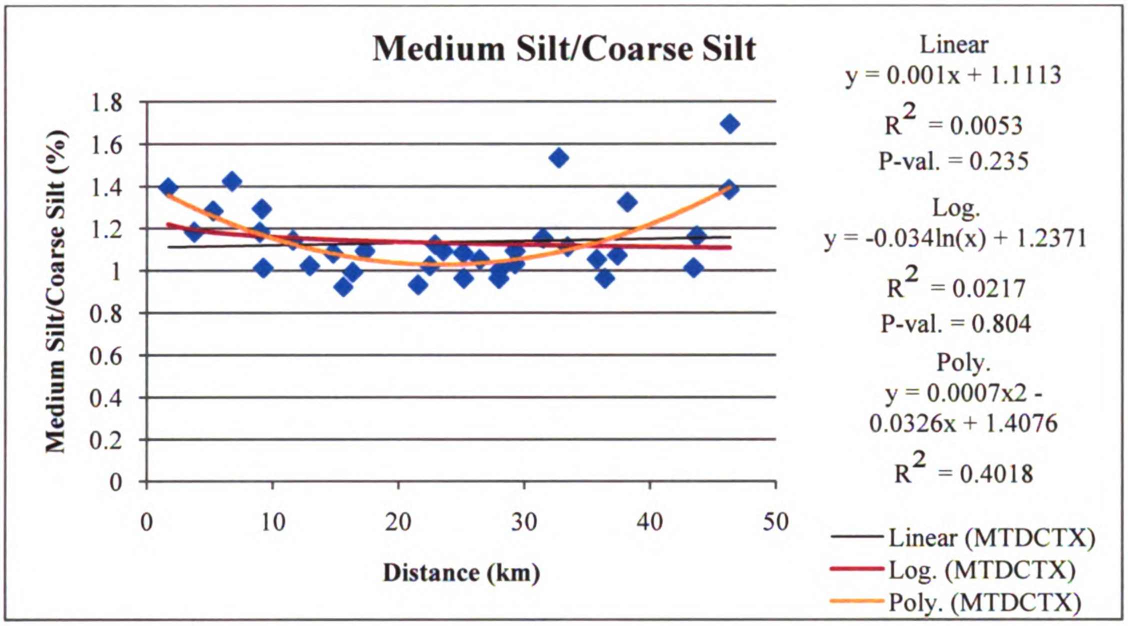

Figure A.57. Scatterplot of medium silt/coarse silt from Iron County transects 2 and 3

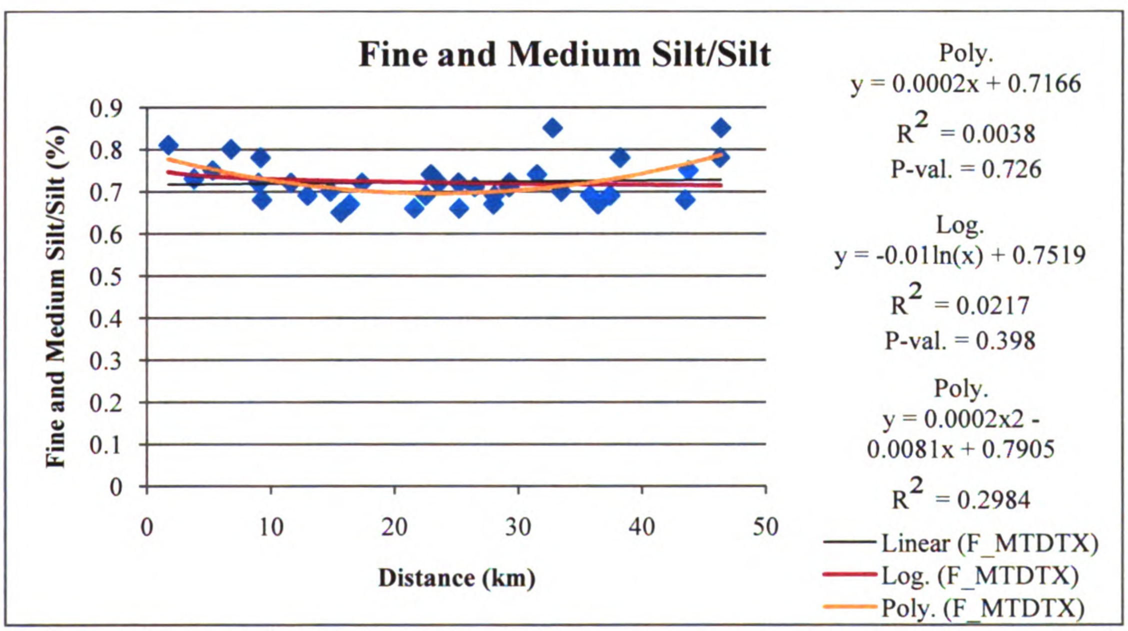

Figure A.58. Scatterplot of fine and medium silt/silt content from Iron County transects 2 and 3

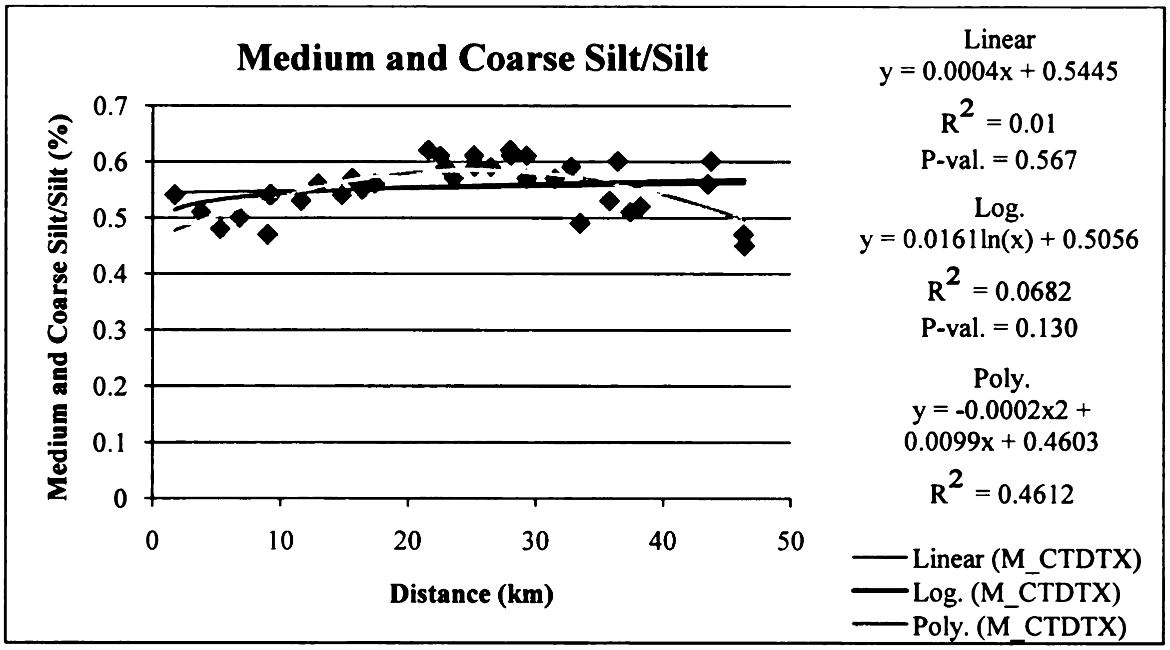

Figure A.59. Scatterplot of medium and coarse silt/silt content from Iron County transects 2 and 3

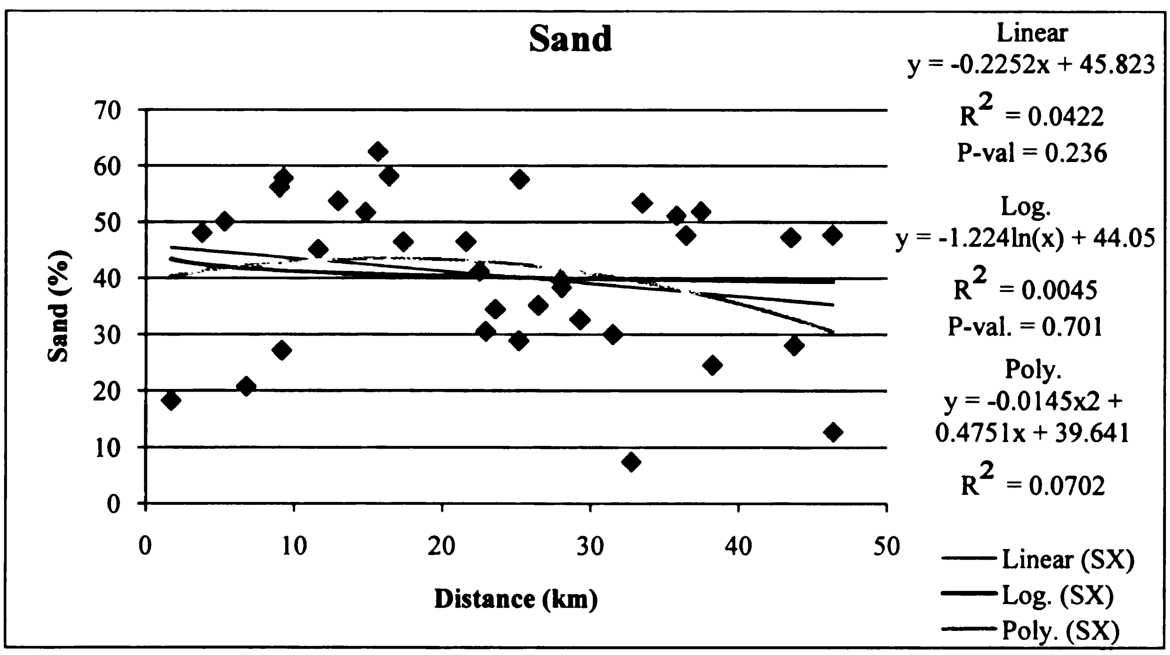

Figure A.60. Scatterplot of sand content from Iron County transects 2 and 3

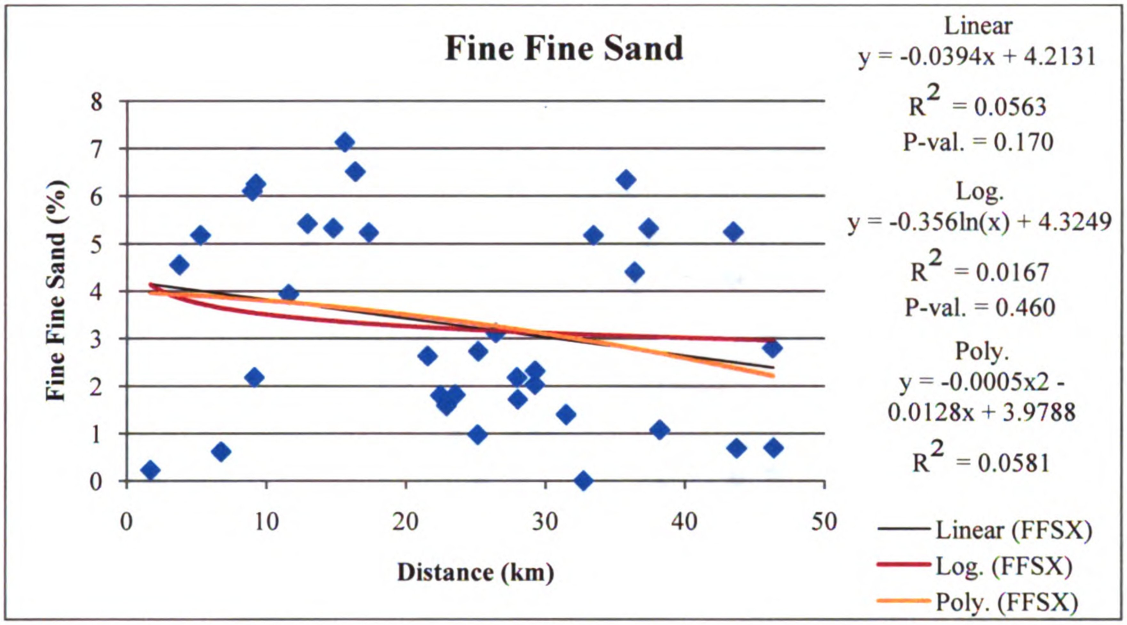

Figure A.61. Scatterplot of fine-fine sand content from Iron County transects 2 and 3

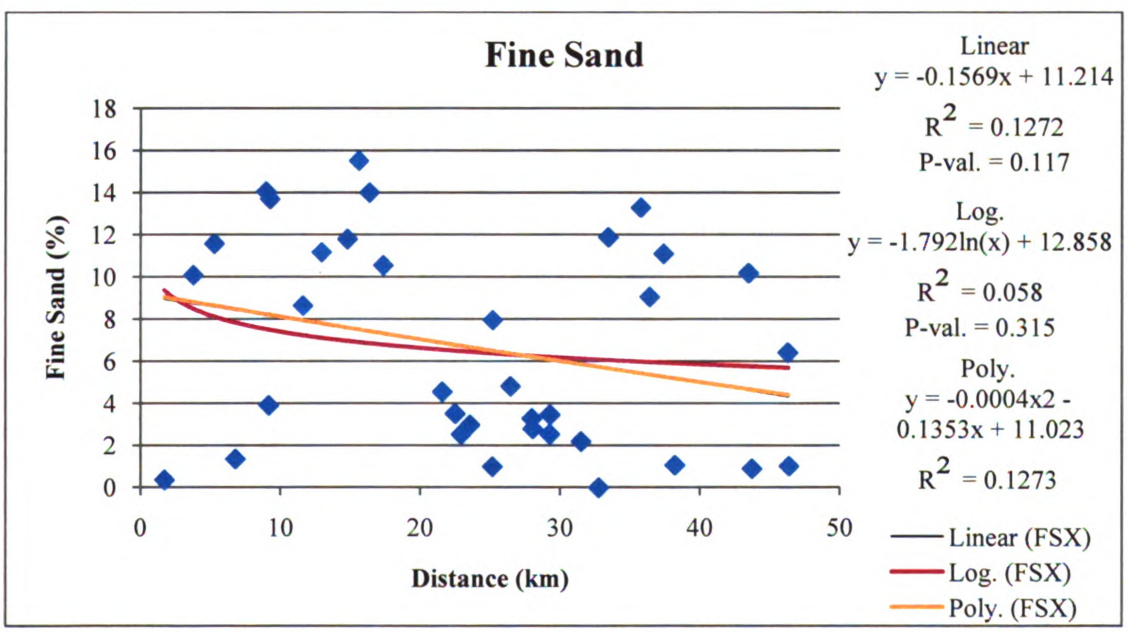

Figure A.62. Scatterplot of fine sand content from Iron County transects 2 and 3

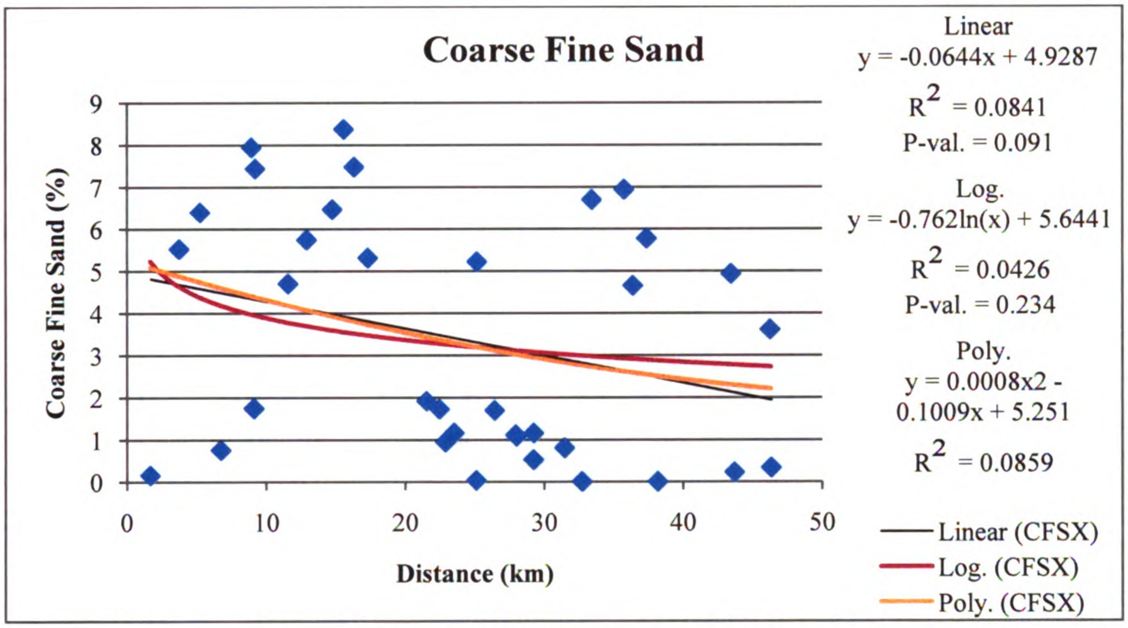

Figure A.63. Scatterplot of coarse fine sand from Iron County transects 2 and 3

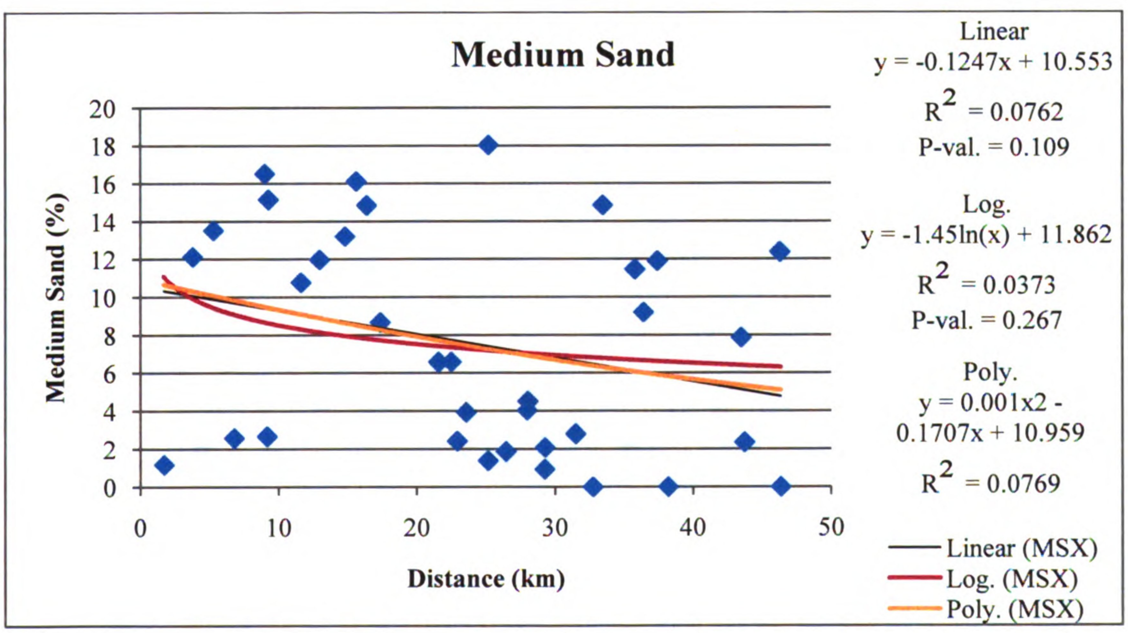

Figure A.64. Scatterplot of medium sand content from Iron County transects 2 and 3

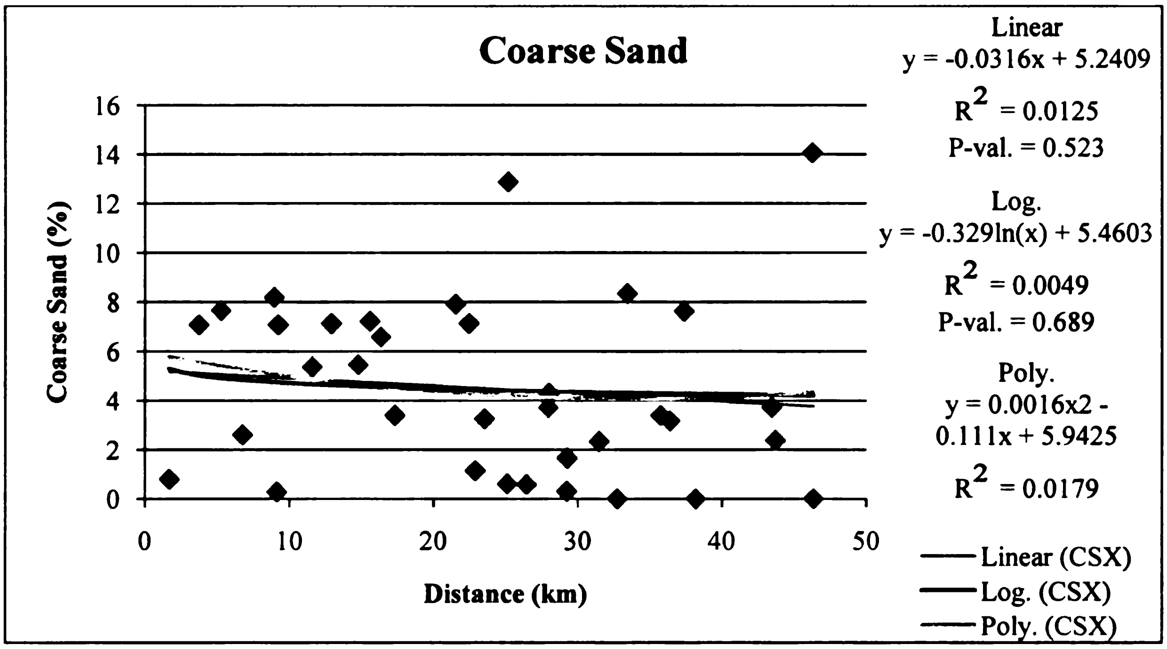

Figure A.65. Scatterplot of coarse sand content from Iron County transects 2 and 3

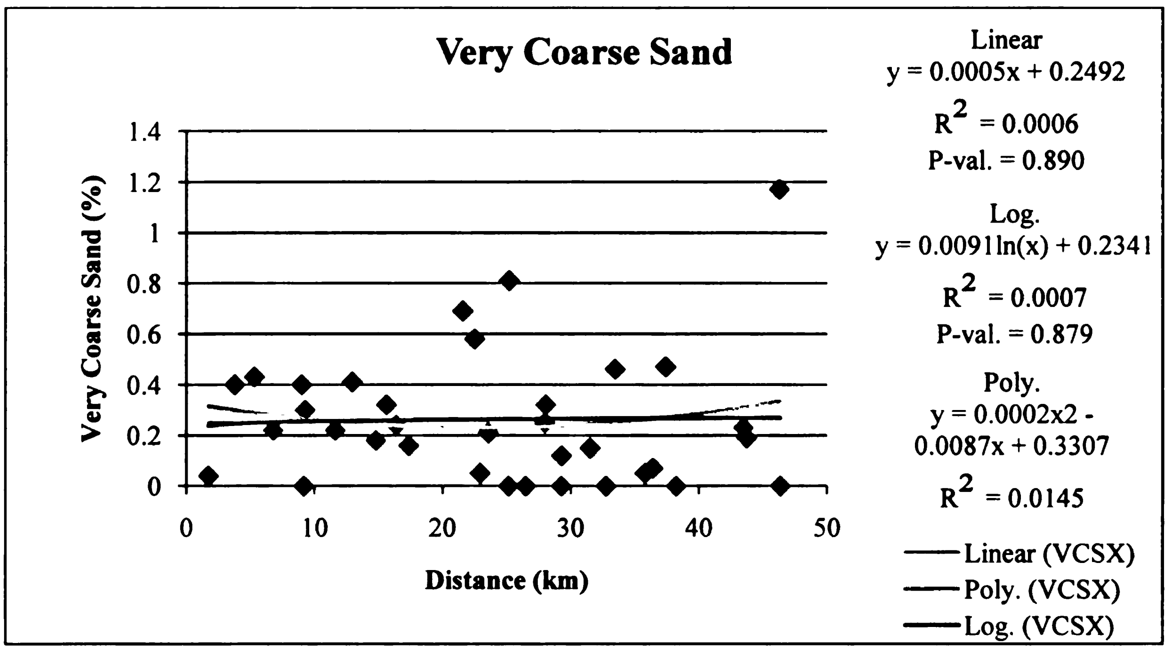

Figure A.66. Scatterplot very coarse sand content from Iron County transects 2 and 3

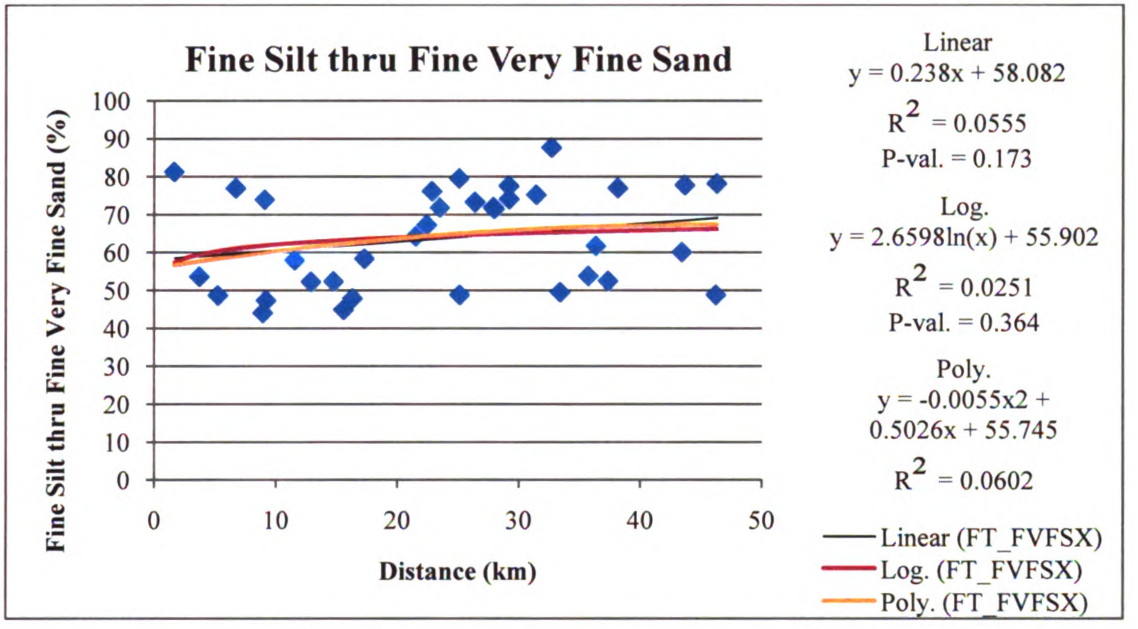

Figure A.67. Scatterplot of fine silt thru fine very fine sand content from Iron County transects 2 and 3

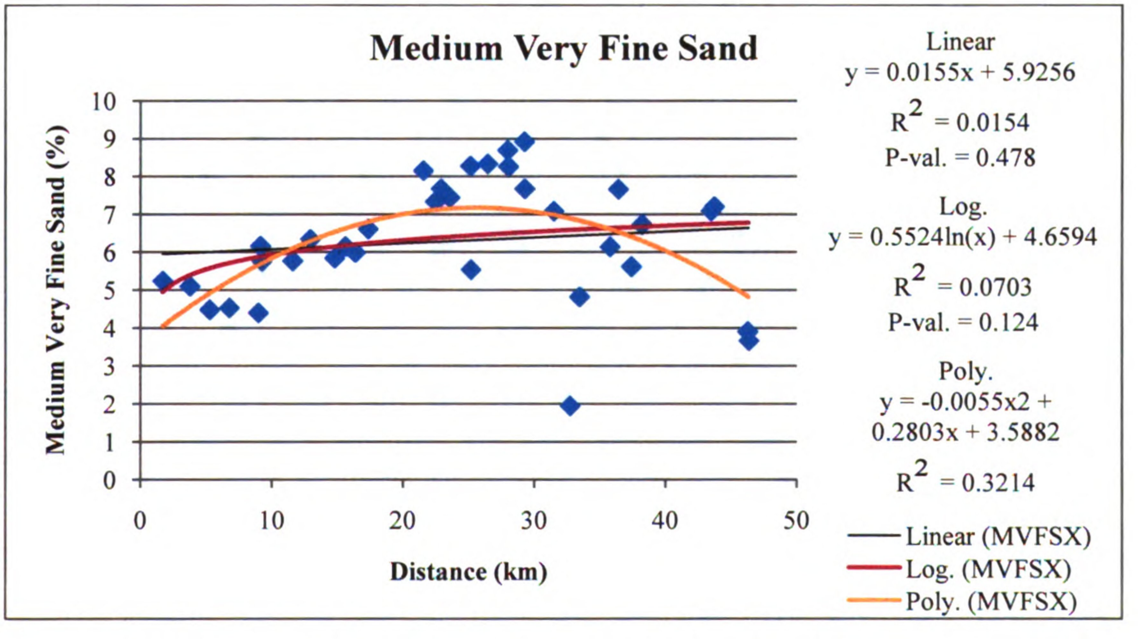

Figure A.68. Scatterplot of medium very fine sand content from Iron County transects 2 and 3

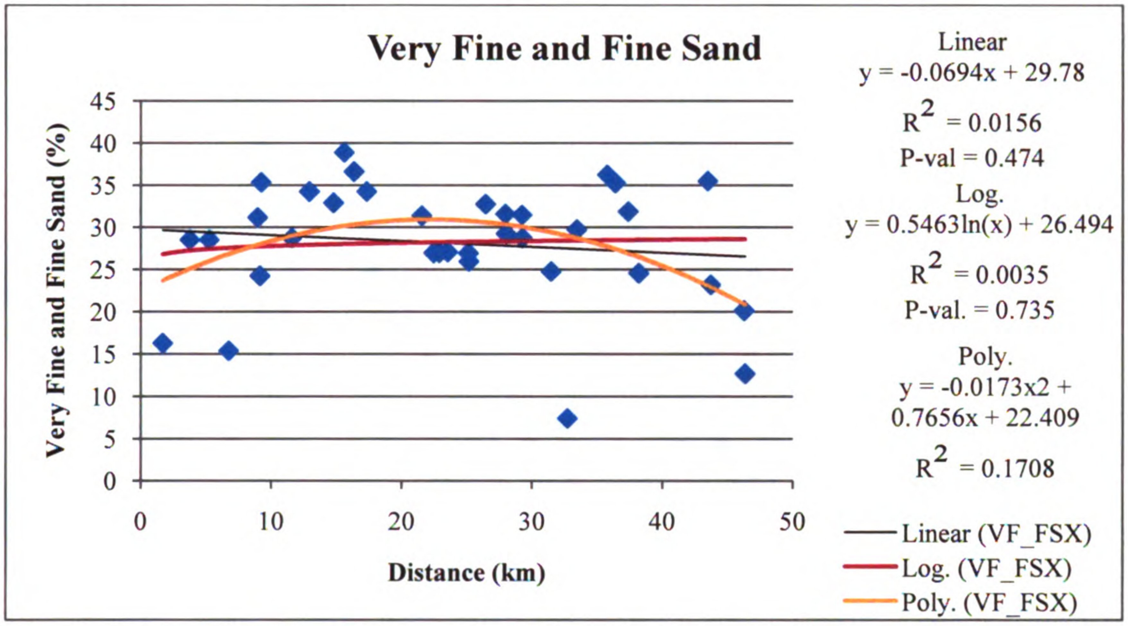

Figure A.69. Scatterplot of very fine and fine sand from Iron County transects 2 and 3

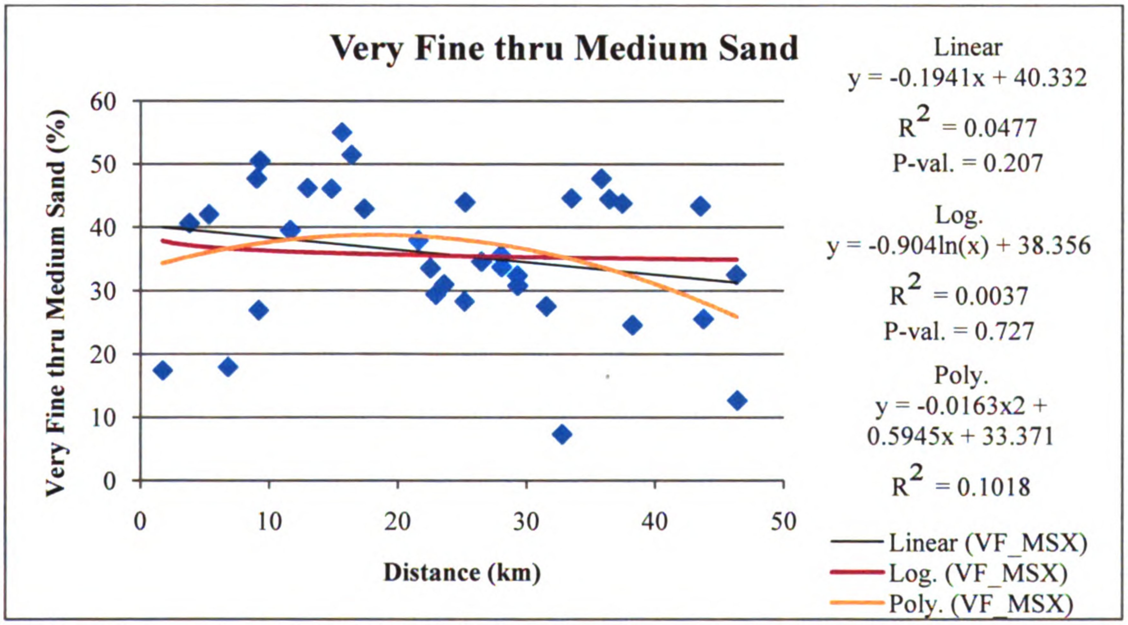

Figure A.70. Scatterplot very fine thru medium sand content from Iron County transects 2 and 3

Iron County Transect 2 & 3

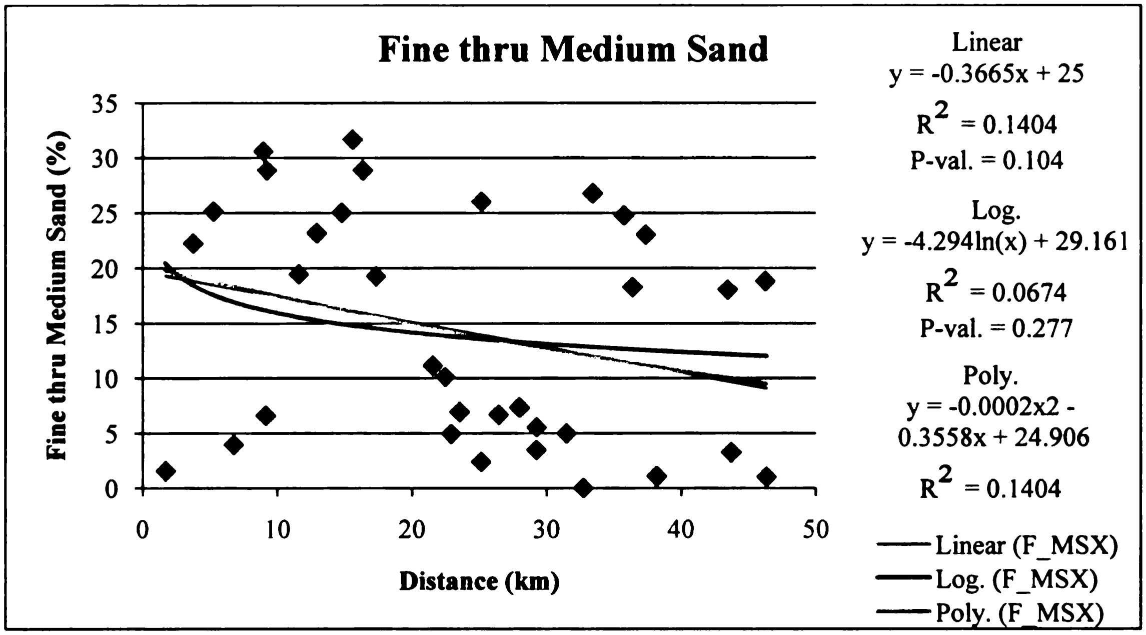

Figure A.71. Scatterplot of fine thru medium sand content from Iron County transects 2 and 3

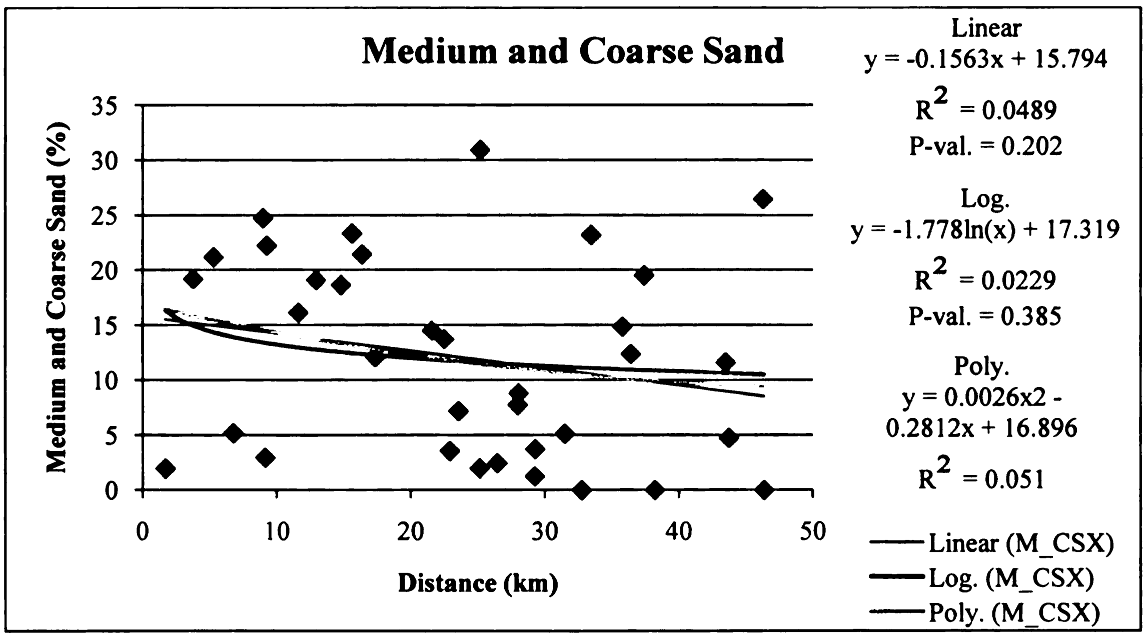

Figure A.72. Scatterplot of medium and coarse sand content from Iron County transect 2 and 3

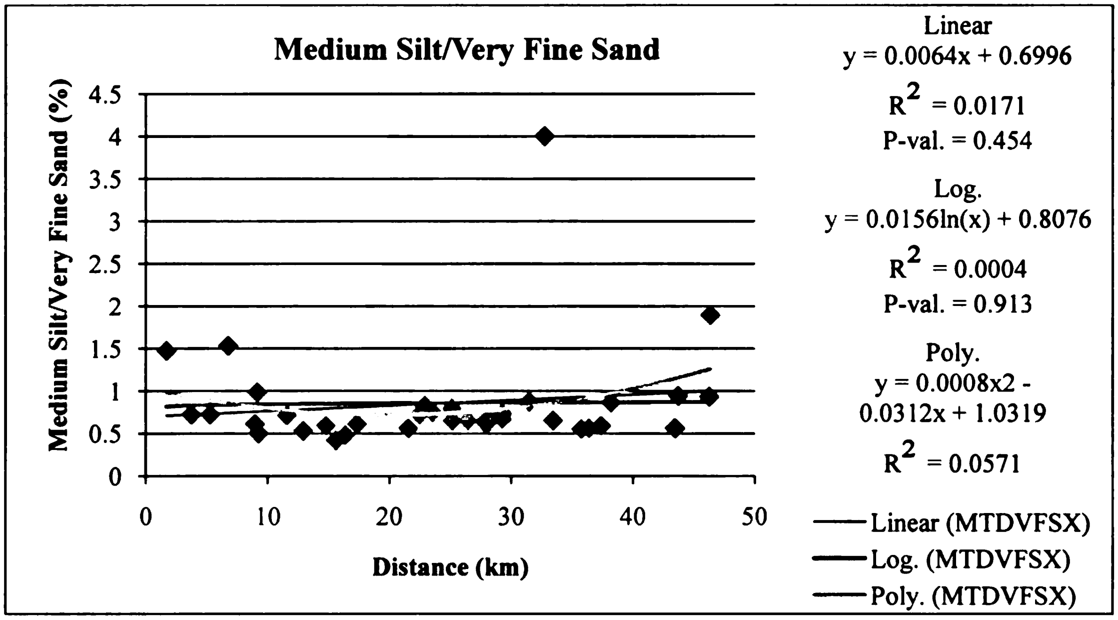

Figure A.73. Scatterplot of medium silt/very fine sand from Iron County transects2 and 3

APPENDIX B

Particle size data

Table B.1. Particle size data for all loess samples from north-central Wisconsin and Iron County

Sample	Thickness (cm)	MWPS[a]	% clay	% silt	% sand	Texture Class[b]	VFSi*	FSi*	MSi*	CSi*	VFS*	FS*	MS*	CS*
179	70	69.21	18.42	53.36	28.22	silt loam	9.87	26.53	14.84	14.18	18.36	7.06	6.41	2.65
246	45	42.54	20.45	60.97	18.58	silt loam	11.88	31.73	17.16	15.87	17.41	2.40	2.27	1.21
247	60	42.79	20.09	62.42	17.49	silt loam	12.75	33.39	16.98	14.99	15.53	2.41	2.61	1.27
250	50	58.52	18.16	58.73	23.11	silt loam	11.00	29.54	16.07	15.15	18.17	3.57	3.70	2.60
252	45	38.98	21.54	60.69	17.77	silt loam	12.67	32.70	16.88	15.10	16.58	3.30	2.00	0.73
299	60	58.97	16.02	57.66	26.32	silt loam	9.71	27.29	15.84	15.82	21.14	4.20	3.72	2.14
339	30	101.53	10.98	49.40	39.62	loam	6.77	21.40	13.35	13.97	21.97	8.39	9.11	4.80
341	40	107.03	11.88	47.30	40.82	loam	6.75	20.32	12.85	13.75	22.65	8.57	9.20	5.58
362	55	28.65	19.29	63.61	17.10	silt loam	11.66	31.65	17.89	17.62	21.18	0.01	0.00	0.00
363	70	27.85	20.93	63.01	16.07	silt loam	11.65	31.41	18.33	18.30	20.27	0.04	0.00	0.00
369	70	88.84	16.37	44.81	38.83	loam	8.14	20.17	12.06	13.21	23.67	10.53	8.68	3.39
372	90	21.92	22.93	71.39	5.68	silt loam	12.54	38.14	22.72	19.23	7.36	0.00	0.00	0.00
373	60	68.36	11.08	44.28	44.63	loam	6.34	17.76	11.61	14.09	32.72	12.94	4.53	0.01
374	50	60.09	15.04	55.45	29.50	silt loam	10.80	27.27	13.86	13.34	20.49	7.50	5.89	0.85
376	95	42.19	14.21	57.79	28.00	silt loam	7.71	24.11	16.65	18.88	28.87	2.54	0.93	0.30
377	85	67.85	14.68	55.95	29.37	silt loam	8.82	24.80	15.38	16.58	24.04	2.98	3.93	3.25
382	35	96.33	10.18	47.37	42.45	loam	6.45	19.73	12.62	13.94	25.29	10.16	7.86	3.71
396	35	32.26	16.32	62.40	21.28	silt loam	10.27	29.17	17.28	17.85	25.08	0.35	0.00	0.00
410	50	221.44	10.70	25.63	63.68	sandy loam	4.96	11.59	6.15	6.00	9.40	17.60	30.99	12.93
523	47	52.34	19.06	59.58	21.36	silt loam	9.96	29.19	17.45	17.02	19.22	2.30	2.30	2.35
527	85	38.43	22.13	62.83	15.03	silt loam	13.22	33.98	17.66	15.84	15.58	0.85	1.29	1.45
529	35	73.80	20.17	55.93	23.91	silt loam	11.51	29.42	15.24	13.88	15.82	3.71	5.29	4.75
537	55	49.90	21.06	59.89	19.05	silt loam	11.12	30.56	17.57	16.61	16.65	1.65	3.58	2.12
540	70	47.11	20.02	60.52	19.46	silt loam	11.10	30.22	17.49	16.86	18.03	1.70	2.68	1.80

Table B.1. Particle size data for all loess samples from north-central Wisconsin and Iron County (continued)

Sample	Thickness (cm)	MWPS[a]	% clay	% silt	% sand	Texture Class[b]	VFSi*	FSi*	MSi*	CSi*	VFS*	FS*	MS*	CS*
545	95	47.78	20.70	61.60	17.70	silt loam	11.17	31.41	18.04	17.06	17.10	0.47	2.14	2.41
547	60	48.37	23.93	58.93	17.14	silt loam	13.25	32.74	16.68	14.81	14.26	1.99	3.97	2.19
665	70	43.56	20.68	61.93	17.39	silt loam	11.68	31.74	17.83	16.83	17.31	0.75	1.92	1.79
666	50	23.12	34.42	61.36	4.22	silty clay loam	22.89	45.52	15.66	9.49	3.91	0.63	0.93	0.90
667	40	52.41	18.21	58.62	23.17	silt loam	11.62	30.35	15.54	14.16	17.70	4.89	4.36	1.39
668	40	45.16	19.11	61.07	19.83	silt loam	11.41	31.18	17.06	15.84	17.21	2.84	3.34	1.12
669	95	63.54	19.66	60.04	20.30	silt loam	11.27	30.65	17.00	15.82	15.60	1.11	4.23	4.03
670	50	57.21	20.44	60.40	19.16	silt loam	11.88	31.73	16.93	15.37	15.44	1.49	3.58	3.34
671	60	57.41	20.46	60.16	19.38	silt loam	11.84	31.46	16.93	15.40	14.83	1.84	4.45	3.06
672	75	45.90	20.60	62.34	17.06	silt loam	12.84	32.90	17.19	15.59	15.23	1.31	2.93	1.89
673	65	60.85	21.27	57.21	21.52	silt loam	11.94	29.58	15.97	15.17	16.73	2.48	4.49	3.41
674	80	38.38	22.32	61.84	15.84	silt loam	13.34	33.61	17.24	15.42	15.21	1.62	2.54	1.02
675	55	59.59	21.34	57.44	21.22	silt loam	13.15	31.22	15.14	13.51	15.73	3.61	4.25	3.16
676	55	19.54	28.85	64.88	6.27	silty clay loam	18.93	41.96	17.41	12.88	8.78	0.03	0.00	0.00
678	90	33.75	22.56	64.12	13.32	silt loam	14.40	35.69	17.56	15.15	14.13	0.86	1.22	0.92
679	75	33.47	21.31	63.78	14.91	silt loam	13.12	34.20	17.80	15.93	15.47	1.16	1.92	0.40
680	50	59.01	21.18	59.51	19.32	silt loam	12.60	31.82	16.33	14.74	15.19	1.38	4.08	3.61
681	60	60.86	22.47	58.11	19.43	silt loam	13.20	31.88	15.80	14.07	15.21	2.02	3.41	4.04
682	60	33.45	20.69	64.75	14.56	silt loam	12.76	34.12	18.22	16.54	16.27	0.29	0.94	0.80
683	50	76.38	10.64	49.67	39.68	loam	5.43	18.01	14.22	17.93	32.02	4.74	4.71	2.83
684	55	112.75	15.57	41.55	42.88	loam	8.25	18.88	10.49	11.59	23.39	10.49	10.25	6.27
685	45	149.66	22.15	40.73	37.12	loam	11.40	21.82	9.88	9.22	13.70	6.40	12.38	14.04
686	50	139.54	9.44	35.90	54.66	fine sandy	5.12	13.83	9.26	11.43	25.77	13.69	13.79	6.78

Table B.1. Particle size data for all loess samples from north-central Wisconsin and Iron County (continued)

Sample	Thickness (cm)	MWPS[a]	% clay	% silt	% sand	Texture Class[b]	VFSi*	FSi*	MSi*	CSi*	VFS*	FS*	MS*	CS*
687	45	84.41	8.01	45.72	46.27	loam	4.54	15.46	12.80	16.90	33.88	8.12	5.84	2.39
688	35	104.56	10.38	46.20	43.43	loam	5.88	17.84	12.53	15.31	29.00	6.33	7.03	5.71
689	40	88.92	9.42	51.01	39.57	silt loam	5.73	19.91	14.21	16.47	28.39	5.81	4.87	4.30
690	40	68.73	12.32	53.26	34.42	silt loam	6.72	21.86	15.08	17.09	27.39	5.04	4.42	2.31
691	35	84.03	5.72	47.68	46.59	very fine sand	3.08	14.05	13.96	19.50	38.60	4.49	2.57	3.47
692	35	73.85	6.34	49.60	44.06	very fine sand	3.51	15.28	14.45	19.72	38.10	4.27	1.93	2.53
693	30	76.17	6.64	48.52	44.84	very fine sand	3.69	15.34	14.02	18.92	36.91	5.33	3.36	2.31
694	55	116.30	9.13	42.40	48.46	loam	5.05	16.16	11.52	13.94	28.11	10.35	8.78	5.70
695	50	98.01	10.91	42.75	46.34	loam	5.68	16.52	11.62	14.17	28.24	10.95	9.52	3.23
696	45	118.17	9.45	48.46	42.09	loam	5.41	18.28	13.59	16.22	26.80	4.54	6.58	7.89
697	50	77.93	10.13	54.34	35.53	silt loam	5.88	21.03	15.53	18.02	28.26	3.28	4.03	3.71
698	50	79.72	12.69	53.86	33.45	silt loam	6.82	21.81	15.41	17.65	26.41	2.79	4.51	4.28
699	40	183.61	9.37	38.41	52.22	fine sandy loam	4.77	14.96	10.57	12.08	17.98	7.94	18.03	12.86
700	50	25.56	20.60	67.27	12.13	silt loam	11.87	34.73	19.92	18.20	15.28	0.00	0.00	0.00
701	55	105.71	12.19	51.61	36.20	silt loam	6.44	21.08	14.78	16.48	23.42	3.51	6.59	7.12
702	40	93.72	10.27	46.96	42.77	loam	5.64	18.38	13.07	15.24	26.19	9.04	9.20	3.17
704	40	136.15	12.62	39.84	47.53	loam	6.92	17.67	10.12	10.89	20.62	11.68	13.97	7.74
705	50	135.56	12.72	40.55	46.73	loam	6.87	17.89	10.46	11.25	20.53	11.09	13.61	7.88
706	55	69.31	16.44	54.23	29.33	silt loam	10.47	26.93	14.08	13.42	19.10	7.15	6.34	2.42
707	55	51.36	17.43	58.09	24.48	silt loam	10.41	28.31	15.96	15.67	20.09	4.10	4.42	1.04
708	50	99.91	14.08	45.81	40.11	loam	7.94	20.53	11.96	12.89	22.85	9.64	9.24	4.70
711	50	128.35	12.18	40.66	47.16	loam	6.24	17.32	10.76	11.99	23.05	11.15	11.98	7.11

Table B.1. Particle size data for all loess samples from north-central Wisconsin and Iron County (continued)

Sample	Thickness (cm)	MWPS[a]	% clay	% silt	% sand	Texture Class[b]	VFSi*	FSi*	MSi*	CSi*	VFS*	FS*	MS*	CS*
713	55	116.29	13.94	41.57	44.48	loam	7.36	18.50	10.79	11.66	21.11	11.77	13.21	5.43
715	65	140.53	10.74	37.66	51.60	loam	5.88	16.03	9.63	10.65	21.62	13.67	15.16	7.06
716	45	143.16	14.99	37.22	47.79	loam	8.21	17.98	8.82	8.76	17.11	14.01	16.52	8.17
717	35	50.67	18.40	64.68	16.92	silt loam	12.51	34.30	17.44	15.00	13.99	1.36	2.58	2.59
719	30	34.05	20.17	65.27	14.56	silt loam	12.19	34.18	18.63	16.77	15.87	0.37	1.18	0.79
720	75	53.98	13.99	58.03	27.98	silt loam	8.83	25.81	15.90	16.93	25.24	3.46	2.07	1.65
721	75	41.05	15.32	60.23	24.44	silt loam	8.58	26.08	17.41	19.06	25.89	1.00	1.38	0.60
722	65	107.54	11.15	40.08	48.77	loam	6.17	17.16	10.40	11.38	22.99	15.89	13.47	2.54
724	70	139.19	9.19	37.94	52.87	fine sandy loam	5.30	15.73	9.82	10.93	22.59	13.97	14.86	6.56
725	60	153.32	7.42	34.73	57.84	fine sandy loam	4.28	13.38	9.12	10.74	23.37	15.47	16.12	7.20
726	70	103.69	14.93	46.76	38.32	loam	8.52	21.69	12.19	12.56	20.07	8.62	10.78	5.34
728	55	41.23	19.63	58.55	21.82	silt loam	11.70	29.67	16.00	15.47	20.29	3.91	2.67	0.27
729	35	122.33	19.37	40.27	40.36	loam	10.06	20.54	9.82	9.53	16.91	11.55	13.53	7.64
730	45	61.73	15.72	55.99	28.29	silt loam	8.84	25.39	15.69	16.51	22.95	3.90	4.41	2.21
731	75	49.75	17.62	59.77	22.61	silt loam	9.40	27.54	17.44	18.18	22.70	0.72	1.68	2.17
732	45	134.22	9.69	43.50	46.81	loam	6.59	19.22	11.00	11.35	20.76	11.08	11.91	7.61
733	60	103.84	11.31	43.37	45.32	loam	6.96	18.98	11.08	11.88	22.93	13.26	11.47	3.39
734	70	146.95	9.32	42.31	48.36	loam	6.68	19.12	10.48	10.38	17.85	11.85	14.86	8.32
735	50	76.25	15.58	55.35	29.07	silt loam	8.77	25.21	15.52	16.05	21.18	3.57	5.20	4.18
736	45	86.25	14.89	54.06	31.06	silt loam	8.23	24.11	15.22	15.95	21.12	3.60	6.24	5.18
737	40	100.76	16.77	46.12	37.11	loam	9.51	22.30	11.77	11.83	19.72	9.43	9.73	5.40
738	50	67.53	16.22	57.08	26.70	silt loam	9.30	26.48	16.01	16.34	21.45	2.65	3.88	3.64
739	45	61.72	15.52	56.85	27.63	silt loam	9.09	26.23	15.83	16.14	21.78	4.22	4.36	2.24

Table B.1. Particle size data for all loess samples from north-central Wisconsin and Iron County (continued)

Sample	Thickness (cm)	MWPS[a]	% clay	% silt	% sand	Texture Class[b]	VFSi*	FSi*	MSi*	CSi*	VFS*	FS*	MS*	CS*
741	40	121.38	10.94	45.29	43.77	loam	6.43	19.67	12.07	12.69	21.80	9.56	10.61	6.77
742	45	43.86	21.02	62.79	16.19	silt loam	12.93	33.44	17.43	15.71	15.60	0.99	1.72	1.98
743	40	54.02	21.29	58.62	20.09	silt loam	12.68	31.77	15.97	14.06	14.11	3.80	5.66	1.92
744	40	19.03	30.13	63.95	5.93	silty clay loam	19.41	42.05	17.29	12.77	8.48	0.00	0.00	0.00
746	40	54.54	21.60	58.09	20.31	silt loam	13.47	31.54	15.31	13.78	16.54	3.21	3.16	2.73
747	40	53.79	19.00	60.76	20.24	silt loam	11.30	31.04	16.95	15.72	16.69	1.99	3.73	2.44
749	70	48.85	20.32	61.85	17.83	silt loam	11.25	31.76	17.94	16.67	16.04	0.61	3.35	2.27
750	60	43.94	22.58	62.71	14.71	silt loam	13.97	35.22	17.21	14.60	12.99	1.06	2.76	2.05
751	70	50.01	21.70	62.35	15.95	silt loam	13.32	33.93	17.27	15.11	13.39	0.95	3.03	2.79
768	40	31.32	18.59	61.44	19.97	silt loam	11.92	31.71	16.50	15.35	23.46	1.07	0.00	0.00
769	60	48.83	14.17	55.67	30.16	silt loam	8.13	23.89	15.55	17.30	27.89	4.80	1.87	0.57
770	55	56.00	15.91	58.88	25.21	silt loam	9.45	27.06	16.45	17.06	22.53	2.19	2.79	2.32
863	62	48.02	16.68	57.87	25.46	silt loam	9.07	25.95	16.60	17.83	24.43	2.52	2.42	1.14
864	52	109.80	11.54	43.73	44.73	loam	5.89	17.72	12.00	13.82	24.63	9.51	11.36	4.91
878	66	165.39	13.68	44.50	41.83	loam	8.13	21.78	11.33	10.32	13.00	6.95	14.19	13.27
879	52	61.15	12.28	54.68	33.03	silt loam	8.12	23.52	14.60	16.11	27.45	5.48	2.95	1.67
883	47	23.32	23.55	66.78	9.67	silt loam	17.49	40.00	16.81	13.05	11.63	1.02	0.00	0.00
884	45	53.00	17.36	59.44	23.19	silt loam	9.27	27.24	17.34	18.08	22.26	0.90	2.35	2.37
Mean	54	74.57	16.43	53.74	29.83		9.63	25.91	14.76	14.76	20.34	5.17	5.81	3.42
Median	50	60.86	16.32	56.85	27.98		9.45	26.48	15.54	15.17	20.29	3.61	4.08	2.54

[a] MWPS: mean weighted particle size by volume (μm)

[b] Nomenclature based on soil texture classes defined by the NRCS

* Clay-free particle size fractions in μm. VFSi: 2-12; FSi:12-25; MSi:25-35; CSi:35-50; VFS: 50-125; FS: 125-250; MS: 250-500; CS: 500-1000

APPENDIX C

Particle Size Distribution Curves

Particle size distribution curves presented in the text are omitted from the appendix.

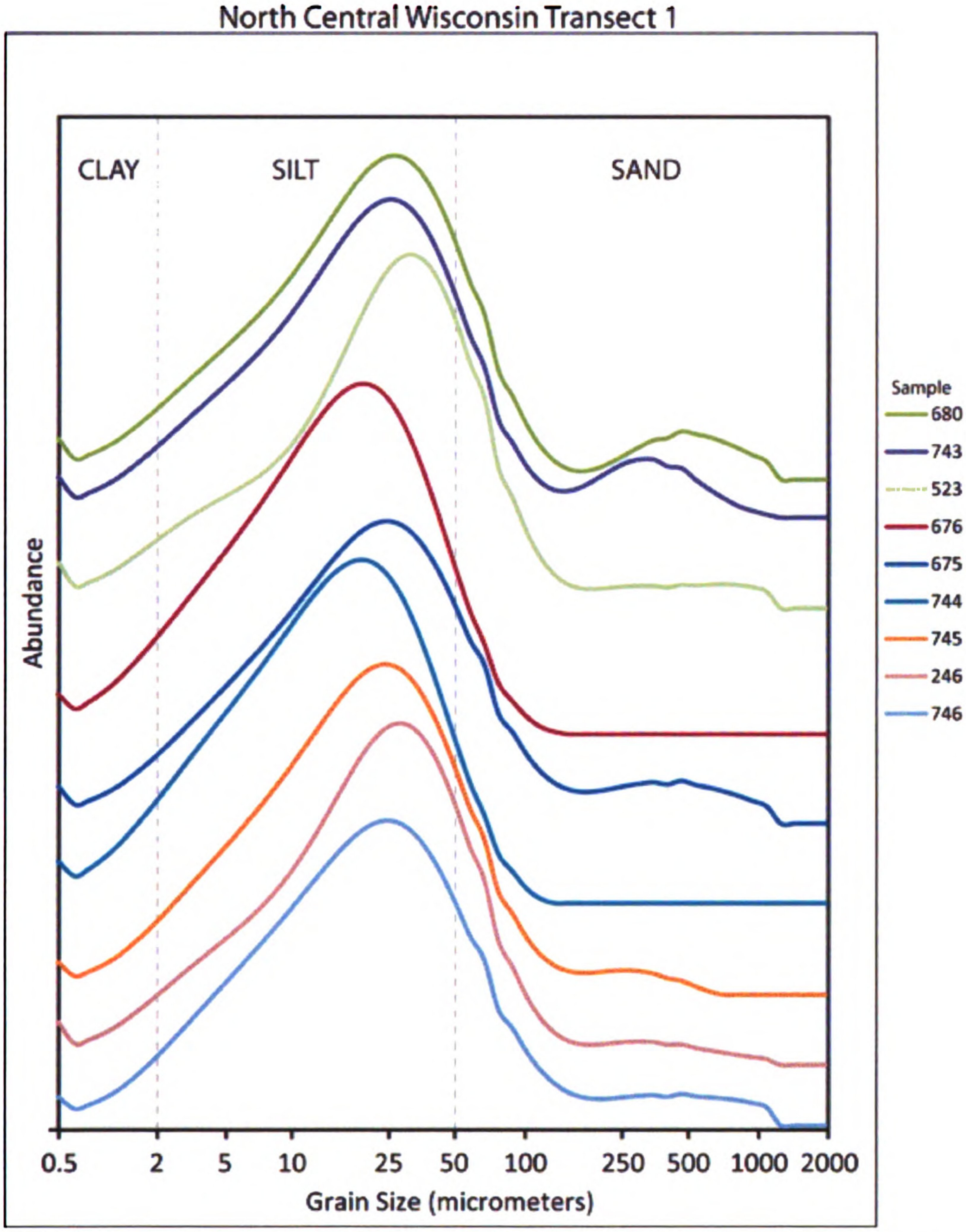

Figure C.1. Continuous particle size distribution curves for representative samples (680, proximal to the Late Wisconsin terminal moraine; 746, distal to the Late Wisconsin terminal moraine) from north-central Wisconsin transect 1. Curves are offset vertically for clarity.

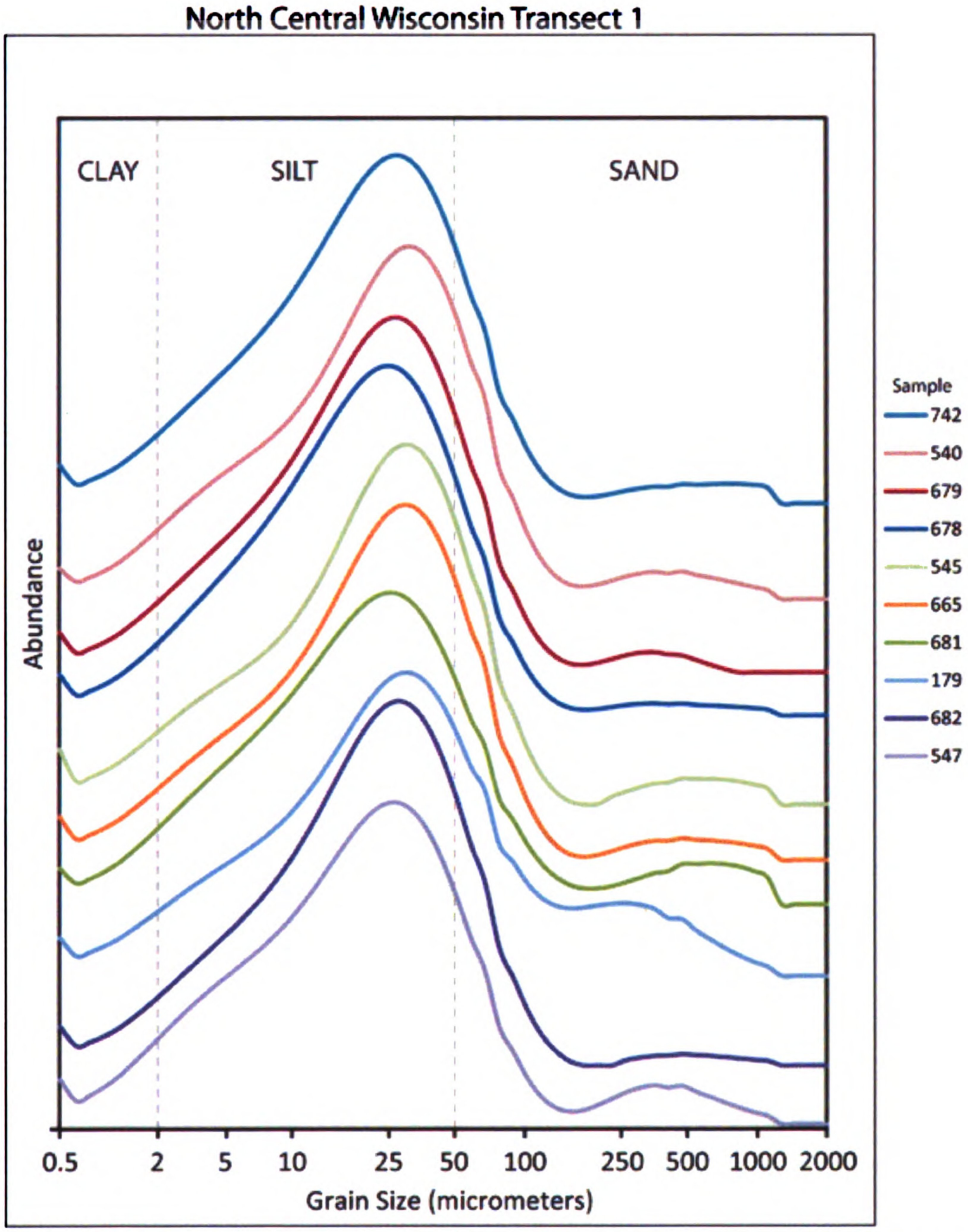

Figure C.2. Continuous particle size distribution curves for representative samples (742, proximal to the Late Wisconsin terminal moraine; 547, distal to the Late Wisconsin terminal moraine) from north-central Wisconsin transect 1. Curves are offset vertically for clairity.

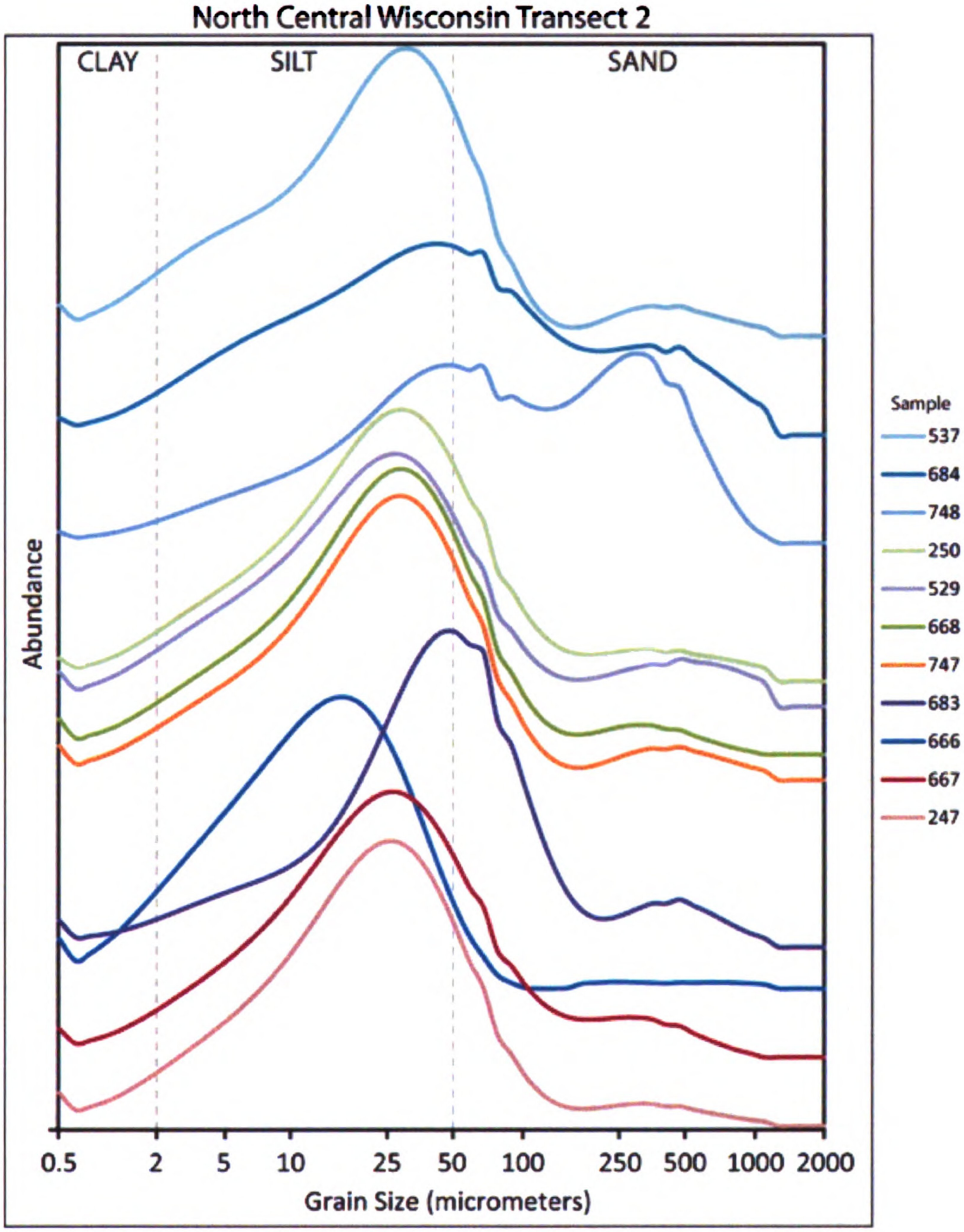

Figure C.3. Continuous particle size distribution curves for representative samples (537, proximal to the Late Wisconsin terminal moraine; 247, distal to the Late Wisconsin terminal moraine) from north-central Wisconsin transect 2. Curves are offset vertically for clarity.

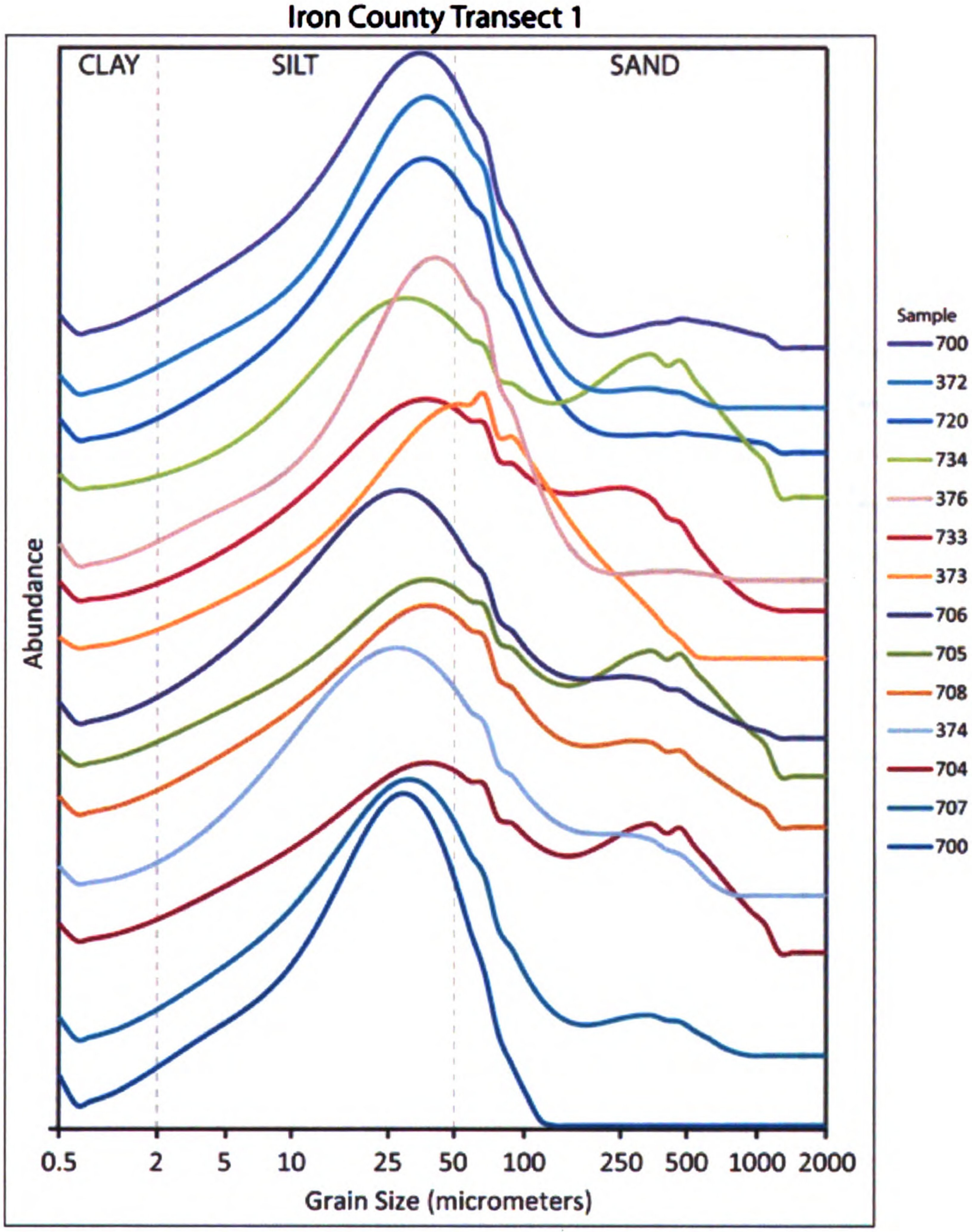

Figure C.4. Continuous particle size distribution curves for representative samples (700, proximal to outwash plain; 707, distal to outwash plain) from Iron County transect 1 (IC 1). Curves are offset vertically for clarity.

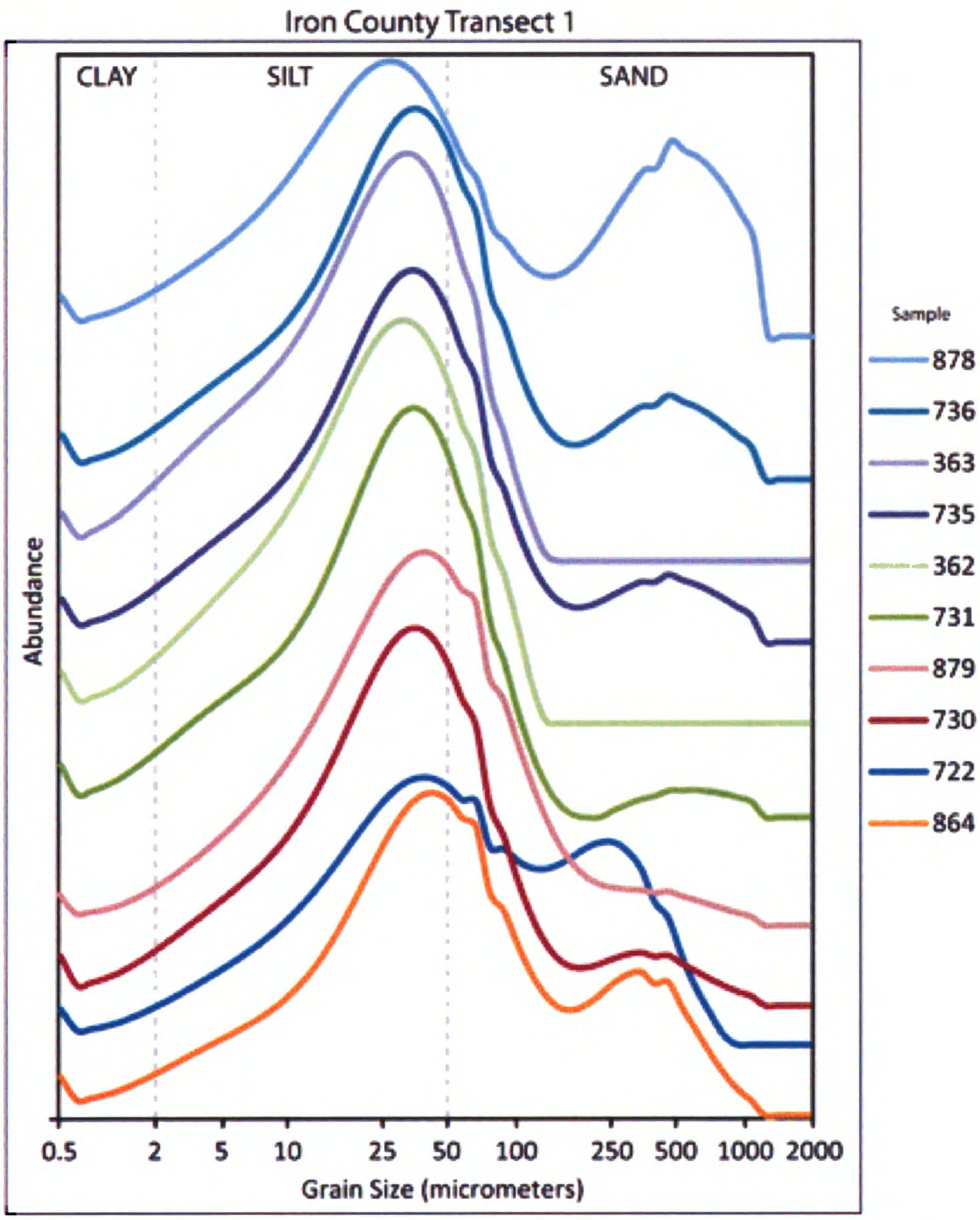

Figure C.5. Continuous particle size distribution curves for representative samples (878, proximal to outwash plain; 864, distal to outwash plain) from Iron County transect 1 (IC 1). Curves are offset vertically for clarity.

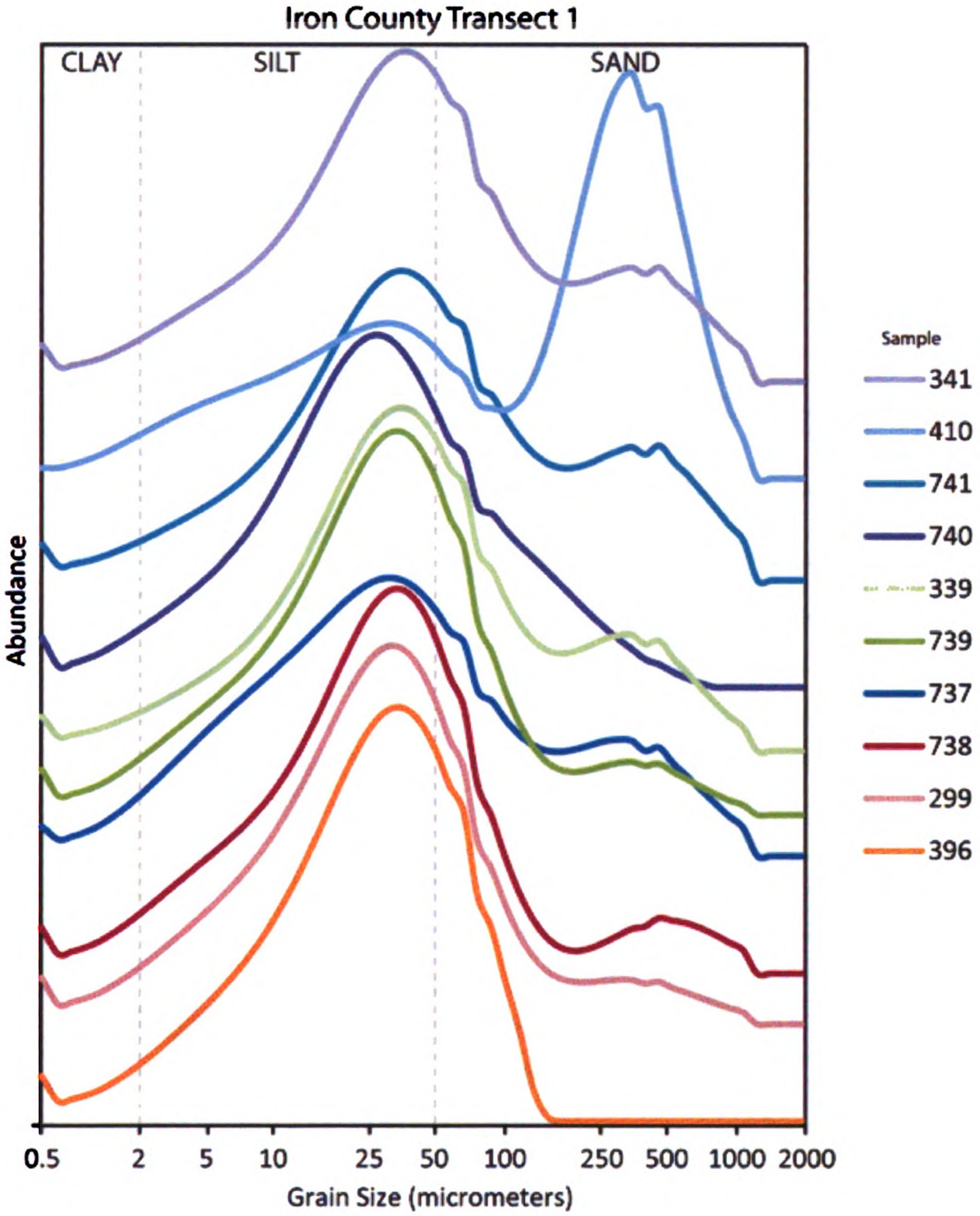

Figure C.6. **Continuous particle size distribution curves for representative samples (341, proximal to outwash plain; 396, distal to outwash plain) from Iron County transect 1 (IC 1). Curves are offset vertically for clarity.**

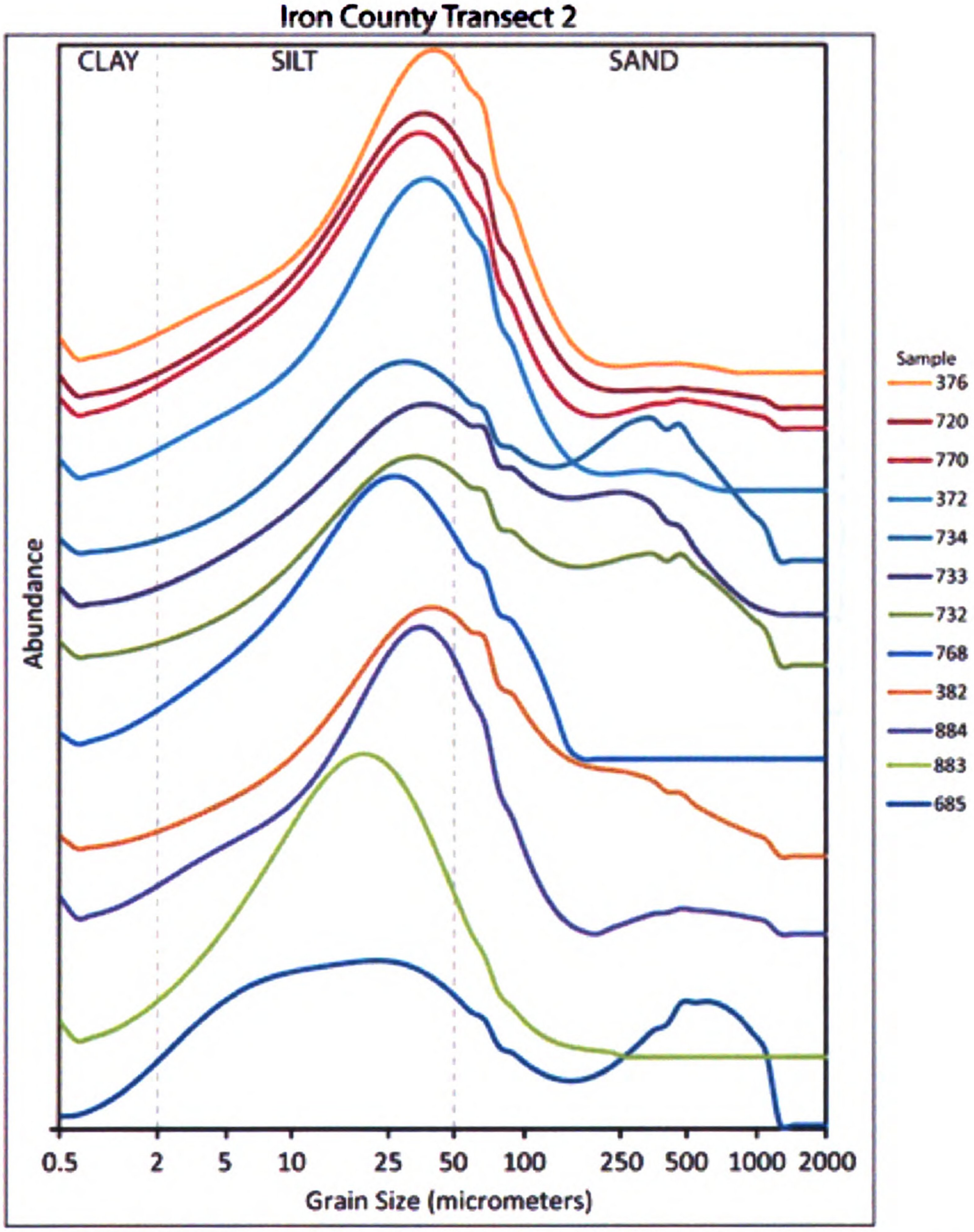

Figure C.7. Continuous particle size distribution curves for representative samples (376, proximal to the Watersmeet Moraine; 685, distal to the Watersmeet Moraine) from Iron County transect 2 (IC 2). Curves are offset vertically for clarity.

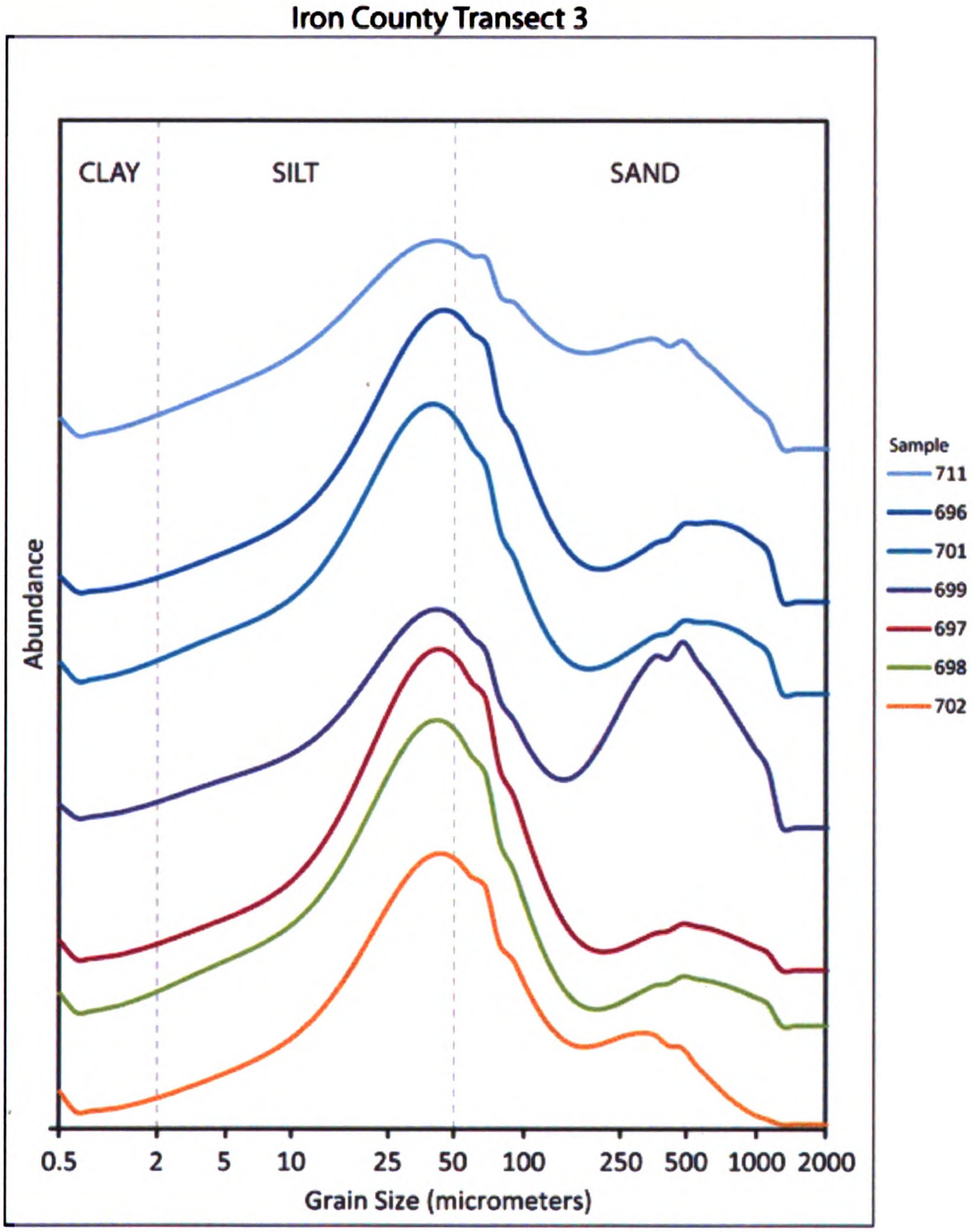

Figure C.8. Continuous particle size distribution curves for representative samples (711, proximal to the Watersmeet Moraine; 702, distal to the Watersmeet Moraine) from Iron County transect 3 (IC 3). Curves are offset vertically for clarity.

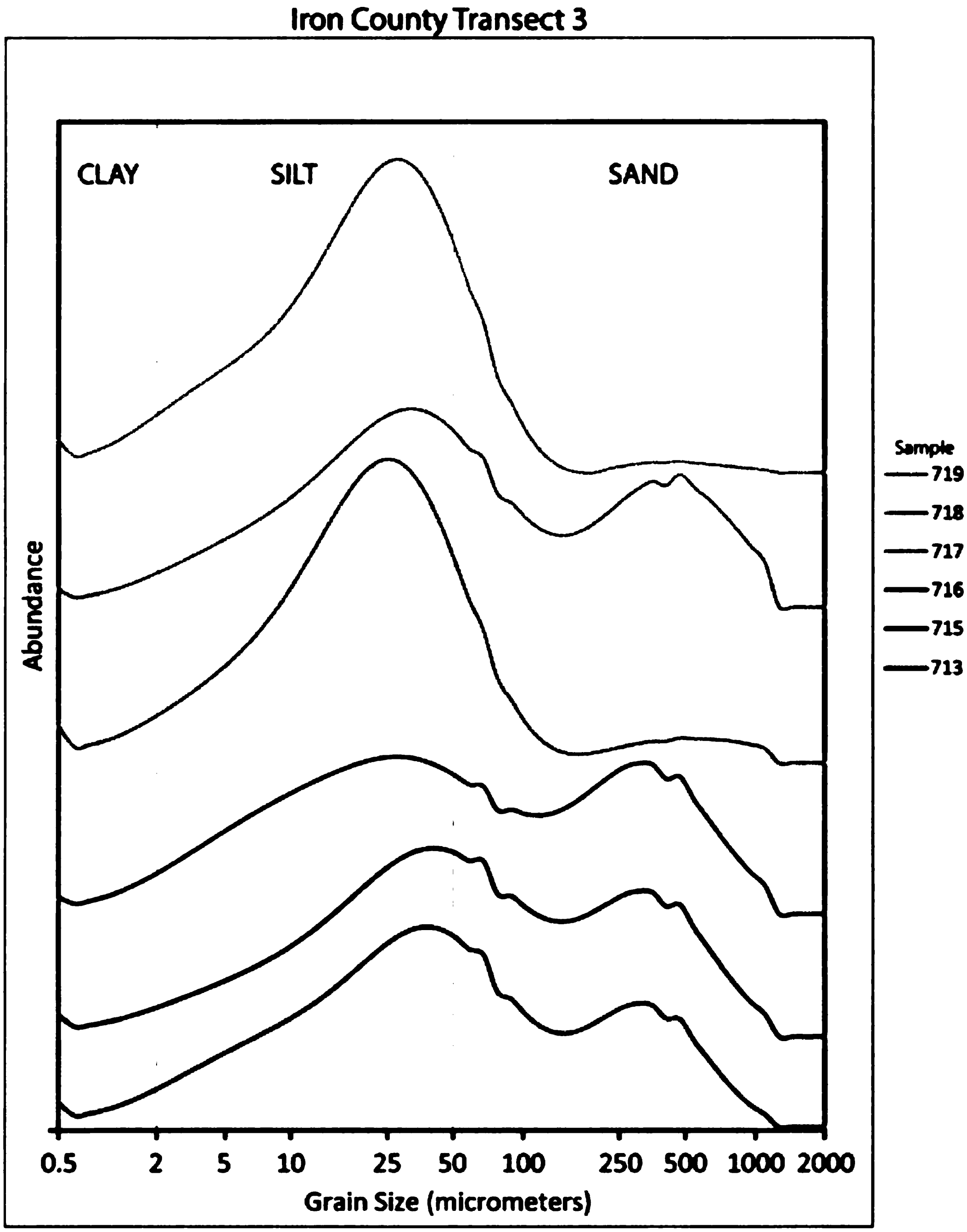

Figure C.9. Continuous particle size distribution curves for representative samples (719, proximal to the Watersmeet Moraine; 692, distal to the Watersmeet Moraine) from Iron County transect 3 (IC 3). Curves are offset vertically for clarity.

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