MAGNETIC SUSCEPTIBILITY OF FLUVIAL SEDIMENT, LOWER FOR RIVER, NORTHEASTERN ILLINOIS, AND IMPLICATIONS FOR DETERMINING SEDIMENT SOURCE AREA

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By Christopher F. Waythomas

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CONVERSION FACTORS

Multiply	*By*	*To obtain*
micron	0.00003937	inch
millimeter (mm)	0.03937	inch
centimeter	0.3937	inch
meter (m)	3.281	foot
kilometer (km)	0.6214	mile
square kilometer (km^2)	0.3861	square mile
cubic meter per kilogram (m^3/kg^{-1})	16.01	cubic feet per pound

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ABSTRACT

The magnetic-susceptibility characteristics of fluvial sediment along the lower Fox River in northeastern Illinois were studied as a means for understanding the provenance of fluvial sediment within the Fox River drainage basin. High- and low-frequency susceptibility and frequency-dependent susceptibility were determined on samples of recently deposited overbank sediment, overbank sediment from flood-plain sequences, main-channel sediment, channel-margin sediment, bar-top sediment, and topsoil from cultivated fields. Relations between magnetic susceptibility and sediment type are useful in delineating sediment source-areas and three distinct source areas are indicated by the data. In general, the magnetic susceptibility of all types of fluvial sediment found along the lower Fox River tends to decrease with increasing distance downstream. This probably results from erosion of the St. Peter Sandstone, which liberates low-magnetic-susceptibility quartz sand into the river. The lack of a corelation between bulk sediment magnetic susceptibility and sediment particle size indicates that magnetic minerals are probably evenly distributed throughout the particle-size distribution of the samples analyzed.

INTRODUCTION

The Illinois River basin is being studied by the U. S. Geological Survey as part of a National Water Quality Assessment (NAWQA) program. The Fox River was selected for study because it is a major tributary draining agricultural land in the upper Illinois River basin, and it flows in a channel that consists of erodible, fine-grained sediment. One of the objectives of the NAWQA program is to identify and determine the effects of various point and nonpoint sources of water pollution. Abnormally large concentrations of sediment in rivers generally are considered to be a type of water pollution. Thus, it is important to identify the primary sources of sediment in rivers and to determine what conditions promote increased sediment concentrations.

The magnetic-mineral content of fluvial sediments and their associated magnetic properties are often useful aids in the study of sediment provenance. Because source areas for fluvial sediment sometimes contain a unique magnetic-mineral assemblage, it may be possible to determine the relative contributions of different source areas to the sediment fractions that comprise the bulk fluvial sediment. Application of magnetic-mineral studies to this problem thus far has been limited to only a few studies within river catchments in Great Britain, Scotland, and the United States (Oldfield and others, 1979; Oldfield and others, 1985; Walling and others, 1979; Thompson and Morton, 1979). The results of these investigations indicate that it is possible to identify various sediment types according to their magnetic-mineral properties and thus trace the sediment back to its source area. Although a variety of magnetic- mineral studies can be used to determine the magnetic attributes of sediments, only bulk magnetic-susceptibility measurements were used in this study. Measurements of bulk magnetic susceptibility were used in an attempt to identify first-order magnetic properties of fluvial sediments in the upper Illinois River basin and to assess the potential for additional magnetic-mineral studies as a means of tracing fluvial sediment input to the river system. In this study, sediments were collected along the lower Fox River, a southward-flowing tributary to the Illinois River in the northeastern part of the upper Illinois River basin (fig. 1).

Purpose and Scope

A study of fluvial sediment magnetic susceptibility was conducted to evaluate potential sediment-source areas in the lower Fox River drainage basin. The purpose of the study is to determine if measurements of bulk sediment magnetic susceptibility are diagnostic of specific sediment source areas, and can be used to understand the origin and dispersal history of fine-grained fluvial sediment in the Fox River.

Description of Study Area

The reach of the Fox River selected for study is the lower one-third of the river. The study reach is about 55 km long and lies between the towns of Ottawa and Yorkville (fig. 1). There are two small dams on the river within the study reach, one upstream at Yorkville and one downstream at Dayton (fig. 2). The Yorkville Dam functions like a spillway because it is only about 2 m high. The Dayton Dam is considerably higher (about 20 m) and is used to generate hydroelectric power. There is a lengthy zone of slack water pstream from each dam that probably allows some sedimentation to occur. Discharge of water over the Yorkville Dam is continuous, except during periods of exceptionally low flow. Streamflow discharge at Dayton Dam, which can be controlled at the hydroelectric plant, is not continuous.

The Fox River has its headwaters in southern Wisconsin and has a drainage basin of approximately 5,000 km2. The present river flows within a much larger valley that was cut by late Pleistocene outwash streams draining the western side of the Lake Michigan sublobe of the Laurentide Ice Sheet (Lineback and others, 1983). The valley contains a considerable thickness of outwash sand and gravel that has been incised since glaciers retreated from the region. The modern channel of the Fox River is flanked by a series of terraces that can be traced almost continuously within the study area to the mouth of the Fox River near its confluence with the Illinois River (fig. 1).

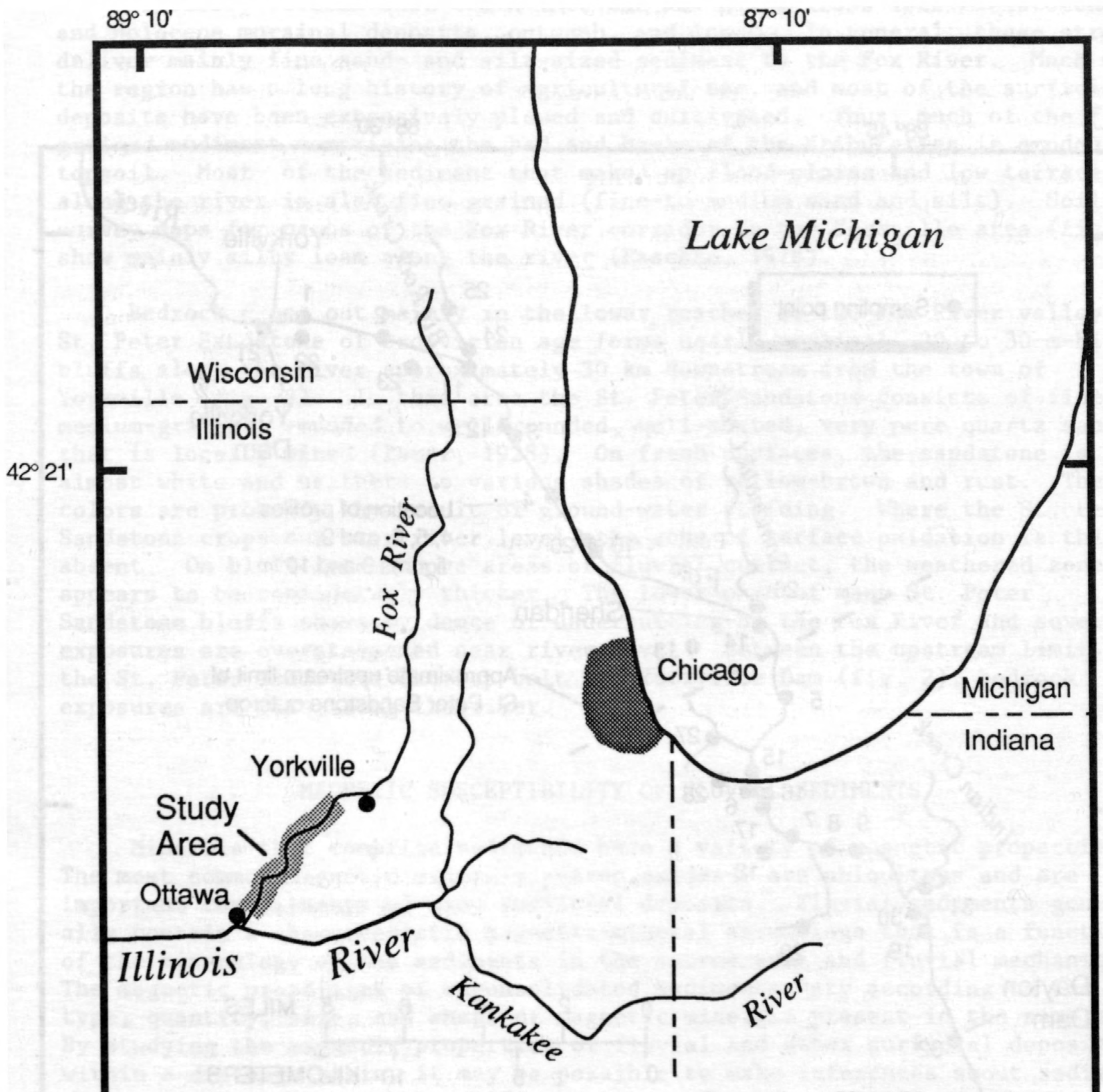

Figure 1.--Study area in northeastern Illinois.

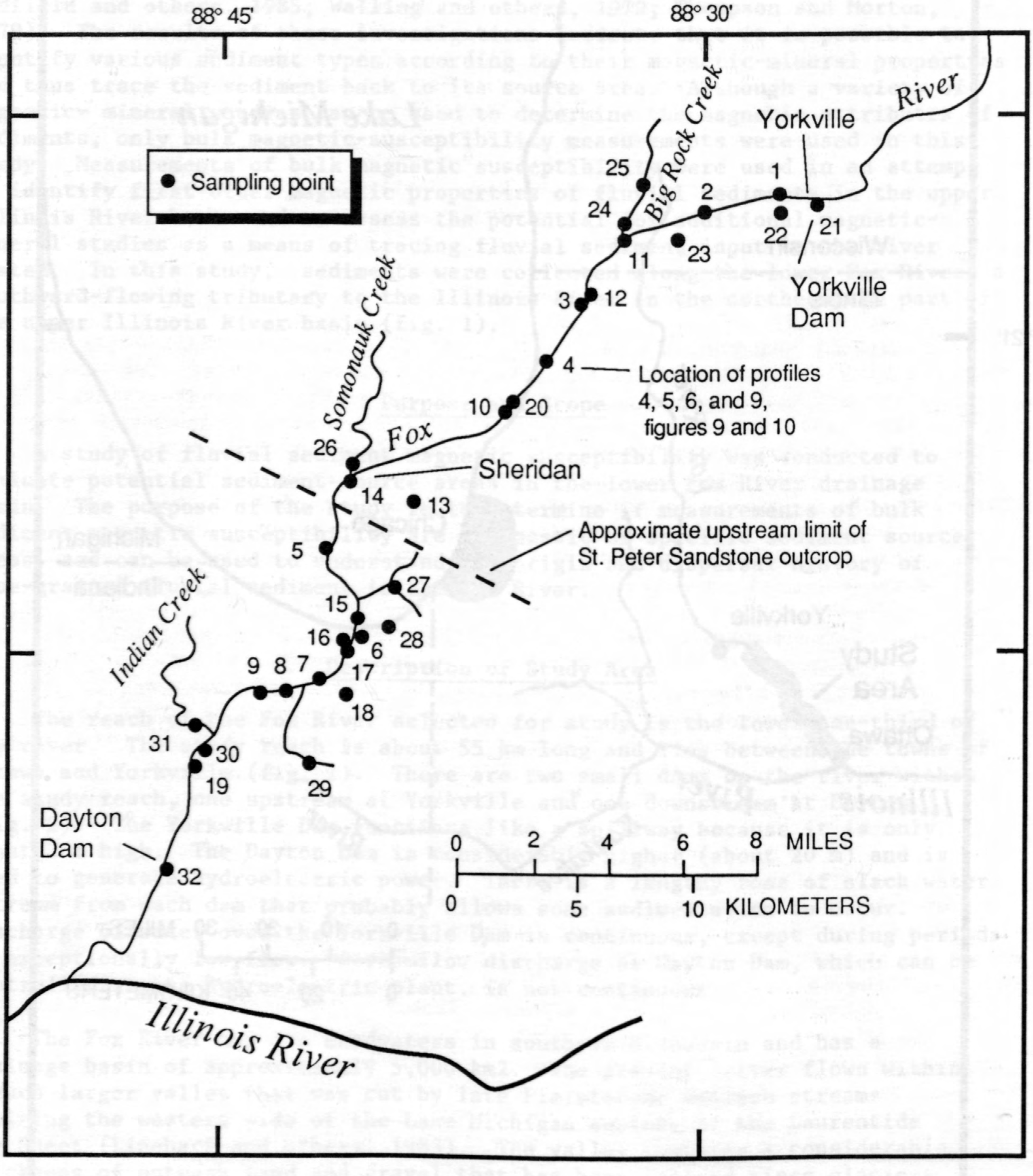

Figure 2.--Location of sediment sampling points in the lower Fox River basin and approximate upstream limit of St. Peter Sandstone outcrop.

Tributary streams that drain into the Fox River cross late Pleistocene and Holocene morainal deposits, outwash, and loess. In general, these streams deliver mainly fine sand- and silt-sized sediment to the Fox River. Much of the region has a long history of agricultural use, and most of the surficial deposits have been extensively plowed and cultivated. Thus, much of the fine-grained sediment comprising the bed and banks of the tributaries is eroded topsoil. Most of the sediment that makes up flood-plains and low terraces along the river is also fine grained (fine-to-medium sand and silt). Soil survey maps for parts of the Fox River corridor in the Yorkville area (fig. 1) show mainly silty loam along the river (Paschke, 1978).

Bedrock crops out mainly in the lower reaches of the Fox River valley. St. Peter Sandstone of Ordovician age forms nearly vertical, 20 to 30-m-high bluffs along the river approximately 30 km downstream from the town of Yorkville (fig. 2). In this area the St. Peter Sandstone consists of fine- to medium-grained, rounded to well-rounded, well-sorted, very pure quartz sand that is locally mined (Lamar, 1928). On fresh surfaces, the sandstone is almost white and weathers to various shades of yellow-brown and rust. These colors are probably the result of ground-water staining. Where the St. Peter Sandstone crops out near river level, the zone of surface oxidation is thin or absent. On bluff faces above areas of fluvial contact, the weathered zone appears to be considerably thicker. The lower part of many St. Peter Sandstone bluffs shows evidence of undercutting by the Fox River and several exposures are oversteepened near river level. Between the upstream limit of the St. Peter Sandstone outcrop belt and Yorkville Dam (fig. 2), bedrock exposures are rare along the river.

MAGNETIC SUSCEPTIBILITY OF FLUVIAL SEDIMENTS

Minerals that comprise sediments have a variety of magnetic properties. The most common magnetic minerals --iron oxides-- are ubiquitous and are important constituents of many surficial deposits. Fluvial sediments generally contain a characteristic magnetic-mineral assemblage that is a function of the mineralogy of the sediments in the source area and fluvial mechanics. The magnetic properties of unconsolidated sediments vary according to the type, quantity, size, and shape of magnetic minerals present in the sample. By studying the magnetic properties of fluvial and other surficial deposits within a drainage basin, it may be possible to make inferences about sediment source (Oldfield and others, 1979; Walling and others, 1979).

One type of magnetic measurement that can be applied to the study of fluvial sediment source is bulk magnetic susceptibility. In general, the magnetic susceptibility of a mineral or sediment reflects the ease with which that mineral or sediment can become magnetized when placed in a magnetic field. Magnetic susceptibility is defined as the ratio of the induced magnetization to the intensity of the magnetizing field (Dearing and others, 1985; Mullins, 1977). Mass susceptibility is the induced magnetization per unit mass divided by the intensity of the magnetizing field (Mullins, 1977).

Naturally occurring substances behave differently when placed in a magnetic field. Although all minerals exhibit some degree of magnetic behavior, ferrimagnetism is the most important among magnetic minerals in soils and sediments (Dearing and others, 1985). Ferrimagnetism results from the unique alignment of the magnetic moments within minerals such as magnetite and maghemite. In these minerals, two-thirds of the iron atoms align themselves in one direction, but the remaining one-third of the iron atoms are aligned in the opposite direction. This results in a strong, positively aligned magnetic moment when ferrimagnetic minerals are placed in an appropriate field (Mullins, 1977; Dearing and others, 1985). Magnetite and maghemite are usually the dominant magnetic minerals that affect the magnetic characteristics of sediments and soils, even if present only in trace amounts (Dearing and others, 1985).

The bulk magnetic susceptibility of fluvial sediment can vary as a function of (1) the types of magnetic minerals contained in the sediment, (2) the quantity of magnetic minerals present, and (3) the magnetic grain size of the magnetic minerals present. Minerals such as quartz and feldspar have very low magnetic susceptibilities (-0.58 and -0.48×10^{-8} m^3 kg^{-1}, respectively), whereas ferromagnetic minerals such as magnetite and maghemite have magnetic susceptibilities that range from 3.9 to 10×10^4 m^3 kg^{-1} (Mullins, 1977).

STUDY METHODS

Sediments from flood-plain sequences, the present channel, and recently deposited overbank material were sampled for magnetic measurements and particle-size analysis (fig. 2). All samples were air dried in a laboratory, then subsampled, put in cube-shaped plastic vials, and weighed. The magnetic susceptibility of the sediment cubes was measured with a Bartington susceptibility meter (model M.S. 2 B) attached to an external dual frequency sensor. The sensor has operating frequencies of 0.46 (low frequency) and 4.6 (high frequency) kHz. Both high- and low-frequency measurements were determined for all samples. At least four measurements were taken sequentially and the susceptibility meter was reset to zero between each measurement. Free-air measurements were not taken and no correction for drift was made. Ninety samples were measured in approximately one hour and several samples were remeasured to check for meter drift. Differences between replicate low-frequency measurements differed by less than 5 percent. Replicate high-frequency susceptibility measurements showed much greater variability. For some samples, the values for high-frequency susceptibility were greater than the values for low-frequency susceptibility.

Frequency-dependent susceptibility (χ_{fd}) was calculated from the high- and low-frequency susceptibility measurements with the following formula (Thompson and Oldfield, 1986):

$$\chi_{fd}\% = \frac{(\chi_{lf} - \chi_{hf})}{\chi_{lf}} \times 100$$

where χ_{lf} and χ_{hf} are the low- and high-frequency bulk susceptibilities, respectively. Frequency-dependent susceptibility is the variation of susceptibility with changes in measurement frequency and is related to the percentage of magnetic grains whose magnetic behavior is intermediate between that of stable single-domain grains and grains exhibiting a superparamagnetic response (Dearing and others, 1985; Thompson and Oldfield, 1986).

Superparamagnetism is a phenomenon characteristic of very fine magnetic grain sizes (0.001-0.01 microns). Such grains have no stable remanent magnetism because they have equivalent thermal vibration and magnetic energies (Thompson and Oldfield, 1986). Superparamagnetic mineral grains assume a magnetic alignment parallel to that of an applied field. Superparamagnetic grains may have a greater effect on the susceptibility of a sample than do mineralogically equivalent single-domain or multi-domain grains (Thompson and Oldfield, 1986). If a sample contains a large percentage of ferrimagnetic grains whose size and shape characteristics place them close to the superparamagnetic/stable single-domain boundary, then pronounced changes in susceptibility with changes in measurement frequency will result. An increase in measurement frequency has the effect of blocking in a portion of the grains that lie within the superparamagnetic/stable single-domain boundary. Grains that become blocked in behave as if they were stable single-domain grains (Maher, 1986). This results in a decrease in susceptibility with increasing measurement frequency. Magnetic grains that occupy the superparamagnetic/stable single-domain boundary region have been termed "viscous" grains because they exhibit a delayed response to the magnetizing field (Mullins and Tite, 1973; Dearing and others, 1985).

In addition to making magnetic-susceptibility measurements, the particle size of some of the fluvial sediments also was determined by sieving and pipette analysis. Magnetic measurements were made on bulk sediment samples rather than individual size-fraction splits. These data were used to examine the relation between magnetic susceptibility and particle size of the sediments.

Fluvial sediments along the Fox River were grouped into six categories, based on their mode of occurrence. Two categories include sediment from within the channel and consist of (1) main-channel sediment from the channel bottom and (2) main-channel sediment from the channel margin. Three additional categories consist of (3) overbank sediment from flood-plain sequences, (4) recently deposited overbank sediment, and (5) topsoil from cultivated fields. Sediment from tributary streams comprises category (6) and consists of both main-channel and channel-margin sediment. Samples of fresh and weathered St. Peter Sandstone bedrock also were collected.

Low-frequency, high-frequency, and frequency-dependent susceptibilities were determined for all of the sample types described above. The data were used to determine if any relation existed between magnetic susceptibility and (1) sediment type, (2) distance downstream for a given sediment type, (3) depth for profiles through flood-plain sequences, and (4) bulk sediment particle size.

MAGNETIC SUSCEPTIBILITY OF DIFFERENT SEDIMENT TYPES

The magnetic susceptibility characteristics of the several sediment groups are given in tables 1 and 2. These data, plotted in figure 3, indicate the general association between magnetic susceptibility and sediment type.

Table 1.--*Low-frequency mass susceptibility of sediment types and St. Peter Sandstone from the lower Fox River area*

[Values for mass susceptibility in 10^{-8} cubic meters per kilogram; NA, not applicable]

Sediment type	Number of samples	Susceptibility Mean	Standard deviation	Coefficient of variation
Main channel	17	99.4	124.8	1.25
Channel margin	11	111.7	83.2	.74
Overbank	43	52.3	15.8	.30
Recent overbank	12	64.0	22.8	.36
Cultivated fields	5	65.8	42.3	.64
Tributary streams	11	57.3	10.2	.18
Fresh St. Peter Sandstone	1	.0	NA	NA
Weathered St. Peter Sandstone	1	114.6	NA	NA

Table 2.--*Frequency-dependent susceptibility of sediment types and St. Peter Sandstone from the lower Fox River area*

[Frequency-dependent susceptibility in percent; NA, not applicable]

Sediment type	Number of samples	Susceptibility Mean	Standard deviation	Coefficient of variation
Main channel	17	10.7	7.6	0.71
Channel margin	11	7.0	6.9	.99
Overbank	43	12.2	6.8	.56
Recent overbank	12	9.6	4.9	.52
Cultivated fields	5	9.4	7.5	.80
Tributary streams	11	11.9	7.8	.65
Fresh St. Peter Sandstone	1	.0	NA	NA
Weathered St. Peter Sandstone	1	20.0	NA	NA

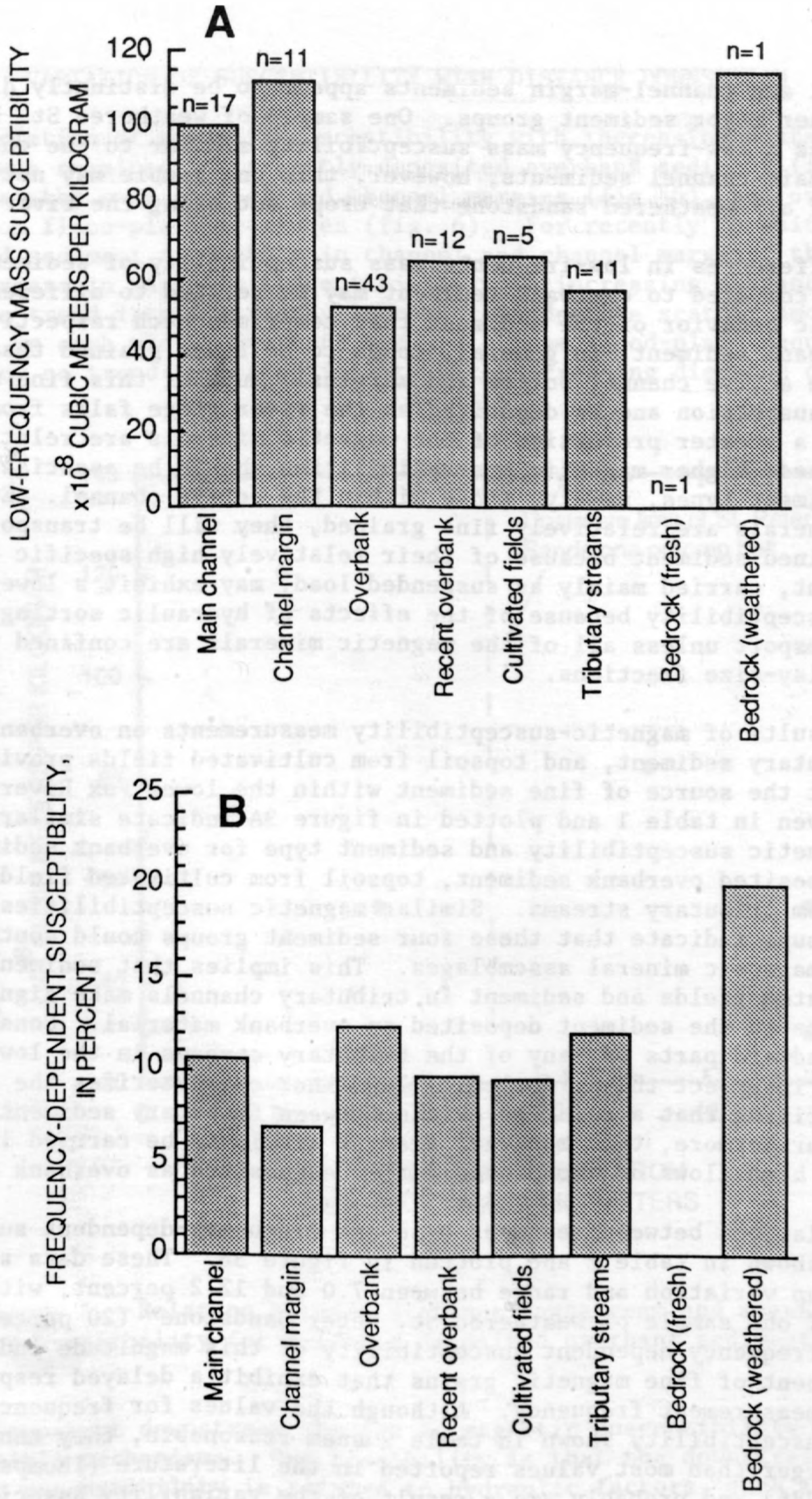

Figure 3.--Relation between (A) low-frequency mass susceptibility and (B) frequency-dependent susceptibility, as a function of sediment type. n = number of samples.

Main-channel and channel-margin sediments appear to be distinctly different from the other major sediment groups. One sample of weathered St. Peter Sandstone has a low-frequency mass susceptibility similar to the channel-margin and main-channel sediments; however, this one sample may not be representative of all weathered sandstone that crops out along the river.

The differences in low-frequency mass susceptibility of sediment within the channel compared to overbank sediment may be related to differences in the hydraulic behavior of the sediment that comprises each respective sediment type. Overbank sediment, in general, tends to be finer grained than sediment found on the active channel bottom and margins. Much of this fine material is carried in suspension and is deposited as the river stage falls from flood levels. If a greater proportion of the magnetic minerals are relatively coarse grained, higher magnetic susceptibilities should be associated with the coarser sediment types, namely, those within the active channel. Even if the magnetic minerals are relatively fine grained, they will be transported with coarser grained sediment because of their relatively high specific gravities. Fine sediment, carried mainly as suspended load, may exhibit a lower bulk magnetic susceptibility because of the effects of hydraulic sorting during fluvial transport unless all of the magnetic minerals are confined to the silt- and clay-size fractions.

The results of magnetic-susceptibility measurements on overbank sediments, tributary sediment, and topsoil from cultivated fields provide information about the source of fine sediment within the lower Fox River basin. The data given in table 1 and plotted in figure 3A indicate similarities between magnetic susceptibility and sediment type for overbank sediment, recently deposited overbank sediment, topsoil from cultivated fields, and sediment from tributary streams. Similar magnetic susceptibilities among the sediment groups indicate that these four sediment groups could contain nearly equivalent magnetic mineral assemblages. This implies that sediment derived from cultivated fields and sediment in tributary channels make significant contributions to the sediment deposited as overbank material. Considering that the headward parts of many of the tributary streams in the lower Fox River basin intersect the agricultural land that characterizes the region, it is not surprising that a relation exists between tributary sediment and topsoil. Furthermore, this material also is likely to be carried in suspension during high flows or floods and later redeposited as overbank material.

The relations between sediment type and frequency-dependent susceptibility are shown in table 2 and plotted in figure 3B. These data show little between-group variation and range between 7.0 and 12.2 percent, with the exception of one sample of weathered St. Peter Sandstone (20 percent). Values for frequency-dependent susceptibility of this magnitude indicate a large component of fine magnetic grains that exhibit a delayed response to changes in measurement frequency. Although the values for frequency-dependent susceptibility shown in table 2 seem reasonable, they tend to be slightly larger than most values reported in the literature (Thompson and Oldfield, 1986) and probably are a result of the variability associated with replicate high-frequency susceptibility measurements.

VARIATION OF SUSCEPTIBILITY WITH DISTANCE DOWNSTREAM

The variation of magnetic susceptibility with increasing distance downstream was examined for recently deposited overbank sediment (fig. 4), sediment from the main channel and channel margins (fig. 5), and overbank sediment from flood-plain sequences (fig. 6). For recently deposited overbank sediment and sediment from the main channel and channel margins, there is a general decrease in magnetic susceptibility with increasing distance downstream. The trend is not strictly linear; considerable scatter among the data is apparent in each plot. Overbank sediments from flood-plain sequences (fig. 6) show no trend in susceptibility with increasing distance downstream.

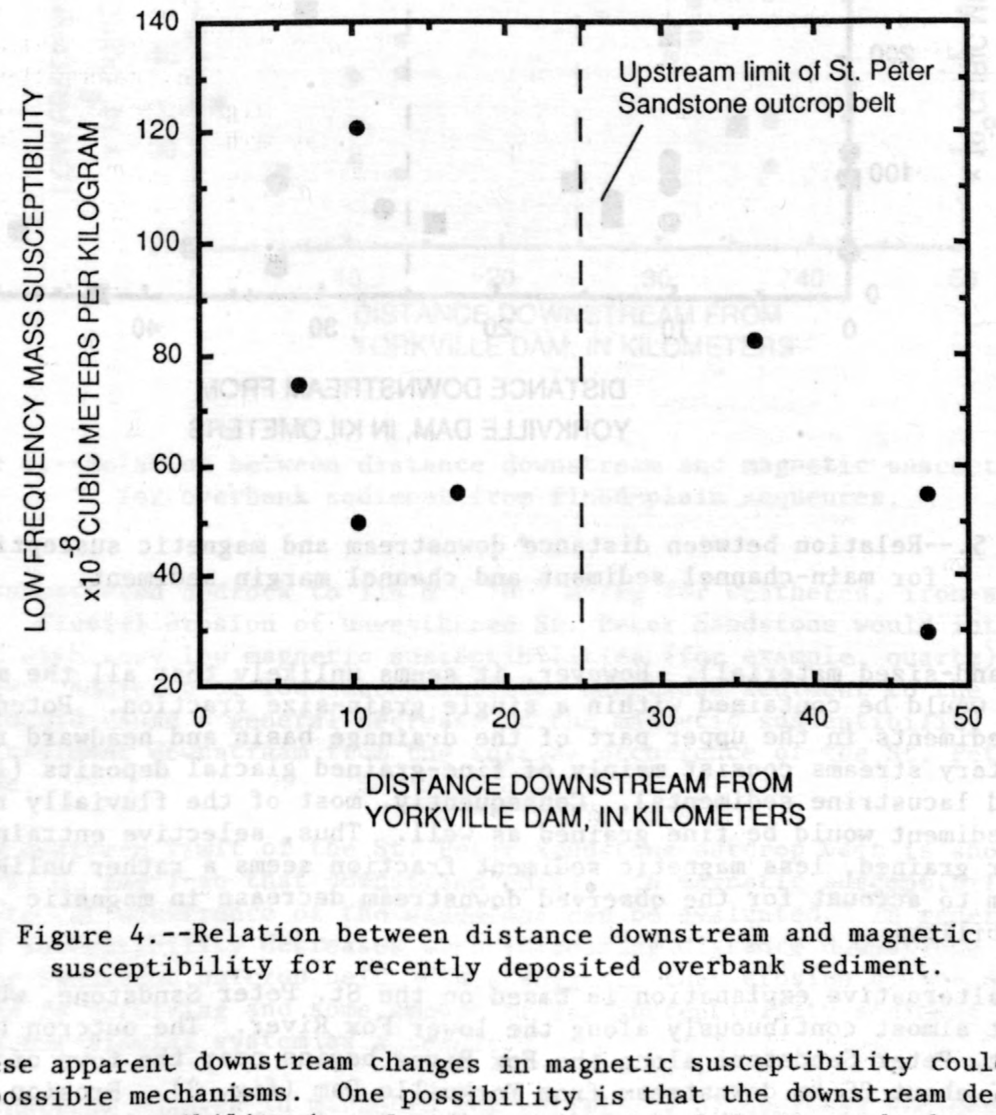

Figure 4.--Relation between distance downstream and magnetic susceptibility for recently deposited overbank sediment.

These apparent downstream changes in magnetic susceptibility could occur by two possible mechanisms. One possibility is that the downstream decrease in magnetic susceptibility is related to hydraulic factors, such that the finer-grained, less magnetic sediment fraction is preferentially eroded and transported downstream. In order for this mechanism to operate, it must be assumed that most of the magnetic minerals are confined to the coarser grain

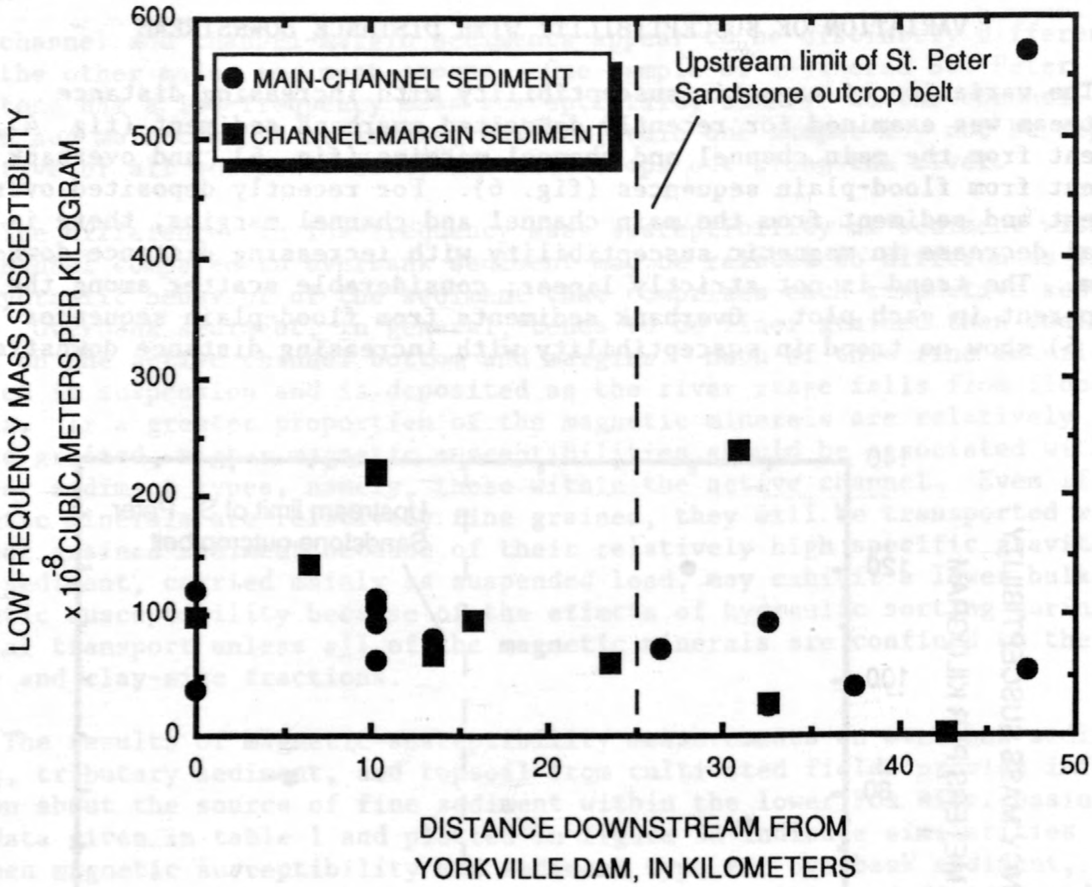

Figure 5.--Relation between distance downstream and magnetic susceptibility for main-channel sediment and channel margin sediment.

sizes (sand-sized material). However, it seems unlikely that all the magnetic minerals would be contained within a single grain-size fraction. Potential source sediments in the upper part of the drainage basin and headward reaches of tributary streams consist mainly of fine-grained glacial deposits (loess, till, and lacustrine sediments). Consequently, most of the fluvially retransported sediment would be fine grained as well. Thus, selective entrainment of the finer grained, less magnetic sediment fraction seems a rather unlikely mechanism to account for the observed downstream decrease in magnetic susceptibility.

An alternative explanation is based on the St. Peter Sandstone, which crops out almost continuously along the lower Fox River. The outcrop belt of the St. Peter Sandstone along the Fox River begins near the town of Sheridan, about 25 km downstream from Yorkville Dam (fig. 2). Erosion of the sandstone tends to liberate sediment that is almost entirely quartz sand. Pure quartz has a magnetic susceptibility of -0.58×10^{-8} m^3/kg (Mullins, 1977). Measured magnetic susceptibilities for St. Peter Sandstone samples collected from the lower Fox River area range from 0.0×10^{-8} m^3/kg for

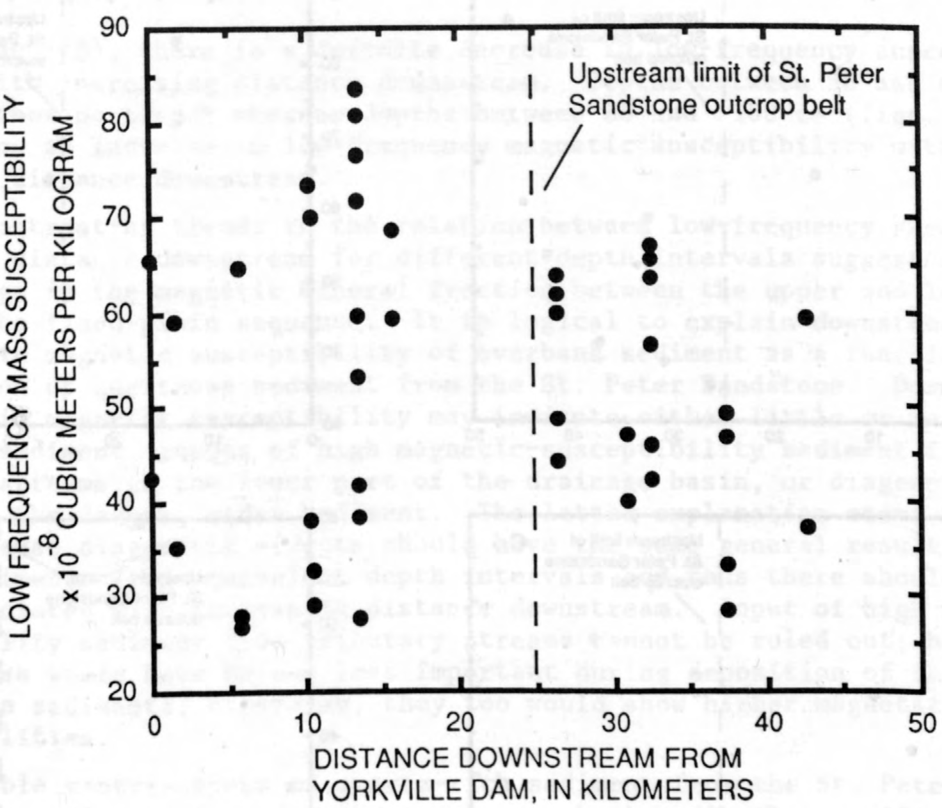

Figure 6.--Relation between distance downstream and magnetic susceptibility for overbank sediment from flood-plain sequences.

fresh, unweathered bedrock to 114.6 × 10^{-8} m^3/kg for weathered, iron-stained bedrock. Fluvial erosion of unweathered St. Peter Sandstone would introduce sediment with very low magnetic susceptibilities (for example, quartz) into the river. Addition of low susceptibility, quartzose sediment to the river system should cause a general decrease in the magnetic susceptibility of fluvial sediment downstream from the initial occurrence of the St. Peter Sandstone.

The upstream limit of the St. Peter Sandstone outcrop belt is shown in figures 5, 6, and 7 so that downstream changes in magnetic susceptibility with respect to the occurrence of the sandstone can be evaluated. In general, magnetic susceptibility decreases with increasing distance downstream from the St. Peter Sandstone outcrop belt. This suggests that erosion of the St. Peter Sandstone is occurring and some amount of low-susceptibility sediment is entering the fluvial system as a result.

Downstream changes in magnetic susceptibility of overbank sediment from flood-plain sequences are best evaluated by examining the data at specific depth intervals. Relations between low-frequency mass susceptibility and frequency-dependent susceptibility plotted against increasing distance downstream for specific depth intervals in the flood-plain are shown in figure 7. These plots indicate that, for depths between 10 and 40 cm

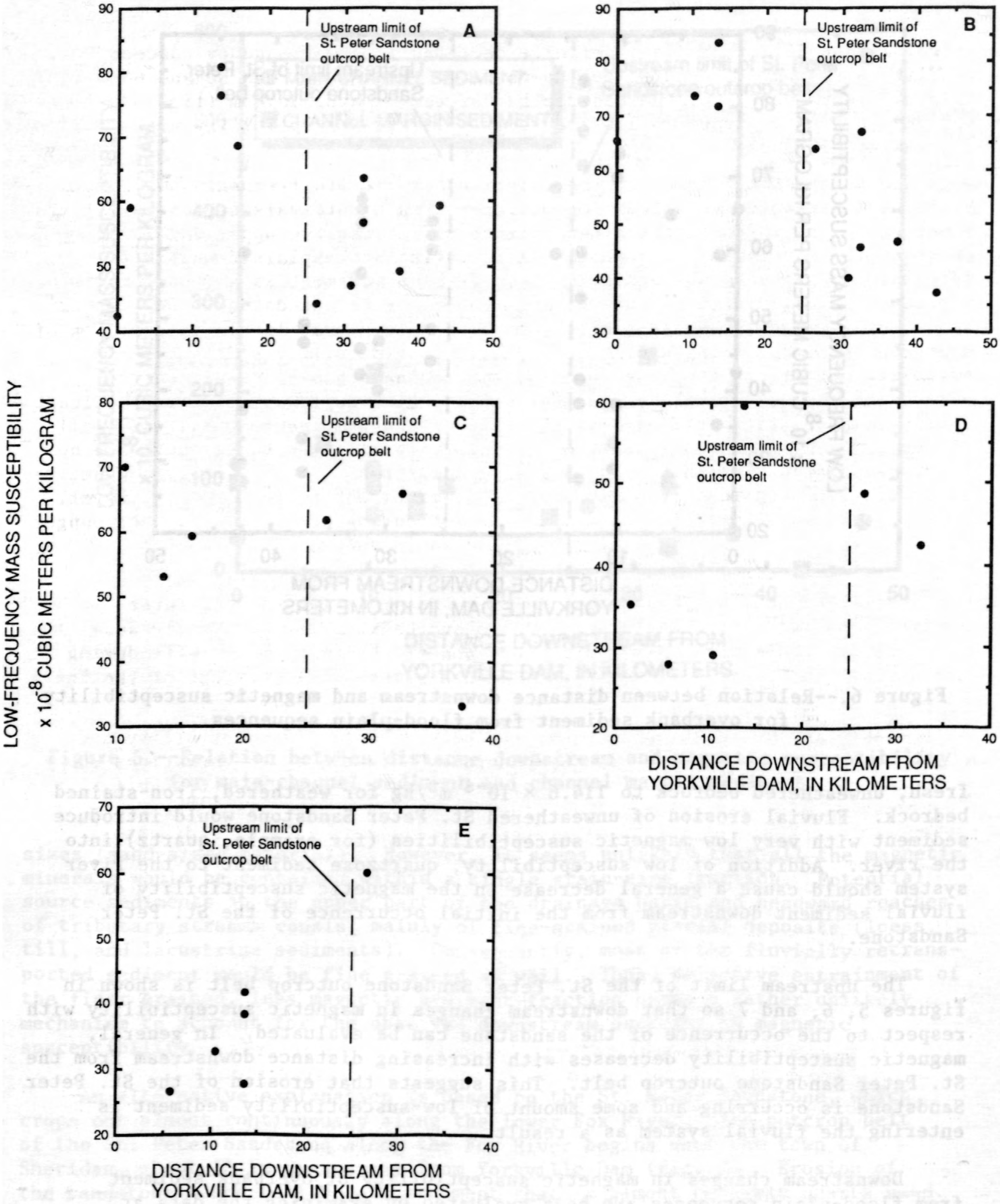

Figure 7.--Relation between distance downstream and magnetic susceptibilities for overbank sediment from specific depth intervals. (A) 10 cm depth, (B) 30-40 cm depth, (C) 30-60 cm depth, (D) 80-90 cm depth, (E) greater than 100 cm depth.

(figs. 7A and 7B), there is a definite decrease in low-frequency susceptibility with increasing distance downstream. Depths between 50 and 60 cm (fig. 7C) show no trend, whereas depths between 80 and >100 cm (figs. 7D and 7E) show an increase in low-frequency magnetic susceptibility with increasing distance downstream.

The contrasting trends in the relation between low-frequency susceptibility and distance downstream for different depth intervals suggest a significant change in the magnetic mineral fraction between the upper and lower parts of the flood-plain sequence. It is logical to explain downstream decreases in magnetic susceptibility of overbank sediment as a function of the introduction of quartzose sediment from the St. Peter Sandstone. Downstream increases in magnetic susceptibility may indicate either little or no input of quartzose sediment, inputs of high magnetic-susceptibility sediment from tributary streams in the lower part of the drainage basin, or diagenetic effects on the deeper, older sediment. The latter explanation seems the least likely because diagenetic effects should have the same general result on all of the sediments from equivalent depth intervals and thus there should be no trend associated with increasing distance downstream. Input of high magnetic-susceptibility sediment from tributary streams cannot be ruled out; however, this process would have become less important during deposition of the younger flood-plain sediments; otherwise, they too would show higher magnetic susceptibilities.

Variable contributions of quartz-rich sediment from the St. Peter Sandstone may also account for changes in overbank sediment magnetic susceptibility. This may imply reduced erosion of the sandstone bluffs during deposition of the basal flood-plain sequence along the lower part of the Fox River.

Trends in the relation between frequency-dependent susceptibility and distance downstream (figs. 4-7) are generally inconclusive. Variations in frequency-dependent susceptibility are mainly due to a small but significant component of fine viscous magnetic minerals such as magnetite. The processes responsible for concentration of magnetic minerals in fluvial sediments, especially those in the 0.03-to-0.05 micron-size range, are complex and probably are the result of several processes. Thus, downstream changes in frequency-dependent susceptibility cannot be easily explained in terms of any of the processes offered in explanation of the downstream trends in low-frequency susceptibility.

VARIATION OF SUSCEPTIBILITY WITH DEPTH IN FLOOD-PLAIN SEQUENCES

The magnetic susceptibility of flood-plain sediment from various depth intervals was evaluated to determine if any depth-related trends in magnetic susceptibility were present. Four profiles of modern flood-plain sediments were sampled at intervals of about 20 cm. Low-frequency mass-susceptibility variations as a function of depth are shown in figures 8, 9 and 10. In general, the low-frequency susceptibility values tend to decrease slightly with depth, although the trend is not linear. Samples from the stratigraphic profile at sampling point 4 (fig. 10) show a more regular decrease with depth than do samples from the other three sampling points (fig. 9). The data from sampling point 4 came from two profiles about 5 m apart. Both profiles show the same trend, although the magnitudes of the susceptibilities are slightly different.

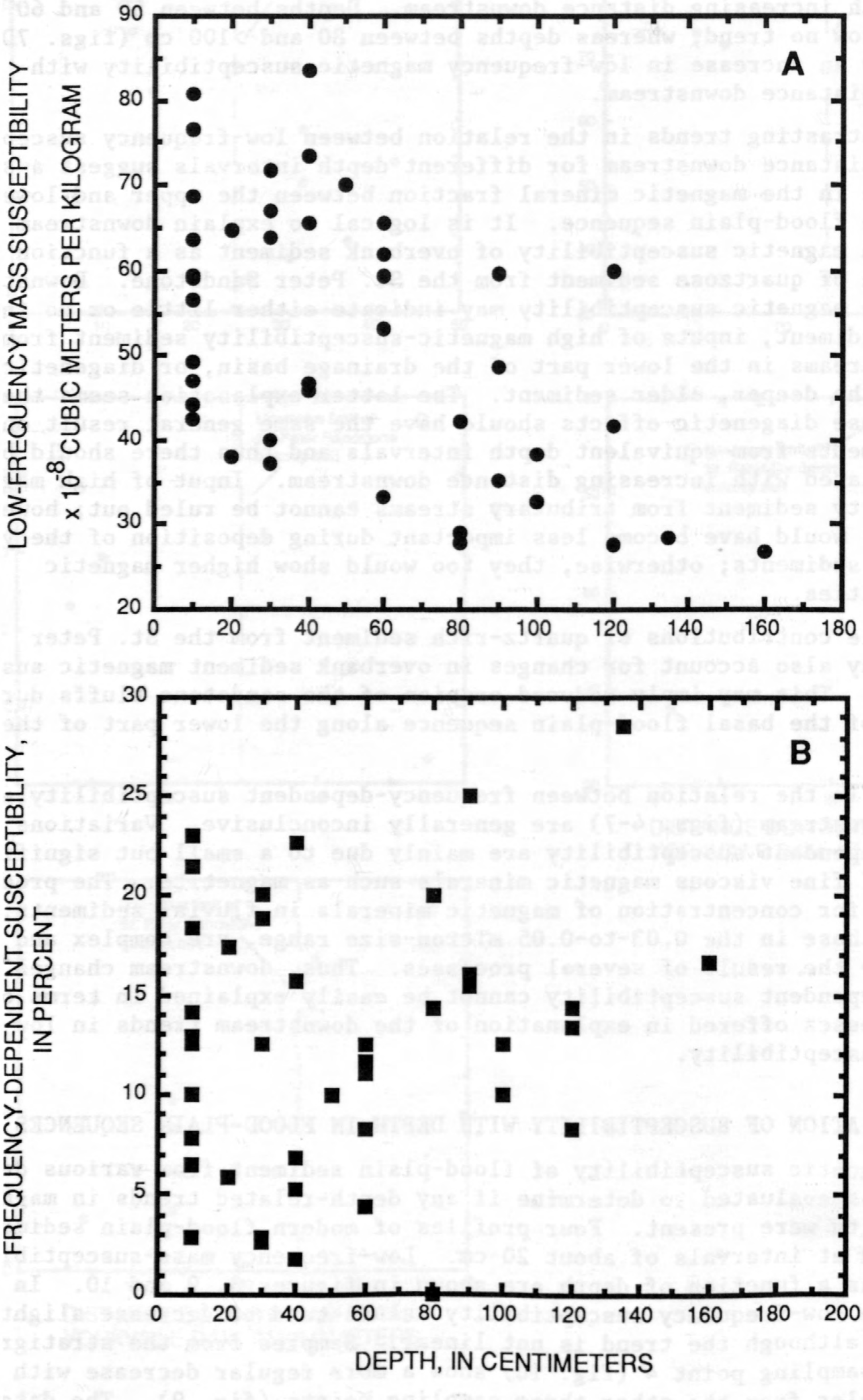

Figure 8.--Relation between magnetic susceptibility and depth below the top of the floodplain surface for floodplain sediments.

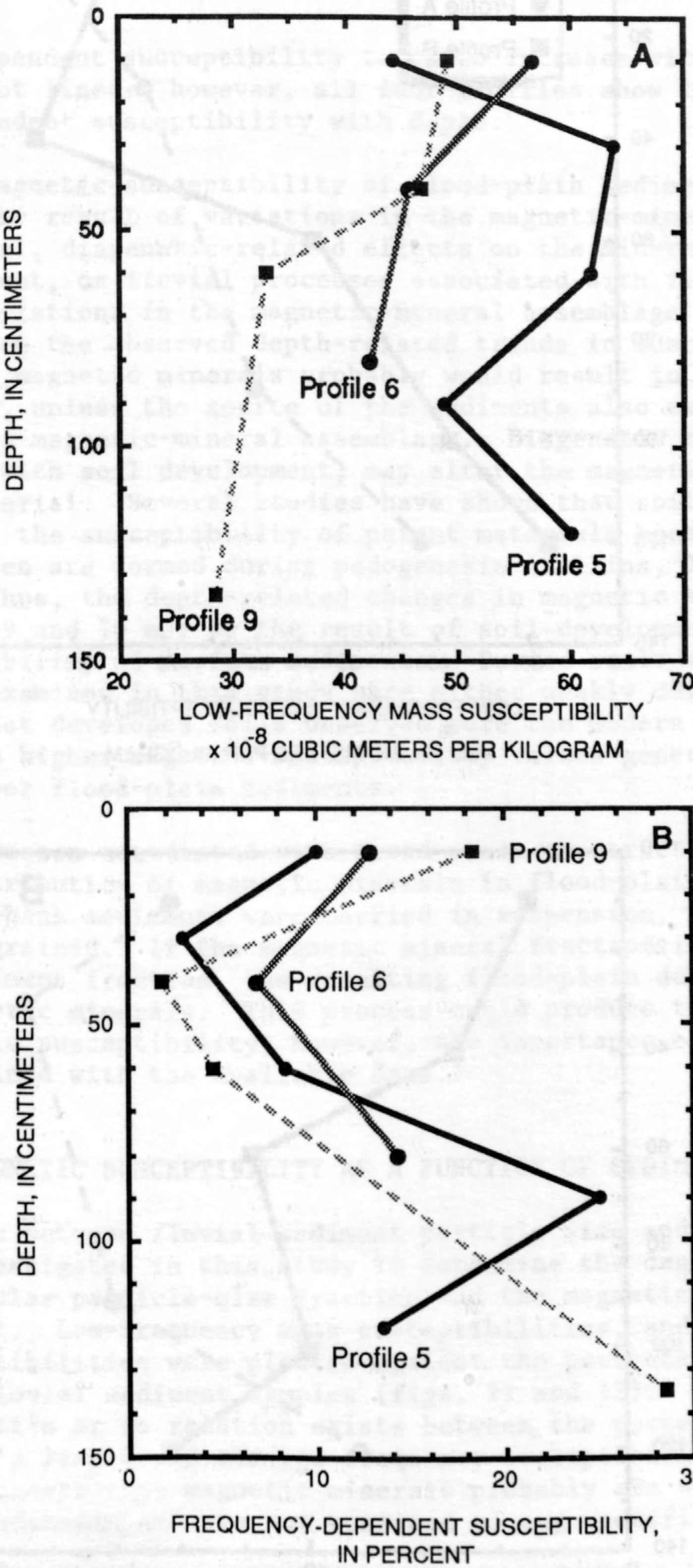

Figure 9.--Relation between magnetic susceptibility and depth for three floodplain profiles.

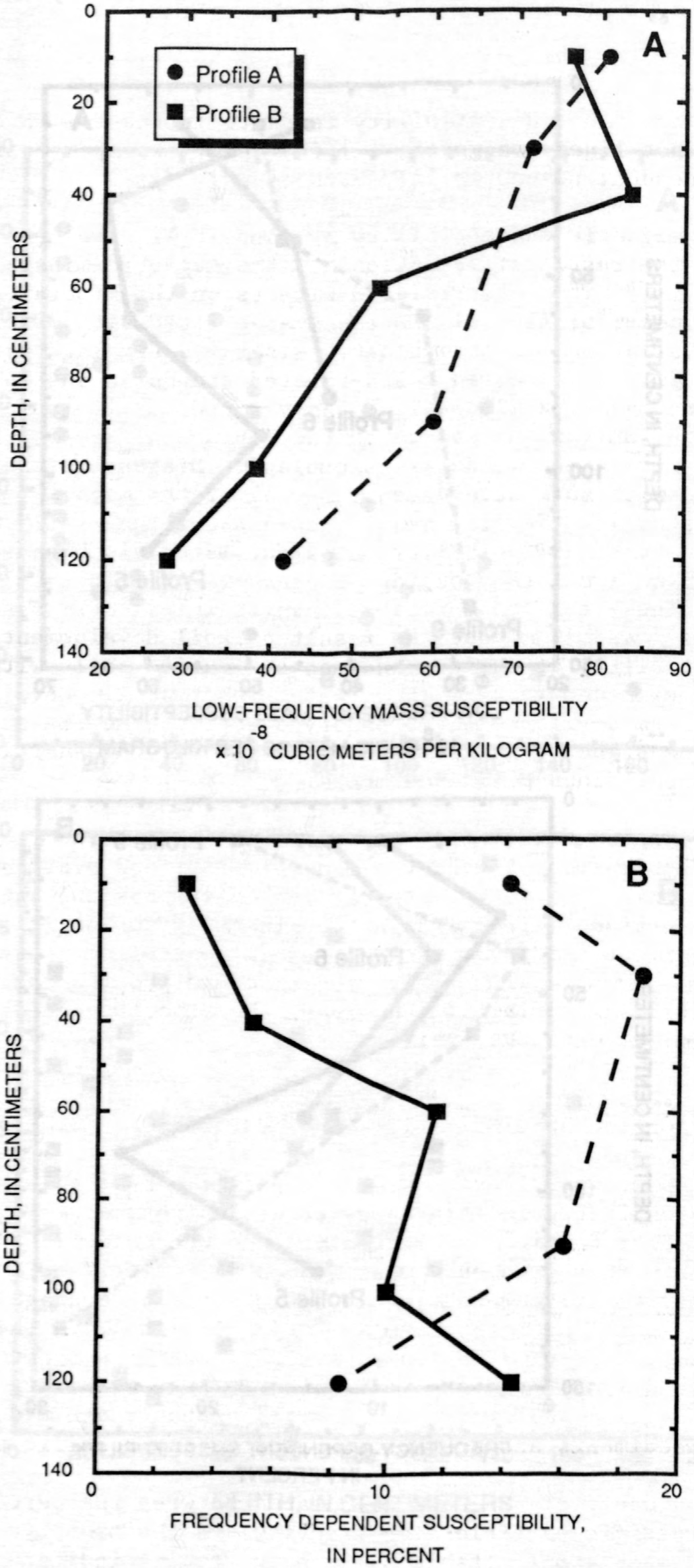

Figure 10.--Relation between magnetic susceptibility and depth for two floodplain profiles from sampling point number 4, figure 2.

Frequency-dependent susceptibility tends to increase with depth. Again, the increase is not linear; however, all four profiles show increasing values of frequency-dependent susceptibility with depth.

Changes in magnetic susceptibility of flood-plain sediments as a function of depth may be the result of variations in the magnetic-mineral assemblage of the parent material, diagenetic-related effects on the mineralogy of the flood-plain sediment, or fluvial processes associated with flood-plain construction. Variations in the magnetic-mineral assemblage probably are unlikely to produce the observed depth-related trends in susceptibility. Variable input of magnetic minerals probably would result in little or no relation to depth, unless the source of the sediments also exhibited a systematic change in its magnetic-mineral assemblage. Diagenetic changes, such as those associated with soil development, may alter the magnetic susceptibility of the parent material. Several studies have shown that soil development tends to increase the susceptibility of parent materials because secondary iron minerals often are formed during pedogenesis (Mullins, 1977; Dearing and others, 1985). Thus, the depth-related changes in magnetic susceptibility shown in figures 9 and 10 may be the result of soil development enriching the magnetic susceptibility of surface sediments. Buried soils within the flood-plain sequences examined in this study were either weakly developed or absent entirely. The best developed soils observed were the modern surface soils. Consequently, the higher magnetic-susceptibility values generally are associated with the upper flood-plain sediments.

Fluvial processes associated with flood-plain construction may have affected the distribution of magnetic minerals in flood-plain sediments. Because most overbank sediments were carried in suspension, they tend to be relatively fine grained. If the magnetic mineral fraction is confined to the fine-grained sediment fraction, the resulting flood-plain deposits should be enriched in magnetic minerals. This process could produce the observed variations in magnetic susceptibility; however, the importance of this process cannot be determined with the available data.

VARIATION OF MAGNETIC SUSCEPTIBILITY AS A FUNCTION OF SEDIMENT PARTICLE SIZE

The relation between fluvial sediment particle size and magnetic susceptibility was investigated in this study to determine the degree of association between a particular particle-size fraction and the magnetic susceptibility of the bulk sediment. Low-frequency mass susceptibilities, and frequency-dependent susceptibilities were plotted against the percentages of sand, silt, and clay in 29 fluvial sediment samples (figs. 11 and 12). These plots indicate that little or no relation exists between the percentage of sand, silt and clay in a sample and the low-frequency susceptibility of the bulk sample. This suggests that magnetic minerals probably are widely dispersed throughout the sediments and are not confined to any specific particle size.

Correlation coefficients were calculated between the percentage of sediment within a specific particle-size fraction and the magnetic susceptibility of the bulk sediment sample (table 3). These results indicate little correlation between particle-size fractions and bulk sediment magnetic susceptibility. This further indicates that the magnetic minerals are not confined to a specific particle-size fraction but are instead widely dispersed throughout the particle-size distribution.

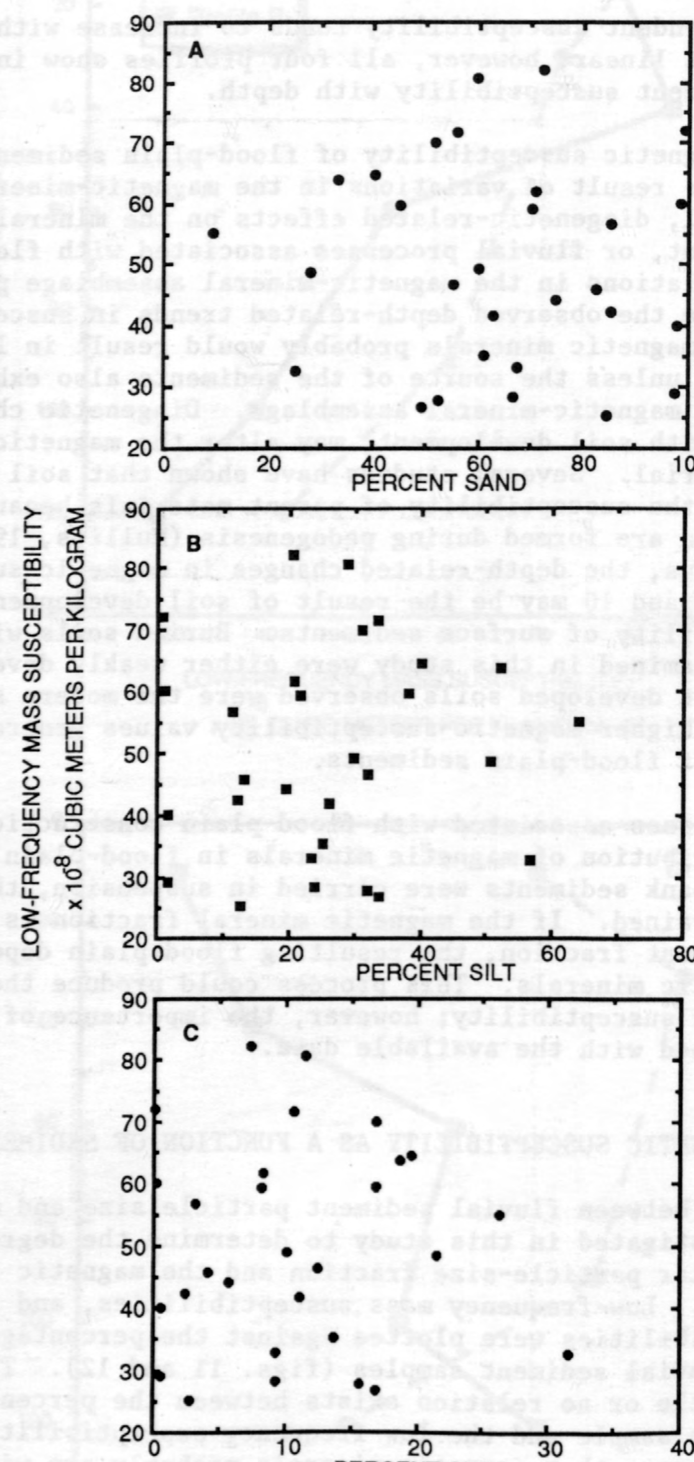

Figure 11.--Relation between (A) percent sand, (B) percent silt, and (C) percent clay and magnetic susceptibility for overbank sediment from the lower Fox River area.

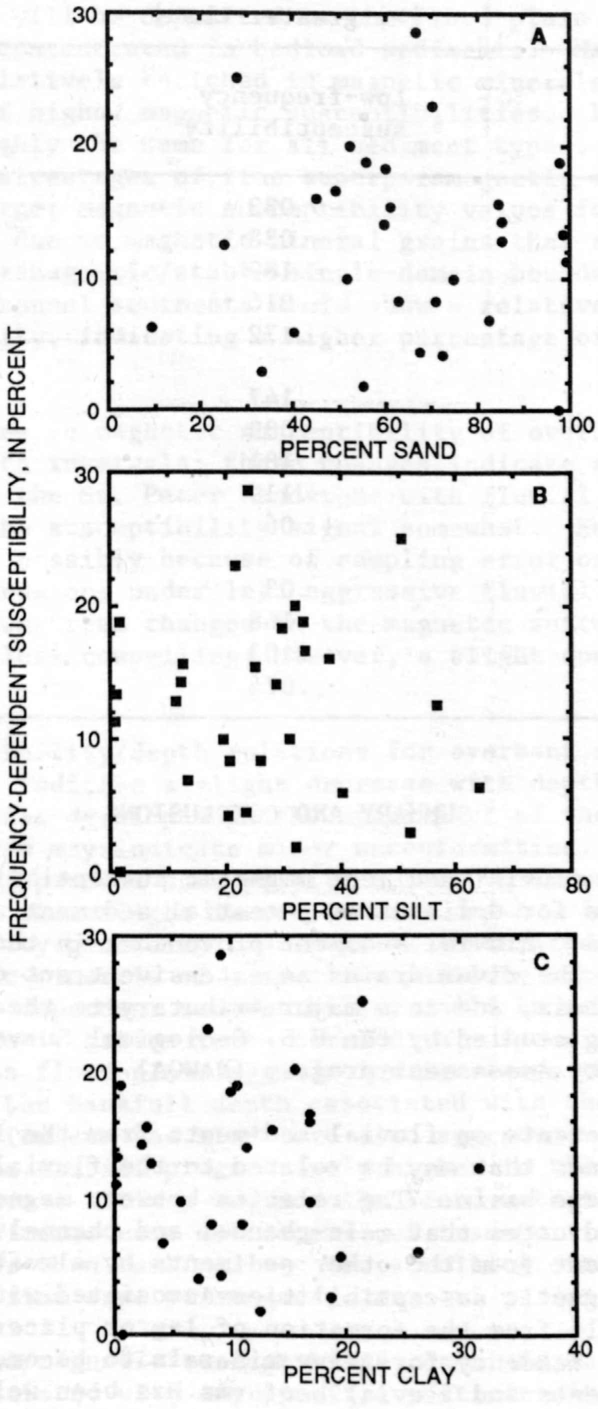

Figure 12.--Relation between (A) percent sand, (B) percent silt, and (C) percent clay and frequency-dependent susceptibility for overbank sediment from the lower Fox River area.

Table 3.--*Correlation coefficients for magnetic-susceptibility particle-size data*

[>, greater than]

Particle-size fraction (millimeters)	Low-frequency susceptibility	Frequency-dependent susceptibility
>4.7	-0.033	0.149
4.7- 2.4	-.088	.084
2.4- 1.2	-.189	.027
1.2- .59	-.016	-.338
.59- .42	.172	-.261
.42- .297	.147	-.213
.297- .21	-.039	-.097
.21- .15	-.181	.164
.15- .074	-.119	.125
.074- .062	.06	.083
.062- .031	.03	.06
.031- .016	.168	-.0089
.016- .008	.103	.0047
.008- .004	.074	.014

SUMMARY AND CONCLUSIONS

Measurements of fluvial sediment magnetic susceptibility were used in this study as a means for delineating potential sediment source areas in the lower Fox River basin. Fluvial sediment provenance in the Fox River basin is important because the river drains an extensive tract of agricultural land in northeastern Illinois, and is a major tributary to the upper Illinois River basin, a region being studied by the U.S. Geological Survey as part of a National Water Quality Assessment program (NAWQA).

Magnetic measurements on fluvial sediments from the lower Fox River area indicate several trends that may be related to the fluvial processes that operate in the drainage basin. The relation between magnetic susceptibility and sediment type indicates that main-channel and channel-margin sediments are significantly different from the other sediments by almost an order of magnitude. The larger magnetic susceptibilities associated with the main-channel sediments could result from the formation of lag or placer concentrates of heavy minerals. The tendency for heavy minerals to become concentrated in channel-bottom sediments and fluvial bedforms has been well documented (Schumm, 1977; Jobson and Carey, 1989) and may provide a hydraulic explanation for the increased susceptibility values of the main-channel sediments.

Alluvial rivers like the Fox River build flood-plains by vertical accretion of fine-grained sediment that has been winnowed from bedload sediment or eroded from the channel banks. If heavy minerals are not entrained, few if any magnetic minerals will be deposited on the flood-plain. Instead, these minerals will become concentrated in bedload sediments. Main-channel sediments could become relatively enriched in magnetic minerals by this process and then would exhibit higher magnetic susceptibilities. Frequency-dependent susceptibility is roughly the same for all sediment types, which indicates approximately equal percentages of fine superparamagnetic minerals. This also indicates that the larger magnetic susceptibility values for main-channel sediment are probably due to magnetic mineral grains that are coarser than the grains in the superparamagnetic/stable single-domain boundary region. Otherwise, the main-channel sediments would show a relatively large frequency-dependent susceptibility, indicating a higher percentage of fine superparamagnetic minerals.

Downstream changes in magnetic susceptibility of overbank sediment are apparent for some depth intervals; these changes indicate that fluvial erosion followed by mixing of the St. Peter Sandstone with fluvial sediment already in the river may lower the susceptibility signal somewhat. Not all depth intervals show this trend, possibly because of sampling error or due to decreased input of St. Peter Sandstone under less aggressive fluvial erosion of the sandstone bluffs. Downstream changes in the magnetic susceptibility of main-channel sediment are less compelling; however, a slight downstream decrease is apparent.

Magnetic-susceptibility/depth relations for overbank sediment comprising flood-plain sequences indicate a slight decrease with depth. The increase may be associated with soils developed in the upper part of the flood-plain. Variations in the trend may indicate minor unconformities. Depth-related changes in frequency-dependent susceptibility for two sites (profile 4, and profiles 5, 6, and 9) show slight increases with depth. Increasing frequency-dependent susceptibility generally indicates an associated increase in the percentage of magnetic minerals of a specific particle size. The upward decrease in frequency-dependent susceptibility could be related to the ability of fine superparamagnetic grains to be carried in suspension and deposited as overbank sediment. As flood-plain aggradation increases the height of the flood-plain surface, the bankfull depth associated with the aggrading flood plain also increases (unless the streambed also aggrades). Thus, magnetic mineral grains must be carried progressively higher in the flow to be deposited as overbank sediment. It may be that the flood waters that deposited the upper flood-plain sediments were not capable of transporting magnetic minerals to flow depths greater than bankfull and the resulting overbank sediments were slightly depleted in fine superparamagnetic mineral grains.

The particle-size/magnetic-susceptibility data indicate that the magnetic minerals are not associated with any specific particle-size class. This could occur if magnetic minerals are found within all particle-size fractions of the sediments sampled in this study and are dispersed relatively evenly.

The data reported herein indicate that sediment-source areas of three specific types can be delineated on the basis of magnetic susceptibility. Sediments associated with the main channel (channel-margin and main-channel sediment) appear to have the highest susceptibilities of all sediment types (from about 100 to about 110×10^{-8} m^3/kg) and form one of the groups. Overbank sediment, sediment in tributary streams, and topsoil from cultivated fields form a second group with low-frequency susceptibilities between 50 and 70×10^{-8} m^3/kg. The third source area consists of sediment derived from fluvial erosion of the St. Peter Sandstone. Fresh, unweathered St. Peter Sandstone has a low magnetic-susceptibility value because it consists of almost pure quartz sand. Introduction of this sediment type into the Fox River appears to lower the susceptibility of fluvial sediments that occur within the outcrop zone of the unit.

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