Development of a Technique for Buried Site Detection Using a Down-Hole Soil Magnetic Instrument | 2003-05

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DEVELOPMENT OF A TECHNIQUE FOR BURIED SITE DETECTION USING A DOWN-HOLE SOIL MAGNETIC INSTRUMENT

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EXECUTIVE SUMMARY

This project has advanced a geophysical approach for identifying buried archaeological sites that combines recently developed down-hole magnetic capabilities with laboratory soil magnetic techniques. Down-hole magnetic susceptibility measurements allow the effective location of paleosols while soil magnetic studies are used to evaluate whether an associated human occupation is likely. This combined geophysical approach has the potential to locate and explore buried archaeological deposits across varied environments in a cost-effective, efficient, and relatively non-invasive manner.

This approach was developed and tested on five sites of varying ages and sedimentary contexts in Minnesota and North Dakota. A protocol was designed to guide the application of the down-hole magnetic susceptibility logger in buried site investigations. The down-hole susceptibility instrument identified major stratigraphic units at each of these sites, including buried occupation layers and non-cultural paleosols. Buried soils at these sites could be recognized by virtue of their enhanced susceptibilities.

Buried cultural soils produced, in some cases, a signal over twice the magnitude of nonarchaeological paleosols. Although this magnitude shift suggested a possible avenue for determining if ancient land surfaces had been occupied by humans, laboratory soil magnetic techniques, which allow an understanding of the changes in composition, concentration, and/or grain size of the magnetic carrier that produce this contrast in magnitude, were found to be much more effective in making this determination. These soil magnetic tests were applied to sediments collected from the down-hole locations.

Comparative soil magnetic studies of both archaeological and nonarchaeological paleosols documented patterns in their magnetic response that could consistently and reliably distinguish those soils associated with human occupation. This signal was an increase in magnetic remanence carried in the coarse soil fraction of all the archaeological soils. Parallel examinations of various soil physical and chemical parameters indicated that the determination of total phosphorus is a potential complimentary technique to aid in discriminating archaeological soils.

Investigations into the origin of the magnetic signature have suggested this remanence resides in burnt clay nodules found in the archaeological soils. These burnt clay nodules were found in both Archaic and Woodland Period deposits and it is suspected that domestic fires produced them. This phenomenon may therefore extend to a wide range of sites and thus provide a technique for buried site identification that is broadly applicable. Future research will focus on expanding the range of settings to which this approach is applied as well as continuing investigations of the burnt clay nodules.

INTRODUCTION

Buried sites present an intractable problem to archaeologists. If they are not located they represent "holes" in the archaeological record (Mosley 1983). Attempts to solve this problem generally utilize locational models based upon physical or cultural data that lead to potential sites. Such sites are evaluated through labor intensive coring or excavation. Surface geophysical methods are sometimes used to test locational models, but often cannot provide the resolution required to discriminate thin archaeological horizons at depth.

This project has advanced a method for the location of buried archaeological sites employing small-diameter down-hole magnetic susceptibility investigations and soil magnetic techniques. This combination of methods, identifying magnetic changes that occur as part of soil development and cultural occupation, provides a relatively non-invasive and inexpensive means of locating and exploring buried archaeological deposits. Such an approach not only allows archaeologists to more effectively locate buried paleosols but also to evaluate whether an associated human occupation is likely.

A lack of appropriate technology has hampered archaeological field studies of magnetic susceptibility. This project follows upon a series of efforts devoted to innovation in magnetic susceptibility down-hole instrumentation in archaeology. These efforts were initiated through a 1997 NCPTT technology transfer grant (MT-2210-8-NC-28) (Dalan 2001) and carried forward through a NSF MRI grant (BCS-0215723; 8/2002-2/2004) (Dalan 2003; Dalan and Bartington 2004). The result is the Bartington MS2H sensor that, coupled with the Bartington MS2 susceptibility meter, measures susceptibility down a small diameter (ca. 25 mm /one-inch) hole made with a push-tube corer. Applications of this technology thus cause only minimal disturbance to the archaeological record and provide a relatively nondestructive means of exploring archaeological sites. Measurements are accomplished rapidly: With a measurement time of approximately 1 second, a 1 m hole can be logged at 2 cm intervals in less than 1 minute.

This project has addressed the last crucial step in the advancement of down-hole geophysical technology in archaeology, namely its application within archaeological practice, in this case in the location and assessment of buried archaeological properties. Down-hole studies were combined with soil magnetic techniques well explored and utilized with the field of environmental magnetism (Evans and Heller 2003; Maher and Thompson 1999, Thompson and Oldfield 1986) and of much potential in archaeological research (Dalan and Banerjee 1996, 1998) to yield an even more effective approach to this problem.

This approach was developed and tested at a number of sites within the Red River Valley region of Minnesota/North Dakota. These sites encompass diverse soil and sedimentary contexts on deposits dating to the early to middle Holocene. Existing soil physical, chemical, and chronologic data for these sites was supplemented with newly collected soil cores and a program of soil physical and chemical tests for comparison with the down-hole and soil magnetic tests.

The five test sites lie within the former lakebed and margins of the southern extension of Lake Aggasiz, an immense proglacial lake that formed over 12,000 years ago. The region encompasses the Sheyenne River Delta with numerous eolian contexts (dune formations), the fine-textured lacustrine plain of glacial Lake Agassiz, the coarser-textured near-shore deposits of Lake Agassiz on the eastern and western perimeters of the lake plain, the till uplands east and west of the lake deposits, and alluvial deposits along the Red and Sheyenne Rivers. Only a handful of sites dating before 2,000 B.P. have been documented within the region. Paleoindian (ca. 9500-8000 B.P.), Plains Archaic (ca. 8000-2000 B.P.), and even Early and Middle Woodland sites are rare. From research at the Rustad (Michlovic 1996; Running 1995) and Canning (Michlovic 1986) sites, it is apparent that deposits of this age may be deeply buried. Buried archaeological sites, from ca. 8000–2000 years in age have been located at depths ranging from <1 m to nearly 2 m.

All test sites are shown in Figure 1. Tests sites that correspond to archaeological sites include the Early Archaic (ca. 7550-7180 B.P.) Rustad site, preserved within alluvial mudflow deposits at the edge of the Sheyenne River Delta (Michlovic 1996; Running 1995), the Middle Archaic Canning site, located in the floodplain of the Red River, and the Woodland Period Dahnke site (Thompson 1990), located on an alluvial terrace at the confluence of the Red and Sheyenne rivers. Two test sites that contain paleosols but are not archaeological sites were planned as controls. The Durler site lies in an area with multiple paleosols in sand dune deposits on the Sheyenne River Delta with dates ranging from 580+/-90 B.P. to 3170+/-110 B.P. (Hopkins and Running 2000). The Malo site is a dated hillslope/wetland complex located on glacial till west of the Lake Aggasiz plain (Malo, 1988). Due to problems with landowner permission, the Malo site was not tested. In addition to the buried soils at the Durler and Malo properties, buried noncultural soils are also present in the sequences at the Rustad and Canning sites. The alluvial fan deposits at the Rustad site contain three buried soils. The archaeological remains are associated largely with the oldest of these. Above the Archaic component at the Canning site are three buried (noncultural) A horizons. The Dahnke site is a stratified site that contains at least two buried Woodland layers. The Ekre property, a final location that was tested, is a potential archaeological site on a terrace remnant along the Sheyenne River. At this location, several buried soils have been identified within eolian and underlying fluvial deposits.

Stratigraphic layers identified by patterns in magnetic susceptibility compared well with data on site layering gained from previous archaeological and soil investigations at these sites. Importantly, buried soils at all sites could be identified by virtue of their enhanced magnetic signal. A protocol for applying the newly developed down-hole instrument in buried sites investigations was also developed. This protocol includes recommendations for horizontal and vertical sampling and procedures for drift correction.

Although buried surface soils clearly correlated with localized increases in magnetic susceptibility, a contrast was apparent between paleosols associated with human occupation and those palesols for which a cultural association was not apparent. (For ease of reference, we refer to these as cultural and noncultural paleosols, even though natural processes of soil formation obviously have proceeded in both.) What we noticed at sites where both cultural and noncultural paleosols were represented was that the magnetic susceptibility of the buried cultural soils was in some cases over twice the magnitude of the buried noncultural soils. Although this magnitude shift suggested a possible avenue for determining if ancient land surfaces had been occupied by humans, it was observed that this relationship between cultural and natural soils varied among the test sites and thus would need to be recalibrated in each new archaeological and natural environment. Laboratory soil magnetic techniques were therefore explored to see if they might reveal a distinctive signature for archaeological soils that would be more broadly applicable.

Laboratory soil magnetic techniques allow an understanding of changes in the composition, concentration, and/or grain size of the magnetic carrier that produce the susceptibility signal. As expected, soil magnetic studies of soils collected from the test sites indicated that a similar soil forming process had occurred in both the buried cultural and natural soils, producing an increase in fine-grained magnetite and maghemite. The cultural soils, however, showed a distinctive increase in not only superparamagnetic (SP) grains but also a distinctive increase in grains at and above the SD (Single Domain) grain size boundary. These remanence-carrying grains were found to reside in the coarse fraction (>0.053 mm, fine sand and larger) of the archaeological soils. A distinctive increase in the ratio of coarse to whole soil remanence allows cultural soils to be separated from noncultural soils.

Nodules of soil within the coarse fraction of archaeological soils were visually and magnetically identified as the source of the distinctive remanence signal. These nodules of soil, in the main, appear to be composed of burnt clay and they are ubiquitous in the archaeological soils studied as part of this project. As they are much more common than artifacts and even microartifacts, the visual recognition of these nodules alone might prove an effective identifier of archaeological horizons. Parallel soil chemical and physical investigations suggest that total phosphorus determinations are a useful corroborative technique for identifying archaeological paleosols.

The burnt clay nodules were found in Archaic and Woodland Period sites. We suspect that domestic fires burning on a fine-grained substrate formed them. As such, we would expect these burnt clay nodules to have a broad distribution in archaeological contexts. With their distinctive magnetic signature they would thus provide wide opportunity for applying a combined down-hole/soil magnetic approach to locate buried archaeological sites.

We plan to broaden our testing of this approach to different types of sites and contexts. We would also like to examine naturally burned horizons to compare their signature to those of archaeological soils and to continue our investigations of the burnt clay nodules.

METHODS

In developing a combined magnetic approach to buried site identification, a series of lenses was applied that focused in increasing detail on the magnetic properties of paleosols and, in particular, archaeological paleosols. The first of these lenses was the down-hole instrument, which allowed vertical changes in volume magnetic susceptibility to be explored at each of the field sites. All remaining lenses consisted of soil magnetic techniques applied to soil samples within a laboratory setting. As successive lenses were applied, the number of samples measured was reduced due to a corresponding increase in time, effort, and expense as well as the magnetically destructive character of these tests.

Reconnaissance-level soil magnetic analyses (Maher 1986), including the measurement of volume and mass magnetic susceptibility (K and X), frequency dependence of susceptibility (X_{fd}), anhysteretic remanent magnetization (ARM), Saturation Isothermal Remanent Magnetization (SIRM), and "S" values (the degree of loss of remanence on a previously saturated sample at selected reverse fields) were completed at Minnesota State University Moorhead (MSUM). More specialized studies were conducted at the Institute for Rock Magnetism (IRM) at the University of Minnesota. These studies, which included high field, and high- and low-temperature investigations, were directed toward confirming models of magnetic grain size, mineralogy, and concentration suggested by the reconnaissance efforts.

The analyses comprising each of the lenses are described as a sequence of six steps below. Following this description of magnetic techniques, parallel investigations of soil physical and soil chemical properties are discussed.

Step 1

Initial investigations employed a Bartington Instruments MS2H down-hole sensor to measure volume magnetic susceptibility along vertical profiles at each of the five field sites. Multiple locations at each of these sites were investigated and a number of sampling schemes and techniques for data collection were tested in order to develop a protocol for the application of this instrument in buried sites investigations. The number of locations tested per site ranged from a minimum of two to a maximum of six. A total of 19 down-hole locations were investigated. An average of three to four down-hole tests were conducted at each of these 19 locations yielding a total of 71 tests completed.

Step 2

Comparative samples were collected at 15 of the 19 down-hole locations. These samples were collected with the small-diameter push-tube corer used to make the hole for the down-hole sensor. From two to four down-hole locations at each site were sampled. Samples were in general collected in 5 cm vertical increments and the soils were packed in small plastic (nonmagnetic) Althor P15 boxes. All samples were measured in the laboratory with a Bartington Instruments MS2B sensor. Magnetic susceptibilities measured for each of these samples were compared to volume susceptibilities gained using the MS2H sensor. The frequency dependence of susceptibility (X_{fd}) was also measured. This quantity is the percent difference in susceptibility measured at two frequencies: For the Bartington MS2B these frequencies are 470 Hz and 4700 Hz.

Measurement of X_{fd} is used to investigate the contribution of ultrafine magnetic grains as these show the most pronounced frequency dependence of susceptibility.

Step 3

Step 3 involved the measurement of ARM, SIRM, and S Values to provide additional information on the mineralogy, grain size, and concentration of the dominant magnetic carrier at each of the five sites and to explore distinguishing magnetic characteristics between natural and cultural paleosols. Initial models of magnetic mineralogy, grain size, and concentration were forwarded at this step. ARM was measured on samples from 11 down-hole locations and SIRM and S values were measured on samples from 8 locations.

Low field magnetic susceptibility is dependent not only on the concentration of magnetic grains in a sample but also on their composition and grain size. A reconnaissance program combining low field mass magnetic susceptibility (X) and anyhysteretic remanent magnetization (ARM) was employed to investigate variations in magnetic grain size across all collected samples (King et al. 1982). ARM is an artificial magnetic remanence (i.e., magnetization in the absence of a magnetic field) produced in the laboratory during the smooth decay of an alternating field to zero in the presence of a weak steady field (Banerjee 1981; Thompson and Oldfield 1986). We employed a peak field of 99 mT and a steady field of 0.1 mT to produce an ARM. ARMs were imparted on a Magnon International AFD 300 alternating field demagnetizer with an ARM coil and measured on an AGICO JR-6 Dual Speed Spinner Magnetometer.

S values measure the degree of loss of remanence (of a previously magnetically saturated sample) at selected reverse fields (Dearing et al. 1985; King and Channell 1991). The measured values provide a means of discriminating between ferrimagnetic minerals (e.g., magnetite and maghemite) and canted antiferrimagnetics (e.g., hematite and geothite). The samples were first saturated in a strong magnetic field (2 T) and the resulting SIRM measured. The samples were then placed in a reversed field of 300 mT. S values were calculated by dividing the absolute value of the magnetization produced in the backfield by the SIRM, i.e., S = -[IRM (-300 mT)/SIRM]. Magnetizations were imparted on an ASC Model IM-10-30 Impulse Magnetizer and measured on an AGICO JR-6 Dual Speed Spinner Magnetometer.

Step 4

The next step involved more intensive studies of samples from a number of key cores to confirm and refine the models suggested by the reconnaissance studies. These analyses were conducted at the IRM at the University of Minnesota. Cores from sites with representative and well-contextualized cultural and natural paleosols were selected for study. Eight cores were used in these tests, two from each of the following sites: Canning, Dahnke, Durler, and Rustad. Selected samples were drawn from each core, with more intensive sampling of one core from each site and less intensive sampling of a second core that was used to confirm patterns observed in the first core.

Hysteresis loops were measured on each of these samples (64 in all). From 13 to 20 samples were measured from each of the four sites. An average of 10 hysteresis loops was measured on intensively sampled cores and an average of 6 samples was drawn from the second core from each site.

Hysteresis loops are produced by subjecting the sample to a cycle of increasing and decreasing magnetic fields. The application of strong magnetic fields results in irreversible changes in magnetization and in the phenomenon called "hysteresis" in which magnetization changes lag behind the applied field (Banerjee 1981; Day et al. 1977). A number of magnetic parameters are measured on hysteresis loops that provide information on magnetic mineralogy, grain size, and concentration. These parameters include saturation magnetization (Js), saturation remanent magnetization (Jrs), coercivity (Hc), and coercivity of remanence (Hcr). Information regarding the contribution of paramagnetic materials (clays) to the magnetic signal (Xp, the high field slope) is also provided. Hysteresis loops were produced using a Princeton Applied Research Vibrating Sample Magnetometer (VSM).

Low temperature studies were also completed at this stage on two samples that hysteresis data suggested had unusual magnetic grain size characteristics. Day et al. (1977) plots of ratios of Jrs/Js versus Hcr/Hc suggested magnetic grains in these samples were much larger in size than those contained in other soils. One samples was from a surface soil at the Rustad site (9-12 cm) and the other was from a buried soil at the Durler site (80-85 cm). As both soils were formed in eolian deposits, the presence of larger (Multidomain) magnetic grains was reasonable. The low temperature studies, however, were conducted to confirm that fine (Superparmagnetic) grains were not responsible for the high Hcr/Hc values that plotted these samples within the Multidomain size range.

The low temperature investigations of these samples involved measuring the susceptibility of these samples at seven different frequencies (1, 3.16, 10, 31.6, 100, 316, and 1000 Hz) in a field of 3 Oersteds (239 A/m) over temperatures ranging from 20 to 300K. Susceptibility at the seven different frequencies was measured at 10K increments. A Quantum Design MPMS-XL Super Conducting Susceptometer was employed to conduct these low temperature investigations.

Step 5

As an understanding of magnetic changes along the length of these cores was obtained, we began to focus on magnetic signatures that distinguished palesols associated with human occupation. For this step we examined textural size separates of larger bulk samples that had been collected as part of the coring program with the truck-mounted Giddings corer. These bulk samples were drawn from buried A or AB horizons and adjacent soil horizons at the Canning and Dahnke sites. A total of 20 samples were used, 9 samples from the Canning site and 11 from the Dahnke site.

We focused our investigations on the coarse fraction of these paleosols as we suspected that this was where archaeological materials might reside and we hoped that these archaeological materials would produce a distinctive magnetic signature. We employed these larger samples in order to produce a sufficient coarse size fraction (from the fine textured Canning and Dahnke soils) to at least fill one of our standard P15 samples boxes (5.28 cc volume) for soil magnetic analyses. This coarse fraction included all materials above 0.053 mm (very fine sand and larger). The percentage of this coarse fraction to the whole soil ranged from 1-10%. The mass of the bulk samples ranged from 110-572 g.

Bulk samples were placed in a beaker, filled with water and a dispersing agent (sodium hexametaphosphate and sodium carbonate) and shaken overnight. Samples were then sieved through a fine mesh (53 μm) to rinse out the silt and clay. All coarse material (very fine sand size and larger) was dried overnight at 105 degrees.

The entire suite of reconnaissance magnetic parameters (X, X_{fd}, ARM, SIRM, S) was measured on both a sample of the whole soil fraction prior to separation and on the coarse fraction resulting from the separation process. Hysteresis loops were completed for all coarse and whole samples and high temperature investigations were applied to a select number of these samples.

High temperature experiments compared a natural paleosol from the Canning site with both the whole soil and the coarse fraction of a cultural paleosol from the same site. A subsample of these P15 box samples was employed in these experiments. Using a furnace-equipped KLY-2 Kappabridge High-Temperature Susceptometer, the susceptibility of these samples was measured as they were heated from room temperature to 700 C and then cooled to 50 C. A second set of hysteresis loops was completed on the heated and cooled samples.

A different separation process was applied to the buried cultural and natural soils sampled at the Rustad site. These samples were dry sieved to produce textural separates. For this separation processes the fine fraction was retained. An alternative size cut-off was used for these samples; the coarse fraction contained all materials 0.25 mm (medium sand) and larger. All reconnaissance parameters as well as hysteresis loops were measured on the whole, coarse, and fine fraction of each of these soils. This separation technique was not as effective for distinguishing cultural soils, as discussed in the Results section below.

<u>Step 6</u>

The last soil magnetic lens focused on the coarse soil fraction where a distinctive magnetic signature for archaeological soils was identified through techniques applied in Step 5. This lens involved the application of soil magnetic techniques to different components of this coarse soil fraction. The aim of these efforts was to discern the origin of the distinctive cultural signature. Coarse fractions from a cultural and natural paleosol at the Canning site and two cultural soils from the Dahnke site were examined.

The coarse fractions were divided using a series of nested screens into size grades of greater than 850 μm, between 250-850 μm, and from 53-250 μm. Magnetic separates of certain of these size subsets were produced using a small Russian-produced (MPM-1) hand-held magnetic separator. Samples of distinctive materials, including charcoal, bone, burnt bone, and light and dark colored nodules, were separated using a petrographic microscope and tweezers. The light and dark nodules were primarily obtained from the larger size grades. These ubiquitous light and dark colored nodules were also visually inspected under a petrographic microscope and photographed. Two MSUM archaeologists, Dr. Michael Michlovic and Dr. George Holley, and Dr. Rolfe Mandel from the Kansas Geological Survey also examined the light and dark nodules.

Size and material subsets and magnetic separates of the coarse fractions were packed into gel caps for hysteresis measurements. Hysteresis loops were produced for most samples using a Princeton Applied Research Vibrating Sample Magnetometer (VSM). A more sensitive Princeton Measurements Corporation Micromag VSM was for utilized for weak (e.g., bone, charcoal) and unusual samples.

Select samples were chosen for two types of low- temperature investigations. The same gel cap samples utilized for hysteresis studies were employed. These low-temperature investigations focused on the light and dark colored nodules that were ubiquitous in the archaeological soils. Low-temperature investigations included the seven frequency runs described under Step 4 above, some conducted on a Lakeshore Cryotonics AC Susceptometer and the others on a Quantum Design MPMS-XL Super Conducting Susceptometer. A second type of low-temperature study on the MPMS Susceptometer involved examining magnetic remanence behavior as samples were warmed and cooled. For these investigations, an initial magnetic field of 2.5T was applied. The samples were then cooled from room temperature (300 K) to 20 K, measuring remanence at 5 K increments. The samples were then given a remanence (also in a 2.5 T field) at 20 K and warmed from 20 K to 300 K, with measurements of remanence made at 5 degree steps.

Soil Chemical and Soil Physical Investigations

Parallel to the soil magnetic investigations were investigations of soil chemical and physical properties. These studies were conducted on cores recovered from the test sites with a hydraulic Giddings probe. With the exception of the Rustad site, which was sampled from the face of the quarry wall, multiple cores were recovered from each of the test sites. Visual inspections of cores and data from chemical and physical tests supplemented previous archaeological and soils data in guiding the selection of samples for soil magnetic tests. This portion of the project also provided a context for understanding observed soil magnetic signatures, aiding in relating the magnetic response to depositional processes, soil formation, and human impact. The potential for complimentary techniques for discriminating cultural soils was also explored.

Representative cores from each site were selected for detailed investigations. Pedologic descriptions were prepared for each of these cores prior to sampling. Cores were, in general, sub-sampled at 5 cm intervals. The following analytical tests were accomplished on the sub-sampled cores: organic carbon, inorganic carbon, extractable phosphorus, total phosphorus (by ICP, NA-Hypobromide method), total iron (by ICP), and pipette particle size (including sand fractionation and coarse/fine silt). In general, all tests were completed on each sample, with the exception of particle size analyses, which were focused on a reduced number of samples.

RESULTS AND DISCUSSION

As part of soil development, surface soil layers become magnetically "enhanced" in comparison to subsoil layers. This can occur through burning and through pedogenic enhancement by both organic (e.g., by magnetotactic bacteria and iron-reducing bacteria) and inorganic (via low-temperature chemical reactions) pathways (Dearing et al. 1996a, 1996b, 1997, 2001; Fassbinder and Stanjek 1993; Fassbinder et al. 1990; Maher and Taylor 1988; Taylor and Schwertmann 1974; Taylor et al. 1987).

Buried topsoils maintain a signature of enhanced magnetic susceptibility providing they have not been gleyed or the iron minerals otherwise reduced. This is the case at the sites tested as part of this research where buried paleosols were distinguished by enhanced magnetic susceptibility values. By way of example, Figures 2 and 3 present stratigraphic and soil magnetic data from selected locations at two of the test sites, the Canning and Dahnke archaeological sites. The soil profiles were produced as part of previously accomplished test excavations. These profiles serve as general indicators of horizons and depths nearby subsequent down-hole tests.

At the Canning site (Figure 2), a surface soil and three underlying buried soils (2Ab and 2Bw, 3Ab and 3Bw, and 4Ab and 4Bw) were encountered. Disturbed Woodland Period materials are scattered throughout the surface horizon. A buried Archaic component has been documented within the deepest buried soil. Peaks in magnetic susceptibility were observed for each of the buried soil horizons.

The Dahnke site is a stratified archaeological site that contains at least two buried Woodland layers and possibly also Archaic Period materials at depth. The soil profile in this case (Figure 3) is derived from a 1987 excavation block near the location of down-hole tests at the Core 3 and Core 5 locations. Unlike the Canning site, buried soils without archaeological associations have not been documented. Peaks in susceptibility coincide with the two buried horizons, although the 2AB horizon is more prominent at the Core 3 location and the 3AB horizon is more prominent at the Core 5 location.

Buried soils at the Canning and Dahnke site are characterized by enhanced susceptibility values. Soils were enhanced from 1.1 to 4 times the susceptibility of underlying base level. Peak susceptibility values for the Canning buried soils were elevated 1.14 to 4 times the base level at that site and the susceptibilities of the Dahnke buried soils were enhanced 1.44 to 3.38 times. Enhancement values within this same range were also characteristic of the other test sites. For example, enhancement factors for buried soils (both archaeological and non-archaeological) at the Rustad site ranged from 1.25-1.58.

Magnetic characteristics of soils will depend on the type of material in which the soils form, the time over which enhancement has been allowed to proceed, climatic variables such as precipitation and temperature, the landform in which the soil develops, and the plant and animal life on and in the soil. Humans are one of the living organisms that may impact soil development and thus human activities may be investigated via soil magnetic techniques.

Archaeologists have long recognized (Aitken 1970; Mullins 1974; Tite and Mullins 1971) that soils from archaeological sites may be even more magnetic than surrounding "noncultural" or non-site topsoils. Because of this, surface variations in magnetic susceptibility have been employed to delimit sites, activity areas, and features (e.g., Batt et al. 1995; Challands 1992; Clark 1990). The extent of a site's occupation, its firing history, the quantity of organic material, and other human-controlled variables are some of the factors that may affect this degree of enhancement (Tite and Mullins 1970).

At the Canning site (Figure 2), susceptibility values for the buried Archaic soil are clearly elevated over the other buried soils in the sequence. Susceptibilities of the buried Archaic layer are enhanced up to 4 times the base level while peak values of the two overlying noncultural buried soils are enhanced from 1.14-1.75 the base level. For the Dahnke soils (Figure 3), variation in susceptibility values was also observed although the two buried soils at this location within the site were both associated with cultural materials. In general, a relatively strong and weak buried soil characterizes each core location. Peak enhancement factors for the two soils were 1.44 and 2.26 for Core 3 and 1.89 and 3.38 for Core 5. At the Rustad site, which contains both a cultural and natural buried soil, enhancement factors for the ca. 8,000-year-old buried cultural soil ranged from 1.5 to 1.58 and the overlying 4,000-year-old buried natural soil from 1.25 to 1.3. At each site, cultural and natural soils are located within a similar matrix (alluvium in the case of the Canning and Dahnke sites and alluvial fan deposits in the case of the Rustad site).

As a whole, the data from our field sites indicate that soils associated with an archaeological component are in general more strongly enhanced than stable land surfaces that people did not occupy. This pattern appears to hold within individual sites but translating these findings across sites has proved difficult. Due to variation in both natural and cultural soils, there is a zone of overlap that makes it difficult to distinguish without question whether a soil is likely to have a cultural association or not. At the Canning site, for example, one of the noncultural buried soils was enhanced 1.75 times over the base level. This is greater than the enhancement observed for the cultural soil at the Rustad site (1.5-1.58) and the weakly expressed cultural soil at the Dahnke site (1.44 for the 3AB at the Core 3 location). It should be mentioned that these enhancement values are based on field data collected with the MS2H and are not the same as those determined from laboratory measurements as will be discussed below.

Though the field data from this project, as well as findings of other archaeological investigations in disparate environments, suggest that contrasts in the magnitude of the magnetic susceptibility signal might serve to separate cultural and noncultural soils, we must conclude that this is not a foolproof method. The magnitude of the susceptibility signal, whether expressed as an enhancement factor, an absolute increase in volume susceptibility, or a percentage increase, does not always provide a reliable means of identifying cultural soils. Based on our tests, we can say that buried soils with enhancement values of less than 1.4 are likely to be noncultural while soils with enhancement values of 1.8 or larger are likely cultural. Soils with enhancement factors between 1.4-1.8 are difficult to interpret. Furthermore, this regionally based model would not be expected to apply to other contexts. Due to the environmental sensitivity of this signal, which depends on local soil forming processes, post-depositional changes, and cultural histories, a model for enhancement contrasts between cultural and natural soils would need to be developed in each new context. It is likely that any newly developed model would also include a zone of overlap between cultural and natural soils. For these reasons, our research has focused on examining magnetic changes that produced these contrasts in susceptibility in a search for a more broadly applicable and distinctive magnetic signature for cultural paleosols. Before exploring distinctive properties of cultural soils, however, we first will discuss the application of the Bartington MS2H field sensor for mapping buried soils.

A comparison of laboratory measurements of collected samples with the down-hole data illustrates the excellent results that are achieved in a field-mapping situation. The graph on the far right of Figures 2 and 3 compares volume susceptibilities gained through down-hole studies with those gained from measuring samples in the laboratory with the MS2B sensor. Results from each site illustrate how effective the MS2H sensor is in recognizing buried soils. In fact, the MS2H is even more effective for resolving these buried soils than more traditional means of sample collection and laboratory measurement: Larger peaks in susceptibility are observed in the MS2H as opposed to the MS2B data for the cultural soils. In comparison to field measurements, the range of enhancement was reduced in the laboratory data. Enhancement factors of 1.1 to 2.3 times base values were observed in the MS2B data. The overlap zone for strong natural and weak cultural soils ranged from 1.2 to 1.6, roughly one third of this total range. Using a magnitude shift to separate cultural and natural soils would be much less effective for the laboratory data.

The MS2B sensor is more sensitive than the MS2H sensor and not subject to the range of temperatures that produce appreciable instrument drift. The origin of the decreased resolution of the laboratory measurements instead lies in the sampling strategy used to collect the soils for measurement. Field measurements were taken at 2 cm increments. Soil samples for measurement with the MS2B sensor were collected with a push-tube corer in 5 cm increments. Not only was vertical control in sampling not as accurate, but also the soils from these 5 cm increments were homogenized to fill the P15 boxes measured with the MS2B sensor. These homogenized, larger samples were not capable of resolving the thin, highly variable, and sometimes highly enhanced layers encountered by the down-hole sensor.

For effective use of the MS2H sensor, we have developed a protocol for its application in buried site detection and investigation. This protocol is based on extensive testing of this instrument not only in the Red River Valley but at other archaeological sites (e.g., the Cahokia Mounds Site and Spiro Mounds) as well. In terms of horizontal sampling, a single down-hole at a site will not suffice. A comparison of the Core 3 and Core 5 locations at the Dahnke site (Figure 3) illustrates how a cultural layer may in some cases provide only a weak magnetic signature. In basic reconnaissance investigations, 2 to 3 down-hole locations should be adequate to identify buried soils if, as in our situation, the general location of a site or potential site is known. If the purpose is not only to find buried layers but also to define their limits or document variations in their signature over space, then more down-hole studies will be required. A detailed grid of down-hole logs would reasonably serve as a basis for constructing a series of susceptibility contour maps at multiple depths akin to the time slices produced with GPR surveys. For guidance in vertical sampling, we suggest that a 2-cm sampling interval is reasonable given the resolution of the instrument and issues of time. In cases where layers are thin (2 cm or less in thickness) and highly variable, it would be appropriate to decrease the sampling interval to produce multiple measurements within each layer.

Instrument drift can be a particular problem for the down-hole sensor due to changing temperature conditions encountered as the instrument is lowered down the core hole. We suggest several options for dealing with instrument drift. We suggest that a rapid reconnaissance down-hole log should first be accomplished to gain an idea of both instrument drift and susceptibility variations down the hole. This rapid down-hole log is most easily accomplished by allowing the MS2H sensor to take readings automatically at approximately 1-second intervals as the sensor is lowered down the hole. This reconnaissance log would proceed as follows: 1) first zero the sensor in air, 2) next log susceptibility down the core hole, lowering the sensor at the appropriate sampling interval in conjunction with timed measurements, and 3) finish with a final reading in air. The difference between the initial zero reading in air and the final air reading (instrument drift) may then be linearly distributed along the readings down the core hole, assuming a constant drift. As these measurements are accomplished rapidly (e.g., a 1 m core hole can be logged in approximately 1 minute), in most cases drift will be minimized.

Information on instrument drift, variations in susceptibility, and stratigraphy can then be used to plan subsequent down-hole measurements at this and other locations. These tests may take more time, and they will be directed toward providing increased detail and vertical control. Depending on instrument drift, more frequent drift corrections may be in order. Bringing the sensor up and taking a reading in air a number of times in the course of logging the core hole allows these more frequent drift corrections. If drift is relatively small in comparison to the range of susceptibility values recorded, it may be appropriate to check drift only every 50 cm or perhaps only every meter. More frequent drift corrections would be required if drift values approach the level of contrast between layers. For example, if a 2-cm recording interval was employed, instrument drift might be checked every 5 or 10 readings (every 10 or 20 cm). Optimally, though this would also take the most time, the sensor would be removed to air and zeroed prior to each measurement. Or even better, an initial air reading, a reading at the measurement point in the core hole, and a final air reading could be obtained, allowing the estimated air value at the time of measurement in the core hole to be subtracted from the measured value. Although more frequent drift correction requires more time, it insures that instrument drift is more accurately distributed and minimizes the possibility that instrument drift will impact interpretation.

Using the Bartington MS2H sensor and MS2 meter connected to a laptop loaded with the Bartington Multisus program would allow any of the measurement sequences described above. Either automatic measurement at approximately 1-second intervals or manual measurements can be taken. Starting depths and vertical increments may be selected and modified as necessary, drift corrections can be accomplished, and a screen graph of the data provides immediate feedback on susceptibility changes with depth. New software developed for Bartington Instruments by Rinita Dalan and Kim Humble for use with all of the Bartington MS2 field sensors will allow increased flexibility in data collection as well as automated documentation of field information and sampling procedures. This newly developed software will render the MS2H sensor even more effective for buried sites investigations.

The performance of the MS2H sensor in buried site investigations is also improved through coupling field studies of susceptibility with laboratory soil magnetic techniques and methods of soil physical and chemical characterization. Therefore, as part of our protocol for the use of the MS2H, we suggest that soils from at least one representative down-hole location at each site be collected. Soil collection is most efficiently done as part of push-tube coring to make the hole for the MS2H sensor. In addition to a representative core documenting site stratigraphy, additional samples from unusual or highly variable layers represented at other down-hole locations should also be collected. The purpose of these samples is not to confirm the down-hole susceptibility measurements as the MS2H has been shown to be an extremely reliable and effective instrument for measuring susceptibility in the field. The collected samples instead provide a means of understanding changes in the concentration, grain size, and composition of the magnetic carrier that have produced the peaks in susceptibility and therefore information useful for determining whether buried soils are associated with cultural occupation.

In this project, investigations of the frequency dependence of susceptibility, as well as measurements of ARM, SIRM, S values, hysteresis parameters and low- and high-temperature investigations, allowed exploration of the grain sizes, concentration, and mineralogy of the magnetic carrier in different layers at each of the field sites. For this report, however, we will not detail these findings but instead focus on comparing the magnetic characteristics of buried cultural and natural soils from these sites. We continue with results from the Canning and Dahnke site to illustrate these characteristics.

We turn first to an examination of the frequency dependence of susceptibility to track variations in the presence of fine (SP) magnetic grains. The central column in Figure 2 presents X_{fd} data for one core from the Canning site. An increase in the frequency dependence of susceptibility, indicating the formation of ultra-fine (Superparamagnetic) magnetic grains as part of soil development, corresponds with the modern surface and each of the three buried A horizons, whether they are associated with cultural materials or not. These percentages were not extremely high as would be expected in young soils in an alluvial setting. Percentages of 3% and 10% were observed for the natural buried soils and a maximum percentage of 6.5% for the buried cultural layer. The frequency dependence of the modern surface soil measured 7%. Figure 3 presents X_{fd} data for the Dahnke 5 core. Values of 4 and 5% were obtained from the two buried cultural soils. For the Danke 3 core, the X_{fd} of the lower cultural soil was 2% and the upper cultural soil was 6%. Though an increase in fine magnetic grains characteristic of developed surface soils was indicated for each of the buried soils at these sites, the magnitude of this increase did not distinguish the cultural soils.

The X_{fd} data as well as other soil magnetic properties revealed similarities between the cultural and noncultural buried soils indicating a similar soil forming processes had proceeded in both. Differences in the enhancement process, however, were indicated as well. Figures 4 and 5, which present selected soil magnetic data derived from samples taken at the down-hole locations presented in Figures 2 and 3, can be used to illustrate these differences and similarities.

First let us consider the grain size of the dominant magnetic carrier, which can be examined by looking at the top row of line plots in Figures 4 and 5 (e.g., X_{fd}, Xferri/Js, ARM/SIRM). Typically, it is a fine-grained magnetite or maghemite that is produced through pedogenic enhancement within surface soil layers. These would be magnetic grains in the superparamagnetic (SP) to stable single-domain size range (SD) (i.e., smaller than 0.1 μm) (Hunt et al. 1995). As discussed above, similar percentages of X_{fd} were observed for both cultural and natural soils indicating a similar proportion of Superparamagnetic (SP) grains. The ratio ARM/SIRM tracks the contribution of fine magnetic grains at and above the SP-SD (Single domain) boundary. The ARM/SIRM ratio is consistently larger for cultural as opposed to natural buried soils in both intra and inter site comparisons. The ratio of the ferrimagnetic portion of the susceptibility signal to saturation magnetization (Xferri/Js) is also related to variations in the content of SP particles of magnetite/maghemite and therefore can be used to corroborate trends seen in X_{fd} data. In the case of our data, however, it appears that a comparison of Xferri/Js values between cultural and natural buried soils produced results intermediate between those observed comparing X_{fd} and ARM/SIRM. The Xferri/Js ratio was larger for the cultural as opposed to natural buried soils at the Canning site and this ratio was similar for the strongly expressed cultural soil in each core at the Dahnke site. Xferri/Js values for the weakly expressed cultural soil in each of the Dahnke cores were similar to those of noncultural soils at the Canning site. Our conclusion based on the measures discussed above as well as other parameters that indicate magnetic grain size is that enhancement in both cultural and natural buried soils has included similar proportions of SP grains but that enhancement at and above the SP-SD boundary is greater for the cultural as opposed to natural soils.

Enhancement by fine grains of magnetite or maghemite is supported by parameters that track magnetic mineralogy (S values and the coercivity parameters Hc and Hcr) as shown in the middle row of Figures 4 and 5. An increase in S values of a similar magnitude is observed for cultural and natural soils from the Canning site and cultural soils from the Dahnke site indicating an increase in magnetite or maghemite. Hcr and Hc values show an inverse relation, with decreased values in the buried soils also representative of enhancement via the addition of magnetically soft (i.e, low coercivity) magnetic grains. In addition, all samples saturated in fields well under 1 T (in general in fields of 0.3T) and Curie points for selected samples from the Canning site were approximately 590 C, in keeping with this magnetic mineralogy.

Magnetic intensity parameters shown in the bottom row of Figures 4 and 5 include X, Xarm, Jrs, and Js. The buried soils exhibit localized increases in these parameters indicating an increase in the concentration of magnetic materials. In actuality, however, only Js is solely dependent on concentration; the other properties will also be influenced by magnetic grain size. The susceptibility graph has been separated into three components for the Canning core and two components for the Dahnke cores. Low field susceptibility (Xlf) is the mass magnetic susceptibility measured on the Bartington MS2B sensor. This signal includes paramagnetic, ferrimagnetic, and diamagnetic material. The paramagnetic proportion of the signal (Xp) has been quantified through measurement of the high field slope in hysteresis measurements. Paramagnetic susceptibility has been subtracted from low field susceptibility to arrive at the contribution to the susceptibility signal from ferrimagnetic grains (Xferri). Susceptibility of ARM (Xarm) is ARM normalized by the biasing field and the mass of the sample.

A localized increase in all intensity parameters is seen for each of the buried soils, whether cultural or natural. A distinction between cultural and natural soils, however, is much more apparent in the X and Xarm data than in Js data. Js values and increases are similar for the cultural and natural soils at the Canning site and also for both soils from the Dahnke site. A marked contrast between cultural and natural buried soils is apparent in X and Xarm values, however, with these parameters much greater for the cultural soil at the Canning site and for the strong cultural soils at the Dahnke site. This suggests that variations in the grain size of the magnetic carrier are at least as important, if not more so, than the concentration of magnetic minerals in distinguishing cultural from natural buried soils. This is a conclusion that was not apparent when we were first employing the down-hole logger to identify buried sites through their enhanced magnetic susceptibility.

In summary, what our magnetic characterizations suggest is that the cultural soils are not just a result of more of the same processes that produce the natural soils: Increased concentrations of magnetic minerals observed in the cultural soils do not occur in the same proportion for the different magnetic grain size ranges as those observed in the noncultural soils. Yes, we do see enhancement in fine-grained magnetite/maghemite that undoubtedly results from similar soil forming processes, but in order to get the added increase in X, ARM, and other parameters, and to retain similar percentages of X_{fd} and S, larger magnetic grains (SD and larger) are also being produced in the cultural soils. Fine-grained magnetic grains are not solely responsible for the marked increase in the signal that is associated in many cases with buried soils identified with cultural occupation, and this is encouraging in a search for a distinctive magnetic signature for archaeological soils.

We won't presume to address the complicated question of exactly what pathways produced the magnetic material in our samples or to detail the magnetic products that resulted from each pathway. The buried cultural and natural soils represent complex natural mixtures and we only aim to identify differences between them that may help us to distinguish soils associated with cultural occupation. What we conclude based on soil magnetic studies at our test sites is that the magnetic changes that occur as part of soil development and cultural occupation are distinctive. Although the addition of SP grains is proportionally the same in cultural and natural soils, the cultural soils are characterized by an additional contribution of SD material and larger. Cultural and natural soils were subject to similar pedogenic formation processes, but cultural additions, in the form of relatively larger (SD and larger) magnetic grains lend a distinctive signature that can be tapped to identify them.

To determine where this additional cultural signal derives from, we worked with textural separates of cultural and natural buried soils. We found that this larger grained, magnetically soft signal was located preferentially within the coarse soil fraction. Archaeological soils tended to be slightly coarser and the coarse fraction (sand fraction) of these soils tended to have appreciably larger X, ARM, and SIRM values than those of noncultural buried soils. As in our comparisons of whole soil susceptibility, however, we were unable to define a magnitude for any of these parameters for which we could in every case identify a soil as cultural.

When we examined the ratio of the coarse fraction to the whole soil for each of these properties, however, a distinctive signature did emerge. We found that the ratio of coarse to whole soil SIRM, showed a marked increase for all archaeological soils. Ratios of coarse to whole soil ARM and X did not distinguish the cultural soils in all cases, probably due to variation across a spectrum of magnetic grain sizes represented by the cultural additions. As a remanence property, SIRM would characterize only those grains at least SD in size. Cultural soils were distinguished by a disproportionate amount of this remanence residing in the coarse soil fraction. Our findings suggest that if the coarse fraction SIRM is approximately equal to the whole soil SIRM, than the soils are not associated with a cultural occupation. Ratios of coarse fraction to whole soil SIRM that are appreciable greater than one, would indicate a likely cultural association.

Figure 6 presents data from Core C samples at the Canning site. The noncultural soil sampled from 40-50 cm has an SIRM ratio under 1, as do underlying horizons represented by the subsequent three samples. The cultural layer was identified in the 98-106 cm layer and it is clearly indicated by a SIRM ratio of over 3.5. The presence of charcoal and dark soil in the 129-132 cm layer was suggestive of a cultural horizon. A relatively high SIRM ratio (approximately 2) supports this, although the presence of archaeological materials at this location has not been verified by excavation. The cultural horizon at the Canning D location was over 30 cm thick and this could also be the case at the Canning C locality with the high SIRM ratio for the 129-132 cm sample representing a continuation of cultural materials at the 98-106 cm depth. Alternatively, the elevated SIRM ratio may be related to movement of cultural material down the soil column, something we may have to be cautious about. Coarse to whole X and ARM ratios track relatively closely the SIRM ratio.

Figure 7 presents results from the Dahnke F location, which would correspond to the record seen in the Dahnke 5 core (Figures 3 and 5) in which a weak cultural soil (in Core F represented by the 80-90 cm sample) overlies a strong cultural soil (represented by both the 100-111 cm and the 111-129 cm samples). The SIRM ratio is approximately 1 for the horizon above the cultural soil. The weak cultural soil is distinctive with an SIRM ratio of 3.17 and the strong cultural soil has SIRM ratios of 5.66 and 4.31. There is some question about the sample from 90-100 cm; a visual inspection of the giddings core in the field indicated a lighter horizon located between the two cultural soils. The SIRM ratio does decrease, but it does not decrease to near 1 but only to 2.4. Again, until we are able to verify the presence of an insitu archaeological horizon between the two soils, we must exercise caution in defining the limits of cultural soils using these properties. Certainly the SIRM ratio shows great promise as an indicator for cultural soils, but its use might be complicated post-depositional movement of particles down the soil column. The results from Dahnke F also illustrate how ratios of coarse/whole X and ARM are not as reliable as the SIRM ratio: The S ratio of the lower soil ranges from 4.31-5.66, while ARM values are 1 or less and X ratios are over 8.

A study by de Jong and others (in press) examined the susceptibility of different size fractions of Gleysolic and Chernozemic soils and underlying tills in five cores from near Saskatoon, Canada. In the till and in the A and B and IC horizons, the susceptibility of the sand and silt fractions was similar or slightly larger than that of the bulk sample. This supports our conclusion that a ratio of near 1 for the coarse (sand) as compared to the whole (bulk) sample is an indicator of conditions that have not been significantly affected by cultural occupation. The only deviations from the pattern that de Jong and other saw in their cores were in two soils characterized by unusual soil forming processes. One was associated with burning (natural) and in this case the sand and silt fraction susceptibilities were lower than those of the bulk soil and the clay fraction susceptibility was higher. The other exception was a soil with a very high salt content and in this case the susceptibilities of the sand and silt fractions were higher than the bulk susceptibility. It is unknown whether the SIRM of these samples would also have been larger than that of the bulk sample. In distinguishing cultural from natural paleosols, we prefer the use of the SIRM ratio to either a ratio of coarse/whole X or ARM as the latter are highly dependent on variations across the SP-SD grain size boundary.

Heating experiments on the coarse and whole fractions of the cultural soil from the Core C location at the Canning site and the whole fraction of a noncultural buried soil from this same location did show promise of discriminating cultural from natural soils (Figures 8-10). Transitions representing two mineral phases or perhaps two blocking temperatures were observed on cooling for both the whole and coarse fractions of the cultural soil (Figure 8-9) that were not observed in the noncultural soil (Figure 10).

Other studies (Weston 2004, Marmet et al 1999) have indicted that examining a sample's response to heating has potential as a means of discriminating archaeological soils and that this variable response might be related to a sample's previous heating history. High-temperature studies of sediments can be difficult to interpret, however, as minerals chemically convert and change over the heating process. One may interpret what is produced but not necessarily the original composition of the sample. Also, heating experiments can be time consuming compared to room temperature techniques. For these reasons, the room temperature property of coarse/whole SIRM offers a number of advantages for discriminating cultural soils. It does not alter magnetic mineralogy and it is a relatively easy and quick parameter to measure. It does require, however, that the coarse fraction is separated from a larger sample.

Certainly the process that we employed to produce our textural separates could be improved. It would be preferable if both fine and coarse fractions were preserved and measured for comparison to the whole sample. For samples from the Rustad site, we tried an alternative process that involved dry sieving. This procedure was not effective for separating and concentrating that portion of the soil in which the distinctive cultural signature resided. We surmise that the failure of this method lies in the lack of a dispersing agent or process; the coarse fraction of the Rustad samples included dried aggregates of silt and clay that would have been separated by the process we used for our other samples.

Examining the coarse fractions under a petrographic microscope indicated that the cultural soils could be distinguished by the presence of distinctive light- and dark-colored nodules (Figure 11). These irregularly shaped nodules averaged 0.5 – 0.75 mm in size, although nodules greater than 1 mm were observed as well as fragments smaller than 0.5 mm. These tan, red, and black nodules were observed within the coarse fractions of cultural soils from both Archaic and Woodland Period sites. Other contents, such as charcoal, shell, and bone, and rock, were not represented in all soils, and were occasionally found in the noncultural soils.

Two archaeologists from the Department of Anthropology and Earth Science at MSUM, Dr. George R. Holley and Dr. Michael Michlovic, examined a sample of these nodules. They independently concluded, as did the project team, that the nodules were burnt clay. A sample of these nodules was sent to Rolfe Mandel at the Kansas Geological Survey, who also identified the majority of the nodules as burnt clay. Both he and Dr. Holley called attention to the variable nature of these nodules, however, and suggested that other materials and coatings were present beyond just oxidized (light) and non-oxidized (dark) agglomerations of clay. Magnetic measurements of the light and dark nodules described below, therefore, may be representative of a mixture of materials. It is also unknown whether the magnetic signal from these nodules derives primarily from the nodules themselves or from magnetic coatings or both.

Magnetic measurements verified that the nodules, in particular the light-colored (tan and red) nodules were the source of the magnetic signal that distinguished the cultural soils. Figure 12 presents the saturation magnetization of various components of the coarse fraction from the cultural soil at the Canning site. Not only did this signal reside preferentially in the coarse fraction, but it was also disproportionately found in the coarsest portion of the coarse fraction. Increasing Js values were observed for the fine (53-250 μm), medium (250-850 μm), and coarse (>850 μm) size subsets of the coarse fraction. Magnetic separates of these size subsets were more magnetic but did not approach Js values of the larger size subsets (a magnetic separate of the medium fraction was not possible as we did not have enough material in this size range to pack two samples for hysteresis measurements). The finest size grade produced Js values similar to those of whole and coarse fractions of noncultural buried soils from the site. Bone, charcoal, and other materials (not shown on this figure) were only weakly magnetic. Dark and light colored nodules were taken largely from the coarsest size grade. The saturation magnetization of the dark colored nodules was similar to that observed for the medium size fraction and for the entire coarse fraction. The light colored nodules were by far the most magnetic materials in the sample.

Low temperature measurements indicated some similarities and some differences between the light and dark nodules. Figures 13 and 14 present the results of the warming and cooling runs for the light and dark nodules. The light colored nodules are magnetically stronger, but otherwise they do not appear all that different from the dark colored nodules. A Verwey transition, indicating magnetite, is observed on the cooling leg for both samples under 100 K. This transition is observed on the warming leg for the dark nodules over a broader span of temperatures but it is not observed for the light colored nodules. As suggested by differences in color, the magnetite in the light nodules may be highly oxidized and thus would not show a Verwey transition.

Low temperature measurements of susceptibility over multiple frequencies (Figures 15-19) provide further information on the light and dark nodules and their host soils. A linear increase in susceptibility over most of the temperature spectrum for the dark nodules indicates a broader distribution of fine grains than observed for the light nodules which peak near room temperature. A slight Verwey transition was observed for the dark nodules (and also on the bulk sample from this cultural soil) which was not observed for the light colored nodules, again suggesting that the magnetite of the light colored nodules has been oxidized. The total spread across all frequencies indicates the concentration or amount of SP material in these samples. This is largest for the light nodules. The concentration of SP material in the dark nodules is similar to that present in the coarse fraction. The concentration of SP material is lowest in the bulk sample of the cultural and noncultural buried soils. These latter low-temperature records are dominated by the paramagnetic fraction (Figures 18 and 19). Calculating X_{fd} across a decade of frequencies allows the proportion or percentage of the SP material in the sample to be assessed. X_{fd} for the coarse fraction and for the light colored nodules is similar (ca. 7.5%), the dark colored nodules are slightly less (ca. 6.5%), and percentages for the whole cultural and noncultural samples are the least.

The low-temperature multiple frequency investigations thus indicate that the concentration of SP material is highest for the light colored nodules, yet the percentage of SP material (as gained from X_{fd} comparisons) is roughly the same for the light and dark nodules and for the entire coarse fraction. This agrees with our findings about magnetic enrichment from the whole soil samples. If the increase in the magnetic signal were due only to SP enrichment, then both concentration and percentage would increase, yet this is not the case. Therefore, we conclude that the light colored nodules are enriched in larger grained (SD) material as well as SP grains and that these larger grains are the source of the distinctive remanence-carrying signal noted in our coarse soil fractions. It is these nodules that allow us to distinguish the cultural from natural buried soils through the measure of coarse/whole SIRM.

A number of studies have looked at magnetic products of burning. Based on soil magnetic investigations of archaeological sediments from Orkney and Cyprus, Peters and Thompson (1999) concluded that burning was potentially an important source of fine-grained magnetic materials. They associated magnetic enhancement of the archaeological soils with SP grains close to the SP-SD boundary. McLean and Kean (1993) focus on wood ash produced in modern fire pits. This wood ash has an appreciable signature that derives from fine-grained iron oxides, probably magnetite, with a large contribution from SP grains. Linford and Canti (2001) conducted experimental studies with fires, considering contributions from ash and thermally altered soil, and exploring the effects of heating temperatures and times. Significant magnetic enhancement via fine-grained magnetic material was observed with short term (1-4) day campfires. Several potential mechanisms for enhancement were suggested including dehydration of lepidocroate to maghemite, conversion of paramagnetic clay minerals, or alternatively physical change in magnetic minerals such as reducing the size of MD particles or separating SP particles.

The focus of our studies has not been on the Superparamagnetic material produced through burning, but on those grains at and above the SP-SD boundary. We surmise that the distinctive nodules in the coarse fractions of the archaeological soils are the result of roasting soil directly beneath domestic fires. Thus, we are not focusing on the more mobile wood ash contribution but on the thermally altered soil. And though these nodules comprise a significant SP component, it is due to their enhancement with larger remanence carrying grains that we are able to track the presence of the thermally altered soil and thus to identify cultural horizons.

The presence of these burnt clay nodules alone might be sufficient for the identification of cultural layers. They are plentiful in our samples and certainly much more numerous than microartifacts. A caution is that we do not yet know if these nodules are also produced through natural fires though we suspect that temperatures would not be high enough to do so. We also do not know enough about the distribution of these nodules across sites and whether they are indeed present on a wide range of archaeological sites. We would suspect that they would not form in coarse textured soils. As the majority of buried sites found to date are in fine-textured environments, this may not be an issue for buried site investigations. These nodules may also be subject to post-depositional processes that alter their spatial distribution. Referring back to Figure 6, nodules were identified in the 129-132 cm layer, but not in the numbers present in the overlying layer. This explains the increase in the coarse/whole SIRM ratio but it does not conclusively identify this horizon as an *in situ* occupation layer; these nodules could have migrated down the soil column. Similarly, nodules identified in the layer intermediate between the two cultural horizons at the Canning site (Figure 7) could either relate to domestic fires at this level or to post-depositional mixing.

From a soil chemical perspective there may be other avenues for corroborating the identification of a buried cultural soil. In terms of the data generated for soils from our test sites, phosphorus levels were seen to track the soil magnetic response more consistently than any other property.

At present, a combined magnetic approach shows great promise for discriminating paleosols associated with human occupation. Future research agendas will focus on expanding these techniques across a broader range of sites and environments, examining samples derived from naturally burned soils, and further exploring the burnt clay nodules. Thin sections of cores from several sites have been prepared and are currently being examined by Dr. Paul Goldberg (Boston University). X-ray diffraction and Mössbauer spectroscopy investigations of the light and dark nodules will also be completed in the near future. These tests will allow us to move forward in understanding the source of these nodules and variation among them.

CONCLUSIONS

This project has offered significant contributions in techniques for buried site detection and in an understanding of anthropogenic effects on soil magnetism. The feasibility of new instrumentation has been demonstrated for mapping and identifying buried archaeological layers, a protocol for applying this instrumentation has been forwarded, a magnetic signature of buried anthropogenic soils has been suggested, and this signature has been used to forward specific lab techniques for discriminating buried land surfaces occupied by humans.

Buried site location is critical in many world areas where landscape change has impacted, and perhaps also preserved through burial, archaeological deposits. As these buried sites become increasingly threatened, the need to document them also increases: In order to protect and manage them we need to know where they are. We cannot keep relying on serendipity to find these buried deposits. It is imperative that we develop effective methods to locate buried sites and that we apply these methods in a systematic fashion to provide information useful in planning (Thompson and Bettis 1981).

Enhanced magnetic properties of developed soils and areas of cultural occupation provide an avenue for identifying buried soils and cultural layers. Down-hole magnetic susceptibility instruments offer a relatively non-destructive, rapid, and inexpensive method for finding and mapping these buried soils and layers.

This project has utilized newly available down-hole magnetic susceptibility technology to address a widespread and pervasive archaeological problem – that of locating and mapping buried archaeological sites. This new technology offers a minimally invasive means of mapping thin horizons and paleosols at depth within a 24-25 mm hole made with a push-tube corer. Measurements are reliable, rapid, and low cost. This technology can be applied to quickly identify subsurface layers or it can be applied as part of a more extensive mapping project to detail the extent, topography, and variation of subsurface layers. This technology is easy to apply with only minimal processing in the form of drift correction required. Forthcoming software will increase the ease of applying the MS2H and other Bartington field sensors.

Combined with soil magnetic techniques, this technology becomes even more effective in buried site investigations. Laboratory soil magnetic techniques provide a means of determining whether layers with enhanced susceptibilities documented through down-hole studies have a cultural association. These techniques track a distinctive magnetic component that we have identified in cultural soils from our test sites. In addition to enhancement of fine (SP) grains, these soils are enhanced additionally with grains at and above the SP-SD boundary. This magnetic component resides preferentially within the coarse (sand) fraction of the cultural soils. Remanence carrying properties of these grains allow us to distinguish these cultural soils.

While further work is required to fully understand this culturally produced signature, we have pinpointed nodules residing in the coarse fraction of the archaeological soils as the place where this magnetic signature resides. We strongly suspect that these nodules are comprised of burnt clay and that they result from burning or roasting of soil beneath domestic fires. Cultural soils can thus be identified by comparing magnetic properties of the whole (bulk) soil to coarse fraction (sand size) and in cases where this ratio is significantly greater than 1 a cultural origin can be assumed.

Whole to coarse SIRM is the most reliable ratio to use. While a ratio of X or ARM may work, magnetic grain size variations will affect their reliability.

Soil coring has traditionally served as one avenue for identifying paleosols. In our Giddings cores, however, we were unable to resolve all buried soils that were identified in larger test excavations. These other buried soils were distinguished in down-hole measurements through enhanced susceptibility values. The larger diameter Giddings cores were also more destructive and involved not only the expense of the coring rig but in several cases issues with access that were not a problem using the push-tube corer. In addition, soils collected with the push-tube corer were appropriate for laboratory soil magnetic tests that provided confirmation of a cultural association. In combination, the field and laboratory soil magnetic studies uniformly detected buried anthropogenic soils in all ages and types of sites in our study. Soil physical and chemical data derived from the Giddings cores did provide a valuable context for our soil magnetic interpretations. Phosphate testing tracked closely the soil magnetic data and hence could provide a corroborative technique for assigning a cultural origin. Another corroborative technique would be the presence of the burnt clay nodules. Ubiquitous in the cultural soils, the presence of these nodules, as well as other microartifacts, could serve as cultural indicators.

A vast literature has been generated within the fields of rock magnetism and environmental magnetism regarding the pedogenic enhancement process. The specific processes of magnetic enhancement in archaeological soils have been of long-standing interest (Longworth and Tite 1977; Mullins 1974; Tite 1972; Tite and Mullins 1971) but have not been so well explored. This project represents a significant contribution to an understanding of the nature and genesis of the magnetic signal of anthropogenic soils, moving beyond enhancement as a magnitude change to look specifically at distinctive enhancement products in soils on which prehistoric people lived.

Our study has focused on archaeological and nonarchaeological contexts in the Red River Valley region. Burnt clay, from fires burning on fine-grained substrates, has produced a distinctive magnetic signature within the archaeological deposits. As such, we think our approach has potential for broad application. Domestic fires and subsequent dispersal of thermally altered soils would characterize a wide range of archaeological contexts. While the magnetically enhanced nodules of soil would probably not form in a coarse-grained matrix, the majority of buried sites described in the archaeological literature to date are found within fine-grained alluvial material.

Therefore, we see the down-hole geophysical and soil magnetic package developed as part of this research as having the potential to approach the identification of buried sites across varied environments. This approach is importantly cost-effective, efficient, and relatively non-invasive. Future research will focus on expanding its use in different geographic regions and to different contexts, ages, and types of sites. Noncultural paleosols that have been burnt as a result of natural fires will also be studied to see if magnetic nodules form in these settings. Further analyses of the burnt clay nodules (micromorphology, Mössbauer spectroscopy, and X-ray diffraction) will be completed to more fully understand the composition and genesis of these soil aggregates.

The combined soil magnetic approach that has been developed will be of benefit not only in archaeology for buried site investigations but also in other disciplines that concern themselves with the identification of ancient land surfaces. This approach also has potential for application in archaeology beyond the identification of buried archaeological sites. For example, this distinctive soil magnetic signal of cultural soils could be used to track the process of earth movement in culturally constructed earthworks and to trace the cultural movement of soil across the landscape.

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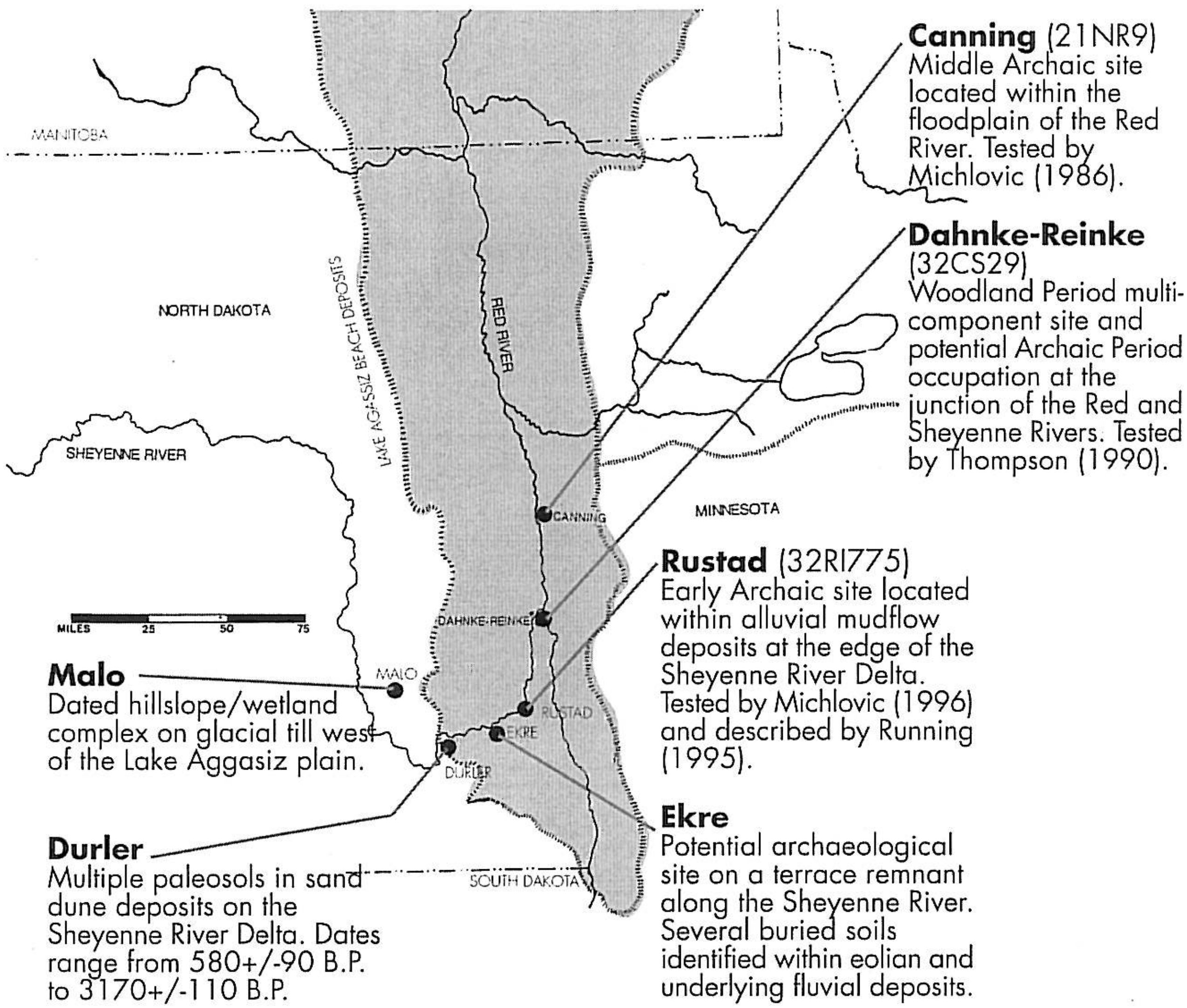

Figure 1. Locations of the six test sites within the Lake Aggasiz region.

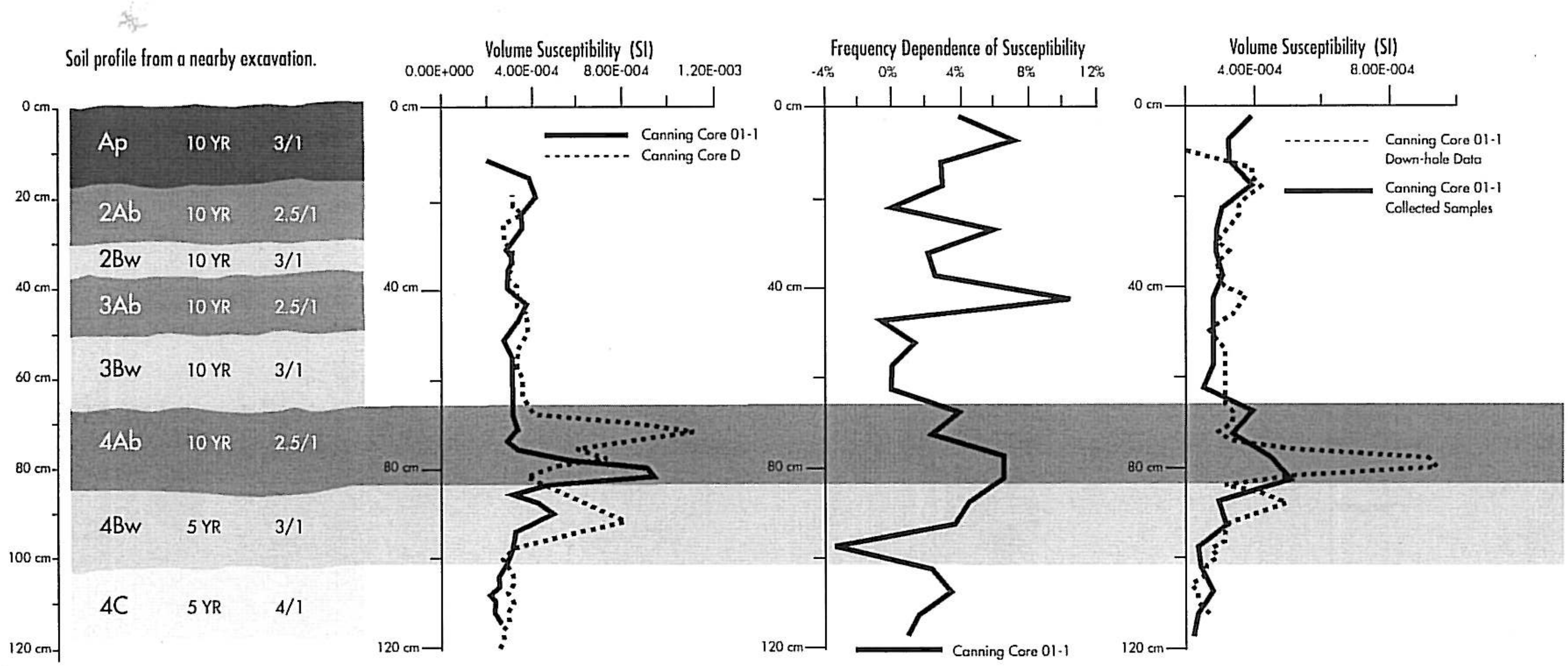

Figure 2. Selected Down-hole and Laboratory Susceptibility Data from the Canning Site.

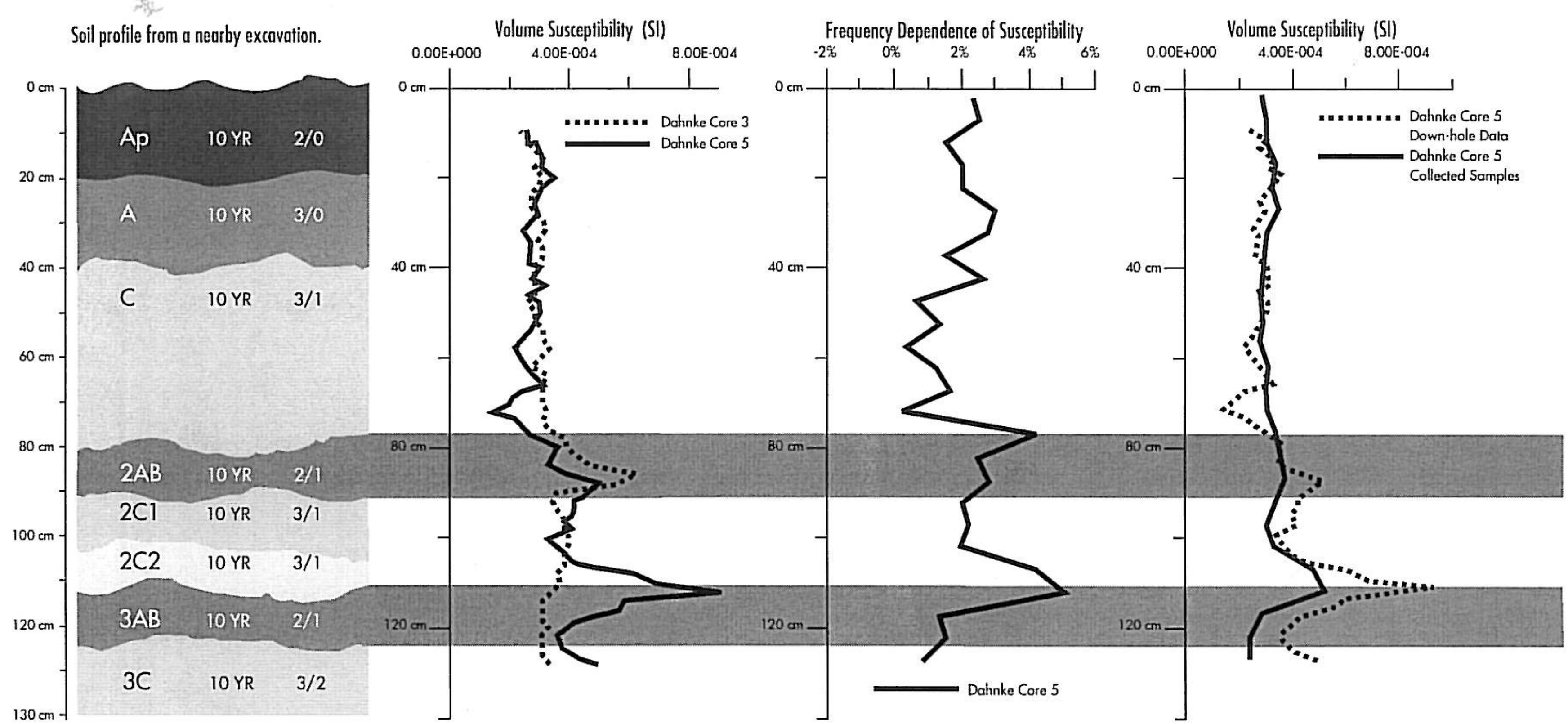

Figure 3. Selected Down-hole and Laboratory Susceptibility Data from the Dahnke Site.

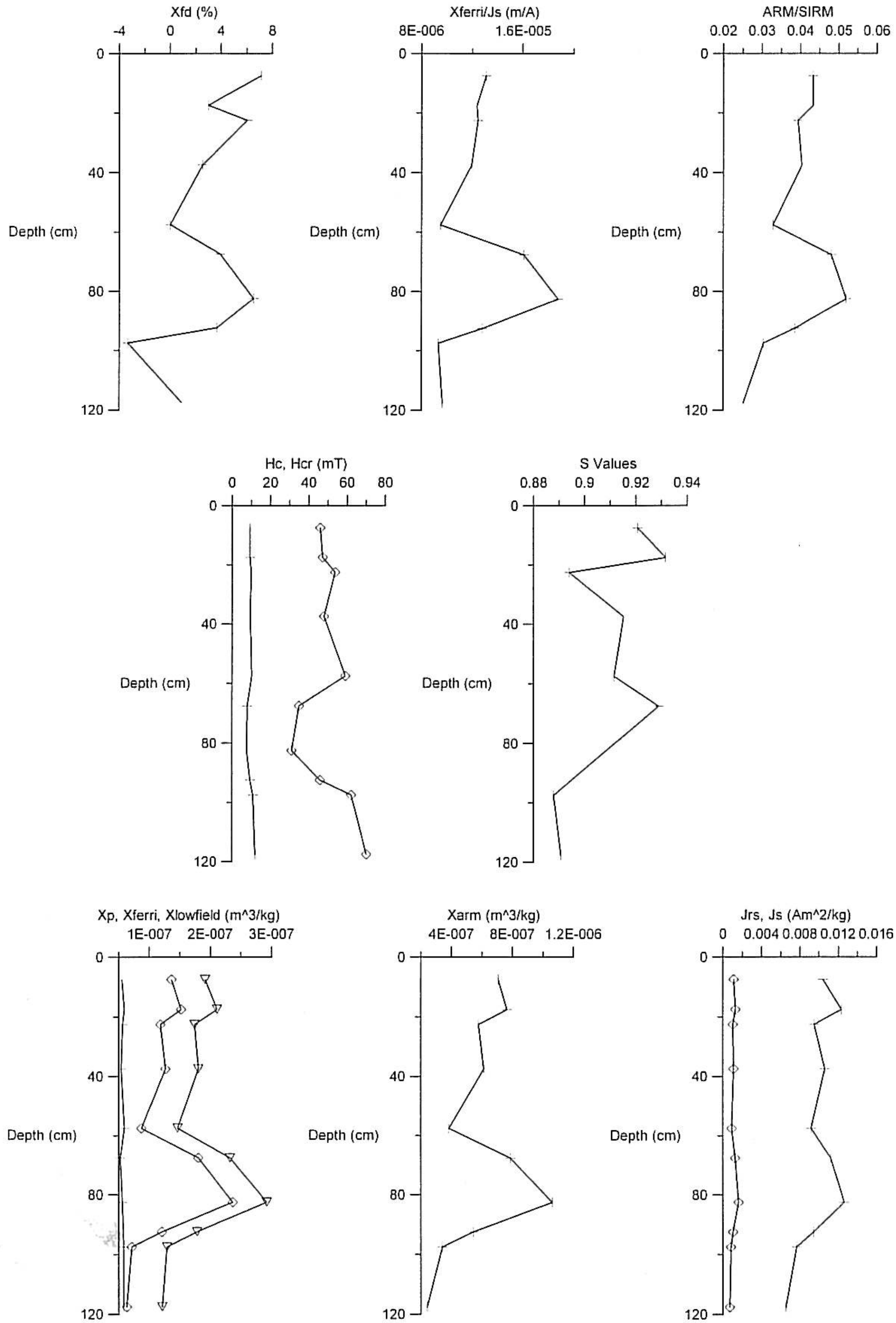

Figure 4. Selected Magnetic Parameters for Canning 01-1.

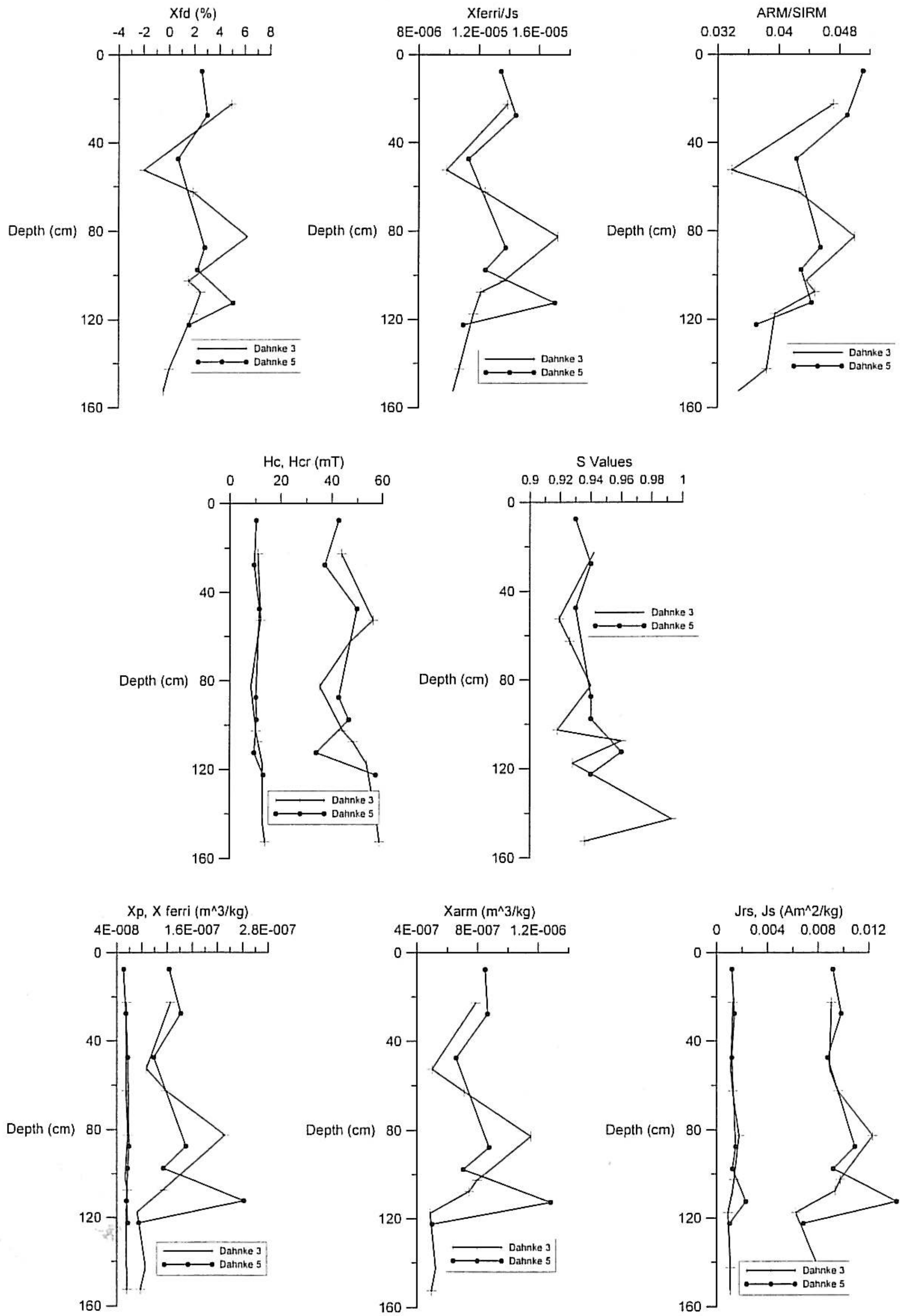

Figure 5. Selected Magnetic Parameters for Dahnke 3 and Dahnke 5.

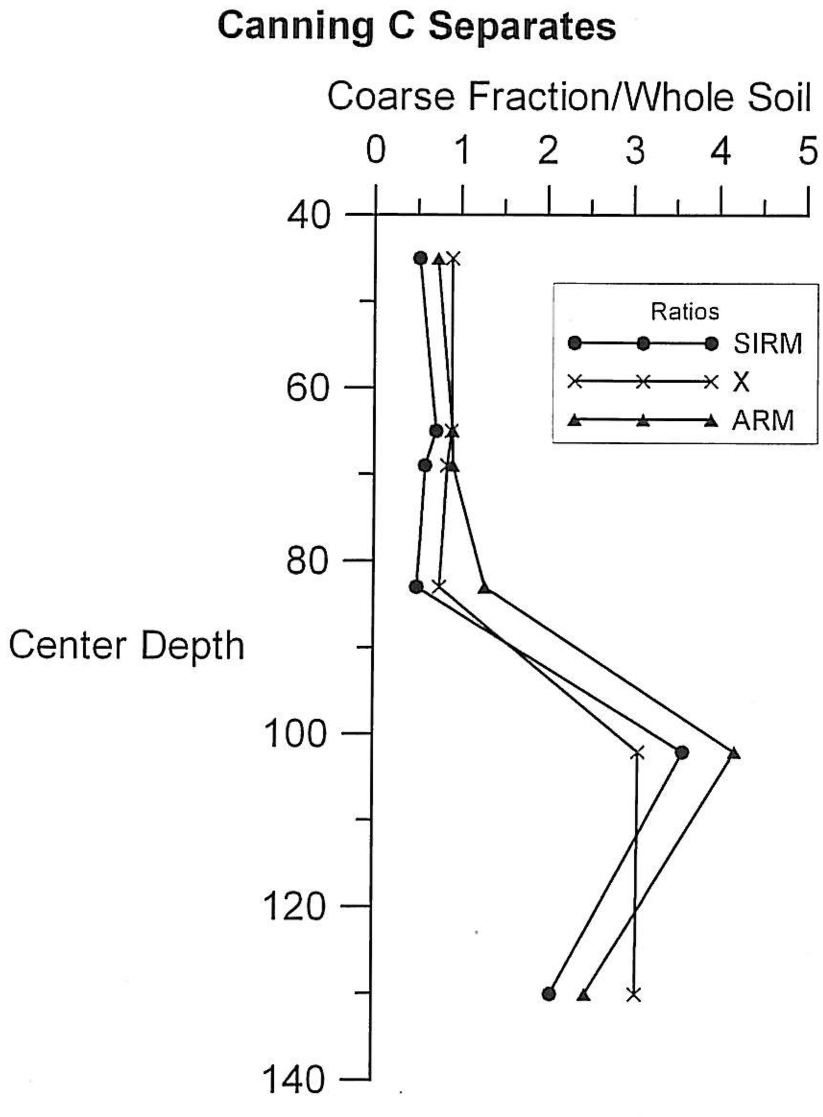

Figure 6. Coarse Fraction/Whole Soil Ratios for Canning C Samples.

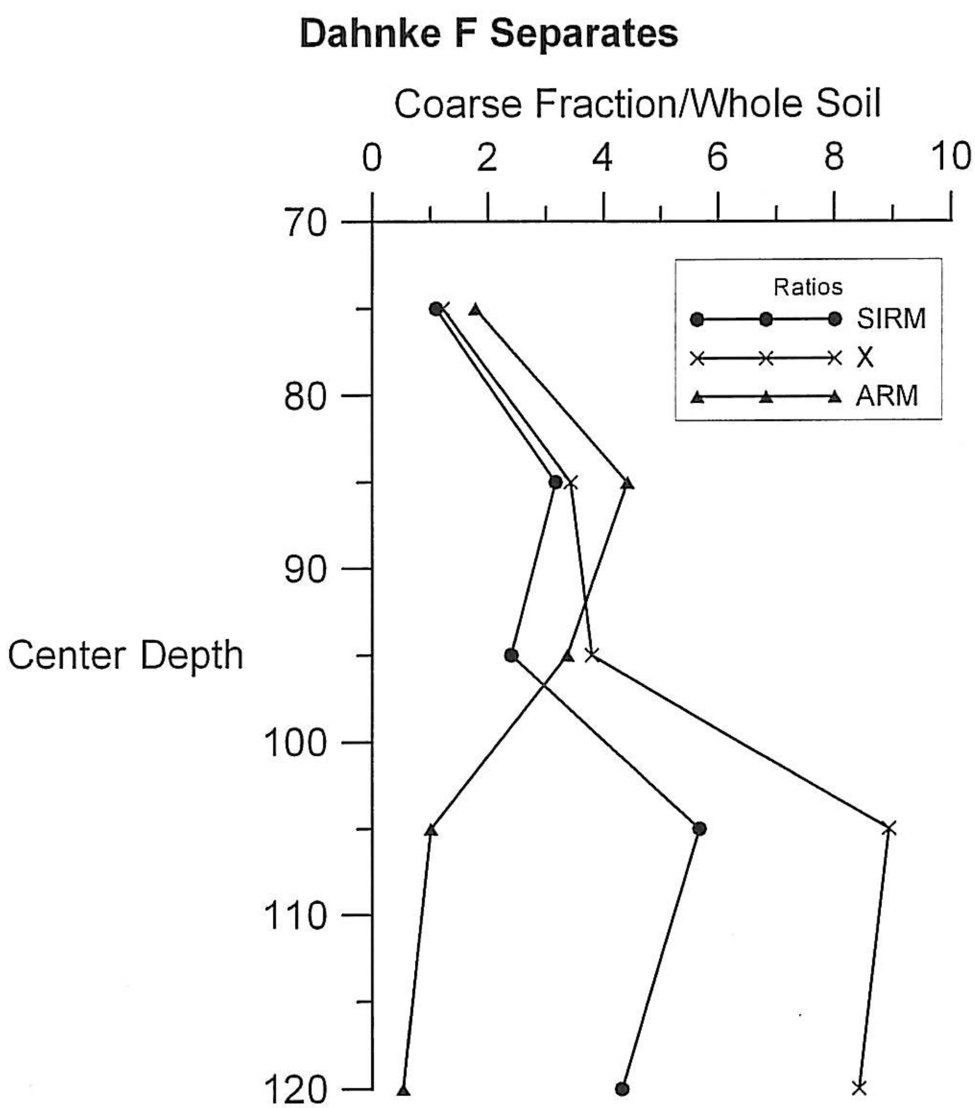

Figure 7. Coarse Fraction/Whole Soil Ratios for Dahnke F Samples.

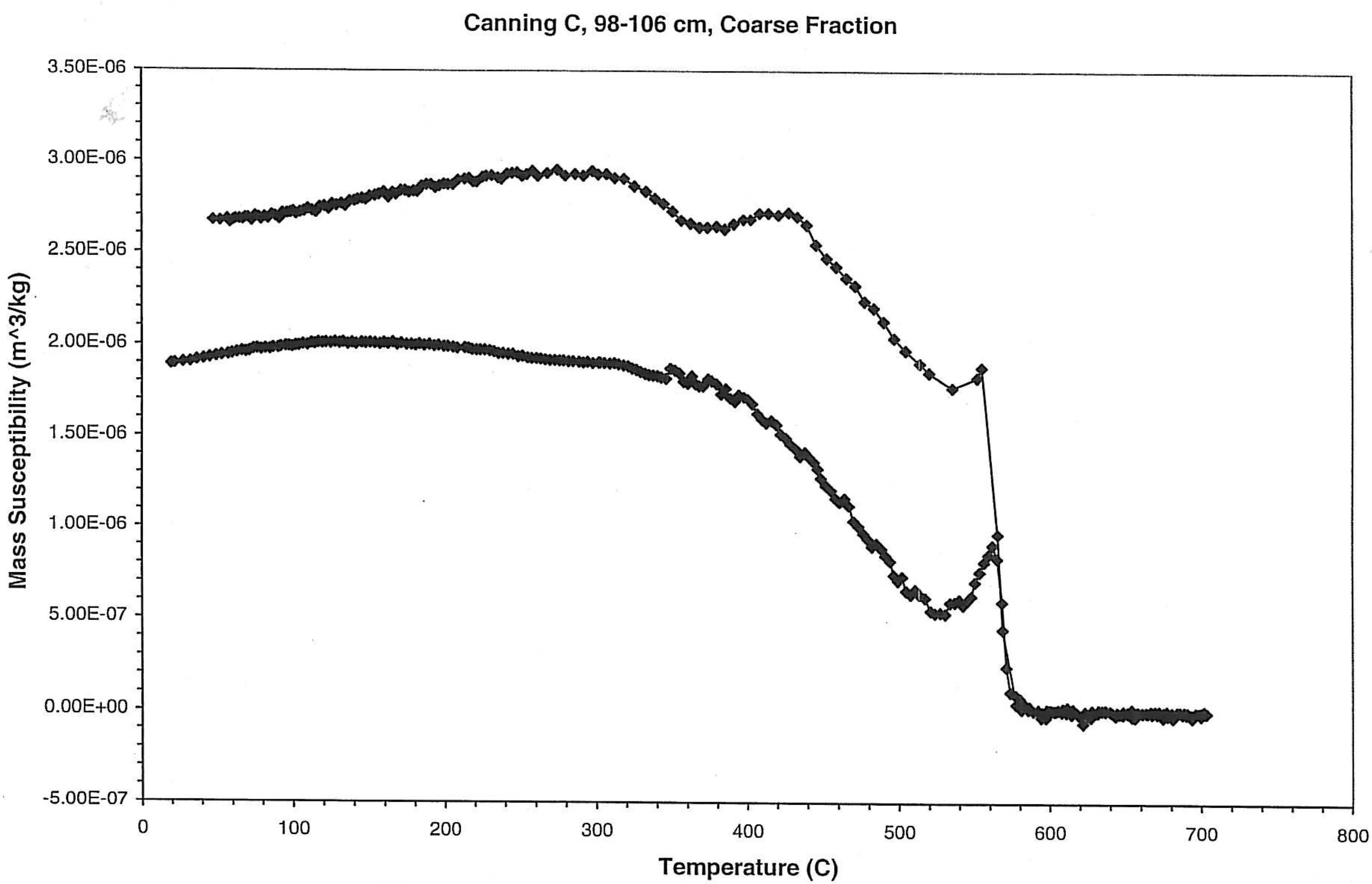

Figure 8. High Temperature Investigations, Canning Site, Cultural Soil, Coarse Fraction.

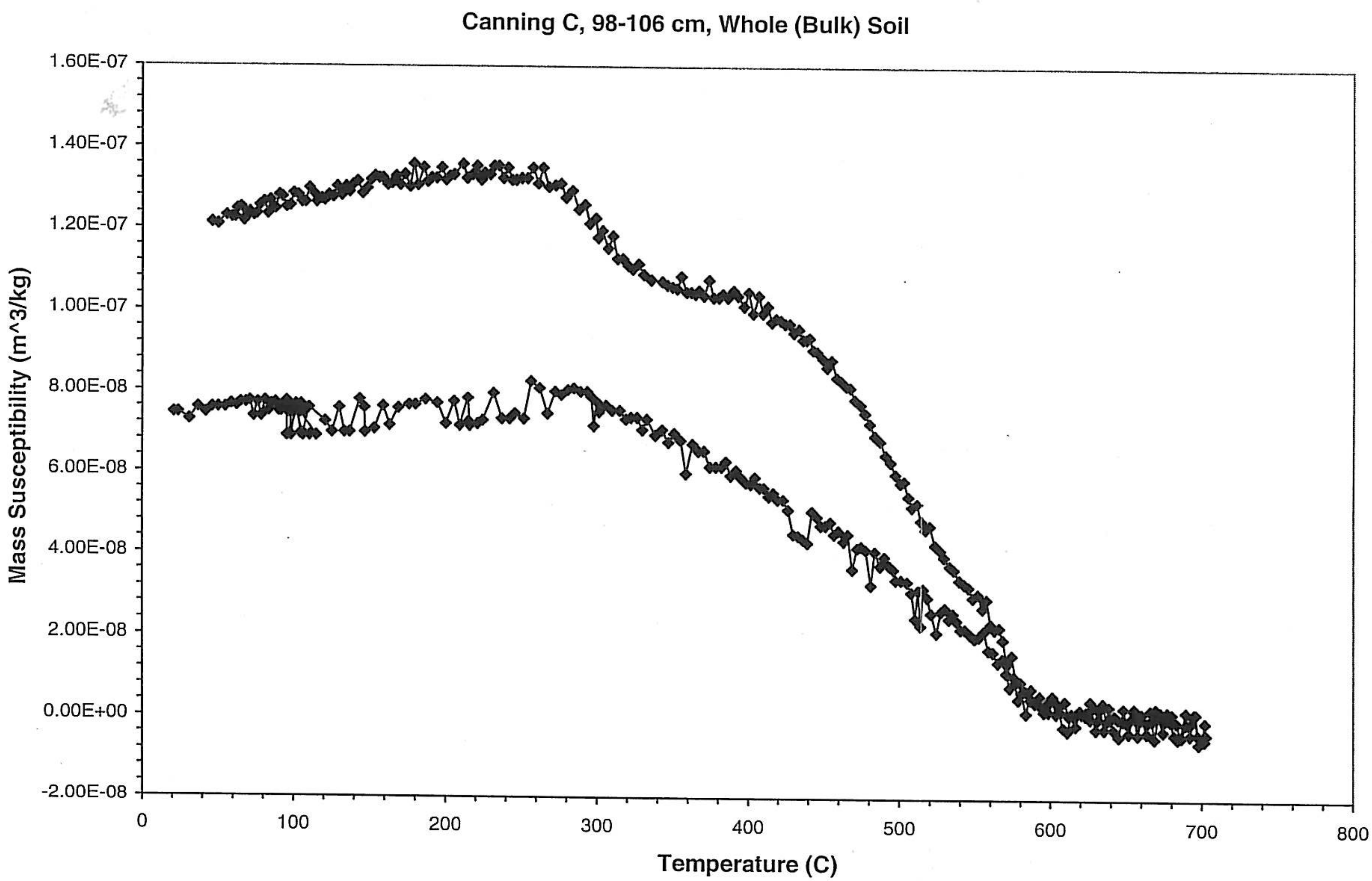

Figure 9. High Temperature Investigations, Canning Site, Cultural Soil, Bulk Sample.

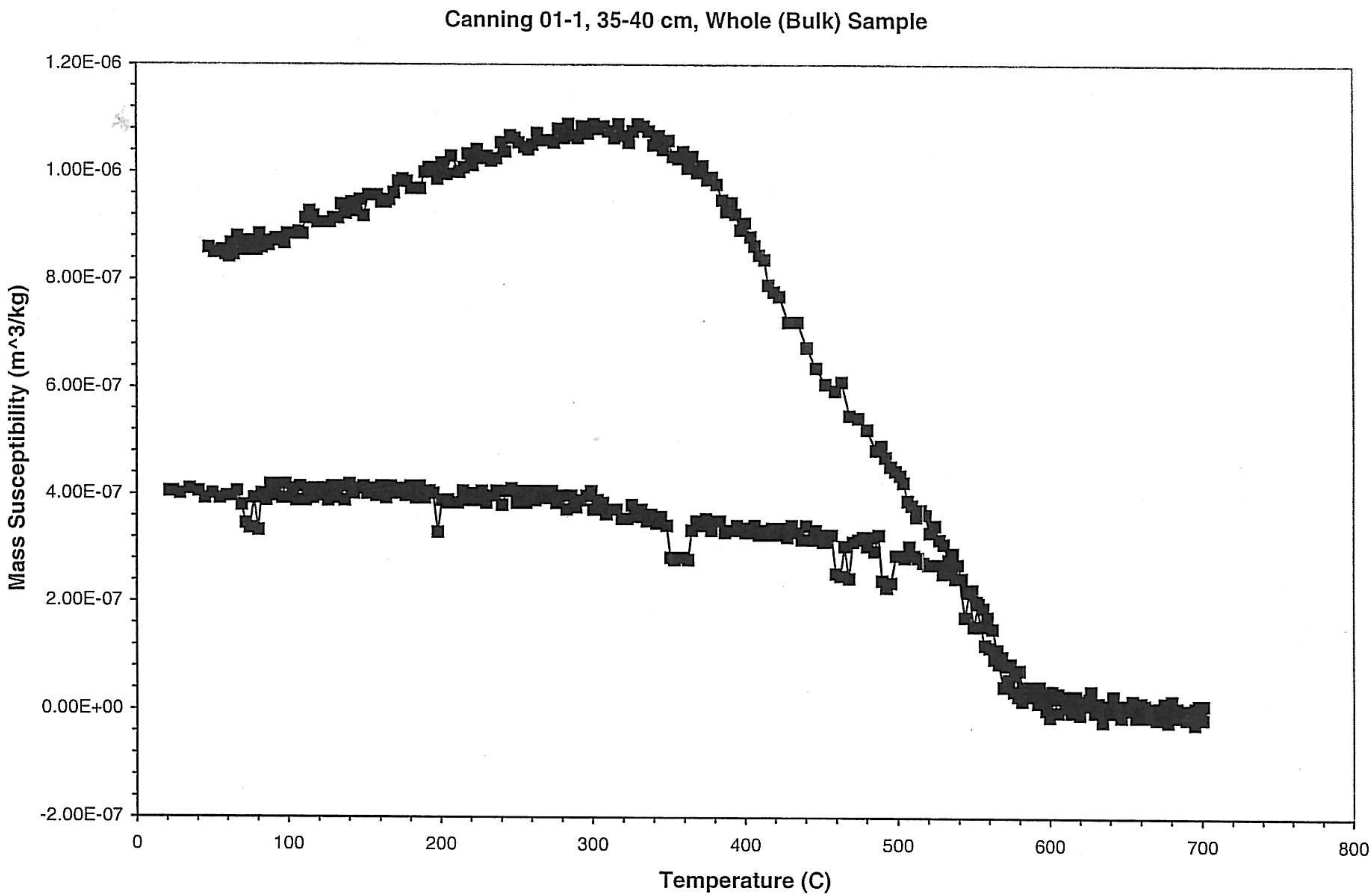

Figure 10. High Temperature Investigations, Canning Site, Natural Paleosol, Bulk Sample.

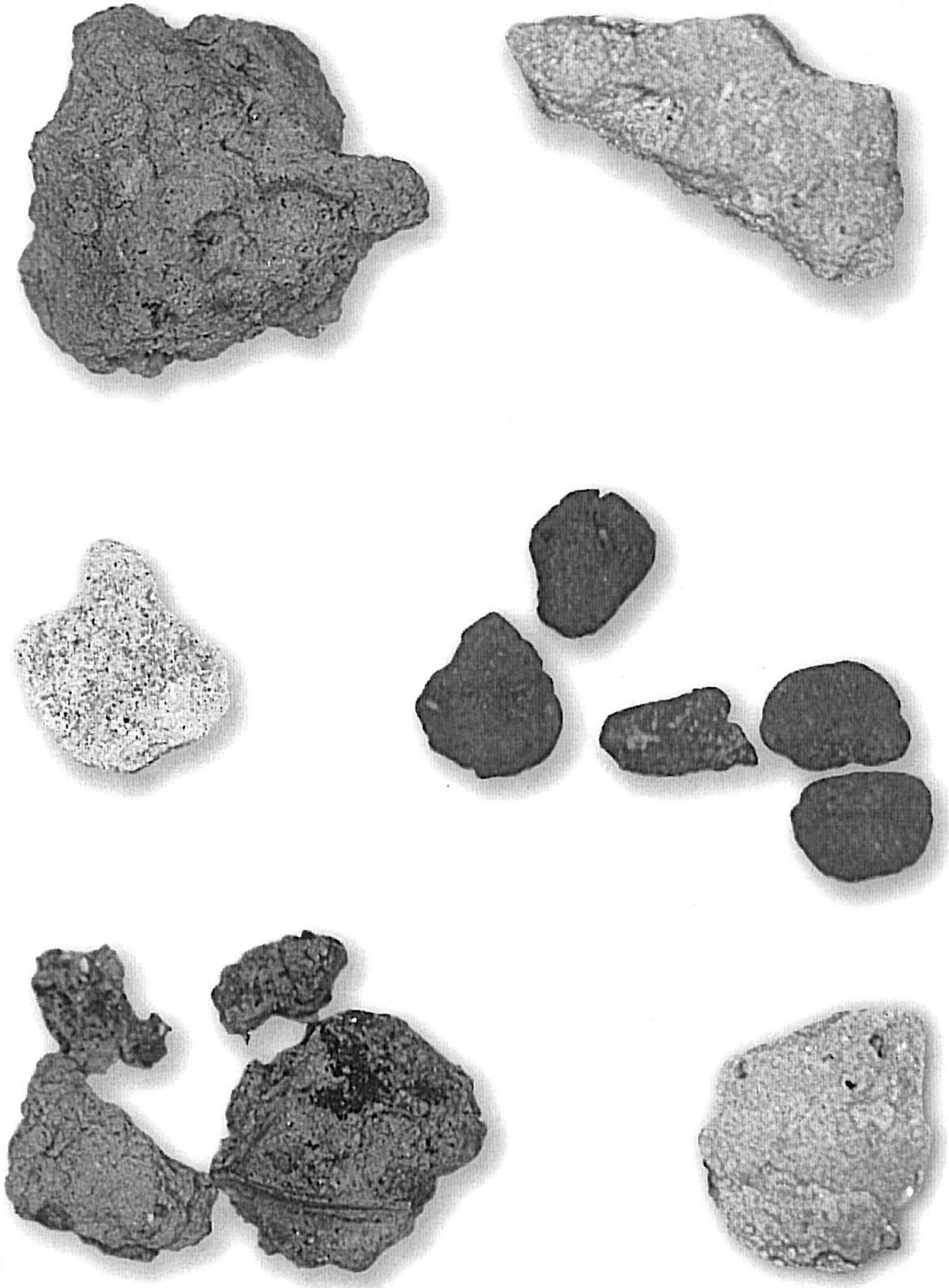

Figure 11. Examples of the light and dark colored nodules (average size is 0.5-0.75 mm).

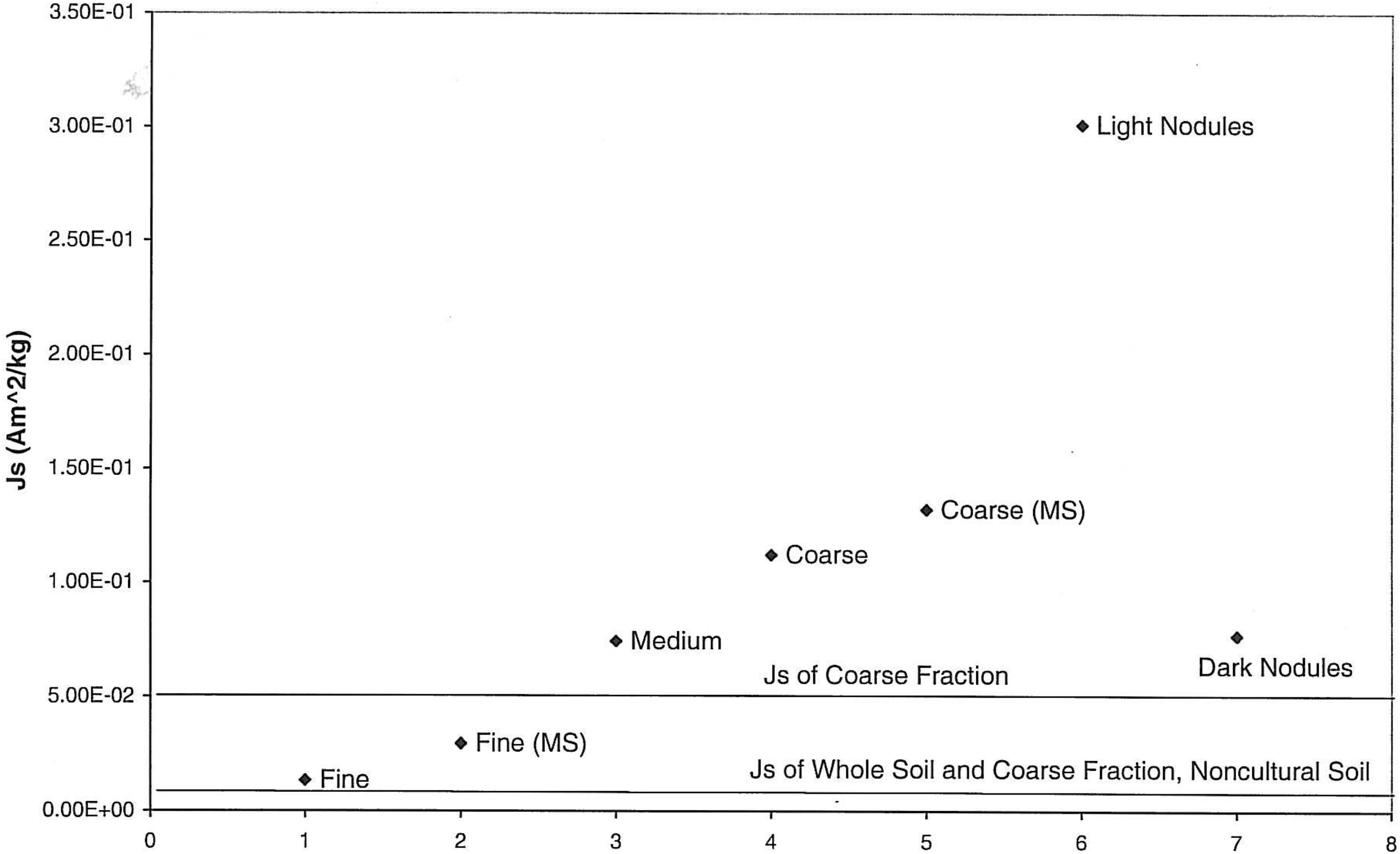

Figure 12. Canning C, 98-106 cm: Coarse Fraction Components.

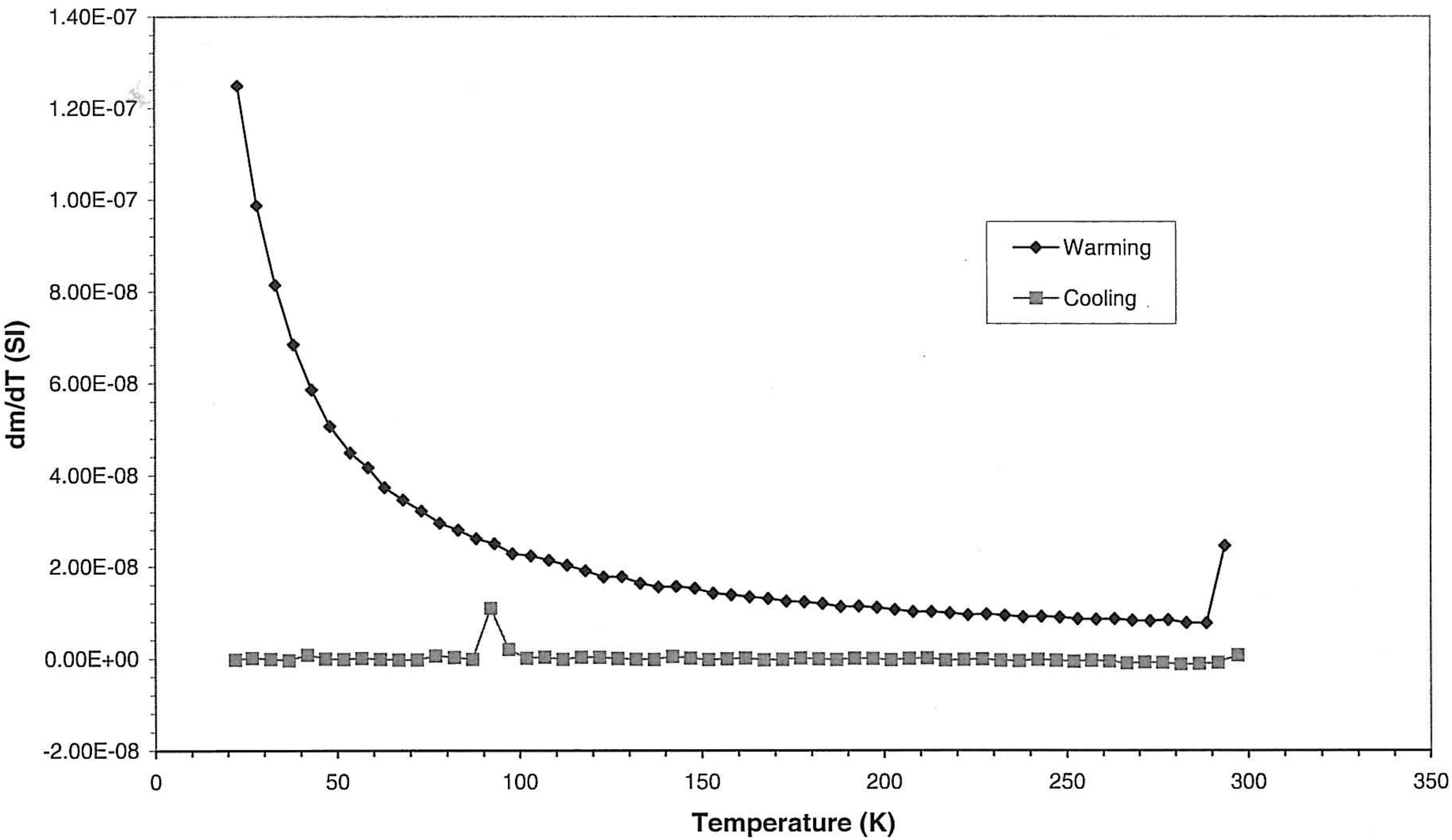

Figure 13. Low Temperature Investigations, Light-Colored Nodules.

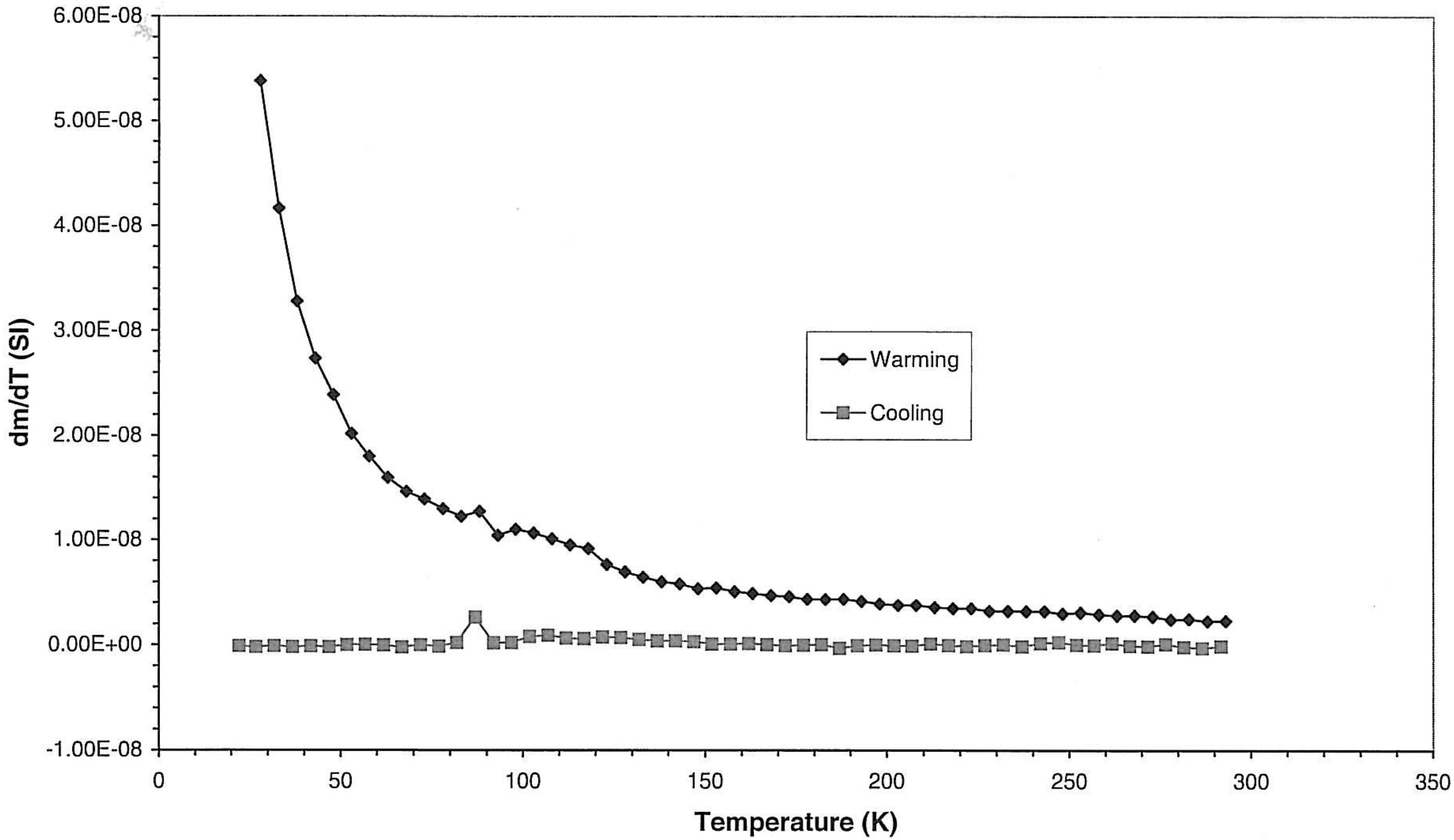

Figure 14. Low Temperature Investigations, Dark-Colored Nodules.

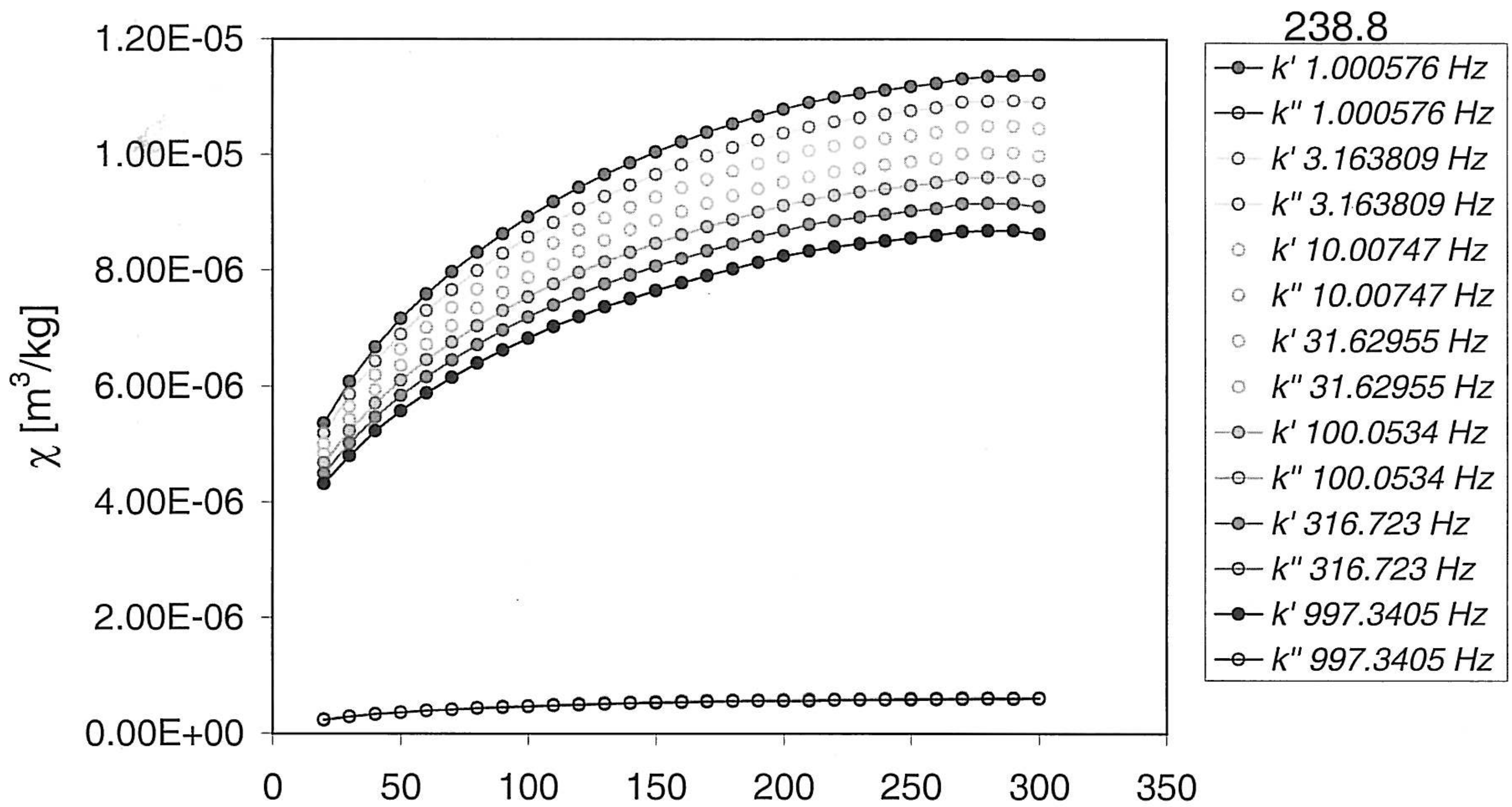

Figure 15. Low Temperature Multiple Frequency Investigations, Light-Colored Nodules.

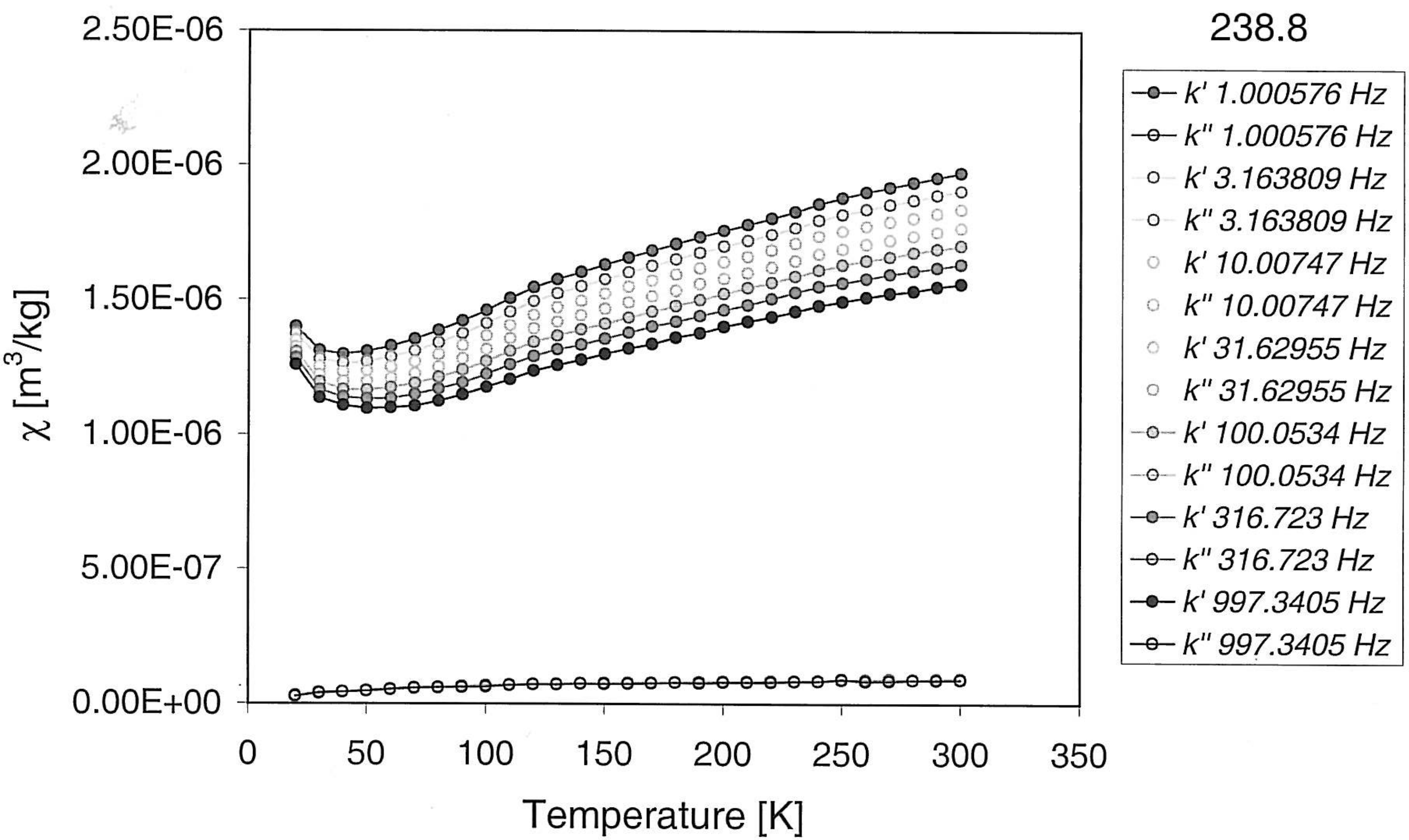

Figure 16. Low Temperature Multiple Frequency Investigations, Dark-Colored Nodules

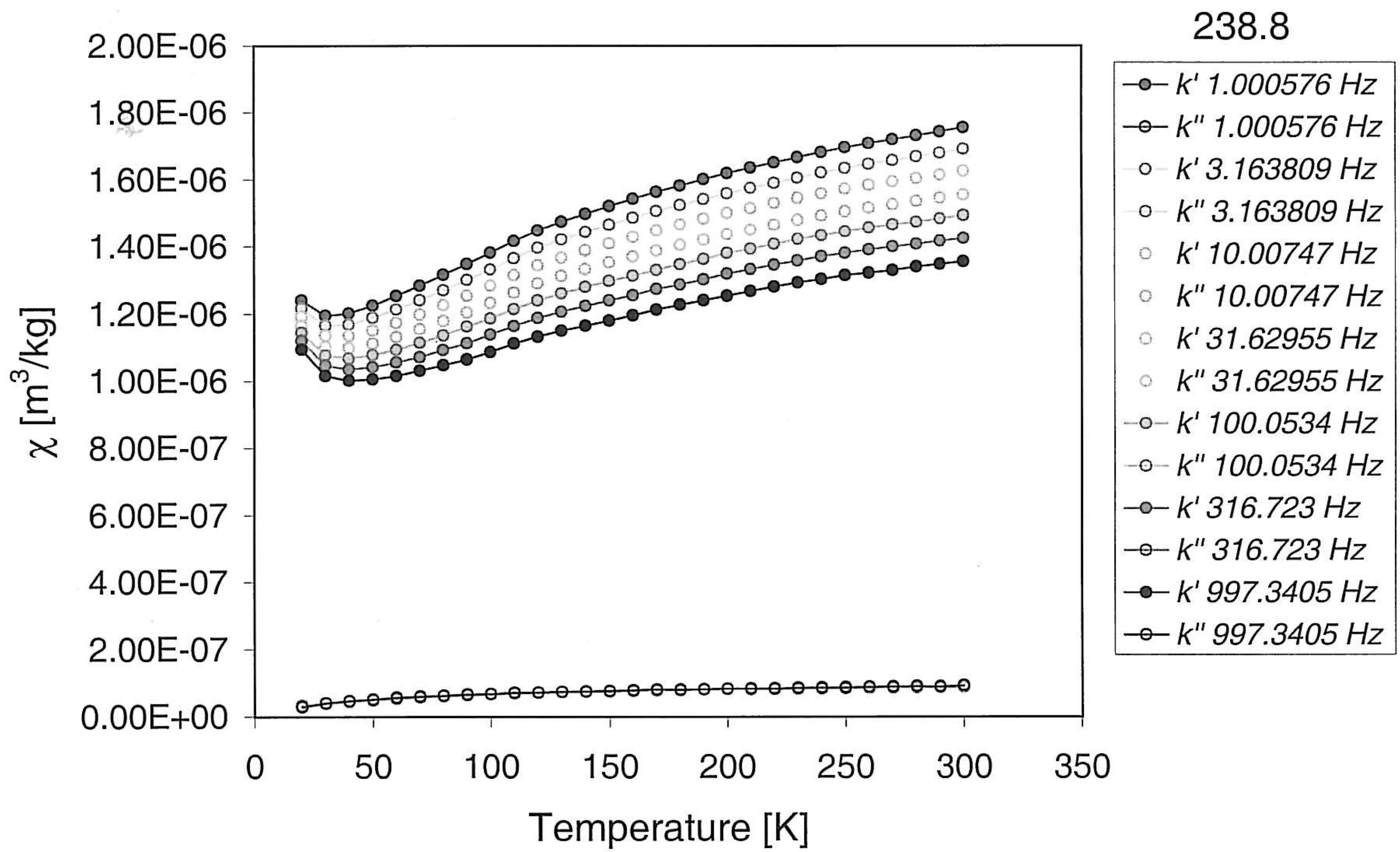

Figure 17. Low Temperature Multiple Frequency Investigations, Cultural Soil, Coarse Fraction.

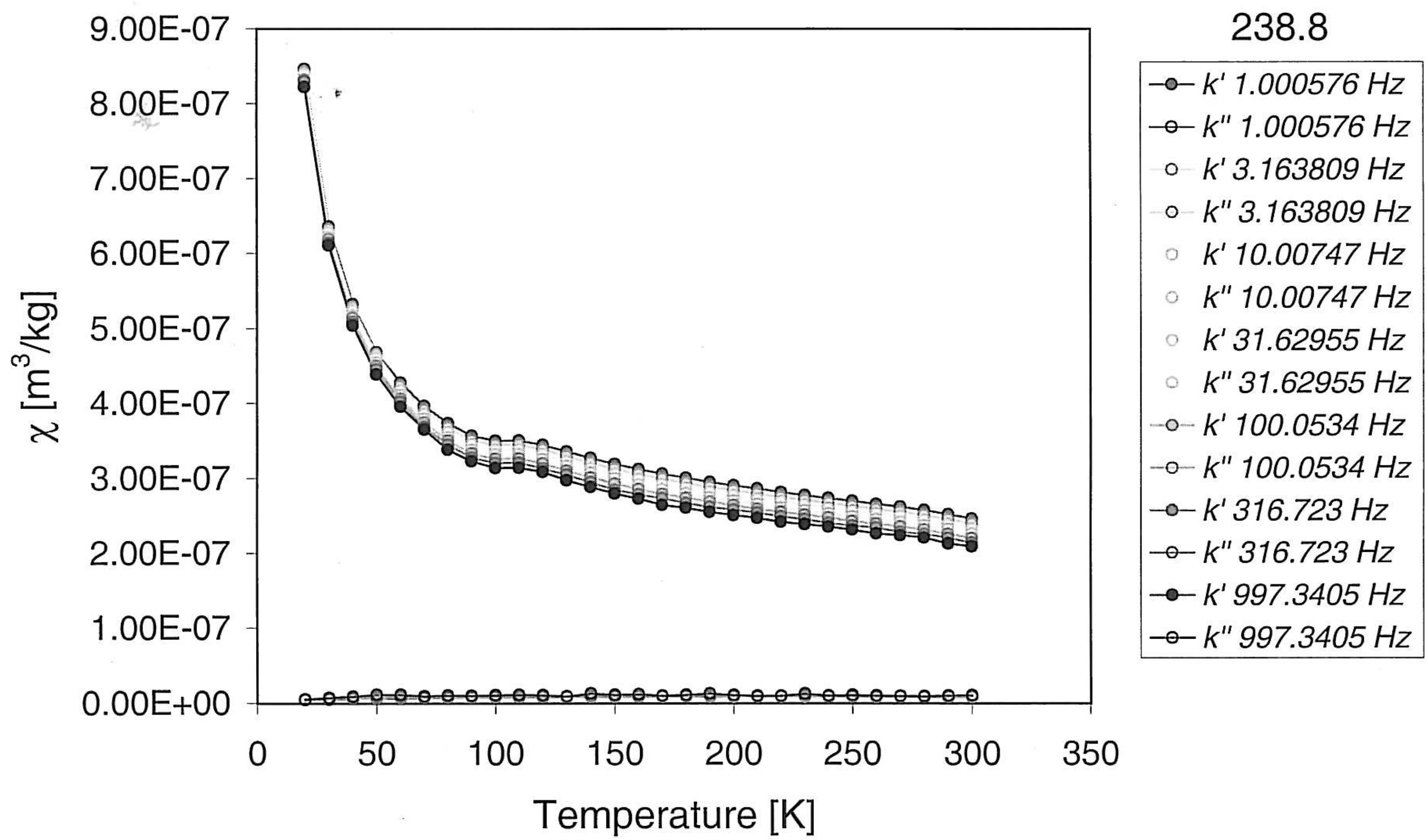

Figure 18. Low Temperature Multiple Frequency Investigations, Cultural Soil, Whole (Bulk) Sample.

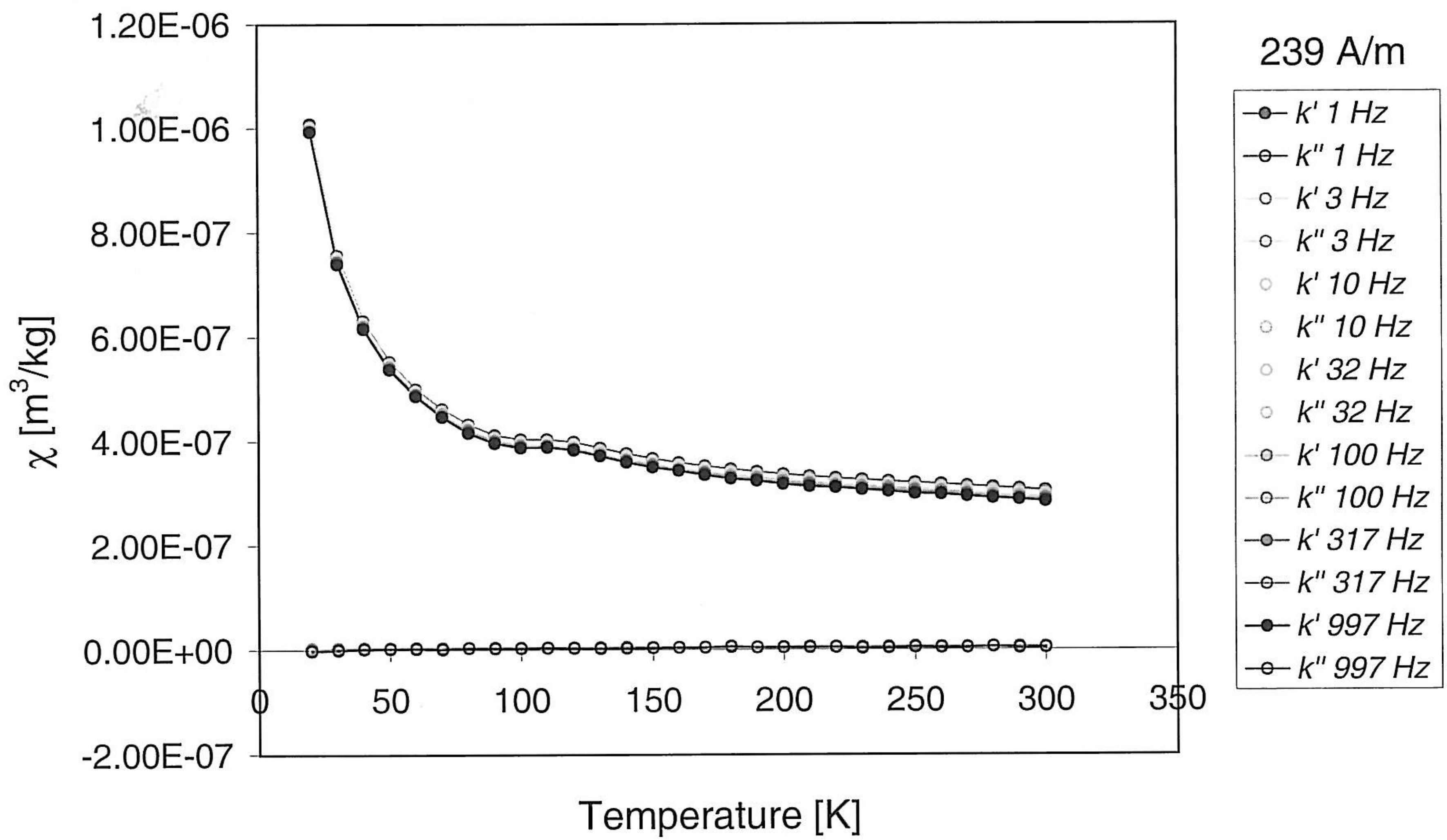

Figure 19. Low Temperature Multiple Frequency Investigations, Natural Soil, Whole (Bulk) Sample.